THE UNIVERSITY OF HULL

KARST WATER STUDIES IN THE MALHAM AREA, NORTH OF THE CRAVEN FAULTS

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by

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ABBREVIATIONS

cm = centimetre(s)

cusec = cubic foot per second

ft = foot, feet

gal = gallon (s)

in = inch(es)

km = kilometre(s)

l = litre

(l/sec = litres per second)

m = metre(s)

min = minute(s)

mm = millimetre(s)

N.G.R. = National Grid Reference

p.p.m. = parts per million

sec = second(s)

INTRODUCTION

"Science invites her admirers here, presenting one a knot of questions to solve respecting these rifted rocks, and those huge fragments of stone, that lie arranged in such orderly array ..."

These words written of the Malham area in 1847 by A. McFarlane seem particularly appropriate to commence a work which attempts to look at a few of the questions regarding 'those rifted rocks'. The study of karst processes is yet in its youthful stages and it is hoped that the research presented in this thesis will advance to some degree knowledge of that part of England which "presents us with creation in its boldest outlines" (McFarlane, 1847), in addition to furthering an understanding of the wider problems of the evolution of limestone terrains.

In contrast to much speculative and theoretical reasoning that typifies some recent writings in limestone studies this work is based primarily on systematic observations carried out on karst waters in the natural environment. There were six interrelated reasons for collecting this information:

(i) To investigate in detail the role of antecedent hydro-meteorological factors, particularly effective precipitation and air temperatures, in initiating;

  (a) temporal variations in solutional losses at the sampling sites,

  (b) variations in the temperature of water recorded at these sites, and

  (c) the pattern of discharge fluctuations recorded at the selected sites.

(ii) In view of the recent separation of karst water into 'allogenic karst water' and 'karst spring water', or into percolation-fed springs and systems of the sink-resurgence type, it was considered important to discover how contrasts in the mode of recharge to the limestone could affect the recorded pattern of solute concentrations at the risings and the pattern of water-temperature variation recorded at the risings.

(iii) Thirdly in view of the fact that recent work has pointed to the role of both lithological factors (Sweeting and Sweeting,1969) and hydrological influences (Pitty,1968, 1971) in affecting mean solute concentrations in karst waters, regional variations in the mean solute concentrations and in the variability of solute concentrations are examined.

(iv) Fourthly to discover those factors instrumental in causing regional variations in the mean temperature of water discharging at karst risings in the field area, and in causing regional variations in the level of fluctuation of water temperature at karst risings.

(v) To investigate seasonal and regional differences in the time taken for circulating water to pass through the limestone systems (flow-through times).

(vi) Lastly to accumulate evidence concerning the nature of water disposition and ground-water flow in the limestones of the field area.

This research was carried out in the Fountains Fell and High Mark upland areas of the central Pennines. These two areas provide a contrasting geological framework for this work, one area (Fountains Fell) being of limestone partially covered by Yoredale and Millstone Grit series, and the other (High Mark) consisting almost completely of Great Scar Limestone. Geological differences have given rise to the hydrological contrasts between the two areas with which some of this research is concerned.

In addition this is an area of the Pennines in which comparatively little work has previously been carried out, earlier interests having been mainly centred on the Ingleborough area to the west, the locality of Malham and Malham Tarn, or in the southern Pennines.

On account of the fundamental significance of geological, hydrological, biological and climatic factors to the operation of karst processes,a full description of these aspects of the field area is included in this work.

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CHAPTER ONE

THE PHYSICAL BASIS

A The Location and Delimitation of the Field Area

B Relief and Drainage

C Climate

D Vegetation and Soils

E Geology

F Bibliography of Chapter 1

THE PHYSICAL BASIS

A The Location and Delimitation of the Field Area

The area in which this research was carried out is located in north-west Yorkshire (Map 1) to the north of the North Craven Fault and comprises the Fountains Fell-Darnbrook Fell upland in the west, and the High Mark limestone region in the east (Map 2).

These two upland units are delimited on the southern margins by the line of the North Craven Fault which for much of its boundary with the field area has brought non-calcareous rock in contact with the Great Scar Limestone of the field area. The other boundaries to the field area are provided by the major rivers and valley systems of the region. The Fountains Fell area is delimited to the south-west by Silverdale and Silverdale Gill, by Penyghent Gill in the north-west, upper Littondale and the River Skirfare in the north-east, and Cowside Beck (Skirfare) and Malham Tarn to the south-east and east. Similarly the High Mark upland is bounded by Cowside Beck (Skirfare) and Malham Tarn to the west and north-west, lower Littondale and the River Skirfare to the north-east and Wharfedale and the River Wharfe to the east. Although the High Mark area so defined actually comprises the upland of High Mark, Proctor High Mark, Hawkswick Clowder and Kilnsey Moor, the name High Mark has been used for convenience in this thesis to denote the area delimited above.

B Relief and Drainage

The Fountains Fell area is an upland moorland region of about 54 square kilometres (21 square miles) in area. The highest point (667.5 m or 2,190 ft OD) is part of a high summit plateau, a remnant of the 610 m (2,000 ft) erosion surface described by McKenny Hughes (1901) and by Sweeting (1950). More striking on a local scale are the thousands of small enclosed hollows which are located in lines along the line of the

Yoredale limestones (Clayton, 1966) and perform an important role in the drainage of the area (see below). To the east of Fountains Fell the High Mark upland forms a high limestone area about 46 square kilometres (18 square miles) in extent. This region is generally about 457 m (1,500 ft) OD and rises to 538 m (1,765 ft) OD at Parson's Pulpit (Map 2). South of this the land falls away to the extensive platform around Malham Tarn at about 396 m (1,300 ft) which provides a large remnant of the 396 m (1,300 ft) erosion surface of Sweeting (1950). The High Mark area is a region of bare limestone pavements, vertical scars or cliffs, dry valleys and large enclosed basins. The formation of the dry valleys has been attributed to the action of former surface streams (Sweeting, 1950; Moisley, 1954), although Clark (1967) believes their origin is closely related to the action of glacial meltwater. In the High Mark area large enclosed basins (Plate 1) of up to 81 hectares (200 acres) in extent have been described by Moisley (1954) who tentatively suggests that they may have originated as large potholes or swallow holes. A number of these features have, however, been ascribed to glacial meltwater action by Clark (1967).

On a much smaller scale are numbers of small enclosed hollows similar to those found on Fountains Fell. There are, however, relatively few in number, as compared to Fountains Fell, and are found chiefly in the western part of the High Mark area in association with boulder clay patches.

The High Mark and Fountains Fell areas occupy an important location regarding the major drainage pattern of the north of England. The major watershed between the Irish and North Sea drainage systems runs from Blackhill to the west of Malham Tarn, across Knowe Fell and Fountains Fell to Penyghent. Rising to the west of Blackhill, Cowside Beck (Ribble) flows westwards to the Ribble and to the sea. Smelt Mill stream, Malham Tarn outflow and Gordale Beck rising to the east of the watershed drain to the Aire. Further north Darnbrook Beck, Cowside Beck (Skirfare) and the Skirfare join the Wharfe and hence eastward. The Skirfare and the Wharfe both flow in major valleys which cut almost to the base of the limestone and provide clearly defined limits of the field area to the north-east and east.

Apart from a few larger streams such as Tennant Gill and Darnbrook Beck the Fountains Fell area is characterised by numerous small local streams flowing off the non-calcareous caprock or over the largely impermeable boulder clay. These streams generally sink on contact with the limestone members of the Yoredales or on contact with the main limestone mass. Many of these streams may sink and resurge several times before finally emerging near the base of the mountain defining the major valleys.

In addition to these small streams which are usually ephemeral in nature, the numerous small enclosed hollows usually collect very local run-off and seepage water which is then channelled underground. Although these hollows may scarcely be termed swallow-holes or swallets in the sense of swallowing an actual stream, they do, because they are so numerous, play an important role in recharge to the limestone systems of the Fountains Fell area.

By contrast the High Mark is characterised by an almost complete absence of any surface drainage either in the form of major streams or as localised drainage. The few exceptions to this are provided by Cotegill, Howgill and Gordale Beck. All three streams are often dry for much of their course, and except in wet conditions Howgill Beck flows only in the lower part of its course. Cotegill provides the only true sinking stream in the whole upland. Small enclosed hollows in the High Mark area appear, for the most part, to be inactive, often containing small stagnant peaty ponds. The large enclosed basins may, however, still play some role in the drainage of the area as is suggested by the regional analysis carried out in Chapter 7.

The two parts of the field area, Fountains Fell and High Mark, show a strong contrast in terms of drainage and the nature of recharge to the limestone. In the Fountains Fell area recharge generally takes place by sinking streams and by rapid percolation through active enclosed hollows. By contrast recharge in the High Mark area is almost purely by percolation. The contrasts between the karst waters of the Fountains Fell systems and those of the High Mark systems frequently observed in this thesis largely reflect these contrasts in the mode of recharge.

C Climate

The following review of the climate of the field area is based largely on the weather recordings made at Malham Tarn Field Centre and the analysis of these recordings carried out by Manley and Straw in 1957. A number of local factors have been considered important in influencing weather conditions at this site. Trees growing to the east and to the west of the weather station at Malham Tarn in addition to the 61 m (200 ft) high cliff of Highfolds Scar north of Malham Tarn House may have an important effect on both wind direction and velocity; the tarn itself is believed to have a slight ameliorating effect on the temperatures recorded at this station, particularly in the autumn months (Manley,1957). However, many parts of the field area may be equally subject to micro-climatic effects, and, although in detail parts of the field area may deviate from the observations made at Malham Tarn, the general weather and climatic pattern prevailing at this site is believed to be representative of most of the field area.

In general terms that part of north-west Yorkshire comprising the Fountains Fell-Darnbrook Fell and the High Mark uplands (see above) may best be described as cool, wet and windy.

On the basis of seven years of air temperature observations at

Malham Tarn and a comparison of these observations with those of Ilkley and Stoneyhurst, 29 and 35 km (18 and 22 miles) distant, Manley (1957) calculated that the mean annual air temperature at Malham Tarn was 7.0°C (44.6°F) over the period 1921 to 1950. Similarly, he calculated a mean annual air temperature range of 12.0°C(21.6°F) with the coldest temperatures occurring in January (1.5°C or 34.7°F) and the warmest in July (13.5°C or 56.3°F). Over the period 1968 and 1969, when the greater part of the present work was carried out, the mean annual air temperature at Malham Tarn was 6.72°C (41.1°F) for both years, 0.28°C (0.5°F) less than the mean calculated by Manley (1957). In both 1968 and 1969 the minimum monthly mean temperature was recorded in February (-0.1°C or 31.8°F in 1968; -2.2°C or 28.0°F in 1969). In 1968 the highest mean monthly temperature was recorded in August (12.8°C or 55.0°F) and in 1969 in July (15.0°C or 59.0°F). The temperature range over both years (12.9°C or 23.2°F in 1968; 17.2°C or 31.0°F in 1969) was therefore considerably greater than the average calculated by Manley (1957).

Of great relevance to this study are factors such as the incidence of air and ground frost and the length of the growing season. Manley (1957) showed that air frost (days on which a minimum air temperature of 0°C (32°F) or less was recorded) could be expected on 90 days each year, and that on 12 days the maximum air temperature would not exceed freezing point. In 1968 and 1969 air frost was recorded on 102 days (1968) and on 121 days (1969), and the maximum daily temperature did not exceed freezing point on 15 days in 1968 and 32 days in 1969. The expected incidence of ground frost (days in which the grass minimum temperature did not exceed -0.89°C or 30.4°F) was calculated by Manley (1957) as 143 days. In 1968 ground frost occurred on 118 days and on 125 days in 1969. This freezing of the ground may be effective in reducing the rate of infiltration to the ground-water and in influencing the temperature of recharge water over the winter period.

The air temperature observations over the period 1968 and 1969 indicate a growing season (period with temperatures greater than 5.6°C or 42°F) of between 6 and 7 months, in close correspondence to that observed by Manley (1957) (15 April to 1 November). The significance of this factor in influencing the level of carbon dioxide in the soil and indirectly the degree of limestone solution is believed to be important by a number of researchers (Chapter 4).

The Malham Tarn area is characterised by a high annual rainfall with a high incidence of measurable precipitation. The mean annual rainfall over the period 1881 to 1915 was 145.8 cm (57.4 in) with measurable rainfall expected on 220 days (Straw,1957). In 1968 153.8 cm (60.57 in) of rainfall occurred at Malham Tarn and almost 28 cm (11 in) of this total was recorded in September of that year (Fig.1). 1969 was considerably drier with only 120 cm (47.26 in) of rainfall recorded at Malham Tarn, November being the wettest month with 19.3 cm (7.59 in) of rainfall recorded (Fig.2). In both years February was the driest month.

A comparison of the annual rainfall totals recorded at Malham Tarn with those of nearby sites suggests that a slight eastward decrease in rainfall occurs over the field area, although the records, however, are incomplete. The total amounts of rainfall recorded at Malham Tarn appear to be comparable with those at Litton 7.2 km (4½ miles) to the north, but higher than amounts recorded at Threshfield 9.7 km (6 miles) to the east (Table 1). In 1961 149.7 cm (58.95 in) of rainfall was recorded at Malham Tarn and 153.7 cm (60.51 in) at Litton. The recorded total at Threshfield of 127.9 cm (50.36 in) was considerably lower. Other comparative rainfall figures may be seen in Table 1.

	1957	1959	1960	1961
Malham	156.8 cm (61.73 in)	116.9 cm (46.02 in)	157.0 cm (61.81 in)	149.7 cm (58.95 in)
Litton	157.1 cm (61.84 in)	130.7 cm (51.44 in)	167.9 cm (66.12 in)	153.7 cm (60.51 in)
Threshfield	-	96.6 cm (38.03 in)	138.5 cm (54.53 in)	127.9 cm (50.36 in)

Table 1 : Rainfall at three stations around the field area (Source: British Rainfall)

In an upland area such as the Fountains Fell, Malham Tarn and High Mark areas of north-west Yorkshire a significant amount of precipitation falls as snow or sleet. Manley (1957) calculated that snow or sleet could be expected to fall on an average of 47 days in the year, and to lie for 40 days. The actual occurrence of snow and sleet falls in 1968 and 1969 was 37 days and 42 days respectively, lying for 43 days in 1968 and, in 1969, persisting at recorded depths of 46 cm (18 in) for 79 days, almost double the expected average. In spring (April) of 1969 a considerable volume of recharge to the ground-water systems in the field area is likely to have been derived from snow melt.

Calculations of amounts of evapotranspiration occurring at Malham Tarn indicated that this factor may be of some importance in controlling the effectiveness of precipitation over the summer period in recharge to the ground-water systems. In 1968 the maximum calculated evapotranspiration calculated for a single week using Penman's (1948) method was 1.88 cm (0.74 in) for the period 10.6.68 to 16.6.68 and 2.26 cm (0.89 in) in 1969 (9.6.69 to 15.6.69). In 1969 the minimum calculated evapotranspiration was -0.30 cm (-0.12 in) for the week 24.11.69 to 30.11.69.

Further information concerning the weather over the period of research is summarised in Figs.1 and 2, which may be used in conjunction with the graphs of spring and river water temperatures, discharge and dissolved calcium and magnesium carbonate variations (Figs. 3a-40b)

D Vegetation and Soils

On account of the significance attributed by many workers to the soil and vegetation environment in influencing amounts and variations of limestone solution, a description of these aspects of the field areas is essential. Recharge and infiltration to the limestone may also be affected by soil type, and soil and vegetation studies also provide important information on the recent geomorphic history of the area.

1 Vegetational History

Table 2 is largely derived from the pollen work of D.C. and M.E. Pigott (1959, 1963) on the muds and peats around Malham Tarn, and summarises the sequence of vegetation changes which are believed to have occurred in the Malham area since the closing phases of the glacial period about 13,000 BC. This period was followed by a gradual climatic amelioration in late-glacial times in which the vegetation appears to have consisted of an open cover of juniper scrub, birch, grasses and sedges. After a short return (about 500 years) to colder conditions in zone III, the climate became warmer and drier. By zone V, birch had been superseded by the growth of hazel woodlands, and by zone VI, pine was dominant, although hazel was still abundant. With increasing rainfall in the late Boreal (zone VI) and Atlantic periods (VIIa) the growth of Sphagnum peat gradually overwhelmed the pine forests. Peat accumulation appears to have begun on Fountains Fell in late zone VIIa

(Pigott and Pigott 1959, 1963) although at lower levels on Fountains Fell, where peat was not forming, the degeneration of forest was succeeded by *Calluna* moors and grass heath. Around Malham Tarn it appears that this climatic shift was associated with the spread of alder. During this period the pollen records also suggest that hazel, elm and oak continued to occupy the limestone areas.

Pollen Zones	
Zone VIII	Enormous rise in herb pollen. Evidence of woodland destruction and increase in grazing and cultivation. Vigorous growth of *Sphagnum* to present day commencing at start of zone VIII.
Zone VIIb	Sudden rise in herb pollen.
Zone VIIa Atlantic Period	Rise in alder and commencement of raised bog growth about 6000 BC. Start of peat growth on gently sloping moorland soils. Decline in pine with growing dominance of oak, elm and alder. Some ash and occasional lime and yew.
Zone VI Late Boreal	Pine dominant associated with abundant hazel and frequent elm. Signs of Mesolithic man at end of zone VI.
Zone V	Extends from rise in hazel with birch declining to the appearance of elm.
Zone IV	Beginning of post-glacial period (8300 BC) Birch only abundant tree. Some hazel.
Zone III	Return of colder conditions for 500 years Open vegetation cover.
Zone II	10,000-8800 BC. Milder (Allerød) period with rapid retreat of ice. Open vegetation cover of juniper, birch, grasses and sedges.
Zone I	Ice front across southern Scotland. Sparse vegetation.

Table 2: Vegetational changes in the Malham area since the glacial period (based on Pigott M.E. and C.D. 1959, 1963)

In zone VIIb an abrupt rise in the proportion of herb pollen and particularly plantago is believed to have been associated with late Neolithic forest clearance. This increase in herb pollen carried through into zone VIII where an even greater rise is believed to have been associated with Iron Age forest clearance. However, from evidence of place names, Moss (1904) considers that even in Saxon and Danish times the Pennine slopes were still largely tree-clad although on the summits were extensive areas of deep peat moors.

2 The Soils and Vegetation of the Present Day

a The Limestone Upland

Bullock (1964) has recognised four major soil groups with intergrades on the Carboniferous Limestone of the Malham Area, but in spite of an altitudinal range of over 183 m (600 ft) no catenary soil sequence such as that described for the Derbyshire Dales by Balme (1953) was identified on the limestone. The main factor affecting the distribution of soils on the Carboniferous Limestone was considered to be the depth to the underlying rock, a factor largely related to the distribution of drift deposits.

In conjunction with these major soil groups, a number of vegetation associations may also be identified (Sinker, 1953, 1960; Bullock, 1964) which bear a close relationship to soil type. On scree slopes and on cliff ledges, such as Highfolds Scar and the north-west slope of Hawkswick, a vegetation association dominated by Sesleria coerulea and Festuca ovina is found (Sesleria-Festuca association is a calcicolous association). There are a few stunted trees on the scars - mainly yews, hazel, mountain-ash and ash. On more level sites the Sesleria-Festuca association still dominates and with the appearance of Agrostis (Agrostis-Festuca association) constitutes the true limestone grassland found over much of the High Mark area, where it is typical of thin rendzina soils. Rendzinas occur whenever limestone is within 20 cm (8 in) of the surface, are characteristically very dark in colour and have an A/C profile. Over large parts of the limestone upland, however, the rendzinas are only 5 to 10 cm (2 to 4 in) thick, a factor which permits drying out in summer and often complete freezing in winter; a consequent inhibiting effect on biological activity is therefore likely. Thin rendzinas under severe leaching have undergone decalcification to the extent that the pH is as low as 4.5.

Bullock (1964) has identified two types of rendzina in the Malham area - scree rendzinas and clint rendzinas. Scree rendzinas contain limestone fragments and may be somewhat deeper than the clint rendzinas which are usually stone free, and which form on solid limestone surfaces. Profile descriptions of these two types are found in Bullock (1964) and are reproduced here.

PROFILE 1

LOCATION	East facing slope above Malham Tarn
GRID REF.	899665
GENETIC GROUP	Rendzina
TYPE	Scree rendzina
ELEVATION	381 m (1250 ft) OD
TOPOGRAPHY	Steep slope
DRAINAGE	Free
PARENT MATERIAL	Limestone scree
VEGETATION	Sesleria-Festuca

Profile Description

0-20 cm (0-8 in)	Very pale grey (10 YR 3/1) dry black,(10 YR 2/1) moist silt loam. Granular structure. Friable. Abundant angular and subangular

Profile Description Cont.

	limestone fragments. Abundant fine fibrous roots. Earthworms. Occasional bleached quartz grains.
20 cm and over (3 in and over)	Shattered limestone scree with interstices filled with black humose material.

PROFILE 2

LOCATION	Seaty Hill Pasture, Malham
GRID REF.	906647
ELEVATION	381 m (1250 ft) OD
TOPOGRAPHY	Flat-bottomed upland valley
DRAINAGE	Free - excessive
PARENT MATERIAL	Solid limestone
VEGETATION	*Festuca-Agrostis* with *Sesleria* sub-dominant

Profile Description

0-10 cm (0-4 in)	Very dark grey (10 YR 3/1) dry loam. Granular structure. Abundant fine fibrous roots. Friable. Occasional bleached quartz grains.
10 cm and above (4 in and above)	Solid limestone with pitted surface but otherwise no signs of weathering.

On deeper rendzina soils and on brown calcareous soils the *Festuca-Agrostis* association replaces the *Sesleria-Festuca* association, although once the soil depth exceeds 46 cm (18 in) *Agrostis-Festuca* is unable to tap the limestone and it, in turn, gives way to an association dominated by *Nardus stricta*.

Brown calcareous soil is the most common soil over the limestone in the lowland drift areas and develops where the limestone is 20 to 46 cm (8 to 18 in) from the surface. The profile is A(B)C with a well developed mull humus horizon varying in thickness from 8 to 25 cm (3 to 10 in). This profile develops on limestone gravel, limestone blocks, or on solid limestone where a thin, plastic, yellow layer is sometimes found between the (B) horizon and the bedrock.

PROFILE 3

LOCATION	Quarry near the entrance to Mastiles Lane (Malham end)
GRID REF.	904657
GENETIC GROUP	Brown calcareous soil
ELEVATION	381 m (1250 ft) OD
TOPOGRAPHY	Morainic mound
ASPECT	Southerly
DRAINAGE	Free
PARENT MATERIAL	Limestone gravel
VEGETATION	*Festuca-Agrostis*

Profile Description

0.25 cm (0-1 in)	Fibrous grass mat
2.5-15 cm (1-6 in)	Very dark brown (10 YR 2/2) silt loam. Moderately well developed crumb structure, common pores, and fine fissures. Few rounded limestone cobbles. Abundant fine, fibrous roots. Earthworms, irregular boundary.
15-36 cm (14-16 in)	Yellowish brown (10 YR 4/4) dry, dark brown (10 YR 2/2), moist, silt loam. Sub-angular blocky structure. Porous. Friable. Common earthworm channels. Some rounded limestone cobbles. Merging boundary to

Profile Description Cont.

36-41 cm (14-16 in) (16 in & above)	Yellowish-brown (10 YR 4/4) dry, silt loam, with patches of very dark greyish brown (10 YR 3/2). Very abundant earthworm activity. Sharp boundary to hard, coarsely crystalline, un-consolidated limestone gravel.

Occasionally some *Nardus* is found on brown calcareous soil, although it is indicative of degradation towards an acid brown earth.

Acid brown earths form the next stage in the sequence of soils over Carboniferous Limestone. Mull Humus is replaced by mor , and biological activity is low. A micro-topography of small hummocks 30 cm (1 ft) high and 91 cm (3 ft) wide is a typical site of acid brown earths. Brown calcareous soils have developed in the troughs resulting in a marked vegetation contrast. *Nardus* is the dominant vegetation type on the acid brown earth hummocks, and *Festuca-Agrostis* is found in the troughs. *Nardus stricta* has a tussocky character which is often accentuated by the action of grazing sheep which avoid it.

Within the limestone part of the field area, acid brown earths are characteristically located on the lowland drift areas, although locally patches of drift in the upland High Mark area have given rise to brown calcareous soils and acid brown earths. These patches of boulder clay are particularly noticeable on account of their vegetation association which contrast with the surrounding limestone grassland. Smith and Rankin (1903) refer to this association as 'limestone heath' - "On the shoulder overlooking Cowside Beck, within a single square yard may be found *Sesleria coerulea*, *Festuca ovina*, *Viola lutea*, *Thymus Serpyllum* *Vaccinium myrtillus*, *Calluna*, *Erica*, *Nardus stricta* and *Polytrichum*; representatives of the limestone hill pasture and the heath growing in mixture." (Smith and Rankin 1903 p.167)

(This is characteristic of a brown calcareous-acid brown earth intergrade).

A typical acid brown earth profile described by Bullock (1964) is as follows:

PROFILE 5

LOCATION	Seaty Hill Pasture, Malham
GRID REF.	908651
GENETIC GROUP	Acid brown earth
ELEVATION	381 m (1250 ft) OD
TOPOGRAPHY	Flat bottomed upland valley
MICRO-RELIEF	Hummocky
DRAINAGE	Impeded in top horizons
PARENT MATERIAL	Glacial drift over limestone
VEGETATION	*Nardus stricta* dominant

Profile Description

A_0	Grass mat. Greasy black humus (7.5 YR 2/1) with abundant roots.
8-25 cm (3-10 in)	Dark yellowish brown (10 YR 4/4) silt loam. Abundant distinct mottles decreasing with depth. Angular block structure. Friable. Abundant roots often associated with the mottling.
25-75 cm (10-30 in)	(7.5 YR 4/4) brown/dark brown silt loam. Coarse angular block structure. Abundant earthworm activity giving humus stained channels. Few coarse fibrous roots. Shale fragments.
76-86 cm (40-34 in)	Very dark greyish brown (10 YR 3/2) silty clay loam and dark yellowish brown silt loam. Abundant humus staining. Rare roots. Few shale

Profile Description Cont.

	fragments. Merging boundary to
86 cm & above (37 in & above)	Unweathered limestone

Under more acid conditions with increased development of peaty humus, two species Carex binervis and Molinia coerulea (purple moor grass) replace Nardus stricta. These two species are indicative of the peaty gleyed podzol stage, which is also associated with a hummocky topography such as found on the western slope of Great Close Hill. These soils consist of black humus of variable thickness lying on a grey A_2 horizon, which may contain patches of freely drained material. An incipient iron pan may be present. Bullock (1964) considers these soils to be the climax soil of the Malham area and a typical profile is as follows:

PROFILE 6

LOCATION	Seaty Hill Pasture, Malham
GRID REF.	908651
GENETIC GROUP	Podzol
TYPE	Peaty gleyed podzol
ELEVATION	381 m (1250 ft) OD
TOPOGRAPHY	Flat bottomed upland valley
MICRO RELIEF	Hummocky
DRAINAGE	Poor
PARENT MATERIAL	Drift
VEGETATION	Nardus stricta

Profile Description

0-1.3 cm (0-½ in)	Grass mat of thick Nardus roots and sheaths

Profile Description Cont.

1.3-8 cm (½-3 in)	Black (7.5 YR 2/1) humified organic matter. No structure apparent. Moist. Abundant fibrous roots. Merging boundary to
8-28 cm (3-11 in)	Grey (10 YR 4/1) silt loam with pockets of yellowish brown (10 YR 5/4). Weakly developed prismatic structure with faces of the structural units lined with humus. Stoneless. Friable. Common coarse fibrous roots. Common pores and fissures.
28-31.7 cm (11-11½ in)	Incipient thin iron pan. No thin black capping apparent. Mainly diffuse iron.
31.7-61 cm (11½-24 in)	Dark brown (10 YR 3/3) silt loam containing a faint, thin, iron pan. Crumbly. Few roots. Stoneless. Common pores and fissures.
61 cm & above (24 in & above)	Yellowish brown (10 YR 5/4) silty clay loam. Abundant green shale fragments. No structure apparent. Abundant very fine pores. Brittle. Rare roots.

Augured to 1.5 m (5 ft) without change.

b The Soils and Vegetation of Fountains Fell

The soils and vegetation of the lower parts of Fountains Fell (below 457 m or 1,500 ft) and on steep slopes up to 549 m (1,800 ft) are similar to those found on the limestone areas. For example, acid brown earths are found on Tennant Gill Farm.

With increasing altitude, peaty gleyed podzols culminate in thick blanket peat which extends over the ridge with lobes down the flatter spurs. Scattered limestone outcrops bear an impoverished gryke and crevice flora and are bordered with *Agrostis* turf; otherwise, owing to drift cover the alternations of bedrock play little part in determining a soil pattern whose major changes are altitudinal. Substantial areas of the Millstone Grit plateau at about 610 m (2000 ft) OD are still completely peat covered and carry a uniform but tussocky moor of *Eriophorum vaginatum* (Cotton Grass) associated with *Descampsia flexuosa*: *Calluna vulgaris* is locally dominant on drier areas. Below the summit plateau, large areas of cotton grass moor are also found with some areas of *Sphagnum*, suggesting active peat formation.

On the summit of Fountains Fell and near the summit margins severe peat erosion has often occurred. Residual peat islands are separated by deep channels, or stand in areas of Millstone Grit debris and peaty silt only partially re-colonized (*Descampsia flexuosa*, *Nardus stricta*). The majority of these peat islands bear a cover of ericaceous shrubs chiefly *Vaccinium myrtillus* (bilberry), *Empetrum nigrum* (crowberry) and *Calluna*.

The erosion of this peat may be due to several factors. Active cutting back by streamlets (Sinker,1960) such as the dendritic headwaters of Darnbrook may be important. In this area, the improved drainage due to Darnbrook Beck has led to the abundant growth of bracken (*Pteridium aquilinum*) on its steep valley sides and the slopes to the north (Sinker,1960). The disintegration of the peat also owes much to the influence of man, either through the effect of artificial draining or burning (Woodhead,1929).

Other more specialised soil and vegetation habitats exist within the field areas, particularly in and around Malham Tarn. In Malham Tarn itself pondweed (*Potamogeten*) and stonewort (*Chara*) are the main vegetation species (Holmes,1965; Sinker,1953, 1960; Sledge,1936). Typical vegetation species found in running water and springs reflect the base rich nature of the water eg. kingcup, lesser spearwort, watercress, brookline and watermint. The fen and carr areas on the western side of the tarn have been described in some detail by Sinker (1960) and represent a rich variety of intergraded habitats and associations.

The vegetation of limestone pavement areas too is distinctive. The grykes of the pavement area provide a shaded equable micro-climate sheltered from the sun and wind, in which a flora closely resembling that of natural ash woods is found (Sinker 1953, 1960). Clapham (1954) describes a typical pavement flora from the pavement above Malham Cove. Common species are *Mercurialis perennis*, *Geranium robertianum*, *Oxalis acetosella* and *Allium ursinum*. Commonest plants are wood sorrel, wood garlic, anemone, harts tongue fern and green spleenwort. A few tree plantations also occur within the field areas notably around Malham Tarn.

The microflora of the Malham Tarn area has been described in some detail by Lund (1961) who discusses the role of a number of algae, notably *Rivularia* and *Phormidium*, in the precipitation of calcium carbonate as tufa in some streams and rivulets. The importance of bryophyte species in tufa formation is recognized by Proctor (1960) who lists *Eurhynchium ripariodes*, *Cratoneuron commutatum*, *Pellia fabbroniana* and *Barbula tophacea* as being of particular interest in this respect.

E Geology

1 Introduction

That part of north-west Yorkshire in which the field area is located is structurally a portion of a larger zone which includes parts of Westmorland, Durham, Northumberland and north-east Cumberland. This larger area, comprising the Askrigg Block in the south and the Alston Block in the north, forms the stable structural unit of the north Pennines. This rigid block (Marr, 1921) in bounded in the south by the Craven Fault system and along its western margin by the Dent Fault. In the southern part of the area, this basement is exposed in valley botoms fringing the block, for example in Ribblesdale and Crummackdale, where the oldest rocks exposed, the Ingletonian grits and slates are believed to be of Late Pre-Cambrian age (Marr, 1921; Wilcockson, 1927; King and Wilcockson, 1934; O'Connor, 1964). In Ordovician and Silurian times rocks characteristic of shallow water conditions, containing a number of breaks in the succession, were deposited round the fringes of the Askrigg Block. Folding during the Caledonian orogeny compressed these rocks into a series of folds with axes trending west-north-west/east-south-east.

Beds of Lower Carboniferous age rest unconformably on this Lower Palaeozoic and Pre-Cambrian basement. At the commencement of the Carboniferous the rigid block stood above the level of the surrounding seas, the defining faults forming a steep faced coast during this period. The result is that the lowest zones of the Carboniferous are not found on the Askrigg Block, although they may be present in the basin area which existed to the south. When the Lower Carboniferous seas did eventually transgress over the irregular hilly surface of the rigid block (Garwood and Goodyear, 1924; Wilcockson, 1927; George, 1958) thick pure limestones (the Great Scar Limestone) were laid down on top of earthy basal limestones deposited in the initial irregularities of the Pre-Carboniferous surface. At the same time, sedimentation in the basin area to the south was of a rather different nature and transition facies may be recognised between the Great Scar Limestone and Lower Yoredales of the block, and the Lower Bowland shales and underlying sediments of the basin (Hudson, 1930). The period of limestone deposition on the block was marked by relatively slow subsidence and a total thickness of 360 to 400 m (1200-1300 ft) of sediment may be found north-east of Settle in contrast with over 1500 m (5000 ft) in the Craven Lowlands.

Further earth movements in Mid-Carboniferous times caused some breaks in sedimentation, and the Mid Craven Fault is believed to have been active at this time.

b The Pre-Carboniferous Basement

On account of its impermeable nature the Pre-Carboniferous basement marks the lower limit of active ground-water circulation in the High Mark and Fountains Fell areas. In addition the depth and topography of the basement appear to have an important effect on both the location of springs and the direction of underground water movement (see chapter 7). Within the field area a few out-crops of Silurian occur near Malham Tarn at an altitude of 366 m (1200 ft) O.D. (O'Connor, 1964) but exposures are few owing to the drift cover. At Great Close Mire and along the east shore of the Tarn, blocks of a basal conglomerate containing pebbles of Silurian slate in a limestone matrix are found; and at Gordale, Silurian and Carboniferous rocks outcrop within a few yards of each other. Nowhere around Malham Tarn is the actual junction visible, but O'Connor (1964) has pointed out that the junction of the Silurian and Carboniferous may be identified by a line of springs, the result of the impervious nature of the Silurian. The spring line is particularly notable between Capon Hall and High-folds scar (Maps 5 and 10) at altitudes around 411 m (1350 ft) O.D. The Geological Survey (six-inch sheet) records that springs issue at the base of

Malham Tarn (about 366 m - 1200 ft O.D.) and these may also represent the junction. O'Connor (1964) suggests that the permanent springs of Cowside Beck (Skirfare) (Map 11) at altitudes of 357 m (1170 ft) and 344 m (1130 ft) O.D. may also be associated with the Pre-Carboniferous basement. Dakyns (1876, 1893) and Raistrick (1931) suggest that the strong springs rising at the foot of Kilnsey Crag (Maps 4 and 6) and in Littondale at altitudes of 198 m (650 ft) O.D. may be thrown out by Silurian rocks in the bottom of the valley hidden by superficial deposits. Wilcockson (1927) in a review of the Pre-Carboniferous topography in the Ribblesdale inlier, illustrated the importance of the old land surface in influencing the line taken by the underground drainage. The springs at Austwick Beck Head, Capel Bank Wood, the Moughton Whetstone Hole, Gillet Brae, Brants Gill and Douk Gill issue along the line of a Pre-Carboniferous valley which occurred along the faulted junction between the Pre-Silurian and Silurian rocks. Fluorescein tests have shown that water rising at Brants Gill is in part derived from water sinking at Gingling Hole on the south-western flank of Fountains Fell, the direction of flow being controlled by basement structures (see Chapter 7). South of Wensleydale Dunham (1959) has shown that the rocks have been folded into a gentle half dome closing northwards but open to the south towards the Craven faults. The altitude of these springs and the movement of water from Fountains Fell north-westwards to Ribblesdale does appear to reflect such a structure with the highest part of the dome centred in the Malham Tarn and Blackhill area.

c The Carboniferous Geology

Table 3 provides a general summary of the sequence of Carboniferous deposits found in the Malham area of north-west Yorkshire. The geological map of the field area (Map 3) is derived from both the Geological Survey six-inch survey of the area (1889-92) and from later more detailed zonal work by Garwood and Goodyear (1942).

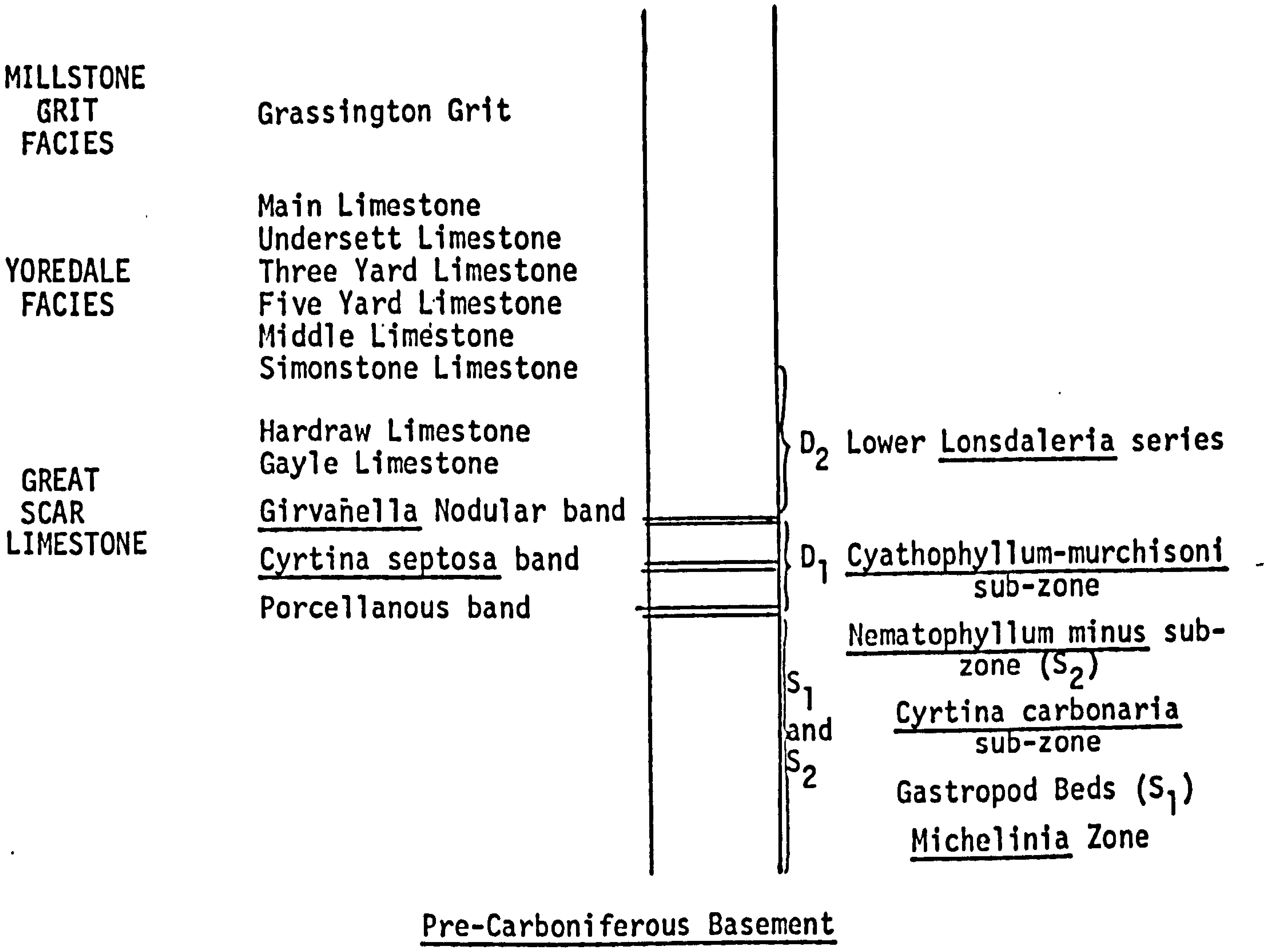

Table 3: Summary of Carboniferous deposits in the Malham area north of the Craven Faults

(i) The Great Scar Limestone

The zonation of the Great Star Limestone found in the field area is summarized in Table 3. The Askrigg Block, on the southern margin of which the field area is located, remained above Dinantian (Lower Carboniferous) sea level until late Seminulan times and the beds of the Great Scar Limestone range from S_1 to D_1 in age (using Vaughan's (1905) Coral/Brachiopod Lower Carboniferous Zonal system, and Garwood and Goodyear's (1924) modifications for northern England). Over 200 m (660 ft) of limestone is present with just over 100 m (330 ft) belonging to the D_1 sub-zone. The Great Scar Limestone is a typical shelf deposit laid down in clear shallow waters on the drowned plateau-like basement. It is composed principally of calcite mudstones, oolites and calcarenites and is sometimes current bedded as is found just below the Cyrtina septosa band. This band mapped by Garwood and Goodyear (1924) occurs about 24-30 m (80-100 ft) below the top of the D_1 sub-zone. In upper Wharfedale it is frequently dolomitised, is about 7.6 - 9.0 m (25 to 30 ft) thick and must provide one possible source of the magnesium carbonate in springs around the High Mark area (see Chapter 7). The upper beds of the D_1 sub-zone overlying the Crytina septosa band consist usually of massive beds of pseudo-breccia separated by thinly bedded crinoidal limestone. These massive beds generally give rise to a succession of low escarpments. The upper limit of the D_1 and the top of the Great Scar (O'Connor 1964) is taken at the Girvanella band, a bed of very dark bituminous limestone containing Girvanella nodules. The true Girvanella band is composed of a compact black limestone with occasional thin shaly partings. It provides a good marker horizon occurring at 510.5 m (1,675 ft) on High Mark and 434 m (1,425 ft) in Darnbrook Beck (Map 3).

The beds of the Great Scar Limestone are remarkably pure. Schwarzacher (1958) from an analysis of 90 samples taken from a vertical succession from Gordale Beck section found the insoluble residue to average 0.5% after treatment with hydrochloric acid. Fluctuations in the amount of this residue were largely due to a variation in the number of idiomorphic quartz crystals which occur in the limestone. Thin section analysis showed an intimate association between these quartz crystals and bedding planes, indicating that migration of silica must have occurred along the bedding planes, and that the quartz crystals were of secondary origin. Normally, debris of recognisable organic origin is the main component of the limestone, foraminifera, shell fragments and crinoid ossicles may contribute up to 50% of the limestone major cycles.

	Percentage
Silica	0.12
Iron Oxide	0.0113
Aluminium oxide	0.02
Manganese dioxide	Trace
Calcium oxide	55.5
Magnesium oxide	0.1
Phosphoric anhydride	0.19
Sulphuric anhydride	0.01
Carbonic anhydride	43.8
Organic matter	Trace
Water	0.04

Calcium Carbonate = 98.5%

Table 4: Analysis of a sample of Great Scar Limestone from Beecroft Quarry, Horton-in-Ribblesdale (from O'Connor, 1964)

Of fundamental importance to the water circulation in the Great Scar Limestone is the existence of well developed joints and bedding planes. Schwarzacher's (1958) work was concerned primarily with the stratification of the Great Scar Limestone. Individual beds were traced laterally in order to establish the persistence of bedding, and petrological studies were carried out in the hope of finding an explanation for the stratification. Schwarzacher (1958) found that the Great Scar succession could be divided into groups of beds, separated by master bedding planes which occurred at intervals of roughly ten metres. These master bedding planes were established by extensive mapping proving their persistence over a wide area. The repetition of master bedding planes suggested they acted as boundaries of a lithological cycle. The D_1 section of the Great Scar Limestone was found to contain nine to ten major cycles.

More recently, however, examination of underground sections by Waltham (1971) has shown that many of the bedding planes bounding the limestone cycles of the D_1 sub-zone are in fact shale beds. If these shale beds are present in the Great Scar Limestone of the High Mark area they may have an important bearing on the level of ground-water movement in the limestone,earlier work by Waltham (1970) having demonstrated that shale beds are of major significance in influencing cave development in north-west Yorkshire.

The regional dip of the beds of the Great Scar Limestone is approximately 5^0 to the north-west, but locally the dips vary in both direction and magnitude.

Wager (1931) showed that the joints of the Great Scar Limestone fall into two groups at right-angles to each other. One set trends in a north-east/south-west direction, parallel to the mineral veins found on the High Mark area (see below), although nearer the North Craven Fault the direction of this set was found to change to a east-northeast/west-south-west direction. Sections seen in vertical scars showed that these joints seldom deviated by more than 10^0 from the vertical. This regional swing in the joint direction Wager (1931) attributed to rotation of joints due to wrenching along the Craven faults. On the eastern flank of Fountains Fell the major direction of water movement appears to be north-west/south-east or west-north-west/east south-east as shown by the tracings carried out by the Craven Pothole Club at Cherry Tree Hole and Darnbrook Pot (Craven Pothole Club, 1970). In addition as recorded above water also flows north-westwards to Ribblesdale from the south-western flank of Fountains Fell. These water maovements are coincident with the other dominant joint direction (north-west/south-east) mapped by Wager (1931) and are indicative of the importance of joints in controlling water movements in the limestone.

In more recent work by Doughty (1968), three types of joints in the Great Scar Limestone are recognised. The shear joints of Wager (1931) have been called conjugate joints. Doughty (1968) found that these joints may extend vertically up to 46 m (150 ft) but more commonly cut through only a few beds at maximum. These joints usually terminated at a bedding plane. Tension joints which bisect the angle between the conjugate joints were identified as the tension fractures of Wager (1931). Their horizontal persistence does not compare to that of the conjugate joints. The third type of joint identified by Doughty (1968) were termed low-angled joints. These were mostly straight joints having no discernible evidence of movement, and which cut through the limestone at angles varying from a few degrees up to 60 degrees from the horizontal. These appear to be associated with faulting. Doughty (1968) measured the horizontal spacing of joints in limestone pavements and considered that the extension of joints across bedding planes interfered with a basically simple pattern. In beds of high joint density, regular spacing was found, whereas the joints which interfered with the regular pattern in beds of low joint density, were projections of joints from other beds. Doughty (1968) also found that the beds belonging to the S zone were characterised by a general similarity in joint frequency, but in D_1 beds a marked rhythmic repetition was noted. In the D_1 limestone nine units were found which corresponded exactly with the cycles described by Schwarzacher (1958). These rhythms of joint frequency generally commenced at the base with a bed of relatively high joint frequency. Higher beds in the rhythm were marked by a decreasing density of joint frequency, the rhythm ending with a massive bed with widely spaced joints. Two basic types of rhythm could also be identified, one showing a fairly regular fall in joint density values from base to top, and those in which high joint densities in the lower half were abruptly followed in a foot or so by massive beds with low joint densities. The average thickness of the rhythm was found to be 9-10 m (30 ft). In addition to the role of shale beds, this vertical variation in joint development may have some influence on the level of groundwater flow within the limestone.

(iii) The Yoredale and Millstone Grit Series

The Yoredale Series is the name given by Phillips (1836) to a particular rhythmic facies of sandstones, shales and limestones found between the Great Scar Limestone and the Millstone Grit. Phillips used the upper Wensleydale sections, being the most complex, as the type area. He commenced the Yoredale series with the shale which lies immediately above the Gayle limestone, as he considered this as marking a distinct change in physical conditions of deposition. Hudson (1924), however, considers that the Girvanella algal horizon (see above) marked the change to Yoredale conditions.

The Yoredale rocks are essentially shallow water deposits, the shale/sandstone/limestone rhythm or cyclothem being dependant upon variations in sedimentation conditions. The occurrence of potholes filled by overlying Hardraw Shales on the top of the Great Scar Limestone exposed in Mill Gill Askrigg (Johns, 1910) and on beds between D_1 and D_2 age in west Cumberland (Edmonds, 1922) points to periods of emergence and erosion during the period of Yoredale sedimentation.

Various theories have been proposed to account for the rhythmic nature of Yoredale sedimentation (Hudson, 1924 ; Brough, 1929; Wanless and Shepard, 1936; Robertson, 1946; Moore, 1958).

During the Lower Carboniferous a shallow sea stretched over the Alston and Askrigg Blocks with a land mass to the north. Slight fluctuations in sea level on this shelf would cause the shoreline to advance or recede. Shallow deltaic sandstones and coarse deposits would be expected to build out from the landmass. These would gradually grade into finer sediments, silts and shales until finally there is little or no sediment coming in, and limestones are formed in clear shallow water. Continuing southwards, first the sandstones die out leaving a limestone/shale series and finally, in the south, a pure limestone like the Great Scar Limestone can develop. It has been suggested by Waltham (1971) that the thin shales in the Great Scar Limestone may be a continuation of contemporaneous clastic deposits on the Alston Block. By D_2 times a Yoredale facies which extended into the field area was developed in Wensleydale, although owing to the lateral changes outlined above, limestone tends to be developed at the expense of the shales and sandstones within the field area. This is particularly true of the lower part of the section, the Gayle cyclothem and Hardraw limestone cannot be separated from one another and are referred to as the Lower Lonsdaleia series. These limestones and their associated non-calcareous cyclothems are described fully by Moore (1958).

With regard to observations on the magnesium content of waters it may be of importance to note that dolomitized beds were recorded by Moore (1958) at the top of the Hardraw Scar Limestone, and at the base of the Undersett Limestone in Wensleydale. It remains unknown, however, if the equivalent beds on Fountains Fell are dolomitized.

Within the field area, which lies to the south of the area described by Moore (1958), it is generally considered that all the Yoredale measures are present from the Main Limestone downwards, but that they lack the usual Wensleydale fauna (Black,1950). The intervening measures are shales and sandstones with considerable lateral variation. The succession found in Darnbrook Beck (Fountains Fell) is recorded by O'Connor (1964) and in this she tentatively identifies all the limestones up to the Main Limestone. The Main Limestone is also identified as being present on Fountains Fell and on the area above Hawkswick in Littondale by Dakyns, Tiddeman, Gunn and Strahan (1890).

Within the field area only the grit capping Fountains Fell (The Grassington Grit) belongs to the Millstone Grit Series. The Grassington Grit rests unconformably on the Main Limestone on Fountains Fell although owing to the presence of a south-easterly overstep (Dakyns,1890, 1892; Chubb and Hudson, 1923) the Millstone Grit Series rests directly on D_1 limestones at Greenhow with the whole of the Yoredales being cut out. No Millstone Grit beds are, however, preserved on High Mark and only the lowest members of the Yoredales are now present (the Lower Lonsdaleia series) and at Parson's Pulpit, about 1.5 m (5 ft) of sandstone - the Dirt Pot Grit is found.

The lower part of the Grassington Grit is conglomeratic and quartz pebbles of up to 25 m (1 in) in diameter are found (O'Connor, 1964). Work on the petrography of the Millstone Grit by Gilligan (1919) has indicated a derivation from a disintegrated granitoid rock. Large pebbles of quartz, feldspar, pegmatite, and igneous rock are common, quartz being the dominant type.

(v) Mineralization

Within the field area mineralization occurs in veins in the D_1 and D_2 limestones of the High Mark area. These veins follow the major north-east/south-west joint direction of the area (Wager, 1931; Raistrick, 1938). These are small fissure veins with no appreciable throw (Raistrick, 1938; Dunham, 1959) although Wager,(1931) records horizontal slickensiding from a lead mine on Proctor High Mark (Wager, 1931). The veins are short and economically poor containing only a thin string of galena for which they were worked and a gangue composed largely of barytes and calcite. On High Mark the only sign of good minerals is associated with the shallowest workings on the highest ground, the whole area being near the base of the zone of mineralization. In no case have extensive surface workings been successfully continued by deep sinking. Raistrick (1938) suggests that between the Wharfe and the Ribble, the richly-mineralized zone has been removed during Tertiary peneplanation leaving only the deepest but poorer parts of the veins. Dolomitization of the wall rocks of the mineral veins has been recorded by Dunham (1959), and dolomite also occurs in Gordale Beck near the North Craven Fault (Waltham, personal communication). Along with the *Cyrtina septosa* band (see above) these sources may be of some importance with regard to the magnesium content of the karst waters. In the High Mark area the highest magnesium carbonate concentrations were recorded on springs nearest to Grassington and it may be of some significance that the foci of the mineralizing fluids appear to be at Grassington and Greenhow (Dunham, 1959).

Other minerals within the field area include coal of which there are two seams in the Millstone Grit on Fountains Fell. These seams are 72 cm (2ft 4in) and 76 cm (2ft 6in) thick and were worked in the early nineteenth century from shallow shafts. Finally, it is of interest to note that south of the field area in the Grizedales rich deposits of calamine (zinc ore) occur as stalactitic and stalagmitic masses, lining cavernous veins or an original cavern (Raistrick 1953).

d Pleistocene and Recent Times

Of some relevance to this work is the composition and distribution of glacial deposits within the field area. Laboratory studies by Groom and Ede (1972) have demonstrated that where a soil contains limestone fragments water passing through the soil may reach a high level of hardness before reaching the bedrock. As much of the drift found on Fountains Fell and High Mark is derived from local Carboniferous material limestone pebbles within the drift may provide an important source of the calcium carbonate in solution in the spring waters.

Secondly, the presence of glacial drift deposits appears to some effect on ground-water recharge particularly in the Fountains Fell area. The thick often impermeable mantle of drift on Fountains Fell inhibits vertical percolation of rainwater and leads to a higher proportion of surface run-off than occurs for example on High Mark where the drift deposits on the plateau are less continuous. Furthermore the numerous small enclosed depressions on Fountains Fell are of great importance as avenues of recharge for percolation waters as well as sinking stream.

During the Pleistocene period, most of the north Pennines appears to have been covered by an ice cap of purely local origin (Raistrick, 1926, 1931). This local ice cap was by-passed by the major ice-streams moving southwards on the western margins, eastwards through the Stainmore and Aire gaps and southwards down the Vale of York (Raistrick, 1926). At the glacial maximum, this large Pennine ice-cap is believed to have covered Blea Moor, Ribblehead and Widdale Fell with its outer fringes covering Dodd Fell and Middle Tongue Area. Ice moved down Semmerdale and Bishopdale into Wensleydale and the Wharfe valley, and south-westwards across the head of Oughtershaw Beck into the Ribble Valley. The east-ward edge of this local ice-cap fed large glaciers in the Wharfe and Skirfare. Movement also occurred across Malham Moor between Fountains Fell and High Mark, but there is no evidence that High Mark was ice free.

In the Skirfare valley drift is limited to the valley bottoms and lower slopes below the first scarp. The upper limit mapped by the Geological Survey occurs between 274 and 305 m (900 and 1000 ft) in the Skirfare valley on the Fountains Fell side north of Litton, and at 213 to 244 m (700 to 800 ft) on the High Mark side of the Skirfare valley in lower Littondale. In Wharfedale the drift limit is up to 274 m (900 ft) in the valley of Howgill Beck south of Kilnsey Crag. On Fountains Fell the upper limit of drift occurs at 518 m (1700 ft) in Darnbrook Beck where the drift is sandstone rich, and on the western flank of Fountains Fell till is found up to 549 m (1800 ft) in Tongue Gill. On High Mark, patches of drift occur at altitudes of up to 503 m (1650 ft) and Millstone Grit erratics are fairly common on the limestone pavements of that area.

Most of the drift deposits near the Tarn are derived predominantly from local limestone and consist of unsorted stones and pebbles in a matrix of limestone rock flour. Some of these deposits originated as a till or ground moraine, others are possibly solifluxion deposits. O'Connor (1964) reports that solifluxion deposits of sandstone, grit and clay underly the peat on the flanks of Darnbrook and Fountains Fell, and that these probably rest on high level till of similar material.

Raistrick (1931) identifies a large number of channels which he considers to be glacial overflow channels associated with meltwater movement during recession of the ice. Some of these as in Wharfedale connected large numbers of ice dammed lakes which existed in small tributary valleys. The channel across the spur at Kilnsey Crag at 341 m (1120 ft) is believed to have taken drainage from the Littondale ice edge into a small lake south of Kilnsey village and then by a channel south of Chapel House at 305 m (100 ft) (Raistrick, 1931).

Other channels have been identified in the vicinity of Malham Tarn (O'Connor, 1964). Clark, (1967) after an examination of the channels existing on the flanks of Ribblesdale, Airedale and Wharfedale identified them as being of sub-glacial origin.

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CHAPTER TWO

TECHNIQUES OF FIELD LABORATORY AND STATISTICAL ANALYSIS

TECHNIQUES OF FIELD, LABORATORY AND STATISTICAL ANALYSIS

A Field Techniques and Sampling Design

Over the period 27.2.68 to 26.2.69 (referred to as Year I) water sampling was carried out at 82 springs and resurgences and at 24 stream and river sites around the High Mark and Fountains Fell areas of north-west Yorkshire. 46 springs were sampled around the High Mark upland and 36 around the Fountains Fell upland. The location of these sites is given in Maps 4-11. All sites were visited at approximately two-weekly intervals and at permanently flowing sites 24 samples were collected over the sampling period. A number of sites were, however, either semi-permanent in nature or flowed only after heavy rainfall, in which cases fewer samples were collected. A description of individual sites is found in Chapter 3.

Over a later period 5.5.69 to 21.5.70 (Year II) sampling was continued at 10 springs around the High Mark area, again at two-weekly intervals. These were sites 3, 4, 5, 19, 27, 48, 49, 56, 57 and 58.

The primary aim of the sampling design was to sample as many of the permanent and semi-permanent springs and resurgences within the field areas as was possible within a two day time period. 'Springs' and'wells' recorded on the 2½ inch and 6 inch Ordnance Survey maps were used as a basis for sampling. Other information on the location of springs and resurgences in the field areas was found in Thornber (1959) and in Moisley (1954). In addition a number of other sites were located during the first month of sampling, and added to the sites located from these sources.

In the High Mark area subsequent field investigations showed that the springs sampled represent about 90% of the permanent and semi-permanent springs within that area. Map 4 is an accurate representation, therefore, of the true distribution of permanent and semi-permanent springs in the High Mark area. Springs recorded in the centre of the field area by the

Ordnance Survey were found to be tiny seepages only.

In the Fountains Fell area it is impossible to assess accurately the percentage of the total population of springs and resurgences represented by the sample. Using the Ordnance Survey maps as a guide it would appear to be of the order of 85% of the recorded springs and wells. Field investigations have, however, shown that the recording of springs and resurgences on the Ordnance Survey maps may require careful checking.

(i) A number of large permanent risings in both field areas are omitted, although temporary and even non-existent springs are often recorded.

(ii) Outlets from what appear to be land drains were occasionally marked as springs.

The type of sampling design employed for this research was influenced by a number of factors notably those practical problems associated with continuous sampling in an area such as north-west Yorkshire. Problems of accessibility and winter climate are inevitably compelling considerations in the selection of sampling sites. However, as the larger part of the total population of springs and resurgences in both areas was sampled the statistical sampling problems are minimal.

The ten springs around the High Mark area on which sampling was continued for a second year were selected on the following considerations:

(i) As many studies in limestone areas have been carried out on systems open to the influence of sinking streams, close study of purely percolation systems was considered particularly desirable.

(ii) A study of a complete range of springs in terms of discharge was considered necessary.

(iii) Springs whose pattern of dissolved calcium carbonate and temperature variation in the first year of sampling was thought to warrant further study (see Chapter 6).

(iv) Sites on which it was practically possible to erect weirs for discharge recording (and on which weirs had previously been constructed).

At all sites samples of water were collected for laboratory analysis in plastic airtight bottles which were completely filled to eliminate or reduce escape of carbon dioxide and consequent chemical changes in water quality. At all sites water temperature was recorded at the time of sampling. A mercury thermometer graduated in tenths of a degree centigrade was used and the temperature was estimated to the nearest 0.01 of a degree centigrade. Water temperature was always read after several minutes immersion in the flowing stream or spring, and with the mercury bulb still fully submerged in the water. The thermometer was calibrated in the laboratory against an accurate check thermometer.

On the ten sites on which recordings of dissolved calcium and magnesium carbonate and temperature was carried out over a second year, discharge was also recorded at the time of sampling (over the period May 1969 to May 1970 - Year II only) using square-notch and V-notch weirs.

1 Sites 3 and 4 (Robin Hood's Well): The combined discharge of sites 3 and 4 was measured using a fully contracted rectangular thin plate weir (British Standards Publication 3680 - 4A) with a 45.72 cm (18 in) wide notch. The maximum recordable discharge on the weir employed was 127.4 l/sec (4.5 cusecs) and this was exceeded on two occasions.

2 Sites 5 (Chapel House Well), 48, 49, 56, 57 and 58: The discharge at these sites was measured using ½-90 degree triangular thin-plate weirs (V-notch weirs) with fully developed contractions (British Standards Publication 3680-4A). The maximum recordable discharge on the weirs employed was 62.3 l/sec (2.2 cusec) and this was exceeded twice at Site 5 only.

3 Sites 19 (Reynards Close spring) and 27 (Moss Beck spring): Discharge at these two springs was measured on broad-crested rectangular concrete

weirs constructed by the Craven Water Board. The width of the notch at Site 19 is 3.048 m (10 ft) and at Site 27 is 2.49 m (8.166 ft).

B Laboratory Techniques

The analysis of water samples for total hardness and calcium hardness was carried out using the standard EDTA titrations (Schwarzenbach, 1957) and BDH water hardness reagents.

1 Total Hardness: 50 ml. samples buffered with 2 ml. of ammonia buffer solution and containing one total hardness indicator tablet were titrated with N/50 EDTA solution until all traces of red colour were lost. The end point of the titration is generally a bright blue.

2 Calcium Hardness: 50 ml. samples buffered with 1 ml. of 4N sodium hydroxide solution and containing one calcium hardness indicator tablet were titrated with N/50 EDTA solution until all traces of red were lost.

3 Magnesium Hardness: was derived by subtracting calcium hardness from total hardness. Bray (1970), however, considers that this method is unsuitable for the investigation of small magnesium concentrations and variations in magnesium concentrations owing to the cumulative effect of the experimental error existing in both the total hardness and the calcium hardness determinations. The consistency of the patterns detected in the analyses carried out for this research suggests that this is too pessimistic a view (Figs.3-40).

4 pH: determinations of water samples were generally carried out in the laboratory using a direct reading pH meter (EIL Model 23A) within 48 hours of collection. Some doubt as to how representative laboratory determination of pH is of water in the natural environment has, however, been shown by Roberson, Feth, Seaber and Anderson (1963). Occasional measurements of field pH were carried out using a portable battery operated meter, but owing to the time available for sampling this was not

practical on a larger scale. Unless otherwise stated pH measurements quoted are mean values resulting from laboratory determination.

C Statistical Analysis

The climatic data used in the statistical analysis of the dissolved calcium carbonate variations and water temperature variations as well as in the calculation of evapotranspiration rates were recorded at Malham Tarn Field Centre meteorological station.

1 The Calculation of Evapotranspiration and Effective Precipitation

Evapotranspiration rates for weekly periods antecedent to sampling were calculated using Penman's method (Penman, 1948). One approximation in the calculation of these evapotranspiration rates is the use of wind speed estimates carried out by the Malham Tarn observers rather than actual measurements using an anemometer. From these evapotranspiration rates weekly effective precipitation was calculated by subtracting the weekly moisture loss by evapotranspiration from the total rainfall for the weekly period. For time periods of less than one week the weekly evapotranspiration amount was divided by, for example, seven to obtain the mean daily evapotranspiration rate for any particular week. This in turn was subtracted from the total precipitation in any single day in the week to give the effective precipitation of the one day periods used in the correlation analysis. This procedure helped to normalize the otherwise highly skewed rainfall data in addition, it is hoped, to providing a more accurate measure of the rainfall effectiveness in influencing the recorded dissolved calcium and magnesium carbonate content, temperature and discharge at the sampling sites.

2 The Correlation Analysis

Temperature and dissolved calcium carbonate variations recorded at springs, risings and streams within the field area were correlated, using Pearsons's Product-Moment correlation, with the mean air and soil temperatures at selected intervals of time prior to sampling, and with the total effective precipitation of selected intervals prior to sampling. This correlation analysis involved the following:

(i) The correlation of water temperature variations and dissolved calcium carbonate variations on springs, risings and surface streams recorded

- (a) over the period 27.2.68 to 26.2.69 - Year I (24 observations on permanently flowing sites)
- (b) over the summer period 1.4.68 to 30.9.68 (11 observations)
- (c) over the winter period - February and March 1968, and October 1968 to February 1969 (13 observations)
- (d) succeeding a week in which gmorer than 7.6 mm (0.3 in) of effective precipitation was recorded at Malham Tarn. This is referred to as the 'wet conditions period'. The mean effective precipitation of the wet conditions period was 39.9 mm (1.57 in) (with 12 observations.)
- (e) succeeding a week in which less than 7.6 mm (0.3 in) of effective precipitation was recorded at Malham Tarn. This is referred to as the 'dry conditions period'; the mean effective precipitation of the dry conditions period was -1.5 mm (-0.06 in) (with 12 observations).

The value of 7.6 mm (0.3 in) is an arbitrary figure chosen so that twelve observations are classed in the dry conditions period and twelve in the wet conditions period.

For the periods (b) to (e) the correlation analysis was carried out on permanently flowing sites only.

The correlation of the water temperature and calcium carbonate observations made over the above time periods with:

(i) the total effective precipitation of single day periods for the first seven days antecedent to sampling;

(ii) the total effective precipitation of overlapping three day periods for the first seven days prior to sampling, ie. firstly with the effective precipitation of days 1, 2 and 3 antecedent, then days 2, 3 and 4 up to days 5, 6 and 7 antecedent;

(iii) the total effective precipitation of each week for twenty-one weeks antecedent to sampling;

(iv) the mean air and soil temperatures of single day periods for the first seven days prior to sampling;

(v) the mean air and soil temperatures of overlapping three day periods for the first seven days prior to sampling (as above);

(vi) the mean air and soil temperatures of each week for twenty-one weeks antecedent to sampling.

Soil temperatures were used in the analysis as the temperature of percolating recharge water is likely to be closely related to the temperature of the soil through which it passes.

In addition, the correlation of the deviations of observed water temperatures from the mean water temperature, with antecedent effective precipitation, using the same antecedent time periods as above, was carried out on twenty-five permanently flowing sites. This was considered necessary as, at least in theory, rainfall pulses could bring about either a fall or a rise in the temperature of the ground-water and hence the water at the rising. Correlation of something more than simple water temperature variations with effective precipitation was therefore required. However, owing to seasonal variations in the temperature of the ground-water (see Chapter 5) the use of deviations of water temperature from the mean water temperature is not entirely satisfactory for this purpose.

Water temperature and dissolved calcium carbonate observations carried out in Year II (May 1969 to May 1970) were correlated with discharge at the time of sampling and the effective precipitation, air and soil temperatures of the selected intervals antecedent to sampling. The same time periods were used as for Year I recordings although the intervals were extended to cover the period of one year antecedent to sampling. No seasonal analysis was carried out but discharge was also correlated with the antecedent climatic variables.

For the analysis of year I observations of water temperature and dissolved calcium carbonate variations the soil temperatures for 20 cm (8 in) below bare soil were used. Over Year II, however, the soil temperatures for 10 cm (4 in) under bare soil were used in the analysis. The choice of depth of soil temperature observations was governed by the completeness or incompleteness of the Malham Tarn meteorological data.

A number of problems, however, occur in the use of this kind of statistical analysis and in the interpretation of the results.

(i) One of the important factors influencing the level of the product-moment correlation is the degree of normality of the data, the amount of dispersion of the observations having a strong influence on the level of the correlation coefficient (Ezekiel,1930; Fisher,1950).

Moser and Scott (1961), however, found the correlation coefficients derived from log transformed data were about the same as those derived from untransformed data, and that Spearman's Rank Correlation produced coefficients of a slightly higher order only.

Histograms of dissolved calcium carbonate variations recorded on a random selection of springs, streams and risings showed a fairly normal distribution with only a slight tendency for positive or negative skew to occur. The calcium carbonate recordings were therefore left untransformed.

Air and soil temperature recordings for time periods antecedent to sampling showed a tendency for a bimodal population distribution, generally with one modal group of temperature values occurring in the 1.67-4.44^{o}C (35 to 40^{o}F) class and the second group occurring in the 10.0-12.8^{o}C (50-55^{o}F) class. These data again were left untransformed.

The distribution of effective precipitation observations for the time intervals prior to sampling shows a tendency for positive skewness, with effective precipitation values in the 0-12.7 mm(0-0.5 in) class predominating. The use of effective precipitation rather than actual rainfall thus eliminating many of the zero rainfall values (by permitting negative precipitation values to occur) reduced the high degree of positive skew shown by the original rainfall data. The distributions of the effective precipitation populations were left untransformed in the correlation analysis. An experimental analysis using log transformed effective precipitation data, however, showed no difference with regard to the significant time periods and little difference in the level of correlation.

The distribution of discharge observations also show a high positive skew, with most discharges occurring in the lower classes and with occasional high discharge occurrences only. These discharge observations were only carried out in Year II of sampling, and were log transformed before the correlation analysis was carried out.

(ii) The second major problem with analysis is the outcome of using climatic variables in the above manner. This is the problem of intercorrelation of the variables. On account of temporal proximity the mean air temperatures of the 0-7 day period antecedent to sampling will for example be closely related to those of the 8-14 day period, and those of the 8-14 day period with the mean air temperature of the 15-21 day period antecedent to sampling. Any true correlation between dissolved calcium carbonate variations and, for example, the mean air temperatures of the 8-14 day period prior to sampling will consequently be reflected in a lower level of correlation between dissolved calcium carbonate variations and the mean air temperatures of the adjacent 0-7 and 15-21 day periods.

The magnitude of this intercorrelation of variables depends on the type of climatic or hydrologic data used, and on the time interval between observations. There is, for example, a much greater degree of 'persistence' (Brooks and Carruthers,1953; Chow,1964) in air and soil temperature observations than in rainfall observations. In addition the further apart in terms of time in which the observations are made, or the greater the time periods over which the climatic data are averaged the less persistence occurs in the data.

One possible method of overcoming this problem of intercorrelation of the independent variables would be the use of partial correlation analysis in which the intercorrelation of the independent variables is held so as to permit the correlation of dependent and independent variables to be calculated (Fisher,1950). Owing to the scale of the analysis required, however, partial correlation was only carried out where interpretation of the simple correlation analysis was difficult. The analysis of the water temperature and dissolved calcium carbonate observations recorded in Year I for each spring (as above) involved the production of 5 correlation matrices (for the 5 periods - year, winter, summer, dry conditions period, wet conditions period) each with 101 variables, 99 of these being the independent climatic variables. This full correlation analysis was carried out for 45 permanently flowing sites and a single matrix of the same dimension was produced for the remaining semi-permanent sites. Furthermore, as one of the chief aims of the correlation analysis concerned the relative significance of the weather of the different time periods in influencing observed dissolved calcium carbonate and water temperature variations product-moment correlation was considered adequate.

(iii) On this kind of correlation analysis involving the use of a large number of independent variables (see above) care is needed in the interpretation of high correlation values owing to the occurrence of chance correlations. On an experimental analysis the correlation of a set of simulated dissolved calcium carbonate values with the effective precipitation of 59 time periods produced five coefficients significant at the 0.05 level of probability.

The standard deviation has been employed in Chapter 7 as a measure of the degree of variability or dispersion in the dissolved calcium and magnesium carbonate content and temperature of the sampled springs and resurgences.

Other minor points concerning the statistical analysis of the data will be found in the relevant chapters.

D Definition of Terms and Problems of Terminology

Before presenting the results of this analysis the meaning of some of the principal terms used in this thesis is briefly discussed. Certain problems have been encountered in the use of these terms in the context of this work and these also are reviewed.

Recharge to ground-water systems in limestone areas may occur either from allogenic streams flowing from less permeable strata at higher levels or by diffuse percolation. Recharge from allogenic sources has been variously designated as allogenic karst water (Pitty, 1966) swallet water (Drew, 1968) and vadose stream water (Williams, 1969) and springs fed by swallet streams are generally referred to as resurgences being the points of re-emergence of formerly surface flowing streams.

However, little is known of the source of many of the springs examined in this thesis. Consequently, the term resurgence is used only where the possibility exists that the rising may be the re-emergence of a surface stream and has not therefore been applied in the context of the High Mark springs.

The principal effect of sinking streams is generally considered to be that of dilution of the limestone ground-water to the extent that the terms swallet water and resurgence have become almost synonymous with dilution processes. Notable exceptions, however, do occur. On High Mark water flowing in Cotegill sinks underground to re-appear at Moss Beck rising (site 27) in Lower Littondale. Although technically therefore a resurgence Moss Beck shows less dilution effects than many known percolation systems. The explanation of this low dilution element at Moss Beck lies in the fact that Cotegill itself is fed almost purely from high level seepage springs which are themselves supplied from percolation sources. The use of the terms swallet water and resurgence in this thesis does not, therefore, automatically imply dilution.

The term percolation water has been generally adopted to describe that proportion of karst water fed by diffuse precipitation which has percolated directly into the limestone bedrock through a soil cover (if present). Springs supplied from such sources are generally referred to as percolation springs. As the terms swallet water and resurgence have come to imply dilution so percolation water and percolation springs are generally characterized by minimal or absent dilution effects and high calcium carbonate concentrations. The analysis of the relationship between the dissolved calcium carbonate fluctuations of High Mark 'percolation springs' and antecedent effective precipitation (Chapter 4) has, however, demonstrated that water from percolation sources may cause dilution of the limestone ground-water. Furthermore, the mean dissolved calcium carbonate concentrations of many High Mark percolation springs is lower than that of some Fountains Fell resurgences. Use of the terms percolation water and percolation spring in this thesis does not therefore, imply high calcium carbonate concentrations or absence of dilution.

One further problem in the use of the terms percolation water and swallet water was encountered. Owing to the presence of a thick mantle of superficial deposits on much of Fountains Fell a large proportion of percolation water appears to enter the ground-water systems through pipes in the floor of numerous small enclosed depressions. The difference, therefore, between percolation water and swallet water on Fountains Fell is therefore essentially one of degree and a continuum appears to exist from swallets receiving very small amounts of local percolation water to swallets engulfing large surface streams. A similar situation in the Dan-yr-Ogof area of South Wales has been described by Newson (1971).

On account of these problems the terms 'dilution water','pulse water' and 'rapidly circulating recharge water' have been more commonly adopted in this thesis to describe that component of ground-water recharge which causes short term pulses in the level of dissolved calcium carbonate at the rising (dilution pulse) or initiates short term pulses in the pattern of water temperature variation recorded at the risings. This water is similar to 'rapidly circulating ground-water', a term used by Hendrickson and Krieger (1964) to describe recharge water occurring in flood periods (Hendrickson and Krieger, 1964 p.61). The work 'recharge' has replaced 'ground' in ground-water (rapidly circulating recharge water) as the effect of this component of recharge on water already in the ground-water system is discussed at several points. On Fountains Fell rapidly circulating recharge water is often in the form of swallet streams entering and passing rapidly through the limestone. On High Mark this component of the water circulation presumably reaches the major ground-water body in the vicinity of the system exit where the major flow zone nears the ground-surface. Slowly circulating recharge water is that component of the ground-water which reaches the ground-water body after relatively slow percolation through soil and bedrock, and constitutes much of the base flow at the springs.

The terms 'sink', 'sinkhole' and 'swallet' are used synonymously in this thesis to denote small enclosed depressions, commonly about 20 m in diameter, which funnel water underground. This water may be in the form of a major allogenic stream or simply small volumes of water collected in the immediate vicinity of the depression (see above). The term karst basin has been specifically used to describe large enclosed drainage basins with diameters in excess of 50 m found on the High Mark plateau.

The term 'flow-through time' has been adopted by Pitty (for example, Pitty, 1966) to denote the time taken for water to pass through a limestone outcrop from "its entry into the limestone mass until it reappears again in the surface streams" (Pitty,1968b p.205). In the case of limestone springs with a large catchment this flow-through time or residence time must obviously encompass a wide range of flow-through times. The method used by Pitty (for example Pitty, 1966) gives the dominant flow-through time for the largest proportion of water in circulation. The results of the correlation analysis reported in Chapters 4-6 demonstrate that antecedent effective precipitation has frequently a near-immediate dilution effect on spring water temperatures and dissolved calcium carbonate concentrations.

Evidently, therefore, at least a small component of water in circulation flows through the limestone within a few days or hours (see dilution water, pulse water and rapidly circulating recharge water). Where very large volumes of pulse water, such as that derived from a sinking stream source, pass rapidly through the limestone the calculated flow-through time is very short (less than 7 days) being the dominant time taken for the major proportion of the flow to pass through the system.

Finally, the terms 'ground-water' and 'ground-water body' are used in a broad context in the following chapters, and refer simply to water in the limestone. Much of this is presumably in transit through the limestone. Use of the term ground-water body does not imply an acceptance of the existence of an integrated ground-water storage zone in the limestone.

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CHAPTER THREE

THE LOCATION, DESCRIPTION AND SUMMARY OF THE CHARACTERISTICS OF SAMPLING SITES

THE LOCATION, DESCRIPTION AND SUMMARY OF THE CHARACTERISTICS OF SAMPLING SITES

A Introduction

The following list of sites are those at which regular recording of dissolved calcium and magnesium carbonate content, pH and water temperature was carried out over the period February 1968 to February 1969 (Year I). On ten of these sites recordings were continued in conjunction with discharge measurements over the period May 1969 to May 1970 (Year II). The following summaries include:

(i) A brief description of the location and altitude of the sampling site. Except where otherwise stated the altitudes of sampling sites have been derived from the OS 6 inch sheets of the area.

(ii) A brief description of the flow characteristics of the site. In this respect a four-fold classification has been adopted. Firstly there are those sites which appear to flow throughout the year. Secondly, there are semi-permanent sites which dry up only after prolonged drought. Flow on these sites occurred on at least 70% of the sampling dates. Thirdly, there are those springs which have been termed 'flood springs' on which flow only occurs following heavy rainfall. On these sites flow occurred on less than 50% of the sampling dates. Finally, there are those springs which could be termed 'semi-permanent flood-springs'. On these sites discharge for most of the year is little more than a trickle, but responds strongly to heavy rainfall.

Although there is obviously a gradation between these four classes of sites, the majority of spring and stream sampling sites may be readily fitted into one of these four classes.

(iii) An estimation of mean discharge is usually given for permanent and semi-permanent springs. Unless otherwise stated this is an estimate deduced purely from observation and from a comparison with those sites on which discharge was accurately measured.

Some attempt has also been made to classify the permanent and semi-permanent springs under the Meinzer system of classification (Meinzer, 1923, 1927, 1942). As this system is based on discharge the classifications made are therefore again based on observation and comparison. Because of the fairly large range of discharges classifying most of the Meinzer springs (see below) it is believed that this assessment is fairly reliable.

Meinzer's Classification of Springs

Magnitude	
I	2832 l/sec (100 cusecs) plus
II	283.2 - 2832.0 l/sec (10-100 cusecs)
III	28.32 - 283.2 l/sec (1-10 cusecs)
IV	378.5 l/min - 28.32 l/sec (0.223 cusecs or 100 Am.gal.* - 1 cusec)
V	37.85 - 378.5 l/min (0.0223 cusecs or 10 Am.gal. - 0.223 cusecs or 100 Am.gal.)
VI	3.785 - 37.85 l/min (0.00223 cusecs or 1 Am.gal. - 0.0223 cusecs or 10 Am.gal.)
VII	0.473 - 3.785 l/min (0.000279 cusecs or 1 Am.pt. - 0.00223 cusecs or 1 Am.gal.)
VIII	<0.473 l/min (<0.000279 cusecs or 1 Am.pt.)

(iv) A note on the mean dissolved calcium carbonate content recorded at the site and the standard deviation (SD) of dissolved calcium carbonate.

(v) A note on the mean dissolved magnesium carbonate content recorded at the site and the standard deviation of dissolved magnesium carbonate.

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* American gallons as used in the Meinzer (1923, 1927, 1942) classification

(vi) A note on the mean water temperature recorded at the rising, and the standard deviation of the water temperature.

(vii) A note on the mean pH.

(viii) A note of the point at which sampling was carried out.

(ix) A note of any peculiarities of the sampling site, for example if the position of a spring's source varies according to discharge.

(x) A note on any known caves associated with the sampled risings.

B Springs and Resurgences

Under Bryan's (1919) system of classification all springs in both the High Mark and Fountain's Fell areas may be classified as either 'depression springs' (due to land surface cutting water table in porous rock) or 'contact springs' (due to porous rock overlying impervious rock).

1 Springs Issuing from the High Mark Upland

All springs rising at the fringes of the High Mark Limestone upland are derived from percolation sources as, with the possible exception of Cotegill, there are no sinking streams located within this area. The water emerging at these springs is always very clear, no discolouration having been noted, even during periods of flood.

Wharfedale: Site 1 (Fig.3a,Map 4) is located in Wharfedale at N.G.R. 9766 6517 at an altitude of 221 m (725 ft) O.D. This spring is semi-permanent in nature, flow having been recorded on 75% of the sampling dates. During periods of medium to high flow water emerges from a rocky hollow at the above grid reference; however, during periods of low discharge the water issues at a point approximately 4.5 m (15 ft) downhill to the north-east. A check of dissolved calcium and magnesium carbonate content, water temperature and pH at both points during a period of high flow showed that the water emerging at the two positions is identical in these characteristics. The mean discharge is estimated to lie within the range of Meinzer Grade V springs. Sampling was carried out at the highest point of flow.

	Mean	S.D.
Dissolved $CaCO_3$	187 p.p.m.	13.0 p.p.m.
Dissolved $MgCO_3$	10.4 p.p.m.	4.1 p.p.m.
Water temperature	7.92°C	0.28°C
pH	7.2	-

<u>Wharfedale: Site 2</u> (Fig.3b,Map 4) is located in Wharfedale at N.G.R. 9767 6519, approximately 30 m (100 ft) to the north-north-east and downslope of site 1. The altitude of the spring is approximately 217 m (712 ft) O.D.; it is semi-permanent in character, flow having occurred on 79% of the sampling dates. The water always emerges at the same point even during periods of low flow. The mean discharge is estimated to lie within the range of Meinzer Grade V springs. Samples were collected at the source.

	Mean	S.D.
Dissolved $CaCO_3$	187 p.p.m.	12.8 p.p.m.
Dissolved $MgCO_3$	9.9 p.p.m.	3.2 p.p.m.
Water temperature	7.95°C	0.33°C
pH	7.2	-

<u>Robin Hood's Well: Site 3</u> (Figs.3c, 36a, Map 4) This spring is a large permanent rising in Wharfedale known as Robin Hood's Well. It is located at N.G.R. 9785 6576 at an altitude of 183 m (600 ft) O.D. Water emerges from a bedding plane along a zone approximately 3.5 m (12 ft) in

length. This spring is subject to very large fluctuations in discharge. During the period March 1969 to April 1970, the combined flow of this spring and spring number 4 (Robin Hood's Cave - see below) was measured at the time of sampling using a square-notch weir (see Chapter 2). During this period the minimum recorded discharge was 4.8 l/sec (0.17 cusecs) and the maximum was over 130.3 l/sec (4.6 cusecs), the maximum recordable discharge on the weir (Plates 3 and 4). This maximum figure, however, includes the discharge from site 4 which flowed during flood periods. The mean discharge was 28.3 l/sec (0.998 cusecs) and the spring may therefore be classified as Grade IV size. Sampling was carried out at the strongest point of flow towards the right side of the spring. Check samples taken at other points of emergence along the bedding plane showed the water to be identical in terms of the characteristics measured.

	Mean	S.D.
Dissolved $CaCO_3$	177 p.p.m.	6.7 p.p.m.
Dissolved $MgCO_3$	9.8 p.p.m.	3.2 p.p.m.
Water temperature	8.20°C	0.09°C
pH	7.4	-

Robin Hood's Well: Site 4 (Figs.3d, 36b, Map 4) is located at N.G.R. 9785 6577 about 6 m (20 ft) upvalley from spring number 3 (Robin Hood's Well) at an altitude of approximately 183 m (600 ft) O.D. This rising may be classified as a flood spring as flow only occurred on 33% of the sampling dates. Those sampling dates on which flow was recorded always succeeded a period of very heavy rainfall. Measurements of dissolved calcium and magnesium carbonate, temperature and pH show this water to be identical in terms of these characteristics to that emerging at the permanent rising at Robin Hood's Well (Site 3).

The water at spring number 4 emerges from a large pipe running under the road (Plate 5) and leading to a small cave(Robin Hood's Cave) 9 m (30 ft) in length* and described by Thornber (1959) as an "upper passage crawl through mud and water with small waterfall at end." (p.173)

Sampling was carried out at the point of issue from the pipe.

	Mean	S.D.
Dissolved $CaCO_3$	179 p.p.m.	11.6 p.p.m.
Dissolved $MgCO_3$	8.2 p.p.m.	1.2 p.p.m.
Water temperature	8.12°C	-
pH	7.4	-

Chapel House Well: Site 5 (Fig.3c, 37a, Map 4) is a large permanent rising in Wharfedale, located at N.G.R. 9762 6642 at an altitude of approximately 200 m (655 ft) O.D. This spring is subject to large fluctuations in discharge. During the period March 1969 to April 1970 a ½-90°'V'-notch weir was installed on level ground about 274 m (300 yd) from the source (see Chapter 2) and discharge was recorded at the time of sampling. During this period the minimum discharge recorded was 3.4 l/sec (0.12 cusecs) and a maximum of over 62.3 l/sec (2.2 cusecs), this being the maximum recordable value on the size of weir used. The mean discharge was 13 l/sec (0.458 cusecs), and the spring may therefore be classified as Grade IV under Meinzer classification. Sampling was carried out at the source of the spring.

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* Recent work (Aug.1971) by the Craven Pothole Club has extended this cave for a further 200 m of largely submerged passage.

	Mean	S.D.
Dissolved $CaCO_3$	198 p.p.m.	6.8 p.p.m.
Dissolved $MgCO_3$	11.4 p.p.m.	3.2 p.p.m.
Water temperature	8.01°C	0.13°C
pH	7.3	

Outgang Hill: Sites 6-9 and 11 are the source springs of a small left hand tributary of Howgill Beck, Wharfedale (Map 6) and which will be called Outgang Beck for future reference. Outgang Beck, and Howgill Beck downstream of the junction with Outgang Beck contain considerable amounts of calcareous tufa which appears to be still actively forming (Plate 12)

Outgang Hill: Site 6 (Fig.4a, Maps 4 and 6) is located near a large pile of limestone boulders at N.G.R. 9721 6714 at a surveyed altitude of 229.8 m (754 ft) O.D. This spring may be classified as a flood spring, flow having occurred on only 24% of the sampling dates. In periods of flood spring 6 is only one of several points of discharge in the immediate area. Sampling was carried out at the source whenever flow occurred. The approximate discharge of this group of flood springs in periods of high discharge is in the order of 14 l/sec (0.5 cusecs).

	Mean	S.D.
Dissolved $CaCO_3$	197 p.p.m.	10.5 p.p.m.
Dissolved $MgCO_3$	9.6 p.p.m.	0.7 p.p.m.
Water temperature	7.87°C	0.30°C
pH	7.3	-

Outgang Hill: Site 7 (Fig.4b, Maps 4 and 6) is located downhill from, and to the south-east of spring number 6 at N.G.R. 9736 6722 and at a surveyed altitude of 224.6 m (737 ft) O.D. This rising may also be classified as a flood-spring, flow having been recorded on 42% of the sampling dates. This spring is also one of the source springs of Outgang Beck, and again in periods of heavy rainfall the point of discharge sampled was one of several in the immediate vicinity. The approximate discharge of this group of flood springs in conditions of high flow would be in the order of 14 l/sec (0.5 cusecs).

	Mean	S.D.
Dissolved $CaCO_3$	199 p.p.m.	8.9 p.p.m.
Dissolved $MgCO_3$	10.1 p.p.m.	2.9 p.p.m.
Water temperature	7.91°C	0.22°C
pH	7.7	-

Outgang Hill: Site 8 (Fig.4c, Maps 4 and 6) This is a permanent spring located at N.G.R. 9728 6715 at a surveyed altitude of 217.3 m (713 ft) O.D. The water issues from the foot of a small limestone outcrop and provides one of the permanent sources of Outgang Beck (Plate 6). Discharge varies considerably and in the summer of 1968 was reduced to a mere trickle. The estimated mean discharge is within the range of discharge governed by Meinzer's Grade IV springs. Sampling was carried out at the source.

Dissolved $CaCO_3$	202 p.p.m.	6.4 p.p.m.
Dissolved $MgCO_3$	12.4 p.p.m.	3.7 p.p.m.
Water temperature	7.96°C	0.19°C
pH	7.3	-

Outgang Hill: Site 9 (Fig.4d, Maps 4 and 6) located at N.G.R. 9730 6713 at a surveyed altitude of 217 m (712 ft) O.D. is the chief source of

Outgang Beck. It is a permanent spring with little obvious variation in discharge. Water issues from a bedding plane along a 3 m (10 ft) length. This bedding plane may be the same as that from which the discharge of spring number 8 occurs, there being a surveyed difference in altitude between the two springs of less than 0.3 m (1 ft). The discharge of spring number 9 is probably within the range of Meinzer Grade IV springs. Sampling was carried out at the point of strongest flow and check samples at two points along the zone of discharge showed the water to be of identical character to the point at which regular sampling was carried out.

	Mean	S.D.
Dissolved $CaCO_3$	202 p.p.m.	6.5 p.p.m.
Dissolved $MgCO_3$	12.3 p.p.m.	4.1 p.p.m.
Water temperature	7.93°C	0.15°C
pH	7.3	-

Outgang Hill: Site 11 (Fig.4e, Maps 4 and 6) is a permanent spring located at N.G.R. 9736 6722 at a surveyed altitude of 206.9 m (679 ft) O.D. Water emerges from a small grassy hollow approximately 3 m (10 ft) from the right hand bank of Outgang Beck. The discharge of this spring is generally low and probably lies within the range of discharges of Meinzer Grade V springs. Sampling was carried out at the source. Owing to the low rate of discharge and seepage of water through the soil it is believed that the temperature of the spring water may, to some extent, be influenced by the soil temperature at time of sampling.

	Mean	S.D.
Dissolved $CaCO_3$	218 p.p.m.	9.1 p.p.m.
Dissolved $MgCO_3$	13.4 p.p.m.	2.9 p.p.m.
Water temperature	8.27°C	1.68°C
pH	7.4	-

Reynard's Close: Site 19 (Figs.5a, 37b, Maps 4 and 6) is a very large, permanent rising in Wharfedale known as Reynard's Close Spring. It is located in a small copse at N.G.R. 9712 6749 at an altitude of 222.5 m (730 ft) O.D. and provides the chief source to Sike's Beck, a small stream south of Kilnsey village in Wharfedale. This is one of the largest springs sampled and provides the water supply for Conistone village in Wharfedale. This spring is subject to very large fluctuations in discharge. During the period March 1969 to April 1970 the minimum of recorded discharge was 28.6 l/sec (1.01 cusecs) and the maximum was 671.2 l/sec (23.7 cusecs). The mean discharge over this period was 229.1 l/sec (8.09 cusecs) which falls within Meinzer Grade III classification of springs. During periods of very high discharge, the water at the springhead domes up about a third of a metre (1 ft) in the air and is obviously under considerable hydrostatic pressure (Plate 8). Discharge was recorded on a broad crested square-notch weir (Plate 7) constructed by the Craven Water Board from whom additional discharge records were obtained. Considerable amounts of quartz sand which may represent the insoluble residue of the limestone have built up behind the weir. Sampling was carried out at the source.

	Mean	S.D.
Dissolved $CaCO_3$	192 p.p.m.	7.2 p.p.m.
Dissolved $MgCO_3$	12.6 p.p.m.	3.2 p.p.m.
Water temperature	7.78°C	0.22°C
pH	7.3	-

Reynard's Close: Site 20 (Figs.5b, Maps 4 and 6) is a left bank tributary spring to Sikesbeck located at N.G.R. 9713 6750 at an altitude of 222.5 m (730 ft) O.D. It is situated about 18 m (20 yd) to the north-east of Reynard's Close spring (Site 19). This spring is semi-permanent, flow having been recorded on 82% of the sampling dates, and is subject to wide variations in discharge. The estimated mean discharge of this spring is within the range of Meinzer Grade IV. Sampling was carried out at the source of the spring which lies at the head of an artificial cutting into the slope. Owing to the very low rate of flow at some sampling dates the water temperature may have been influenced by the air and soil temperatures at the time of sampling.

	Mean	S.D.
Dissolved $CaCO_3$	193 p.p.m.	7.8 p.p.m.
Dissolved $MgCO_3$	11.3 p.p.m.	2.6 p.p.m.
Water temperature	7.74°C	0.27°C
pH	7.4	-

Kilnsey Cave: Site 21 (Fig.5c, Maps 4 and 6)is the small rising at Kilnsey Cave in Wharfedale. This site is located at N.G.R. 9738 6838 at an altitude of 198 m (650 ft) O.D. Although a sample was collected at every visit, the rising from the cave mouth is not permanent, the additional samples having been collected at points of discharge at lower levels than the cave. On account of water from the cave exit mixing directly with that of lower levels during high flow conditions, it was not possible to check if all sources of flow were of the same character. This may therefore be a source of error in the records of this site. Furthermore, in periods of low flow the discharge at all points was reduced to a trickle and water temperatures recorded on these dates may have been affected by air and soil temperatures at the time of sampling. At no time was Kilnsey Cave seen to flood.

	Mean	S.D.
Dissolved $CaCO_3$	157 p.p.m.	19.7 p.p.m.
Dissolved $MgCO_3$	7.6 p.p.m.	2.2 p.p.m.
Water temperature	8.47°C	0.78°C
pH	7.7	-

Kilnsey: Site 22 (Fig.5d, Maps 4 and 6) This spring is located at N.G.R. 9738 6840 approximately 46 m (50 yd) upvalley from Kilnsey Cave at an altitude of 198 m (650 ft) O.D. It is semi-permanent in nature, flow having been recorded on 63% of the sampling dates. This spring may be classified as a semi-permanent flood spring, discharge apart from flood periods being either nil or little more than a trickle. The water emerges at the head of a rocky, moss-covered channel, and it was at this point that samples were collected.

	Mean	S.D.
Dissolved $CaCO_3$	203 p.p.m.	11.5 p.p.m.
Dissolved $MgCO_3$	7.2 p.p.m.	1.5 p.p.m.
Water temperature	8.16°C	0.24°C
pH	7.4	-

Kilnsey: Site 23 (Fig.5e, Maps 4 and 6) This spring is located approximately 46 m (50 yd) upvalley from site 22 at N.G.R. 9737 6843 and at an altitude of 198 m (650 ft) O.D. This site, too, may be classified as a semi-permanent flood spring. Although flow was recorded on 58% of the sampling dates, significant discharge only occurred after heavy rainfall. Sampling was carried out at the source which lies at the head of a steep rocky moss and tufa covered bank.

	Mean	S.D.
Dissolved $CaCO_3$	204 p.p.m.	11.9 p.p.m.
Dissolved $MgCO_3$	6.7 p.p.m.	1.5 p.p.m.
Water temperature	8.16°C	0.20°C
pH	7.4	-

Kilnsey: Site 24 (Fig.6a, Maps 4 and 6) This is a rising located about 4.5 m (5 yd) upvalley from site 21 at N.G.R. 9739 6844 and at an altitude of 198 m (650 ft) O.D. This is a semi-permanent spring, discharge having been recorded on 90% of the sampling dates. Discharge varies considerably and the exact point of emergence of the water from the limestone depends on this factor. At least three levels of flow may be identified and were sampled. At medium to low discharge conditions water emerges from a bedding plane at the head of a steep tufa covered bank; during periods of medium to high flow it issues in addition from a second bedding plane about half a metre (1½ ft) higher; during flood conditions water emerges at a still higher bedding plane creating a small waterfall as it falls past the lower sites of discharge. The estimated mean discharge of this spring lies within Meinzer Grade IV springs although in flood periods discharges are in the order of 57-85 l/sec (2-3 cusecs). Sampling was carried out at the highest point at which flow occurred. Check samples indicated that the water at the three points of discharge was identical in terms of the characteristics measured.

	Mean	S.D.
Dissolved Ca CO_3	207 p.p.m.	10.7 p.p.m.
Dissolved $MgCO_3$	7.3 p.p.m.	1.8 p.p.m.
Water temperature	8.13°C	0.18°C
pH	7.4	-

Kilnsey: Site 25 (Fig.6b, Maps 4 and 6) is a spring located approximately 9 m (10 yd) upvalley from site 24 at N.G.R. 9736 6846 and at an altitude of 198 m (650 ft) O.D. This is a semi-permanent spring flow having been recorded on 75% of the sampling dates. Discharge characteristics are, however, in several respects like that of a semi-permanent flood spring. The spring reacts very strongly to heavy rainfall but after a few days the discharge falls away to little more than a persistent trickle. During low flow the water seeps out at the head of a mossy bank of boulders but during flood flow it emerges at a higher bedding plane forming a small waterfall as at site 24. Sampling was carried out at the highest point of flow. Again a check was made at a period of flood discharge on all points of flow to ascertain that samples collected at the two sources were comparable.

	Mean	S.D.
Dissolved $CaCO_3$	205 p.p.m.	11.3 p.p.m.
Dissolved $MgCO_3$	7.0 p.p.m.	1.8 p.p.m.
Water temperature	7.95°C	0.44°C
pH	7.4	-

Kilnsey: Site 26 (Fig.6c, Maps 4 and 6) is a spring located at N.G.R. 9733 6852 at an altitude of 198 m (630 ft) O.D. The water issues from a bedding plane into a concrete trough at the foot of a single ash tree in the field across the road from North Cote Farm, north of Kilnsey village in Wharfedale. This spring is a permanent rising. The discharge fluctuations are much less than the other Kilnsey Springs (sites 19-25) and even over a long dry period maintains an estimated 364-455 l/min (0.214 - 0.268 cusecs). The mean discharge is estimated to lie within the range of Meinzer Grade IV-V springs. Sampling was carried out at the source.

	Mean	S.D.
Dissolved $CaCO_3$	208 p.p.m.	15.8 p.p.m.
Dissolved $MgCO_3$	8.8 p.p.m.	2.7 p.p.m.
Water temperature	8.01°C	0.17°C
pH	7.3	-

Sites 1-26 are located in Wharfedale on the eastern margins of the High Mark upland. The following sites (27-42) are located in Littondale on the north-eastern margins of the High Mark area.

Moss Beck: Site 27 (Fig.6d, 38a, Map 4) is a very large permanent rising in Littondale known as Moss Beck. The sampling point (see below) is located at N.G.R. 9683 6913 at an altitude of 213 m (700 ft) O.D. This spring is subject to considerable fluctuations in discharge. Over the period March 1969 - April 1970 the minimum recorded discharge was 21 l/sec (0.74 cusecs) and the maximum was 691 l/sec (24.4 cusecs). The mean discharge was 190.9 l/sec (6.74 cusecs) which falls within Meinzer's Grade III classification of springs. The discharge readings were carried out on a broad-crested concrete weir constructed by the Craven Water Board

(Plate 9) from whom additional discharge readings were obtained (see Chapter 2). Although the source of Moss Beck varies according to discharge, sampling was always carried out at a permanent rising located at a concrete trough in the stream bed. Although the stream emerges much further up the hill in periods of flood this point provides the highest point of discharge in periods of low flow. Check samples indicated the water emerging at this point to be identical in terms of dissolved calcium and magnesium carbonate, temperature and pH to the flood rising further uphill.

	Mean	S.D.
Dissolved $CaCO_3$	172 p.p.m.	9.9 p.p.m.
Dissolved $MgCO_3$	8.2 p.p.m.	2.1 p.p.m.
Water temperature	7.67°C	0.30°C
pH	7.5	-

<u>Sleet's Gill Beck: Site 29</u> (Fig.7a, Map 4) is a rising located at N.G.R. 9612 6946 at an altitude of 236 m (775 ft) O.D. The sampling site was a deep clear pool on Sleets Gill Beck on the uphill side of the road. Although it was very difficult to detect the exact point of emergence of the water from the limestone, for most of the year this pool appeared to be the source of flow. Discharge at this point over the sampling period was seldom more than a trickle although water emerging at a higher altitude from Sleet's Gill Cave during flood periods would add to the discharge. Some readings at Sleet's Gill Beck pool may be of doubtful value as vertical temperature profiles in the sampling pool showed a temperature stratification with depth. This was observed during the dry summer months of 1968 and suggested that at that period the point of discharge into the pool was dry or almost dry. Even in 'flood' periods the discharge of Sleet's Gill Beck is low.

	Mean	S.D.
Dissolved $CaCO_3$	222 p.p.m.	14.0 p.p.m.
Dissolved $MgCO_3$	11.6 p.p.m.	3.4 p.p.m.
Water temperature	8.43°C	1.74°C
pH	7.3	-

Cotegill: Site 30 (Fig.7b, Maps 4 and 7) is located at N.G.R. 9459 7026 at an altitude of 236 m (775 ft) O.D. It is a small flood spring positioned about 4.5 m (5 yd) from the left bank of Cotegill. Flow was recorded on only 33% of the sampling dates. Sampling was carried out at the source whenever flow occurred.

	Mean	pH
Dissolved $CaCO_3$	195 p.p.m.	9.4 p.p.m.
Dissolved $MgCO_3$	10.2 p.p.m.	1.3 p.p.m.
Water temperature	8.19°C	2.19°C
pH	7.6	-

Cotegill: Site 31 (Fig.7c, Maps 4 and 7) is a small spring located on the right bank of Cotegill at N.G.R. 9464 7017 at an altitude of 250 m (820 ft) O.D. This spring is semi-permanent, flow having been recorded on 96% of the sampling days. Water issues from below a small pile of boulders where a wall meets Cotegill. During severe flood periods water collects behind this wall and seepage from this standing water may have influenced the quality of samples collected at these times. The discharge of this spring is always low and is estimated to lie within Grades V or VI of the Meinzer classification. Sampling was always carried out at the source.

	Mean	S.D.
Dissolved $CaCO_3$	176 p.p.m.	16.4 p.p.m.
Dissolved $MgCO_3$	6.9 p.p.m.	2.1 p.p.m.
Water temperature	7.64°C	2.91°C
pH	7.8	-

Cotegill: Site 32 (Fig.7d, Maps 4 and 7) is a small permanent spring located at N.G.R. 9458 7012 near the junction of the main left hand tributary of Cotegill with Cotegill at an altitude of 251 m (825 ft) O.D. This spring provides the water supply for Arncliffe Cote and Hawkswick Cote farms. The discharge is usually low (estimated Meinzer Grade V) and is not subject to major fluctuations. Sampling was carried out at the source.

	Mean	S.D.
Dissolved $CaCO_3$	185 p.p.m.	15.8 p.p.m.
Dissolved $MgCO_3$	7.2 p.p.m.	2.1 p.p.m.
Water temperature	7.81°C	2.61°C
pH	7.6	-

Cotegill: Site 33 (Fig.8a, Maps 4 and 7) is a small permanent spring located on the right bank of Cotegill at N.G.R. 9459 7010 and at an altitude of 251 m (825 ft) O.D. It issues from under a large boulder or small outcrop approximately 91 m (100 yd) upstream of the junction of the main left bank tributary of Cotegill with Cotegill. The discharge is always low (Meinzer Grade V or VI) and does not fluctuate greatly. Sampling was carried out at the source.

	Mean	S.D.
Dissolved $CaCO_3$	182 p.p.m.	17.3 p.p.m.
Dissolved $MgCO_3$	7.5 p.p.m.	1.7 p.p.m.
Water temperature	8.05°C	2.50°C
pH	7.7	-

Cotegill: Site 34 (Fig.8b, Maps 4 and 7) is a small permanent spring on Cotegill located at N.G.R. 9449 7003 and at an altitude of 259 m (850 ft) O.D. The spring lies about 3 m (10 ft) from the left bank of Cotegill opposite a large section in boulder-clay exposed on the right bank by stream undercutting. The discharge is always low (estimated Meinzer Grade VI) and does not fluctuate greatly. Sampling was carried out at the source.

	Mean	S.D.
Dissolved $CaCO_3$	182 p.p.m.	19.3 p.p.m.
Dissolved $MgCO_3$	7.6 p.p.m.	1.8 p.p.m.
Water temperature	7.76°C	3.22°C
pH	7.9	-

Cotegill: Site 35 (Fig.8c, Maps 4 and 7) is a permanent rising about 3 m (10 ft) from the right bank of Cotegill near the point at which a wall joins the stream. It is located at N.G.R. 9438 6998 at an altitude of 274 m (900 ft) O.D. The average discharge of this spring is estimated to lie within the range of Meinzer Grade V springs. The water issues from below an area of small moss-covered limestone stones and small amounts of quartz sand may be found at the rising. Sampling was carried out at the source.

	Mean	S.D.
Dissolved $CaCO_3$	187 p.p.m.	18.7 p.p.m.
Dissolved $MgCO_3$	8.0 p.p.m.	2.3 p.p.m.
Water temperature	7.31°C	0.90°C
pH	7.5	-

Cotegill: Site 37 (Fig.9a, Maps 4 and 7) is a spring located at N.G.R. 9385 7004 at an altitude of 351 m (1150 ft) O.D. This spring is one of the source springs of the left hand tributary of Cotegill. It issues from a small rocky hollow near an old mining waste tip on the right side of the tributary. This was the only source spring sampled as the true source of this tributary lies in a small marshy area in which no clearly defined spring emerges. The spring is semi-permanent, flow having been recorded on 95% of the sampling days. The discharge is always low (within Meinzer Grades V) and does not vary greatly. Sampling was carried out at the source.

	Mean	S.D.
Dissolved $CaCO_3$	187 p.p.m.	9.9 p.p.m.
Dissolved $MgCO_3$	10.3 p.p.m.	4.0 p.p.m.
Water temperature	7.87°C	1.42°C
pH	7.4	-

Cotegill: Site 38 (Fig.9b, Maps 4 and 7) is a small spring located at N.G.R. 9433 7008 and at an altitude of 290 m (950 ft) O.D. It issues about 18 m (20 yd) from the right bank of Cotegill tributary stream near a sunken concrete water tank (surrounded by a wooden fence). This spring is semi-permanent, flow having been recorded on 80% of the sampling days. The discharge is low (Meinzer Grade V) and does not vary greatly. Sampling was carried out at the source.

	Mean	S.D.
Dissolved $CaCO_3$	252 p.p.m.	8.7 p.p.m.
Dissolved $MgCO_3$	11.8 p.p.m.	1.9 p.p.m.
Water temperature	8.04°C	1.50°C
pH	7.1	-

Bluescar: Site 39 (Fig.9c, Maps 4 and 7)is one of a group of three springs (39-41) located south-east of Bluescar cliffs in Littondale. Site 39 is a permanent rising located at N.G.R. 9407 7057 and at an altitude of 259 m (850 ft) O.D. Discharge at this site is usually low (Meinzer Grade V) although in periods of flood, water issues at several points in the immediate vicinity of the sampled spring. The sampling point lies at the head of a moss-covered stony slope which stretches like an alluvial fan below the spring.

	Mean	S.D.
Dissolved $CaCO_3$	215 p.p.m.	18.7 p.p.m.
Dissolved $MgCO_3$	10.7 p.p.m.	4.3 p.p.m.
Water temperature	7.81°C	0.09°C
pH	7.4	-

Bluescar: Site 40 (Fig.9d, Maps 4 and 7)is located at N.G.R. 9403 7062 and at an altitude of 259 m (850 ft) O.D. This is a flood spring at which flow was recorded on 26% of the sampling dates. Water emerges at the head of a small grass-covered gully after heavy rainfall. Discharge varies greatly with the estimated maximum in the order of 57 l/sec (2 cusecs). Sampling was carried out at the source whenever flow occurred.

	Mean	S.D.
Dissolved $CaCO_3$	173 p.p.m.	8.8 p.p.m.
Dissolved $MgCO_3$	7.7 p.p.m.	1.2 p.p.m.
Water temperature	7.66°C	0.18°C
pH	7.5	-

Bluescar: Site 41 (Fig.9e, Maps 4 and 7)is a permanent rising located downhill from and to the north of Site 48 at N.G.R. 9399 7064 and at an altitude of 255 m (835 ft) O.D. This water emerges from a stony springhead near a small fenced-in concrete water-supply tank. The discharge of this spring is similar to that at Site 5 - Chapel House (Meinzer Grade IV) and is subject to similar strong fluctuations in discharge. Sampling was always carried out at the source.

	Mean	S.D.
Dissolved $CaCO_3$	177 p.p.m.	8.6 p.p.m.
Dissolved $MgCO_3$	11.5 p.p.m.	4.7 p.p.m.
Water temperature	7.73°C	0.13°C
pH	7.5	-

Bluescar: Site 42 (Fig.10a, Maps 4 and 7) is a small spring located at N.G.R. 9409 7099 at an altitude of 213 m (700 ft) O.D. The spring issues from a small marshy hollow behind a roadside barn and is the source of a small left hand tributary to the stream supplied by sites 39-14. This spring is semi-permanent, flow having been recorded on 83% of the sampling dates. Discharge is usually low and is estimated to lie within the range of Meinzer Grade V springs. Sampling was carried out at the source.

	Mean	S.D.
Dissolved $CaCO_3$	244 p.p.m.	16.9 p.p.m.
Dissolved $MgCO_3$	9.4 p.p.m.	1.7 p.p.m.
Water temperature	7.76°C	2.72°C
pH	7.5	-

Sites 46-52 lie to the south-west of Arncliffe village in Littondale (Map 8)

Arncliffe: Site 46 (Fig.10b, Maps 4 and 8) is located at N.G.R. 9299 7139 at an altitude of 251 m (825 ft) O.D. This is a permanent spring and the water emerges from an open bedding plane at the foot of a small limestone outcrop. Discharge is low and does not vary greatly; the mean discharge is estimated to lie within the range of Meinzer Grade V springs. Sampling was carried out at the point of emergence from the open bedding plane. To avoid confusion it should be noted that another small spring is located about 9 m (10 yd) to the south-west of site 46. This also emerges from an open bedding plane at the foot of a small limestone outcrop, but was not sampled owing to its minute discharge, even after heavy rain.

	Mean	S.D.
Dissolved $CaCO_3$	154 p.p.m.	10.1 p.p.m.
Dissolved $MgCO_3$	11.6 p.p.m.	4.3 p.p.m.
Water temperature	7.86°C	0.78°C
pH	7.5	-

Arncliffe: Site 47 (Fig.10c, Maps 4 and 8) is the permanent spring which provides the water supply for Arncliffe village. It is located at N.G.R. 9282 7143 at an altitude of 236 m (775 ft) O.D. It is not possible to assess the discharge of the spring as the rising itself is enclosed in a large fenced-in concrete water-supply tank. Sampling was carried out at one of the overflow pipes from this tank, but it is not considered that this causes any source of error in the records of this site.

	Mean	S.D.
Dissolved $CaCO_3$	163 p.p.m.	10.2 p.p.m.
Dissolved $MgCO_3$	8.8 p.p.m.	2.3 p.p.m.
Water temperature	7.69°C	0.26°C
pH	7.5	-

Arncliffe: Site 48 (Figs.10d and 38b, Maps 4 and 8)is a small permanent spring located at N.G.R. 9277 7142 at an altitude of 236 m (775 ft) O.D. The water issues from a small marshy hollow near an isolated fragment of wall, which runs parallel to the stream caused by this spring. This spring was weired in the period March 1969 - April 1970 using a ½-90° 'V' notch weir (see Chapter 2). The minimum recorded discharge over this period was 0.57 l/sec (0.020 cusecs) and the maximum was 2.55 l/sec (0.090 cusecs). The mean discharge which was 0.91 l/sec (0.032 cusecs) classifies this spring as Meinzer Grade V. Sampling was carried out at the source.

	Mean	S.D.
Dissolved $CaCO_3$	163 p.p.m.	11.7 p.p.m.
Dissolved $MgCO_3$	9.5 p.p.m.	2.8 p.p.m.
Water temperature	7.70°C	0.53°C
pH	7.5	-

Arncliffe: Site 49 (Figs.11a and 39a, Maps 4 and 8) is a small permanent spring located at N.G.R. 9273 7139 at an altitude of 236 m (775 ft) O.D. It lies upvalley (south-west) from site 48 and was also weired during the period March 1969 - April 1970 using a ½-90°'V' notch weir (see Chapter 2). The minimum recorded discharge was 0.34 l/sec (0.012 cusecs) and the maximum was 2.27 l/sec (0.080 cusecs). The mean discharge of 0.71 l/sec (0.025 cusecs) classifies this spring as Meinzer Grade V. Sampling was carried out at the source.

	Mean	S.D.
Dissolved $CaCO_3$	164 p.p.m.	11.8 p.p.m.
Dissolved $MgCO_3$	9.3 p.p.m.	2.3 p.p.m.
Water temperature	7.71°C	0.69°C
pH	7.5	-

Arncliffe: Site 50 (Fig.11b, Maps 4 and 8) is located at N.G.R. 9275 7139 at an altitude of 238 m (780 ft) O.D. It lies between sites 48 and 49 but at a slightly higher altitude. This is a permanent spring but the discharge during the summer months of 1968 fell to almost zero, with the result that the temperature of samples collected during this period may have been affected by the air temperatures at the time of sampling. Discharge is always low and the estimated mean discharge lies within the range of discharge of Meinzer Grade V springs. Sampling was carried out at the source which is a stony area of about one square metre (11 square feet) in area.

	Mean	S.D.
Dissolved $CaCO_3$	162 p.p.m.	11.8 p.p.m.
Dissolved $MgCO_3$	9.7 p.p.m.	2.7 p.p.m.
Water temperature	8.15°C	1.41°C
pH	7.5	-

Arncliffe: Site 51 (Fig.11c, Maps 4 and 8) is a permanent spring located at N.G.R. 9258 7130 at an altitude of 239 m (785 ft) O.D. It is a small spring which feeds a left hand tributary to the stream rising at site 52 (see below). The discharge is always low and the estimated mean discharge lies within the range of discharge covered by Meinzer Grade V springs. Sampling was carried out at the source which is a mossy hollow at the head of the stream.

	Mean	S.D.
Dissolved $CaCO_3$	158 p.p.m.	9.9 p.p.m.
Dissolved $MgCO_3$	7.1 p.p.m.	1.7 p.p.m.
Water temperature	7.85°C	1.36°C
pH	7.4	-

Arncliffe: Site 52 (Fig.11d, Maps 4 and 8) is a small permanent spring located at N.G.R. 9258 7128 at an altitude of 240 m (786 ft) O.D. The spring issues from a marshy area beside a single thorn-bush. The discharge is usually low but in periods of flood, water emerges at a number of additional points in the immediate proximity of the spring. The estimated mean discharge is within the range of discharge of Meinzer Grade V springs. Sampling was carried out at the source.

	Mean	S.D.
Dissolved $CaCO_3$	157 p.p.m.	10.2 p.p.m.
Dissolved $MgCO_3$	7.6 p.p.m.	1.4 p.p.m.
Water temperature	7.85°C	0.96°C
pH	7.6	-

Sites 53-59 are located on the western and south-western margins of the High Mark Upland.

Cowside: Site 53 (Fig.12a, Maps 4 and 11) is a large permanent rising in the upper reaches of Cowside Beck (Skirfare). It is located at N.G.R. 8917 6933 at an altitude of 357 m (1170 ft) O.D. The rising is about 91 m (100 yd) from the left bank of Cowside Beck at the head of a steep rocky channel. The mean discharge of this spring is in the order of 28 l/sec (1 cusec) (Meinzer Grade IV spring). In flood periods water emerges about two thirds of a metre (2 ft) uphill from the normal source of flow. Samples were collected at the source, where a considerable amount of quartz sand had collected.

	Mean	S.D.
Dissolved $CaCO_3$	166 p.p.m.	9.9 p.p.m.
Dissolved $MgCO_3$	5.9 p.p.m.	1.4 p.p.m.
Water temperature	7.28°C	0.17°C
pH	7.4	-

Cowside: Site 54 (Fig.12b, Maps 4 and 11) is a flood spring located near the source of Cowside Beck (Skirfare) at N.G.R. 8892 6919, at an altitude of 363 m (190 ft) O.D. This is a flood spring on which definite flow was recorded on 25% of the sampling dates. On a further 12% of the sampling dates a very small trickle of water was observed at this site but was unsampled owing to the impossibility of detecting the source. At flood stage the water emerges at three distinct points which test samples showed to be identical in terms of the characteristics measured. Sampling was carried out on the upvalley point of flow.

	Mean	S.D.
Dissolved $CaCO_3$	161 p.p.m.	13.0 p.p.m.
Dissolved $MgCO_3$	5.6 p.p.m.	1.2 p.p.m.
Water temperature	7.24°C	-
pH	7.5	-

Malham Tarn: Site 55 (Fig.12c, Map 4) is a very large permanent spring located at N.G.R. 8868 6732 at an altitude of 278 m (1240 ft) O.D. The water emerges from a large sandy hollow near a barn at Waterhouses, and is one of the major feeder springs of Malham Tarn. Howarth, Fennell, Bean, Branson, Ackroyd, Kendall and Lower Carter (1900) believed that this spring was a re-rising of water sinking on Knowe Fell, although the low degree of dissolved calcium carbonate and water temperature variation recorded suggests that this system may be fed by percolation sources probably in the High Mark area. Although the spring was only sampled over a four month winter period, major fluctuations in discharge were observed. The mean discharge in this period is estimated at 57-85 l/sec (2-3 cusecs) (Meinzer Grade III) with maximum discharges of over 283 l/sec (10 cusecs).

	Mean	S.D.
Dissolved $CaCO_3$	166 p.p.m.	9.7 p.p.m.
Dissolved $MgCO_3$	6.5 p.p.m.	1.6 p.p.m.
Water temperature	7.38°C	0.12°C
pH	7.3	-

Malham Tarn: Site 56 (Figs.12d and 39b, Map 4) is a permanent spring located on the eastern margin of Malham Tarn at N.G.R. 8982 6698 at an altitude of 378 m (1240 ft) O.D. It is the more northerly of two springs which unite after a short distance to flow down an artificially lined channel into Malham Tarn. Sampling was carried out at the source which has the appearance of a small well artificially lined with blocks of limestone. The water bubbles up through quartz sand which lines the bottom of the spring pool. The discharge of this spring is considered in conjunction with site 57 (see below).

	Mean	S.D.
Dissolved $CaCO_3$	193 p.p.m.	4.2 p.p.m.
Dissolved $MgCO_3$	6.1 p.p.m.	1.9 p.p.m.
Water temperature	7.42°C	0.22°C
pH	7.3	-

Malham Tarn: Site 57 (Figs.12e and 40a, Map 4) is located about 18 m (20 yd) to the south of site 56 at N.G.R. 8982 6697 and at a slightly higher altitude of 378 m (1240 ft) O.D. This spring is semi-permanent, flow having been recorded on 83% of the sampling days. During periods of high discharge this spring (site 57) rises about two thirds of a metre (2 ft) uphill from its usual source which, like site 56 lies in an artificially constructed, though now partially destroyed well-head. The discharge of this spring was measured in conjunction with that of site 56, in the period March 1969 - April 1970, using a ½-90°'V' notch weir.

The combined discharges of sites 56 and 57 recorded a minimum of 0.08 l/sec (0.003 cusecs) over the recorded period. At this stage of low discharge all flow was originating at site 56, site 57 being dry. The maximum recorded combined discharge was 6.2 l/sec (0.219 cusecs). The mean discharge was 2.2 l/sec. (0.078 cusecs). Although geographically separate, these springs were identical with regard to the dissolved calcium and magnesium carbonate levels, although the water temperature at site 57 tended to be fractionally lower (see Chapter 7).

	Mean	S.D.
Dissolved $CaCO_3$	193 p.p.m.	4.2 p.p.m.
Dissolved $MgCO_3$	6.4 p.p.m.	2.0 p.p.m.
Water temperature	7.29°C	0.13°C
pH	7.3	-

Malham Tarn: Site 58 (Figs.13a and 40b, Map 4) is a small spring located at N.G.R. 9001 6673 at an altitude of 381 m (1250 ft) O.D. The water emerges from a small opening below a large boulder on the scree below Great Close Scar near Malham Tarn. This is a semi-permanent rising, flow having been recorded 92% of the sampling dates. Over the period March 1969 - April 1970 the discharge at the site was measured using a ½-90° 'V' notch weir (Plate 10). The minimum recorded discharge was zero, and the maximum 7.6 l/sec (0.268 cusecs). The mean discharge over the period was 1.9 l/sec (0.067 cusecs). This site may, therefore, be classified as a Grade V spring under Meinzer's classification. Sampling was carried out at the source and water issuing from this spring flows westwards to Malham Tarn.

	Mean	S.D.
Dissolved $CaCO_3$	185 p.p.m.	4.1 p.p.m.
Dissolved $MgCO_3$	5.9 p.p.m.	2.0 p.p.m.
Water temperature	7.36°C	0.42°C
pH	7.5	-

Malham Tarn: Site 59 (Fig.3b, Map 4) is a small spring located at the base of the scree beneath Great Close Scar, Malham Tarn at N.G.R. 9009 6659, at an altitude of 378 m (1240 ft) O.D. This is a semi-permanent rising, flow having been recorded on 92% of the sampling dates. The discharge of this spring is usually very low but in flood periods may attain an estimated flow of about 91 l/min (0.05 cusecs). The estimated mean discharge lies within the range of Meinzer's Grade VI springs. Sampling was carried out at the source and water emerging at this site flows eastwards to Great Close Mire.

	Mean	S.D.
Dissolved $CaCO_3$	171 p.p.m.	8.0 p.p.m.
Dissolved $MgCO_3$	5.8 p.p.m.	1.6 p.p.m.
Water temperature	7.26°C	2.11°C
pH	7.6	-

2 Springs Issuing from the Fountains Fell Upland

Newbarn: Site 60 (Fig.14a, Maps 5 and 8) is a rising located at N.G.R. 9268 7205 at an altitude of 224 m (735 ft) O.D. Water bubbles up at the foot of a wall on the northern edge of the farm track between Newbarn and Hullbarn. This is a semi-permanent rising on which flow occurred on 83% of the sampling dates. Variations in discharge are large, fluctuating between zero and approximately 57-58 l/sec (2-3 cusecs). The estimated mean discharge of this rising lies within the range of discharges of Meinzer Grade IV. The stream supplied by this spring sinks again near Newbarn, but it is not known whether the water has been artificially piped away or flows into a natural sinkhole. Sampling was carried out at the source.

	Mean	S.D.
Dissolved $CaCO_3$	238 p.p.m.	12.0 p.p.m.
Dissolved $MgCO_3$	8.8 p.p.m.	2.9 p.p.m.
Water temperature	7.89°C	2.04°C
pH	7.2	-

Bown Scar: Site 61 (Fig.14b, Maps 5 and 8) is a permanent spring which is the source of a right hand tributary of Bown Scar Beck, Littondale. The spring is located at N.G.R. 9199 7213 and an altitude of 253 m (830 ft) O.D. The discharge at this site does not vary greatly and the average discharge is in the order of Meinzer Grade V springs. Sampling was carried out at the source which lies near the head of a small rocky valley cut by the stream.

	Mean	S.D.
Dissolved $CaCO_3$	198 p.p.m.	17.3 p.p.m.
Dissolved $MgCO_3$	9.0 p.p.m.	8.7 p.p.m.
Water temperature	7.80°C	0.46°C
pH	7.6	-

Bown Scar: Sites 62 and 63 (Figs.14c and d, Maps 5 and 8) are at a large rising in Bown Scar Wood at N.G.R. 9188 7219 and at an altitude of 261 m (855 ft) O.D. Sampling was carried out at two points of resurgence at Bown Scar. Site 62 is a semi-permanent rising located on the right (downvalley) side of the resurgence. The water here emerges from an open bedding plane and flow was recorded at this point on 74% of the sampling dates. Sampling was always carried out at the point of discharge from the open bedding plane.

Site 63 is located on the left (upvalley) side of the resurgence. During flood conditions flow issues from an open bedding plane which, although structurally the same bedding plane as that at site 62, is physically separated from the resurgence at 62 by a large section of bedrock. Although at first sight one would imagine that the flow has been simply divided by this obstruction, chemical and temperature measurements indicated two distinct risings. Sampling at site 63 was carried out at the open 'flood-flow' bedding plane whenever flow occurred and at a lower bedding plane, approximately a half metre (1.5 ft) below, whenever discharge at that point ceased. This discharge from the lower bedding plane also occurs below site 62 but was not sampled at that point.

It is recognised that site 63 may have to be considered as two separate sampling points, as no checks were possible to see if water emerging from the upper and lower bedding planes were identical. The mean combined discharge of sites 62 and 63 is probably in the order of 57-58 l/sec (2-3 cusecs) (Meinzer Grade III) but this twin-rising is subject to very large fluctuations in discharge. Associated with this rising is Bown Scar Cave of which 126 m (415 ft) of passage have been explored (Thornber, 1959).

	Mean	S.D.
Site 62		
Dissolved $CaCO_3$	152 p.p.m.	32.9 p.p.m.
Dissolved $MgCO_3$	6.9 p.p.m.	1.5 p.p.m.
Water temperature	7.41°C	0.67°C
pH	7.6	-
Site 63		
Dissolved $CaCO_3$	151 p.p.m.	30.8 p.p.m.
Dissolved $MgCO_3$	7.5 p.p.m.	3.3 p.p.m.
Water temperature	7.34°C	0.78°C
pH	7.7	-

Scoska Cave: Site 64 (Fig.15a, Map 5) is the small permanent rising at Scoska Cave, Littondale about 1½ km (1 mile) upvalley from Arncliffe village. This rising is located at N.G.R. 9153 7243 at an altitude of 305 m (1000 ft) O.D. The water emerges from a large cave mouth. The discharge at this rising is generally low, the estimated mean discharge lying within the range of discharges classifying Meinzer Grade V springs. Discharge fluctuations too, are low and severe flooding at the rising was never observed.

Over 914 m (3000 ft) of open passage are known at Scoska Cave (Thornber, 1959). Sampling was carried out about 6 m (20 ft) inside the cave entrance.

	Mean	S.D.
Dissolved $CaCO_3$	174 p.p.m.	26.7 p.p.m.
Dissolved $MgCO_3$	6.0 p.p.m.	2.4 p.p.m.
Water temperature	7.03°C	1.17°C
pH	7.9	-

White Sike Barn: Site 67 (Fig.15b, Map 5) is a permanent rising located in Littondale at N.G.R. 9102 7321 at an altitude of 245 m (805 ft) O.D. Water emerges at the foot of a wall about 69 m (75 yd) downvalley from White Sike Barn. The discharge of this rising is generally fairly low, the estimated mean discharge lying within the range of discharges classifying Meinzer Grade V springs. Discharge fluctuations too, are usually small. Sampling was carried out at the source.

	Mean	S.D.
Dissolved $CaCO_3$	183 p.p.m.	18.7 p.p.m.
Dissolved $MgCO_3$	7.6 p.p.m.	3.1 p.p.m.
Water temperature	7.66°C	1.40°C
pH	7.5	-

Fosse Beck: Site 69 (Fig.15d, Map 5) is a large permanent rising located in Littondale at N.G.R. 9032 7382 at an altitude of 274 m (900 ft) O.D. The water emerges from the foot of a pile of rocks on the slope opposite Litton village and is the source of a small stream known as Fosse Beck. This rising also provides the water supply of East Garth Farm Litton. A note in the Journal of the Craven Pothole Club (Anon, 1962) describes a small bedding plane cave associated with this rising. The passage discovered is 30 m (100 ft) long and trends upvalley. The discharge of Fosse Beck rising is fairly large, the estimated mean discharge lying within the range of discharges classifying Meinzer Grade IV springs. Discharge fluctuations are also considerable. Sampling was carried out at the source.

	Mean	S.D.
Dissolved $CaCO_3$	111 p.p.m.	22.9 p.p.m.
Dissolved $MgCO_3$	6.9 p.p.m.	2.6 p.p.m.
Water temperature	7.03°C	0.96°C
pH	7.8	-

Lower Hesleden: Site 71 (Fig.16a, Map 5) is a permanent rising located about 274 m (300 yd) upvalley from Lower Hesleden Farm Littondale on the southern side of Pen-y-ghent Gill at N.G.R. 8856 7447 and at an altitude of 297 m (975 ft) O.D. Water from this spring provides the water supply to Lower Hesleden Farm. Mean discharge is estimated to be in the order of 364-455 l/min (0.214 - 0.268 cusecs) (within the range of Meinzer Grade IV-V springs). Discharge fluctuations are relatively small and do not exhibit the extremes shown at either Fosse Beck rising (Site 69) or Bown Scar Risings (63 and 64). There is no known cave system associated with the rising at Lower Hesleden. Some discolouration of the water was noted at higher discharges. Sampling was carried out at the source before the water is channelled into a large water collecting tank.

	Mean	S.D.
Dissolved $CaCO_3$	123 p.p.m.	15.3 p.p.m.
Dissolved $MgCO_3$	15.5 p.p.m.	7.3 p.p.m.
Water temperature	7.08°C	0.79°C
pH	7.6	-

Blishmire: Site 73 (Fig.16b, Maps 5 and 9) is a small rising located about 457 m (500 yd) north-west of Blishmire House at N.G.R. 8553 7299 and at an altitude of 404 m (1325 ft) O.D. This is a semi-permanent rising, flow having been recorded on 81% of the sampling dates. Discharge is always low, the estimated mean discharge being in the range of 23-68 l/min (0.014 - 0.040 cusecs) (Meinzer Grade V-VI). Sampling was always carried out at the source which lies at the head of a rocky hollow.

	Mean	S.D.
Dissolved $CaCO_3$	210 p.p.m.	18.8 p.p.m.
Dissolved $MgCO_3$	13.6 p.p.m.	3.7 p.p.m.
Water temperature	7.43°C	2.61°C
pH	7.7	-

Sites 74 to 76 are the three source springs of a small stream which rises and sinks about 366 m (400 yd) to the west of Blishmire House

(Map 9).

Blishmire: Site 74 (Fig.16c, Maps 5 and 9) is a small permanent spring located just downstream of the junction of the flows from sites 75 and 76. It is situated on the right bank at N.G.R. 8554 7257 and at an altitude of 418 m (1370 ft). This spring is of very small discharge, estimated as being in the order of 4.5 - 45.0 l/min (0.003 - 0.026 cusecs) (Meinzer Grade VI). On several sampling dates it was noted that small pieces of flow stone had been discharged by this spring. This site was sampled at the source which is a small opening in the bedrock.

	Mean	S.D.
Dissolved $CaCO_3$	91 p.p.m.	29.3 p.p.m.
Dissolved $MgCO_3$	11.4 p.p.m.	5.6 p.p.m.
Water temperature	7.91°C	2.09°C
pH	7.8	-

Blishmire: Site 75 (Fig.17a, Maps 5 and 9) is a very small permanent rising located at N.G.R. 8554 7256 at an altitude of 421 m (1380 ft) O.D. It provides a second permanent source of the stream. This rising might be more accurately described as a seepage, the water originating in a small muddy hollow at the head of the stream. Discharge at this site is also always low and is estimated as between 4.5 - 45.0 l/min (0.003 - 0.026 cusecs). Sampling was carried out at the source.

	Mean	S.D.
Dissolved $CaCO_3$	92 p.p.m.	33.8 p.p.m.
Dissolved $MgCO_3$	9.8 p.p.m.	4.3 p.p.m.
Water temperature	7.45°C	3.06°C
pH	7.7	-

Blishmire: Site 76 (Fig.17b, Maps 5 and 9) is a 'flood-spring' source to this small stream. It is located at N.G.R. 8552 7255 at an altitude of 242 m (1390 ft) O.D. Flow was recorded at this point on only 22% of the sampling visits. At these times the water emerged from bedrock at the head of a rocky hollow. This site may be identified by the presence of fossil coral in the bedrock surrounding the rising. Sampling was carried out at the source whenever flow occurred.

	Mean	S.D.
Dissolved $CaCO_3$	57 p.p.m.	7.8 p.p.m.
Dissolved $MgCO_3$	5.4 p.p.m.	1.3 p.p.m.
Water temperature	7.57°C	2.55°C
pH	7.5	-

Blishmire: Site 78 (Fig.17c, Maps 5 and 9) is a permanent rising located about 274 m (300 yd) south-west of Blishmire House at N.G.R. 8531 7237 and at an altitude of 427 m (400 ft) O.D. The mean discharge of this rising is in the order of 364-455 l/min (0.214 - 0.268 cusecs) (Meinzer Grade IV or V), and the fluctuations are very large. During flood periods it is estimated that this site has a discharge in the order of 57-85 l/sec (2-3 cusecs). The water issues from an opening in the bedrock, and is highly discoloured during flood periods. Sampling was carried out at the source.

	Mean	S.D.
Dissolved $CaCO_3$	92 p.p.m.	38.6 p.p.m.
Dissolved $MgCO_3$	14.0 p.p.m.	7.9 p.p.m.
Water temperature	6.32°C	3.06°C
pH	7.8	-

Silverdale: Site 80 (Fig.18a, Map 5) is a permanent spring located at the source of Silverdale Gill at N.G.R. 8417 7140 and at an altitude of 408 m (1340 ft) O.D. Water emerges from a bedding plane at the foot of a small bedrock outcrop. The mean estimated discharge lies within the range of discharges classifying Meinzer Grade V springs, and fluctuations in discharge are usually slight. Sampling was carried out at the source.

	Mean	S.D.
Dissolved $CaCO_3$	172 p.p.m.	24.5 p.p.m.
Dissolved $MgCO_3$	8.2 p.p.m.	2.4 p.p.m.
Water temperature	7.34°C	1.99°C
pH	7.4	-

Tongue Gill: Site 81 (Fig.18b, Map 5) is one of the permanent sources of Tongue Gill located at N.G.R. 8413 6977 at an altitude of 354 m (1160 ft) O.D. Water at this rising has been artificially channelled in a covered conduit from its true source. It is not known, therefore, if more than one spring contributes to the source of flow at this site. The mean discharge at the point of issue of the conduit is estimated to be in the order of 136 - 272 l/min (0.018 - 0.035 cusecs) (Meinzer Grade V) and considerable fluctuationsin discharge were observed.

Sampling was carried out at the point of exit of the conduit. As a result of this artificial channelling temperature variations recorded at the rising may reflect the air-temperature at the time of sampling rather than the ground-water temperatures.

	Mean	S.D.
Dissolved $CaCO_3$	203 p.p.m.	29.5 p.p.m.
Dissolved $MgCO_3$	9.3 p.p.m.	3.1 p.p.m.
Water temperature	7.82°C	2.12°C
pH	7.6	-

Tongue Gill: Site 82 and 83 (Figs.18c and 19a, Map 5) are two permanent risings located at N.G.R. 8321 6789 at an altitude of 274 m (900 ft) O.D. Both risings emerge in a marshy area near the left bank of Tongue Gill. Site 82 is about 2 m (2 yd) upvalley and to the right of site 83. Although these sites are recorded on the O.S. 2½ inch and 6 inch sheets as a 'spring', the possibility exists that both these sites have been artificially channelled from their true sources. The discharge at both sites is always low (estimated Meinzer Grade V to VI) and observed discharge fluctuations are also of a small scale. Sampling was always carried out at the sources.

	Mean	S.D.
Site 82		
Dissolved $CaCO_3$	190 p.p.m.	19.9 p.p.m.
Dissolved $MgCO_3$	18.8 p.p.m.	7.2 p.p.m.
Water temperature	9.07°C	2.84°C
pH	7.5	-
Site 83		
Dissolved $CaCO_3$	158 p.p.m.	26.0 p.p.m.
Dissolved $MgCO_3$	17.0 p.p.m.	7.9 p.p.m.
Water temperature	8.96°C	2.77°C
pH	7.8	-

Rough Close: Site 87 (Fig.19b, Map 5) is a permanent rising located in the corner of a field at N.G.R. 8475 6819 and at an altitude of 360 m (1180 ft) O.D. The water emerges at a point lying approximately 457 m (500 yd)south-west of Rough Close Farm. The possibility exists also that this rising has been channelled from a source further upslope. The discharge at this site varies from almost nil to approximately 57 l/sec (2 cusecs), the estimated mean discharge lying within the range of discharges classifying Meinzer Grade IV springs. Sampling was carried out at the described point of issue.

	Mean	S.D.
Dissolved $CaCO_3$	203 p.p.m.	47.3 p.p.m.
Dissolved $MgCO_3$	9.2 p.p.m.	2.7 p.p.m.
Water temperature	7.61°C	3.05°C
pH	7.6	-

High Lathe: Site 88 (Fig.19c, Map 5) is a permanent spring located about 274 m (300 yd) south-west of High Lathe Farm at N.G.R. 8511 6744 and at an altitude of 369 m (1210 ft) O.D. The discharge of this spring is fairly constant the estimated mean discharge being in the order of 14 l/sec (0.5 cusecs) (Meinzer Grade IV). Water bubbles up through the floor of a semi-circular shaped hollow and flows westwards to join Catrigg Beck and hence into Stainforth Beck. The floor of the hollow is covered with small limestone pebbles and quartz sand. Water emerging at this site is always clear and has never the peaty colour associated with some of the risings around Fountains Fell. Sampling was always carried out at the source.

	Mean	S.D.
Dissolved $CaCO_3$	197 p.p.m.	18.0 p.p.m.
Dissolved $MgCO_3$	13.3 p.p.m.	4.2 p.p.m.
Water temperature	7.49°C	0.15°C
pH	7.2	-

Blackhill: Site 89 (Figs.20a, Maps 5 and 10) is a permanent spring located at N.G.R. 8618 6632 at an altitude of 427 m (1400 ft) O.D. The water emerges at a rocky hollow, at the head of a long mossy 'flush'. This spring appears to be situated to the south of the North Craven Fault as the rock found in the spring head is Millstone Grit. Furthermore, the water is acid in character (pH 4.8) and always contained <16 p.p.m. of dissolved calcium carbonate (see Chapter 7). The discharge at this site is usually low and the estimated mean discharge lies within the range of discharges classifying Meinzer Grade V springs.

	Mean	S.D.
Dissolved $CaCO_3$	9.2 p.p.m.	1.8 p.p.m.
Dissolved $MgCO_3$	7.8 p.p.m.	1.0 p.p.m.
Water temperature	6.84°C	0.89°C
pH	4.8	-

Blackhill: Site 90 (Fig.20b, Maps 5 and 10) is a permanent spring located at N.G.R. 8620 6634 and at an altitude of 427 m (1400 ft) O.D. Like site 89 the water emerges at the head of a long mossy flush. This site is also considered to lie on or to the south of the North Craven Fault owing to its low pH and low dissolved calcium carbonate content (See Chapter 7). Discharge at this site is fairly constant and the mean discharge is estimated as lying within the range of discharges of Meinzer Grade V springs.

	Mean	S.D.
Dissolved $CaCO_3$	8.9 p.p.m.	0.6 p.p.m.
Dissolved $MgCO_3$	7.1 p.p.m.	1.1 p.p.m.
Water temperature	6.77°C	1.37°C
pH	4.9	-

Blackhill: Site 91 (Fig.20c, Maps 5 and 10) is a permanent spring emerging from a small peaty hollow at N.G.R. 8625 6642 and at an altitude of 430 m (1410 ft) O.D. This site is believed to be located north of the North Craven Fault as it contains very much higher amounts of dissolved calcium carbonate than sites 89 or 90. Discharge at this site is generally low and large fluctuations were not observed. Mean discharge is estimated to be in the order of 114-182 l/min (0.015 - 0.024 cusecs) (Meinzer Grade V)

	Mean	S.D.
Dissolved $CaCO_3$	119 p.p.m.	27.5 p.p.m.
Dissolved $MgCO_3$	65.6 p.p.m.	18.9 p.p.m.
Water temperature	6.90°C	1.14°C
pH	7.1	-

Blackhill: Site 92 (Fig.20d, Maps 5 and 10) is a very small permanent spring located on the north side of the valley north of Blackhill at N.G.R. 8652 6654 and at an altitude of 427 m (1400 ft) O.D. Water emerges from a bedding plane at the foot of a small bedrock outcrop. The discharge of this spring is always low, being in the order of 4.5 - 45.0 l/min (0.003 - 0.026 cusecs) (Meinzer Grade VI). Sampling was always carried out at the source although occasionally owing to the very low rate of discharge it was impossible to collect a sample.

	Mean	S.D.
Dissolved $CaCO_3$	189 p.p.m.	9.0 p.p.m.
Dissolved $MgCO_3$	71.8 p.p.m.	12.2 p.p.m.
Water temperature	7.85°C	1.99°C
pH	7.6	-

Blackhill: Site 93 (Fig.21a, Maps 5 and 10) is a permanent spring also located on the north side of the valley at Blackhill at N.G.R. 8662 6658 and at an altitude of 427 m (1400 ft) O.D. Water emerges from a small semi-circular shaped spring head, the bottom of which is covered in a silty deposit. Discharge at this site is usually low and does not fluctuate greatly. The mean discharge is estimated to be in the order of 45-71 l/min (0.026 - 0.042 cusecs) (Meinzer Grade V spring). Sampling was carried out at the source.

	Mean	S.D.
Dissolved $CaCO_3$	193 p.p.m.	5.6 p.p.m.
Dissolved $MgCO_3$	71.0 p.p.m.	9.0 p.p.m.
Water temperature	7.30°C	1.06°C
pH	7.4	-

Limekiln Hill: Site 94 (Fig.21b, Maps 5 and 10) is a spring located east of Capon Hall at N.G.R. 8722 6680 at an altitude of 411 m (1350 ft) O.D. This is a semi-permanent site,flow having been recorded on 88% of the sampling dates. Water rises and sinks within the space of a metre (about one yard) although it is not known whether the sink is a natural phenomena or whether the water has been artificially channelled off. Sampling was carried out at the source where the water flows through a narrow cleft in bedrock before sinking. Mean discharge at this site is in the order of Meinzer Grade VI springs.

	Mean	S.D.
Dissolved $CaCO_3$	189 p.p.m.	14.1 p.p.m.
Dissolved $MgCO_3$	7.5 p.p.m.	1.5 p.p.m.
Water temperature	7.43°C	0.48°C
pH	7.4	-

Limekiln Hill: Site 95 (Fig.21c, Maps 5 and 10) is a spring located near the foot of Limekiln Hill at N.G.R. 8730 6689 and at an altitude of 419 m (1375 ft) O.D. This is a flood spring, flow having been recorded on only 29% of the sampling visits. Water emerges from a small rocky hollow at the head of an artificially lined channel in which it flows for about 137 m (150 yd) before sinking. This sink appears to be man-made, the water having been channelled off underground. Sampling was carried out at the source whenever flow occurred.

	Mean	S.D.
Dissolved $CaCO_3$	176 p.p.m.	14.3 p.p.m.
Dissolved $MgCO_3$	7.7 p.p.m.	2.1 p.p.m.
Water temperature	7.24°C	0.14°C
pH	7.3	-

Limekiln Hill: Site 96 (Fig.21d, Maps 5 and 10) is located to the northwest of Higher Tren House Farm at N.G.R. 8760 6683 and at an altitude of 404 m (1325 ft) O.D. Although the spring itself is semi-permanent, a small well lies about a metre (3 ft) away and this provides a source of flow during dry periods. Sampling was carried out at the spring whenever flow occurred; at other times samples were collected from the nearby well, check samples having shown the water at these two points are identical in terms of dissolved calcium and magnesium carbonate content, temperature and pH. This site is one of the major sources of water supply to Malham Tarn. Discharge is usually quite large, the estimated mean discharge being in the order of 14 l/sec (0.5 cusecs) (Meinzer Grade IV). Fluctuations of discharge are considerable, varying from nil during periods of drought to floods in the order of 57-85 l/sec (2-3 cusecs).

	Mean	S.D.
Dissolved $CaCO_3$	234 p.p.m.	16.9 p.p.m.
Dissolved $MgCO_3$	9.8 p.p.m.	3.2 p.p.m.
Water temperature	7.70°C	1.80°C
pH	7.5	-

Higher Tren House: Site 97 (Fig.22a, Maps 5 and 10) is a small permanent seepage site located in a marshy area south-south-east of Higher Tren House Farm at N.G.R. 8775 6633 and at an altitude of 395 m (1295 ft) O.D. It is impossible to isolate individual seepages within this marshy area and sampling was carried out where sufficient seepage had collected to give rise to a small stream. As a result the temperature of water collected at this site is likely to be influenced by air temperature at the time of sampling. Discharge at this sampling site is always low being in the order of 4.5 - 45.0 l/min (0.003 - 0.026 cusecs) (Meinzer Grade VI)

	Mean	S.D.
Dissolved $CaCO_3$	267 p.p.m.	15.3 p.p.m.
Dissolved $MgCO_3$	8.6 p.p.m.	2.9 p.p.m.
Water temperature	8.67°C	3.37°C
pH	7.3	-

Cowside Beck: Site 98 (Fig.22b, Maps 5 and 11) is a large spring located at N.G.R. 8884 6919 at an altitude of 357 m (1170 ft) O.D. and is the highest permanent source of Cowside Beck (Skirfare). The estimated mean discharge at this rising is in the order of 28-57 l/sec (1-2 cusecs) (Meinzer Grade III). Fluctuations in discharge are considerable with estimated maximum discharges being around 227-283 l/sec (8-10 cusecs). During periods of high flow the water is discoloured and emerges from several points in the immediate vicinity of the permanent rising. Sampling was always carried out at the source.

	Mean	S.D.
Dissolved $CaCO_3$	175 p.p.m.	18.9 p.p.m.
Dissolved $MgCO_3$	6.3 p.p.m.	2.1 p.p.m.
Water temperature	7.31°C	0.31°C
pH	7.3	-

Cowside Beck: Site 99 (Fig.22c, Maps 5 and 11) is a large permanent spring located at N.G.R. 8909 6933 at an altitude of 344 m (1130 ft) O.D. The water issues from the left bank of Cowside Beck (Skirfare) at a point where the main stream takes a sharp right hand bend. The estimated mean discharge of this spring is in the order of 57-85 l/sec (2-3 cusecs) (Meinzer Grade III) and considerable variations in discharge were observed. During periods of flood the estimated discharge is in the order of 227-283 l/sec (8-10 cusecs) and the water is discoloured. Sampling was always carried out at the source.

	Mean	S.D.
Dissolved $CaCO_3$	163 p.p.m.	18.9 p.p.m.
Dissolved $MgCO_3$	6.7 p.p.m.	1.5 p.p.m.
Water temperature	7.26°C	0.34°C
pH	7.3	-

Sites number 101-105 are the source springs of Thoragill Beck, a small stream located on the south western flank of Fountains Fell (Map 11).

Thoragill Beck: Site 101 (Fig.22d, Maps 5 and 11) is a permanent spring located at N.G.R. 8902 6998 at an altitude of 366 m (1200 ft) O.D. This water was sampled where it emerged from a pipe about 4 cm (1.5 in) in diameter, feeding a water trough by the roadside at Thoragill Beck Barn. This water has been piped directly from a spring about 91 m (100 yd) upslope at the above grid reference. As the rate of discharge from the pipe is always high it is not considered that sampling at the pipe has introduced any error in the temperature or chemical recordings of this site.

	Mean	S.D.
Dissolved $CaCO_3$	229 p.p.m.	19.4 p.p.m.
Dissolved $MgCO_3$	6.0 p.p.m.	2.2 p.p.m.
Water temperature	7.76°C	1.49°C
pH	7.4	-

Thoragill Beck: Site 102 (Fig.23a, Maps 5 and 11) is a permanent rising located a short distance upslope from Thoragill Beck House at N.G.R. 8894 7006 at an altitude of 375 m (1230 ft) O.D. The mean discharge of this spring is estimated to be about 227-273 l/min (0.134 - 0.161 cusecs) (Meinzer Grade V). The discharge is, however, subject to considerable variation with maximum discharges estimated at around 57 l/sec (2 cusecs). Sampling was carried out about 18 m (20 yd) from the source with the result that water temperatures recorded at periods of low flow may reflect the air temperatures at the time of sampling rather than the temperature of the ground-water.

	Mean	S.D.
Dissolved $CaCO_3$	180 p.p.m.	22.9 p.p.m.
Dissolved $MgCO_3$	6.9 p.p.m.	2.5 p.p.m.
Water temperature	8.51°C	2.71°C
pH	7.9	-

Thoragill Beck: Site 103 (Fig.23b, Maps 5 and 11)is a permanent spring located in the corner of a field north-north-east of Thoragill Beck House at N.G.R. 8891 7014 and at an altitude of 381 m (1250 ft) O.D. The discharge of this spring is usually low and is fairly constant. The mean discharge is estimated to lie within the range of discharges of Meinzer Grade VI springs. Sampling was always carried out at the source.

	Mean	S.D.
Dissolved $CaCO_3$	176 p.p.m.	26.1 p.p.m.
Dissolved $MgCO_3$	5.9 p.p.m.	1.5 p.p.m.
Water temperature	8.33°C	1.69°C
pH	7.8	-

Thoragill Cave: Site 104 (Fig.23c, Maps 5 and 11) is a permanent rising at Thoragill Cave located at N.G.R. 8898 7023 at an altitude of 381 m (1250 ft). The water emerges from a mass of limestone boulders and is collected in a small concrete pool before being piped off for water supply at a barn near Darnbrook House. The estimated mean discharge at

Thoragill Cave rising is in the order of 364-455 l/min (0.214 - 0.268 cusecs) (Meinzer Grade V) but variations are large and in flood period discharges are estimated to be in excess of 57 l/sec (2 cusecs). During flood periods the water is discoloured. Associated with this rising is a small cave about 30 m (100 ft) long (Thornber, 1959).

	Mean	S.D.
Dissolved $CaCO_3$	127 p.p.m.	20.4 p.p.m.
Dissolved $MgCO_3$	6.0 p.p.m.	4.2 p.p.m.
Water temperature	7.14°C	0.48°C
pH	7.7	-

Thoragill Beck: Site 105 (Fig.23d, Maps 5 and 11) is a small permanent spring which provides the source of a left hand tributary to Thoragill Beck. This spring is located at N.G.R. 8911 7020 at an altitude of 363 m (1190 ft) O.D. Discharge is usually low and the estimated mean discharge lies within the range of discharges classifying Meinzer Grade V springs. Sampling was carried out at the source in a small rocky hollow.

	Mean	S.D.
Dissolved $CaCO_3$	175 p.p.m.	27.9 p.p.m.
Dissolved $MgCO_3$	5.8 p.p.m.	1.5 p.p.m.
Water temperature	7.90°C	1.78°C
pH	7.8	-

C Stream Sites

These sampling sites are located on surface streams and rivers, most of which are fed by ground-water discharge through a spring or springs. These sites are considered as a separate group as their characteristics may have altered as a result of surface flow.

Outgang Beck: Site 10 (Fig.24a, Maps 4 and 6) at N.G.R. 9735 6721 at a surveyed altitude of 207.3 m (680 ft) O.D. and is located on Outgang Beck just upstream from the junction of water from site number 11 (see above) with the main stream. Stream flow at this point is permanent.

	Mean	S.D.
Dissolved $CaCO_3$	186 p.p.m.	10.2 p.p.m.
Dissolved $MgCO_3$	12.0 p.p.m.	3.2 p.p.m.
Water temperature	8.67°C	1.49°C
pH	7.7	-

Howgill Beck: Site 12 (Fig.24b, Maps 4 and 6) at N.G.R. 9742 6733 at a surveyed altitude of 192.0 m (630 ft) O.D. is located on Howgill Beck, upstream of the entry of Outgang Beck and just downstream of the bridge over Howgill. This is a permanently flowing site.

	Mean	S.D.
Dissolved $CaCO_3$	204 p.p.m.	11.7 p.p.m.
Dissolved MgCO	13.8 p.p.m.	4.9 p.p.m.
Water temperature	8.68°C	3.54°C
pH	7.8	-

Outgang Beck: Site 13 (Fig.24c, Maps 4 and 6) at N.G.R. 9743 6732 at a surveyed altitude of 192.9 m (633 ft) O.D. is located on Outgang Beck just upstream of its junction with Howgill Beck. Stream flow at this site is permanent.

	Mean	S.D.
Dissolved $CaCO_3$	176 p.p.m.	9.9 p.p.m.
Dissolved $MgCO_3$	11.9 p.p.m.	5.2 p.p.m.
Water temperature	9.04°C	2.78°C
pH	7.8	-

Howgill Beck: Site 14 (Fig.25a, Maps 4 and 6) at N.G.R. 9745 6733 at a surveyed altitude of 190.5 m (625 ft) O.D. is located on Howgill Beck about 18 m (20 yd) downstream of the junction of Outgang Beck with Howgill Beck. Water temperature profiles taken across the stream at this point indicated that the two flows had thoroughly mixed at this point. Stream flow at this site is permanent.

	Mean	S.D.
Dissolved $CaCO_3$	184 p.p.m.	7.9 p.p.m.
Dissolved $MgCO_3$	12.8 p.p.m.	3.2 p.p.m.
Water temperature	9.21°C	2.59°C
pH	7.8	-

Howgill Beck: Site 15 (Fig.25b, Maps 4 and 6) at N.G.R. 9762 6732 at a surveyed altitude of 181.1 m (594 ft) O.D. is located on Howgill Beck just upstream of its junction with White Beck. Stream flow at this site is permanent.

	Mean	S.D.
Dissolved $CaCO_3$	171 p.p.m.	10.8 p.p.m.
Dissolved $MgCO_3$	12.3 p.p.m.	4.0 p.p.m.
Water temperature	9.44°C	3.22°C
pH	7.8	-

White Beck: Site 16 (Fig.25c, Maps 4 and 6) at N.G.R. 9762 6733 at a surveyed altitude of 181.4 m (595 ft) O.D. is located on White Beck upstream of the point of inflow of Howgill Beck but downstream of the point at which a small spring or land drain discharges into the right side of White Beck stream. Flow at this site is permanent.

	Mean	S.D.
Dissolved $CaCO_3$	178 p.p.m.	12.0 p.p.m.
Dissolved $MgCO_3$	11.7 p.p.m.	3.0 p.p.m.
Water temperature	8.71°C	1.60°C
pH	7.8	-

White Beck: Site 17 (Fig.26a, Maps 4 and 6)at N.G.R. 9765 6730 at a surveyed altitude of 180.4 m (592 ft) O.D. is located on White Beck about 91 m (100 yd) downstream of the point of inflow of Howgill Beck, where a wooden bridge crosses White Beck. Water temperature profiles taken across the stream at this point indicated that the two flows had thoroughly mixed. Streamflow at this site is permanent.

	Mean	S.D.
Dissolved $CaCO_3$	175 p.p.m.	12.1 p.p.m.
Dissolved $MgCO_3$	12.2 p.p.m.	4.2 p.p.m.
Water temperature	8.81°C	1.95°C
pH	7.9	-

River Wharfe: Site 18 (Fig.26b, Maps 4 and 6) at N.G.R. 9790 6748 and at an estimated altitude of 180 m (590 ft) O.D. is located on the River Wharfe just downstream of Conistone Bridge. Samples were collected as near mid-river as possible. Stream flow at this point is permanent but is subject to very large variations in discharge.

	Mean	S.D.
Dissolved $CaCO_3$	137 p.p.m.	29.5 p.p.m.
Dissolved $MgCO_3$	12.9 p.p.m.	4.2 p.p.m.
Water temperature	8.50°C	3.35°C
pH	7.9	-

Littondale: Site 28 (Fig.26c, Map 4) at N.G.R. 9653 6933 at an estimated altitude of 219 m (718 ft.) O.D. is located in Littondale on a small, unnamed stream upvalley from and in the same field as Moss Beck. This stream is fed largely by small seepage springs which were impossible to sample individually. Stream flow at this site is semi-permanent, flow having been recorded on 88% of the sampling dates. The discharge at the sampling point is usually low (estimated 91 - 136 l/min) (0.012 - 0.018 cusecs), but is subject to fairly large fluctuations.

	Mean	S.D.
Dissolved $CaCO_3$	203 p.p.m.	18.2 p.p.m.
Dissolved $MgCO_3$	10.8 p.p.m.	2.7 p.p.m.
Water temperature	8.73°C	2.40°C
pH	7.7	-

Cotegill: Site 36 (Fig.27a, Maps 4 and 7) at N.G.R. 9437 6997 at an estimated altitude of 277 m (910 ft) O.D. is the lowest part of Cotegill, Littondale, on which permanent flow occurs. During periods of drought, Cotegill normally sinks in its bed just downstream of the sampling point which lies about 46 m (50 yd) upvalley from the spring sampling site number 35 (see above).

	Mean	S.D.
Dissolved $CaCO_3$	157 p.p.m.	9.6 p.p.m.
Dissolved $MgCO_3$	6.7 p.p.m.	1.9 p.p.m.
Water temperature	8.43°C	3.58°C
pH	8.2	-

River Skirfare: Site 43 (Fig.27b, Maps 4 and 8) at N.G.R. 9325 7199 at an estimated altitude of 219 m (718 ft) O.D. is located on the River Skirfare about 91 m (100 yd) downstream from Arncliffe Bridge near Arncliffe village church. Water temperature profiles taken across the stream indicated that thorough mixing of the flow from Cowside Beck with that of the Skirfare had occurred by this point. River flow at this site is permanent but is subject to very large variations in discharge.

	Mean	S.D.
Dissolved $CaCO_3$	139 p.p.m.	16.6 p.p.m.
Dissolved $MgCO_3$	7.6 p.p.m.	2.2 p.p.m.
Water temperature	9.31°C	3.07°C
pH	8.1	-

River Skirfare: Site 44 (Fig.27c, Maps 4 and 8) at N.G.R. 9308 7202 at an estimated altitude of 219 m (720 ft) O.D. is located on the River Skirfare just upstream of the point of inflow of Cowside Beck. River flow at this point is permanent, although during drought periods a large component of the discharge is derived from large springs approximately one kilometre (two thirds of a mile) upstream on the right bank of the river. Discharge fluctuations over the sampling period were very large.

	Mean	S.D.
Dissolved $CaCO_3$	129 p.p.m.	23.9 p.p.m.
Dissolved $MgCO_3$	9.1 p.p.m.	3.2 p.p.m.
Water temperature	8.35°C	2.17°C
pH	7.7	-

Cowside Beck (Skirfare): Site 45 (Fig.28a, Maps 4 and 8) N.G.R. 9308 7198 at an estimated altitude of 219 m (720 ft) O.D. is located on Cowside Beck (Skirfare) just upstream of its junction with the River Skirfare. Stream flow at this site is permanent but is subject to very large fluctuations in discharge.

	Mean	S.D.
Dissolved $CaCO_3$	144 p.p.m.	16.0 p.p.m.
Dissolved $MgCO_3$	6.1 p.p.m.	1.8 p.p.m.
Water temperature	9.79°C	4.03°C
pH	8.2	-

White Sike Barn: Site 65 (Fig.28b, Map 5) at N.G.R. 9103 7317 and at an estimated altitude of 251 m (825 ft) O.D. is located on a small stream downvalley of spring site 65. This stream is fed by small seepage springs which are too small to sample individually. Stream flow at this site is permanent.

	Mean	S.D.
Dissolved $CaCO_3$	156 p.p.m.	15.0 p.p.m.
Dissolved $MgCO_3$	6.0 p.p.m.	2.0 p.p.m.
Water temperature	8.47°C	3.56°C
pH	8.1	-

White Sike Barn: Site 66 (Fig.28c, Map 5) at N.G.R. 9097 7326 and at an estimated altitude of 251 m(825 ft) O.D. is located on a small stream which flows beside White Sike Barn, Littondale during flood periods. Flow was only recorded on 25% of the sampling visits.

	Mean	S.D.
Dissolved $CaCO_3$	142 p.p.m.	-
Dissolved $MgCO_3$	4.9 p.p.m.	1.7 p.p.m.
Water temperature	6.93°C	2.67°C
pH	8.0	-

River Skirfare: Site 70 (Fig.29a, Map 5) at N.G.R. 9048 7402 and at an estimated altitude of 248 m (815 ft) O.D. is located on the River Skirfare at Litton. Sampling was carried out at a point about 91 m (100 yd) upstream from the ford crossing the river to East Garth Farm, and upstream of the entry point of water from Fosse Beck (site number 69). Stream flow at this site occurred on only 46% of the sampling visits and was subject to very large fluctuations in discharge.

	Mean	S.D.
Dissolved $CaCO_3$	102 p.p.m.	20.9 p.p.m.
Dissolved $MgCO_3$	7.5 p.p.m.	2.8 p.p.m.
Water temperature	6.36°C	2.83°C
pH	8.0	-

Hesleden Beck: Site 72 (Fig.29b, Map 5) at N.G.R. 8856 7447 and at an estimated altitude of 277 m (910 ft) O.D. is located on Hesleden Beck (the lower section of Pen-y-ghent Gill) just upstream of the point of inflow of water from spring site 71. Stream flow at this site was recorded on only 42% of the sampling dates and was subject to very large variations in discharge.

	Mean	S.D.
Dissolved $CaCO_3$	64 p.p.m.	9.8 p.p.m.
Dissolved $MgCO_3$	6.6 p.p.m.	2.4 p.p.m.
Water temperature	6.15°C	2.92°C
pH	7.8	-

Blishmire: Site 77 (Fig.30, Maps 5 and 9) at N.G.R. 8531 7230 and at an estimated altitude of 430 m (1410 ft) O.D. is located on Blishmire Close stream, a small stream draining part of the north-west slope of Fountains Fell. Sampling was carried out a short distance upstream of the road. Flow at this site is semi-permanent (flow was recorded on 75% of the sampling dates) and is subject to large fluctuations in discharge.

	Mean	S.D.
Dissolved $CaCO_3$	92 p.p.m.	25.9 p.p.m.
Dissolved $MgCO_3$	12.1 p.p.m.	4.1 p.p.m.
Water temperature	6.68°C	4.76°C
pH	7.9	-

Rainscar: Site 79 (Fig.31, Map 5 and 9) at N.G.R. 8520 7215 and at an estimated altitude of 439 m (1440 ft) O.D. is located on a small stream which sinks about 457 m (500 yd) to the south of Blishmire House and about 274 m (300 yd) to the north-east of Rainscar House. Sampling was carried out on this stream just before it sinks into one of several depressions in the immediate vicinity. This stream is subject to large fluctuations in discharge and in flood water overflows from the usual sink into several adjacent ones. Flow at this site is permanent.

	Mean	S.D.
Dissolved $CaCO_3$	102 p.p.m.	44.5 p.p.m.
Dissolved $MgCO_3$	18.5 p.p.m.	8.6 p.p.m.
Water temperature	8.15°C	5.20°C
pH	8.0	-

Tongue Gill: Site 84 (Fig.32a, Map 5) at N.G.R. 8271 6772 and at an estimated altitude of 229 m (750 ft) O.D. is located on a small right bank tributary to Tongue Gill, near Billinger Barns, Stainforth. Sampling was carried out just upstream of the point at which this tributary joins Tongue Gill. Flow at this site is permanent, but is subject to large fluctuations in discharge.

	Mean	S.D.
Dissolved $CaCO_3$	91 p.p.m.	18.2 p.p.m.
Dissolved $MgCO_3$	10.3 p.p.m.	3.0 p.p.m.
Water temperature	8.88°C	2.81°C
pH	7.8	-

Tongue Gill: Site 85 (Fig.32b, Map 5) at N.G.R. 8271 6769 and at an estimated altitude of 229 m (750 ft) O.D. is located on Tongue Gill just upstream of the point of entry of the above mentioned tributary (site number 84). Flow at this site is permanent but is subject to large fluctuations in discharge.

	Mean	S.D.
Dissolved $CaCO_3$	150 p.p.m.	20.4 p.p.m.
Dissolved $MgCO_3$	11.2 p.p.m.	3.1 p.p.m.
Water temperature	9.23°C	3.98°C
pH	8.1	-

Rough Close: Site 86 (Fig.33, Map 5) at N.G.R. 8452 6835 at an estimated altitude of 358 m (1175 ft) O.D., is located on the small stream flowing to the west of Rough Close Farm, on the south-western margins of Fountains Fell. Sampling was carried out at the roadside. This stream is semi-permanent, flow having been recorded on 88% of the sampling dates. It is, however, subject to large variations in discharge.

	Mean	S.D.
Dissolved $CaCO_3$	122 p.p.m.	46.3 p.p.m.
Dissolved $MgCO_3$	7.3 p.p.m.	2.0 p.p.m.
Water temperature	7.40°C	4.24°C
pH	7.5	-

Tennant Gill: Site 100 (Fig.34, Maps 5 and 11) at N.G.R. 8888 6950 and at an estimated altitude of 378 m (1240 ft) O.D. is located on a stream known as Tennant Gill which flows on the south-east flank of Fountains Fell. Sampling was carried out at the roadside. Flow at this site is semi-permanent (occurring on 96% of the sampling dates) and is subject to large variations in discharge.

	Mean	S.D.
Dissolved $CaCO_3$	80 p.p.m.	20.9 p.p.m.
Dissolved $MgCO_3$	7.1 p.p.m.	1.9 p.p.m.
Water temperature	8.90°C	5.39°C
pH	7.9	-

Darnbrook Beck: Site 106 (Fig.35, Maps 5 and 11) at N.G.R. 8992 7055 and at an estimated altitude of 323 m (1060 ft) O.D. is located on Darnbrook Beck, just downstream of the road-bridge. Flow at this point is semi-permanent (flow was recorded on 75% of sampling visits) as the total flow of Darnbrook Beck sinks further upvalley during dry periods. The stream at the sampling site is subject to very large variations in discharge. Some contamination of the water is believed to occur due to effluent seepage from the barns at Darnbrook Farm.

	Mean	S.D.
Dissolved $CaCO_3$	64 p.p.m.	18.2 p.p.m.
Dissolved $MgCO_3$	5.6 p.p.m.	1.7 p.p.m.
Water temperature	7.87°C	4.98°C
pH	7.8	-

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CHAPTER FOUR

VARIATIONS IN DISSOLVED CALCIUM AND MAGNESIUM CARBONATE IN SPRINGS AND RESURGENCES IN THE HIGH MARK AND FOUNTAINS FELL AREAS OF N.W. YORKSHIRE

A Review of Literature on Limestone Solution

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H Effective Precipitation and Dissolved Calcium Carbonate Variations: The High Mark Area

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L Dissolved Magnesium Carbonate Variations

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VARIATIONS IN DISSOLVED CALCIUM AND MAGNESIUM CARBONATE IN SPRINGS AND RESURGENCES IN THE HIGH MARK AND FOUNTAINS FELL AREAS OF N.W. YORKSHIRE

A Review of Literature on Limestone Solution

The aim of this review is simply to summarize those factors appearing in the literature which could initiate temporal and spatial variations in the dissolved calcium and magnesium carbonate concentrations in the karst waters of the study area. Although many of these have been reviewed elsewhere (Hohlt, 1948; Sweeting, 1964; Pitty, 1966b; Douglas, 1968a; Stringfield and LeGrand, 1969) it is of some value to reconsider these factors in the context of north-west Yorkshire. This study is chiefly concerned with variations in dissolved calcium and magnesium carbonate concentrations in karst waters rather than the total amount of limestone being removed from an area. It is therefore important to differentiate between solute concentration and rate of solution.

1. Factors thought to Initiate Temporal Variations in Limestone Solution

Records of dissolved solids concentrations in spring and streams rarely span more than a few years. Consequently the factors reviewed here are those likely to give rise to either seasonal variations in limestone solution or to short term variations occurring over a few days or hours.

Much of this thesis is based on the acceptance that the seasonal rhythm in dissolved calcium carbonate concentration observed by a number of workers (for example, Pitty, 1966a, & b; Shuster and White, 1971) reflects a direct positive relationship between temperature and dissolved calcium carbonate variations(probably arising out of increased soil carbon dioxide production at higher temperatures as argued by Pitty), and that the degree to which the dissolved calcium carbonate wave in the spring waters is out of phase with the air temperature wave provides a measure of the flow-through time of the karst waters (Pitty, 1966b).

The various processes which may give rise to a seasonal rhythm are however reviewed here as many of the conclusions from this research throw light on the real significance of these processes. Seasonal variations in limestone solution have been attributed to a number of factors. Corbel (1957, 1959, 1960) believed that on account of the greater solubility of carbon dioxide at low temperatures limestone solution would be greater in cold climates and presumably at colder times of the year. At 0°C one litre of water can dissolve 1.8 litres of carbon dioxide at atmospheric pressure, but at 15°C this solubility falls to one litre and at 100°C there is a complete elimination of the gas (Fraipont, 1950) A seasonal temperature contrast of about 20°C was recorded in both sampling years (Figs. 1 and 2) in north-west Yorkshire and may have some effect on seasonal variations in limestone solution. Paterson (1972) has suggested that this temperature control on carbon dioxide solubility may account for calculated negative correlations between air temperature and dissolved calcium carbonate variations in spring waters in the Oxford region. Most workers however accept that the inverse relationship between carbon dioxide solubility and temperature has little notable effect, and other factors, principally the source and availability of carbon dioxide, are now generally considered to be of greater significance.

Rainfall variability and consequent recharge and discharge variations has been considered important in influencing both seasonal and short term variations in dissolved chemical load (Leopold, Wolman and Miller, 1964; Hendrickson and Krieger, 1964). On many springs and streams a simple inverse correlation between total hardness concentration and discharge has been observed (Groom and Williams,1965; Douglas,1968; Jennings,1972), and may be related to several processes. Of prime importance and of great relevance to this study is the rate of ground-water flow or the time circulating ground-water is in contact with limestone. High volumes of recharge and discharge involve a rapid transit of water through the underground system reducing the time of contact with the limestone for solution to take place. Davis (1930) supposed that the greatest factor in the solution of limestone caverns was the slowness of movement of the ground-water and that the greatest solution took place where ground-water moved very slowly and equilibrium between ground-water and limestone was attained. Pitty (1968d) demonstrated a positive relationship between the mean dissolved calcium carbonate content of limestone drainage water or cave seepage water and the time of flow through the limestone, an idea often suggested or implied by other workers (Swinnerton, 1942; Zötl, 1965) although without actual measurement. In north-west Yorkshire low dissolved solids concentrations might therefore be expected in the winter months with high volumes of rainfall input, a rapid transit of water through the limestone and high discharges. In the drier summer months, however, the solute concentrations would increase with higher evapotranspiration, lower recharge and consequent discharge, and the longer residence time of the circulating water.

Several factors may however complicate such a simple relationship between rainfall variability and dissolved calcium carbonate concentrations. Likens, Borman, Johnson and Pierce (1967) found no correlation between dissolved calcium and magnesium and discharge in streams in the Hubbard Brook area, New Hampshire and Pitty (1966a) has pointed out that owing to the flushing-out of ground-water by rainstorms a positive correlation between dissolved calcium carbonate and discharge may be observed at some karst springs, and in streams fed by ground-water discharge. This expulsion of ground-water from risings by rain was also observed by Smith and Mead (1962) who observed that on several Mendip risings after a period of rainfall the discharge increased within a short period but that the dissolved calcium carbonate content showed little change. Newson (1971) records considerable differences in the extent of the dilution influence at different risings following heavy rainfall. These studies illustrate the problem of using discharge as an independent variable in the analysis of dissolved calcium carbonate fluctuations at limestone springs. Antecedent effective precipitation therefore has been widely used in this thesis as it is believed to be a more appropriate variable.

Secondly, a simple relationship between volume of recharge and rate of flow of water through the limestone is complicated by temperature and viscosity considerations. It is known that an increase in water temperature of 0.56°C is sufficient to increase the rate of flow by 1½% through viscosity effects (Walton, 1970). Such effects will therefore tend to counteract the influence of greater winter recharge on the rate of ground-water flow and consequent dissolved solids concentrations.

Recharge to limestone aquifers may occur either by rainfall falling directly onto the limestone and reaching the limestone by slow infiltration through a soil cover (percolation water - Drew, 1968; Newson, 1971), or from allogenic streams flowing from less permeable strata at higher levels (Brown, 1966). The chemical and physical characteristics of water entering limestone areas from non-calcareous terrains (allogenic karst water - Pitty, 1966b, 1968a) is an important negative factor in influencing recorded variations in the solute concentration of calcium carbonate in many karst waters. Because of it s briefer and superficial contact with limestone this water is usually low in dissolved calcium carbonate and as a result provides a strong dilution influence. Pitty (1968a) observed a high (r = .82) correlation between the degree of water hardness in the streams of the Peak district and southern Pennines and the percentage of limestone in the catchment. This dilution factor by allogenic karst water is of considerable importance in the Fountains Fell area where many of the drainage systems receive recharge from sinking streams rising inthe Yoredale and Millstone Grit area. Although with the exception of Cotegill there are no sinking streams in the High Mark area water entering the limestone through joints in the limestone pavement or on limestone outcrops also appears to exert a low dilution effect on the solute concentration of the ground-water. The ratio of percolation to allogenic recharge may also vary seasonally. Low dissolved solids concentrations in resurgences in the winter months may therefore be associated with a high proportion of swallet recharge, whereas high concentrations in summer may be related to a predominance of percolation recharge.

Although in many limestone regions areas of bare rock may be exposed on the surface in the form of, for example, limestone pavements, rainfall frequently has to pass through a soil zone before reaching the limestone bedrock. The importance of the soil environment in effecting the characteristics of percolating rainwater and hence in the solution of limestone has been discussed by many workers (Adams and Swinnerton, 1937; Pitty, 1966b). Although little can be added to the extensive literature review carried out by Pitty (1966b) on this subject an attempt is made here to summarize some of the main considerations. In the soil zone carbon dioxide is released by the action of microorganisms on organic matter, a process the significance of which in limestone solution was appreciated as early as 1886 by McKenny Hughes, and by plant root respiration. Rainwater percolating through the soil zone is enriched by this soil carbon dioxide and becomes a powerful solvent. The amount of carbon dioxide available is fundamental to limestone solution. Humus rich soil contains up to 9 times as much carbon dioxide as atmospheric air and recently manured soil up to 250 times as much (Adams and Swinnerton, 1937). Such concentrations minimise the importance of atmospheric carbon dioxide or snow-trapped carbon dioxide in influencing limestone solution.

Variation in soil carbon dioxide production is of extreme significance in influencing not only the absolute amount of calcium carbonate in solution but also variations in the rate of limestone solution. Pitty (1966b) having observed a seasonal fluctuation in the level of dissolved calcium carbonate in cave waters considered that this rhythm could be attributed to inferred seasonal changes in the output of carbon dioxide in the soil as organisms increased their biochemical activity in response to higher temperatures and greater insolation. Smith and Mead (1962) and Smith (1965) were, however, unable to detect any seasonal variation in the amount of dissolved calcium carbonate in the Mendip area. Although in general it appears that increase in temperature may stimulate soil microorganisms many experiments and opinions on this subject are contradictory. Cutler, Crump and Sandon (1923) found no correlation between bacterial numbers and daily changes in mean soil temperatures, although in cold periods the bacterial and protozoan numbers fell in number. Russell and Appleyard (1915) reached the conclusion that the amount of carbon dioxide in the soil is independent of temperature except where the latter falls below 5°C.

Soil carbon dioxide production may be related to a number of other factors. Russell (1961) indicates that when air supply is cut off or reduced by increasing moisture content in the soil the carbon dioxide content of the soil air rises to a very high percentage and may attain 25% (Trombe, 1952). Water present in the soil reduces ventilation and prevents the escape of carbon dioxide by diffusion and will dissolve free carbon dioxide (Trombe, 1952). Burges (1958) has pointed out the importance of soil moisture in microorganic activity, and Seifert (1960, 1961) found that microbial activity increased with increasing water content to about 60-80% of the water holding capacity but decreased in water-logged soils. The amount and type of food available also influences microorganic activity (Burges 1958). Smyk and Drzal (1964a and b) have shown that microorganisms capable of dissolving calcium carbonate may be found not only within the soil zone but also within the bedrock.

Other biotic factors may also be of importance in the initiation of a seasonal rhythm in dissolved calcium carbonate concentrations. Gams (1966) points out that the direct consumption of calcium per hectare of oak wood is 64 kilograms per year, and 78 kilograms per hectare per year of beech wood. Although much of this may be recycled the annual autumnal leaf fall may provide a seasonal contribution to the calcium carbonate in drainage waters of limestone areas. Within the field area direct release of nutrients from decaying grass litter in the autumn may conceivably give rise to a seasonal variation in dissolved calcium carbonate concentrations in spring waters.

The fifth process that could theoretically give rise to a seasonal rhythm in dissolved calcium carbonate concentrations is the heating or cooling of circulating recharge water with depth. Thraikill (1968) considered that the cooling of percolating water with increasing depth thus increasing the solubility of carbon dioxide could lead to further solution at depth. Cooling of percolating water in summer may result in undersaturation and further solution. This factor of solution or corrosion by the cooling of karst water was referred to as "Abkühlungskorrosion by Bögli (1964). Stringfield and Le Grand (1969) quote the observations made by Carson (1964) in Tolleys Cave, Virginia. Carson noted that the ratio of solution to deposition varied with the season, with calcium carbonate precipitation in caves being dominant in winter owing to the warming of seepage water as it enters a cavern in winter. Within the field area the analysis of water temperature variations (Chapter 5) has demonstrated that rapidly circulating recharge pulses or dilution pulses tend to cool the temperature of the groundwater in summer and raise it in winter. Although it is unknown if such equilibrium considerations have any measurable effect the possibility that seasonal variations in the amount of limestone in solution in many springs and risings in north-west Yorkshire may be a reflection of calcium carbonate precipitation in winter and calcium carbonate solution in summer has to be considered.

Several other factors may conceivably give rise to a seasonal rhythm and may be briefly considered. In north-west Yorkshire a large proportion of precipitation occurs as snow and during certain periods of the year water from melting snow forms a significant element of recharge to the limestone reservoir. Williams (1949) has shown that air in snow drifts contains twice as much carbon dioxide as atmospheric air. This concentration he attributes to daily freeze-thaw at the surface of the snow releasing carbon dioxide which the snow bas absorbed from the atmosphere. Rain or meltwater passing through the snow could therefore absorb carbon dioxide to saturation. Observations carried out by Gams (1966), however, demonstrated that lowest hardness values could be associated with snow melt, and a similar situation has been observed in north-west Yorkshire (see below). Temporal variations in rainfall chemistry have been recorded by Likens, Bormann, Johnson and Pierce (1967), and Raistrick and Gilbert (1963) found the pH of rainfall to vary between 3-8 and 6.2, with a mean value of 4.6 The acidity of rainfall in north-west Yorkshire Sweeting (1966) attributes partially to the effect of atmospheric pollution, and Gorham (1958) has demonstrated that sulphur dioxide pollution is an important source of acidity in rainfall. The chemical content of rainfall is however only of significance in areas where it may constitute a major fraction of the dissolved solids in the drainage waters leaving the area and is therefore probably of little importance as a variable in north-west Yorkshire.

Although the solubility of carbon dioxide varies inversely with the temperature (see above) the relationship between carbon dioxide solubility and pressure is positive. Under ordinary atmospheric conditions when air exerts a pressure of one atmosphere the partial pressure due to carbon dioxide is 0.0003 atmospheres. At this pressure at 16°C about 43 parts per million of calcium carbonate can be dissolved (Adams and

Swinnerton, 1937). Presumably with a tendency for higher atmospheric pressures to occur in the British Isles in the summer months (Brooks, 1949) greater amounts of atmospheric carbon dioxide could be dissolved. The greater amounts of carbon dioxide present in the soil zone will however exert pressure on water passing through the soil several hundred times as great as the carbon dioxide in the atmospheric air Seasonal variations in atmospheric pressures are therefore of minimal significance.

As samples were always collected at approximately the same time diurnal variations, if they occur, will have little effect on the observed seasonal pattern. Although diurnal variations have been recorded on surface streams due to biotic activity (Slack, 1967), these effects appear to be absent in spring water (Shuster and White, 1971).

2. Factors Thought to Initiate Spatial Variations in Limestone Solution

Because of a high degree of overlap between factors initiating temporal patterns in limestone solution and those thought to initiate spatial variations,this review of spatial factors is included here rather than at the beginning of Chapter 7. In addition Chapter 7 is concerned with the distributional aspects of several karst water characteristics, not simply of limestone solution.

Variations in the structural,lithological and chemical characteristics of calcareous rocks has frequently been demonstrated as being an important factor both in the solution of limestone and in karst landform development (Cvijic, 1924; Morgan, 1942; Sweeting, 1958; Hack, 1960; Monroe, 1960; Verstappen,1960; Croce, 1964; Roglic, 1964; Verstappen, 1964; Sweeting, 1966). Several works are, however, of particular relevance to this study in north-west Yorkshire. Sweeting and Sweeting (1969) have recently carried out a detailed study on the influence of rock composition, texture and porosity in relation to limestone weathering and landform development. The proportion of intergranular calcite or cement (sparry calcite) was found to be of particular importance in influencing both the form of land form development in north-west Yorkshire and County Clare, and in influencing regional variations in limestone solution in north-west Yorkshire. Pools on the limestone in western areas averaged 60-80 p.p.m. of dissolved calcium carbonate and those in the east 120-160 p.p.m. Limestone springs and streams, however, represent a much more complex hydrological situation than rock pools, and dissolved calcium carbonate concentrations in springs and streams may result from various factors, some of which have already been reviewed. Detailed studies of variations in rock lithology and chemistry within the field area are, however, essential before a full evaluation of the role of geological factors in initiating spatial patterns in limestone solution within the comparatively small area of High Mark and Fountains Fell may be made.

Rauch and White (1970) conclude from a detailed study of lithological controls on cave development in the Appalachians that grain size effects and the presence or absence of dolomite are the dominant controls. Work by Waltham (1970) has demonstrated the importance of shale beds in controlling cave development in north-west Yorkshire. The presence of shale beds may have a direct influence on dissolved calcium carbonate concentrations in the karst waters. Imbt (1950) has suggested that the oxidation of carbonaceous material from shales interbedded with limestones would involve a release of carbon dioxide which would be able to combine and form carbonic acid, and that by this process solution of carbonate rocks could be accomplished at depth. This factor has not previously been considered in the context of north-west Yorkshire where both the Yoredale Series and the Great Scar Limestone (Waltham, 1971) contain numerous shale bands. The association of cave development with shale beds has also been noted by Myers (1948) and Long (1967).

Variations in soil properties within an area or between widely separated areas may give rise to spatial variations in limestone solution. Pitty (1972) suggests that the higher concentrations of dissolved calcium carbonate in the limestone waters of Derbyshire as compared to Yorkshire may be related to the greater fertility of the soils on the Derbyshire limestone, soils on the limestone uplands in Yorkshire being generally more acid. Within the High Mark area variations in soil acidity are closely related to the depth to the underlying limestone (chapter one) a factor which varies considerably within the area. The production of organic acids in the soil zone is another factor in limestone solution whose importance has frequently been suggested (Adams and Swinnerton, 1937; Hohlt, 1948; Schoeller, 1962; Groom and Williams, 1965; Stringfield and Le Grand, 1966) although little quantitative work on this factor has been carried out. In laboratory experiments Murray and Love(1929) demonstrated that soil bacteria had the ability to generate acids capable of dissolving calcium carbonate. In the Fountains Fell and Darnbrook Fell area water often reaches the limestone bedrock as percolation through small enclosed depressions or swallets. A large number of these depressions appear to be fed not by surface flowing streams but by seepage at root level from the surrounding peat soils. This seepage was observed in sections in the sides of enclosed depressions occurring on slopes as low as 2-3° even in fairly dry conditions (Plate 11). The pH of this seepage water was found to be extremely low (3.8 to 4.2), and this acidity may be attributable to organic acids produced in the peat zone. The water is also low in dissolved calcium carbonate (5 to 8 p.p.m. of dissolved calcium carbonate) and is therefore a very potent solvent on reaching the limestone. The effect of soil depth on the rate of water movement has been noted by Drew (1968) and slow percolation of water through deep soils may have a considerable effect on the dissolved calcium carbonate content of the water especially when limestone pebbles are present (Groom and Ede, 1972). Spatial variations in soil properties may therefore provide a contributing factor to spatial variations in limestone solution within the field area.

Various factors that have been reviewed above may also initiate spatial variations in limestone solution. As Pitty (1968d) has shown mean dissolved calcium carbonate concentrations in karst waters may be closely related to flow-through time. Regional variations in flow-through time arising out of variations in joint development or distance travelled by the water may therefore effect the recorded spatial patterns in limestone solution. The effect of mode of recharge on dissolved solids concentrations has already been reviewed and contrasts between the Fountains Fell and High Mark areas may be related to this factor.

Although many of the following pages are concerned with the influence of hydrometeorological factors on the observed temporal and spatial patterns in limestone solution many of the processes discussed in this review are affected directly or indirectly by these factors.

B Graphical Analysis of Dissolved Calcium Carbonate Variations in N.W. Yorkshire

All springs and risings around the High Mark and Fountains Fell uplands in north-west Yorkshire show some degree of seasonal variation in the amount of limestone in solution (Figs 3a-23d; 36a-40b). On some sites this seasonal variation is readily detectable although on others the variation over the year is of a very low order. The springs emerging south-west of Arncliffe village in the lower part of Cowside Beck valley (Map 8) all show a broad distinct seasonal variation in dissolved calcium carbonate. Site 47 for example (Fig. 10c) recorded its minimum concentration of dissolved calcium carbonate in March (26.3.28) of 142 p.p.m. and in mid-September reached a maxima of 176 p.p.m. Similarly sites 51 and 52 recorded a minimum concentration of dissolved calcium carbonate on 26.3.68 but attained their maxima much earlier in the year in June and July (Figs 11c and d). Around the Fountains Fell area this seasonal variation is generally more pronounced that that recorded on the High Mark springs as an examination of the graphs of dissolved calcium carbonate variations (Figs 3a-40b) demonstrates. At Scoska Cave rising (site 64) an annual range of 105 p.p.m. dissolved calcium carbonate was recorded with the maximum recorded concentration (218 p.p.m.) occurring in mid-August and the minimum (113 p.p.m.) in early October (Fig. 15a)

At a number of sites, however, particularly around the High Mark upland, this seasonal variation is very low and, at a few sites, scarcely identifiable. Sites 56-59 located on the eastern side of Malham Tarn

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show the lowest annual range in dissolved calcium carbonate. At site 58 the lowest dissolved calcium carbonate (178 p.p.m.) was recorded on 27.2.69 and the highest (193 p.p.m.) on 19.9.68 with an annual range of only 15 p.p.m. dissolved calcium carbonate (Fig.13a). Similarly, at site 56 (Fig.12d) although the absolute concentrations were higher, the annual recorded range was only 16 p.p.m. dissolved calcium carbonate (183 p.p.m. on 27.3.68 to 199 p.p.m. on 19.9.68).

Superimposed upon these broad seasonal changes in dissolved calcium carbonate are short term fluctuations which vary greatly from spring to spring in their intensity of expression. An inspection of Figs.3a-40b shows a marked tendency for these short term pulses to be much more strongly developed on the Fountains Fell risings than on the springs around High Mark. This, however, is only a general rule and a number of the High Mark springs do show a high degree of development of short term pulses. At site 26 (Fig.6c), for example, in the High Mark area short term pulses are strongly developed and make it difficult to identify any seasonal variation in dissolved calcium carbonate.

Although a casual inspection of these short term fluctuations in dissolved calcium carbonate suggests a relationship with rainfall through a dilution effect, a closer examination of individual peaks and troughs indicates a more complex relationship. A visual comparison of the graphs of hydrometeorological conditions with those of dissolved calcium carbonate suggests that the dissolved calcium carbonate low recorded on all springs and resurgences on 26.3.68 is related to the heavy precipitation in the period immediately prior to sampling, much of this falling as sleet or snow, and at a time when ground temperatures were low. At site 11, however, three distinct peaks in dissolved calcium carbonate content may be identified (Fig.4e) occurring (a) in early May, (b) in July and August and (c) in mid-September and October. A visual analysis suggests a relationship between these peaks and heavy precipitation in the period immediately prior to sampling. On a visual inspection, therefore, both peaks and troughs in dissolved calcium carbonate appear to be related to rainfall pulses. The visual relating of specific rainfall periods to specific pulses in the pattern of dissolved calcium carbonate, however, necessitates an immediate or near-immediate rainfall effect. If, however, this effect is delayed for a period of greater than a few days owing to, for example, tightness of joints, this visual or graphical analysis may be misleading.

A number of general points concerning variations in dissolved calcium carbonate in the High Mark and Fountains Fell areas of north-west Yorkshire may be summarized from this brief graphical analysis.

1. All springs and resurgences show some degree of seasonal variation in dissolved calcium carbonate.
2. This seasonal variation appears to be more strongly developed in the Fountains Fell area than in the High Mark area.
3. All springs and resurgences show a pattern of short term fluctuations or pulses in dissolved calcium carbonate.
4. These pulses appear to be related in some manner to rainfall pulses although the relationship may be complex.
5. Short term pulses in dissolved calcium carbonate are generally better developed in the Fountains Fell area than in the High Mark area.

C Mean Dissolved Calcium Carbonate, Calcium Carbonate Variability and Flow-through Time

Pitty (1968d) has demonstrated the existence of a close positive correlation between flow-through time (see p.58) and mean dissolved calcium carbonate. It would appear that although seasonal variations in dissolved calcium carbonate may be attributed to the production of carbon dioxide in the soil zone, the absolute concentration of dissolved calcium carbonate is related to the time the water has taken to pass through the limestone massif. Implicit in this relationship is the suggestion that the percolating water is dissolving either at a constant rate (linear relationship) or at a gradually increasing or decreasing rate. It does not appear to take into account the factor of calcium carbonate precipitation in caves and joints and as such would appear to exist only for those waters either undersaturated or in a state of equilibrium with respect to dissolved carbon dioxide. However, only where large caves occur is chemical precipitation likely to have any notable effect on the solute concentration of calcium carbonate.

Calcium carbonate precipitation in surface streams may, however, exert considerable influence on calculated flow-through times illustrating that such stream sites must be sampled either at their spring source or excluded from the flow-through analysis. Outgang stream is fed by two permanent springs of identical chemical and physical characteristics (Fig.4b and c for sites 7 and 8). The correlation of dissolved calcium carbonate variations with antecedent air temperature indicated a lag time of 74 days on each spring. However, 137 m (450 ft) downstream at site 10, the apparent lag time of dissolved calcium carbonate behind air temperatures had increased to 108 days; after a further 128 m (420 ft) (site 13) this 'lag' was calculated at 117 days. Between sites 10 and 13 water from a small tributary spring with a calculated lag time of 108 days entered the main stream. This increase in apparent lag time of 43 days within a stream length of 265 m (870 ft) can only be due to biochemical precipitation of calcium carbonate in the stream bed, evidence of which is plentiful in terms of resultant physical forms (Plate 12) and chemical analyses.

The correlation of mean dissolved calcium carbonate and flow-through time of springs in both the High Mark and Fountains Fell areas is, however, of a low order.

Of much greater interest in the High Mark area is the high correlation between flow-through time and the standard deviation of dissolved calcium carbonate (Fig.42). As observed above two types of variation may be observed in the pattern of dissolved calcium carbonate fluctuation recorded on springs and risings. (i) seasonal variation and (ii) short term pulses which appear to be principally related to dilution by rainfall. The regression of the standard deviation of dissolved calcium carbonate on flow-through time demonstrates that the longer the water takes to pass through the limestone the more the seasonal dissolved calcium carbonate wave is suppressed (dilution influences being relatively low on most High Mark springs - see Figs.3a-13b) in a manner similar to the suppression of a seasonal temperature wave with depth below the ground surface. This suppression of the seasonal dissolved calcium carbonate wave may be due to two factors:

(i) Chemical precipitation within the system at certain seasons or under certain flow conditions;

(ii) Further solution of calcium carbonate within the bedrock at certain seasons or under certain flow conditions.

In either case the seasonal dissolved calcium carbonate wave arising out of changes in soil carbon dioxide production is preserved to some degree in the pattern of variation recorded at the risings.

Owing to the strong dilution effects of sinking streams and of fast percolation (see below) in the Fountains Fell area no relationship was observed between flow-through time and dissolved calcium carbonate variation (Fig.44) This contrast between the High Mark area and the Fountains Fell area is illustrated by the correlation between mean dissolved calcium carbonate content of risings in the latter area with the standard deviation of calcium carbonate ($\underline{r}$ = -.44)(Fig.41) a relationship which illustrates the extreme dilution effects of sinking stream water on the pattern of dissolved calcium carbonate variation. In the High Mark area no relationship was found between these two variables (Fig.45)

D Air Temperature and Dissolved Calcium Carbonate Variations: The High Mark Area

The correlation of dissolved calcium carbonate observations made on springs around the High Mark area over the period February 1968 to February 1969 with antecedent air temperature shows a similar positive correlation between these two variables to that identified by Pitty (1966b; 1968a, b, c) although the level of correlation was found to vary considerably from spring to spring. At Malham Tarn spring 56 only 12% of the dissolved calcium carbonate variance could be explained by the highest positive correlation with air temperature in the twenty weeks prior to sampling (with the mean air temperature of the 22-28 day period prior to sampling). Similarly at Kilnsey spring 26 only 14% the dissolved calcium carbonate variance may be explained by the antecedent air temperature factor (with the mean air temperature of 29-35 day period prior). By contrast the springs near Arncliffe (sites 47-50) all show a high positive correlation with the air temperature 22-28 days previous to sampling. At site 50, for example, 72% of the dissolved calcium carbonate variance may be explained by the air temperature of the 22-28 day period previous to sampling, and at site 47 70% may be explained by the air temperature of the same period. Around the High Mark area 62% of the springs (26 out of 42) showed a positive correlation with antecedent temperature that was significant at the 0.01 level. *

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* Significance levels have been used simply to facilitate (a) a comparison between the two field areas regarding the importance of the independent variable, in this case air temperature and (b) a comparison between different seasons. Unlike the coefficient of determination this method takes into account the number of observations made of the dependent variable.

The graphs of dissolved calcium carbonate variations of those springs with a high level of correlation between dissolved calcium carbonate and antecedent temperature generally show a well defined seasonal pattern in dissolved calcium carbonate variation and a low degree of development of short term pulses. This has already been observed in the case of the Arncliffe springs. By contrast sites with a strong development of short term pulses (eg. site 25 Fig.6c) or sites with very little detectable seasonal variation in dissolved calcium carbonate (eg. site 56 Fig.12d) generally exhibit a low level of correlation between dissolved calcium carbonate and antecedent air temperature.

The pattern of correlation between dissolved calcium carbonate and the mean temperature of successive weekly periods prior to sampling is important to an understanding of the relationship between these two variables. Most High Mark springs show a steady, although not uninterrupted, rise to a maximum in the level of positive correlation with these antecedent temperature time periods. A progressive decline in the level of positive correlation was then observed. On those springs on which correlations between dissolved calcium carbonate and the antecedent temperature of weekly time periods up to one year prior to sampling were carried out, this progressive decline in positive correlation gradually transformed into a progressive increase and fall in the level of negative correlation between these two variables. The highest level of negative correlation was at times higher than the highest positive correlation.

With progressively greater time periods antecedent to sampling the correlation again becomes positive (approximately 1 year in addition to the time of initial highest positive correlation time period or flow-through time).

The problem arises as to which, if any, correlation represents the true flow-through time of water through the limestone:

(i) the highest positive correlation of the first positive cycle ie. at n days prior to sampling;

(ii) the highest negative correlation in the first negative cycle ie. at n days ±6 months;

(iii) the highest positive correlation of subsequent positive cycles (n days + 1 year, 2 years etc.)

(iv) the highest negative correlation of subsequent negative cycles (n ± 6 months) + 1 year, 2 years etc.

The weight of evidence is in favour of interpreting the highest positive correlation of the first positive cycle as being indicative of the flow-through time through the limestone. Correlation analysis on Fountains Fell resurgences provided flow-through times (shown by the highest correlation in the first positive cycle) of less than one week (eg. 4 days for Fosse Beck rising - site 69, Littondale) a situation in accord with results obtained by dye testing. Furthermore, Drew's work in the Mendips (Drew, 1968) using pyranine tracer suggests that time lags of the order shown by the initial positive cycle (see below) are acceptable for the movement of percolation water through massive limestone and Pitty (1968b) provides strong evidence for accepting the time lags shown by the initial positive cycle for observations carried out at Gordale Beck and Crowdwell rising.

Although in the statistical analysis of the observations carried out for this research (see Chapter 2) correlation coefficients were calculated between both dissolved calcium carbonate and antecedent air temperature and between dissolved calcium carbonate and antecedent soil temperatures the results show little difference between the two. Out of 39 High Mark springs analysed in this way 20 showed a higher correlation between dissolved calcium carbonate and soil temperature. One possible explanation may lie in the relative proportion of bare pavement to soil covered rock in the catchment of these springs "The relative amounts of water recharged by percolation through soil and by direct entry into outcropping rocks ... may have an appreciable effect on the chemical character of the ground-water." (Hendrickson and Krieger, 1964 p.61)

The flow-through period derived from the correlation of dissolved calcium carbonate with antecedent soil temperature is generally several days shorter than that derived from the correlation of dissolved calcium carbonate with antecedent air temperature. At Moss Beck rising (site 27) the mean air temperature of day 26 prior to sampling explained 40% of the observed dissolved calcium carbonate variance but the soil temperature of day 23 explained 47% of the variance. (Although the correlations were carried out with the mean temperature of weekly periods, except for the first week, the more exact flow-through times given above were estimated by interpolation based on the degree of correlation with the weekly temperatures either side of the week showing the highest correlation (Pitty, 1968d)). The shorter flow-through associated with soil temperatures may be attributed to the lag of soil temperatures behind air temperatures which has been observed by a number of workers (Keen and Russell, 1921; Russell, 1961).

In future discussion of flow-through times the lag time between dissolved calcium carbonate variation and antecedent air temperature is used as this is the more appropriate variable (Pitty, 1966b). It should be pointed out that different antecedent time periods to those used by Pitty (1966b) have been employed, unfortunately making exact comparison with his work difficult.

Flow-through times on High Mark springs* vary between 9 days

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* Flow-through times were calculated on sites with the highest positive correlation (between dissolved calcium carbonate variation and antecedent temperature) being significant at the 0.01 level of probability. Pitty (1968d) excludes all sites on which less than 50% of the dissolved calcium carbonate variance was extracted by the antecedent temperature factor but owing to the varying number of observations made on different sites this was not deemed satisfactory for this work.

(site 35) and 108 days (site 11) although the majority of sites (78%) exhibit a flow-through time of less than 42 days (Fig.46) (21 out of 27). Owing to the lack of knowledge of the distance these waters have traversed and to the great range of rates of movement of water in limestone terrains (Stringfield and Le Grand, 1969) it is difficult to compare these results with other areas. Hanshaw, Back and Rubin(1965) using C_{14} determinations to calculate apparent velocities of ground-water in the Floridian limestone aquifer found flow rates of between 2 and 12 m per year between wells, a rate of movement obviously considerably slower than that observed above on any of the High Mark springs. Rates of flow calculated by Drew (1968) for percolation water were 2-2½ weeks for water travelling a distance of 60 m (200 ft) in the Mendips, and 17 days for a distance of 0.4 km (¼ mile) in the Cotswolds. It seems likely that water emerging from many of the High Mark springs has traversed in some instances several kilometres of limestone (see Chapter 7), there being no springs in the interior of this upland area. Rates of flow, though showing considerable variation, appear therefore to be comparatively swift in the High Mark limestone upland, although Burdon (1967) reports maximum flow rates in one area of 420 m per day and in another 4500 m per day.

E Seasonal Variations in Flow-Through Times on High Mark Springs

Correlations of dissolved calcium carbonate variations recorded over:

(a) the winter period (October to March 1968-69)
(b) the summer period (April to September 1968)
(c) the wet conditions period (rainfall greater than 7.6 mm or 0.3 in in week previous to sampling)

(d) the dry conditions period (rainfall less than 7.6 mm or 0.3 in in week prior to sampling)

were carried out with antecedent air and soil temperatures (see Chapter 2) in an attempt to understand further the factors underlying the relationship between dissolved calcium carbonate variations and antecedent temperatures.

The correlation of these seasonal observations with antecedent temperatures shows a level of correlation which is similar in many respects to that observed from the correlation analysis of the year's observations (Fig.46). Nor was any consistent difference in the level of correlation between the summer and winter periods observed (Fig.46) On some springs the level of correlation between winter readings and antecedent temperature was higher than in the summer. At site 8 (Outgang spring) the air temperature of the 99-105 day period prior to sampling extracted almost 47% of the winter dissolved calcium carbonate variance but in summer only 36% of the dissolved calcium carbonate variance could be explained by antecedent air temperature. On other sites, however, the level of correlation was greater in the summer than in the winter. At site 41 the antecedent air temperature factor (of 8-14 day period) could explain only 12% of the dissolved calcium carbonate variance in the winter but 39% in the summer (22-28 day period). The higher level of correlation between antecedent temperature and dissolved calcium carbonate variations in winter on some sites suggests that either

(a) Micro-organic activity is important in bringing about fluctuations in dissolved calcium carbonate even in the cool season, or

(b) Some other factor is initiating seasonal variations in dissolved calcium carbonate.

The level of correlation between antecedent temperature and dissolved calcium carbonate variations in the dry conditions period was, however, generally higher than those occurring in the wet conditions period as illustrated in Fig.46. In the dry conditions period 78% of the High Mark springs showed a correlation with antecedent temperature significant at the 0.01 level of probability. By contrast only 35% reached this level of correlation in the wet conditions period. These percentages illustrate the significance of the dilution factor even in an area such as High Mark where all recharge is from percolation sources (Chapter 1). At site 46, for example, antecedent air temperature extracted over 54% of the dry conditions period dissolved calcium carbonate variance although in the wet conditions period this factor extracted only 34% of the variance. There were, however, a few exceptions to this general rule. At Chapel House Well (site 5) antecedent air temperature could account for 65% of the dissolved calcium carbonate variance in the dry conditions period but 71% in the wet conditions period. It must be pointed out that although the percentage variance extracted by the antecedent temperature factor may be similar in order for the seasonal period correlations as for the complete year, the seasonal correlations are based on only 11-13 observations (Chapter 2) as compared to 24 on permanently flowing sites.

Although the level of correlation between seasonal observations of dissolved calcium carbonate and antecedent temperature is similar to that between the year's observations and antecedent temperature the pattern of correlation shows some contrast. As observed above the correlation coefficients from the analysis of the year's observations show a gradual climb to a peak. The correlation coefficients resulting from the correlation of seasonal observations with the temperature of pre-set time intervals prior to sampling, produced a much more erratic pattern particularly in the case of the winter and wet conditions periods. At site 48 near Arncliffe the mean air temperature of the 22-28 day period prior to sampling explained just over 74% of the dissolved calcium carbonate variance over the winter period; however, the mean air temperature of the 36-42 day period could explain just under 74% of the variance, and that of the 85-91 day period could explain just over 73% of the dissolved calcium carbonate variance in the same season. This factor has made the identification of seasonal flow-through times difficult, particularly with regard to the winter and wet condition periods. Although the pattern of correlation coefficients is more consistent over the summer and dry condition periods it is still irregular as compared to the patterns observed from the analysis of the year's observations. Correlation analysis using air temperatures averaged over a longer time interval would probably eliminate or reduce this problem. In part, however, this problem arises out of the narrower temperature range when only part of the year is taken into consideration.

The histograms in Fig.46 illustrate the seasonal contrasts in the flow-through times as indicated by the statistical analysis of the seasonal observations. During the winter, and to a lesser degree in the wet conditions period, not only does the level of correlation tend to be lower than in the summer and dry conditions periods, but the flow-through times indicated vary considerably from spring to spring. By contrast over the summer and dry conditions periods the consistency of the flow-through times is much greater and in many respects more comparable to the flow-through times based on the year's observations. In the summer period all springs with the highest positive correlation with antecedent temperature significant at the 0.01 level of probability show flow-through times of less than 42 days (Fig.46).

Owing to the low number of seasonal observations made and to the problems of interpretation of the time lags outlined above only a few tentative observations may be made concerning the seasonal variation in flow-through time.

(i) A comparison of the histograms of the flow-through times calculated for the dry conditions period with those of the summer period indicates some tendency for longer flow-through times to exist in the dry conditions period. The modal class for the summer period is 22 - 28 days and for the dry period is 57-63 days. Rainfall would, therefore, appear to be an important factor in determining the length of the lag of dissolved calcium carbonate recorded at the risings behind air temperature.

(ii) This is further supported by the occurrence of a higher percentage of springs with a high level of correlation (significant at 0.01 level) between dissolved calcium carbonate and antecedent temperature in the dry conditions and summer periods than in the winter and wet conditions period.

(iii) The generally higher level of correlation between the two variables in the winter period in contrast to the wet conditions period suggests that high rainfall may either reduce or mask the effect of air and soil temperature on the level of dissolved calcium carbonate. Dissolved calcium carbonate variations in the summer and dry conditions period would therefore appear to be closely related to antecedent temperatures, while those in the winter and wet conditions periods are more closely related to rainfall.

(iv) The histograms (Fig.46) indicate a slight tendency for winter flow-through times to be longer than those in summer. This may be a reflection of either the effect of temperature on viscosity, a factor which is discussed in more detail in Chapter 5, or the effect of winter freezing of the soil (see Chapter 1) cutting off or reducing recharge to the limestone.

F Air Temperature and Dissolved Calcium Carbonate Variations: The Fountains Fell Area

Around the Fountains Fell upland a much lower percentage of the springs and risings show a high positive relationship of the complete years' (February 1968-February 1969) dissolved calcium carbonate observations with antecedent air temperatures than was observed on High Mark (38% as compared to 62%). In addition, the flow-through times are generally much shorter on Fountains Fell risings than on High Mark risings. An examination of Fig.46 shows that most Fountains Fell risings which show a high positive relationship between dissolved calcium carbonate and antecedent temperature have a flow-through time of less than two weeks. This contrasts with the High Mark area where the modal class (Fig.46) is flow-through times within the range of 22 to 28 days.

These contrasts in both the level of positive correlation between the two variables and the length of the flow-through time indicated reflect the basic geological and hydrological contrasts between the two areas. On High Mark recharge is almost purely by rainfall percolation through open pavement joints, a thin soil cover or small enclosed depressions. On the Fountains Fell area recharge through the limestone is largely as sinking streams collected on the non-calcareous caprock or as 'fast' percolation through numerous open depressions. These depressions or swallets appear to function as local catchments for percolation water which is funnelled downwards into the limestone often through an open pipe in the depression floor. As much of the Fountains Fell area, unlike the High Mark area, is masked by considerable thicknesses of drift and peat (Chapter 1) the function of these depressions in directing percolation water quickly into the limestone drainage systems is of paramount importance.

The High Mark and Fountains Fell areas also show marked contrasts in the degree of cave development as witnessed by the large number of known systems in the latter area (Thornber, 1959). Only one important active cave is known within the High Mark area (Sleets Gill Cave - Long, 1969) although several minor caves such as Robin Hood's Cave and Kilnsey Cave have also been recorded (Thornber, 1959).

These contrasts in the mode of recharge to the limestone and in the development of cave systems may provide the main explanation of the shorter flow-through times and lower level of positive correlation (between dissolved calcium carbonate and antecedent temperature) recorded on Fountains Fell risings. If the lag time between the above variables is a reliable index of flow-through time through the limestone it is obvious that the above contrasts will give rise to shorter flow-through times on Fountains Fell drainage systems. The lower level of positive correlation found on Fountains Fell risings may be attributed to the extreme dilution effect of sinking streams on the ground-water.

A number of Fountains Fell risings show a complete lack of any definite correlation, either positive or negative, between dissolved calcium carbonate variations over the year and antecedent temperature. This is the case at sites 98 and 99 for example. One explanation is provided by the correlation analysis of seasonal observations (see below).

G <u>Seasonal Variations in Flow-Through Times on Fountains Fell Risings</u>

An examination of Fig.46 shows a number of aspects to the correlation of seasonal observations of dissolved calcium carbonate with antecedent temperature.

(i) The level of correlation between dissolved calcium carbonate and antecedent temperature tends to be greater in the summer and dry conditions periods, as witnessed by the percentage of the springs showing a high positive correlation between the two variables.

In the summer and dry conditions periods 62% and 66% respectively of the springs showed this high positive correlation whereas in winter and the wet conditions period the percentages were only 15% and 8% respectively.

(ii) The pattern of seasonal variation in flow-through time yields little information. Possibly a slight tendency for shorter flow-through times exists in summer as opposed to winter, although no definite conclusion may be made.

The contrasts between the summer and dry conditions periods and the winter and wet conditions periods may be due to:

(a) In the summer and dry conditions periods the dilution factor will be at a minimum owing to the drying up of sinking streams.

(b) Variations in dissolved calcium carbonate in the wet conditions and winter periods may be more closely related to rainfall variations than to variations in soil carbon dioxide production. In the winter period micro-organic activity would be expected to be minimal.

(c) In both the High Mark area and the Fountains Fell area the contrast between the dry and wet conditions periods is more severe than that occurring between the winter and summer periods. On High Mark springs the dissolved calcium carbonate variation shows a high positive correlation with antecedent temperature on 78% of the springs in the dry period but 35% in the wet period (summer 43%, winter 48%). On Fountains Fell risings 66% show a high positive correlation between these two variables in the dry conditions period and only 8% in the wet conditions period (62% in summer and 15% in winter). These figures illustrate the significance of rainfall in masking the positive association of dissolved calcium carbonate and antecedent temperature.

Site 98 located on the eastern margin of Fountains Fell illustrates these points. During the winter and wet conditions periods the correlation between dissolved calcium carbonate and antecedent temperature is low and negative with an indefinite flow-through time ($\underline{r}$ = -.57 for 120-126 day period in the wet conditions period; $\underline{r}$ = -.56 for 29-35 day period in the winter). Observations in the summer, however, showed the highest positive correlation with the air temperature 36-42 days antecedent to sampling ($\underline{r}$ = +.87) and in the dry conditions period with the air temperature 64-70 days prior to sampling ($\underline{r}$ = +.88). It would appear that this system is essentially of a sink-resurgence type in the winter and wet conditions periods when strong dilution pulses drown any effect of positive association with temperature. In the summer and dry conditions periods percolation would appear to be the chief source of recharge to the system and a strong correlation between dissolved calcium carbonate and antecedent temperature occurs.

As on the High Mark springs the Fountains Fell risings generally show a lower level of positive correlation between dissolved calcium carbonate and antecedent temperature in the winter and wet conditions periods than in the summer and dry periods (unless, as at site 98, a negative correlation exists for the winter and wet conditions periods.)

H Effective Precipitation and Dissolved Calcium Carbonate Variations: The High Mark Area

The correlation of variations in dissolved calcium carbonate recorded over the year (February 1968 - February 1969) with antecedent effective precipitation suggests a very complex relationship between these two variables. Of the springs sampled around the High Mark area 31% showed a highly significant (0.01 level) negative correlation with the antecedent effective precipitation occurring for the most part within the seven days prior to sampling (Fig.47). Rainfall occurring within a short period prior to sampling has a distinct dilution effect on the amount of dissolved calcium carbonate recorded at many springs.

The extent of this dilution factor varies greatly from spring to spring. Over 62% of the variance in dissolved calcium carbonate recorded at site 26 (Fig.6c) is extracted by the negative correlation between this variable and the effective precipitation of the fourth day prior to sampling (_r_ = -.79) At site 53 (Fig.12a), however, only 22% of the dissolved calcium carbonate variance is extracted by the antecedent effective precipitation factor for day four prior to sampling. A visual comparison of the graphs of dissolved calcium carbonate at these two sites strongly suggests that the short term pulses in dissolved calcium carbonate relate to dilution by effective precipitation.

This variation in the degree of dilution effect of rainfall may be related to the mode of recharge to the limestone system. Dilution effects might be expected to be great on those systems in which a large element of the catchment is open jointed pavement, open swallets or large basins. An examination of the probable catchment of site 26 shows the existence of large pavement areas, and the presence of a large basin, Doukabottom, in this part of the High Mark upland may not be entirely unrelated to the strong dilution pulses recorded at site 26. Springs with catchments characterised by deep soil cover and a lack of enclosed basins may show less sign of dilution.

A further factor influencing the extent of dilution by effective precipitation may be the depth of the major flow zone. Those systems with their major flow zones close to the ground surface may be more effected by dilution pulses than those at greater depth.

In addition to the dilution effect of effective precipitation on dissolved calcium carbonate as indicated by the high negative correlation between these two variables, many springs also show a positive correlation between dissolved calcium carbonate and the effective precipitation of some other period prior to sampling. Only on 7% of the High Mark springs was this positive correlation significant at the 0.01 level of probability although on most springs a lower level of positive correlation between these two variables was recorded.

At Robin Hood's Well (site 3) the dissolved calcium carbonate variation correlated positively with the total rainfall of the third day prior to sampling ($\underline{r}$ = +.58) but negatively with the fourth day prior to sampling ($\underline{r}$ = -.25) Although the negative correlation succeeding the positive correlation may be simply due to the intercorrelation of the rainfall of day three prior to sampling with that of day four (see Chapter 2) one other possibility presents itself. A positive correlation between dissolved calcium carbonate and rainfall succeeded by a negative correlation may indicate a push-out effect similar to that described by Pitty (1966a, 1968c) and Douglas (1968a), with rainfall flushing-out at least some water which has been in contact with the rock for a longer period of time (see literature review). As the lag times or flow-through times derived from the correlation of dissolved calcium carbonate with antecedent temperature are generally much longer (36-42 days on Robin Hood's Well) than the few days lag in the effect of rainfall pulses this 'flushing-out' of the system appears to be only partial in nature probably effecting only those feeder channels close to the exit of the system.

The correlations of dissolved calcium carbonate with antecedent effective precipitation is not considered indicative of the relationship between dissolved calcium carbonate and discharge. The relationship of discharge to effective precipitation and of dissolved calcium carbonate and water temperature to discharge is considered in Chapter 6.

I Seasonal Variations in the Relationship of Dissolved Calcium Carbonate to Effective Precipitation on High Mark Springs

Correlations of dissolved calcium carbonate variations in the summer, winter, wet and dry conditions periods (see Chapter 2) were carried out with antecedent effective precipitation in order to see if any seasonal effects in the influence of rainfall on dissolved calcium carbonate concentrations occurred.

In the winter period 30% of the High Mark springs on which correlation analysis was carried out, showed a strong negative correlation with effective precipitation occurring within one week prior to sampling. For the summer period, however, 48% revealed a strong negative correlation between the two variables. An examination of the histograms in Fig. 47 shows, however, a marked tendency for the summer dilution effect to be much slower than that in the winter. The summer period correlations on most springs suggest dilution of dissolved calcium carbonate by rainfall occurring 22-28 days prior to sampling. On account of the generally lower precipitation in the summer dilution effects appear to be slower in manifesting themselves at the springs.

A similar situation to the summer exists for the dry conditions period, with the dissolved calcium carbonate variations of 50% of the springs showing a high negative correlation with the antecedent effective precipitation 22-28 days prior to sampling. In the wet conditions period, however, only 1 spring out of 21 (5%) revealed a high negative correlation between dissolved calcium carbonate and antecedent effective precipitation (Fig.47)

The explanation of the higher level of negative correlation between dissolved calcium carbonate and effective precipitation in the summer (48% of the springs) and dry conditions periods (50%) in contrast to the winter (30%) and wet conditions periods (5%) is problematical. In wet periods a more complete mixing of water in the system, high in dissolved calcium carbonate, with dilution water, low in dissolved calcium carbonate, occurs than in the drier parts of the year. Consequently no well defined positive correlation from a flush-out effect, or negative correlation from a dilution effect occurs.

A related explanation is that during the summer and dry periods ground-water storage is low and hence any rainfall pulses will have a greater effect on dissolved calcium carbonate than at periods of considerable ground-water storage. It is notable that in the summer and dry periods 0% and 6% of the springs respectively show a high positive correlation with antecedent effective precipitation suggesting that flushing-out may be of minimal importance in those periods. During these periods recharge of the limestone is low owing to high soil moisture deficits and lower rainfall. The low degree of flushing-out in the summer and dry conditions periods is especially of interest in that the correlation of dissolved calcium carbonate with antecedent air temperature was particularly marked in these periods (see above).

J Effective Precipitation and Dissolved Calcium Carbonate Variations: The Fountains Fell Area

The correlation of dissolved calcium carbonate variations recorded on Fountains Fell risings with antecedent effective precipitation showed a pattern of correlation which both contrasted with and paralleled the relationship between these two variables observed in the High Mark area. Of the Fountains Fell springs and resurgences 76% showed a high negative correlation (significant at 0.01 level) with the effective precipitation occurring within one week prior to sampling (usually that of day 4), as compared to only 31% on High Mark springs. The dilution effect of rainfall appears therefore to be very much greater on Fountains Fell than on High Mark systems and reflects the basic difference between the two areas in type of karst drainage system. On Fountains Fell recharge by sinking streams and fast percolation (see above) through numerous small enclosed depressions provides an important element of the limestone recharge, a feature which is almost entirely absent on High Mark where only a few large enclosed basins exist and where only one sinking stream (Cotegill) is known.

Unlike the High Mark systems no positive correlations between dissolved calcium carbonate and antecedent effective precipitation were found preceding the negative correlation. This suggests that any flushout by rainfall is minimal and that:

(i) the storage capacity of the Fountains Fell systems if of a low order as compared to the High Mark systems.

(ii) the storage capacity is low as compared to the volume of recharge occurring after rainfall from sinking streams and fast percolation.

K Seasonal Variations in the Relationship of Dissolved Calcium Carbonate to Effective Precipitation on Fountains Fell Risings

Unlike the High Mark springs the pattern of dissolved calcium carbonate variation recorded at most of the risings around Fountains Fell in the four seasonal periods (see Chapter 2) revealed the closest correlation (negative) with the effective precipitation occurring within one week antecedent to sampling (Fig.47) There is, however, a slight tendency for the dilution effect of effective precipitation to be delayed on a number of springs. The tendency for more immediate dilution effects to occur on most Fountains Fell risings at all times of the year is undoubtedly a further reflection of recharge by sinking streams.

A much greater percentage of Fountains Fell springs show a negative correlation with effective precipitation significant at 0.01 level in the winter and wet conditions periods (58% and 82% respectively) than in the summer and dry periods (36% and 46% respectively). This situation is the complete reverse of that observed on High Mark springs. It would appear that in the summer and dry periods most Fountains Fell systems are relatively unaffected by dilution (recharge by sinking streams being minimal owing to their generally intermittent flow characteristics). As in the High Mark area most recharge at this period probably occurs through percolation which owing to the deep soil and drift cover may be less effective on Fountains Fell than on High Mark where soils are thin or absent.

L Dissolved Magnesium Carbonate Variations

Observations of dissolved magnesium carbonate variations were subjected to the same type of statistical analysis as was carried out for the dissolved calcium carbonate and water temperature observations (see Chapter 2) but owing to considerations of space no attempt is made here to discuss these results. A visual analysis of the recorded variations in dissolved magnesium carbonate may be carried out from the graphs in Figs.3a-40b, from which it is apparent that many springs and resurgences show a low but definite seasonal variation in the solute concentration of magnesium carbonate.

M Conclusions

The following conclusions may be listed:

1. Almost all sampled springs show a detectable degree of seasonal variation in the level of dissolved calcium carbonate. This seasonal variation is attributed primarily to seasonal changes in soil carbon dioxide as demonstrated by Pitty (1966b, 1968b, 1968c, 1968d).
2. The pattern of dissolved calcium carbonate variations on most springs shows a strong positive correlation with antecedent air temperatures,

a correlation most readily attributable to the greater biochemical production of carbon dioxide in the soil due to increased root and micro-organic respiration at higher temperatures (Pitty, 1966b).

3. In the High Mark area variations in dissolved calcium carbonate are suppressed the longer the flow-through time of the karst water. This relationship further points to the role of soil carbon dioxide fluctuations in initiating dissolved calcium carbonate fluctuations.
4. The flow-through times of High Mark springs are highly variable ranging from 9 days to 108 days, although the majority of the karst drainage systems have flow-through times of less than 42 days. In the Fountains Fell area, however, fewer springs show a high positive relationship with antecedent air temperatures (than on High Mark) and flow-through times are shorter. These contrasts between the High Mark and Fountains Fell areas essentially reflect basic differences in the mode of recharge to the limestone, and in the degree of development of underground systems.
5. The flow-through time derived from the correlation of dissolved calcium carbonate with antecedent soil temperatures is generally several days shorter than that derived from the correlation of dissolved calcium carbonate with antecedent air temperatures. This may be attributed simply to the lag of soil temperatures behind air temperatures.
6. Calcium carbonate precipitation in surface streams may affect the calculated flow-through time, illustrating that sampling for flow-through analysis must be carried out at spring sites only (when signs of chemical precipitation exist), or such sites eliminated completely from the analysis.
7. In both the High Mark and Fountains Fell areas the antecedent air temperature factor is of much greater importance in initiating (indirectly) dissolved calcium carbonate variations in the dry conditions

and summer periods than in the wet conditions and winter periods. This phenomenon is more pronounced in the Fountains Fell area and reflects the high significance of the dilution factor in that area. This seasonal contrast, which is present in both areas, may be attributed to the lower level of soil carbon dioxide production in the colder part of the year.

The following conclusions are chiefly concerned with the role of effective precipitation in initiating dissolved calcium carbonate variations at the risings.

8. The dilution factor is of much greater significance in the Fountains Fell area than the High Mark area. In the Fountains Fell area 71% of the risings showed a high negative correlation between dissolved calcium carbonate variations and antecedent effective precipitation as opposed to only 31% on High Mark. This contrast further reflects the contrast between the two areas in the mode of recharge to the limestone. On High Mark recharge is almost purely by percolation through a thin or absent soil cover; by contrast on Fountains Fell recharge by sinking streams and by 'fast percolation' through enclosed depressions is of major importance.

   Within the High Mark area considerable contrasts exist between springs in the importance of the dilution factor, a phenomenon which may be related either to the presence or absence of limestone pavement within the catchments or to the depth of the major flow zone.

9. These negative correlations between dissolved calcium carbonate and antecedent effective precipitation are usually with the effective precipitation occurring within one week prior to sampling.
10. On a number of High Mark springs a positive association between dissolved calcium carbonate and antecedent effective precipitation

(preceding the negative correlation) suggests a flush-out effect may be occurring. This phenomenon was not observed on Fountains Fell systems where dilution effects are sufficiently powerful to overwhelm any positive flush-out occurrence.

11. On Fountains Fell systems dilution effects are near-immediate at all periods in contrast to High Mark where dilution effects are delayed in the summer and dry conditions periods. The dilution effects on Fountains Fell are, however, more severe in the winter and wet conditions periods than in the summer and dry conditions periods. In the High Mark area these dilution and flush-out effects appear merely as a complication in the positive association of dissolved calcium carbonate and antecedent air temperature, although in Fountains Fell systems these processes may mask the air temperature effect at some sites particularly at some periods of the year.

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CHAPTER FIVE

VARIATIONS IN WATER TEMPERATURE IN RIVERS, SPRINGS AND RESURGENCES IN THE HIGH MARK AND FOUNTAINS FELL AREAS

A Review of the Literature on the Temperature of Natural Waters

B Some Introductory Comments on the Pattern of Water Temperature Variations Observed on Springs and Streams in N.W. Yorkshire

C Temperature Variations on Surface Streams

D Temperature Variations on the High Mark Springs

E Temperature Variations on the Fountains Fell Springs and Risings

F The Relationship between the Lag of Dissolved Calcium Carbonate Behind Air Temperatures (Flow-Through Time) and the Lag of Water Temperatures Behind Air Temperatures

G Conclusions

H Bibliography of Chapter 5

VARIATIONS IN WATER TEMPERATURE IN RIVERS, SPRINGS AND RESURGENCES IN THE HIGH MARK AND FOUNTAINS FELL AREAS

A Review of the Literature on the Temperature of Natural Waters

The recording of ground-water temperatures is a technique which has been applied by a number of workers both in the study of limestone terrains and in the field of ground-water hydrology. It is, however, a field of research which has not been widely developed and which could probably yield a large amount of information of value to both the hydrogeologist and to the geomorphologist.

Perhaps the earliest study of the temperatures of springs was that carried out by Sorby in 1859. Sorby observed that on springs with an annual temperature range of less than 2.78 C (5°F), the mean temperature of the water approximated very closely to the mean temperature of the air at similar altitudes. Springs issuing at higher altitudes were found to have a lower mean temperature than those emerging in lowland areas. Sorby further pointed out that water moving at shallow levels below the ground surface might be expected to show much greater variation in temperature than water flowing at depth. The greater the depth below the ground surface the less the seasonal changes in air temperature were reflected in seasonal changes in the temperature of the bedrock, and in the temperature of the ground-water.

More recently Mossetti (1961), working on the Timavo River in the Trieste karst area, has illustrated the value of temperature recording in the study of karst drainage systems. Temperatures recorded at the point where the Timavo River disappeared underground were compared with temperatures at a rising 40 km away, the water of which was known to be derived in part from the sinking river. Temperatures were also recorded at an intermediate point 15 km from the sink. An approximate time lag of ¾ to 1 month between sink and cave, and about 1 to 1¼ months between sink and rising is indicated by Mossetti's graphs. The annual range of temperature at the rising was less than 2°C as compared to a range of 11°C at the sink.

Schneider (1964) in studying the dolomite and limestone aquifer of the Cenomanian-Turonian formation of Central Israel found a very low, scarcely detectable, vertical water temperature gradient in wells. He concluded that this phenomenon must be the result of very rapid circulation, particularly with regard to the vertical component of the flow. Schneider (1964) also recorded a westward increase in temperature with increasing depth of the aquifer. This increase in temperature he attributes to the manifestation of the regional geothermal gradient. From an increase in temperature of 6°C with an increase in the depth of the aquifer of 200 m he calculates a geothermal gradient for the area of 1°C for 33 m.

Schneider (1964) quotes Garza's (1962) work on the Edwards and associated limestones in the San Antonio area, Texas. Garza (1962) reported that in wells yielding water containing less than 500 parts per million of dissolved solids there is little change in temperature with depth in the aquifer even though the wells ranged in depths from 100 to 2,500 ft in depth. Like Schneider (1964) Garza (1962) attributes this lack of a vertical temperature gradient to free and rapid circulation.

A great deal of work, on ground-water temperatures has, however, been carried out in non-limestone areas. Not only have these studies elucidated a number of factors affecting the temperature of ground-water, they also serve to illustrate the scope of this technique in the study of ground-water conditions in limestone areas.

Norris and Spieker (1962a and b) used temperature-depth profiles in glacial aquifers to study the effect of till lenses on the recharge of these aquifers from surface rivers. Winslow (1962) working on the flood plain of the Mohawk River near Schenectady, New York, used ground-water temperatures to demonstrate that recharge to the sand and gravel aquifer underlying the flood plain took place from the river, and to show the principal paths of flow between the Mohawk River and nearby wells which tapped this aquifer. A similar study was carried out by Rhodehamel and Lang (1962) along the Mullica River, New Jersey. Temperature recordings indicated that, because the horizontal permeability of the aquifer was greater than the vertical permeability, water movement was largely of a horizontal nature.

By recording fluctuations in the temperature of ground-water at varying depths in sands, silts and clay material Heath (1963) calculated that penetration of air temperature fluctuations in this material was not much greater than 18 m (60 ft). He observed that the depth of penetration of the air temperature fluctuations or waves was proportional to both the amplitude and the period of the waves. The shortest air temperature fluctuations (diurnal) were only detectable to a depth of 0.3 to 0.6 m (1 to 2 ft) whereas seasonal changes of temperature, depending upon geological and hydrological conditions, penetrated to depths of 18 m (60 ft). Temperature fluctuations of the ground-water lagged behind the fluctuations of air temperature to a degree dependent upon the depth of the ground-water.

The work of Pluhowski and Kantrowitz (1963) in New York demonstrates the effect of land surface conditions on the temperature of ground-water. They found that the temperature of ground-water at shallow depths in summer under deforested areas was 1.7 to 2.8°C (3 to 5°F) higher than under wooded areas, and that the annual range of temperature at a depth of 3.7 to 4.6 m (12 to 15 ft) was 3.3°C (6°F) greater under the deforested area than under the wooded zone.

Perhaps the study that has the greatest analogy to the work carried out by Mossetti (1961) on the Trieste karst, is that of Schneider (1962a and b). Schneider used precise measurements of ground-water temperatures in wells to study ground-water movement and recharge conditions in shallow glacial aquifers in Minnesota. These measurements were correlated (graphically) with temperatures in a nearby lake from which recharge to the aquifers occurred, particularly after pumping of the wells. The difference in phase between the cyclical ground-water thermographs and the graph of the mean daily air temperature was used to estimate the average time of travel of water from the lake to the wells under the prevailing hydraulic gradient (the mean daily air temperature being approximately the same as the temperature of the lake when the air temperatures are above 0°C or 32°F). The average lag time for water to move from the lake to a well 61 m (200 ft) away was 2 to 4 months and to a well 259 m (850 ft) away 5 to 7 months. The lag in the minimum temperatures he found was greater than the lag of the maximum temperatures owing to the effect of viscosity differences on the rate of flow, and to variations in pumpage.

Birman (1969) working on a geothermal survey of Johnson Valley in southern California found a direct relationship between ground temperature (not ground-water temperature) at a depth of 3 m (10 ft) and the depth to the water-table. Thermal lows were a reflection of a shallowing of the ground-water table in the area. He used this relationship to plot maps showing the indicated surface of the ground-water table for the area. Birman (1969) also reported a time lag of 2.5 months between air temperature and the ground temperature at a depth of 3 m (10 ft).

Research on factors affecting the temperature of water in surface streams is a field of study which has attracted few workers, possibly due to a belief in the self-evidence of these factors. Moore (1964) observed the importance of stream orientation in influencing water temperatures in Oregon. He found that east-west flowing rivers were much warmer in summer than those flowing north-south, although on cloudy days a much closer agreement between the two existed. Both Moore (1964) and

Ineson and Downing (1964) comment on the effect of ground-water discharge on the temperatures of surface waters.

In this review of research carried out on ground-water and surface water temperatures a number of basic factors have emerged as being of importance in influencing both absolute water temperatures and fluctuations in water temperatures. These factors in addition to other factors of general importance may be summarized as follows:

(i) The mean annual air temperature of the area, and the period and amplitude of air temperature fluctuations (Sorby, 1859; Heath, 1963; Heath and Trainer, 1968)

(ii) The temperature of recharge water. Schoeller (1962) considers this factor to be of great importance in limestone areas and demonstrates the cooling effect of a rainstorm on the temperature recorded at two springs. Heath (1963) in considering sands, silts and clays believes its influence to be significant, however, only where the water table is close to the land surface.

(iii) Mode of recharge ie. from rivers (Norris and Spieker,1962a and b; Winslow, 1962), lakes (Schneider, 1962a and b) and rainfall.

(iv) The nature of the ground surface. This includes factors such as vegetation cover (Schoeller, 1962; Pluhowski and Kantrowitz, 1963) and aspect (Schoeller, 1962).

(v) The depth of the ground-water body or major flow zone (Sorby, 1859; Heath, 1963).

(vi) The permeability of the aquifer (Norris and Spieker, 1962a and b; Rhodehamel and Lang, 1962)

(vii) Length of time the water has been in the aquifer (Mossetti, 1961; Schneider, 1962a and b) and rate of circulation in the aquifer (Garza, 1962; Schneider, 1964).

(viii) The viscosity of the water. An inverse relationship exists between viscosity and temperature. An increase of 0.56°C (1°F) in the ground-water temperature lowers the viscosity sufficiently to increase the rate of flow by 1½% (Walton, 1970).

(ix) The thermal conductivity of the zone of aeration or vadose zone. Heath (1963) points out that the thermal conductivity is greater in winter than in summer owing to the higher moisture content.

(x) The geothermal gradient. This is a constant factor over the year (Heath, 1963; Schneider, 1964)

(xi) The contribution of water from deep-seated or thermal sources (Schoeller, 1962)

(xii) The influence of man through the use of ground-water for air conditioning, sewage disposal, water-supply, vegetation clearance (Brashears, 1941; Schneider, 1962a and b, 1964) Apart from man's effect on ground-water temperatures through the removal of vegetation, the other aspects of man's influence are considered to be negligible within the field area. Water supply is from surface streams and springs and is therefore unlikely to effect changes in ground-water temperatures.

B Some Introductory Comments on the Pattern of Water Temperature Variation Observed on Springs and Streams in N.W. Yorkshire

All springs and streams around the High Mark and Fountains Fell areas, on which temperature observations were recorded, show a pattern of water temperature variation characterized by short term temperature pulses superimposed upon a broad seasonal variation. On some springs this broad seasonal variation may be scarcely recognizable, or it may be difficult to differentiate between any long term seasonal change and the effect of short term pulses. At Robin Hood's Well (Site 3) an annual temperature range of only 0.42°C was observed (Fig.3c). Although the lowest recorded temperature (7.91°C) occurred in late March (26.3.68) and the temperature maxim~~a~~um (8.33°C) occurred in June and August (19.6.68 and 16.8.68), it is difficult to determine whether these extremes are part of a gradual seasonal change in water temperature or simply the result of short term temperature fluctuations resulting from rainfall pulses.

By contrast surface streams generally show a very pronounced seasonal temperature variation. On the River Wharfe at Conistone Bridge (Site 18), for example, a temperature range of 11.96°C was observed over the sampling period (Fig.26b). Short term temperature pulses at this site are also readily identifiable, and are much more apparent than at most springs and resurgences. The degree of development of these short term temperature pulses varies not only spatially (ie. from site to site) but also over time, seasonal variations in the development of these pulses often being apparent.

The statistical analysis of the observations is primarily aimed at identifying those factors of principal importance in determining the recorded temperature variation. Research in the field of ground-water temperatures has usually involved a purely graphical analysis to express the relationship between ground-water temperatures and some of the factors outlined above. Both Mossetti (1961) and Schneider (1962a and b) for example, make a simple visual comparison of the thermographs of wells and resurgences with those of air-temperature. A review of the methods of statistical analysis used for this research has been given in Chapter 2.

C Temperature Variations on Surface Streams

The temperature variations of all surface streams on which recordings were made show this pattern of short term pulses superimposed upon broad seasonal temperature waves (Figs.24a-35). All surface streams in the field area on which temperature recordings were carried out contain a varying proportion of water derived from springs and resurgences. In the case of the River Wharfe at Conistone Bridge (Site 18, Fig.26b) a large component of the river discharge must usually be derived from ground-water discharge at the hundreds of springs and resurgences in upper Wharfedale and Littondale. In contrast to this is site 10 located on a small spring-fed stream known as Outgang stream. The discharge at this site is derived for the most part from two permanent springs only (sites 8 and 9).

At some sites the temperature of surface waters are greatly influenced by this ground-water contribution. Ineson and Downing (1964) point out the effect of ground-water contributions from the chalk in raising river temperatures on the River Stour in Kent in winter, and lowering the river temperatures in summer. On sites such as the River Wharfe at Conistone (Site 18) and Cowside Beck at Arncliffe (Site 45), the effect of the temperature of the ground-water contribution appears to be minimal, the river water temperature being principally related to air temperature variations about the time of recording.

On a number of sites, however, the effect of the ground-water component on stream and river temperatures is marked. Stream sites located at short distances downstream of points of ground-water discharge generally show a lower annual temperature range than those recorded on, for example, the River Wharfe (11.96°C) and Cowside Beck (13.26°C). Sites 8 and 9 which are the major permanent spring sources of Outgang stream had a temperature range of 0.68°C and 0.89°C respectively over the period February 1968 to February 1969. At stream site 10, 137 m (450 ft) from the source springs the recorded temperature range was 6.03°C over the same period. At site 13, 128 m (420 ft) further downstream (265 m - 870 ft from the springs) this range had risen to 8.01°C; a small spring

(Site 11) with a temperature range of 5.16°C entering the stream on the right bank is unlikely to have exerted much influence on account of its permanently low discharge.

The seasonal effect of the ground-water temperatures on the stream water may be illustrated by examining the water temperature changes downstream on particular days. On 16.8.68 the temperature of source spring 9 was 8.20°C (8.22°C at site 8). At site 10 the recorded temperature on the same date was 12.75°C and at site 13 was 13.73°C, an increase of 5.51° - 5.53°C. On 3.1.69 the spring water temperatures were 7.88°C and 7.90°C. By site 10 this had fallen to 6.72°C and by site 13 to 5.72°, a total drop of only 2.18° - 2.16°C. The effect of ground-water discharge on the temperature of stream water at these sites would therefore appear to be more marked in winter.

The statistical analysis of temperature variations observed at surface water sites provides additional information not only concerning the role of ground-water discharge temperature on surface streams but also the role of air temperature and precipitation. Observations made in summer on the River Skirfare at Arncliffe upstream of the junction with Cowside Beck (site 44) suggested that at this period of the year the thermal effect of the large permanent risings located about 1 km (two-thirds of a mile) upvalley of this site was strong. The correlation of summer temperature observations at this site with antecedent temperature suggested a time lag between air temperature and water temperature in the order of 8-14 days (_r_ = +.85 with the air temperature of the 8-14 day period antecedent). This lag time may almost certainly be related to the effect of ground-water discharge on the river temperatures at this site. This effect is particularly important in summer, as during that period the River Skirfare is usually dry upstream of the large risings, and flow at site 44 during the summer period is almost completely derived from the ground-water discharge at these springs.

At all other stream and river sites on which observations of water temperature were made, water temperatures may be related principally to the air temperatures at or near the time of recording. At site 65 for example, observations made over the year correlate most closely with the mean air temperatures of the day previous to sampling ($\underline{r}$ = +.87). The observed water temperatures in both winter and summer and the dry and wet conditions periods also relate most closely to the mean air temperature of a few days prior to sampling.

The seasonal relationship of observed temperature on surface streams to effective precipitation, however, suggests that a simple relationship between air temperature and water temperature may not always exist. On the River Wharfe at Conistone Bridge temperatures in the winter correlate most closely with the precipitation two days prior to sampling ($\underline{r}$ = +.77). Summer water temperatures, however, correlate most closely to the precipitation occurring 22-28 days prior to recording ($\underline{r}$= -.66). The correlation of water temperatures and antecedent temperature on the River Wharfe during the summer months, however, suggests that the water temperatures of this period are related to the air temperatures near the time of recording ($\underline{r}$ = +.95 with the air temperature of day 4 antecedent).

This apparent conflict may also be related in some way to seasonal variations in mode of recharge to the river. During the winter months a high component of the river recharge will be from surface runoff in contrast to the dry summer months when the ground-water component of the river discharge will be relatively high. Temperature effects therefore introduced through the medium of effective precipitation will consequently show a greater lag in summer than in winter. The apparently contradictory correlation of water temperature with the air temperatures four days prior to recording is evidently related to more direct heating of the river water by solar radiation.

The relationship between water temperature deviations from the mean water temperature and effective precipitation shows that this direct heating is of greatest importance at periods of low discharge. A negative correlation between these two variables at, for example, the River Wharfe at Conistone (site 18) and the River Skirfare at Arncliffe Bridge (site 43) showed that there is some tendency on surface streams for the greatest deviations of water temperature from the mean water temperature to be associated with low amounts of rainfall. At periods of low precipitation and presumably low discharge the direct influence of solar radiation is an important factor in effecting temperature variations.

Before concluding this brief discussion of water temperature variations observed on surface streams one further aspect in the relationship of water temperature and rainfall should be stated. On surface streams, rainfall tends to have a negative effect on water temperatures in the summer months and a positive effect in the winter. Temperature observations made over the summer months at site 12, for example, show a strong negative correlation with the effective precipitation 22-28 days previously ($\underline{r}$ = -.77), whereas those made in the winter period show a strong positive correlation with the effective precipitation of the 0-7 day period prior to recording ($\underline{r}$ = +.79). This seasonal effect of precipitation is also marked on many of the underground drainage systems and is discussed further below.

D Temperature Variations on the High Mark Springs

1 The Relationship between Water Temperature Variations and Antecedent Air Temperatures: Initial Comments on the High Mark Springs

Water temperature observations recorded on springs emerging from the High Mark upland generally show a high level of correlation with the air temperatures of some time previous to recording, in a manner analogous to that observed between dissolved calcium carbonate and antecedent air temperatures. At 97% of the High Mark springs (38 out of 39) the water temperature observations show a correlation significant at the 0.01 level of probability with the mean air temperatures of some period antecedent to recording. At 35 out of 39 sites (90%) these two variables correlate at a level of probability greater than 0.001.

In the High Mark area the lag of spring water temperatures behind air temperatures varies between 1 and 15 weeks, although 46% of the springs (18 out of 39) exhibit lag times of less than 14 days (Fig.48). At Cotegill, site 34, for example, the recorded water temperatures show the highest correlation with the mean air temperatures of the 0-7 day period prior to recording ($\underline{r} = +.96$). By contrast water temperature variations recorded at Cowside site 53, show the greatest correlation with the mean air temperatures of the 78-84 day period prior to sampling ($\underline{r} = +.88$). Regional variations in these lag times are shown in Map 26 and are discussed in Chapter 7.

2 The Relationship between Water Temperature Variations and Effective Precipitation: Initial Comments on the High Mark Springs

The correlation of water temperature variations with antecedent air temperatures is closely related to the observed seasonal wave in the recorded water temperatures (Figs.3a-40b). In addition to this correlation recorded water temperature variations on a number of springs show a correlation with the effective precipitation occurring some time previous to recording. The correlation of the water temperature recordings carried out over the complete year (February 1968 to February 1969) with effective precipitation was generally low. Only on 3 sites (13%) was the level of correlation between these two variables significant at the 0.01 level of probability, although the seasonal analysis (see below) demonstrates that the effective precipitation factor is of major importance in influencing water temperature fluctuations. 36% of the springs, however, showed a high correlation (significant at 0.01 level) between water temperature deviations from the mean water temperature (over the complete year) with antecedent effective precipitation.

The relationship between water temperature variations and antecedent effective precipitation is extremely complex and will be examined in detail at a number of sites.

In general, however, it appears that the development of short term water temperature pulses is related to the action of dilution water or rapidly circulating recharge water (see Chapter 2) derived from rainfall in the period immediately prior to sampling.

An examination of a number of High Mark springs will help to clarify and enlarge upon these initial comments.

3 Robin Hood's Well (Site 3)

a The Relationship between Water Temperature and Effective Precipitation

Robin Hood's Well is a large permanent rising in Wharfedale (see Chapter 3) which shows a scarcely distinguishable seasonal variation in temperature and a low magnitude of short term temperature pulse development. A visual analysis of these pulses, and short term pulses recorded at other sites, strongly suggests that they result from the action of rapidly circulating recharge water or dilution water (see Chapter 2), derived from rainfall in the period immediately prior to the temperature recordings. A visual comparison of the graphs of temperature variations (Fig.3c) and that of rainfall (Fig.1) suggests that the temperature low recorded on 26.3.68 at Robin Hood's Well and at other sites is, for example,a short term pulse resulting from the 132mm (5.2 in) of rainfall occurring in the 7 days prior to the recording.

The relationship between temperature variation and effective precipitation is further clarified when one examines the statistical correlation between these two variables. The correlation of water temperature deviations from the mean water temperature with antecedent effective precipitation at Robin Hood's Well revealed a positive relationship with the effective precipitation of the 3-5 day period prior to recording (r = +.55). The greater the effective precipitation in this period the greater the temperature recorded at the rising deviated from the mean. The factor of antecedent effective precipitation at Robin Hood's Well, however, assumes a greater importance when the correlation between simple temperature variations (unrelated to a mean) and antecedent effective precipitation is considered. Again the effective precipitation of the 3-5 day period appears to be of dominant importance, but of greater significance is the fact that now over 59% of the variance of water temperature is explained by the correlation (r = -.77). The negative correlation indicates that for the most part this rapidly circulating component has a lowering effect on the temperature of the ground-water which the lack of a seasonal variation (Fig.3c) suggests remains nearly constant throughout the year. This high negative correlation also explains why the correlation of temperature deviations from the mean with antecedent effective precipitation is lower and explains less of the temperature variance. If rapidly circulating recharge pulses generally have a lowering influence on the temperature of the ground-water a mean water temperature will be recorded which is lower than the true mean temperature of the ground-water body. Deviations from this mean temperature will not therefore be representative of deviations from the true mean temperature of the ground-water.

However, if the temperature of the rapidly circulating recharge component is generally lower than the temperature of the ground-water body as the correlations indicate, how does one explain the higher ground-water temperature? It is suggested that in the case of Robin Hood's Well heat from the interior of the earth may be the significant factor. With an annual recorded temperature range of only 0.42°C it only requires the ground-water temperature to be raised at the maximum by this amount for all recharge to be of a lower temperature than the ground-water. The Meteorological Office (1960) quote a figure of 0.56°C (1°F) increase in temperature per 15 m (50 ft) of depth, although it is stated that at shallower depths this general increase is overlaid by changes originating from the surface. Van Orstrand (1951) quotes figures for England showing an increase in temperature of 1°C for every 30-40 m in depth. These figures are derived from temperature measurements taken at depths of over 300 m and are therefore unlikely to reflect surface conditions.

An examination of the graph of temperature variations observed at Robin Hood's rising reveals one further feature which requires explanation. Short term temperature pulses, although of low magnitude, show a marked seasonal contrast in their degree of development (Fig.3c) In the spring and early summer of 1968 these pulses were especially noticeable, but were scarcely detectable in the late summer, autumn and early winter of that year. It would appear that in spring and early summer the temperature of the rapidly circulating recharge water provides the greatest contrast with the bedrock and the temperature of the principal ground-water body; hence in this period the temperature pulses are most strongly developed. In the later part of the year, however, there appears to be less contrast between the temperature of the rapidly circulating recharge water and that of the major ground-water body. Heating up of the bedrock through the penetration of high summer temperatures, in addition to a greater heat exchange between bedrock and percolating recharge water (partially due to a slower rate of flow in summer, see below) are factors which are probably of importance. Consequently the high amounts of rapidly circulating recharge water reaching the ground-water body in late summer and winter (almost 432 mm - 17in of effective precipitation occurring between 30.8.68 and 31.10.68) provide less contrast to the ground-water body in terms of temperature than the spring and early summer recharge.

One factor may be of importance in further explaining this seasonal contrast in the degree of short term temperature pulse development. This is the relative volume of the rapidly circulating recharge component to that of the ground-water storage within the karst drainage system. If the ground-water storage is large temperature pulses derived from rapidly circulating recharge water will have little effect on the temperature of the ground-water and the water emerging at the spring. If, however, the ground-water storage is low or nil short term pulses will be an extremely important characteristic of the pattern of recorded temperature variation. The seasonal variation in temperature pulse development recorded at Robin Hood's Well may therefore be an indication of slight seasonal variations in the amount of ground-water storage in the system.

b Water Temperature and Antecedent Effective Precipitation: Seasonal Aspects

The correlation of the water temperature observations at Robin Hood's Well (over the complete year) with antecedent effective precipitation shows that for the most part observed water temperature variations are most clearly related to the effective precipitation of the 3-5 day period antecedent to recording. The separation of the water temperature observations into those occurring in the wet conditions period and those occurring in the dry conditions period, and the correlation of these classified observations with antecedent effective precipitation affords further information.

Over the dry conditions period the observed water temperature fluctuations at Robin Hood's Well are most closely correlated with the total effective precipitation of the 22-28 day period prior to recording (r = -.71). By contrast the effective precipitation of the 0-7 day period antecedent, appears to be the most significant during the wet conditions period (r = -.77).

A similar situation exists when the summer and winter observations are treated separately. Over the summer period 53% of the water temperature variance is explained by the correlation with the effective precipitation of the 8-14 day period (r = .73), and almost 76% by the correlation with the effective precipitation of day 4 antecedent in the winter period (r = -.87)

These time lags (varying from 3 days to 3 weeks) are indicative of the time required for rapidly circulating recharge water to reach the major ground-water body and to influence the water temperature variations recorded at the rising. Over the winter and wet conditions periods higher recharge brings about a greater rate of flow (than occurs in the summer and dry conditions periods) through the limestone, either through a steepening of the hydraulic gradient or simply through the 'push-through' effect of continuous heavy rainfall. These seasonal contrasts in time lags between effective precipitation and water temperature will be discussed further below.

c Water Temperature and Antecedent Air Temperatures

The relationship between spring water temperature and antecedent temperature at Robin Hood's Well is, however, more difficult to see. The correlation of water temperatures over the complete year (1968-69), with antecedent air temperature produced a coefficient of r = +.32 for the 43-39 day period prior to recording, and r = +.32 for 78-84 day period. The correlation of water temperatures with antecedent soil temperatures, however, suggests that day 4 prior to recording may be more important (r = +.35). The correlation of water temperatures recorded over Year II

(May 1969 to May 1970) with antecedent air temperatures, helps to clarify the situation. Water temperatures correlated with antecedent air temperature resulted in a coefficient of $\underline{r} = +.64$ for the 8-14 day period prior to recording. This time period would appear to be of the same order as that taken for rapidly circulating recharge water to enter and pass through the system.

d Chapel House Well: Site 5

Around the High Mark area only one other spring is similar to Robin Hood's Well with regard to the relationship between water temperature and antecedent effective precipitation, and water temperature and antecedent temperatures. This is site 5 known as Chapel House Well and in terms of geographical location is the closest large permanent spring to Robin Hood's Well. The correlation of the temperature variations recorded at Chapel House Well (recordings made between February 1968 and February 1969) with antecedent effective precipitation gave a correlation or $\underline{r} = -.49$ for the total precipitation of the 3-5 day period prior to sampling. As at Robin Hood's Well the correlation of temperature deviations from the mean with antecedent effective precipitation was lower ($\underline{r} = +.23$ for the 4-6 day period), again suggesting that rainfall usually has a lowering effect on the temperature of the groundwater.

This negative influence of rainfall is further illustrated by the seasonal correlations. Over the summer period the correlation between water temperatures and antecedent effective precipitation is highly negative ($\underline{r} = -.87$ for day 3) but unlike the majority of sites (see below) is also negative in the winter ($\underline{r} = -.64$ for day 7) although now only 41% of the water temperature variance is explained by antecedent effective precipitation in contrast to 75% in the summer period. As at Robin Hood's Well the effect of terrestrial heat is indicated.

The relationship between water temperature and antecedent temperature at Chapel House Well is also very similar to that observed at Robin Hood's Well. Over the period February 1968 to February 1969 the recorded fluctuations showed the closest relationship with the air temperature of day 5 prior to recording ($\underline{r}$ = +.74). A similar time lag was found using the observations recorded over the period May 1969 to May 1970 (see Chapter 6).

At both Robin Hood's Well and at Chapel House Well a near-coincidence of the time lags between water temperature and effective precipitation, and between water temperature and antecedent air temperatures exists. This suggests strongly that air and soil temperature variations are being transmitted into the drainage system largely through the medium of rapidly circulating recharge water rather than through any direct heating or cooling of ground-water by seasonal changes in the temperature of the bedrock.

e <u>Reynard's Close Spring: Site 19</u>

Reynard's Close Spring (site 19) is a very large permanent rising located south-west of Kilnsey village in Wharfedale. At this site (Fig.5a) a broad seasonal change in water temperature is more apparent than at either Robin Hood's Well or Chapel House Well where no definite seasonal change in water temperature could be identified, (Figs.3c and 3e). At Reynard's Close Spring short term temperature pulses are also more striking. As at Robin Hood's Well and Chapel House Well the lowest recorded temperature over the period February 1968 to February 1969 occurred on 26.3.69 following the same period of very heavy precipitation. At Reynard's Close Spring the water temperature on this date fell to 7.22°C. The maximum recorded temperature (8.18°C) occurred on

2.10.68, 15 weeks and 6 weeks after the two maxima recorded at Robin Hood's Well (Fig.3c) and 24 weeks after the maximum recorded temperature at Chapel House Well (Fig.3e).

The statistical analysis of these temperature observations reveals a number of similarities and contrasts between the Robin Hood's Well and Chapel House Well systems and the Reynard's Close system. The correlation of the temperature variations (over the complete year, February 1968 - February 1969) with antecedent effective precipitation is of a very low order ($\underline{r}$ = +.25 for days 1-3; $\underline{r}$ = +.38 for day 2 prior to recording). However, the correlation of temperature deviations from the mean with antecedent effective precipitation shows a much better relationship, ($\underline{r}$ = +.78 for the 0-7 day period prior to recording). This is in complete contrast to the situation at Robin Hood's Well and at Chapel House Well. At Reynard's Close it appears from this analysis that rainfall pulses may have either a positive or negative effect on the ground-water, in contrast to the Robin Hood's Well and Chapel House Well systems where it was shown that these pulses had a predominantly negative effect. At Reynard's Close Spring the greater the total effective precipitation in the 0-7 day period prior to recording, the greater the observed water temperature at the rising deviates from the mean water temperature. The correlation of temperature deviations with the total effective precipitation of overlapping 3 day periods suggests that the precipitation of the 3-5 day period prior to recording may be of particular importance ($\underline{r}$ = +.76).

Seasonal variations in the effect of precipitation pulses (rapidly circulating recharge water) on the temperature of the ground-water may, however, be identified. The correlation of the summer water temperature observations with antecedent effective precipitation discloses a negative relationship between these two variables during this period ($\underline{r}$ = -.66 for the 22-28 day period prior to recording). Over the winter period, however, rapidly circulating recharge water appears to have a predominantly positive effect on the ground-water (r = +.62 for day 1 prior to recording). In contrast to Robin Hood's Well and Chapel House Well where rapidly circulating recharge water tends to have a lowering effect on the temperature of the ground-water in both summer and winter (although less significantly so in the winter at Chapel House Well) at Reynard's Close this component of recharge appears to bring about a drop in the spring water temperature in the summer but during the winter period water temperatures tend to rise following precipitation. In simple terms there is a tendency at Reynard's Close rising (and at most High Mark risings - see below) for rainfall to increase the temperature of ground-water in winter and to lower it in summer. Reynard's Close system would consequently appear to be a shallower system than either Chapel House Well or Robin Hood's Well systems, as the influence of internal heat remains undetected.

As at Robin Hood's Well and Chapel House Well there appears to be a seasonal variation in the lag time between the actual occurrence of rainfall and the recording of a related water temperature change. Over the winter period rainfall appears to bring about a change in temperature at the rising within 24 hours (r = +.62 for day 1 prior to recording) whereas in the summer period there appears to be a time lag in the order of 22-28 days (r = -.66).

Water temperature variations recorded at Reynard's Close Spring over the period February 1968 to February 1969 are also highly correlated with the mean air temperatures of the 71-77 day period antecedent to recording (r = +.81). The relationship between these two factors, antecedent effective precipitation and antecedent air temperature, is discussed later.

f Seasonal Analysis of the Relationship between Effective Precipitation and Water Temperature Variations

The seasonal correlation analysis of the water temperature observations with antecedent effective precipitation provides a great deal of information about the importance of the effective precipitation factor in influencing recorded water temperature variations.

(i) On 87% of the High Mark springs (20 out of 23) on which seasonal analysis was carried out, antecedent effective precipitation has a strong negative influence in summer and a strong positive effect in winter on the temperature of water discharging at the springs. This has already been observed at Reynard's Close rising (site 19) above. A few additional examples may be given. Outgang Hill, site 9, provides a correlation of *r* = -.66 for the summer period between spring water temperature and antecedent effective precipitation (of the 22-28 day period antecedent) and a correlation of *r* = +.67 with the effective precipitation of day 2 antecedent in the winter. Similarly at Arncliffe, site 52, summer water temperatures are most closely correlated with the total effective precipitation of the 22-28 day period antecedent (*r* = -.72), but in winter the precipitation of day 2 prior to recording appears to be the most significant (*r* = +.63).

(ii) On the remaining three springs on which seasonal analysis was carried out effective precipitation has a negative effect on the spring water temperatures in both the summer and winter seasons. These sites are Robin Hood's Well (site 3), Chapel House Well (site 5), both of which are discussed above, and Kilnsey, site 26.

(iii) There is a tendency for a longer time lag to exist in the summer (than in the winter) between the occurrence of effective precipitation and subsequent changes of water temperature at the spring. 70% of the High Mark springs show this longer summer time lag.

Three sites already discussed, Outgang Hill, site 9, Reynard's Close, site 19, and Arncliffe, site 52 provide examples of this seasonal phenomenon. The greater volume and frequency of recharge occurring in the winter period and hence the greater degree of circulation of water through the system provides the likely explanation.

(iv) Although most sites (70%) show a longer lag between effective precipitation and water temperature variation in the summer than in the winter this situation is undoubtedly reversed on a few sites. This feature has been observed at Chapel House (see above) and it also occurs at site 56, a small spring lying to the east of Malham Tarn on the south-western margins of High Mark. At site 56 temperature variations occurring in the summer period appear to be related most closely to the effective precipitation of the 8-14 day period prior to recording ($\underline{r}$ = -.68), but those occurring in the winter to the effective precipitation of the 15-21 and/or the 29-35 day period prior to recording ($\underline{r}$ = +.53). Similarly, at site 41. Water temperature variations recorded over the summer period correlate most closely with the effective precipitation of day 3 prior to recording ($\underline{r}$ = -.71), but over the winter this time lag increases to 15-21 days ($\underline{r}$ = +.60). At all these sites (sites 9, 52, 56 and 41) the negative effect of precipitation in the summer and its positive effect in winter is apparent from the correlations.

In the discussion of the Robin Hood's Well system it was suggested that higher recharge in the winter period with a resultant steepening of the hydraulic gradient, or simply a faster rate of push-through, would account for a shorter time lag in winter. It is now apparent, however, that some additional factor must be involved. This may be the factor of viscosity. In winter lower temperatures cause an increase in the viscosity of water with a consequent fall in the rate of flow (see above). It would appear, therefore, that on springs revealing a greater time lag in the winter than in the summer the increase in the rate of flow arising out of increased recharge in the winter period is insufficient to overcome the decrease in velocity resulting from increased viscosity at lower temperatures.

In addition to this explanation the influence of frozen ground could have a profound influence on the amount and rate of percolation recharge to some systems in the winter months (Schneider, 1961). In 1968 ground frost was recorded on 118 days at Malham Tarn meteorological station, and on 125 days in 1969. The expected incidence of ground frost at Malham Tarn was calculated by Manley (1957) as 143 days (see Chapter 1).

(v) The level of correlation between water temperature variation and antecedent effective precipitation is much lower in the wet conditions period than in the dry conditions period. 96% of the High Mark springs showed a higher level of correlation between these two variables in the dry conditions period than in the wet conditions period. A similar phenomenon was observed in the seasonal analysis of dissolved calcium carbonate variations (Chapter 4).

On Robin Hood's Well and Chapel House Well the recorded temperature variations appear to be introduced principally through the medium of rapidly circulating recharge water. On most other sites, however, the lag time between effective precipitation and temperature variation is considerably shorter than the lag time prevailing between water temperature variation and the period of time having the most closely correlated air and soil temperature variations. It is believed that this contrast may be related to the development of a definite seasonal trend in the temperature of the ground-water. At Robin Hood's Well and Chapel House Well little definite seasonal trend may be observed and hence almost all water temperature variations may be attributed to the influence of rapidly circulating recharge water. Heath (1963) has pointed out that the temperature of recharge water has a significant effect on the ground-water temperature only where the 'watertable' is relatively close to the land surface or where the zone of aeration is composed of highly permeable material. The lack of seasonal variation at Robin Hood's Well and Chapel House Well may be attributed to the fact that the ground-water systems of both these springs may be too deep-seated to be affected by seasonal temperature changes at the ground surface except through the medium of rapidly circulating recharge water near the point of discharge. The flow zones of all other sites, however, appear to be within the range of influence of seasonal ground surface temperature changes, and hence a broad seasonal change in water temperature may be observed in addition to the short term pulses resulting from rapidly circulating recharge water. The correlation of water temperature with antecedent temperature is strongly related to this seasonal trend, whereas the correlation of water temperature with effective precipitation is strongly related to the input of short term water temperature variations through the medium of rapidly circulating recharge water. Seasonal trends in bedrock and ground-water temperature have been shown to lag behind air and soil temperature changes (Heath,1963; Birman,1969), and the time lag calculated between spring water temperature and antecedent air and soil temperatures must be related to that time lag. On very shallow systems this time lag may therefore be very short as at site 30 (see below), but on deeper systems this lag may extend to several months (Reynard's Close - site 19, Outgang spring - site 9, and site 53; see below). On very deep systems the major ground-water body or flow zone may be beyond the detectable influence of seasonal temperature changes originating on the ground surface (see Robin Hood's Well and Chapel House Well).

In limestone areas the importance of moving recharge water in transmitting these surface temperature conditions to depth is probably of greater significance than the direct transmission of heat through the bedrock. When the rate of recharge circulation is reduced, for example through the increasing depth of the major flow zone, heat exchange between bedrock and percolating recharge is greater with a consequent decrease in and eventual elimination of seasonal bedrock and water temperature changes. All discharging systems, however, must by definition have some section of their major flow zone close to the ground surface (near the point of discharge); it is in these sections that the groundwater or water in the major flow zone is most subject to short term temperature pulses originating from rapidly circulating recharge water. Deeper parts of the system are subject only to the broad seasonal temperature variations resulting from bedrock and slowly circulating recharge temperature changes. Very deep sections of the systems will be uninfluenced by such seasonal variation.

Some systems, however, on account of having very shallow flow zones may be recharged almost completely by rapidly circulating recharge water. On these very shallow systems it is largely spurious to differentiate between the two lag times (water temperatures - antecedent air temperatures, water temperatures - antecedent effective precipitation), both short term temperature pulses and the broad seasonal temperature change being transmitted directly into the system by the action of rapidly circulating recharge. The relationship of the lag of water temperatures behind air temperatures with the rate of flow of water through the limestone is discussed further at the end of this chapter.

The results from a few springs may serve to illustrate and clarify the above considerations.

g Cowside Beck: Site 53

Cowside site 53 is a large permanent spring on the western margin of the High Mark area. The correlation of recorded water temperature variations over the year (February 1968 to February 1969) with antecedent air and soil temperatures reveals the existence of a 10-12 week time lag between these two variables (r = +.88 for the correlation with the mean air temperature of days 78-84 prior to recording). Deviations of water temperatures from the mean water temperature correlated with antecedent effective precipitation, however, indicate a time lag of only 3-5 days (r = +.58 for the 3-5 day period prior to recording). The former time lag, it is suggested, is related to the time of penetration of the seasonal temperature wave to the major flow zone, the latter time lag being related to temperature variation input through the medium of rapidly circulating recharge probably near the system exit.

A similar explanation may be provided for Reynard's Close spring (see above).

At Robin Hood's Well and Chapel House Well these two lag times coincide, and it was concluded that almost all recorded water temperature variations could be related to the input of surface temperature conditions through the medium of rapidly circulating recharge, the major groundwater body or flow zone being beyond the reach of seasonal temperature changes.

h Cotegill: Site 30

At site 30, however, these two lag times also coincide but the pattern of temperature variation recorded at that site (see Fig.7b) is in strong contrast to that recorded at either Robin Hood's Well or Chapel House Well. At site 30 an annual temperature range of 8.46°C was observed over the recording period (February 1968 to February 1969) with the highest recorded temperature (11.86°C) occurring on 4.9.68, and the lowest (3.40°C) on 26.2.69. The correlation of observed water temperature variations with antecedent effective precipitation revealed a time lag in the order of 16-28 days depending upon the season of the year, and the correlation of water temperature variations with antecedent air temperatures indicated a time lag of the same order. These factors suggest that, in addition to the well developed short term temperature pulses, the very pronounced seasonal variation in water temperature recorded at this site must also be closely related to the action of rapidly circulating recharge water. The conclusion is that the flow zone of this system must lie at a very shallow depth.

i Seasonal Analysis of the Relationship between Antecedent Air Temperatures and Water Temperature Variations

(i) At all seasons of the year (summer, winter, dry conditions and wet conditions periods) water temperatures recorded on High Mark springs are highly correlated with antecedent air temperatures. The highest correlation between water temperatures and antecedent temperature is significant at the 0.01 level of probability on 95% of the springs in summer, 91% in winter, 100% in the dry conditions period and 82% in the wet conditions period (Fig.48).

(ii) There is a tendency for the lag of water temperatures behind air temperatures to be greater in the winter and wet conditions periods than in the summer and dry conditions periods. 77% of the High Mark springs show an increase in lag time from summer to winter, and 64% an increase from the dry conditions period to the wet conditions period.

At Cowside, site 53, for example, water temperature observations carried out over the summer period correlated most closely with the air temperatures of the 36-42 day period prior to recording (r = +.92). Those observations made in the winter period, however, correlate most highly with the air temperatures 120 - 126 days previous (r = +.93).

This seasonal variation in the lag time between air temperatures and spring water temperatures is reflected to a lesser degree in the correlations based on the wet conditions recordings and the dry conditions recordings. Over the dry conditions period the lag time is in the order of 50 - 5 6 days (r = +.83 for the correlation with the mean air temperatures of the 50 - 56 day period antecedent), but in the wet conditions period this had increased to 10 - 11 weeks (r = +.95 for the correlation with the mean air temperatures of the 71 - 77 day period antecedent). The wet and dry conditions correlations would appear to be a less extreme reflection of the winter-summer division of observations.

The pattern of time lag variation at Cowside, site 53, is characteristic of the majority of High Mark springs. At only 2 sites (9%) on which seasonal analysis was carried out was the winter time lag actually shorter than the summer time lag, and although the wet conditions and dry conditions time lags were not always a reflection of the winter - summer division, they were always less extreme.

This situation would appear to be in some contrast to the time lag variation revealed by the seasonal correlation with effective precipitation. It would appear then that the effect of low winter temperatures on the viscosity of recharge waters is of much greater significance on the movement of more slowly circulating recharge water than on the movement of the dilution (rapidly circulating) component. Consequently, the rate of heating or cooling of the bedrock occurs at a slower rate in winter than in summer. A similar effect was observed by Schneider (1962a). He observed that the lag of the minimum ground-water temperatures recorded in wells behind the temperature of recharge water from rivers, was greater than the lag of the maximum. He attributed this difference to both variations in pumpage and to the effect of viscosity on the rate of flow.

In addition the occurrence of ground frost (see above) may have a greater effect on the more slowly circulating component of recharge. This component probably occurs at points furthest away from the system exit, in more upland areas where the effect of ground frost may be more severe.

E Temperature Variations on the Fountains Fell Springs and Risings

Unlike the High Mark area where springs are known to be fed purely by rainfall percolation, risings located around the Fountains Fell upland may be supplied either by rainfall percolation or by swallet streams, or by a combination of these types of recharge. Seasonal variations in the relative contributions made by percolation and swallet waters may also be important on risings fed by both types of recharge. In spite of this apparently basic difference between the mode of recharge of the High Mark springs and at least some of the Fountains Fell systems, risings located around the flanks of Fountains Fell show a pattern of seasonal and short term temperature variation similar to that recorded on the springs of the High Mark area. However, on a number of springs the influence of swallet recharge on the temperature of the spring waters may be detected.

1 The Relationship between Water Temperature Variations and Antecedent Air Temperatures: Initial Comments on the Fountains Fell Risings

All Fountains Fell risings on which correlation analysis of the water temperature data was carried out showed a high positive correlation ($P > 0.001$) with the mean air temperatures of some time antecedent to recording. In this area the lag times varied between 2 days (Limekiln Hill, site 94) and 78-84 days (High Lathe, site 88), with 50% of the risings showing time lags of less than 28 days (see Fig.48). Regional variations in this time lag are mapped in Map 27 and are discussed in Chapter 7.

2 The Relationship between Water Temperature Variations and Effective Precipitation: Initial Comments on the Fountains Fell Risings

Although the water temperature observations carried out on the Fountains Fell risings show only a low level of positive correlation with antecedent precipitation (no sites show a correlation significant at the 0.01 level) the seasonal analysis indicates a strong relationship between these two variables (see below). The correlation of water temperature deviations from the mean water temperature with antecedent effective precipitation, however, shows a high positive correlation (correlation significant at 0.01 level) between these two variables on 56% of the Fountains Fell risings on which this analysis was carried out.

An examination of the water temperatures recorded at Cowside, site 99, and their relationship to these antecedent hydro-meteorological variables will serve to illustrate and develop these points.

3 Cowside Beck: Site 99

Site 99 is a large permanent rising emerging from the eastern margin of Fountains Fell near the head of Cowside Beck (see Chapter 3). Minimum and maximum temperatures recorded at this site in addition to the range of temperatures recorded (Fig.22c) are comparable to many High Mark springs. Like the High Mark springs the pattern of observed temperature variation is also characterized by short term temperature pulses superimposed upon a broad seasonal temperature change.

The correlation of observed temperature variations (for the complete year February 1968 - February 1969) at site 99 with antecedent effective precipitation revealed a low level of correlation with the effective precipitation of the 1-3 day period prior to recording (r = +.38 for the correlation with the effective precipitation of the 1-3 day period; r = +.40 for day 2 antecedent).

The correlation of seasonal temperature recordings with antecedent effective precipitation, and the correlation of water temperature deviations from the mean with antecedent effective precipitation did, however, show a much closer relationship between water temperature variation and effective precipitation than is suggested by the above coefficients. Temperatures recorded over the summer period show the closest relationship to the effective precipitation of the 22-28 day period prior to recording (r = -.85) and those in the winter period with the previous day (r = +.65) Temperature deviations from the mean temperature (over the complete year) show the closest relationship to the effective precipitation of the 3-5 day period prior to recording (r = +.63). Similar conclusions to those made for the High Mark springs may be deduced from the statistical analysis of this rising. Effective precipitation over the summer months tends to have a lowering effect on the temperature of the ground-water and the spring water, and tends to take a longer time to affect the observed water temperatures at the springs. In winter effective precipitation tends to raise the temperature of the ground-water, and the effect is more immediate than that occurring in the summer. The results of the analysis of observations made over the dry and wet conditions periods seems to reflect the summer-winter division of water temperature observations. As discussed earlier in connection with the High Mark springs the effect of seasonal temperature variations on the viscosity of the rapidly circulating component of recharge does not appear to overcome the effect of seasonal variations in the volume of recharge on the rate of flow of the rapidly circulating recharge component through the limestone.

As at many of the High Mark springs the recorded water temperature variations at site 99 may be related not only to precipitation in the first few weeks prior to recording but also to the air temperature variations several weeks prior to recording. Water temperatures recorded over the complete year (February 1968 to February 1969) appear to relate most closely to the air temperatures 50-56 days prior to recording ($\underline{r}$ = +.87). Over the winter period water temperatures recorded at the rising correlate most highly with the air temperatures 50-56 days antecedent to recording ($\underline{r}$ = +.91); and in the summer with the air temperatures 8-14 days antecedent ($\underline{r}$ = +.96).

4 Seasonal Analysis of the Relationship between Antecedent Air Temperatures and Water Temperatures

(i) At all seasons of the year (summer, winter, dry conditions and wet conditions) water temperatures at the risings are highly correlated with antecedent air temperatures. 100% of the risings on which seasonal analysis was carried out showed a level of correlation significant at the 0.001 level between these two variables during all four time periods.

(ii) The lag of water temperatures behind air temperatures tends to be greater in the winter and wet conditions periods than in the summer and dry conditions periods. 77% of the Fountains Fell risings show an increased time lag from summer to winter, and 54% from the dry conditions to the wet conditions periods. This is a similar phenomenonto that recorded on High Mark springs where it was attributed to viscosity effects and the occurrence of ground frost. At Fosse Beck rising (site 69), for example, the lag of water temperatures behind air temperatures in the summer appears to be in the order of 8-14 days ($\underline{r}$ = +.93 for the correlation with the mean air temperature of the 8-14 day period antecedent), but in the winter this lag increases to 22-28 days ($\underline{r}$ = +.94). In the dry conditions period the lag between these two variables is also 22-28 days ($\underline{r}$ = +.95) but in the wet period it appears to increase to 36-42 days ($\underline{r}$ = +.86)

As on many of the High Mark risings it would appear that slowly circulating recharge water is of greater significance in effecting temperature variations than the rapidly circulating component. Although the correlation of water temperature with effective precipitation shows a lag time between these two variables of 0-28 days (depending upon season) the correlation of temperature with antecedent temperature indicates a lag between these two variables of between six and eight weeks. As on the High Mark springs the relationship between water temperature and effective precipitation is attributed to the input of temperature variations through the medium of rapidly circulating recharge. The relationship between water temperature and antecedent air temperature is related to the slow penetration of seasonal temperature waves to the ground-water both directly through the medium of recharge and indirectly through the temperature interchange between this recharge (principally the slow circulating component) and bedrock.

On some systems in the Fountains Fell area an important element of the rapidly circulating recharge component may be sinking streams. The effect of these streams on the pattern of temperature variation recorded at the risings differs only in degree to the effects brought about by the rapidly circulating recharge component on High Mark systems. As already discussed the effect of recharge water on the temperature of ground-water discharge appears to be primarily related to three factors:

(i) The volume of recharge relative to the amount of ground-water storage;

(ii) The temperature of the recharge relative to the temperature of the bedrock and of the ground-water body;

(iii) The rate of flow or circulation through the limestone system.

When a large volume of rapidly circulating recharge water (eg. sinking streams) enters a system a well developed temperature pulse will be recorded at the rising at some time subsequently. On Fosse Beck rising (site 69) the short term pulses (Fig.15d) occurring on 3.10.68 and 31.10.68 may be the result of influxes of swallet water. At Thoragill Cave rising (and at a large number of other Fountains Fell risings) pulses recorded on these dates may also be related to sinking stream recharge. However, there appears to be little difference in the degree of development of short term temperature pulses on many risings between the High Mark and the Fountains Fell areas. This lack of contrast would suggest that sinking streams generally form an insignificant element of recharge to the ground-water systems of Fountains Fell except in periods succeeding heavy rainfall.

5 Scoska Cave: Site 64

The statistical analysis of the temperature recordings made at Scoska Cave (site 64) do, however, suggest strongly that this rising is largely fed by rapidly circulating recharge water either from a sinking stream or as at Cotegill, site 30, by rapidly circulating percolation water. As at many other sites (see above) the correlation of temperature variations (over the year February 1968 to February 1969) with antecedent effective precipitation is low ($\underline{r}$ = +.33 for total effective precipitation of days 1-3 prior to recording), although the separation of these recordings on a seasonal basis shows that a strong relationship does exist between these two variables. Over the winter period the water temperature observations related most closely to the effective precipitation 24-48 hours prior to recording (r = +.79) and over the summer period to the effective precipitation 22-28 days prior to recording (r = -.88). In these respects Scoska Cave rising is similar to many other risings (see below).

The correlation of water temperature variations with antecedent air temperatures, however, reveals a lag effect between these two variables of the same order as that between water temperature and effective precipitation. (This coincidence of time lags has also been recorded at sites in the High Mark area - see above). At Scoska Cave the correlation of water temperature variations (for the complete year) with antecedent air temperatures reveals a lag effect of 7 days (r = +.89 for the correlation with the mean air temperature of day 7 antecedent to recording). Over the summer period this lag also appears to be in the order of 7 days (r = +.97), and in the winter the correlation with the mean air temperatures of the 0-7 day period antecedent provides the highest correlation coefficient (r = +.91). Water temperature variations recorded at Scoska Cave would, therefore, appear to be introduced largely through the medium of rapidly circulating recharge water possibly a sinking stream.

A number of risings issuing from the Fountains Fell upland show a very pronounced seasonal temperature variation similar to that recorded on a number of springs in the Cotegill area of the High Mark upland. This large seasonal temperature variation on the Cotegill springs was attributed to the shallowness of the major flow zone. Although this factor may also be operative in the Fountains Fell area, one additional explanation may be suggested.

On the Fountains Fell upland numerous enclosed depressions and swallow holes are found, features which are comparatively rare on the High Mark upland. In the former area, therefore, a large component of recharge enters the system through enclosed depressions either as sinking streams or as percolation. The presence of peat and considerable thicknesses of boulder clay on the Fountains Fell upland reduces the rate of vertical percolation and encourages lateral movement of percolation recharge towards these depressions which function, in effect, as small catchments channelling the recharge swiftly into the ground-water system. On High Mark, however, recharge is generally by slow percolation, although the open joints of the limestone pavement areas may have a similar function in the hydrological system to the enclosed depressions of the Fountains Fell area. Owing to this contrast in the rate of recharge to the two systems arising out of basic geomorphic differences the impact of air temperature on the temperatures of water discharging at many of the Fountains Fell risings may be more immediate than on many High Mark springs, and broad seasonal changes in the temperature of recharge and the temperature of bedrock may exist to greater depths in the Fountains Fell area.

6 Seasonal Analysis of the Relationship between Water Temperature and Effective Precipitation

(i) Of the Fountains Fell risings on which this seasonal analysis was carried out 100% showed a summer negative effect of effective precipitation and a winter positive effect. This may be seen, for example, on Scoska Cave, site 64 - see above. This phenomenon of the seasonal contrast in the effect of effective precipitation on the temperature of water discharging at the springs and risings was also observed on the majority (87%) of High Mark springs (see above)

(ii) Of the Fountains Fell risings on which seasonal analysis was carried out 100% showed a longer time lag in the summer and dry conditions periods than in the winter and wet conditions periods. This phenomenon, which contrasts with the seasonal variation in the relationship between water temperature and antecedent air temperatures in both areas (see above), was also observed on High Mark springs.

(iii) The level of correlation between water temperatures and antecedent effective precipitation is lower in the wet conditions period than in the dry conditions period on 100% of the Fountains Fell risings (on which seasonal analysis was carried out). A similar relationship was observed on High Mark springs. In addition the seasonal analysis of the relationship of dissolved calcium carbonate variations with effective precipitation yielded a similar result and possible explanations may be found in Chapter 4.

F The Relationship between the Lag of Dissolved Calcium Carbonate Fluctuations behind Air Temperatures (Flow-Through Time) and the Lag of Water Temperatures behind Air Temperatures

The lag of spring water temperatures behind air temperatures provides a measure of the time taken for the seasonal air temperature wave at the ground surface to be transmitted through the limestone to the ground-water zone and to the point of ground-water discharge at the spring. Implicit in much of the foregoing discussion has been the importance of water circulation within the limestone in the transmission of both seasonal and short term surface temperature variations through to the rising. Pitty (1966, 1968a) has demonstrated that the lag of dissolved calcium carbonate variation behind air temperatures provides a direct measure of the flow-through time of water through the limestone system and, in one case studied Pitty (1968b) showed a similar lag to that of water temperatures behind air temperatures. From the analysis carried out in this chapter it appears that the lag of water temperature behind air temperature, while not necessarily also a direct measure of the flow-through time of water through the limestone, is nevertheless closely allied to the water circulation system. The bases of this conclusion may be summarized in a few statements.

(i) The analysis of the relationship between water temperature variations and effective precipitation has demonstrated that direct transmission of at least short term temperature effects occurs through the medium of rapidly circulating recharge.

(ii) On shallow systems where both the seasonal and short term temperature fluctuations appear to be introduced directly through the medium of rapidly circulating recharge or dilution water the water temperature lag (behind air temperatures) and the flow-through times coincide. At Cotegill, site 32, for example, both the flow-through time and the water temperature lag time are in the order of 8-14 days.

(iii) In systems in which the rate of ground-water circulation is slower, the lag of spring water temperatures behind air temperature tends to be greater than the flow-through time. The seasonal air temperature wave is not, therefore, carried directly through the system by circulating water (except on shallow systems as outlined above), but is delayed to some degree possibly owing to heat exchange between percolating water and the bedrock. On 84% of the High Mark springs and 87% of the Fountains Fell risings the lag of spring water temperatures behind air temperatures is greater than or equal to the flow-through time. The few exceptions to this rule are those sites on which the seasonal water temperature wave has been distorted owing to air temperature influence at the time of sampling. This may be observed at

Arncliffe, site 50, for example (see Fig.11b) where owing to the very low rate of flow at the spring on a few summer recording dates air temperatures at the time of sampling has altered the true ground-water temperature.

(iv) The speed of the transmission of the seasonal air temperature wave through the limestone to the point of ground-water discharge (water temperatures on 46% of the High Mark springs lag behind air temperatures by less than 14 days) points to the importance of rapid water circulation in transmitting the temperature effects. By contrast, Schneider (1962) observed a temperature time lag of between 2-4 months for the passage of the seasonal temperature wave through only 61 m (200 ft) of glacial deposits.

(v) Both the flow-through time and the lag of water temperatures behind air temperatures are of longer duration in winter than in summer on most karst systems, suggesting that viscosity effects may influence both the flow-through time and the temperature lag time, a factor further emphasizing the role of water circulation in the transmission of the seasonal temperature wave.

G Conclusions

The following conclusions arising out of this analysis of water temperatures recorded in north-west Yorkshire may be summarized.

1 The pattern of water temperature fluctuation recorded on almost all sites is that of short term temperature pulses superimposed upon a broad seasonal temperature wave.

2 The role of circulating water is of primary importance in introducing both these elements of temperature variation to the ground-water.

3 The pattern of water-temperature variation recorded at most sites shows a high level of positive correlation with air temperatures some time

prior to recording. The lag of water temperatures behind air temperatures is a measure of the time of penetration of the air temperature wave to the major flow zone and to the point of discharge. In contrast to less permeable regions (Schneider, 1962a and b; Birman, 1969) the speed and depth of penetration of the air temperature wave is great and is closely related to the water circulation in the limestone.

4 Short term water temperature fluctuations are closely related to the action of dilution or rapidly circulating water. This rapidly circulating water tends to have a positive effect in winter on the temperatures of the ground-water, and a negative effect in summer. Although theoretically this seasonal warming and cooling of circulating water may give rise to calcium carbonate precipitation in winter, and limestone solution in summer (Abkühlungskorrosion of Bögli, 1964; Thraikill, 1968) the analysis of the relationship of dissolved calcium carbonate and effective precipitation (Chapter 4) has demonstrated a dilution effect on dissolved calcium carbonate concentrations by rapidly circulating water at all seasons of the year. Any seasonal temperature affects are therefore insufficient to mask the overall dilution effect of rapidly circulating water.

5 At a number of sites almost all temperature effects (short term pulses and, if present, the seasonal temperature wave) are introduced through the medium of rapidly circulating water.

6 There is a dominant tendency for the effects of rapidly circulating or dilution water on the temperature of the ground-water to take place more rapidly in the winter than in the summer in both areas.

7 In both areas, however, the lag of water temperatures behind air temperatures is greater in the winter period than in the summer period. This is a similar phenomenonto that observed by Schneider (1962a). In winter viscosity effects and ground-freezing effects cancel out the effect of greater winter recharge on the speed of water circulation,

although rarely (except on a few High Mark springs) are these effects sufficient to reverse the effect of greater winter rainfall on the rapidly circulating or dilution component (see Conclusion 6).

8 The effect of the geothermal gradient is observable at a few sites only.

9 Ground-water discharge has an important cooling effect in summer, and warming effect in winter on the temperature of surface streams in the field areas. This was also observed on chalk streams by Ineson and Downing (1964). The winter temperature effects are of greatest importance. The role of ground-water discharge on river temperatures is emphasised by the existence of a time lag in the order of several weeks between air temperatures and river temperatures, on some sites.

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CHAPTER SIX

SELECTED CASE STUDIES AND THE ANALYSIS OF DISCHARGE VARIATIONS

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SELECTED CASE STUDIES AND THE ANALYSIS OF DISCHARGE VARIATIONS

A Introduction

Variations in the temperature and solute content (principally dissolved calcium carbonate) of karst waters in the High Mark and Fountains Fell areas of north-west Yorkshire were analysed separately in Chapters 4 and 5. One of the aims of this chapter is to attempt to integrate that analysis by considering water temperature and dissolved calcium and magnesium carbonate variations jointly at selected case study sites.

Discharge measurements were carried out at ten High Mark sites over the year May 1969 to May 1970 (see Chapter 3) in conjunction with measurements of dissolved calcium and magnesium carbonate, and water temperature. In addition, therefore, this chapter considers a further dependent variable, that of discharge, and by the use of correlation analysis attempts to clarify the relationship between spring discharge variations and effective precipitation. Thirdly, previous analysis (Chapters 4 and 5) has pointed to the operation of a 'push-out' effect on a number of the limestone drainage systems, notably Robin Hood's Well, site 3. The recording of discharge in conjunction with solute concentrations and water temperature permits further analysis of this phenomenon.

A number of factors were important in the selection of the ten sites for further study. Firstly, in view of the number of studies on sink-resurgence systems (Groom and Williams, 1965; Ford, 1966) it was thought valuable to concentrate the available resources on springs which are believed to be fed purely or primarily from percolation sources. Robin Hood's Well (site 3) was chosen as there was some indication that push-out effects were occurring at this site (see Chapter 4). Weirs constructed by the Craven Water Board already existed on Reynard's Close rising (site 19) and Moss Beck rising (site 27), although their size alone', in terms of discharge (Plates 7, 8 and 9) pointed to an important role in the drainage of the area and therefore warranted inclusion. Arncliffe sites 48 and 49 were examples of springs showing a strong seasonal factor in the pattern of dissolved calcium carbonate and water temperature variation, and were therefore included. The Malham Tarn sites (sites 56, 57 and 58), in addition to being in close proximity to the Malham Tarn Field Centre and therefore of wider interest, contrasted with the Arncliffe risings in showing a very low degree of seasonal dissolved calcium carbonate and water temperature variation. A further factor in the selection of these case study sites was the desire to have a complete range of springs in terms of discharge. Finally the field problems concerned with the installation of the weir plates for discharge recording, and the need to conform as closely as possible to the British Standard (1965) specifications for the use of thin-plate weirs were other compelling factors in the choice of case study sites.

The pattern of correlation between the mean air temperatures of set period prior to sampling and fluctuations in the four measured variables (dissolved calcium and magnesium carbonate, water temperature and discharge) is similar in many respects for all variables and for all 10 springs. This pattern is characterized by an alternating sequence of rising and declining positive correlations and rising and declining negative correlations with approximately 5 to 7 months between the maximum positive (or negative) correlation in the initial sequence and the maximum negative correlation (or positive) in the succeeding sequence. In the case of dissolved calcium and magnesium carbonate and water temperature this pattern begins with a positive sequence of correlations; in the case of discharge the correlation pattern begins with a negative sequence. The correlation analysis was stopped at the 52nd week antecedent to sampling. A positive association between dissolved calcium carbonate fluctuations and antecedent temperatures has already been demonstrated by Pitty (1966). On the basis of the evidence of this worker in conjunction with that from the analysis of dissolved calcium carbonate variations carried out in Chapter 4, the negative correlation sequences (between dissolved calcium carbonate variations and antecedent temperatures) cannot be taken as indicative of any direct causal link between these two variables. In the following discussion only the highest positive correlation in the initial positive sequence (in the case of the dissolved calcium and magnesium carbonate, water temperature analysis) is considered. Further discussion of the antecedent air temperature factor is carried out at the end of this chapter.

The results of the statistical analysis of the observations carried out at the ten sites are summarized in Tables 6-14.

B Robin Hood's Well: Site 3

1 The Antecedent Effective Precipitation Factor

Dissolved calcium carbonate variations recorded at Robin Hood's Well appear to be influenced by the total effective precipitation of the 1-3 day period prior to sampling. The correlation analysis of dissolved calcium carbonate variations using single day period suggests that, of these three days, the effective precipitation occurring in the 24-48 hour period antecedent may be the most significant.

The relationship of dissolved calcium carbonate variations with antecedent effective precipitation, however, is in marked contrast to that observed in the previous year of recording (February 1968 - February 1969). Over this earlier year the relationship between these two variables was positive suggesting a push-out effect by rainfall (see Chapter 4). Over the period May 1969 to May 1970, however, the relationship was negative, a phenomenon which would suggest that either ground-water storage over this latter period was lower (therefore little push-out effect) or the dilution effect was much more dominant in the second year of sampling, effectively masking any push-out.

Dissolved magnesium carbonate variations were most highly correlated with the effective precipitation 4-6 days prior to sampling.

Recorded variations in water temperature appear to be most strongly influenced by the effective precipitation of the third day prior to sampling with 56% of the variance extracted (in Year I, February 1968 - February 1969, 59% of the water temperature variance was extracted by the effective precipitation occurring 3-5 days previous). The correlation of water temperature deviations from the mean water temperature with effective precipitation, however, extracted only 42% of the variance, illustrating again the predominantly negative influence of effective precipitation pulses on the temperature of the ground-water discharging at Robin Hood's Well (Chapter 5).

Discharge variations recorded at Robin Hood's Well at the time of sampling were most highly correlated with the effective precipitation of the 2-4 day period prior to measurement with almost 72% of the variance extracted by this factor. Of this period the single day correlations suggest that the effective precipitation of day 2 is the most dominant.

Following a period of heavy rainfall, therefore, the analysis indicates that the following sequence of changes in the four variables may be observed at Robin Hood's Well.

(i) The dilution of dissolved calcium carbonate within the following 72 hour period, with maximum dilution occurring within 24 to 48 hours. This would appear to be dilution of water already in the system.

(ii) The occurrence of the major discharge pulse within 24 to 96 hours probably attaining a maximum within 24 to 48 hours. This pulse is made up of both push-out water and actual flood water as a negative correlation (Table 6) was observed between discharge and dissolved calcium carbonate (r = -.40), discharge and dissolved magnesium carbonate (r = -.50) and discharge and water temperature (r = -.58).

(iii) An alteration in the temperature of water at the rising (usually a fall in water-temperature) within 48 to 72 hours. The overlap of this time period with the lag of discharge behind effective precipitation has given rise to the discharge-water temperature correlation recorded below.

(iv) A drop in the level of dissolved magnesium carbonate at a maximum 4 to 6 days after the rain period.

2 The Antecedent Air Temperature Factor

Variations in dissolved calcium carbonate at Robin Hood's Well (site 3) are most highly correlated with the mean air temperatures of the 50-56 day prior to sampling (r = +.82), a time lag of similar length to the 41 days recorded in Year I (February 1968 - February 1969).

The level of correlation between dissolved magnesium carbonate and antecedent temperature is of a much lower order, the peak correlation recorded being that of r = +.32 between dissolved magnesium carbonate and the air temperatures of the fifth day prior.

The mean air temperatures of the 8-14 day period prior to sampling show the highest positive correlation with water temperature variations (r = +.64), and discharge variations recorded at the time of sampling with the air temperatures of the fifth day antecedent (r = -.66).

3 The Discharge Factor

Only 16% of the dissolved calcium carbonate variance at Robin Hood's Well is extracted by this factor, although in the case of dissolved magnesium carbonate variance the discharge factor could explain 25%

Table 6

Summary of Results of Correlation Analysis of Year II Observations at Robin Hood's Well, Site 3

Recorded Variable	Antecedent Effective Precipitation of:	Antecedent Air Temperatures of:	Discharge at Time of Sampling
Dissolved $CaCO_3$	Days 1-3 (r = -.58) Day 2 (r = -.50)	Days 50-56 (r = +.82)	r = -.40
Dissolved $MgCO_3$	Days 4-6 (r = -.64)	Day 5 (r = +.32)	r = -.50
Water temperature	Days 2-4 (r = -.73) Day 3 (r = -.75)	Days 8-14 (r = +.64)	r = -.58
Water temperature deviations from mean water temperature	(r = +.65)	-	-
Discharge	Days 2-4 (r = +.85) Day 2 (r = +.83)	Day 5 (r = -.66)	-

of the variance.

Water temperature variations were most highly correlated with discharge (r = -.58), this fact probably reflecting to a large degree the high correlation of water temperature variations with effective precipitation.

At Robin Hood's Well the greatest proportion of dissolved magnesium carbonate, water temperature and discharge variance was extracted by the antecedent effective precipitation factor. In the case of dissolved calcium carbonate a higher percentage of the variance was extracted by the antecedent air temperature factor.

C Robin Hood's Well (Flood Spring): Site 4

Little analysis was carried out as only five measurements were recorded at this site. When flow occurred at this site measurements of the four variables were identical to those at the permanent rising (site 3).

A correlation of dissolved calcium carbonate with discharge suggested there might be some tendency for positive correlation between these two variables at flood periods (r = +.18).

D Chapel House Well: Site 5

1 The Antecedent Effective Precipitation Factor

Dissolved calcium carbonate variations recorded at Chapel House Well appear to be most closely related to variations in effective precipitation occurring three days prior to sampling (r = -.62), although the effective precipitation of the fourth day prior to sampling shows the highest correlation with recorded dissolved magnesium carbonate variations. Water temperature fluctuations are most strongly influenced by the effective precipitation 2-4 days prior to recording. The correlation of effective precipitation with water temperature deviations from the mean water temperature is lower and, as at Robin Hood's Well, suggests a predominantly negative (lowering) effect of rainfall on groundwater temperatures.

The discharge recorded at the time of sampling is also most highly correlated with the effective precipitation occurring 2-4 days prior to measurement.

Following a period of heavy rainfall the statistical analysis therefore suggests the following sequence of changes in the recorded variables may be observed at Chapel House Well:

(i) A rise in discharge 24-96 hours later, with the peak discharge probably being recorded in the 24-48 hour period. This discharge pulse is made up of both 'push-out water' and dilution or flood water.

(ii) A change in water temperature (usually a fall) and a lowering of the dissolved calcium carbonate level, 24 to 96 hours after the rain with the maximum temperature change and dilution probably occurring 48 to 72 hours after the rain. This phase at the rising represents the discharge of a larger flood or dilution component than occurred at the time of maximum discharge.

(iii) A fall in the level of dissolved magnesium carbonate 3-5 days after the heavy rainfall, maximum dilution probably occurring on the fourth day.

2 The Antecedent Air Temperature Factor

The mean air temperatures of the 50-56 day period antecedent to sampling show the highest positive correlation with dissolved calcium carbonate variations recorded at Chapel House ($\underline{r}$ = +.79). This is a shorter flow-through time than the 77 days recorded in the previous year

Table 7

Summary of Results of Correlation Analysis of Year II Observations at Chapel House Well, Site 5

Recorded Variable	Antecedent Effective Precipitation of:	Antecedent Air Temperatures of:	Discharge at Time of Sampling
Dissolved $CaCO_3$	Days 2-4 (r = -.60) Day 3 (r = -.62)	Days 50-56 (r = +.79)	r = -.57
Dissolved $MgCO_3$	Days 3-5 (r = -.55) Day 4 (r = -.60)	Days 64-70 (r = +.76)	r = -.53
Water temperature	Day 3 (r = -.76) Days 2-4 (r = -.81)	Day 6 (r = +.76)	r = -.68
Water temperature deviations from mean water temperature	Day 3 (r = +.49)	-	-
Discharge	Days 2-4 (r = +.85) Day 2 (r = +.80)	Day 5 (r = -.51)	-

(February 1968 - February 1969) although the dissolved magnesium carbonate variations at Chapel House Well are most closely correlated with the air temperatures 64-70 days antecedent ($\underline{r}$ = +.50). Recorded water temperature variations exhibit the highest correlation with the air temperatures of the sixth day prior to recording ($\underline{r}$ = +.76). This similarity between the water temperature-antecedent air temperature time lag and the water-temperature effective precipitation time lag was also observed in the previous year (Chapter 5), indicating the importance of rapidly circulating water in introducing water temperature variations to the ground-water system at Chapel House.

Discharge at the time of sampling also appears to be influenced by the air temperatures a short period prior to measurement ($\underline{r}$ = -.51 for the correlation with the air temperatures of the fifth day prior to recording.)

3 The Discharge Factor

The correlations of dissolved calcium and magnesium carbonate with discharge at the time of sampling are higher than those observed on Robin Hood's Well, with 33% and 28% of the variance being explained by this factor. Over 45% of the water temperature variance could be explained by the discharge factor.

At Chapel House Well the greatest percentage of dissolved magnesium carbonate, water temperature and discharge variance was extracted by the antecedent effective precipitation factor. In the case of dissolved calcium carbonate a higher percentage of the variance was extracted by the antecedent temperature factor.

E Reynard's Close: Site 19

1 The Antecedent Effective Precipitation Factor

Variations in dissolved calcium carbonate show the closest correlation with the effective precipitation of the 1-3 day period prior to sampling (r = -.53). The analysis employing single day periods indicated that, of these three days, the rainfall occurring in the third day prior to sampling was of greatest significance in effecting dissolved calcium carbonate variation (r = -.51).

The effective precipitation of the 5-7 day period prior to sampling yields the highest correlation with the variations in dissolved magnesium carbonate recorded at Reynard's Close spring.

The correlation of recorded water temperature variations with antecedent effective precipitation is highest for the effective precipitation of the 1-3 day period prior to sampling (r = -.60) although correlation of temperature deviations from the mean temperature suggest that the effective precipitation of the 2-4 day period may be more important (r = +.68).

Unlike Robin Hood's Well and Chapel House Well this latter correlation is higher than that between simple water temperature variations and effective precipitation variations, suggesting that at Reynard's Close the warming effect of rainfall on the ground-water is more important than at either Robin Hood's Well or Chapel House Well.

Discharge variations at Reynard's Close correlate highest with the effective precipitation variations of the second day prior to measurement (r = +.84) although the total effective precipitation of the week prior to measurement is of importance (r = +.83).

Following a period of heavy rainfall the analysis therefore suggests the following sequence of changes might be observed at Reynard's Close spring:

Table 8

Summary of Results of Correlation Analysis of Year II Observations at Reynard's Close, Site 19

Recorded Variable	Antecedent Effective Precipitation of:	Antecedent Air Temperatures of:	Discharge at Time of Sampling
Dissolved $CaCO_3$	Days 1-3 (r = -.53) Day 3 (r = -.51)	Days 50-56 (r = +.76)	r = -.411
Dissolved $MgCO_3$	Days 5-7 (r = -.68) Day 7 (r = -.61)	Days 8-14 (r = +.50)	r = -.40
Water temperature	Days 1-3 (r = -.60) Day 3 (r = -.60)	Days 22-28 (r = +.84)	r = -.40
Water temperature deviations from mean water temperature	Days 2-4 (r = +.68) Day 3 (r = +.68)	-	-
Discharge	Days 0-7 (r = +.83) Days 1-3 (r = +.80) Day 2 (r = +.84)	Days 8-14 (r = -.68)	-

(i) A rise in discharge reaching a peak within 24-48 hours.

(ii) A change in water temperature (could be either a rise or a fall) and a drop in the level of dissolved calcium carbonate, reaching a maximum, 48-72 hours after the rainfall. This is probably associated with a higher component of dilution or flood water than in (i).

(iii) A drop in the level of dissolved magnesium carbonate 5-7 days after the rain probably at a maximum about seven days after the rainfall.

This pattern is very similar to that at Chapel House.

2 The Antecedent Air Temperature Factor

As at Robin Hood's Well and Chapel House Well the air temperatures of the 50-56 day period prior to sampling shows the highest positive correlation with dissolved calcium carbonate variations ($\underline{r}$ = +.76). Dissolved magnesium carbonate variations are most highly correlated with the mean air temperatures 8-14 days antecedent ($\underline{r}$ = +.50) and recorded water temperatures correlate most closely with the mean air temperature of the 22-28 day period antecedent to recording($\underline{r}$ = -.91).

Discharge variations at Reynard's Close correlate most highly with the air temperatures of the 8-14 day period antecedent.

3 The Discharge Factor

Only 17% of the dissolved calcium carbonate variance may be explained by discharge at the time of sampling, although nearly 56% of the dissolved magnesium carbonate variance was extracted by this factor. The discharge factor extracted only 16% of the water temperature variance unlike Robin Hood's Well and Chapel House Well where of the three variables water temperature provided the highest correlation with discharge.

At Reynard's Close Spring variations in discharge and in dissolved magnesium carbonate are more closely related to fluctuations in effective precipitation. Water temperature variations (unlike Robin Hood's Well and Chapel House Well) are most closely correlated with air temperature fluctuations antecedent to sampling. The higher level of correlation between water temperature and antecedent air temperatures at Reynard's Close Spring than at Robin Hood's Well and Chapel House Well is probably related to the appearance of a more distinct seasonal trend in water temperature at this spring.

F Moss Beck: Site 27

1 The Antecedent Effective Precipitation Factor

The effective precipitation of the 29-35 day period prior to sampling provides the highest correlation with dissolved calcium carbonate variations ($\underline{r} = -.65$) although that of the third day prior may be of greater significance in reflecting a true causal relationship ($\underline{r} = -.62$).

Almost 53% of the variance of dissolved magnesium carbonate is extracted by the effective precipitation of the seventh day prior to sampling. Water temperature variations recorded at Moss Beck correlate highest with the effective precipitation 29-35 days antecedent, and discharge with effective precipitation occurring 24-48 hours previous.

Following a period of heavy rainfall the analysis suggests that the following changes in the four measured variables may be recorded at Moss Beck:

(i) A rise in discharge reaching a peak within 24-48 hours, although as at Reynard's Close discharge variations over the period of a week appear to be affected.

(ii) A fall in the level of dissolved magnesium carbonate within 5-7 days after the rain period, maximum dilution probably occurring 7 days after rainfall.

(iii) Dilution of dissolved calcium carbonate occurs probably 3 days after the rainfall (or possibly 29-35 days after the rainfall.)

(iv) A change in water temperature may occur 29-35 days after the rainfall. The correlations with the rainfall of the 29-35 day period may, however, be chance correlations of the kind mentioned in Chapter 2.

2 The Antecedent Air Temperature Factor

The mean air temperature of the 8-14 day period prior to sampling shows the highest positive correlation with dissolved calcium carbonate fluctuations ($\underline{r}$ = +.88), a flow-through time of shorter duration than that of 26 days recorded from the analysis of Year I observations.

The correlations between dissolved magnesium carbonate and antecedent temperature are again lower than those between dissolved calcium carbonate and antecedent temperature. The air temperatures of the 43-49 day period provide the highest positive correlation with recorded dissolved magnesium carbonate variations ($\underline{r}$ = +.66).

The air temperatures of 29-42 day period appear to exert the greatest influence on the recorded water temperatures at Moss Beck ($\underline{r}$ = +.93), a time lag of similar order to that recorded from the previous year's (Year I) observations analysis (43-49 days).

Discharge variations correlate highest with the mean air temperatures of 8-14 days antecedent to recording, a time lapse of similar length to the flow-through time.

3 The Discharge Factor

Dissolved calcium and magnesium carbonate variations show the highest correlation with discharge ($\underline{r}$ = -.57 and $\underline{r}$ = -.55 respectively). Water temperature variations show the lowest ($\underline{r}$ = -.33). At Moss Beck, as at Reynard's Close rising, variations in discharge and dissolved magnesium carbonate are most closely related to fluctuations in effective

Table 9

Summary of Results of Correlation Analysis of Year II Observations at Moss Beck, Site 27

Recorded Variable	Antecedent Effective Precipitation of:	Antecedent Air Temperatures of:	Discharge at Time of Sampling
Dissolved $CaCO_3$	Days 29-35 (r = -.65) Days 2-4 (r = -.62) Day 3 (r = -.62)	Days 8-14 (r = +.88)	r = -.57
Dissolved $MgCO_3$	Days 5-7 (r = -.64) Day 7 (r = -.73)	Days 43-49 (r = +.66)	r = -.55
Water temperature	Days 29-35 (r = -.67) Day 7 (r = -.36)	Days 29-35 (r = +.92)	r = -.33
Water temperature deviations from mean water temperature	-	-	-
Discharge	Days 0-7 (r = +.81) Days 2-4 (r = +.79) Day 2 (r = +.83)	Days 8-14 (r = -.60)	-

precipitation Water temperature variations and dissolved calcium carbonate are most closely correlated with antecedent air temperatures.

The results of the analysis of the four recorded variables on the remaining five springs are summarized in Tables 10-14. Only a brief summary of these results will be made.

G Arncliffe: Site 48

1 The Antecedent Effective Precipitation Factor

The statistical analysis suggests the following sequences of changes in the recorded variables may be observed following a period of heavy rainfall:

(i) An increase in discharge reaching a peak within 24 hours.

(ii) Dilution of dissolved magnesium carbonate within one week. There is a suggestion in the analysis that two dilution pulses may be recorded

(iii) Dilution of dissolved calcium carbonate at a maximum on the third day following rainfall.

2 The Antecedent Air Temperature Factor

Again dissolved calcium carbonate and water temperature show a high level of correlation with antecedent air temperatures.

3 The Discharge Factor

A very low level of correlation exists between dissolved calcium carbonate and discharge, and between water temperature and discharge. This probably reflects the high degree of seasonal variation in these two variables (Figs.10d and 38b) illustrated by the high correlations with the antecedent air temperature factor. Over 34% of the dissolved magnesium carbonate variance may, however, be extracted by the discharge factor.

H Arncliffe: Site 49

1 The Effective Precipitation Factor

The statistical analysis suggests the following sequence of changes in the recorded variables may be observed following a period of heavy rain:

(i) A rise in discharge reaching a maximum within 24 hours;

(ii) Dilution of dissolved calcium carbonate reaching a maximum in 48-72 hours;

(iii) Dilution of dissolved magnesium carbonate 5-7 days after the rainfall, maximum dilution probably occurring on the seventh day.

2 The Antecedent Air Temperature Factor

Of note is the very high level of correlation between dissolved calcium carbonate and antecedent air temperatures, and water temperature and antecedent air temperature. In contrast to the springs so far examined in this chapter dissolved magnesium carbonate variations also show a higher level of correlation with antecedent air temperatures than with effective precipitation. This phenomenon was also observed at Malham Tarn site 58 (see below).

3 The Discharge Factor

As at Arncliffe site 48 a very low level of correlation between dissolved calcium carbonate and discharge, and between water temperature and discharge was observed, although dissolved magnesium carbonate showed a higher level of correlation.

Table 10

Summary of Results of Correlation Analysis of Year II Observations at Arncliffe, Site 48

Recorded Variable	Antecedent Effective Precipitation of:	Antecedent Air Temperatures of:	Discharge at Time of Sampling
Dissolved $CaCO_3$	Day 3 (r = -.59)	Days 36-42 (*r* = +.87)	*r* = -.18
Dissolved $MgCO_3$	Days 0-7 (*r* = -.66) Days 1-3 (*r* = -.60) Days 5-7 (*r* = -.57)	Days 36-42 (*r* = +.52)	*r* = -.59
Water temperature	-	Days 64-70 (*r* = +.89)	*r* = -.09
Water temperature deviations from mean water temperature	-	-	-
Discharge	Day 1 (*r* = + 81)	Days 8-14 (*r* = -.37)	-

Table 11

Summary of Results of Correlation Analysis of Year II Observations at Arncliffe, Site 49

Recorded Variable	Antecedent Effective Precipitation of:	Antecedent Air Temperatures of:	Discharge at Time of Sampling
Dissolved $CaCO_3$	Day 3 (r = -.55)	Days 36-42 (r = +.86)	r = -.16
Dissolved $MgCO_3$	Days 5-7 (r = -.56) Day 7 (r = -.62)	Days 36-42 (r = +.68)	r = -.46
Water temperature	Day 7 (r = -.50)	Days 22-28 (r = +.92)	r = -.15
Water temperature deviations from mean water temperature	Day 2 (r = +.46)	-	-
Discharge	Day 1 (r = +.85)	Days 29-35 (r = -.50)	-

I Malham Tarn: Site 56

1 The Effective Precipitation Factor

The following changes in the recorded variables following a rain period at Malham Tarn site 56 are suggested by the statistical analysis:

(i) An increase in discharge within one week probably at a maximum within the 24-48 hour period.

(ii) A drop in the level of dissolved calcium carbonate within three days with maximum dilution probably occurring on the third day following the rain.

(iii) A fall in the level of magnesium carbonate 8-14 days after the rain period.

(iv) Although a higher correlation exists between water temperature and the effective precipitation of the 22-28 day antecedent, the correlation with the effective precipitation of the 0-7 day period antecedent ($\underline{r} = -.53$) may be more meaningful in terms of a true cause-effect relationship. Furthermore, it is the effective precipitation of the 0-7 day period which has the strongest influence on discharge, and a high correlation ($\underline{r} = -.68$) exists between discharge and water temperature variations.

2 The Antecedent Air Temperature Factor

In the case of the four recorded variables at Malham Tarn site 56 the percentage variance extracted by the air temperature factor is lower than at the Arncliffe sites. The correlation between dissolved magnesium carbonate and antecedent temperature is particularly low.

3 The Discharge Factor

A low level of correlation exists between dissolved calcium and magnesium carbonate fluctuations and discharge at the time of sampling.

Table 12

Summary of Results of Correlation Analysis of Year II Observations at Malham Tarn, Site 56

Recorded Variable	Antecedent Effective Precipitation of:	Antecedent Air Temperatures of:	Discharge at Time of Sampling
Dissolved $CaCO_3$	Days 1-3 (*r* = -.60) Day 3 (*r* = -.57)	Days 50-56 (*r* = +.69)	*r* = -.37
Dissolved $MgCO_3$	Days 8-14 (*r* = -.40)	Days 50-56 (*r* = +.17)	*r* = -.26
Water temperature	Days 0-7 (*r* = -.53) Days 22-28 (*r* = -.58)	Days 57-63 (*r* = +.65)	*r* = -.68
Water temperature deviations from mean water temperature	-	-	-
Discharge	Days 0-7 (*r* = +.76) Days 2-4 (*r* = +.76) Day 2 (*r* = +.73)	Days 8-14 (*r* = -.71)	-

Nearly 47% of the water temperature variance is, however, extracted by the discharge factor.

J Malham Tarn: Site 57

1 The Antecedent Effective Precipitation Factor

The statistical analysis suggests that the following changes may be recorded at this site following rainfall.

(i) A rise in discharge within 24 hours.

(ii) A dilution of dissolved calcium carbonate in the three days following the rain, with maximum dilution probably occurring 48 to 72 hours after the rain.

(iii) A fall in the level of dissolved magnesium carbonate 8-14 days after the rain period.

(iv) A possible change in water temperature 29-35 days after the rainfall may be recorded.

2 The Antecedent Air Temperature Factor

Dissolved calcium carbonate and water temperatures again show the closest correlation with antecedent air temperatures.

3 The Discharge Factor

At this site water temperature and dissolved calcium carbonate variations show the closest correlation with discharge (r = -.66 and r = -.50). Dissolved magnesium carbonate variations show little relationship to discharge (r = -.10). The relationship of these three variables to the discharge factor is therefore in marked contrast to that observed at Arncliffe sites 48 and 49.

Table 13

Summary of Results of Correlation Analysis of Year II Observations at Malham Tarn, Site 57

Recorded Variable	Antecedent Effective Precipitation of:	Antecedent Air Temperatures of:	Discharge at Time of Sampling
Dissolved $CaCO_3$	Days 1-3 (r = -.63) Day 3 (r = -.58)	Days 43-49 (r = +.78)	r = -.50
Dissolved $MgCO_3$	Days 8-14 (r = -.58)	Days 50-56 (r = +.24)	r = -.10
	Day 7 (r = -.35) Days 29-35 (r = -.64)	Days 22-28 (r = +.79)	r = -.66
Water temperature deviations from mean water temperature	Day 1 (r = + 48)	-	-
Discharge	Day 1 (r = +.83)	Day 5 (r = -.37)	-

K Malham Tarn: Site 58

1 The Antecedent Effective Precipitation Factor

Following a period of heavy rain the statistical analysis suggests the following sequence of changes at this site.

(i) An increase in discharge in the succeeding seven days. The 3-day and single day analysis suggests that there may be two discharge pulses (Table 14) although this suggestion of two pulses may arise from the problems of intercorrelation discussed in Chapter 2.

(ii) A dilution of dissolved calcium carbonate 2-4 days after the rain period, with maximum dilution probably occurring in the 24-48 hour period.

(iii) The effect of rainfall on dissolved magnesium carbonate and on water temperatures is obscure at this site.

2 The Antecedent Air Temperature Factor

Dissolved magnesium carbonate, water temperature and discharge variations all correlate more highly with antecedent air temperatures than with effective precipitation. Dissolved calcium carbonate, however, shows a higher level of correlation with antecedent effective precipitation ($\underline{r} = -.70$).

3 The Discharge Factor

As at the other Malham Tarn springs dissolved magnesium carbonate variations show a very low level of correlation with discharge. Both dissolved calcium carbonate and water temperatures show a higher level of correlation with this factor.

A number of points may be abstracted from this review of ten High Mark springs.

Table 14

Summary of Results of Correlation Analysis of Year II Observations at Malham Tarn, Site 58

Recorded Variable	Antecedent Effective Precipitation of:	Antecedent Air Temperatures of:	Discharge at Time of Sampling
Dissolved $CaCO_3$	Days 2-4 (r = -.70) Day 2 (r = -.69)	Days 43-49 (r = +.52)	r = -.56
Dissolved $MgCO_3$	-	Days 57-63 (r = +.72)	r = -.63
Water temperature	Day 7 (r = -.30)	Day 1 (r = +.85) Days 29-35 (r = +.83)	r = -.63
Water temperature deviations from mean water temperature	-	-	-
Discharge	Days 0-7 (r = +.76) Days 2-4 (r = +.68) Day 7 (r = +.64)	Days 8-14 (r = -.81)	-

L The Antecedent Effective Precipitation Factor

The role of this factor varies considerably from spring to spring although a general pattern may be deciphered. The correlations demonstrate that a period of heavy rainfall is followed, within less than seven days, by an increase in discharge at all ten risings. This rapid response of discharge to heavy precipitation argues against the existence of any large ground-water storage zone or zone of saturation within the limestone that could absorb or prolong the appearance of consequent discharge pulses (see Chapter 7).

The timing and duration of these pulses varies from spring to spring and undoubtedly reflects factors such as catchment size, mode of recharge, and maturity of the subterranean system. At Malham Tarn site 58, for example, the analysis of the relationship between discharge and antecedent effective precipitation suggests a poorly integrated system in which the rain from one particular rain period is retarded, affecting discharge at the rising over the succeeding seven day period (as indicated by the highest correlation between discharge and antecedent effective precipitation). By contrast the highest correlation between discharge and antecedent effective precipitation at Reynard's Close site 19, and Moss Beck site 27 is with the total effective precipitation of a single day period ($\underline{r} = +.84$ and $\underline{r} = +.83$ for day 2 antecedent). This suggests the existence of a more efficient drainage system with recharge pulses being directed immediately into a main channel and through to the rising. Arncliffe site 49 also shows the highest discharge - antecedent effective precipitation correlation with a single day period (rather than a 3-day or 7-day period). In this case, however, the highest correlation is with the effective precipitation occurring within 24 hours prior to sampling. Again a highly integrated efficient system is suggested, although of a much smaller catchment size than Reynard's Close or Moss Beck (as illustrated by absolute discharge contrasts).

Although on all sites dilution of dissolved calcium carbonate appears to begin shortly after the occurrence of rainfall, dilution tends to reach a maximum after the major discharge pulse has appeared. This may be related to the arrival of a larger element of actual flood or dilution water at the rising than occurred during the passage of the major discharge pulse. Much of the major discharge pulse appears to be composed of water already in the system - 'push-out water'. The correlation of the three recorded variables with discharge, shows that some dilution of dissolved calcium and magnesium carbonate, and water temperature does, however, occur at the time of maximum discharge.

Although the timing of the dissolved magnesium carbonate dilution pulse varies considerably from spring to spring there is a tendency for the maximum dilution of dissolved magnesium carbonate to occur after the maximum dilution of dissolved calcium carbonate. The timing of the water temperature pulse consequent upon heavy rainfall also varies considerably from spring to spring.

H The Discharge Factor

The correlation of dissolved calcium and magnesium carbonate content and water temperature with discharge at the time of sampling demonstrates that discharge is simply another variable dependent upon antecedent hydro-meteorological factors principally effective precipitation. Any correlation between, for example, dissolved calcium carbonate fluctuation and discharge is basically a reflection of two circumstances:

(a) the degree of coincidence of the dissolved calcium carbonate - antecedent effective precipitation time lag and the discharge - antecedent effective precipitation time lag;

(b) the level of correlation between the two dependent variables, discharge and dissolved calcium carbonate, and antecedent effective precipitation.

Any correlation analysis involving the substitution of antecedent effective precipitation for discharge is inaccurate. Furthermore, the use of discharge as an independent variable in the analysis of dissolved solids fluctuations at karst springs is meaningless unless considered in the context of antecedent hydro-meteorological conditions.

N The Antecedent Air Temperature Factor

On 8 out of 9 case study sites (89%) dissolved calcium carbonate variations showed a higher level of correlation with the air temperatures of some period antecedent to sampling than with antecedent effective precipitation or discharge. On the analysis of the previous year's (February 1968 to February 1969) dissolved calcium carbonate observations only 67% (28 out of 42 sites) of High Mark springs showed a higher correlation between dissolved calcium carbonate and antecedent air temperature than between dissolved calcium carbonate and antecedent effective precipitation. The antecedent effective precipitation factor, however, appears to have been more dominant in the previous year as, in that year, dissolved calcium carbonate variations on only 5 out of the 9 case study sites (56%) correlated more highly with antecedent air temperatures than with antecedent effective precipitation. Malham Tarn site 58 is the only case study site to show a higher correlation between dissolved calcium carbonate and effective precipitation during the second year of analysis. It is notable that in the previous year all the Malham Tarn sites (sites 56-58) showed a higher correlation between dissolved calcium carbonate and antecedent effective precipitation. In both years therefore, the antecedent air temperature factor has a greater effect on the dissolved calcium carbonate variations recorded at the majority of High Mark springs, although this is less true in

Year I (February 1968 - February 1969) than in Year II (May 1969 - May 1970).

The relationship between dissolved magnesium carbonate and antecedent hydro-meteorological factors is the reverse of that recorded for dissolved calcium carbonate. On 7 out of the 9 case study sites (78%) dissolved magnesium carbonate variations are more closely related to the antecedent effective precipitation factor than to antecedent air temperatures, and on 5 out of the 9 sites (56%) are more closely related to discharge than antecedent air temperatures. No comparative figures are available at the moment for the previous years' observations.

It appears, therefore, that antecedent air temperatures have an important influence on the levels of both dissolved calcium carbonate and dissolved magnesium carbonate (although less so with dissolved magnesium carbonate). Evidence has already been provided (Pitty,1966) that the link between dissolved calcium carbonate and air temperatures reflects seasonal changes in soil carbon dioxide due to increased root and microbial respiration at higher temperatures. The solubility of magnesium carbonate is also related to the availability of carbon dioxide and the link between dissolved magnesium carbonate and antecedent air temperatures may be explained in a similar manner, although dissolved magnesium carbonate levels are more closely related to effective precipitation variability than are dissolved calcium carbonate levels. On 6 out of the 9 case study sites the lag of dissolved magnesium carbonate behind air temperatures was of a similar order to that of dissolved calcium carbonate behind air temperatures. The remaining three sites showed the maximum dissolved magnesium carbonate dilution effects (as evidenced by the dissolved magnesium carbonate - antecedent effective precipitation correlation analysis) and these effects appear to have distorted the dissolved magnesium carbonate lag time on these sites.

Some workers (Hendrickson and Krieger,1964) have suggested that seasonal changes in dissolved solids may be due to seasonal changes in the rate of recharge, an increase in the rate of recharge giving rise to a decrease in dissolved solids Although the correlation of dissolved calcium carbonate with antecedent effective precipitation (which provides a measure of rate of recharge to the limestone) has shown a degree of negative correlation which could initiate a seasonal pattern in the dissolved calcium carbonate levels, the antecedent air temperature factor has been demonstrated to be of greater significance on the majority of springs in initiating the observed seasonal pattern.

On 7 out of the 9 (78%) High Mark case study sites water temperature variations correlate more highly with antecedent air temperatures than with the effective precipitation factor. This correlation arises from the penetration of the seasonal air temperature wave through to the ground-water system as discussed in Chapter 5. At Robin Hood's Well, site 3 and Chapel House Well, site 5 (the two exceptions) the effective precipitation factor is of greater importance in initiating water temperature fluctuations than antecedent air temperature. This phenomenonwas also observed in the analysis of the first year's observations (February 1968 - February 1969) of water temperature at these two sites, and is discussed in Chapter 5.

On 7 out of the 9 (78%) High Mark case study sites a high negative correlation between discharge and antecedent air temperature was observed. This negative correlation may be readily explained. The general coincidence of low rainfall, high evapotranspiration rates and high soil moisture deficits in the summer months may give rise to low discharges at periods of high (summer) temperatures.

0 Conclusion

The relationship of the four recorded variables with antecedent effective precipitation is for the most part immediate and largely reflects the action of rapidly circulating water probably in the vicinity of the system exit. Seasonal variations in air temperatures have a longer term effect on the four recorded variables. This effect is more closely related to the action of more slowly circulating ground-water.

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CHAPTER SEVEN

THE DISTRIBUTION OF SPRINGS, AND A GEOGRAPHICAL ANALYSIS OF THEIR CHEMICAL AND PHYSICAL CHARACTERISTICS

THE DISTRIBUTION OF SPRINGS, AND A GEOGRAPHICAL ANALYSIS OF THEIR CHEMICAL AND PHYSICAL CHARACTERISTICS

A The Distribution of Springs

1 The High Mark Area

Most springs in the High Mark area are peripheral in location (Map 4), the higher interior parts of the area being almost devoid of springs with the exception of a few minor seepages and occasional very temporary flood springs.

Map 4 shows in addition a very distinctive pattern in the location of these peripheral springs. They are usually located in groups, physically isolated from other groups. Large single springs are comparatively rare. There is also some tendency for springs belonging to a large group to be smaller in terms of discharge than those of a group of less springs. Very large springs, generally have only one other spring within the group, eg. Reynard's Close rising - site 19 with site 20, and this second spring is often intermittent in character.

On the basis of a geographical analysis of the location of High Mark springs the following groups of springs or isolated springs may be recognized.

1 Wharfedale: sites 1 and 2

2 Robin Hood's Well: site 3, and the flood rising at Robin Hood's Well: site 4

3 Chapel House Well: site 5

4 Outgang Hill: sites 6-9 and 11 (sites 6 and 7 are flood springs) (Map 6)

5 Reynard's Close: site 19, with a semi-permanent rising at site 20 (Map 6)

6 The Kilnsey group of springs: sites 21-26 (Map 6)

7 Moss Beck: site 27

8 Sleet's Gill Beck: site 29

9 The Cotegill springs: sites 30-35, 37, 38, although this group could be subdivided into those springs which emerge in the main valley of Cotegill (sites 30-35) and those which emerge along the left bank tributary (sites 37, 38) (Map 7)

10 The Bluescar springs: sites 39-42

11 The Arncliffe group of springs: sites 46-52

12 Upper Cowside Beck springs: sites 53 and 54

13 Malham Tarn main feeder spring: site 55

14 Malham Tarn springs: sites 56 - 59

This locational grouping, particularly striking in the field, conforms closely to the variations in water quality which are discussed below.

The majority of springs in the High Mark area are located on the north-eastern and eastern flanks of the upland, and a large proportion of the total discharge from the High Mark limestone upland takes place in lower Littondale and Wharfedale, eg. Moss Beck: site 27 with a mean discharge of 190.9 l/sec (6.74 cusecs); Reynard's Close: site 19 with a mean discharge of 229.1 l/sec (8.09 cusecs). On the northwestern and southern margins of the upland only Cowside, site 53 and Malham, site 55 are estimated to have mean discharges of over 14 l/sec (0.5 cusecs).

A number of factors may be of importance in influencing the pattern of spring distribution and discharge in the High Mark area.

(i) The tilt of the basement (Pre-Carboniferous) rocks. The basement rocks appear at an altitude of 378 m (1240 ft) O.D. at Malham Tarn but are not visible in Wharfedale or lower Littondale at an altitude of 183 m (600 ft) O.D. There therefore appears to be approximate north west/south east axis of basement tilt in the High Mark area with a basement gradient of not less than 1:45 (calculated from its appearance at Malham Tarn at 378 m - 1240 ft O.D. and its non-appearance at Arncliffe, site 52 at 240 m - 786 ft O.D., Kilnsey, site 26 at 198 m - 630 ft O.D. and Robin Hood's Well, site 3 at 183 m - 600 ft O.D.) This sloping basement is probably of major importance in directing water movement towards lower Littondale and Wharfedale. The possibility exists that some water movement may take place from the Fountains Fell area through the High Mark massif to Wharfedale or lower Littondale. This, however, is not considered likely as dissection everywhere, except near Malham Tarn, is sufficient to intercept such a flow, although the water temperature characteristics of Robin Hood's Well (see Chapter 5), may be explicable in terms of such a deep-seated water movement.

(ii) The observed grouping of High Mark springs may result from the influence of basement structures or basement topography on the direction of water movement. This factor has been previously recorded by Wilcockson (1927) in Ribblesdale.

(iii) The dip of the limestone strata, although locally variable is regionally towards the north-east and east at an angle of less than 5^0. The importance of master bedding planes (Schwarzacher, 1958; Doughty, 1967) may be of considerable significance in this respect.

(iv) The highest parts of the High Mark upland are located towards the southern and western parts of the region (Map 2). If topography provides an indication of the location of major water divides within the High Mark limestone, springs emerging in Wharfedale and lower Littondale will have larger catchment areas than those emerging in upper Cowside Beck (Skirfare) or around Malham Tarn. Consequently the greatest amount of discharge will be recorded in lower Littondale and Wharfedale.

2 The Fountains Fell Area

The distribution of risings in the Fountains Fell area (Map 5) is much more complex than in the High Mark area. A number of points may however be made.

(i) The influence of the Pre-Carboniferous basement again appears to be of importance in directing the major water movements within the area. The largest springs and resurgences in the Fountains Fell area, as on High Mark, tend to be located on the north-eastern and eastern margins. This distribution may be due to the tilt of the basement northwards away from the North Craven Fault. In upper Littondale and Cowside Beck (Skirfare) dissection has cut across northerly and north-easterly movements of water with large springs occurring at, for example, Lower Hesleden (site 71), Fosse Beck (site 69), Bown Scar (sites 62 and 63), Cowside Beck - Skirfare (sites 98, 99).

Owing to the incomplete dissection of the limestone on the western and north-western flanks of Fountains Fell, however, major water movements in this area may not have been intercepted and fluorescein tracings carried out by Heys (1951) has demonstrated water movement from Gingling Hole on the south-western flank of Fountains Fell to Brants Ghyll in Ribblesdale. As previously observed Wilcockson (1927) has pointed to the role of basement topography in such movements.

The map of sampled springs and resurgences in the Fountains Fell area (Map 5) may therefore give a slightly misleading picture of major subterranean water movements in some parts of the area.

(ii) The tendency for locational grouping of springs in the Fountains Fell area is less developed than in the High Mark area, and large risings tend to occur in isolation, eg. Fosse Beck, site 69. There are, however, a few exceptions to this:

(a) Bown Scar risings: sites 61-63;

(b) The Blishmire risings: sites 74-76, 78 (Map 9);

(c) Tongue Gill: sites 82 and 83;

(d) Thoragill Beck: sites 101-105

(e) Some spatial grouping of springs may possibly be identified in the area west of Malham Tarn (eg. Blackhill sites 89-91; Blackhill sites 92-93; Limekiln Hill - sites 94 and 95) (Map 10). These springs are closely related to the proximity of the junction of the Carboniferous limestone with the basement rocks.

Unlike the High Mark area these spatial groupings of risings do not conform to any grouping made on considerations of water quality.

B Regional Variations in Mean Dissolved Calcium Carbonate

1 In High Mark Springs

An examination of Map 12 reveals two major aspects to the pattern of geographical variation in the mean dissolved calcium carbonate content of spring waters in the High Mark area.

(i) A broad pattern showing a general decline in the mean dissolved calcium carbonate content towards the northern and northwestern parts of the area. Of 18 springs sampled in Wharfedale only 3 contained less than 185 p.p.m. of dissolved calcium carbonate and 8 over 200 p p.m. By contrast of the 10 springs sampled in the Arncliffe and Cowside Beck (Skirfare) area (sites 46-55) none contained more than 166 p.p.m. of dissolved calcium carbonate. Sweeting and Sweeting (1969) also observed a distinct regional variation in limestone solution in north-west Yorkshire with pools on limestone in western areas averaging 60-80 p.p.m. of dissolved calcium carbonate, and those in the east 120-160 p.p.m. Sweeting and Sweeting (1969) consider that this regional variation may be due to differences in rock lithology as limestones with a greater percentage of crystalline calcite occur in the west.

It does not seem likely, however, that variation in rock lithology within the much smaller area of High Mark could alone account for the observed regional variation. Pitty (1968) has demonstrated a positive association between the mean dissolved calcium carbonate content of karst waters and the flow-through time of the water through the limestone. In the High Mark area, therefore, regional variations in flow-through time may be an additional factor in influencing the observed regional variation in dissolved calcium carbonate levels. A comparison of Maps 12 and 16 shows a broad agreement in the pattern of regional variation in these two variables.

(ii) There is a high degree of conformity between the locational grouping of springs discussed above and the level of dissolved calcium carbonate in the spring water. Springs within each group tend to have the same or very similar levels in both the mean dissolved calcium carbonate content and in the recorded variations. Wharfedale sites 1 and 2 both recorded a mean dissolved calcium carbonate content of 187 p.p.m. At Robin Hood's Well the mean dissolved calcium carbonate content at the permanent rising (site 3) was 177 p.p.m. and at the flood rising (site 4) was 179 p.p.m. At times of flow on both risings the levels were identical (Figs.3c and d); at Outgang Hill sites 6-9 differences in the level of mean dissolved calcium carbonate are also due to the varying degrees of permanency of flow (mean calculated from different number of observations). At Reynard's Close the mean dissolved calcium carbonate content at sites 19 and 20 differs by only 1 p.p.m. Many further examples are apparent from map 12.

A number of exceptions to this coincidence of locational grouping with levels of dissolved calcium carbonate do occur. Outgang Hill site 11, for example, contains a higher level of mean dissolved calcium carbonate than sites 6-9 (218 p.p.m. as compared to 197-202 p.p.m.), and a comparison of the graph of dissolved calcium carbonate fluctuation at site 11 with those at sites 6-9 (Figs. 4a, b, c, d and e) further illustrates this lack of conformity with the locational grouping. Similarly water emerging at Kilnsey Cave (site 21) is in contrast with that emerging at sites 22-25 in the same locational group. Seasonal fluctuations in the level of dissolved calcium carbonate at Kilnsey site 26 (Fig.6c) appear to exclude this site also from the Kilnsey group, although the level of mean dissolved calcium carbonate is similar to sites 22-25.

In spite of these exceptions a general statement may be put forward. In the High Mark area the geographical grouping of springs closely reflects similarities in the levels of dissolved calcium carbonate. A broader analysis, however, demonstrates that this phenomenon is part of a wider regional variation in the level of dissolved calcium carbonate. The meaning of this pattern in terms of disposition and movement of water within the High Mark area is discussed below.

2 In Fountains Fell Springs

The pattern of geographical variation in the level of dissolved calcium carbonate in Fountains Fell risings contrasts with that of the High Mark area in several respects.

(i) There is little readily identifiable overall regional pattern in the level of dissolved calcium carbonate in Fountains Fell risings. A slight tendency for springs containing a lower level of dissolved calcium carbonate to be located on the north-westerly flanks of Fountains Fell (sites 69, 71,74-76, 78) might, however, be identified.

(ii) A locational grouping of risings in the Fountains Fell area is rarely reflected in similarities in the level of dissolved calcium carbonate. This contrasts strongly with the High Mark area. Although Bown Scar sites 62 and 63 are similar in the mean level of dissolved calcium carbonate the pattern of variation over the year at these two sites was quite different (Figs.14c and d). Site 61 of this group has a higher mean dissolved calcium carbonate content than that recorded at sites 62 and 63 (198 p.p.m. as compared with 152 and 151 p.p.m. respectively). Similarly, although the mean dissolved calcium carbonate content of three of the Thoragill group of springs (sites 101-105) is similar, the recorded pattern of variation (Figs.22d, 23a,b,c,and d) is quite different at all sites.

(iii) A much greater degree of contrast in the level of dissolved calcium carbonate exists on Fountains Fell risings than on High Mark. In the High Mark area the range of mean dissolved calcium carbonate between the two extreme springs (Arncliffe site 48 with a mean of 154 p.p.m. and Cotegill site 38 with a mean of 252 p.p.m.) was 98 p.p.m. dissolved calcium carbonate. In the Fountains Fell area (excluding Blackhill sites 89 and 90 - see below)the range was 210 p.p.m. (Blishmire site 76 with 57 p.p.m., Lower Tren House site 97 with 267 p.p.m.)

These contrasts between the High Mark and Fountains Fell areas undoubtedly arise out of the contrasts in the mode of recharge between the two areas discussed in Chapters 1, 4 and 5. In the Fountains Fell area the very large local contrasts between risings in the levels of dissolved calcium carbonate reflects the existence of essentially sink-resurgence drainage systems alongside essentially percolation recharged systems. The high level of correlation between dissolved calcium carbonate and the degree of variation in the level of dissolved calcium carbonate (Fig.41) is indicative of the importance of the dilution factor in influencing the level of dissolved calcium carbonate in the Fountains Fell area (see Chapter 4).

In the Blackhill area a major contrast exists between Blackhill sites 89 and 90 and all other sampling sites in both the Fountains Fell and High Mark area. The mean dissolved calcium carbonate content at sites 89 and 90 was only 9 p.p.m. At Blackhill site 91, however, less than 91 m (100 yd) distance the mean level of dissolved calcium carbonate was 19 p.p.m. and at site 92 was 189 p.p.m. A similar contrast exists between the mean pH of these sites. At sites 89 and 90 the mean pH was 4.8 and 4.9 respectively; at sites 91 and 92 the pH was 7.1 and 7.6 respectively. These contrasts are believed to result from the presence of the North Craven Fault between sites 90 and 91 (Map 5) with the water at sites 80 and 90 emerging from joints in the Millstone Grit which in this area has been downthrown against the Great Scar Limestone. The exact position of the fault was not, however, visible in the field.

C Regional Variations in the Degree of Variability of Dissolved Calcium Carbonate

1 In High Mark Springs

Map 14 shows the pattern of geographical variation in the level of dissolved calcium carbonate fluctuation of High Mark springs as measured by the standard deviation. Seasonal variations in the level of dissolved calcium carbonate appear to be largely the outcome of soil micro-organic activity in the plant-root zone (Pitty, 1966), and the short term fluctuations have been attributed to the action of rapidly circulating re-charge or dilution pulses. Map 14, therefore, illustrates regional variations in the operation and effect of these two processes, although in the High Mark area the additional factor of flow-through time exerts some influence on the degree of recorded variation (see Chapter 4).

(i) Springs emerging in Wharfedale and in the Malham Tarn area tend to show less variability in the level of dissolved calcium carbonate than those in the northern parts of the area at Cotegill, Bluescar and Arncliffe. This regional pattern is basically a reflection of two interrelated factors.

(a) the depth of the major flow path of the drainage system beneath the ground surface. Other factors being equal deeper systems will be less open to short term dilution effects than shallower systems. Only near the point of discharge may deep-seated systems be subject to dilution effects. Evidence has already been presented (Chapter 5) to suggest that some of the Wharfedale springs may be risings of deep-seated flows, eg. Robin Hood's Well, site 3.

(b) the length of the flow-through time of the karst water. It has been demonstrated in Chapter 4 that the longer the flow-through time the lower the dissolved calcium carbonate variation tends to be. Many of the Cotegill risings for example have flow-through times of less than two weeks (Map 16) and all show a very pronounced seasonal variation in the level of dissolved calcium carbonate (Figs.7b-9b).

(ii) There is a high degree of similarity in the degree of dissolved calcium carbonate variation in springs of the same locational group. Spring sites 56-58 of the Malham Tarn group show a very low degree of dissolved calcium carbonate variation, with the standard deviation of dissolved calcium carbonate less than 5 p.p.m. At the other extreme Cotegill, sites 31-35 show the highest degree of variation in dissolved calcium carbonate (of High Mark springs) with standard deviations of between 15.8 and 19.3 p.p.m.

A number of exceptions again appear. In the Kilnsey group of springs sites 21 and 26 once again contrast with the other four sites (sites 22-25) of the group. Site 26 shows a high degree of short term fluctuation indicative of strong dilution effects.

2 In Fountains Fell Springs

Several observations may be made concerning the geographical variations of this factor in the Fountains Fell area.

(i) The degree of variation in dissolved calcium carbonate recorded on Fountains Fell risings is generally much greater than that recorded on High Mark springs (Maps 14 and 15). Short term dilution pulses are strongly developed on many Fountains Fell risings (Figs.14a - 23d) and have an important influence on the level of dissolved calcium carbonate in this area.

(ii) A high degree of variability in the degree of fluctuation of dissolved calcium carbonate exists between adjacent sites (in contrast to the High Mark area). At Bownscar, site 61, for example, the standard deviation of dissolved calcium carbonate is 17.3 p.p.m.

and at Bownscar site 62 is 32.9 p.p.m. These contrasts are believed to arise out of the juxtaposition of predominantly percolation recharged systems with predominantly stream-sink fed systems.

(iii) In spite of the large local contrasts in the level of dissolved calcium carbonate fluctuation some degree of regional variation may be detected. Risings located in the southern and south-eastern part of the Fountains Fell upland (sites 88-105) tend to show lower standard deviations of dissolved calcium carbonate than elsewhere in the upland. This low variability suggests that most of these sites are percolation recharged springs.

A very high level of variability in dissolved calcium carbonate was recorded in the Blishmire area between Fountains Fell and Penyghent. Risings sampled in this area appear to be derived from local drainage only, and are often resurgences of small streams which successively sink underground on the limestone member of the Yoredale cyclothems to reappear a short distance downslope on contact with the shale or sandstone member.

D Regional Variations in Flow-Through Times

1 Of High Mark Springs

Several aspects of the regional pattern in flow-through time in the High Mark area may be enumerated (Map 16).

(i) Springs emerging in Wharfedale, south of Kilnsey village tend to have longer flow-through times than any other part of the High Mark area.

(ii) Springs issuing in the valley of Cotegill have the shortest flow-through times in the High Mark area. With the exception of site 38 all Cotegill springs have flow-through times of less than 20 days.

(iii) The Arncliffe group of springs have flow-through times of 22 to 29 days, and the length of flow-through becomes progressively shorter upvalley (Cowside Beck). At site 46, for example, the calculated flow-through is 29 days, at sites 48 and 49 it is 25 days, 23 days at site 50 and 22 days at sites 51 and 52.

A number of factors may be of importance in explaining this regional pattern.

(a) Fig.43 illustrates the relationship of flow-through time to the distance to the nearest large enclosed basin on the High Mark upland. These basins (eg. Plate 1) vary in extent, the smallest being about 4 acres in extent and the largest about 200 acres (Moisley, 1954). Clark (1967) attributes their origin to glacial action although Moisley (1954) suggests that they may have developed from ancient potholes. The scattergraph (Fig.43) suggests that some relationship exists between flow-through time and distance to these basins, a situation which would seem to support Moisley's (1954) hypothesis. Old flow paths established by pre-existing sinking streams may now be of importance in directing the flow of percolation derived water within the limestone massif. It may be that these basins, irrespective of their origin, function as surface or subsurface catchments for percolation water which is then funnelled downward along a definite flow zone.

Hanshaw et alia (1965) and Stringfield and Le Grand (1966) have demonstrated that in the Floridian aquifer the dissolved solids content of the ground-water increases as a function of the length of the flow-path and the residence time in the aquifer, the length of the flow-path being the distance between the recording well and the major recharge zone of the limestone. As all the High Mark basins are located in the highest parts of the upland, and hence in the major zone of recharge, the distance to the basins may be providing a simple index of the distance to the major zone of recharge. The broad similarity of the maps showing regional variations in mean dissolved calcium carbonate, dissolved calcium carbonate variation and flow-through times on High Mark springs (Maps 12, 14 and 16) may, therefore, be explicable in a manner similar to that demonstrated on the Floridan aquifer by Hanshaw et alia (1965).

(b) Although length of flow-path appears to be the major controlling factor in determining regional variations in flow-through time in the High Mark area one further factor should be briefly considered. Doughty (1967) has shown that considerable vertical variability exists in the intensity of jointing in the beds of the Great Scar Limestone. The flow-through time of a particular spring may, therefore, be also related to the joint intensity of the particular bed or beds through which the water is passing.

2 Of Fountains Fell Springs

Owing to the strong dilution influence of allogenic water on many of the Fountains Fell systems no flow-through times could be calculated on a number of sites (see Chapter 4). A number of observations may, however, be made.

(i) In contrast to the High Mark area, no broad regional variation is apparent in the flow-through times of karst water on Fountains Fell. This contrast must again be attributed to factors already discussed, ie. mode of recharge and the effect of dilution.

(ii) No large basins of the type recorded on High Mark are found on Fountains Fell. The length of the flow path may again be a factor in determining regional variations in flow-through time but no data was available on this variable.

E Regional Variations in Mean Dissolved Magnesium Carbonate

1 In High Mark Springs

Two areas in which springs containing relatively high amounts of dissolved magnesium carbonate occur may be identified from Map 18.

(i) Of the twelve spring sites south of Kilnsey village in Wharfedale only one contains less than 10 p.p.m. of dissolved magnesium carbonate.

(ii) The Bluescar springs and those feeding the left bank tributary of Cotegill also contain a relatively high amount of dissolved magnesium carbonate.

Springs issuing to the east of Malham Tarn (sites 56-59) contain the lowest concentration of dissolved magnesium carbonate. All contain less than 6 p.p.m. Several factors may be of significance in influencing this regional pattern.

(a) Regional variations in the availability of magnesium carbonate for solution may be important. Garwood and Goodyear (1924) record that the cyrtina septosa band of the Great Scar Limestone is frequently dolomitized in upper Wharfedale, as seen, for example in Threshfield quarry in the south-eastern part of the High Mark area.

(b) A very general agreement between the pattern of regional variation in flow-through time (Map 16) and in mean dissolved magnesium carbonate (Map 18) suggests that flow-through time may have some influence on the level of dissolved magnesium carbonate.

The locational and chemical grouping of High Mark springs previously identified is further reflected in the levels of dissolved magnesium carbonate. Wharfedale sites 1 and 2 both contain a mean dissolved magnesium carbonate content of 10 p.p.m.; Kilnsey 22-25 of 7 p.p.m.; and Cotegill sites 31-35 of 7-8 p.p.m. dissolved magnesium carbonate. Further examples are apparent from Map 18.

2 In Fountains Fell Springs

Map 19 shows the pattern of regional variation in the mean dissolved magnesium carbonate content of Fountains Fell risings.

(i) The range of concentration of dissolved magnesium carbonate in Fountains Fell risings tends to be greater than that recorded on High Mark. In the High Mark area the greatest mean concentration was 13 p.p.m. at Outgang Hill, site 11, and the lowest was 6 p.p.m. (Cowside Beck, site 53; Malham Tarn, sites 56-59), all located on the western and south-western margins of the area. On Fountains Fell, however, the maximum dissolved magnesium carbonate concentrations were recorded at Blackhill sites 91-93 (66, 72 and 71 p.p.m. respectively) and the lowest concentrations at White Sike Barn site 66 (5 p.p.m.) Blackhill sites 91-93, however, are exceptional in their dissolved magnesium carbonate concentration. Elsewhere in the Fountains Fell area (and High Mark area) no other spring contains a level greater than 19 p.p.m. of dissolved magnesium carbonate (Tongue Gill, site 82). At sites adjacent to Blackhill sites 91-93 the level of dissolved magnesium carbonate was 8 p.p.m. (Blackhill site 89) and 7 p.p.m. (Blackhill site 90). The exceptionally high levels of dissolved magnesium carbonate in the waters of sites 91-93 may indicate the presence of dolomite in the vicinity, possibly associated with the fault zone (North Craven Fault) or the proximity of the Pre-Carboniferous basement.

(ii) With the exception of Blackhill sites 91-93, springs containing a relatively high mean dissolved magnesium carbonate concentration tend to be located on the northern and western flanks of Fountains Fell (Map 19). Examples of these sites are Lower Hesleden site 71 with 16 p.p.m.; Blishmire sites 73, 74, 75, 78 with 13, 11, 10 and 14 p.p.m. dissolved magnesium carbonate respectively; Tongue Gill sites 82 (19 p.p.m.) and 83 (17 p.p.m.) Risings located on the north-eastern (Littondale) and eastern (Thoragill Beck and Cowside Beck sources) margins of Fountains Fell tend to contain lower levels of dissolved magnesium carbonate (between 6 p.p.m. - Thoragill site 103 and 9 p.p.m. - Bown Scar site 61). This regional pattern may also be due to regional variations in the availability of magnesium carbonate for solution. Moore (1958) records the existence of a partly dolomitized limestone at the base of the Underset limestone (Map 3) of the Yoredale series. On account of topography the Underset cyclothem outcrops closer to risings on the northern and western flanks of Fountains Fell than those on the north-eastern and eastern margins.

F Regional Variations in the Degree of Variability of Dissolved Magnesium Carbonate

1 In High Mark and Fountains Fell Springs

Owing to the low concentrations of dissolved magnesium carbonate present in the waters of the field areas, and to the consequent high percentage experimental error in the analyses (see Chapter 2) little discussion may be made of the regional aspects of this variable. It is, however, apparent from Maps 20 and 21 that the variability in the concentration of dissolved magnesium carbonate is much greater on Fountains Fell springs than on High Mark sites. This greater degree of variability appears to be primarily the outcome of the greater dilution factor on

Fountains Fell, although, in addition, many Fountains Fell sites do show a pronounced seasonal pattern in the level of dissolved magnesium carbonate (Figs.14a-23d).

G Regional Variations in Mean Water Temperature

1 Of High Mark Springs

In the High Mark area two contrasting areas may be identified in terms of the mean temperature of water emerging at the risings. In Wharfedale mean water temperatures tend to be high. At Robin Hood's Well (site 3), for example, the mean recorded water temperature was 8.20°C and at the Kilnsey springs the mean recorded water temperature was over 8.00°C on five (sites 21-24, 26) of the six risings. By contrast in the western and south-western margin of the upland recorded water temperatures were low. The highest mean water temperature in this area (of sites 53-59) was recorded at Malham Tarn site 56 (7.42°C). Mean recorded temperatures at sites 53-59 varied between 7.24°C at Cowside Beck (Skirfare) site 54 and Malham Tarn site 56 (7.42°C). This distinct regional pattern present in the mean temperature of water emerging from High Mark springs (Map 22) is primarily a reflection of a high negative correlation between mean spring water temperature and the altitude of the rising (Fig.49). Such a relationship has been previously recorded by Sorby (1859) for springs in the Sheffield region. The temperatures of these springs, he discovered, approximated closely to the mean air temperatures at the altitude of the rising. The temperature of High Mark springs therefore appears to closely reflect the mean air temperature prevailing in their catchments.

Although a linear regression line has been plotted in Fig.49, this does not exclude the possibility of a curvilinear relationship occurring between these two variables in the High Mark area. At the upper end of the water-temperature scale, at Robin Hood's Well site 3, it has been suggested (see Chapter 5) that heat from the earth's interior may be a significant factor influencing recorded temperature. At other sites the influence of catchment aspect may distort a simple temperature/ altitude relationship.

At a few sites deviation of mean water temperature from the line of regression of water-temperature on altitude may be attributed to the influence of air and soil temperatures on discharging waters at the time of sampling. This influence is especially of importance in the summer months at periods of low discharge. Sites at which air temperature interference may have occurred at some period over the time of sampling are indicated by a special symbol in Fig.49. It must be emphasized that this 'contamination' of ground-water temperatures may have occurred at a few sites only.

Some further processes may cause considerable deviation from the regression line.

(i) Water emerging at Cotegill site 33 may be simply a re-rising of stream water from Cotegill, which has short-circuited a meander. The mean recorded water temperatures at this site may therefore be the outcome of factors influencing surface water temperatures eg. direct solar radiation (Chapter 5).

(ii) A few sites are cooler than suggested by the regression of water temperature on altitude. At Cotegill site 35 this deviation is 0.42°C. Water at this site emerges at the base of a long steep slope and the altitude of the rising may not therefore provide a relative index of the altitude of the catchment (relative to other High Mark springs). This may also provide the explanation of the deviation at Bluescar sites 40 and 41.

(iii) Mean temperatures of flood-springs having been calculated on the basis of recordings carried out in flood conditions only, may not be strictly comparable with those at permanently flowing sites, eg. Cotegill site 30.

These considerations are, however, of minor importance and do not significantly effect the close relationship between spring-water temperature and the altitude of the rising observed on High Mark.

The geographical and chemical grouping of springs is further reflected in the mean water temperatures of the springs, although even within a group those springs emerging at slightly higher altitudes tend to be cooler than those discharging at lower levels. The Outgang Hill group of springs provides a good example.

Outgang Hill	Altitude (Surveyed)	Mean Temperature (°C)
Site 6	229.8 m (754 ft)O.D.	7.87
Site 7	224.6 m (737 ft)O.D.	7.91
Site 9	217.3 m (713 ft)O.D.	7.96
Site 8	217.0 m (712 ft)O.D.	7.93
Site 11	207.0 m (679 ft)O.D.	8.27

2 Of Fountains Fell Springs

In the Fountains Fell area it is difficult to identify any distinctive regional pattern in the level of mean water temperature at the rising. A number of observations may, however, be made.

(i) Very low mean water temperatures were recorded at Blackhill sites 89-91 (Map 23). The influence of aspect may be important here. This area is climatically very exposed and snow tends to lie for longer periods than on other areas of similar altitude.

(ii) Fig.50 shows the relationship between mean water temperature and the altitude of the Fountains Fell risings, and emphasizes further the contrast between the karst water systems of Fountains Fell and those of High Mark. In the Fountains Fell area little relationship appears to exist between these two variables (although qualifications to this statement have to be made - see below). Many of the Fountains Fell drainage systems have sections of their courses on the ground-surface prior to sinking. The temperatures of these surface streams is closely allied to factors such as discharge, depth and rate of flow, and altitudinal climatic controls (of the scale found on Fountains Fell) have little effect on their temperature. Geographical variations in the mean water temperature of Fountains Fell resurgences are therefore unlikely to reflect the altitude of the springs catchments. Furthermore owing to the greater rates of flow-through of karst water in the Fountains Fell area (see above) there is less contact between circulating water and bedrock than occurs on High Mark systems. Consequently the interaction of bedrock temperatures with those of circulating water is small. Surface temperature fluctuations may therefore be transmitted through to the rising with little alteration.

(iii) Although the overall relationship between water temperature and altitude on Fountains Fell is masked by a number of interfering factors, principally that of dilution by allogenic water mentioned above, the altitudinal factor is still apparent in some parts of the area. Fig.51 shows the regression of spring water temperatures on altitude for upper Littondale risings only (spring sites 60-64, 67-69, 71). It is not known why, of the Fountains Fell risings, the Littondale risings should exhibit such a close relationship between water temperature and altitude. Possibly minimal recharge from allogenic streams, or closer association between circulating water and bedrock may be important factors.

In the Fountains Fell area, therefore, although altitude of the rising (reflecting mean air temperatures in the catchment) is an underlying factor in explaining the regional variation shown in Map 23 this factor is often masked by severe allogenic influences on many systems.

H Regional Variation in the Degree of Variability of Water Temperature

1 Of High Mark Springs

Regional contrasts in the degree of spring water temperature fluctuation in the High Mark area are strong. Springs located to the west of Malham Tarn (sites 53-58) and in Wharfedale near the North Craven Fault (sites 1-9) show very little variation in water temperature over the year, in contrast to those near Arncliffe and in Cotegill valley. These examples appear to be part of a broad increase in the degree of variability in water temperature northwards from the North Craven Fault.

Water temperature variations, as seen in Chapter 5 are of two types: (a) short term pulses arising out of the action of rapidly circulating rainfall pulses, and (b) a broad seasonal variation resulting from the penetration of the seasonal air temperature wave to the groundwater. Of primary importance in the effect of these two interrelated processes (see Chapter 5) is the depth of the major flow-zone beneath the ground surface, and the flow-through time of the karst water. Drainage systems flowing close to the ground surface will show both a well developed seasonal water temperature wave and possibly well developed short term temperature pulses. Cotegill sites 31-34 (SDs = 2.91, 2.61, 2.50, 3.22°C) for example appear to be the points of discharge of very shallow systems probably not more than a few feet below ground-surface. Water movement in some of these drainage systems may be taking place only through the limestone boulders and scree of the valley floor, and, as suggested above (site 33) may be in some cases simply the re-rising of stream water shortcircuiting stream meanders.

By contrast the risings at Robin Hood's Well and Chapel House Well (sites 3 and 5) appear to be the discharge points of deep drainage systems scarcely affected by either the seasonal or short term temperature effects (SD = 0.09 and 0.13°C respectively). These sites have already been discussed in Chapter 5 and 6.

Although depth to the major flow-zone may be of great importance in influencing variations in the development of the seasonal temperature wave on High Mark springs, the depth of penetration of the seasonal air temperature wave into the bedrock is closely related to the permeability of the limestone. As shown in Chapter 5 the transmission of air temperature effects to the ground-water is largely through the medium of circulating water and contrasts between catchments in flow-through time may therefore be a significant additional factor in understanding regional patterns in the degree of water temperature fluctuation.

The pattern of regional variation in the degree of fluctuation of water temperature as shown in Map 24 is believed therefore to provide a direct measure of: (a) variations in the depth of the flow-zone of different systems, (b) regional variations in flow-through time of High Mark drainage systems.

2 Of Fountains Fell Springs

A much more complex geographical pattern in this factor is once more discovered in the Fountains Fell area (Map 25).

(i) Water temperature variability tends to be much greater in the Fountains Fell area than on High Mark. In the High Mark area the mean standard deviation of water temperature was 0.80°C as compared to 1.53°C on Fountains Fell risings. Again the same factors may be enumerated. Surface temperature fluctuations on Fountains

Fell are transmitted rapidly through the system through open caves and potholes, and there is little dampening of these fluctuations through contact with bedrock. This permeability factor has been discussed earlier. In addition the mixture of water derived from percolation recharge with that derived from sinking stream recharge probably initiates greater variation in water temperature than could occur where sinking stream recharge is negligible.

(ii) Risings located on the north-western and western flanks of Fountains Fell (sites 73, 76, 78, 80-83, 87) show a high degree of variability in water temperature with standard deviations frequently exceeding 2.5^{o}C. Sites on the north-eastern, eastern and south-eastern flanks (sites 60-64, 67-69, 71, 93-96, 98, 99, 101, 103-105) show a relatively low degree of variability.

Although this regional pattern may be again indicative of the depth of the flow-zones beneath the ground surface, recharge by sinking streams through open potholes (permeability factor) allows large variations in water temperature to be transmitted to greater depths than occurs on High Mark.

I Regional Variations in the Lag of Spring Water Temperatures behind Air Temperatures

1 On High Mark and Fountains Fell Springs

In Chapter 5 it has been stated that, with the exception of a few sites, the lag of water temperatures behind air temperatures is a measure of the time of penetration of the seasonal air temperature wave through to the major flow-zone of the system. Owing to the importance of circulating water in transmitting this seasonal air temperature wave (in addition to short term effects) - see Chapter 5, the lag of water temperatures behind air temperatures is closely allied to, but usually longer than, the actual flow-through time of the system (Maps 26 and 27).

J Ground-Water Disposition and Circulation in Limestone

The problem of karst water disposition and circulation, a topic of controversy for over half a century (Martel, 1894, 1921; Grund, 1903; Davis, 1930; Lehmann, 1932; Zötl, 1965) is still largely unresolved. Basically two apparently opposite viewpoints may be identified.

1 Explicit in many theories of cave origin and development (Davis, 1930; Swinnerton, 1932; Rhoades and Sinacori, 1941; Bretz, 1942; Sweeting, 1950) and in other ground-water studies in limestone areas (Ineson and Downing, 1965) is the assumption that an interconnected and integrated zone of permanent saturation exists in limestone areas, an idea usually associated with the name of Grund. Grund (1903) recognized a zone of saturation with sea level as the base level in the Adriatic region. This zone of saturation is separated from the unsaturated vadose zone or 'zone of aeration' (Sokolov, 1967) by a water table or piezometric surface. A number of workers have, however, demonstrated the existence of large perched water bodies within this zone of aeration (Newbury, 1968; Kennard and Knill, 1969) due to the non-uniform permeability of the strata of soluble rocks and the presence of local aquicludes. The idea of a zone of aeration separated from a zone of permanent saturation by a steady or fluctuating water table is obviously an oversimplification in many limestone areas.

2 The opposite viewpoint is put forward by those who maintain that circulation takes place largely in independent discrete drainage systems. Martel (1921) believed that the water occurred in underground streams and described results of tracer experiments on limestone streams. Lehmann

(1932) considered that interconnection of water carrying channels was improbable, and recent work reported by Zötl (1965) has revealed groundwater systems in which the water table concept has no apparent place. Doubt on the validity of a simple water table concept with regard to Yorkshire limestone areas was first suggested by the work of the Yorkshire geological society in 1900 who demonstrated that the courses of the underground waters in the vicinity of Malham Tarn crossed each other and yet maintained a separate identity (Howarth, Fennell, Bean, Branson, Ackroyd, Kendall and Lower Carter, 1900). More recent work (Drew, 1966; Pitty, 1966) also points to the discrete nature of water movement in other limestone areas in Britain.

It is obvious from even these few brief comments that water disposition and circulation in limestone areas may be extremely complex, and considerable variation may be expected in different limestone areas. Indeed, there is strong evidence to suggest that both types of water disposition may occur. The type of observational work which includes analyses of karst water (Sweeting, 1960; Sweeting and Gerstenhauer, 1960; Smith and Mead, 1962; Williams, 1963; Ford, 1964, 1966) and the identification of factors instrumental in causing variations in solutional losses (Pitty, 1966) has led to a greater understanding of water circulation and disposition in many limestone areas. It is believed that the karst water studies recorded in this work particularly in the foregoing regional analysis permit a number of observations and tentative conclusions to be made concerning water disposition and circulation in the High Mark and Fountains Fell areas of north-west Yorkshire.

K The Nature of Water Disposition and Circulation in the High Mark Limestone Upland

Water movement in the High Mark area is believed to occur in major, essentially discrete, flow-zones radiating from the central upland zone of maximum recharge. A number of factors have been considered in arriving at this conclusion.

(i) The peripheral location of springs in physically isolated groups or as large single springs strongly suggests that these areas represent the discharge points of major flow-zones within the limestone, which are essentially discrete in character.

(ii) The close conformity of the chemical and physical parameters observed to these locational aspects of the springs. As the term 'flow-zone' implies, therefore, this ground-water movement is believed in many cases, to occur as a belt or zone of movement rather than a single flow moving along a single joint or cave system. South-west of Arncliffe village, for example, sites 46-52 are considered to be the discharge points of one of these flow-zones, although the horizontal distance between the two extreme springs (site 46 and site 52) is 100 m (110 yd). The flow-zone which discharges at Reynard's Close risings sites 19 and 20 is by contrast only a few metres in width and may be simply one large stream of flow.

(iii) The rapid response of discharge at the risings to heavy precipitation (see Chapter 6) suggests that no very large ground-water body exists to dampen the precipitation pulses. There is, however, evidence to suggest that some degree of ground-water storage exists on many of these systems, eg. Robin Hood's Well site 3, as demonstrated by the push-out effects discussed in Chapter 6.

(iv) Although a broad regional pattern is apparent in many of the recorded variables, eg. mean dissolved calcium carbonate it is believed this is explicable in terms of length of flow-zone (see above) rather than due to the existence of an integrated ground-water body within the High Mark upland.

(v) The concept of a unified interconnected ground-water body in the High Mark area may also be rejected on two other lines of evidence.

(a) It has already been observed that the accordance of the chemical and physical parameters measured with the locational grouping of springs is not perfect. Site 11 was observed to vary considerably in its observed properties from sites 6-9 of the Outgang Hill group; likewise sites 21 and 26 of the Kilnsey group showed certain dissimilarities with the other sites (sites 22-25) of the group. These exceptions, although few in number, make the acceptance of an integrated ground-water body concept difficult, although they may easily be explicable in terms of convergence of relatively minor flow paths towards the major flow-zone. Cotegill sites 37 and 38 which emerge at a much higher altitude than their neighbours are believed to be the points of discharge of an essentially local perched drainage system.

(b) On the assumption that an integrated ground-water body does exist within the High Mark area, an evenly distributed peripheral distribution of springs might be expected. However, as already discussed, a marked peripheral grouping of springs occurs.

Essentially, therefore, water movement in the High Mark area appears to be discrete in nature, with major flow-zones radiating from the central upland areas. These flow lines may be guided by basement structures or by ancient sink-resurgence paths, and little topographical control appears to exist. Owing to the proximity of the impervious basement deep-seated circulation cannot take place, although many systems may have parts of their flow-zone at or near the unconformity.

L The Nature of Water Disposition and Circulation in the Fountains Fell Upland

Water circulation in the Fountains Fell area appears to take place in discrete drainage systems, and there is no evidence to suggest the existence of an integrated water body within the limestone of this area.

(i) Springs in close proximity have often very different physical and chemical properties (see regional analysis and Maps 12-27).

(ii) The swiftness of the flow-through times through the limestone mass argues against the existence of an integrated water body.

(iii) Water circulation in the Fountains Fell area appears to be essentially of a sink-resurgence type, although on many of these systems percolation recharge may contribute a greater proportion to the total flow than the sinking stream component. Unlike the High Mark area these systems discharge at single springs only, rather than at groups of springs.

M Conclusions

The conclusions from this regional analysis may be summarized in a number of points.

1 A locational grouping of springs around the High Mark area is reflected to a high degree in similarities in recorded chemical and physical properties of the water.

2 In the Fountains Fell area little locational grouping of springs occurs and, when present, rarely reflects similarities in recorded physical and chemical properties of the water.

3 The broad regional patterns in mean dissolved calcium carbonate and the standard deviation of dissolved calcium carbonate are closely related to flow-through time. The distance to the area of maximum recharge

or the length of the flow-path may be an important factor influencing the regional pattern in flow-through time.

4 In contrast to the High Mark area a high degree of local variation in mean dissolved calcium carbonate, standard deviation of calcium carbonate and flow-through time exists on Fountains Fell and reflects the juxtaposition of systems recharged by allogenic karst water and those fed predominantly by percolation.

5 The regional pattern in mean dissolved magnesium carbonate levels in limestone springs appears to be primarily related to the availability of magnesium carbonate for solution. This is particularly notable in the Blackhill area where the line of the North Craven Fault may be identified from contrasts in the quality of the spring waters.

6 Regional variation in the mean water temperature of High Mark springs is basically a function of altitudinal changes in climate, although aspect may be of some importance.

7 Although altitudinal climatic effects also appear to be of some importance in effecting mean water temperatures on Fountains Fell risings, the overall pattern is confused by the action of allogenic karst water.

8 Regional variations in the standard deviation of water temperature relates to factors such as depth of major flow-zone, variation in subterranean passage development (contrast between Fountains Fell and High Mark areas), mode of recharge and flow-through time.

9 Basement structures may play an important role in directing water movement in both the High Mark and Fountains Fell areas. Water movement in both areas appears to be essentially discrete in nature.

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CHAPTER EIGHT

CONCLUDING REMARKS

CONCLUDING REMARKS

Unlike much previous research in limestone hydrology this work has involved the continuous study over time of a large number of karst drainage systems. Consequently it has been possible, while stressing the uniqueness of each karst drainage system, to identify the dominant factors influencing karst water characteristics and karst water movement in a major limestone area.

Partial chemical analyses of spring waters at 82 sites has shown that almost all sampled springs emerging from the High Mark and Fountains Fell uplands show a detectable seasonal wave in the level of dissolved calcium carbonate. A number of different explanations for this seasonal pattern may be found in the literature. Although some of these have already been extensively reviewed by Pitty (1966) it is valuable to re-examine the main theories in view of the findings in north-west Yorkshire presented in this thesis.

It is unlikely that any theory which relies on a negative association between limestone solution and air temperature can account for the observed seasonal variations in limestone solution in north-west Yorkshire. Corbel (1957, 1959, 1960) considered that the greater solubility of carbon dioxide at lower temperatures would lead to a greater intensity of limestone solution in cold climates and presented data which appeared to support his conclusions. In north-west Yorkshire, however, almost all springs and streams on which systematic measurements were carried out contained their maximum concentrations of dissolved calcium carbonate in the summer and autumn months (Figs. 3a-40b). If a negative relationship between limestone solution and temperature is to be considered a lag effect of greater than six months is essential. Such a negative relationship may be dismissed on several grounds. Firstly, on almost all sites the seasonal water temperature peak is in approximate coincidence with the seasonal dissolved calcium carbonate peak. As the relationship between water temperature and air temperature is undoubtedly positive (Chapter 5) it is probable that the relationship between dissolved calcium carbonate and air temperature is also positive. Secondly fluorescein tracings carried out by the Craven Pothole Club on a number of Fountains Fell systems have shown lags of a few days only between water sinking in swallets and its emergence at a rising (for example site 99). A delay therefore of 6-8 months of a winter peak in solution (the maximum dissolved calcium carbonate concentrations at site 99 occurred in August) appears to be unacceptable. Finally, many of the surface streams showed a summer peak in dissolved calcium carbonate (Figs. 24a-35), a phenomenon which again indicates a positive relationship between limestone solution and temperature.

Three major reasons for a summer maximum in limestone solution need to be examined. Firstly some workers (for example Hendrickson and Krieger, 1964) have suggested that seasonal changes in dissolved solids may be due to seasonal changes in the rate of recharge to the ground-water. In the Fountains Fell area 76% of the risings showed a high negative correlation between dissolved calcium carbonate variations and antecedent effective precipitation and a similar high negative correlation was found on 31% of the High Mark springs (Chapter 4). As much of the rainfall and therefore most of the recharge to the High Mark and Fountains Fell systems occurs in the winter period it would seem possible that such a negative correlation could give rise to a seasonal variation in dissolved calcium carbonate concentration in the spring waters with minimum concentrations occurring in the winter months. The statistical analysis of the relationship between dissolved calcium carbonate and antecedent hydro-meteorological conditions (Chapter 6) has however demonstrated that for the majority of case study sites (67% in year 1, 89% in year 2) the antecedent air temperature factor extracts a greater percentage of the dissolved calcium carbonate variance than the effective precipitation factor.

Although seasonal variations in recharge may well serve to emphasize the seasonal pattern in dissolved calcium carbonate, the temperature variable appears to be of greater significance. Variations in effective precipitation do however appear to have a marked effect on short term fluctuations of dissolved calcium carbonate. It has been proposed (Bögli, 1964, Thraikill, 1968) that the cooling of percolating water with increasing depth thus increasing the solubility of carbon dioxide could give rise to further solution at depth (Abkühlungskorrosion). Cooling of percolating water in summer may result in considerable undersaturation and further solution and warming of percolating water in winter could give rise to precipitation. Within the field area the analysis of water temperature variations (Chapter 5) has demonstrated that recharge pulses or dilution pulses tend to have a positive effect on the temperatures of the ground-water and spring water in winter and a negative (cooling) effect in summer. Theoretically, therefore, this seasonal warming and cooling of the ground-water could give rise to a seasonal wave in the dissolved calcium carbonate concentrations in the spring waters. The analysis of the relationship between dissolved calcium carbonate and antecedent effective precipitation has, however, demonstrated a dilution effect by rapidly circulating water at all seasons of the year, (Chapter 4). Any seasonal temperature effects therefore appear to be insufficient to mask the overall dilution effects of rapidly circulating water. Furthermore, an examination of the graphs of recorded temporal variations in water temperature and dissolved calcium carbonate shows that those springs with the greatest development of a seasonal dissolved calcium carbonate wave also exhibited the greatest seasonal range in water temperature. The seasonal mediating effect and consequent solutional effect described above therefore appears to be least operative on those springs showing the greatest seasonal development in dissolved calcium carbonate variation.

Finally seasonal variation in dissolved calcium carbonate has been attributed to the greater biochemical production of carbon dioxide in the soil arising out of increased root and microbial respiration at higher temperatures (Pitty, 1966). The degree to which the seasonal dissolved calcium carbonate wave in the spring waters is out of phase with the air temperature wave provides a direct measure of the time taken for the water to pass through the limestone system (flow-through time). The existence of a high negative correlation between the standard deviation of dissolved calcium carbonate and the calculated flow-through time (Chapter 4) supports the conclusion that variations in dissolved calcium carbonate are initiated at or near the ground-surface, and are suppressed as water moves through the limestone aquifer. On springs emerging in the valley of Cotegill (sites 31-34) with flow-through times of less than 14 days standard deviations of between 8.6 and 10.6 p.p.m. of dissolved calcium carbonate were recorded. By contrast standard deviations of less than 4.0 p.p.m. were recorded on Wharfedale springs with calculated flow-through times of greater than 40 days (eg: sites 3,5,8,9 and 20). In some areas the calculation of flow-through times may be impossible owing to almost complete suppression of the seasonal dissolved calcium carbonate wave with increased residence time of the circulating water (for example in areas with a thick soil or drift cover). This may provide one explanation of the lack of correlation of calcium hardness with antecedent air temperature at a number of percolation springs in Gower reported by Groom and Ede (1972).

Flow-through times of High Mark springs were found to be highly variable ranging from 9 days to 108 days although the majority of the drainage systems have flow-through times of less than 42 days. By contrast owing to stronger dilution effects in the Fountains Fell area fewer springs show a high positive relationship with antecedent air temperatures, and flow-through times are shorter. These contrasts are believed to reflect the basic differences between the two areas in the mode of recharge to the limestone and in the degree of conduit development. In the Fountains Fell area sinking streams formed on the largely impermeable Millstone Grit and Yoredale caprock, and 'fast percolation' through numerous enclosed depressions provide the major sources of recharge to the limestone. By contrast on High Mark no open conduits leading large concentrated volumes of water underground exist, and recharge is almost purely by diffuse percolation through a thin or absent soil cover. Cave development is also much greater in the Fountains Fell area than in High Mark.

On High Mark there is some evidence to suggest that flow-through time may be related to the length of flow-path. Fig.43 suggests that some relationship exists between flow-through time and the distance to the nearest large enclosed basin on the High Mark plateau. Such a relationship would support Moisley's (1954) suggestion that some of these basins may have developed from ancient potholes. Old subterranean flow paths established by ancient sinking streams may be now of importance in directing the flow of percolation derived water within the limestone massif. If the flow-through time of High Mark springs is a direct function of channel length this suggests that little variation exists within the High Mark area in terms of subterranean channel development. On the evidence of figure 43 it would appear that ground-water flow-rates in the High Mark area are in the order of 60 to 80 m per day. The thinness of the soil cover on much of High Mark and the possibility of pre-existing swallet-resurgence conduits now being used by percolation waters provide the probable explanations of these rapid flow rates.

A number of important factors have emerged from a study of the relationship between seasonally divided observations (ie: recordings carried out in the summer period, the winter period, the dry conditions period and the wet conditions period) and antecedent air temperature. In both the High Mark and Fountains Fell areas antecedent air temperature is of much greater significance in initiating dissolved calcium carbonate variations in the summer and dry conditions periods than in the winter and wet conditions periods. In the Fountains Fell area this contrast is more pronounced and reflects the high dilution element occurring in the wetter periods of the year. It appears from this seasonal analysis therefore that variations in soil carbon dioxide production is of maximum importance in the summer and drier periods in influencing variations in limestone solution. During the colder and wetter parts of the year, however, rainfall variations may be of greater significance.

The relationship between variations in dissolved calcium carbonate and antecedent effective precipitation was also investigated in some detail. In the Fountains Fell area 76% of the risings showed a high negative correlation between dissolved calcium carbonate variations and antecedent effective precipitation as opposed to only 31% on High Mark. This difference again reflects the contrast between the two areas in mode of recharge and conduit development described above. Within both areas considerable differences exist between springs in the significance of this dilution element. Within the High Mark area this is believed to be the result of two factors. Firstly the proportion of bare rock and limestone pavement may be important. Open joints in limestone pavement areas allow direct entry of rainfall into the bedrock and ground-water system in contrast to soil covered areas where the dilution influences are dampened by the slow passage of the water through the soil cover. Secondly the depth of the major flow-zone beneath the ground-surface may be of some importance in determining the extent of dilution. On shallow systems water quickly reaches the major flow zone with little suppression of the dilution influences. Even on more deep-seated flows dilution effects may penetrate to the major flow-zone near the point of ground-water discharge. On Fountains Fell differences in the significance of the dilution factor may additionally be related to the relative importance of swallet sources and percolation sources in providing recharge to the ground-water systems. Open vertical potholes within the limestone also allow these dilution effects to penetrate to greater depths than would occur in a purely percolation system.

The negative correlations between temporal variations in dissolved calcium carbonate and antecedent effective precipitation usually demonstrate a time-lag of less than one week for the dilution pulses to appear at the rising. Evidently therefore some component of recharge 'flows-through' the limestone within a few days. It should be emphasized again therefore that 'flow-through time' refers to the dominant residence time of the largest volume of water in circulation.

In addition to this negative correlation between variations in dissolved calcium carbonate and antecedent effective precipitation a positive association between these two variables was also observed on a number of High Mark springs (preceding the negative correlation) suggesting a partial flushing out of the system by the dilution water. The much longer time lag between dissolved calcium carbonate variation and antecedent temperature variation (flow-through time) on many of the springs indicates that these flushing out effects are only partial in nature probably involving water entering the system near its exit where the rate of water circulation is more rapid.

Further evidence of this partial flush out effect is provided by the case study analysis carried out in Chapter 6. A detailed investigation of the relationship of discharge, dissolved calcium and magnesium carbonate and water temperature with antecedent effective precipitation and air temperature was carried out at nine selected case study sites in the High Mark area. The statistical analysis of these spring water characteristics with antecedent effective precipitation suggested that following a rain period certain specific variations in the karst water characteristics might be predicted. Heavy rainfall is usually followed within seven days by an increase in discharge at the nine risings. The timing and duration of this discharge pulse varies from spring to spring and undoubtedly reflects the characteristics of the surface and subsurface catchment such as catchment shape, size and morphology, as well as recharge factors. Although on all sites dilution of dissolved calcium carbonate appears to begin shortly after the occurrence of heavy rainfall the statistical analysis suggests that dilution tends to reach a maximum after the major discharge pulse has passed. This may be related to the arrival of a larger element of actual flood of dilution water at the rising than occurred during the transit of the major discharge pulse. Much of the major discharge pulse appears to be composed of water flushed out of the system, a conclusion which supports the evidence derived from the analysis of dissolved calcium carbonate variations.

Although the timing of the dissolved magnesium carbonate dilution pulse varies considerably from spring to spring there is a tendency for the maximum dilution of dissolved magnesium carbonate to occur after the maximum dilution of dissolved calcium carbonate. The timing of the water temperature pulse consequent upon heavy rainfall is also highly variable from spring to spring.

The correlation of dissolved calcium and magnesium carbonate content and water temperature with discharge at the time of sampling emphasizes that discharge is basically dependent upon two factors. Of first importance is the degree of coincidence of the lag of dissolved calcium carbonate fluctuation behind effective precipitation, a factor which must be closely related to the degree of ground-water storage within the system. Secondly the level of correlation between the two dependent variables (in this case discharge and dissolved calcium carbonate) and antecedent effective precipitation is important.

A study of the temperatures of the limestone waters, a property often neglected by karst workers, has identified a few of the processes significant in introducing air temperature effects to the karst drainage systems. At almost all sampling sites the pattern of water temperature fluctuation recorded was that of short term temperature pulses superimposed upon a broad seasonal temperature wave. The pattern of water temperature variation recorded at most sites shows a high level of positive correlation with the air temperatures some time prior to recording. The lag of water temperatures behind air temperatures is a measure of the time of penetration of the seasonal air temperature wave to the major flow zone and to the point of discharge. In contrast to less permeable regions (Schneider,1962 a & b) the speed and depth of transmission of the seasonal temperature wave is great. The role of circulating water was found to be of paramount importance in introducing both the short term temperature pulses and the broad seasonal temperature wave to the ground-water. The bases of this conclusion may be briefly summarized. The analysis of the relationship between spring water temperatures and effective precipitation has shown that direct transmission of at least short term temperature effects occurs through the medium of rapidly circulating recharge. On shallow systems where both the seasonal and short term water temperature fluctuations appear to be introduced directly through the medium of rapidly circulating recharge or dilution water the lag of spring water temperatures behind air temperatures coincides with the flow-through time or residence time of the karst water. On systems in which the rate of ground-water circulation is slower the lag of the spring water temperatures behind air temperatures is greater than the flow-through time. The seasonal air temperature wave is not therefore carried directly through the system by circulating water (except on the shallow systems as outlined above) but is delayed to some degree possibly owing to heat exchange between percolating water and bedrock. Finally the speed of transmission of the seasonal air temperature wave through the limestone to the point of ground-water discharge (water temperatures of 46% of High Mark springs lag behind air temperature by less than 14 days) points to the importance of rapid water circulation in transmitting the temperature effects.

Short term water temperature pulses are closely related to the action of rapidly circulating recharge water or dilution water. As stated above this rapidly circulating component tends to have a positive effect in winter on the temperature of the spring waters and a negative effect in summer. Furthermore its effect on the spring water temperatures is more immediate in winter than in summer probably due to the greater volumes of recharge occurring in the winter months. By contrast however, the lag of spring water temperatures behind air temperatures is greater in the winter period than in the summer. This phenomenon is similar to that observed by Schneider (1962a). In winter viscosity effects and ground freezing cancel out the influence of greater winter recharge on the rate of water circulation. A fall of temperature of 0.56°C in the ground-water temperature raises the viscosity sufficiently to reduce the rate of flow by 1½% (Walton, 1970). Seasonal temperature contrast of more than 10°C known to occur on surface streams within the field area may initially vary the rate of flow by over 26%. With the exception of a few High Mark springs these effects are, however, rarely sufficient to reverse the effect of greater winter recharge on the rapidly circulating (dilution) component.

The ground-water component of river discharge was observed to have an important thermal effect. Ground-water discharge from springs has a cooling effect on the temperature of surface streams in summer and a warming effect in winter, a phenomenon also observed by Ineson and Downing (1964) on chalk streams. The winter temperature effects are of greater importance.

Finally a spatial analysis of the recorded karst water characteristics was under-taken. In the High Mark area a marked locational grouping of springs was found and this coincided to a high degree with similarities in the recorded karst water characteristics. It would appear that water movement in the High Mark area occurs along certain well defined zones possibly controlled by basement topography or by the line of pre-established sink-resurgence paths. By contrast little locational grouping of springs was observed in the Fountains Fell area and when present rarely reflected similarities in the karst water characteristics. The broad regional patterns in mean dissolved calcium carbonate and in the standard deviation of dissolved calcium carbonate of the spring waters observed on High Mark are essentially related to the flow-through time which in turn may be related to the length of the flow-path (see above). The influence of lithology on limestone solution appears to be a constant factor within the High Mark area, although contrasts between dissolved calcium carbonate concentrations in, for example, springs draining the Jurassic oolitic limestones (Paterson, 1972) and those draining the Carboniferous limestone of High Mark may well be the outcome of lithological differences. On Fountains Fell a high degree of local variation in mean dissolved calcium carbonate, in the standard deviation of dissolved calcium carbonate and the flow-through time was recorded and reflects the juxtaposition of systems recharged by allogenic karst waters and those fed predominantly from percolation sources. The regional pattern in the mean dissolved magnesium carbonate level in springs appears to be primarily related to the availability of magnesium carbonate for solution. This is particularly notable in the Blackhill area where the line of the North Craven Fault may be identified from contrasts in the quality of the spring waters. Further investigations are however, needed into the sources of magnesium carbonate in the field areas. Regional variations in the mean water temperature of High Mark springs is basically a function of altitudinal changes in climate, although aspect may be of some importance. Although altitudinal climatic effects also appear to be of some significance in effecting the mean water temperatures of Fountains Fell risings, the overall pattern is confused by the action of allogenic karst water. Regional variations in the standard deviation of water temperatures appears to be related to factors such as depth of the major flow-zone, variations in subterranean conduit development (contrast between Fountains Fell and High Mark), mode of recharge and flow-through time.

In both the High Mark and Fountains Fell areas basement structures appear to play an important role in directing water movement. An examination of spring distribution, spatial patterns in the recorded physical and chemical parameters, the response of discharge to antecedent effective precipitation, and the residence time of circulating ground-water also leads to the conclusion that water movement in both areas is essentially discrete in nature.

Attention has been continusouly drawn to the contrast between the High Mark percolation systems and the Fountains Fell systems recharged by both percolation and sinking stream sources. Although as a group the Fountains Fell systems show greater dilution effects than the High Mark percolation systems this contrast is essentially one of degree. Kilnsey Crag spring site 26 for example classifiable as a percolation spring shows dilution effects as strong as those recorded at springs 98 and 99 known to be supplied at least in part from swallet sources. On High Mark even the more deep-seated flows such as Robin Hood's Well (sites 3 and 4) show some signs of dilution.

Finally it should be emphasized that the analysis of the observations carried out in north west Yorkshire presented in this thesis is still essentially in a preliminary stage. Some of the conclusions made are necessarily tentative and more thoroughly tested conclusions may require more sophisticated statistical analysis and the accumulation of comparable data from other areas.

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THE UNIVERSITY OF HULL

KARST WATER STUDIES IN THE MALHAM AREA, NORTH OF THE CRAVEN FAULTS

Volume 2

Figures, Maps and Plates

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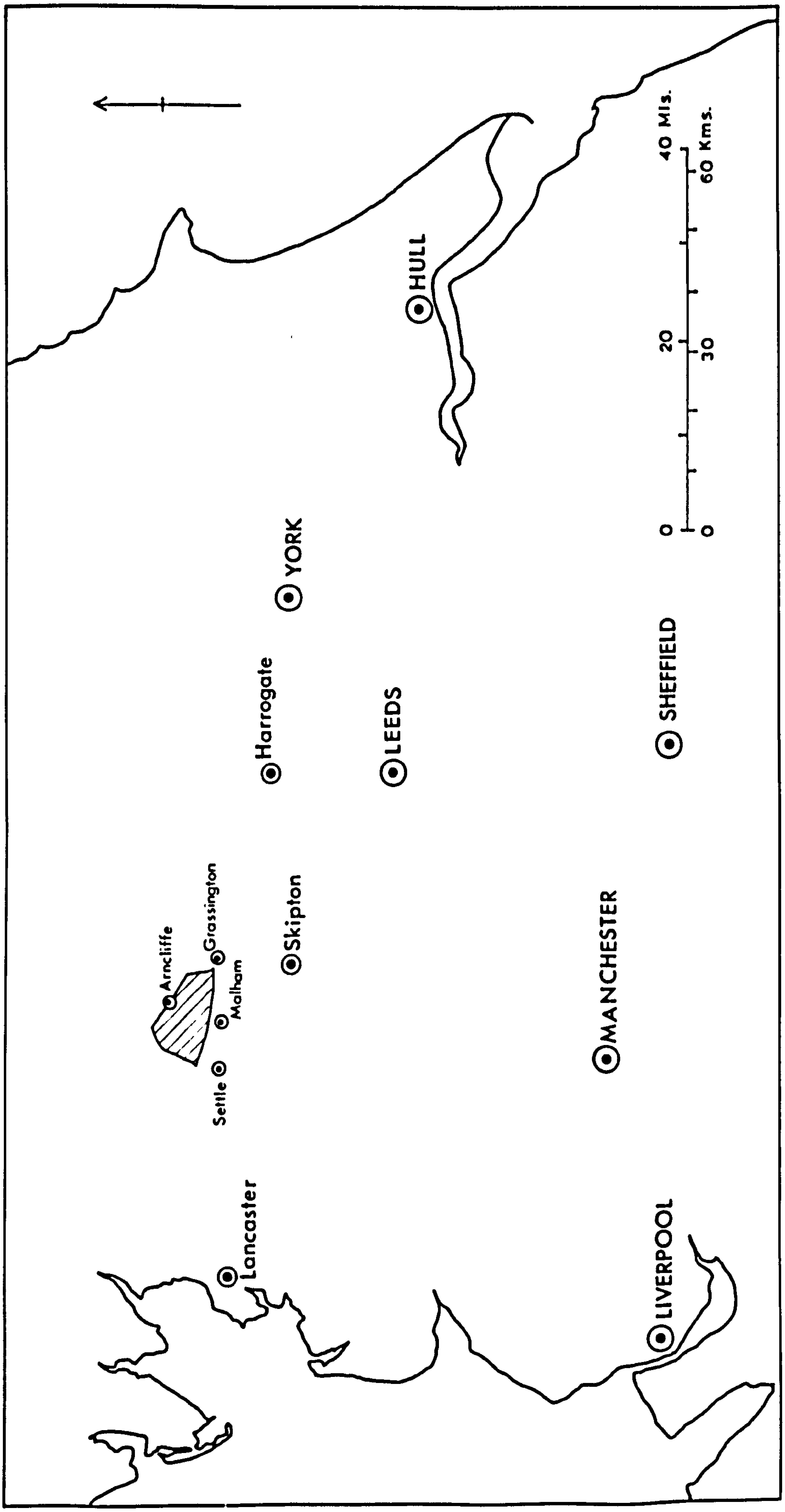
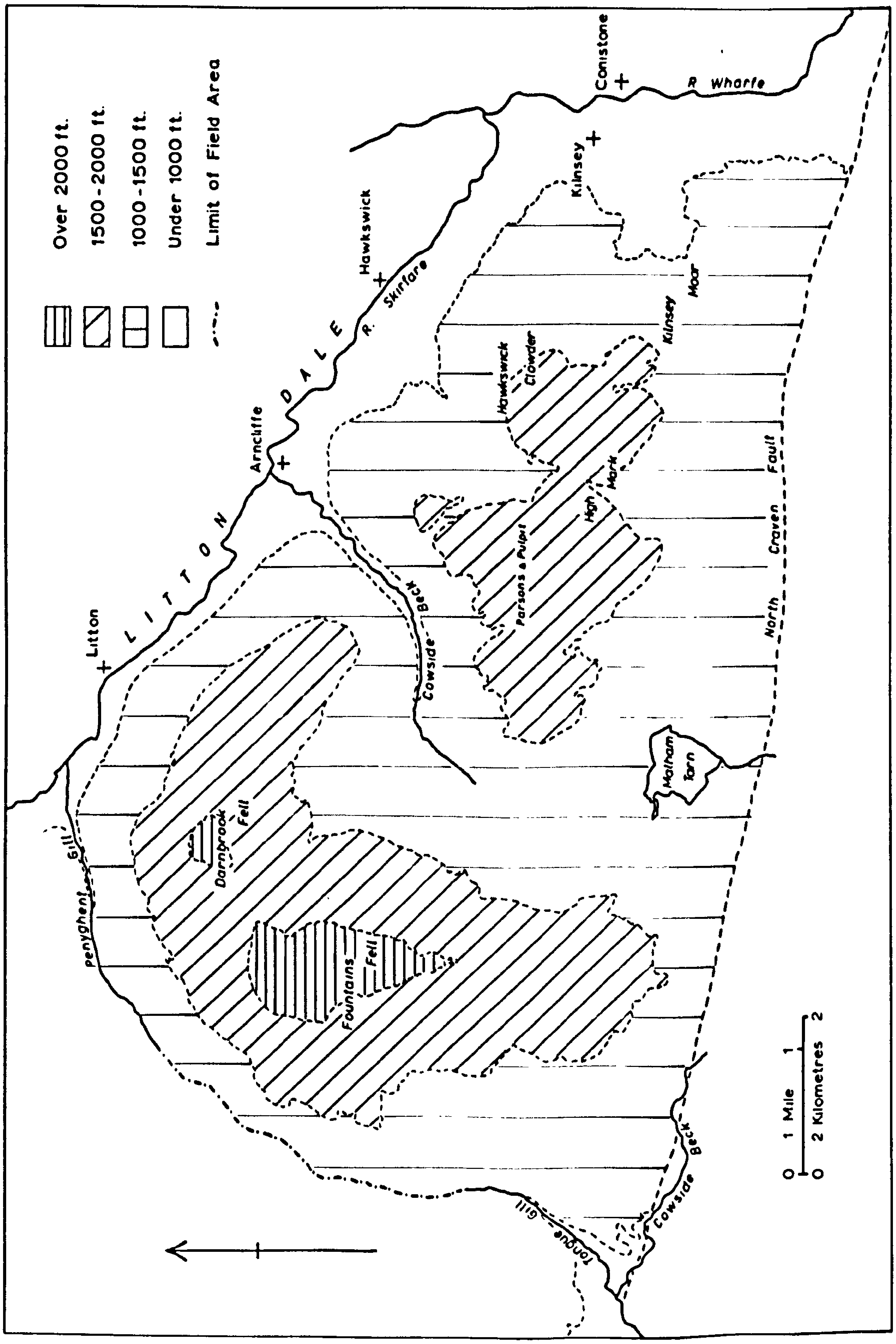
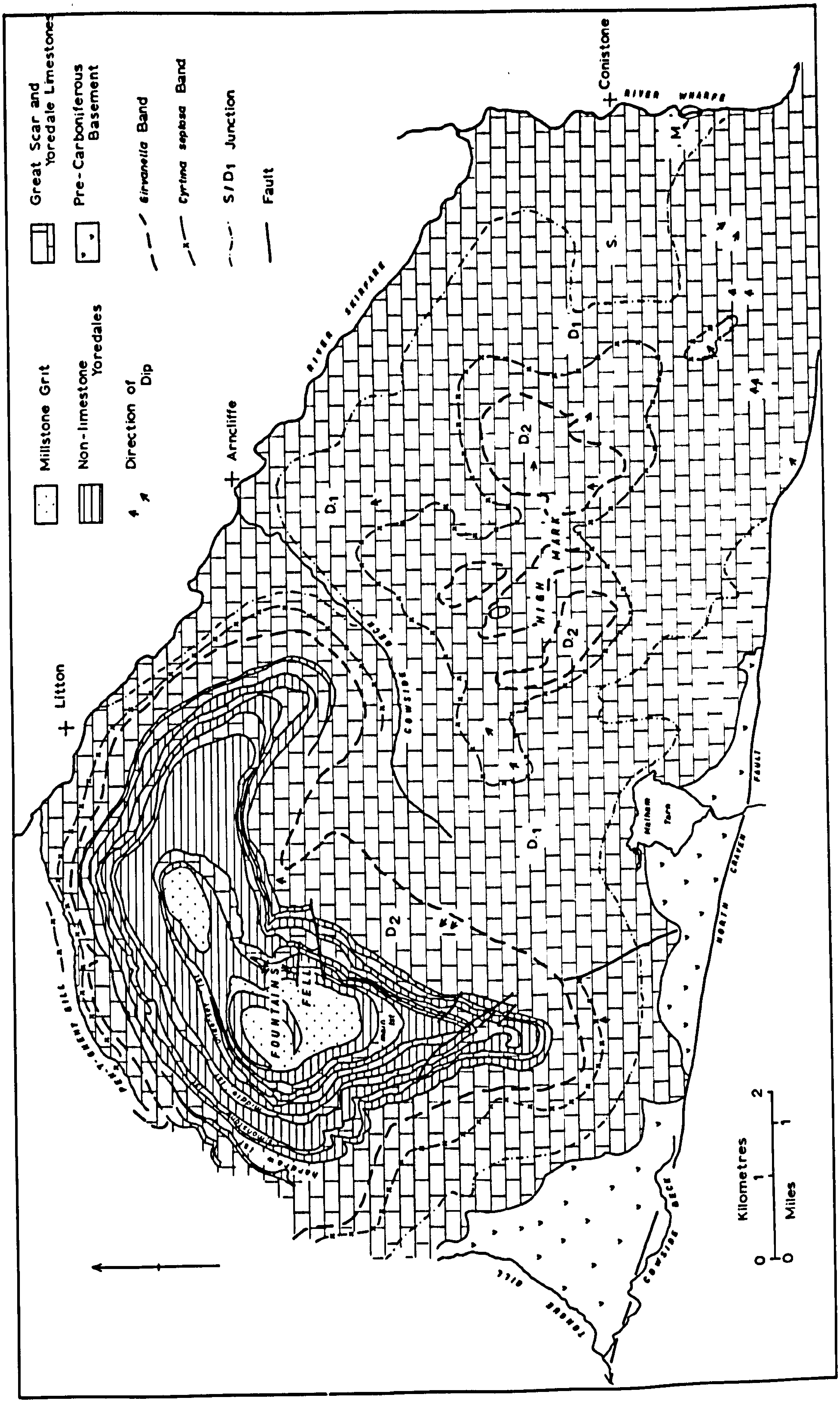


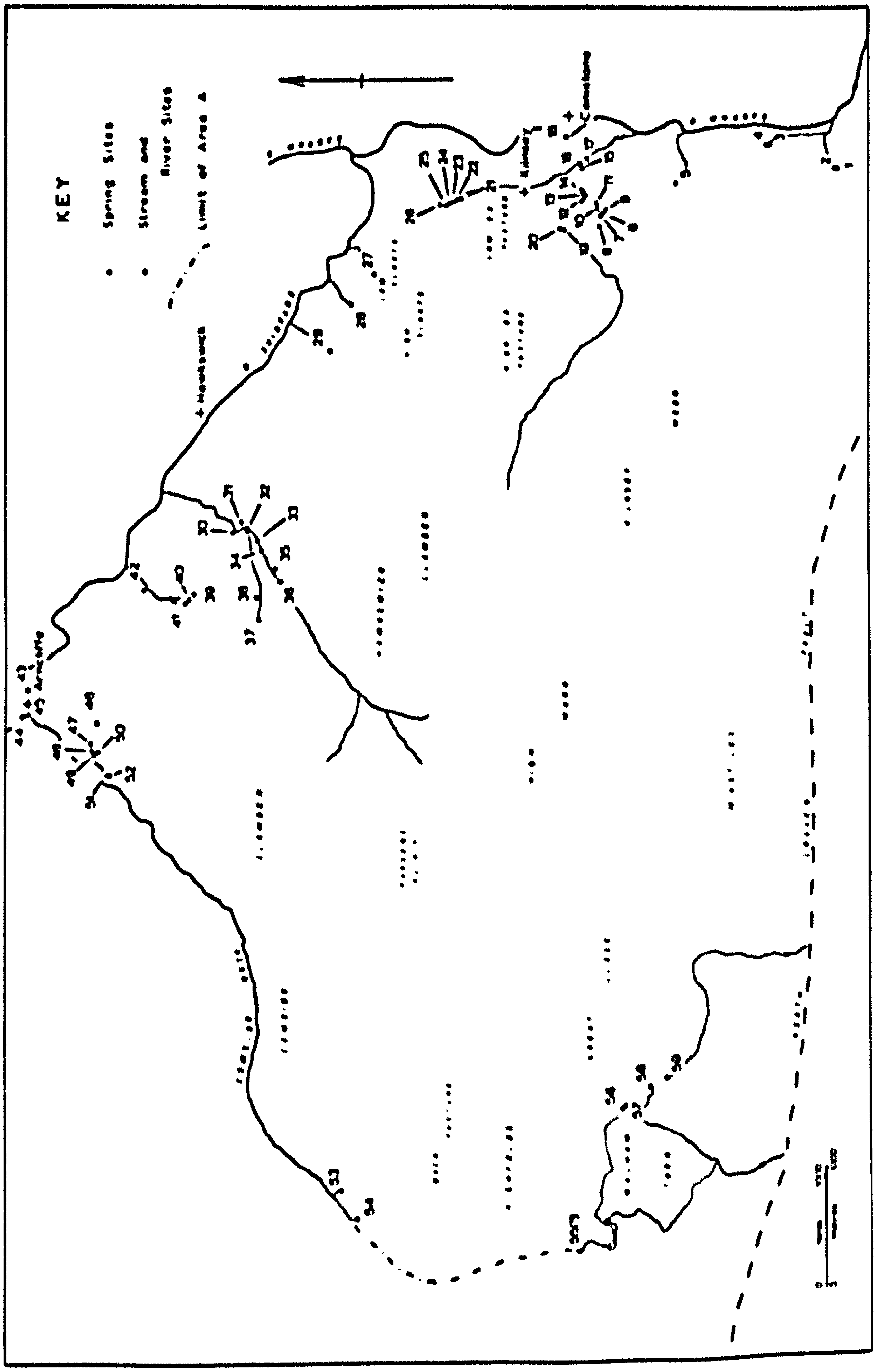
Map 1 The location of the High Mark and Fountains Fell area



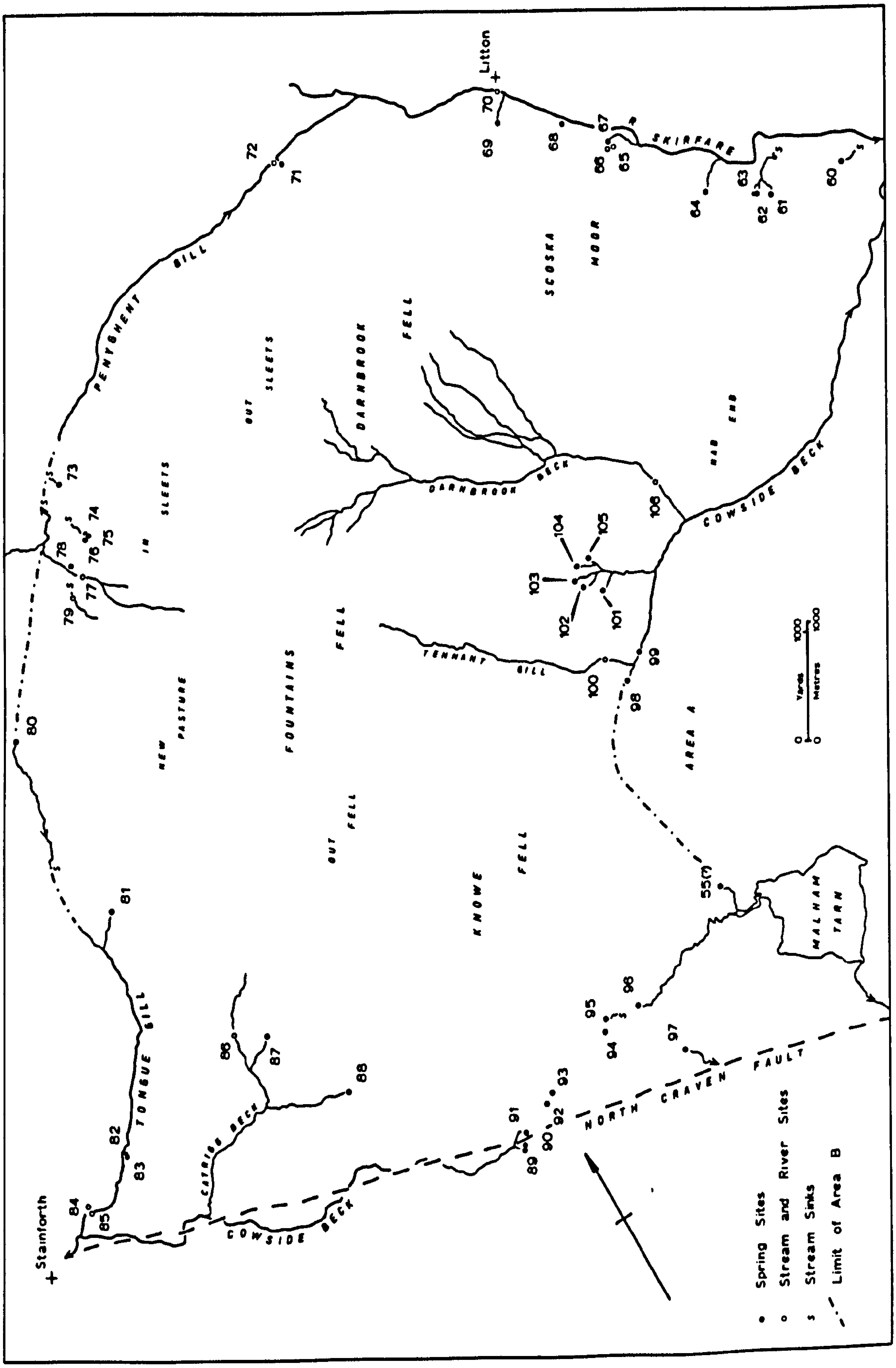
Map 2 The relief and drainage of the High Mark and Fountains Fell area



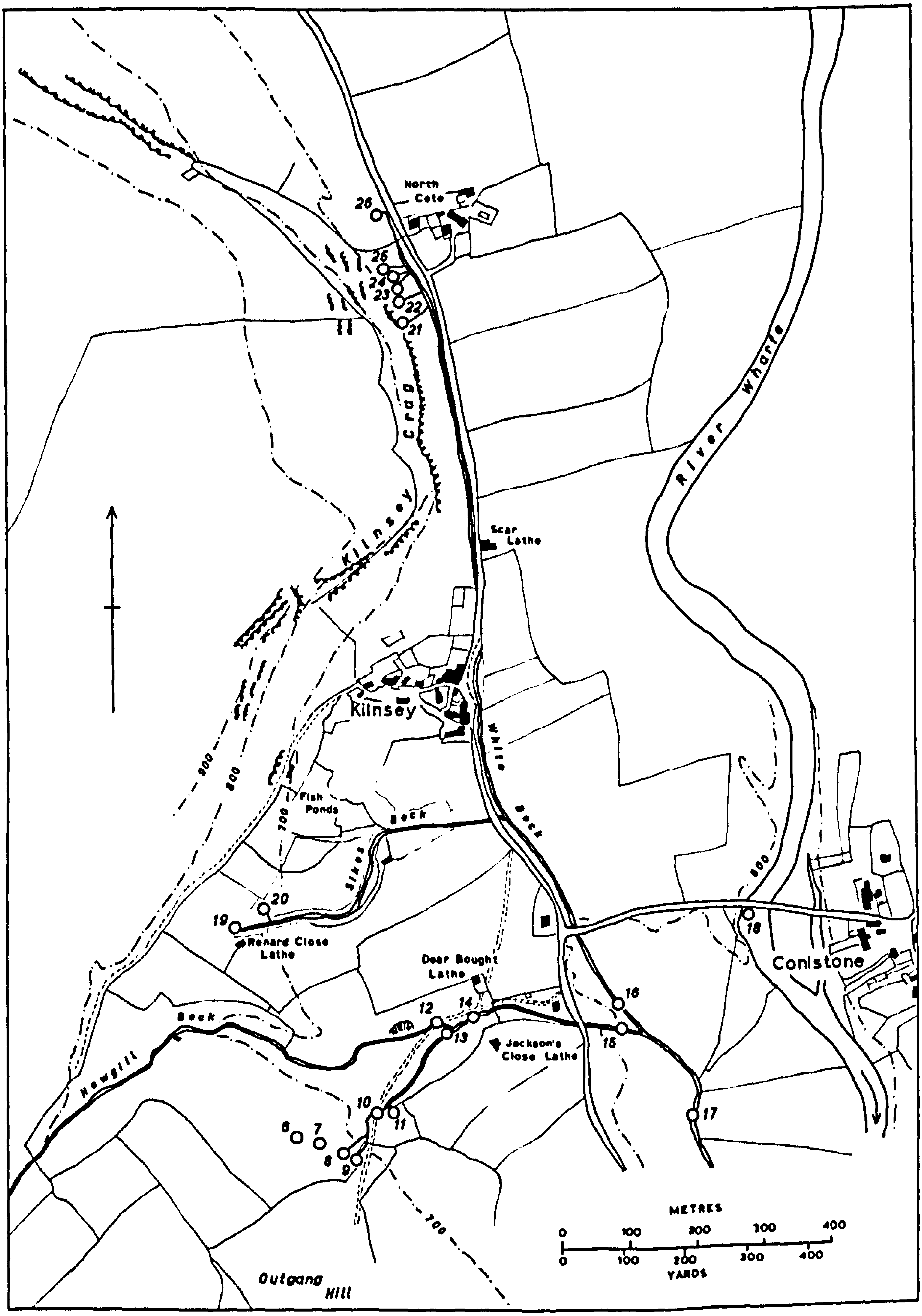
Map 3 The geology of the High Mark and Fountains Fell area



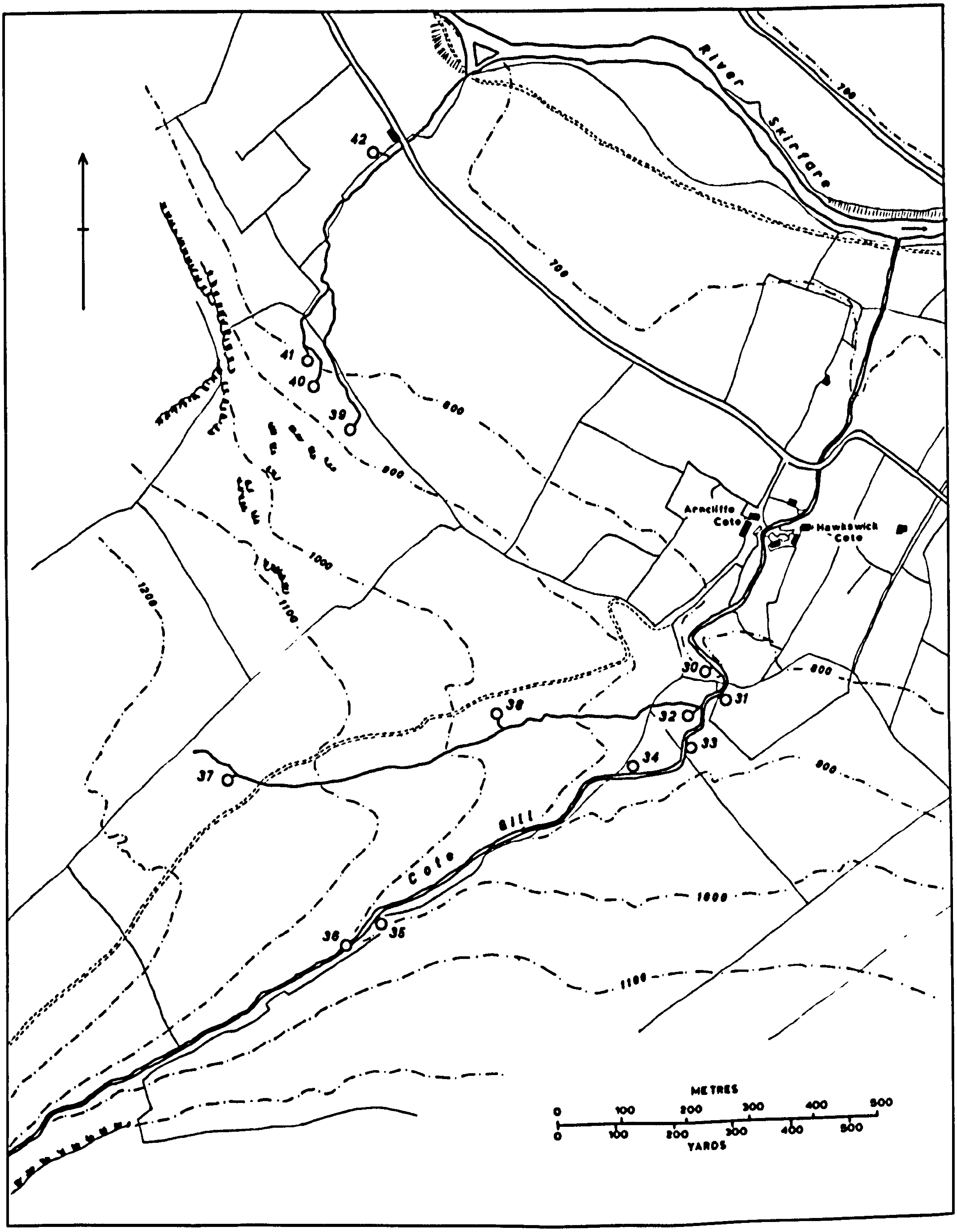
Map 4 The location of sampling sites in the High Mark area



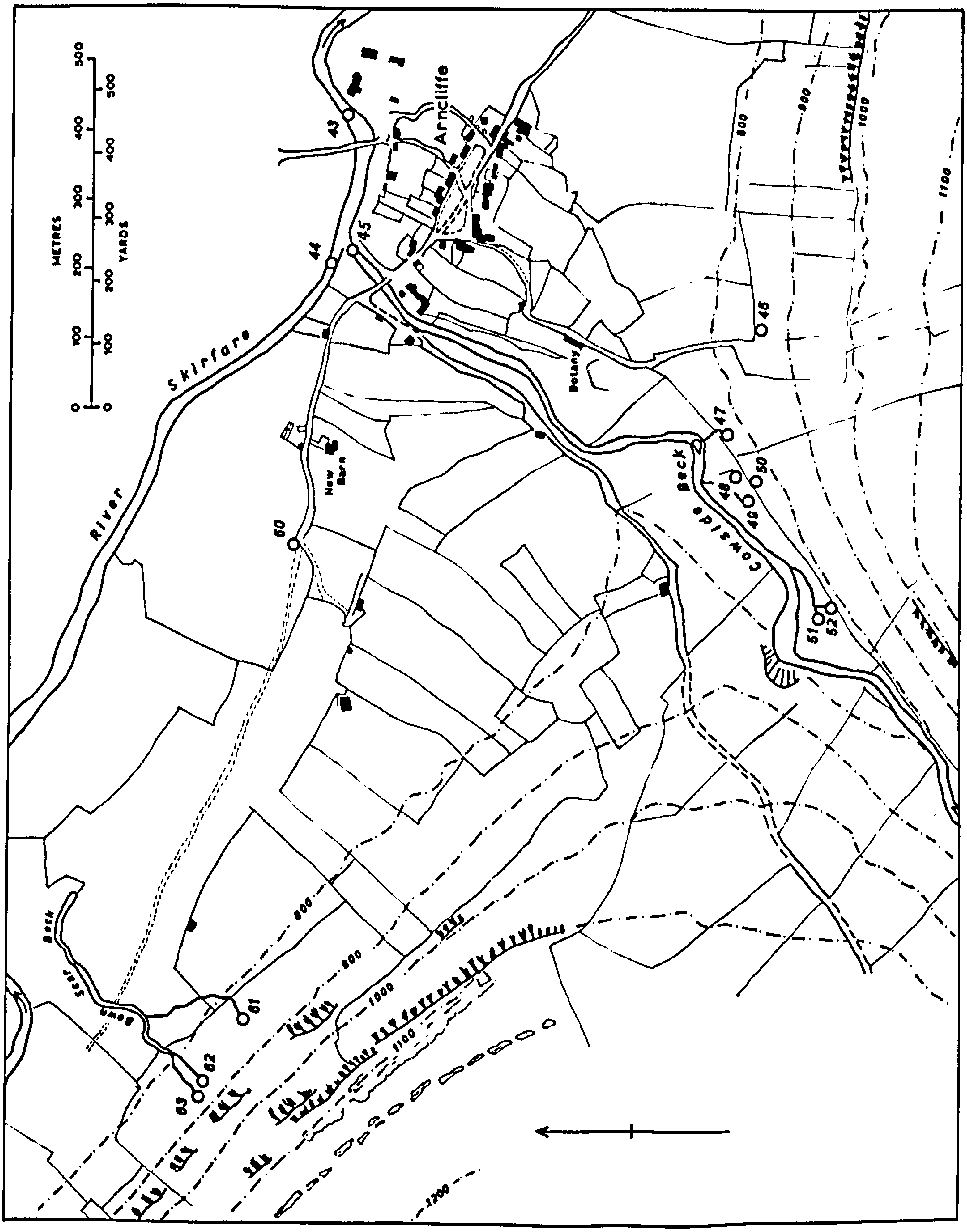
Map 5 The location of sampling sites in the Fountains Fell area



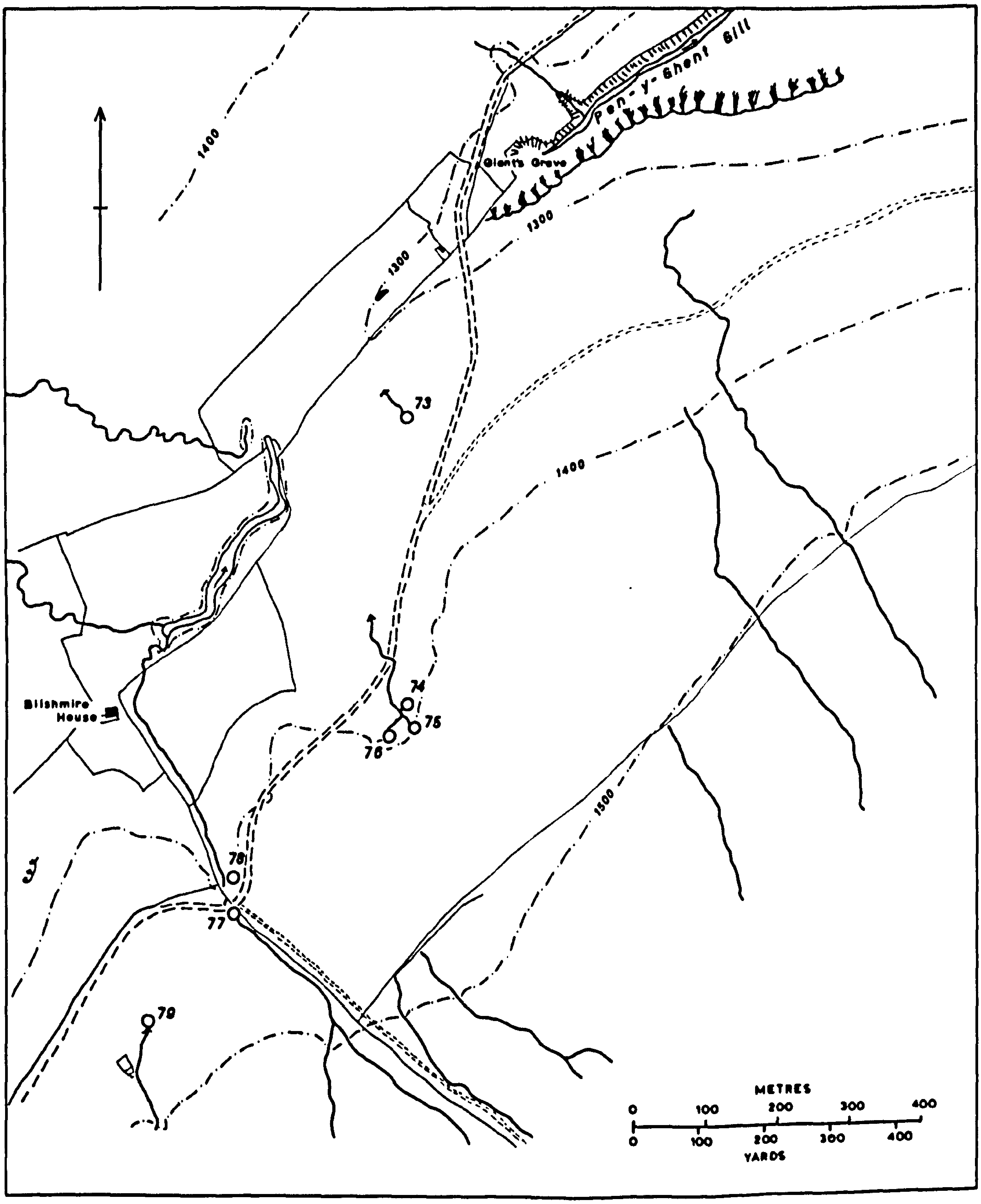
Map 6 The location of sampling sites 6-26 in Wharfedale



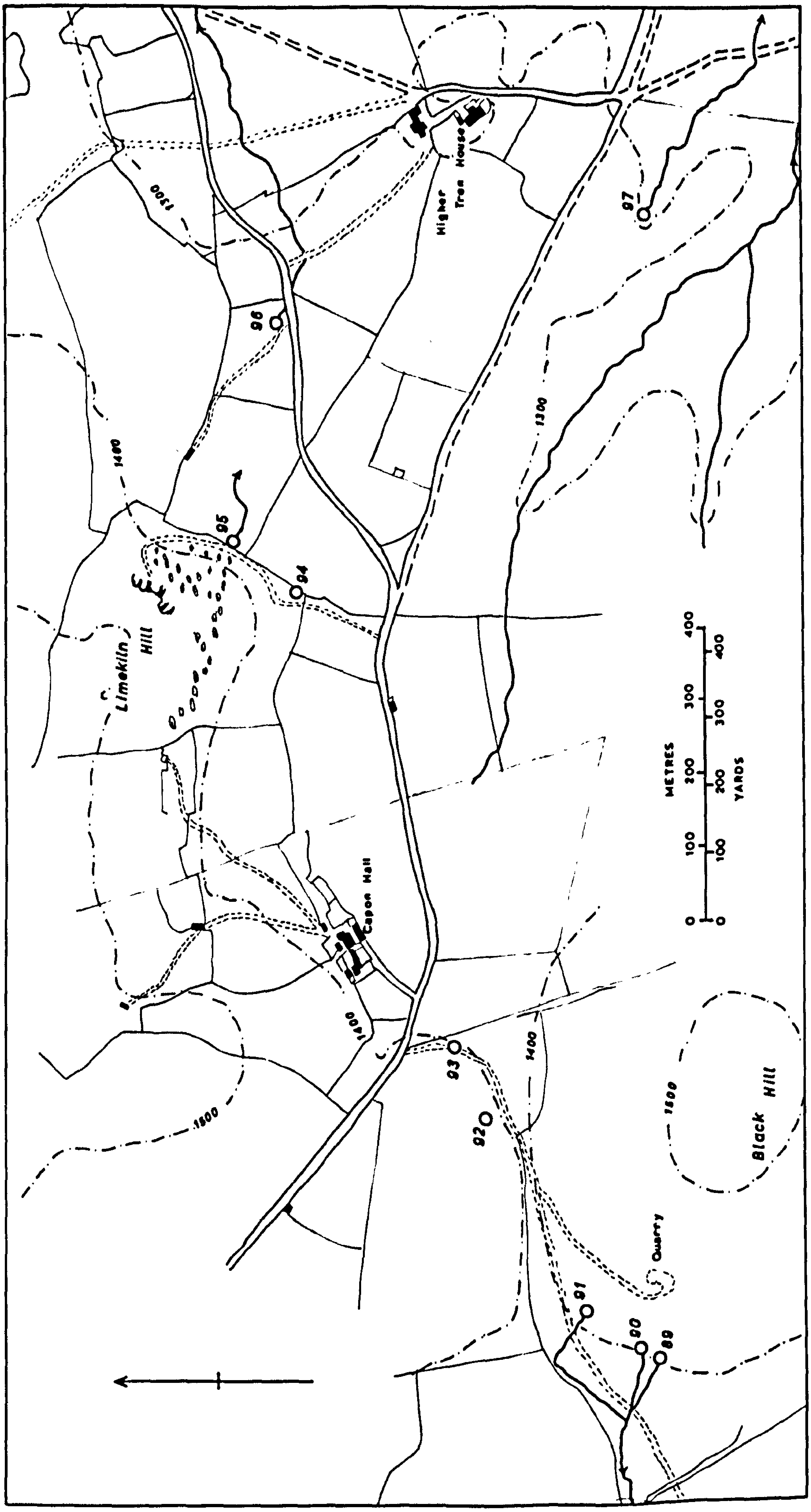
Map 7 The location of sampling sites 30-42 in Littondale



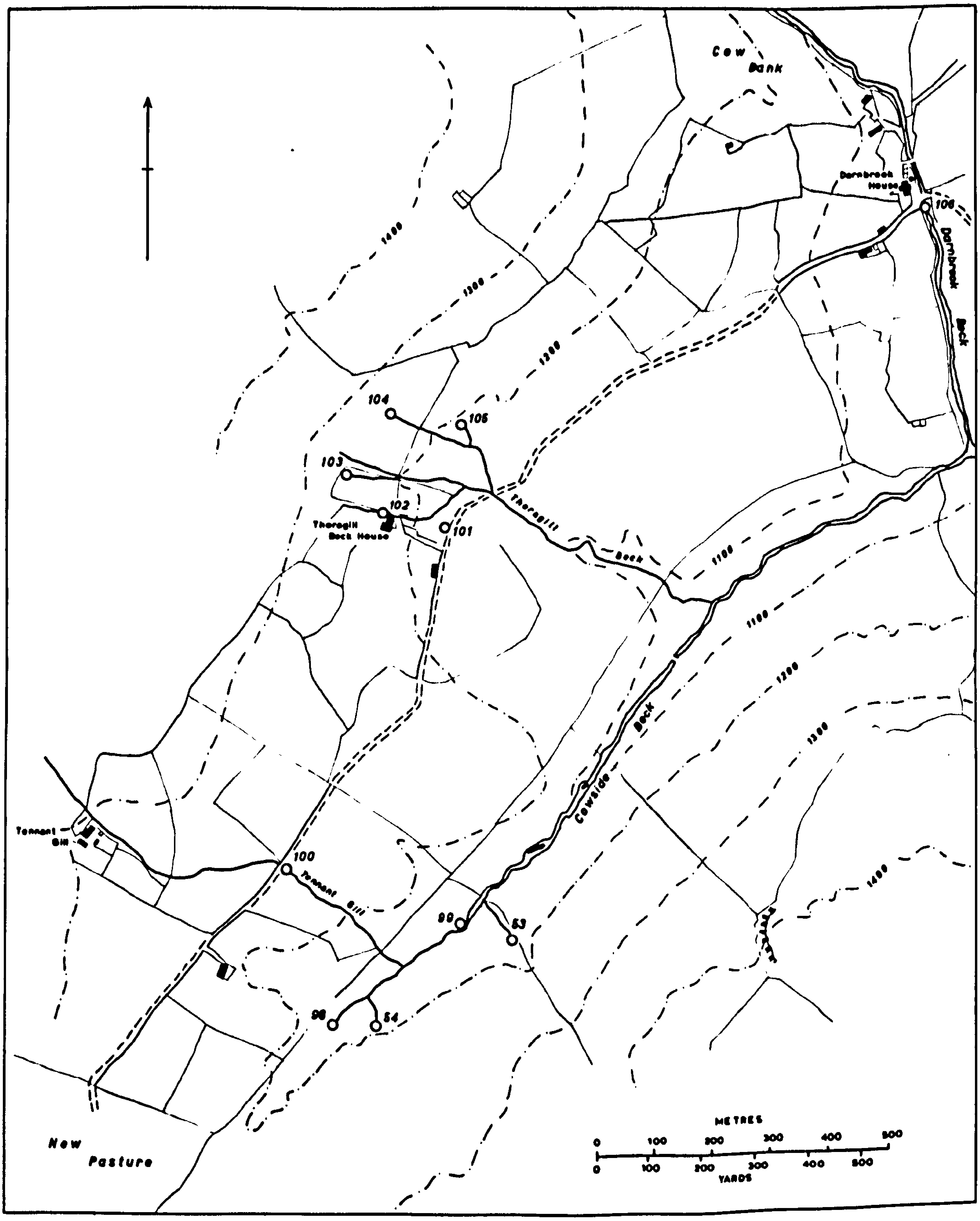
Map 8 The location of sampling sites 43-52 and 60-63 in the Arncliffe area



Map 9 The location of sampling sites 73-79 on the north-western flanks of Fountains Fell



Map 10 The location of sampling sites 89-97 in the Blackhill area, west of Malham Tarn



Map 11 The location of sampling sites 53, 54, 98-106 on the eastern margins of Fountains Fell

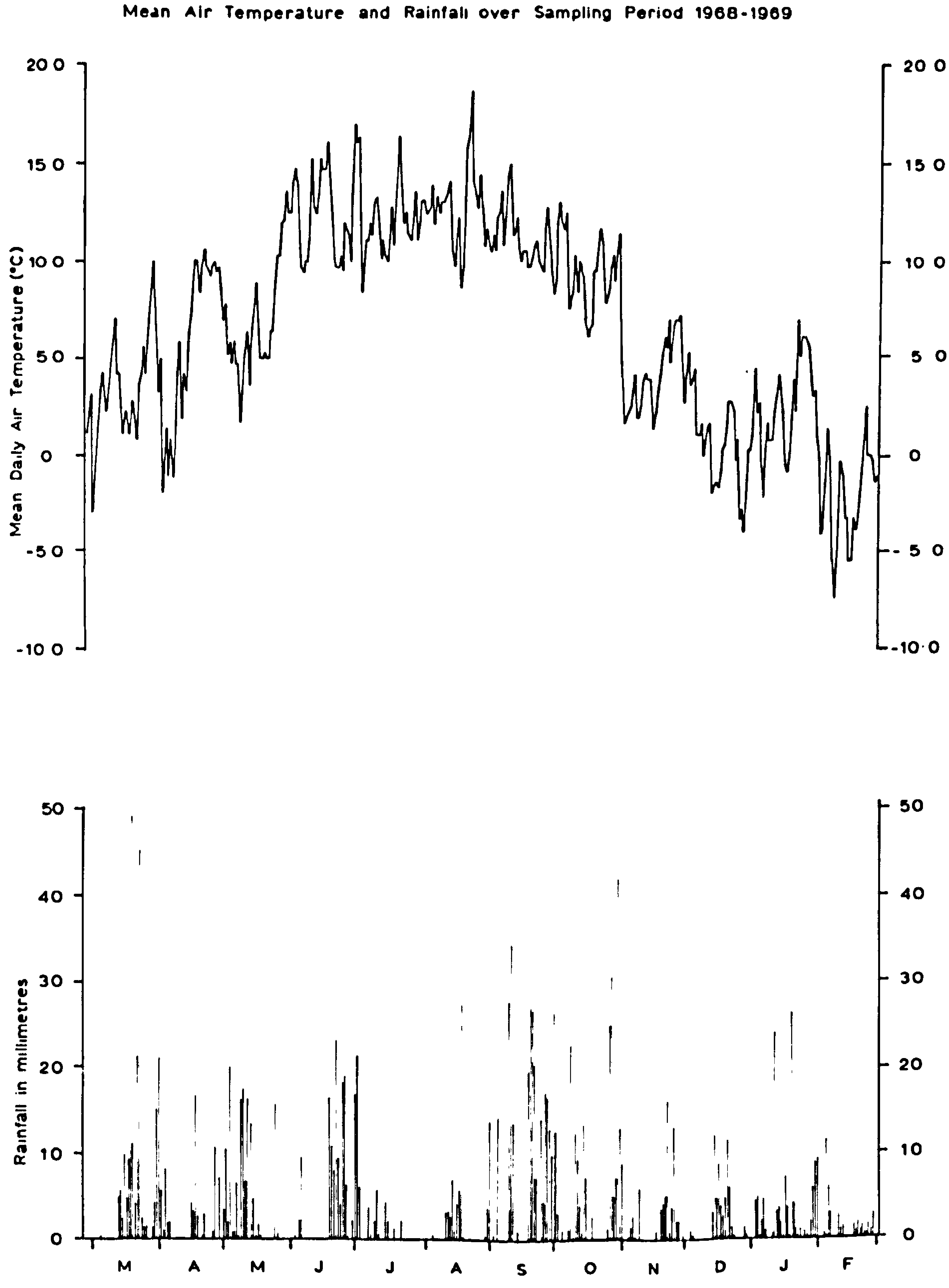
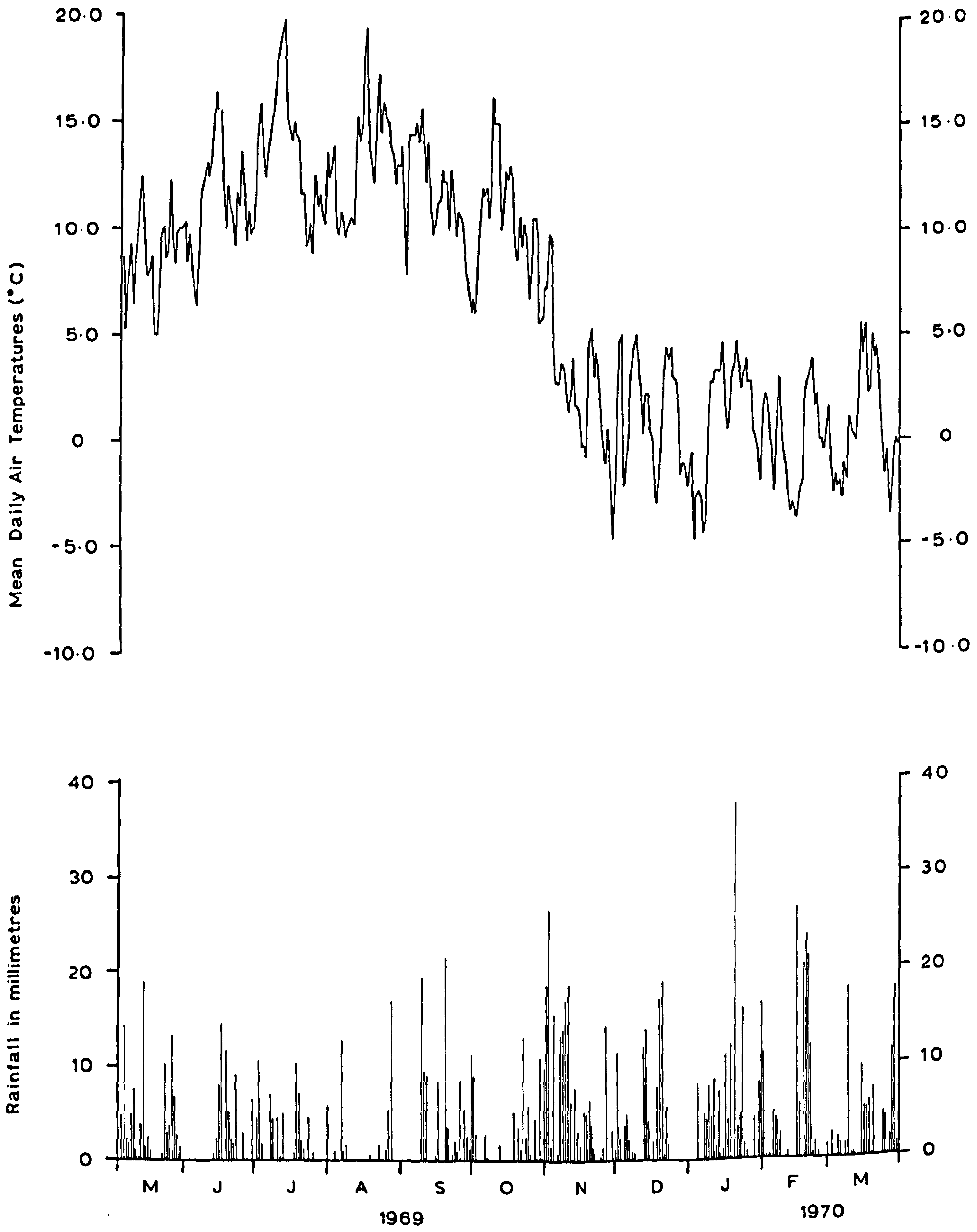


Fig.1 Mean daily air temperatures and rainfall over year I sampling period (February 1968 - February 1969)



Mean Rainfall and Air Temperatures Over Sampling Period 1969-70

Fig.2 Mean daily air temperatures and rainfall over year II sampling period (May 1969 - May 1970)

Figs. 3a - 40b

Graphs illustrating dissolved calcium and magnesium carbonate, water temperature and discharge (year II only) recordings carried out at the sampling sites in north-west Yorkshire

Figs. 3a - 13b

High Mark springs (year I observations)

Figs. 14a - 23d

Fountains Fell springs (year I observations)

Figs. 24a - 35

Stream sampling sites (year I observations)

Figs. 36a - 40b

High Mark case study sites (year II observations)

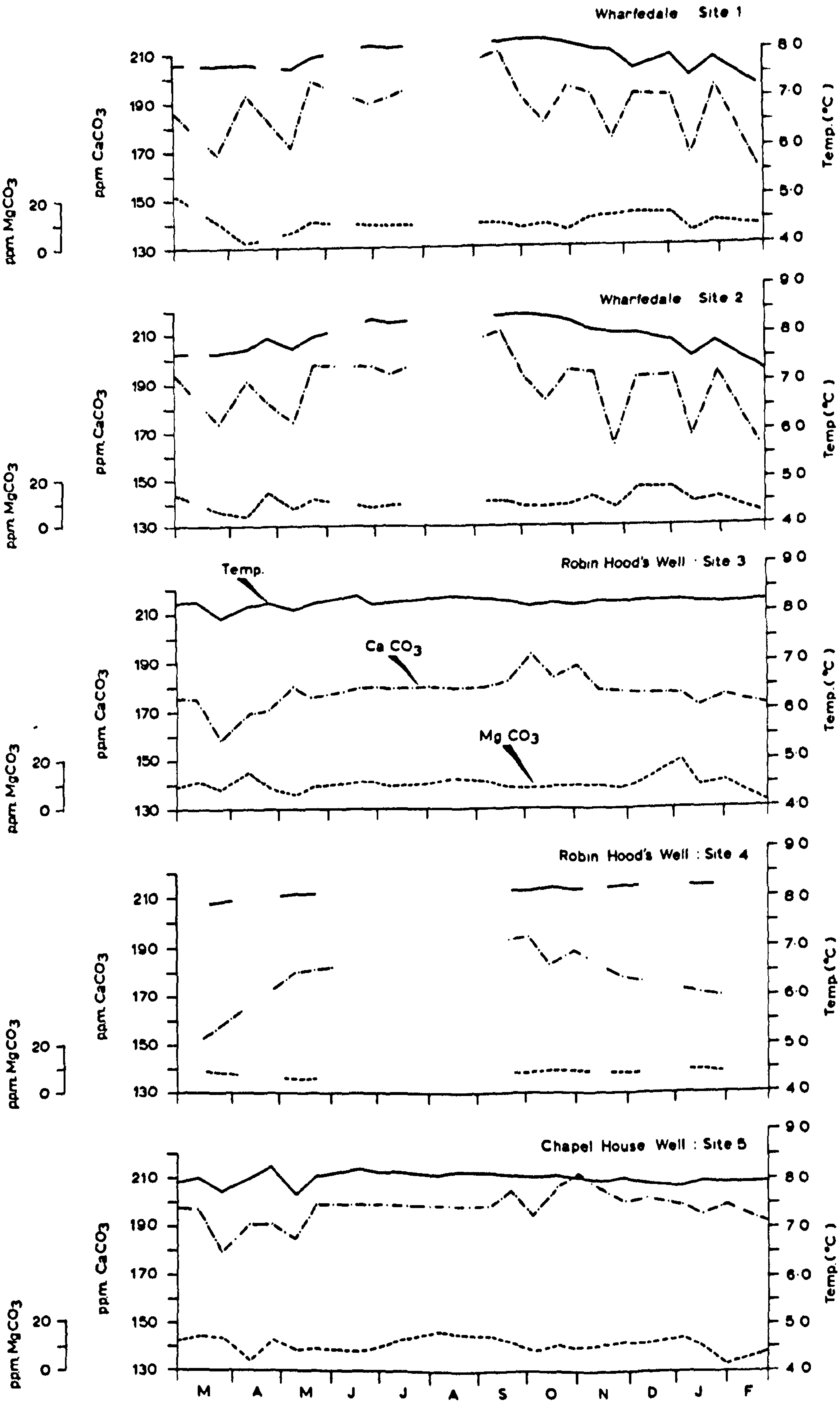
Fig.3a

Fig.3b

Fig.3c

Fig.3d

Fig.3e



Figs.3a-3e Dissolved calcium and magnesium carbonate and water temperature variations recorded at Wharfedale sites 1 and 2, Robin Hood's Well sites 3 and 4, and Chapel House Well site 5 (year I)

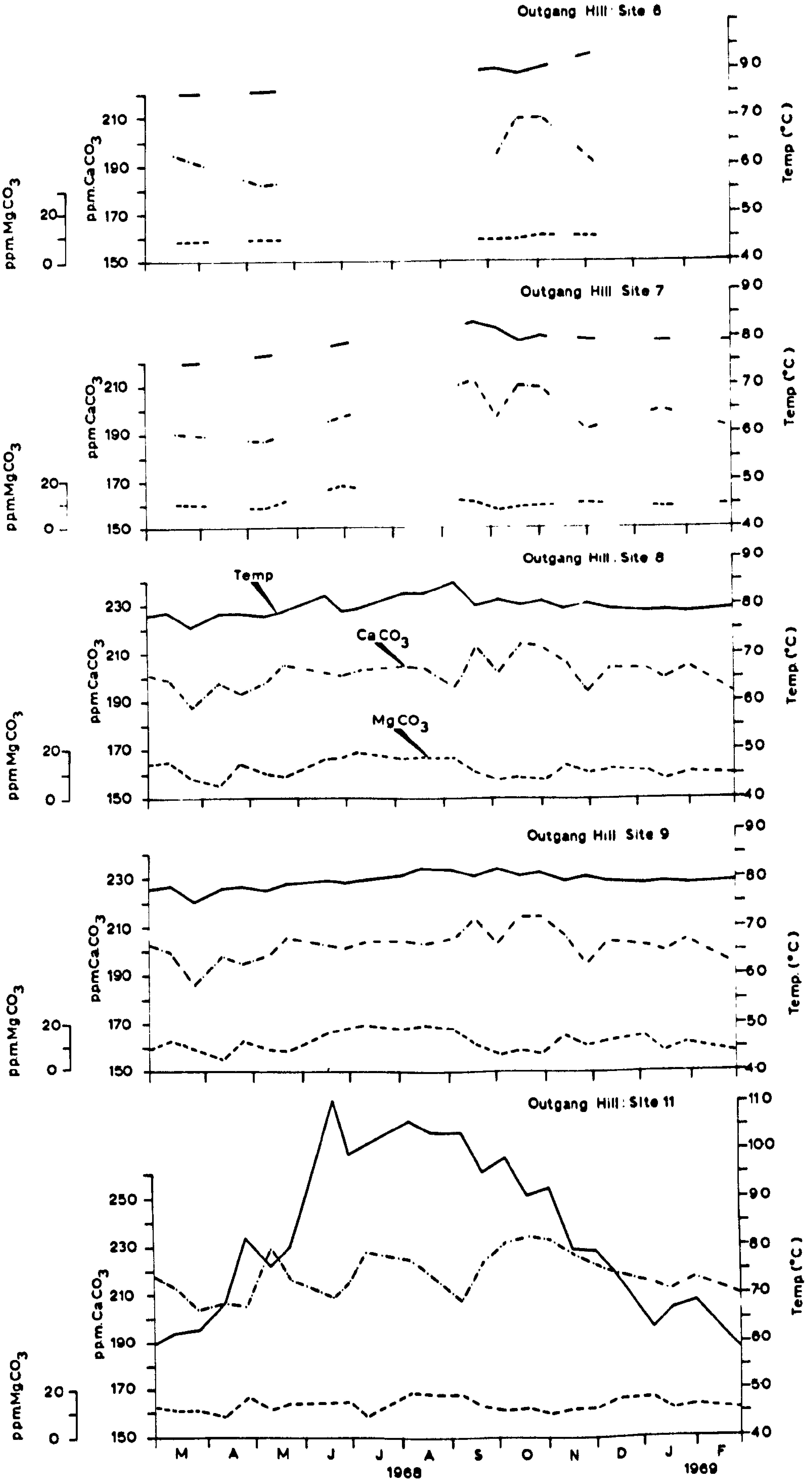


Fig.4a

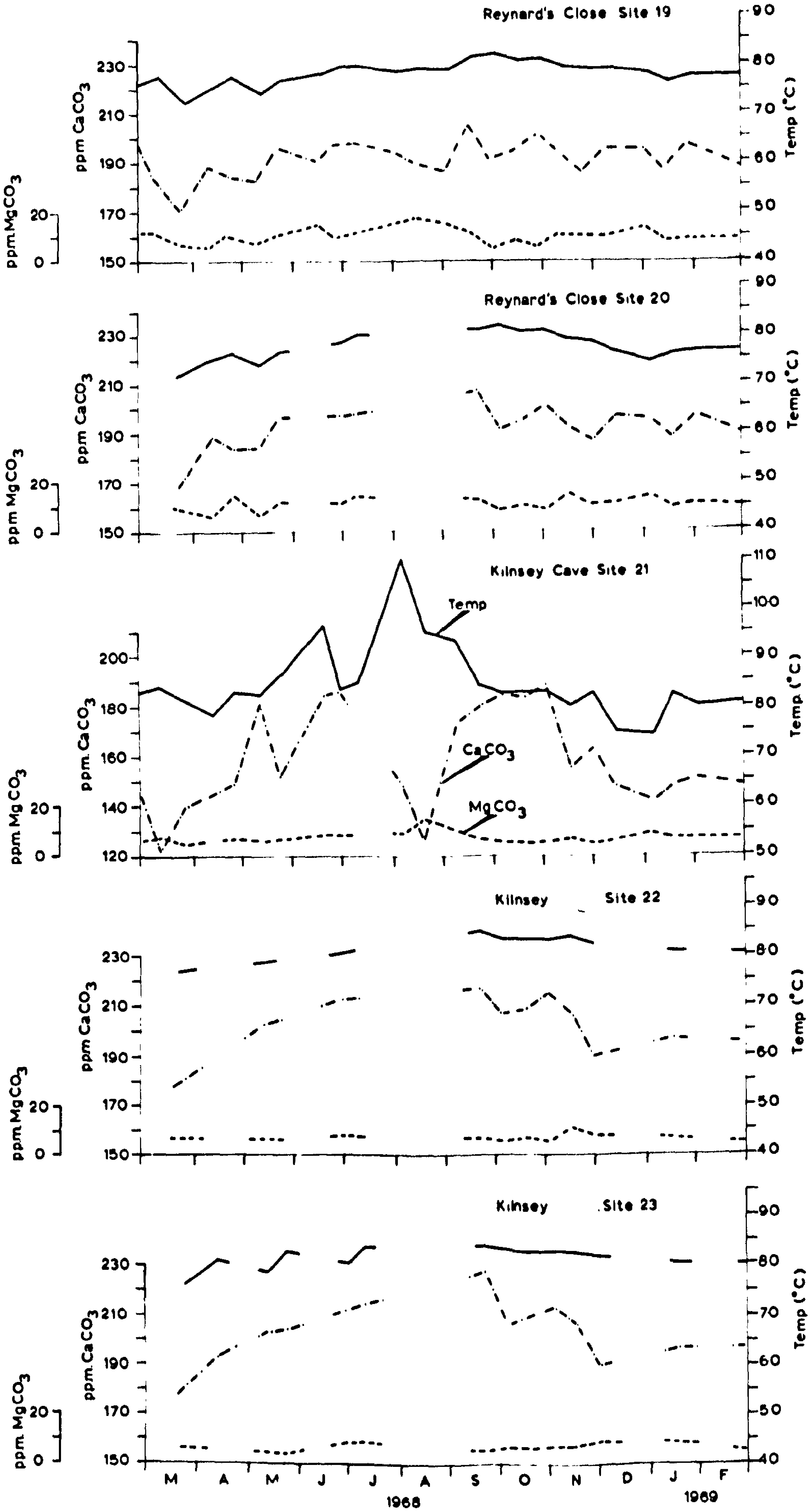
Fig.4b

Fig.4c

Fig.4d

Fig.4e

Fig.4a-4e Dissolved calcium and magnesium carbonate and water temperature variations recorded at Outgang Hill sites 6, 7, 8, 9 and 11 (year I)



Figs.5a-5e Dissolved calcium and magnesium carbonate and water temperature variations recorded at Reynard's Close sites 19 and 20, Kilnsey Cave site 21, and Kilnsey sites 22 and 23 (year I)

Fig.6a

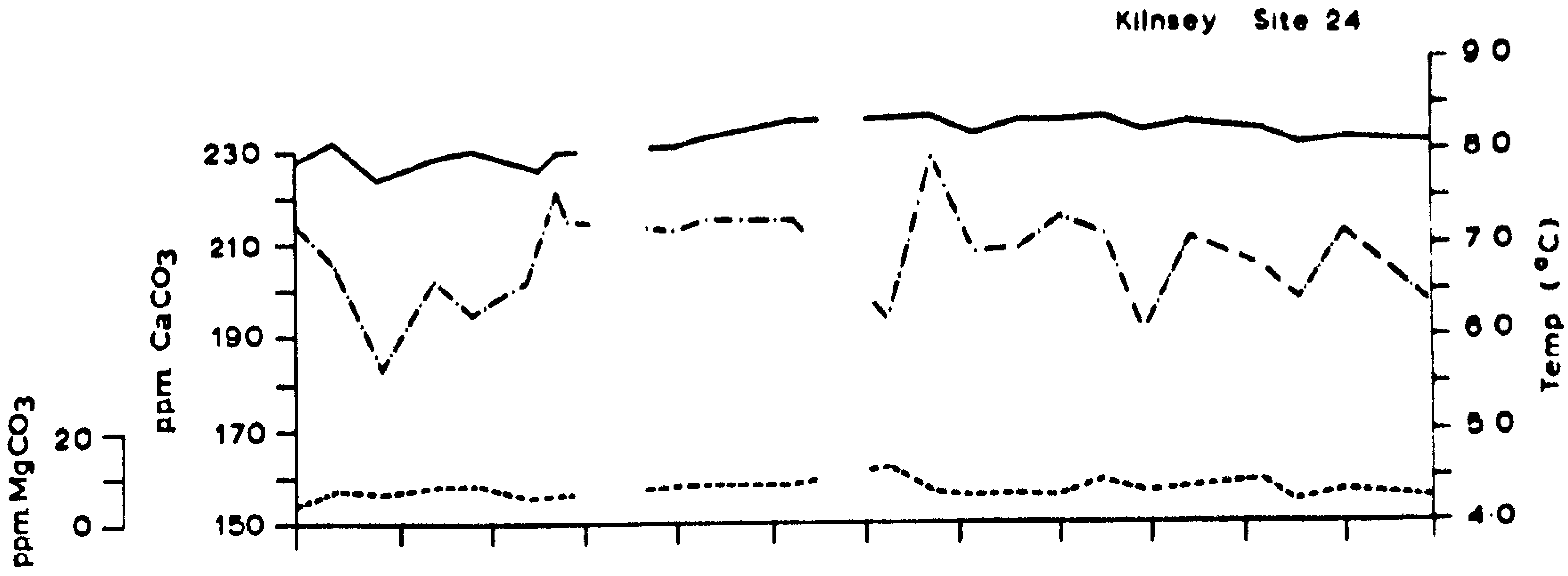


Fig.6b

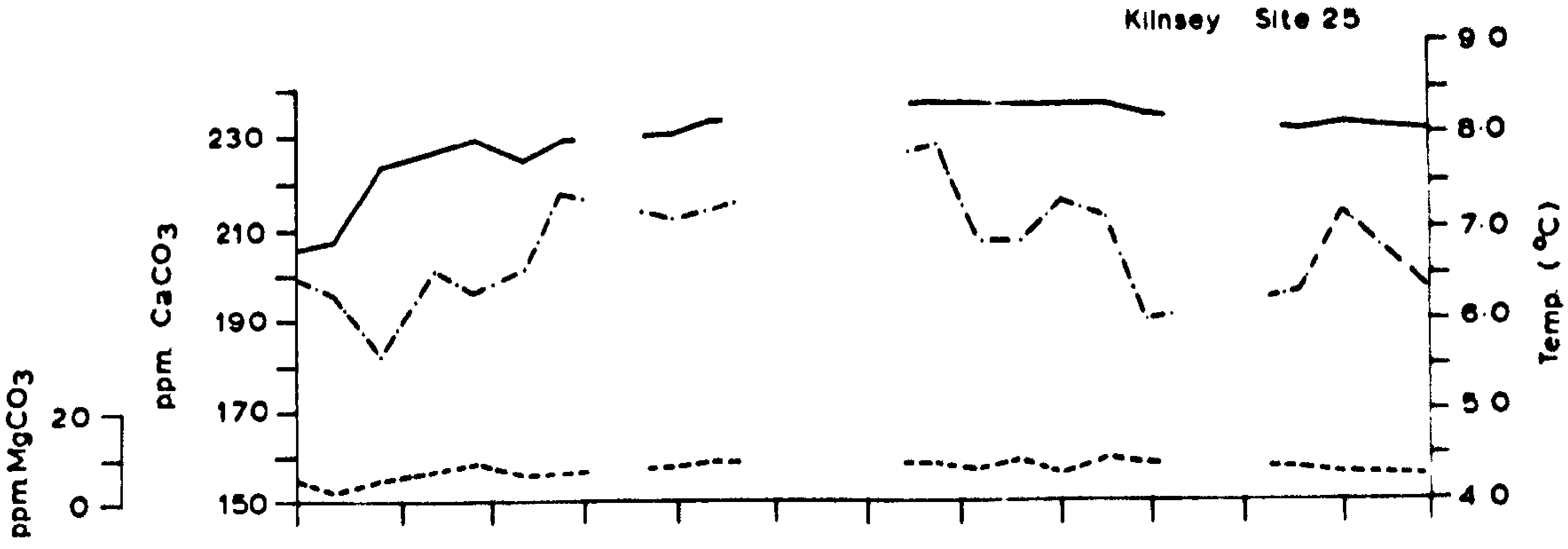


Fig.6c

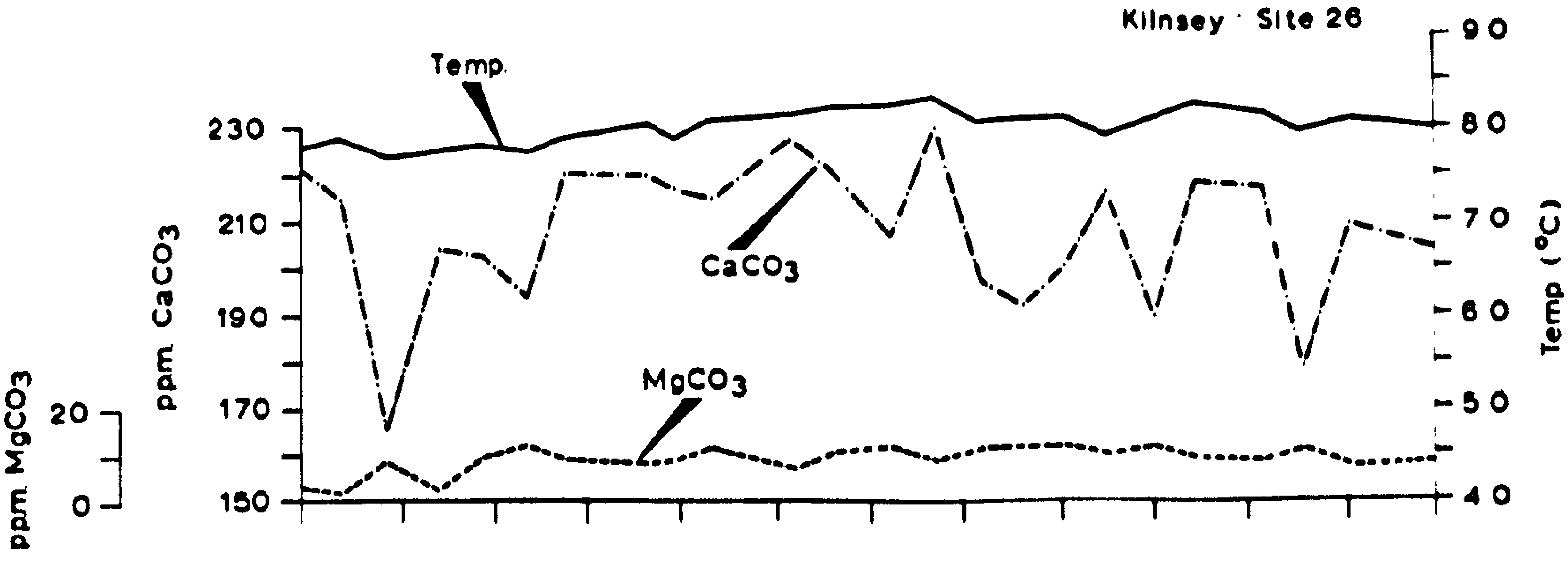
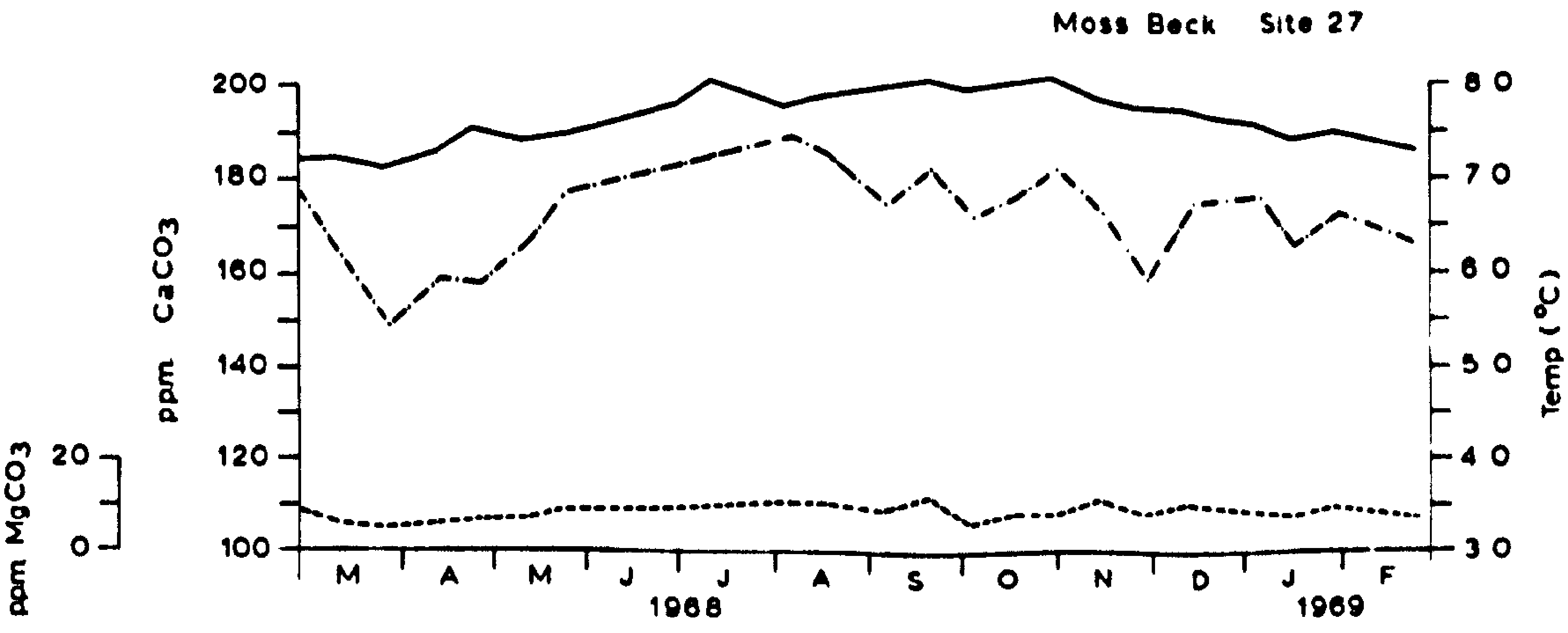


Fig.6d



Figs.6a-6d Dissolved calcium and magnesium carbonate and water temperature variations recorded at Kilnsey sites 24, 25 and 26, and Moss Beck site 27 (year I)

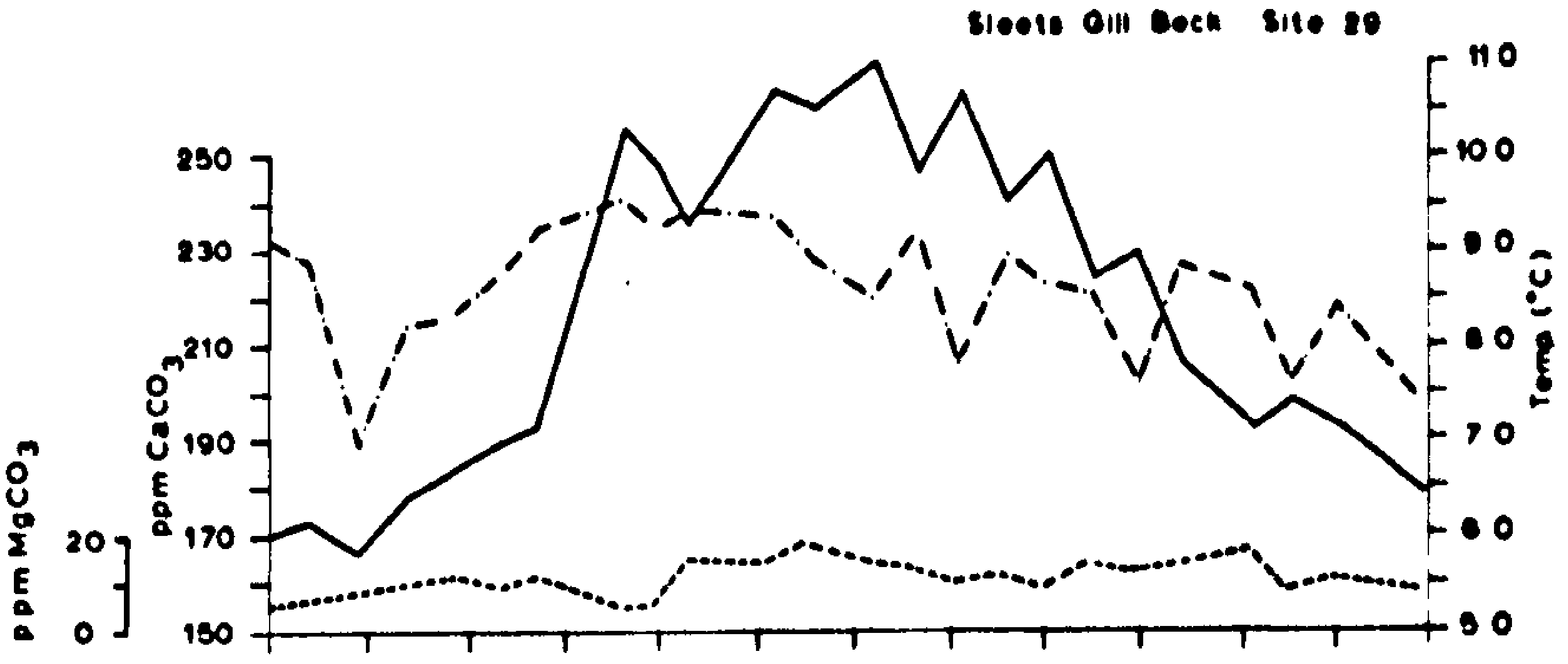


Fig.7a

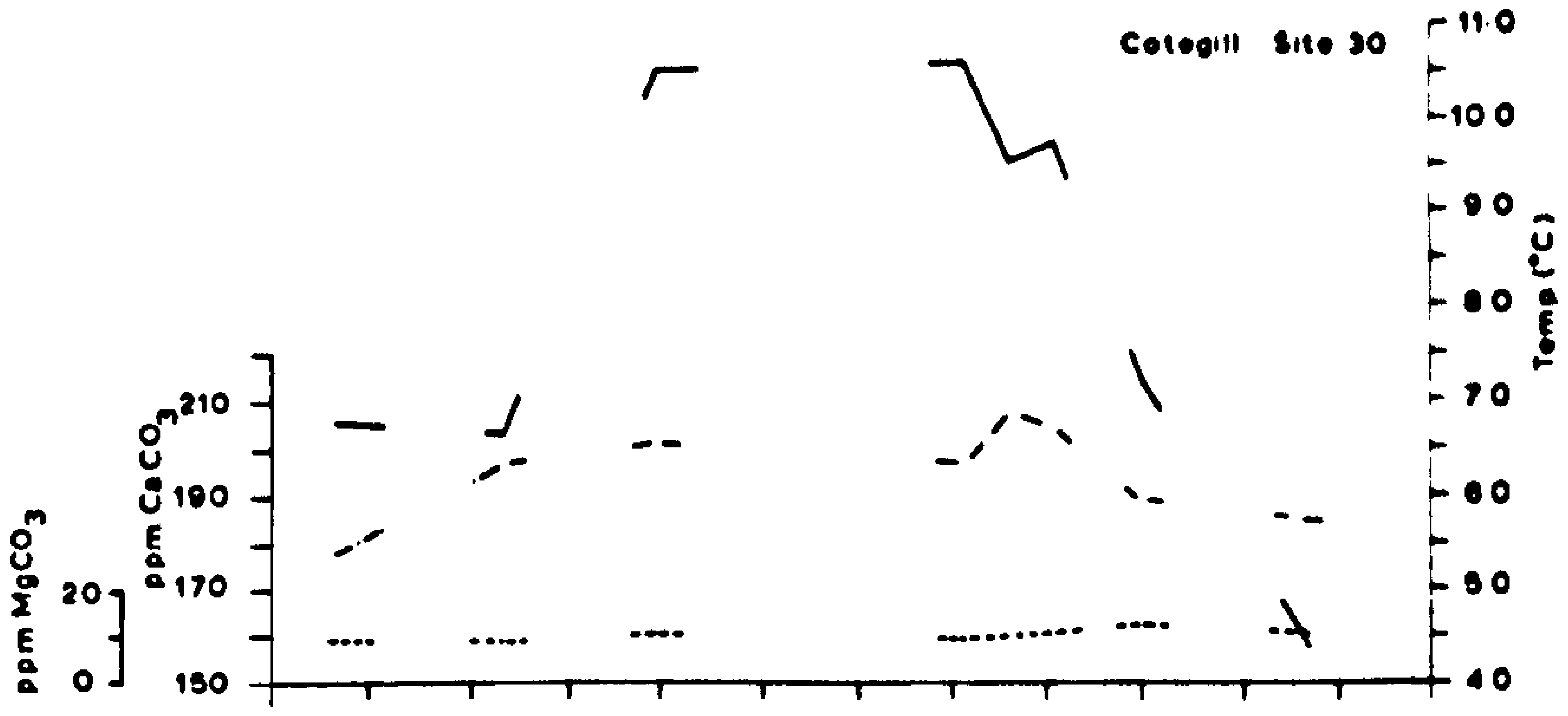


Fig.7b

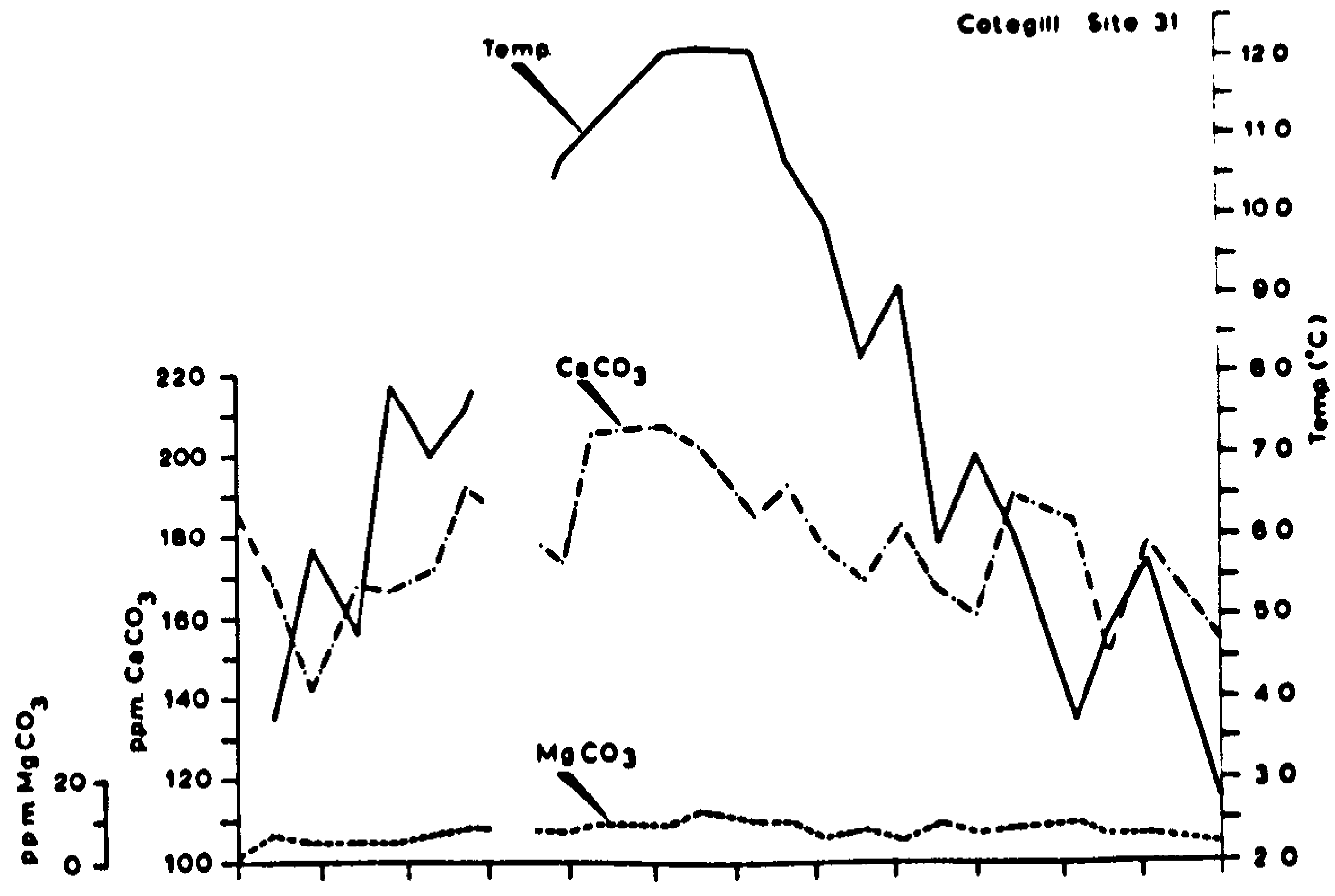


Fig.7c

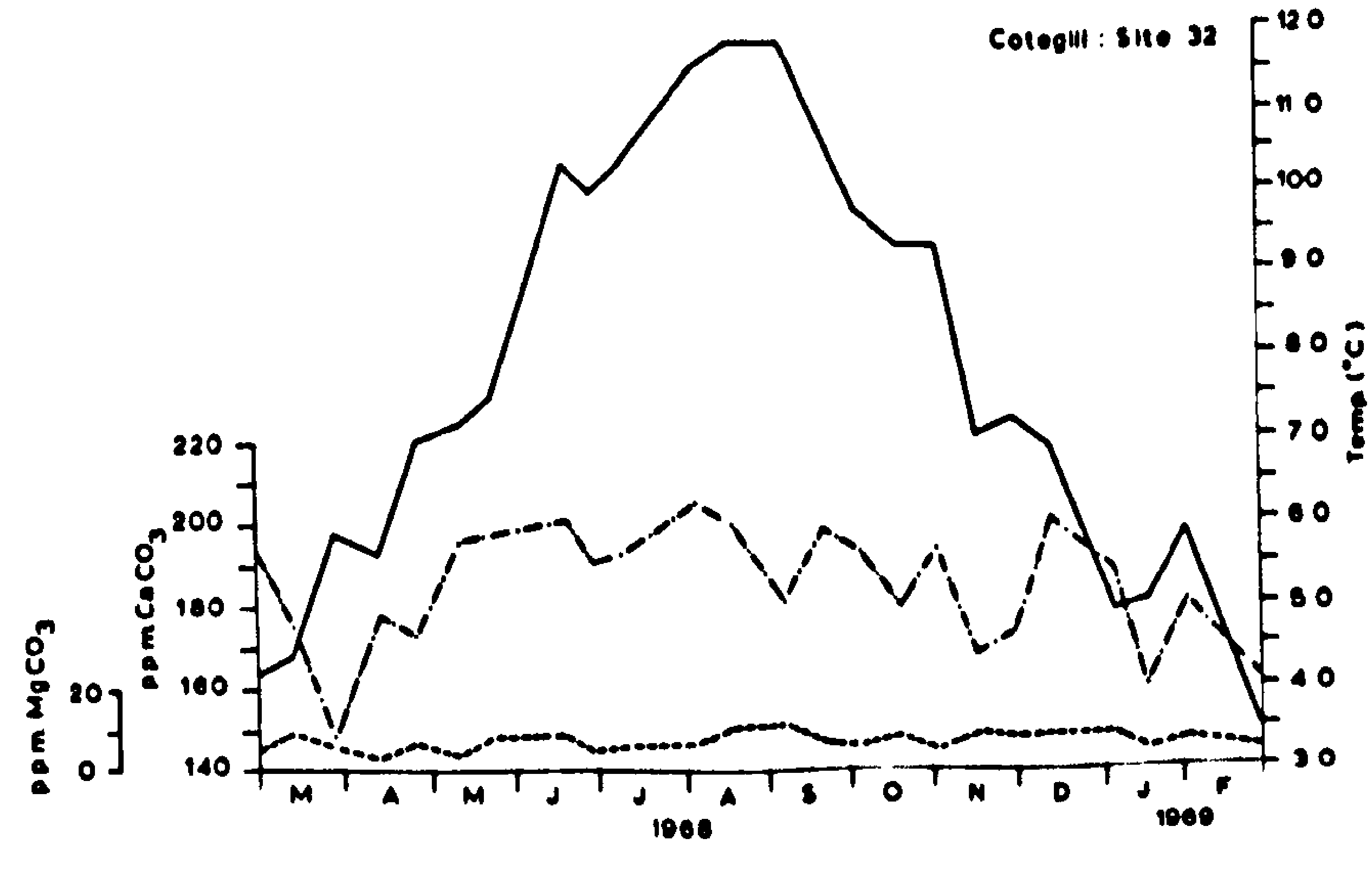


Fig.7d

Figs.7a-7d Dissolved calcium and magnesium carbonate and water temperature variations recorded at Sleets Gill Beck site 29, and Cotegill sites 30, 31 and 32 (year I)

Fig.8a

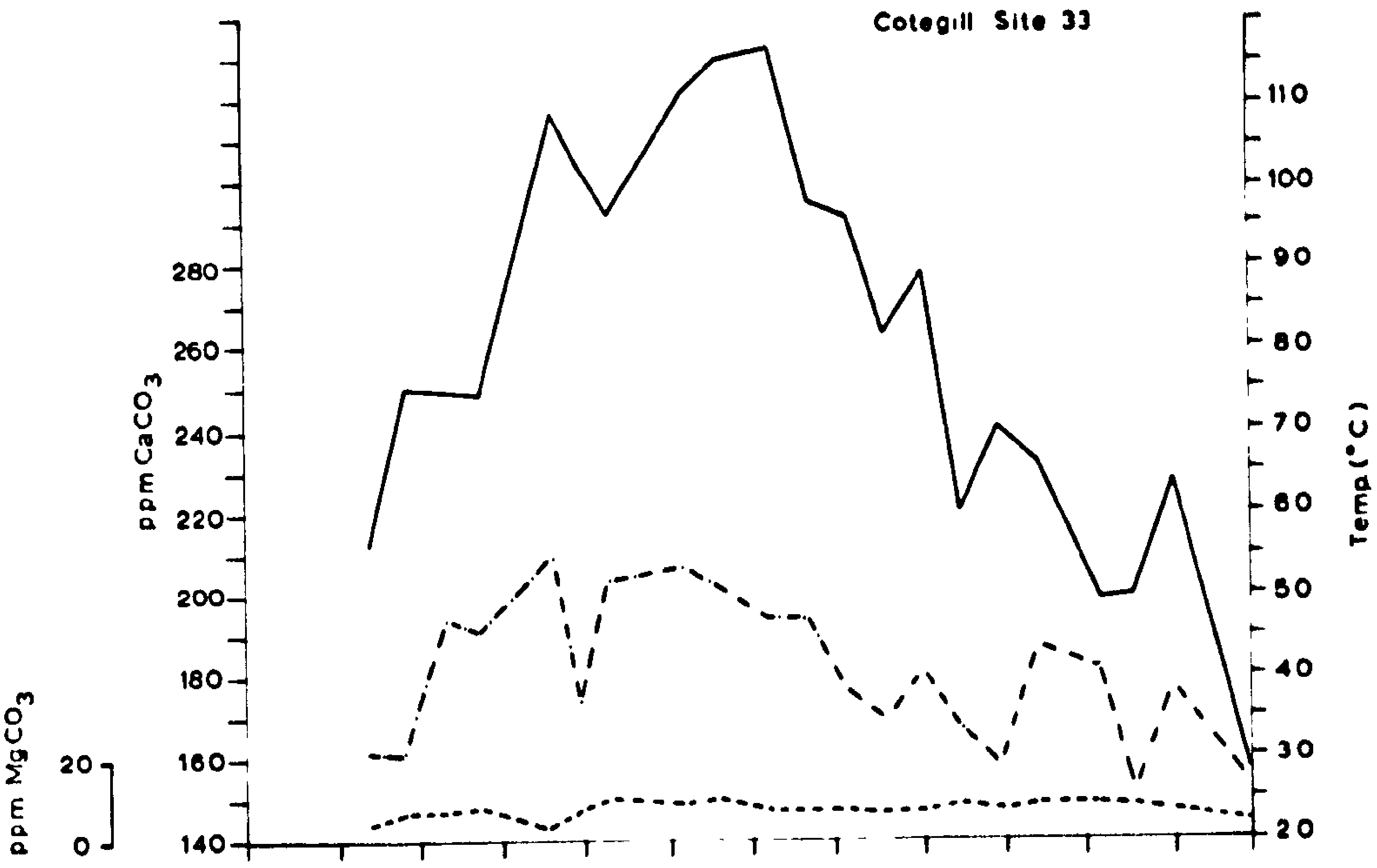


Fig.8b

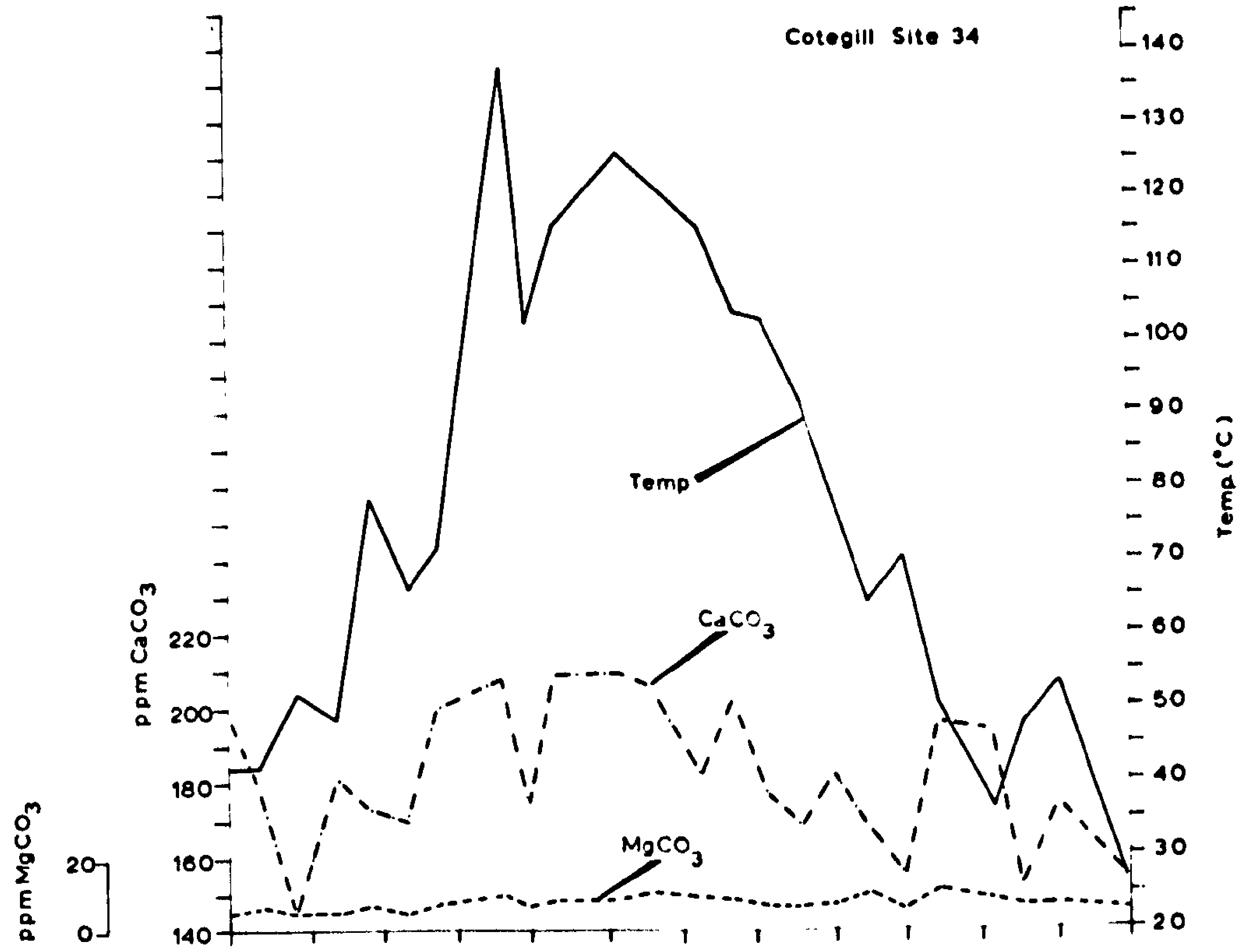
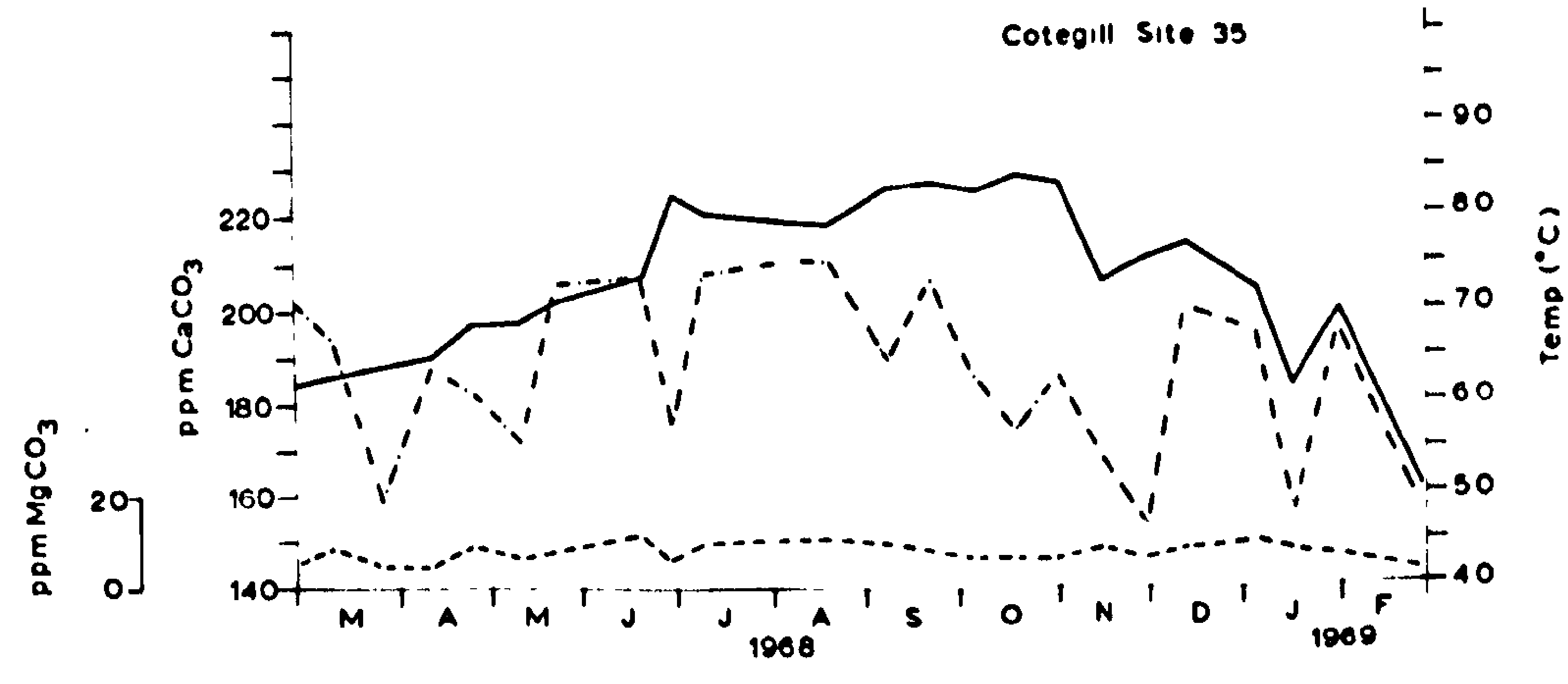


Fig.8c



Figs.8a-8c Dissolved calcium and magnesium carbonate and water temperature variations recorded at Cotegill sites 33, 34 and 35 (year I)

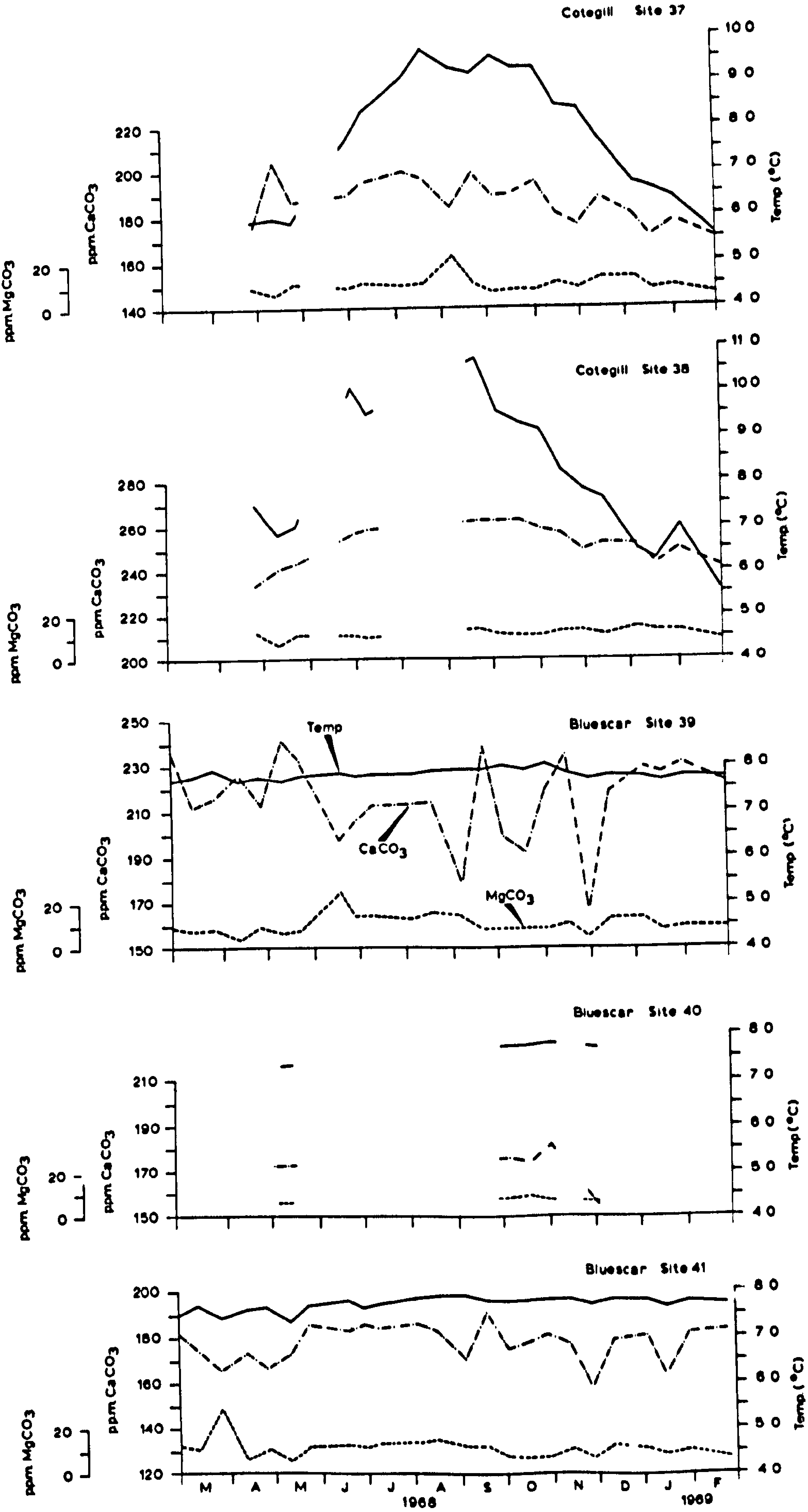


Fig.9a

Fig.9b

Fig.9c

Fig.9d

Fig.9e

Figs.9a-9e Dissolved calcium and magnesium carbonate and water temperature variations recorded at Cotegill sites 37 and 38, and Bluescar sites 39, 40 and 41 (year I)

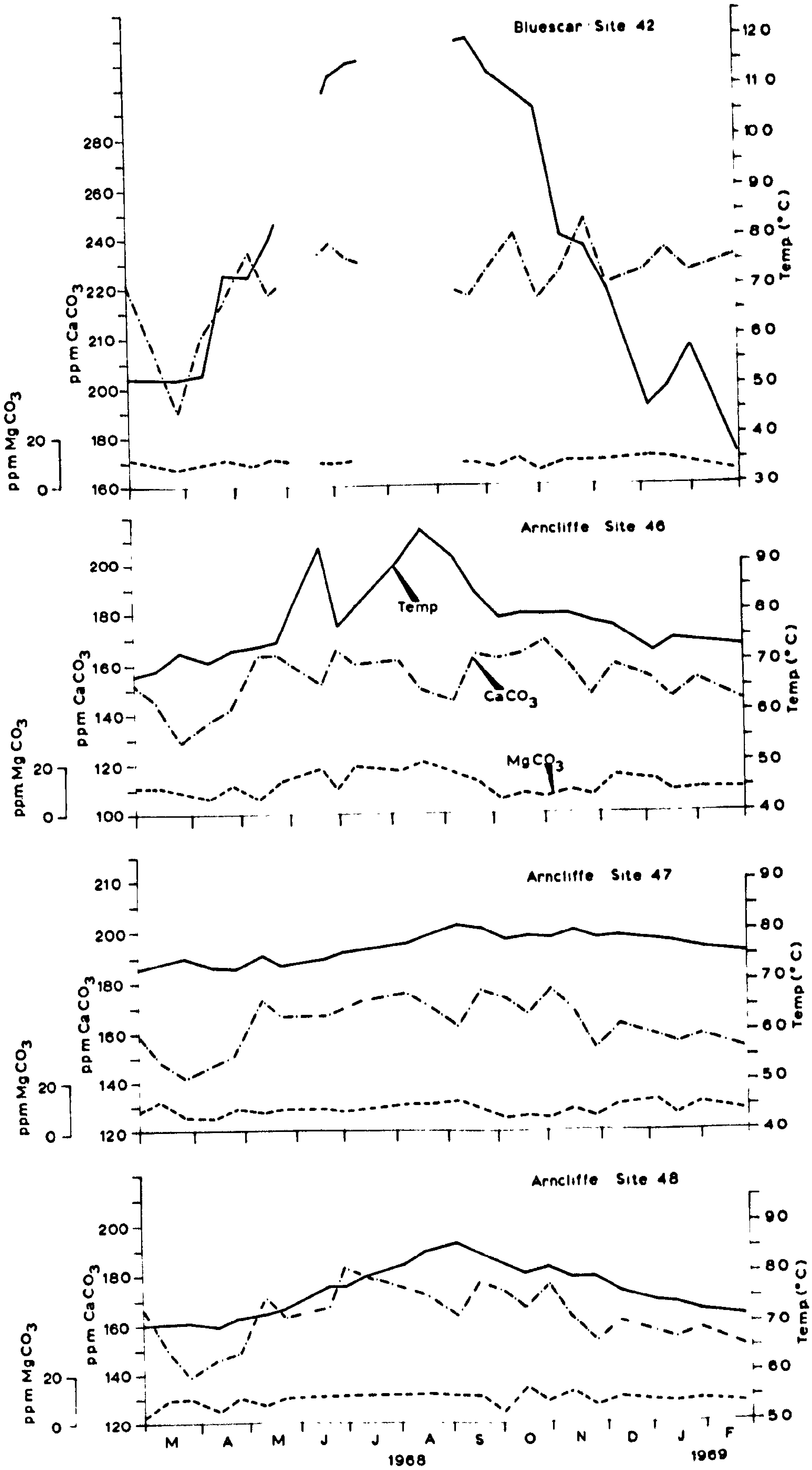


Fig.10a

Fig.10b

Fig.10c

Fig.10d

Figs.10a-10d Dissolved calcium and magnesium carbonate and water temperature variations recorded at Bluescar site 42, and Arncliffe sites 46, 47 and 48 (year I)

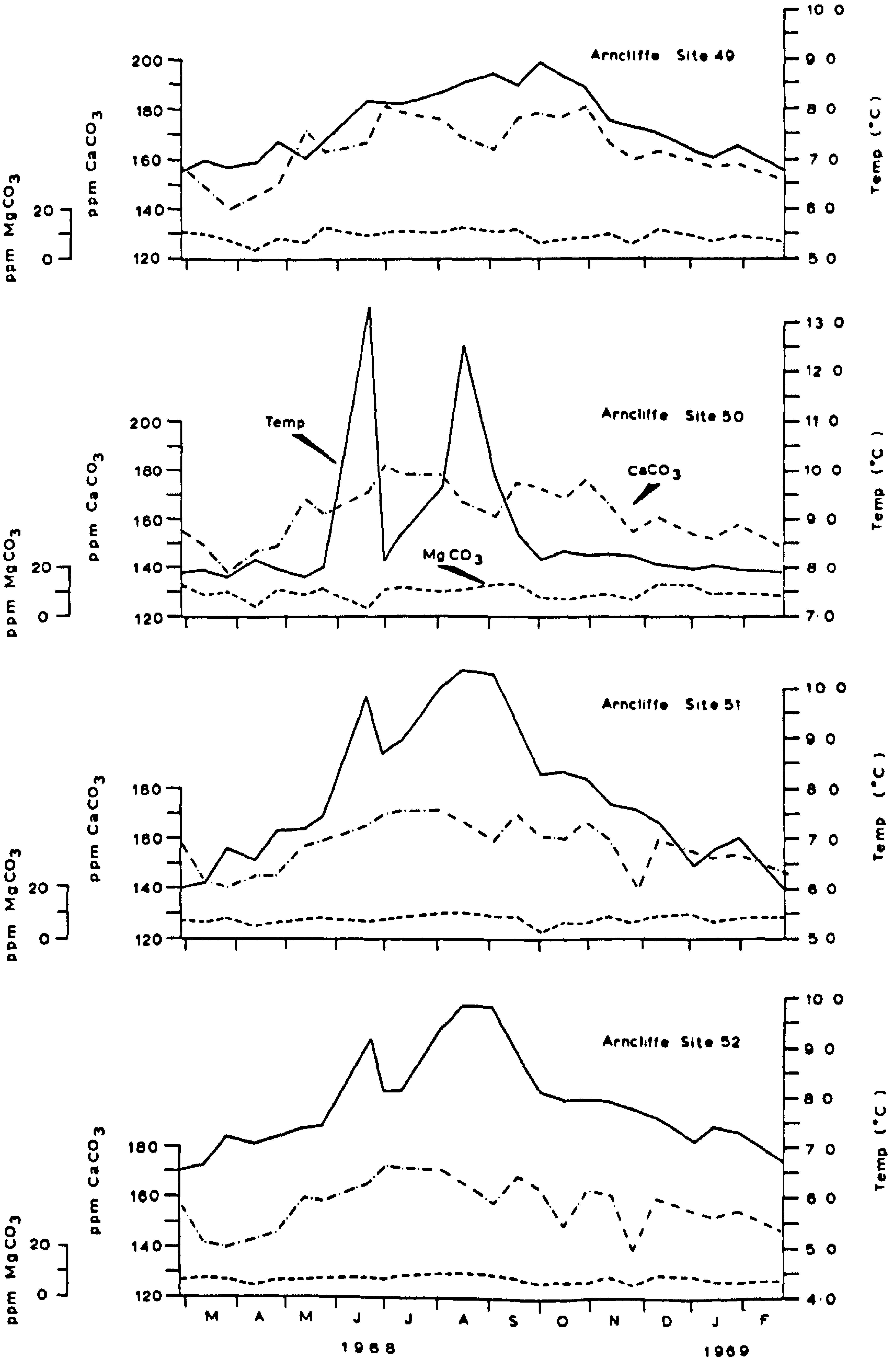


Fig.11a

Fig.11b

Fig.11c

Fig.11d

Figs.11a-11d Dissolved calcium and magnesium carbonate and water temperature variations recorded at Arncliffe sites 49, 50, 51 and 52 (year I)

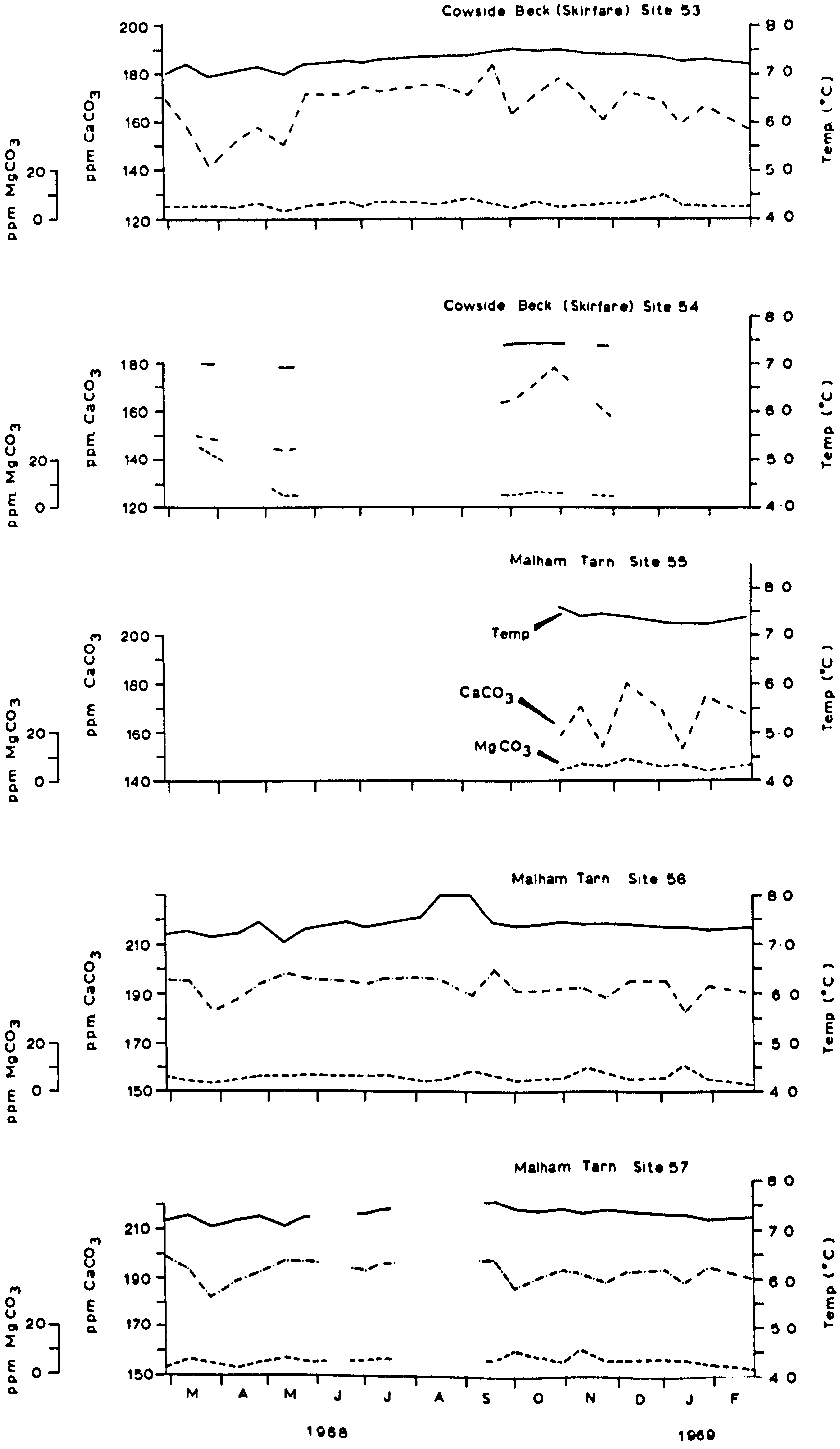


Fig.12a

Fig.12b

Fig.12c

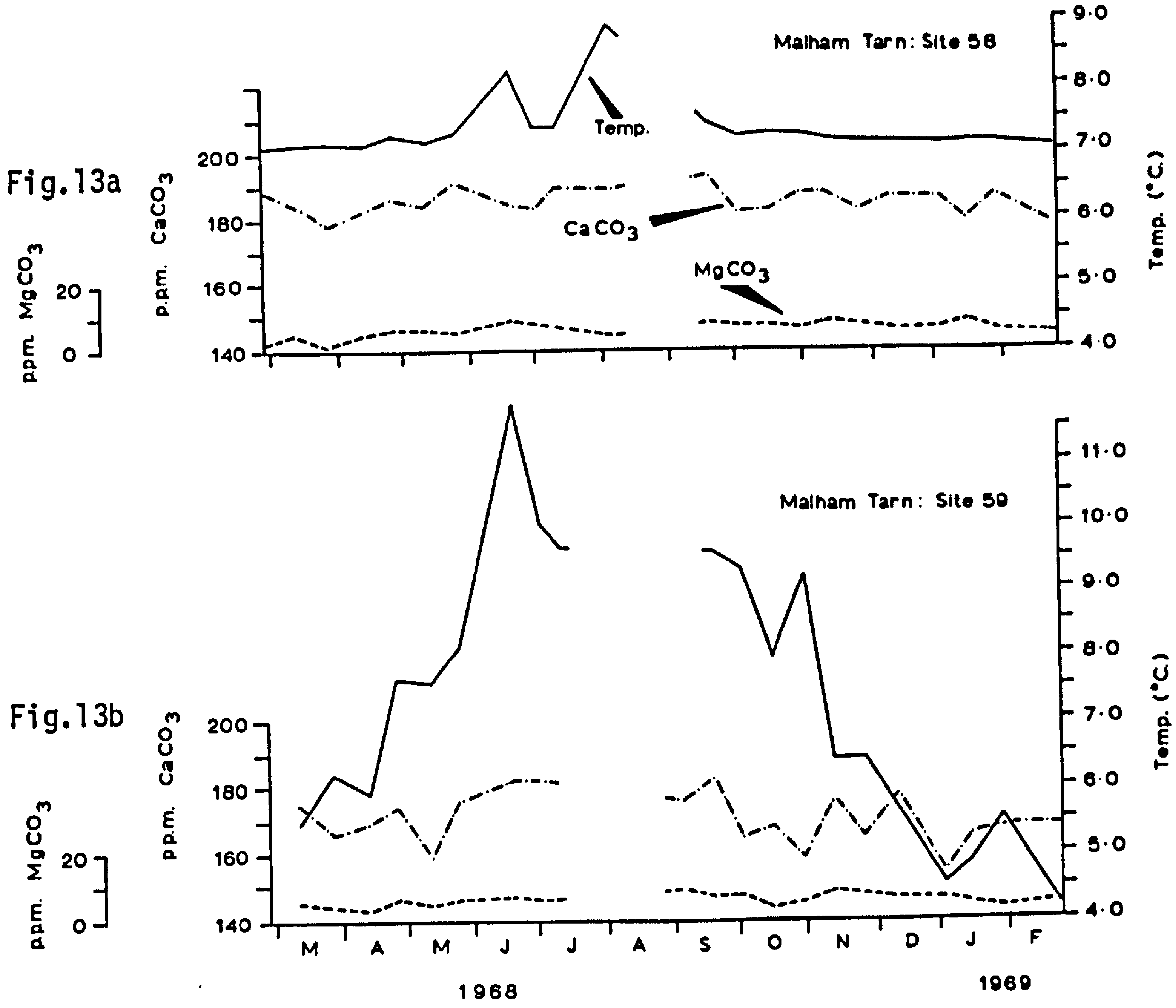
Fig.12d

Fig.12e

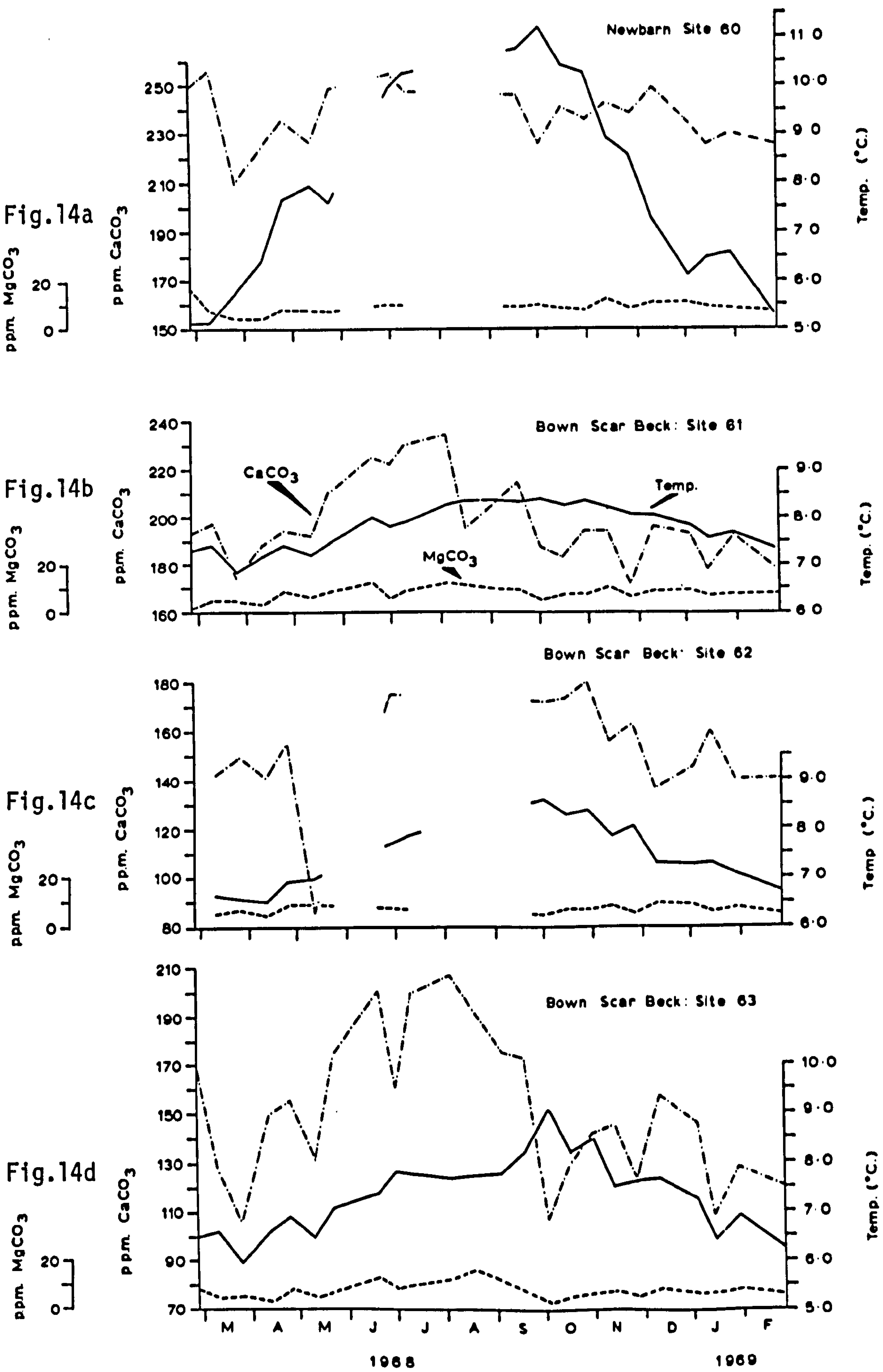
Figs.12a-12e Dissolved calcium and magnesium carbonate variations recorded at Cowside Beck (Skirfare) sites 53 and 54, and Malham Tarn sites 55, 56 and 57 (year I)

Fig.13a

Fig.13b



Figs.13a & 13b Dissolved calcium and magnesium carbonate and water temperature variations recorded at Malham Tarn sites 58 and 59 (year I)



Figs.14a-14d Dissolved calcium and magnesium carbonate and water temperature variations recorded at Newbarn site 60, and Bown Scar Beck sites 61, 62 and 63 (year I)

Fig.15a

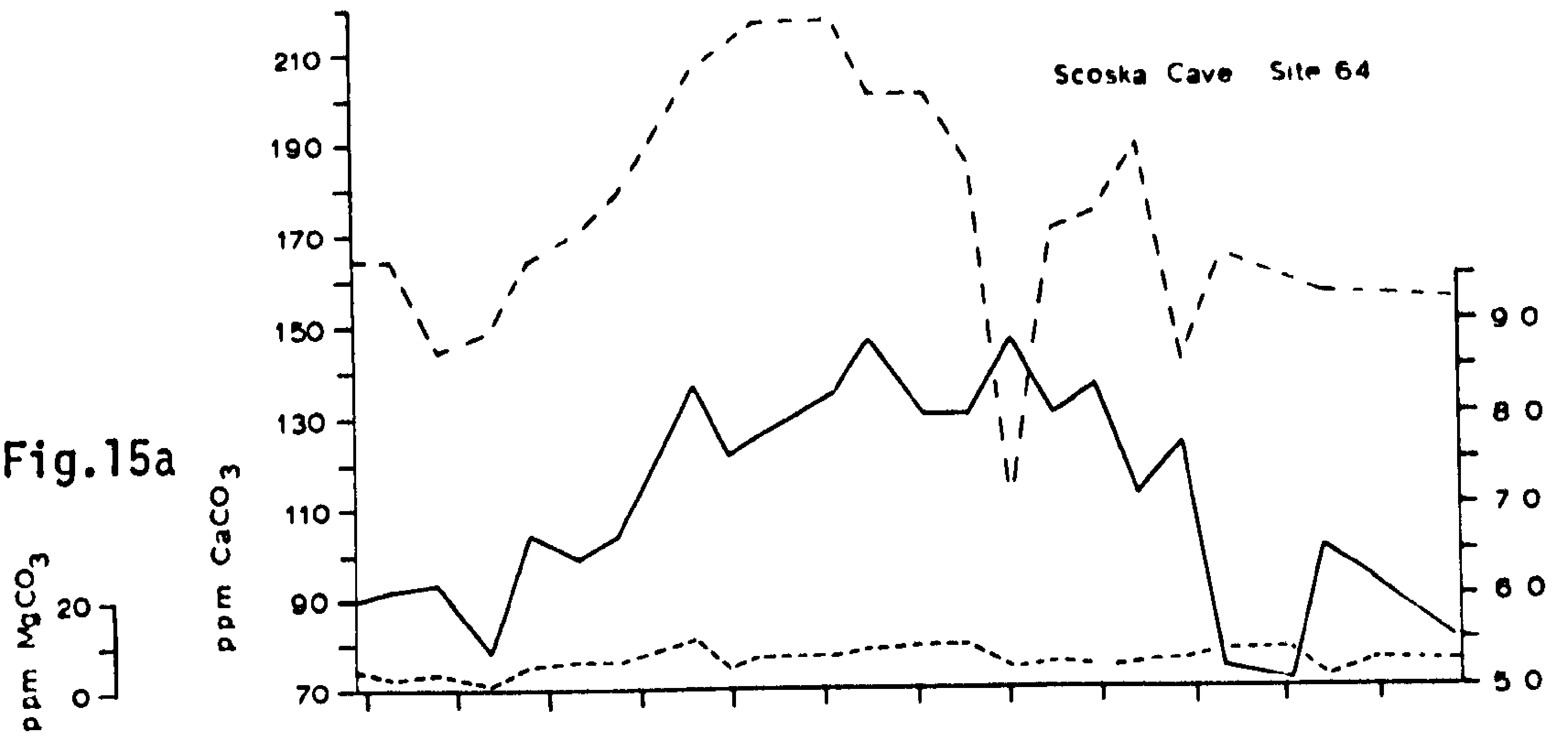


Fig.15b

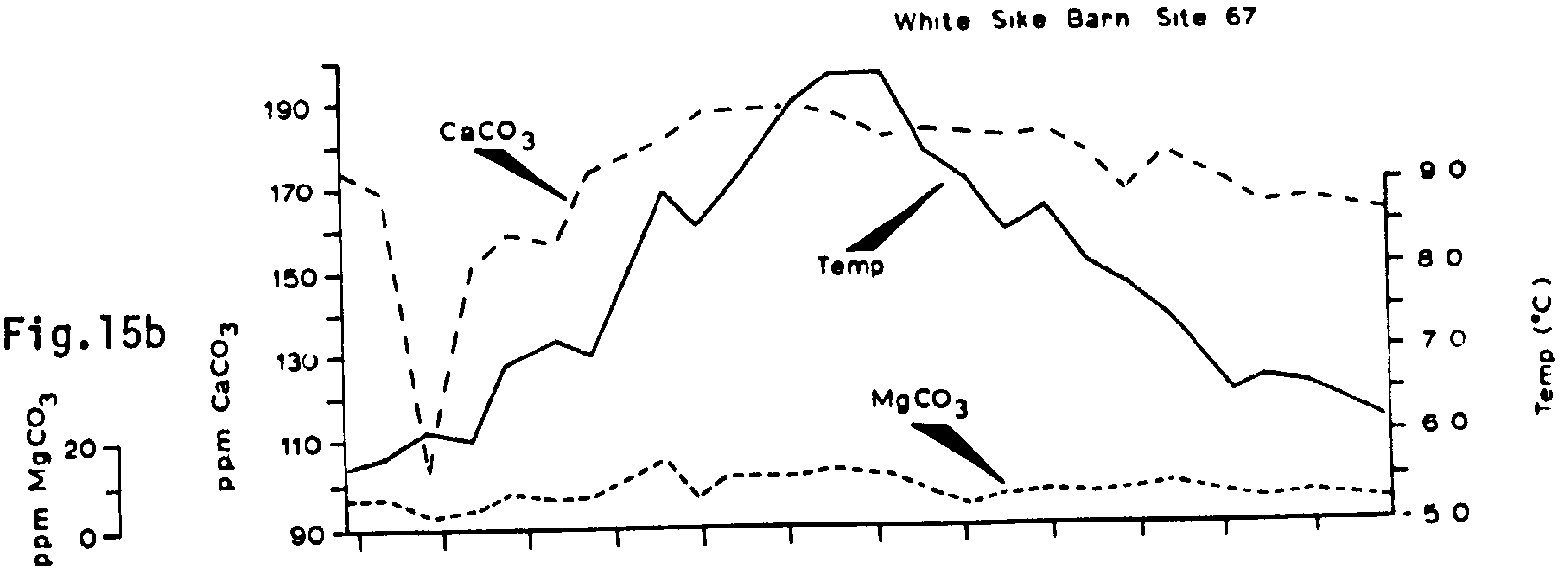
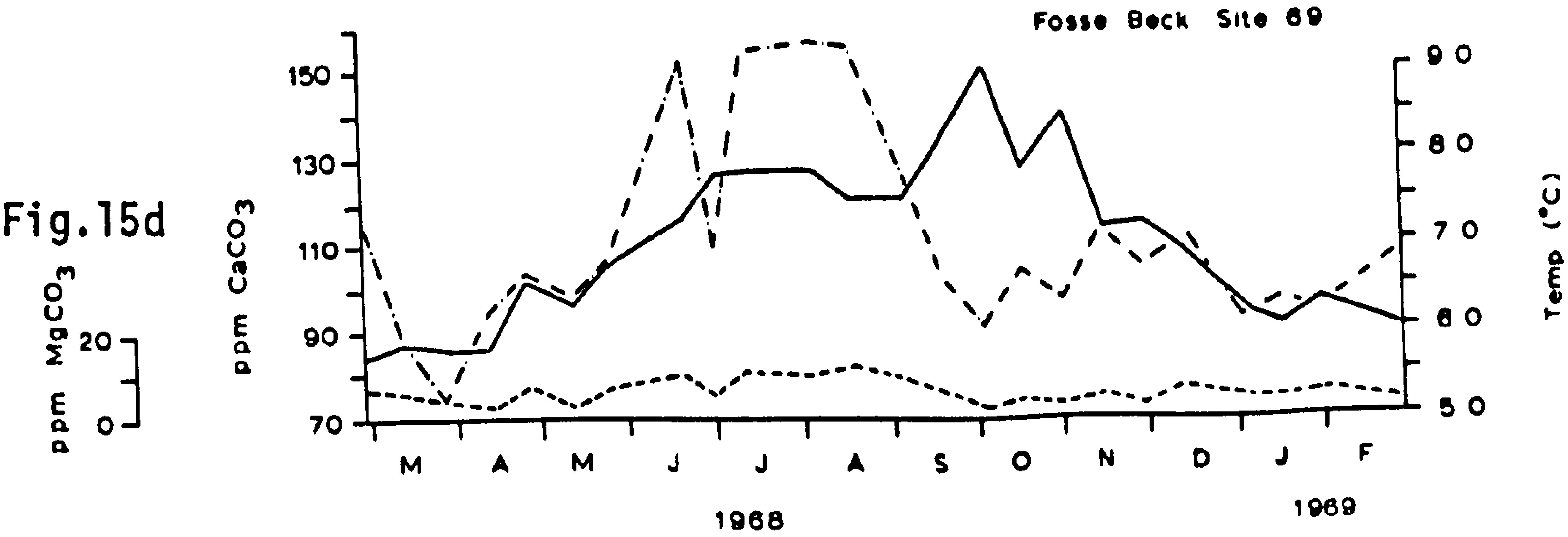


Fig.15c

Fig.15d



Figs.15a-15d Dissolved calcium and magnesium carbonate and water temperature variations recorded at Scoska Cave site 64, White Sike Barn site 67, Roselbar Wood site 68 and Fosse Beck site 69 (year I)

Fig.16a

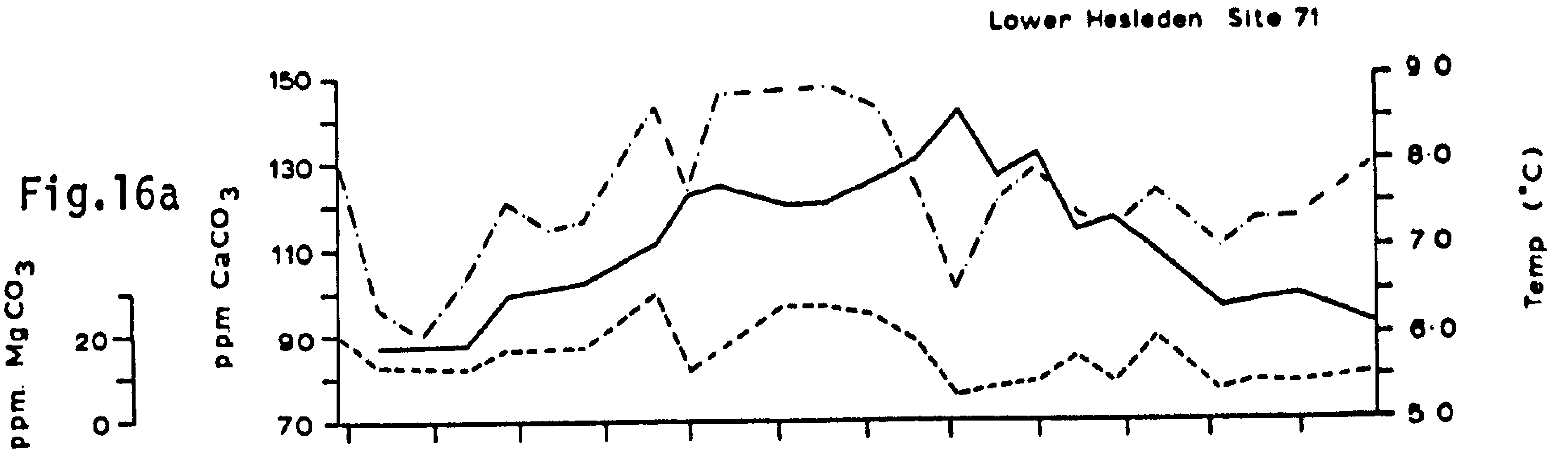


Fig.16b

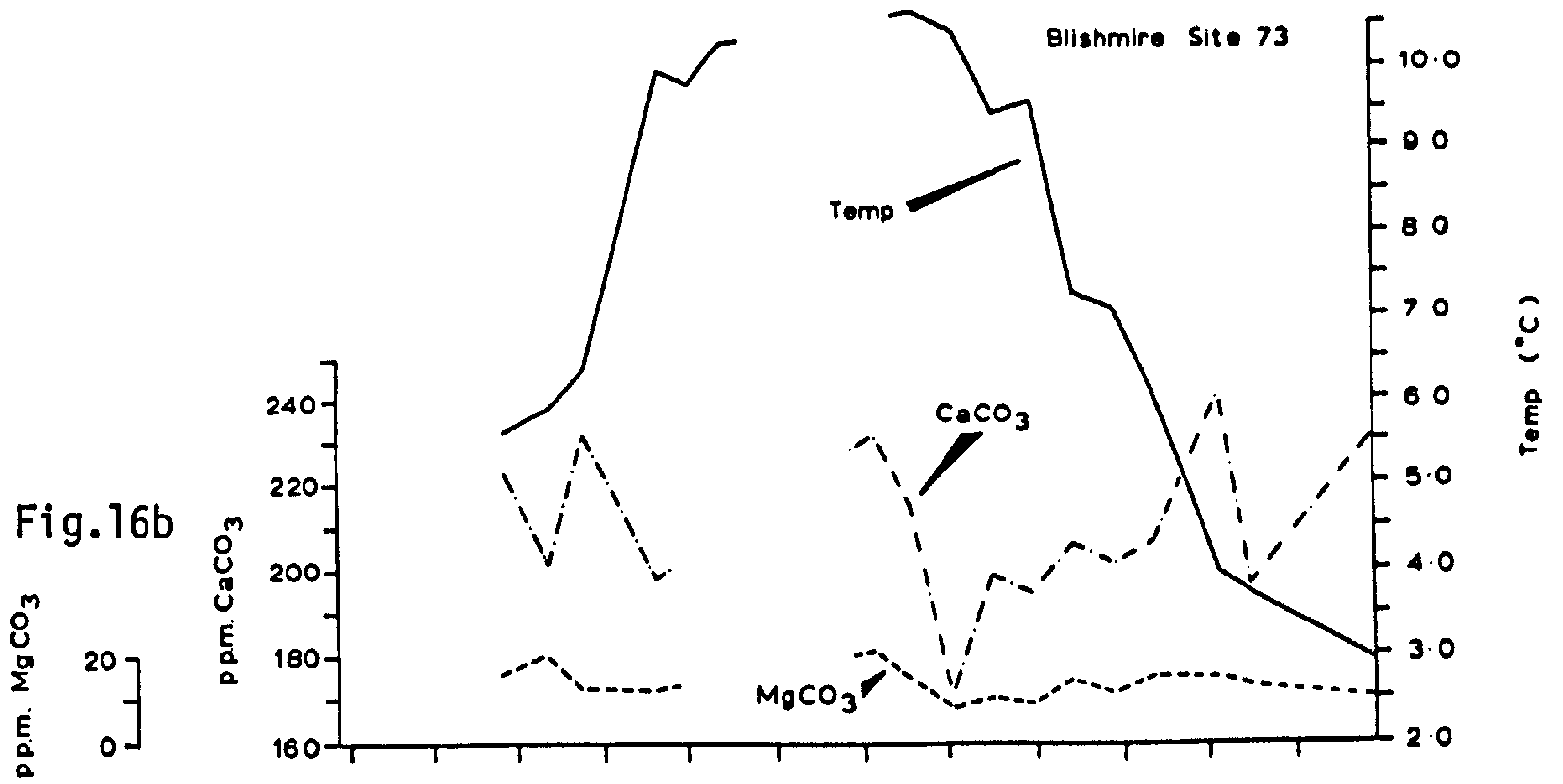
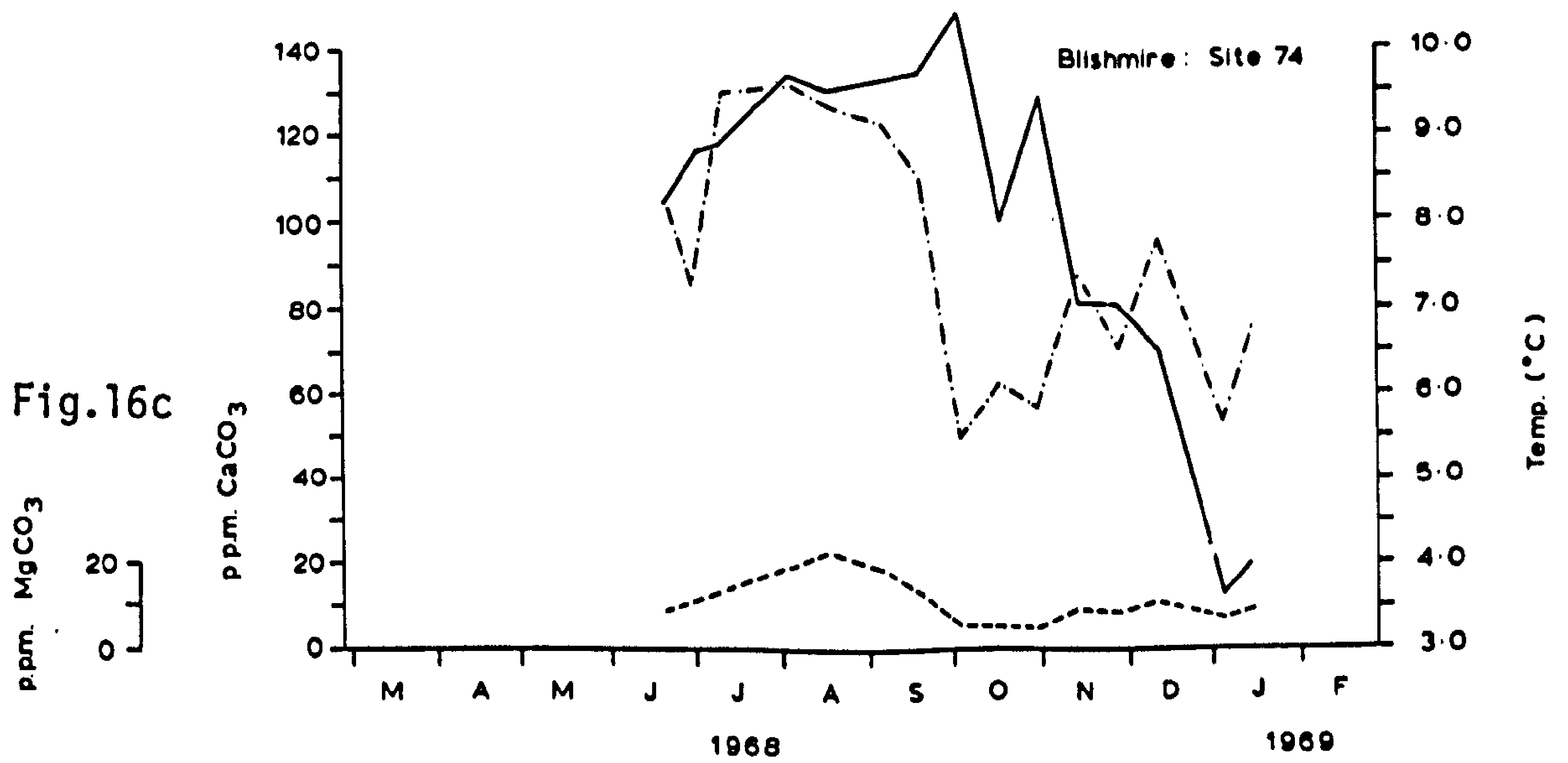


Fig.16c



Figs.16a-16c Dissolved calcium and magnesium carbonate and water temperature variations recorded at Lower Hesleden site 71 and Blishmire sites 73 and 74 (year I)

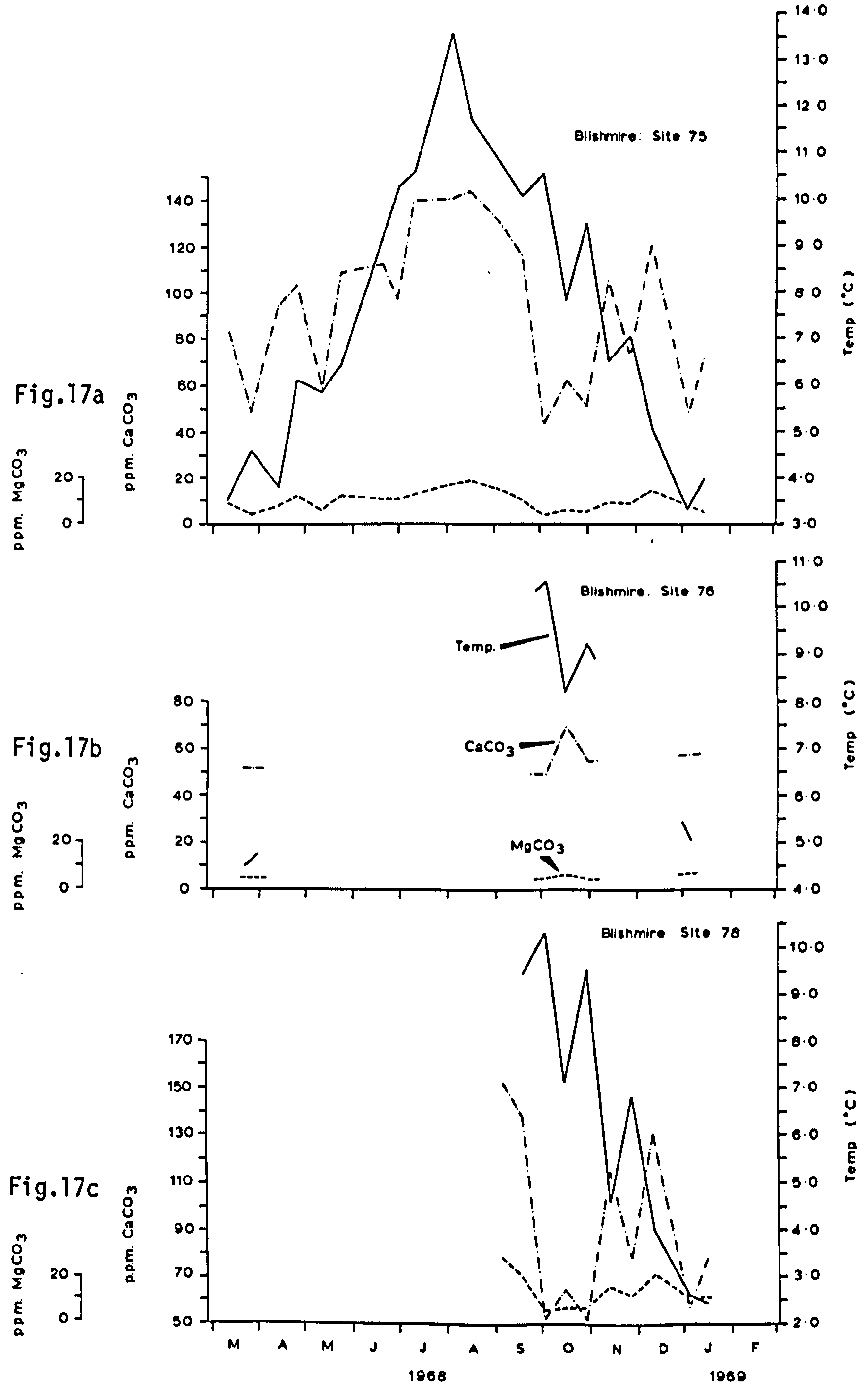
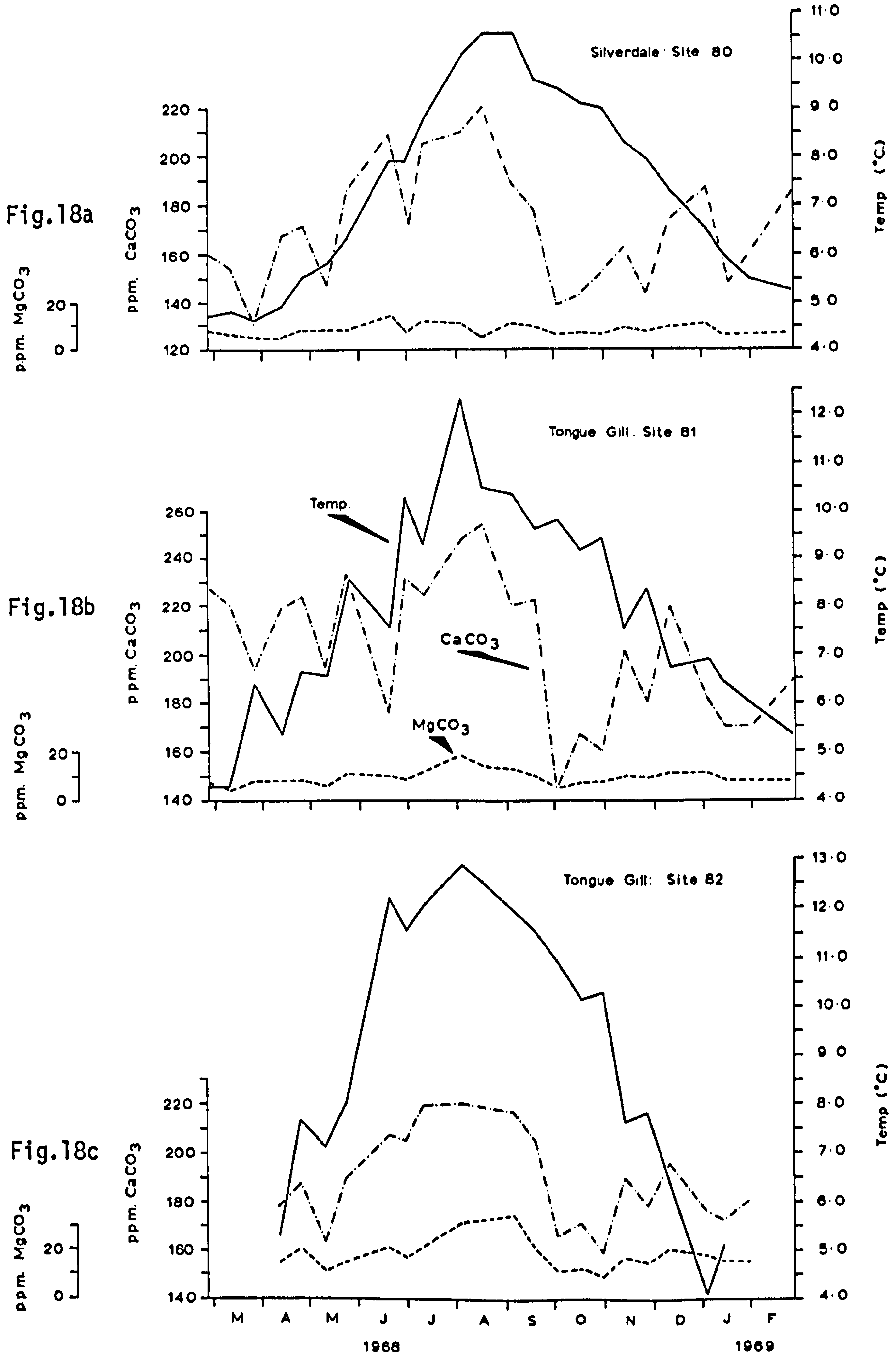


Fig.17a

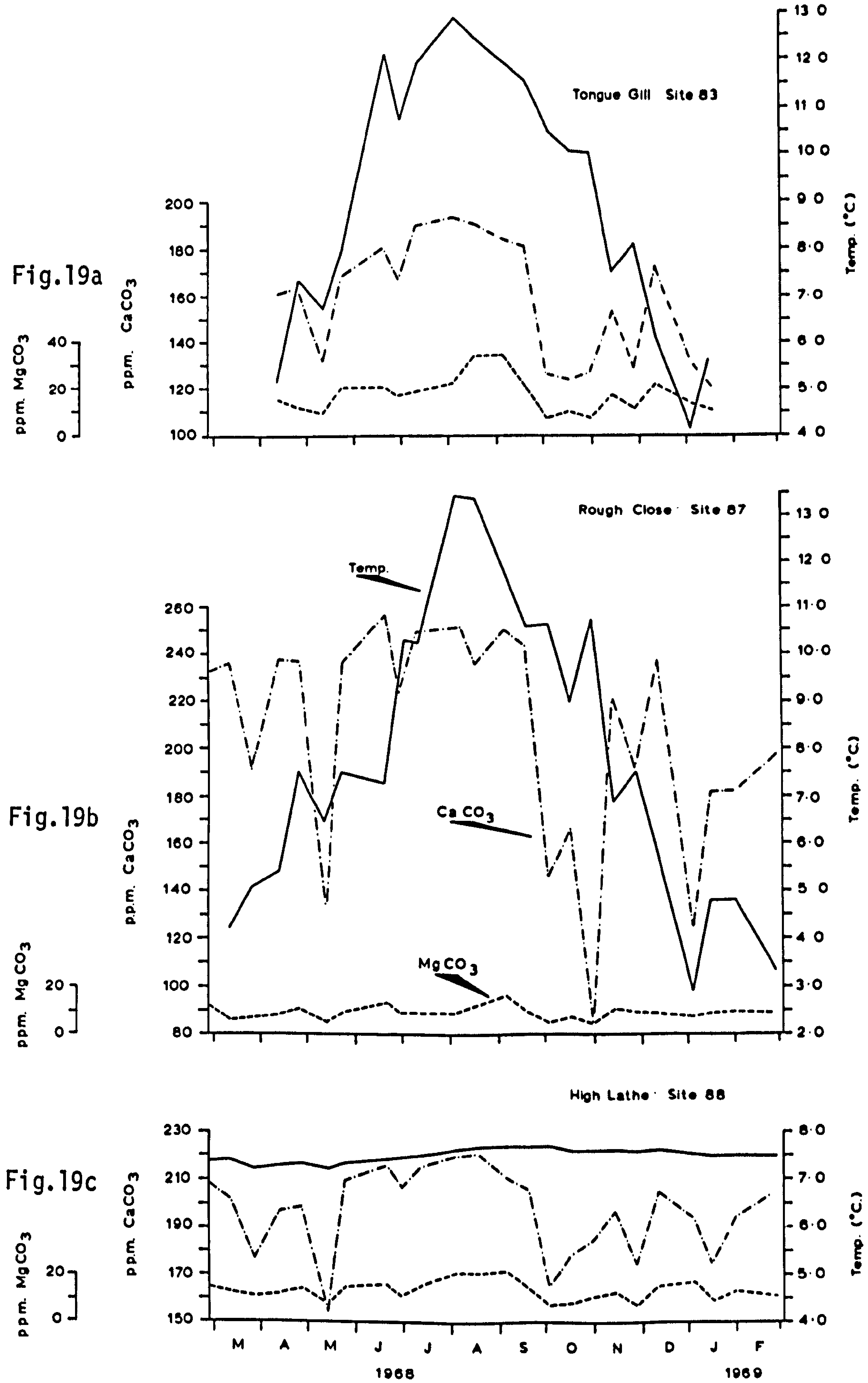
Fig.17b

Fig.17c

Figs.17a-17c Dissolved calcium and magnesium carbonate and water temperature variations recorded at Blishmire sites 75, 76 and 78 (year I)



Figs.18a-18c Dissolved calcium and magnesium carbonate and water temperature variations recorded at Silverdale site 80, and Tongue Gill sites 81 and 82 (year I)



Figs.19a-19c Dissolved calcium and magnesium carbonate and water temperature variations recorded at Tongue Gill site 83, Rough Close site 87 and High Lathe site 88 (year I)

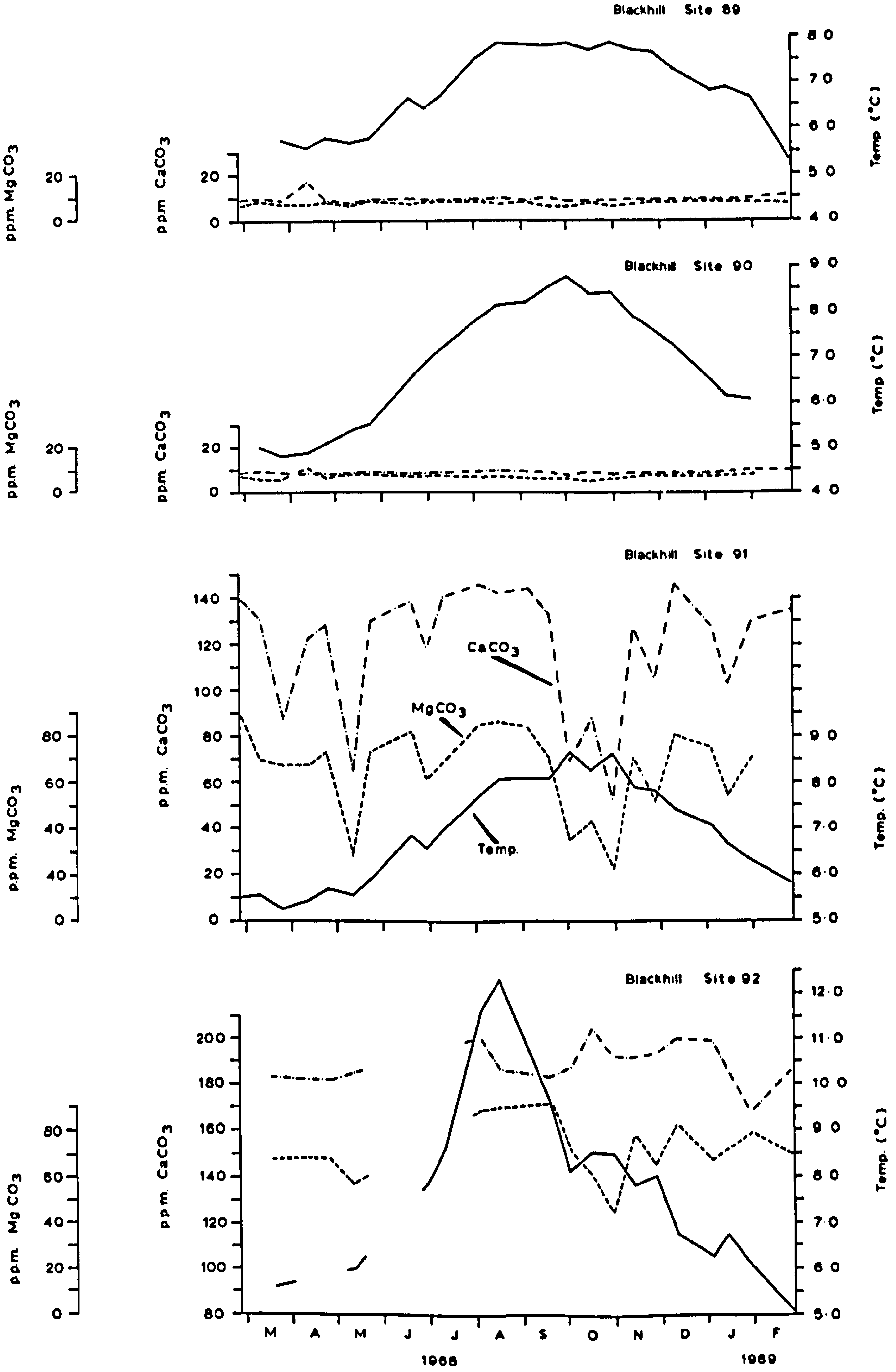


Fig.20a

Fig.20b

Fig.20c

Fig.20d

Figs.20a-20d Dissolved calcium and magnesium carbonate and water temperature variations recorded at Blackhill sites 89, 90, 91 and 92 (year I)

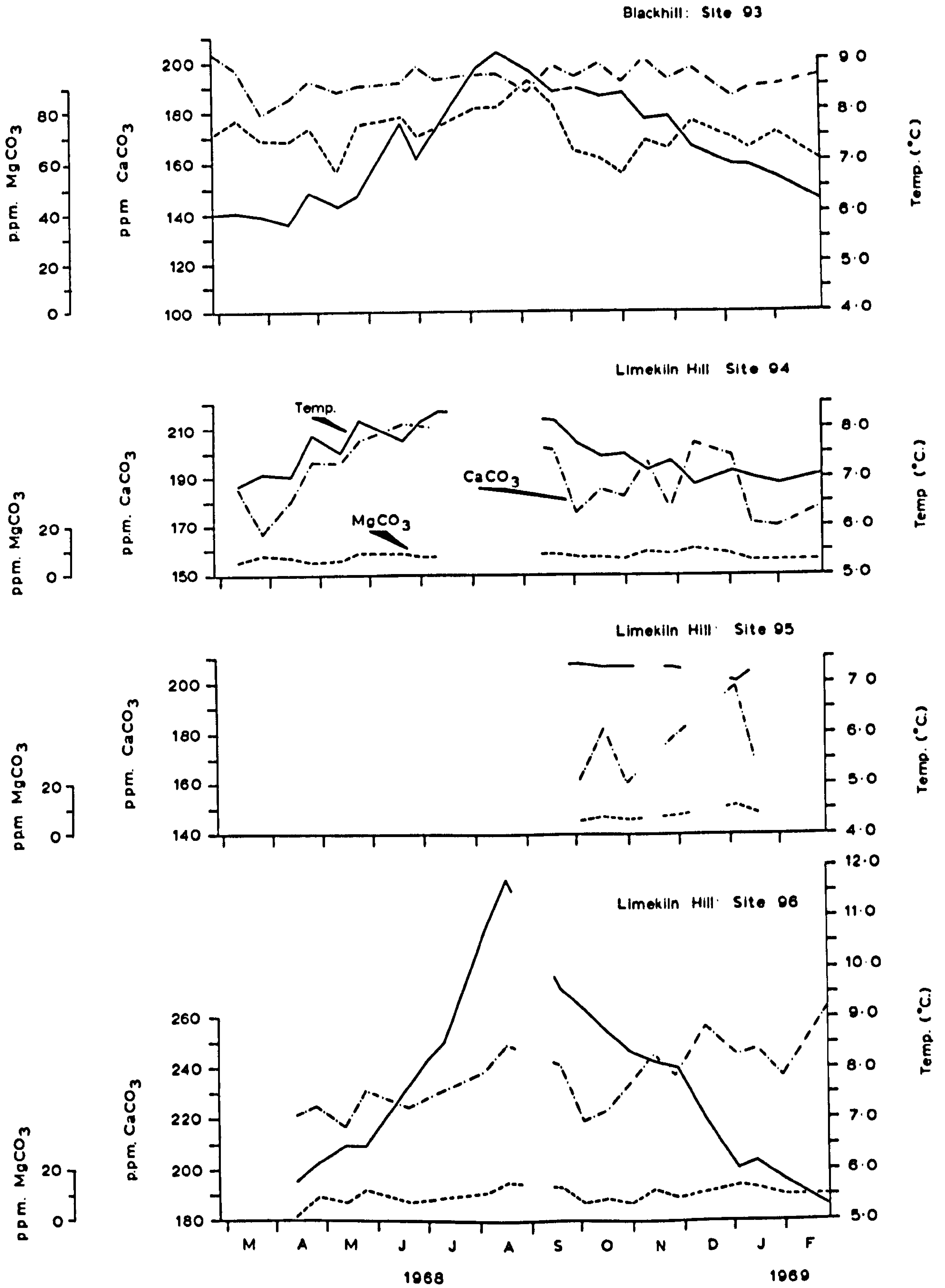


Fig.21a

Fig.21b

Fig.21c

Fig.21d

Figs.21a-21d Dissolved calcium and magnesium carbonate and water temperature variations recorded at Blackhill site 93 and Limekiln Hill sites 94, 95 and 96 (year I)

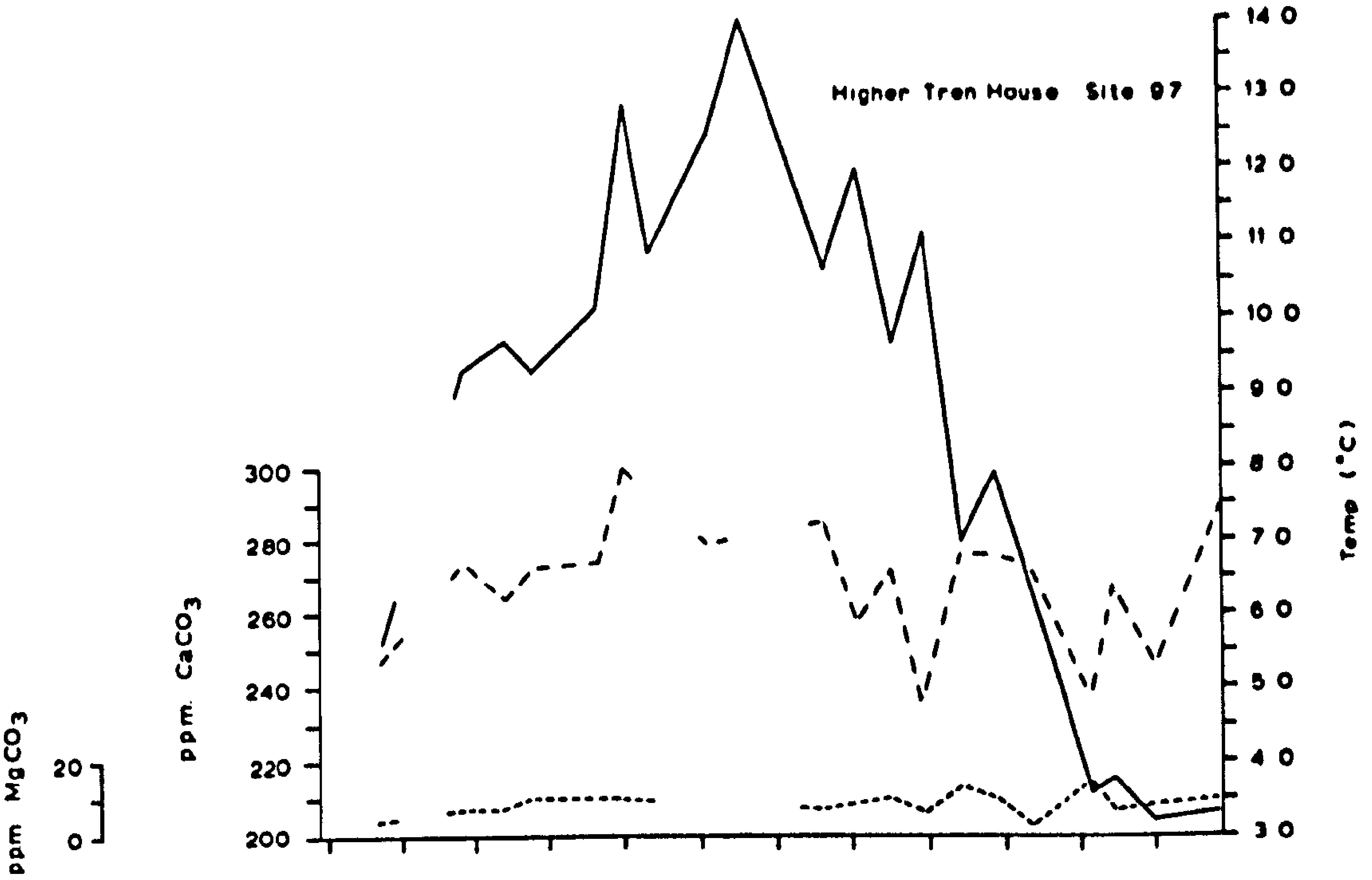


Fig.22a

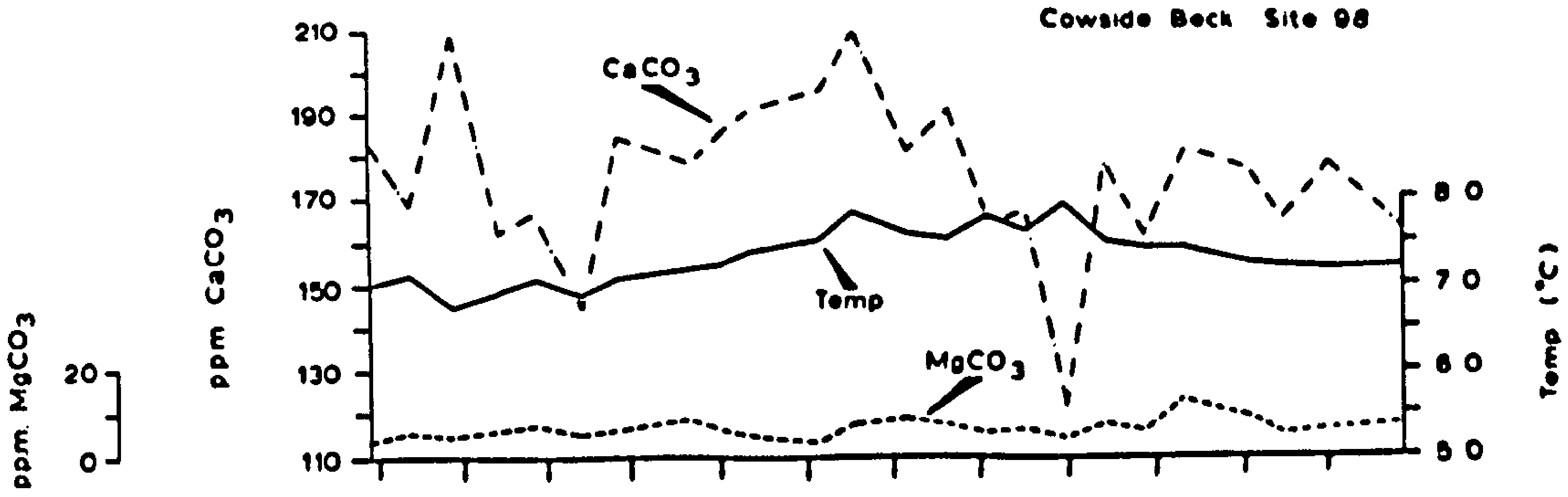


Fig.22b

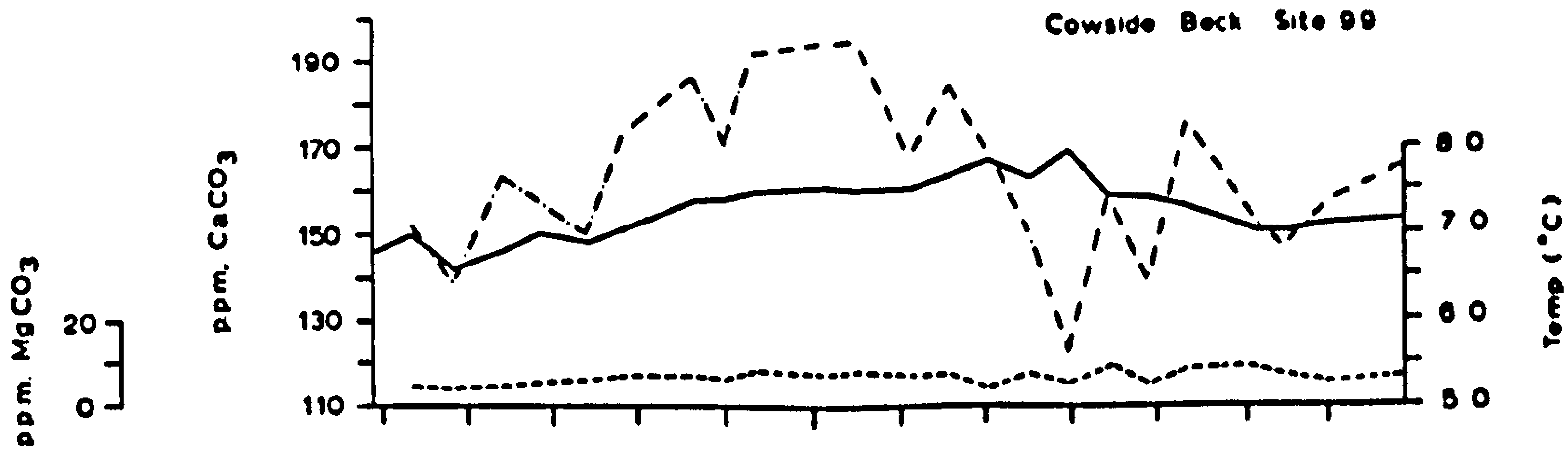


Fig.22c

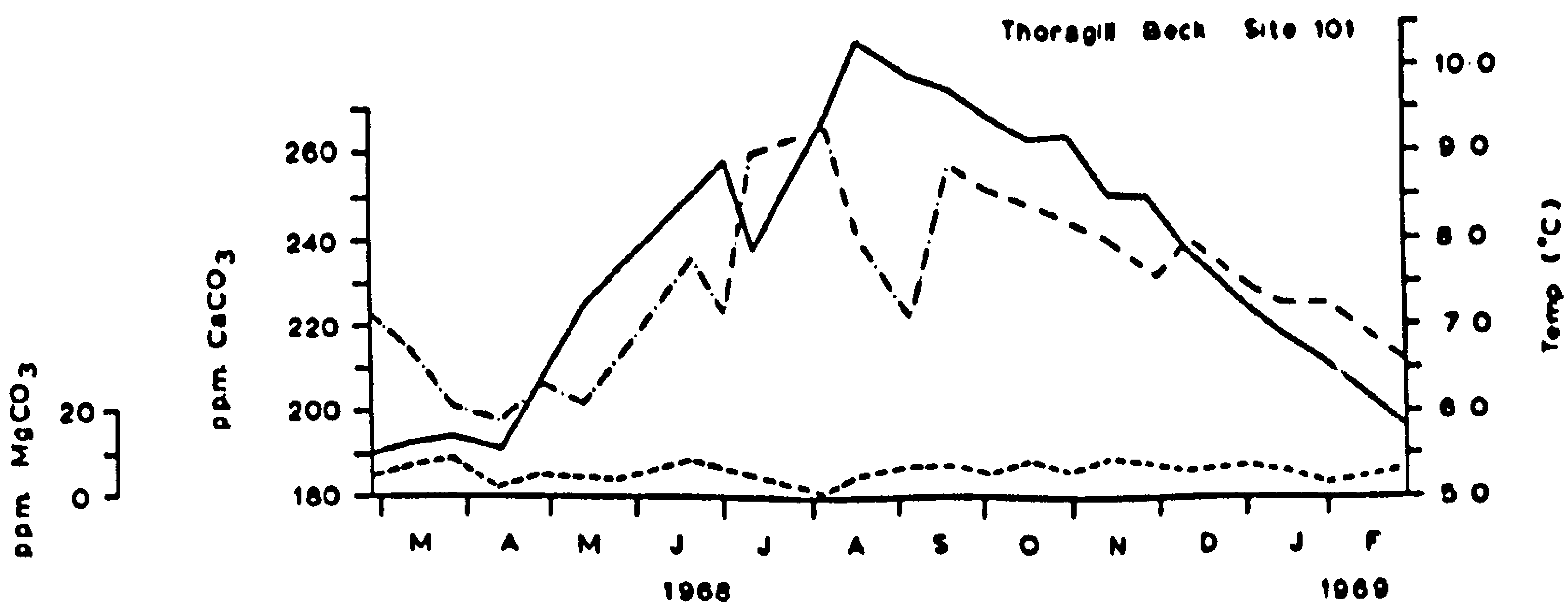


Fig.22d

Figs.22a-22d Dissolved calcium and magnesium carbonate and water temperature variations recorded at Higher Tren House site 97, Cowside Beck sites 98 and 99 and Thoragill Beck site 101 (year I)

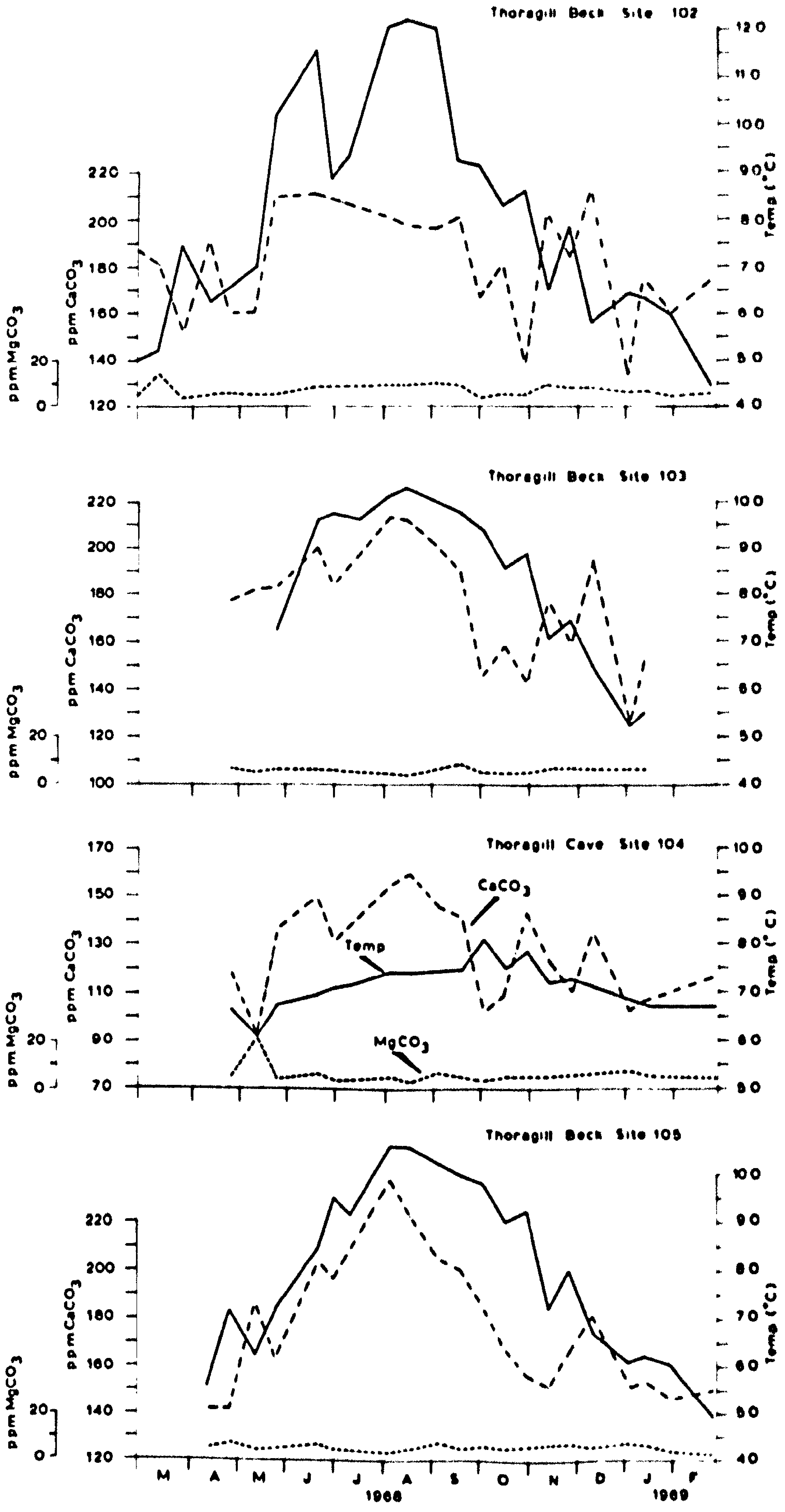


Fig.23a

Fig.23b

Fig.23c

Fig.23d

Figs.23a-23d Dissolved calcium and magnesium carbonate and water temperature variations recorded at Thoragill Beck sites 102 and 103, Thoragill Beck site 105 (year I)

Fig.24a

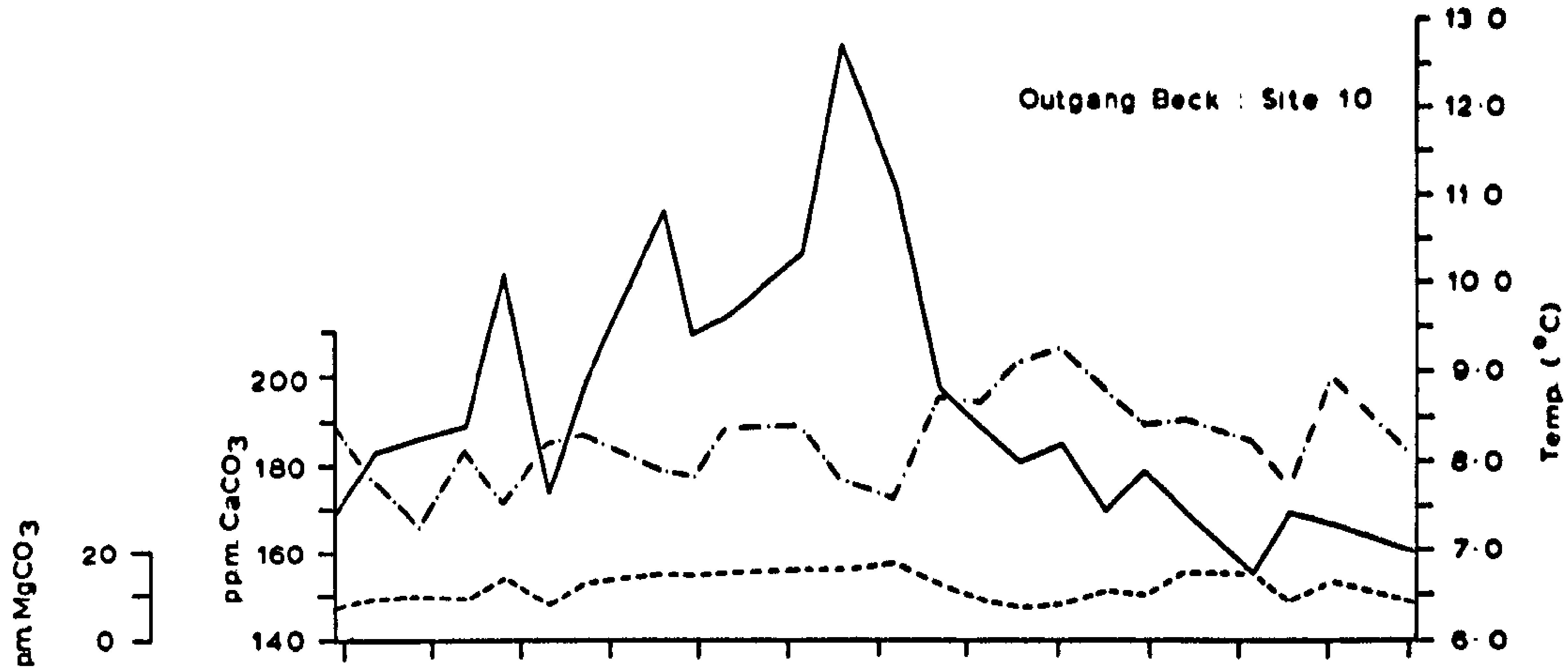


Fig.24b

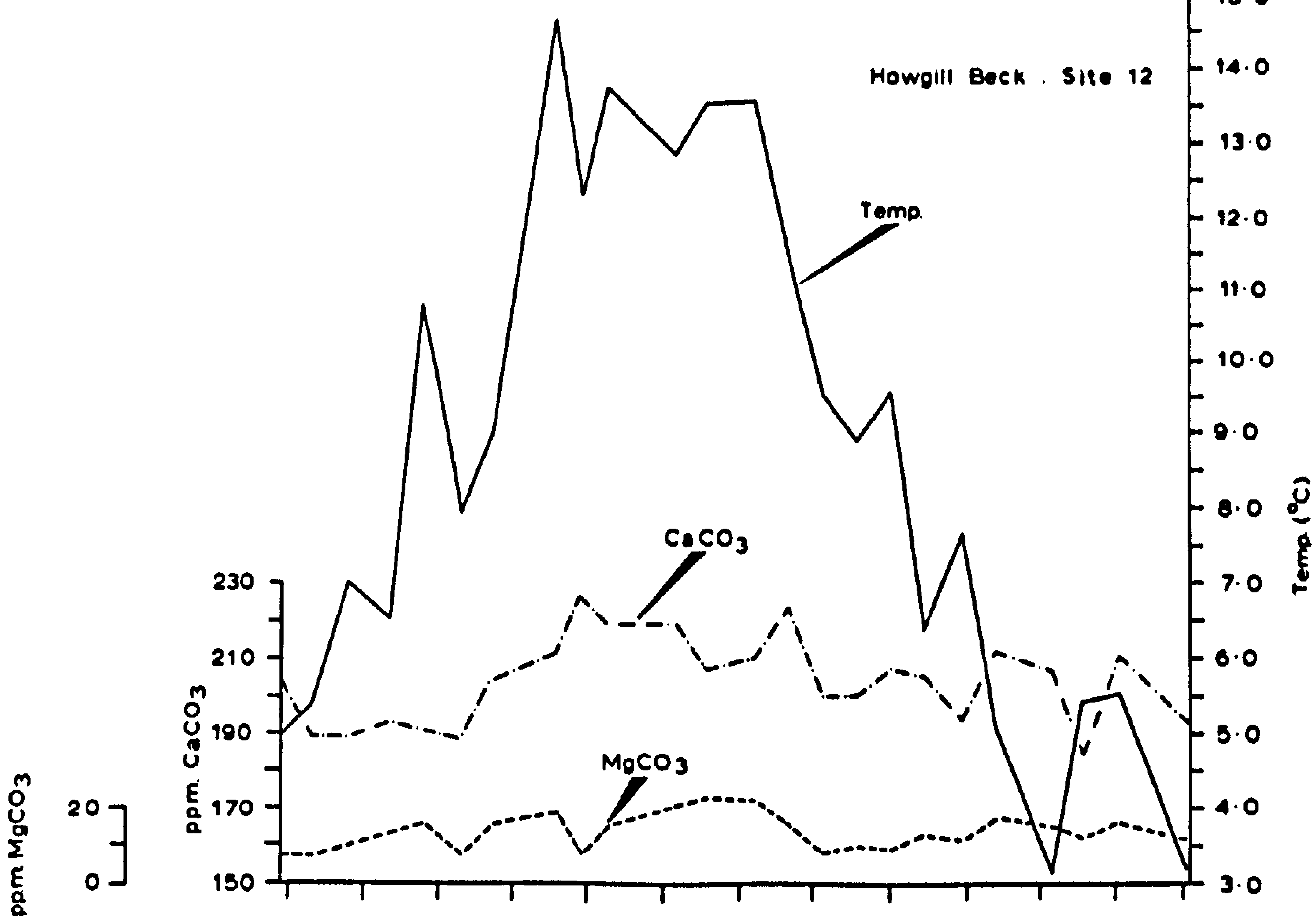
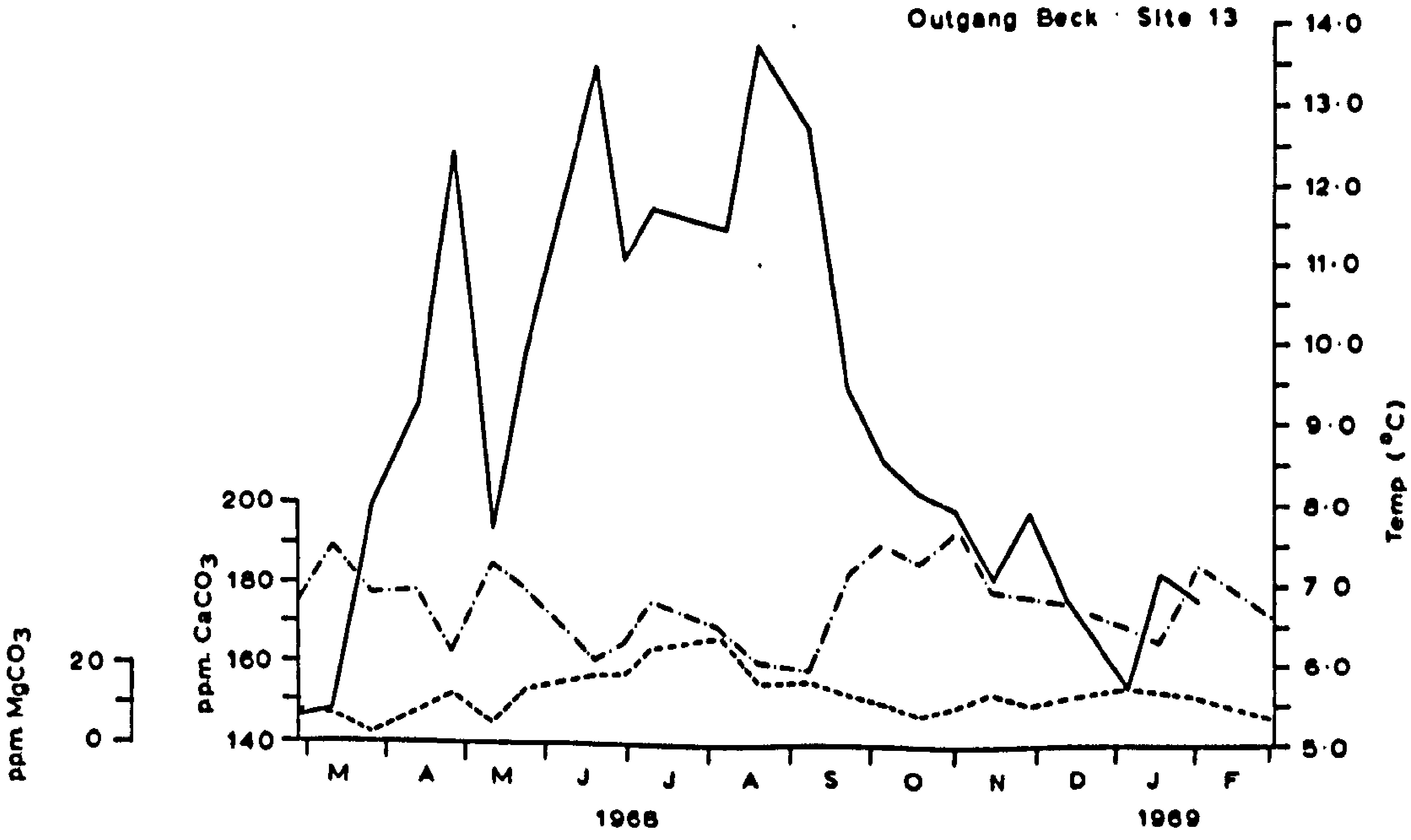


Fig.24c



Figs.24a-24c Dissolved calcium and magnesium carbonate and water temperature variations recorded at Outgang Beck site 10, Howgill Beck site 12 and Outgang Beck site 13 (year I)

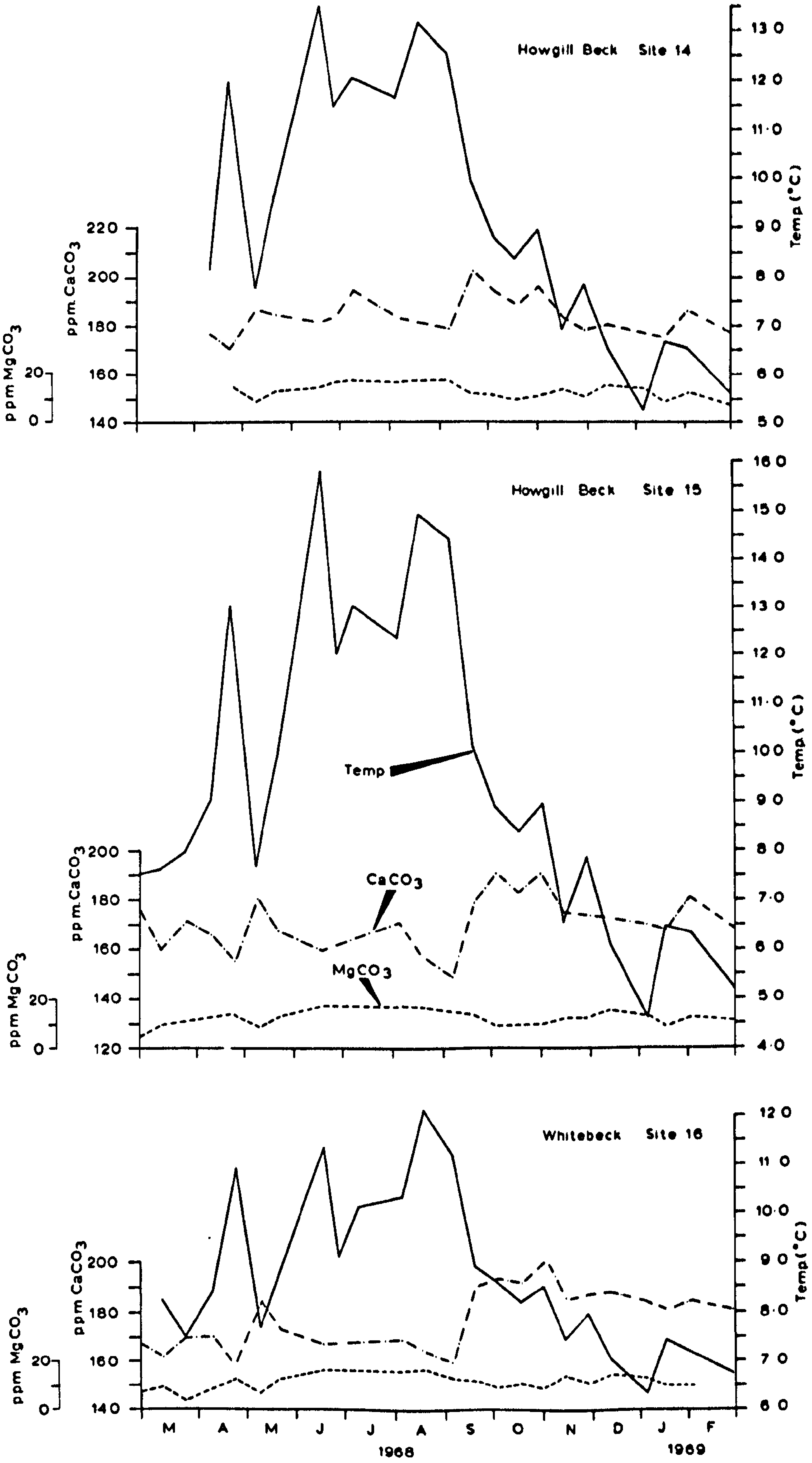


Fig.25a

Fig.25b

Fig.25c

Figs.25a-25c Dissolved calcium and magnesium carbonate and water temperature variations recorded at Howgill Beck sites 14 and 15 and Whitebeck site 16 (year I)

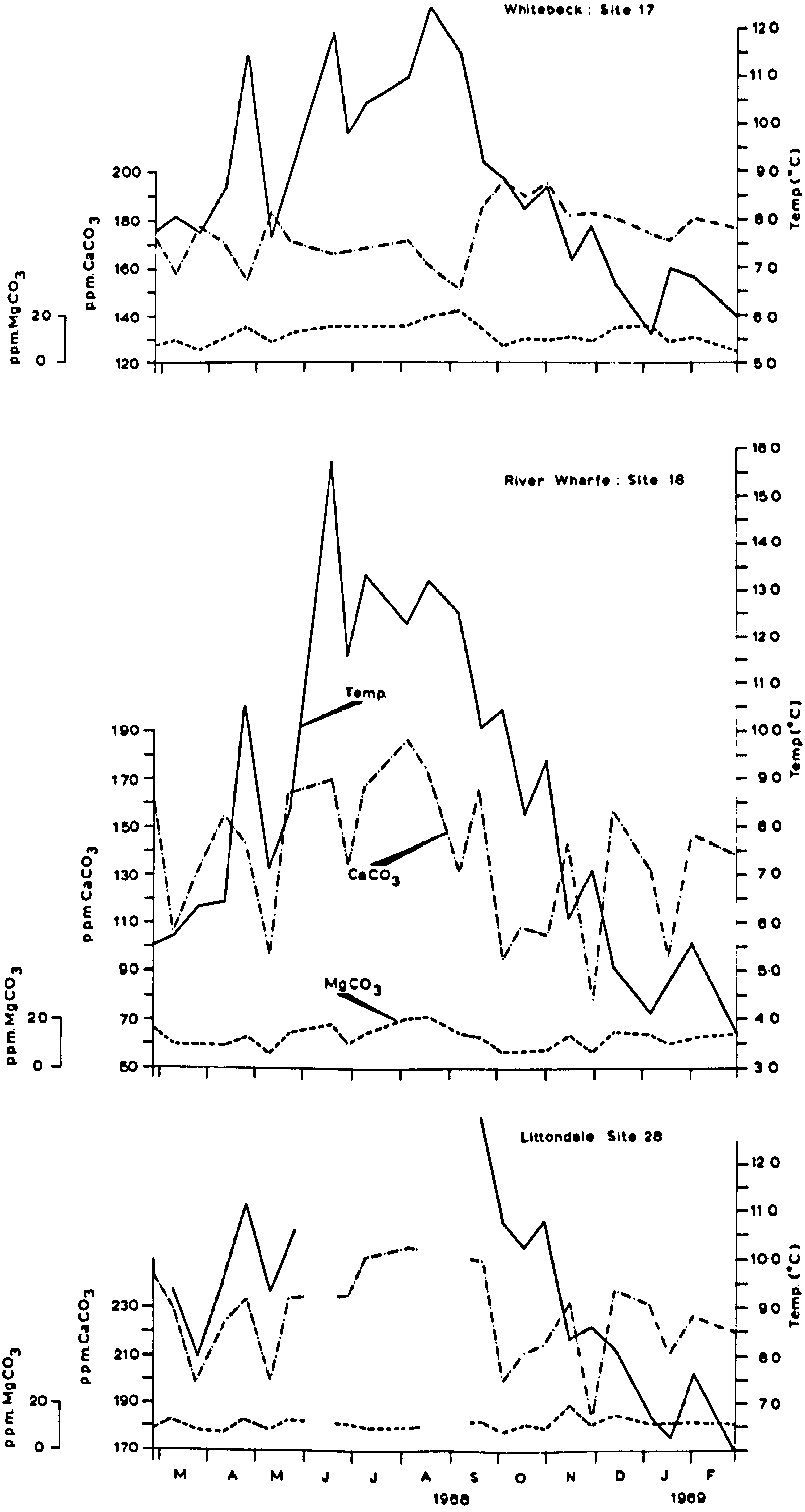


Fig.26a

Fig.26b

Fig.26c

Figs.26a-26c Dissolved calcium and magnesium carbonate and water temperature variations recorded at Whitebeck site 17, River Wharfe site 18 and Littondale site 28 (year I)

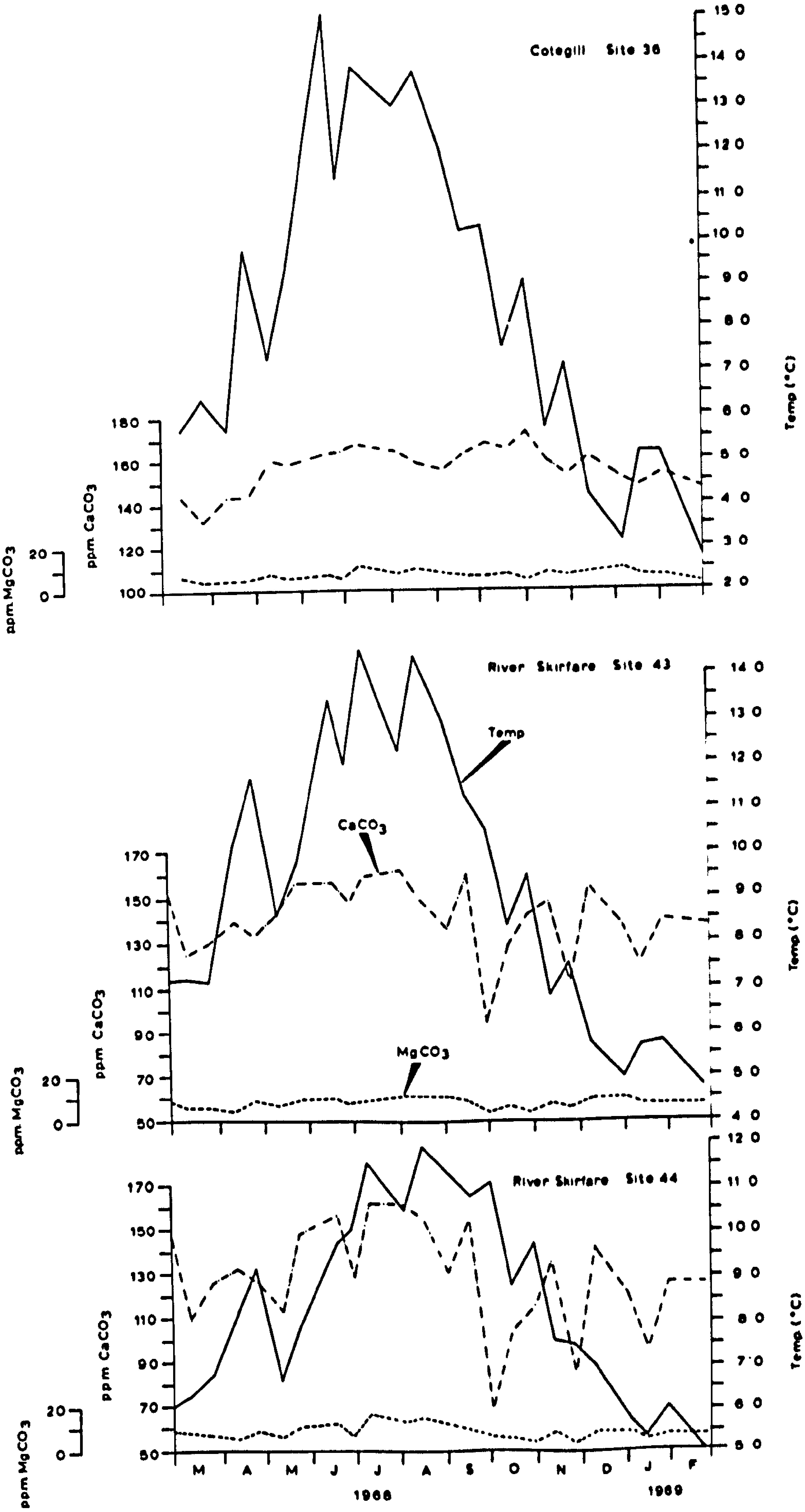


Fig.27a

Fig.27b

Fig.27c

Figs.27a-27c Dissolved calcium and magnesium carbonate and water temperature variations recorded at Cotegill site 36 and River Skirfare sites 43 and 44 (year I)

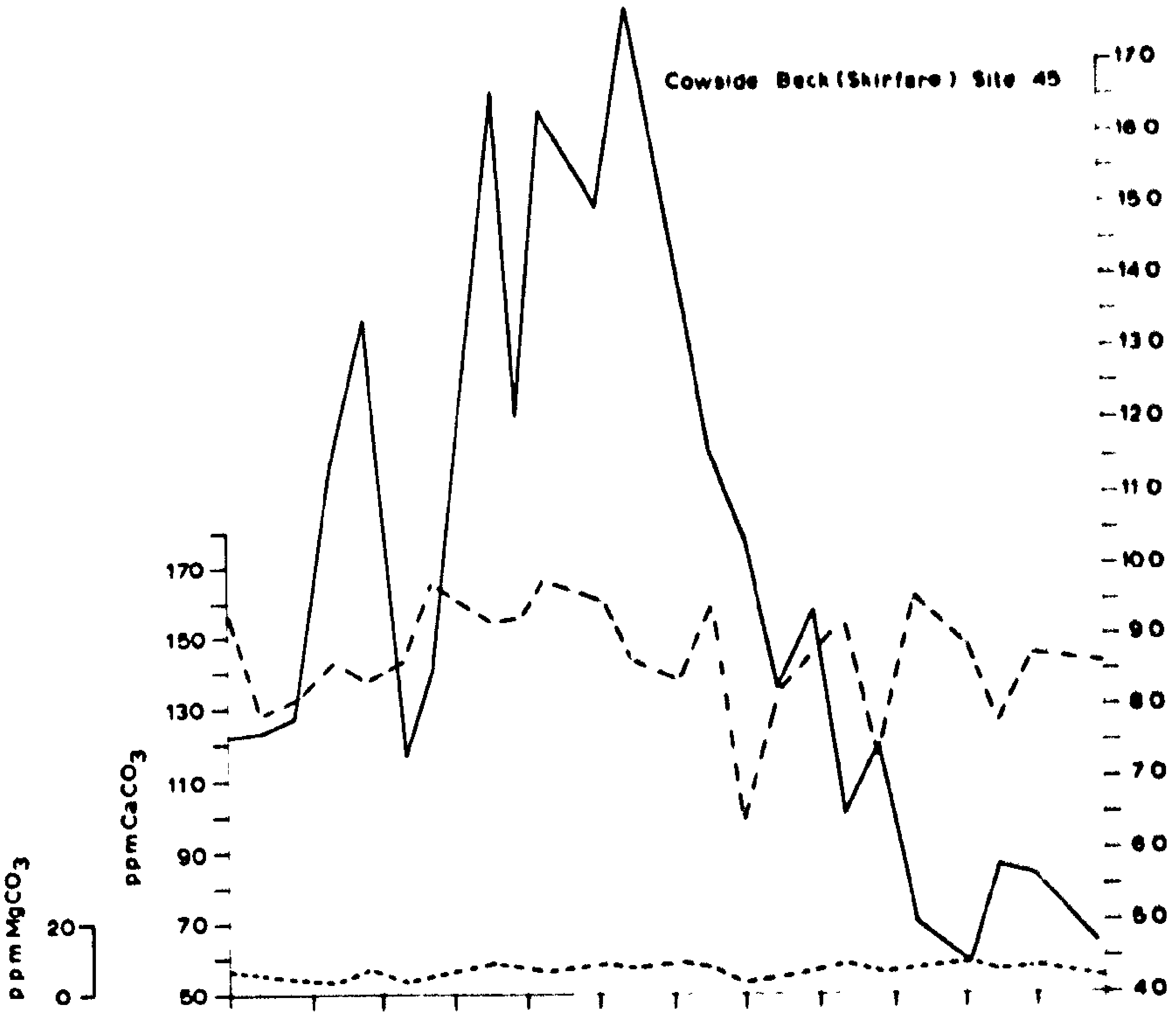


Fig.28a

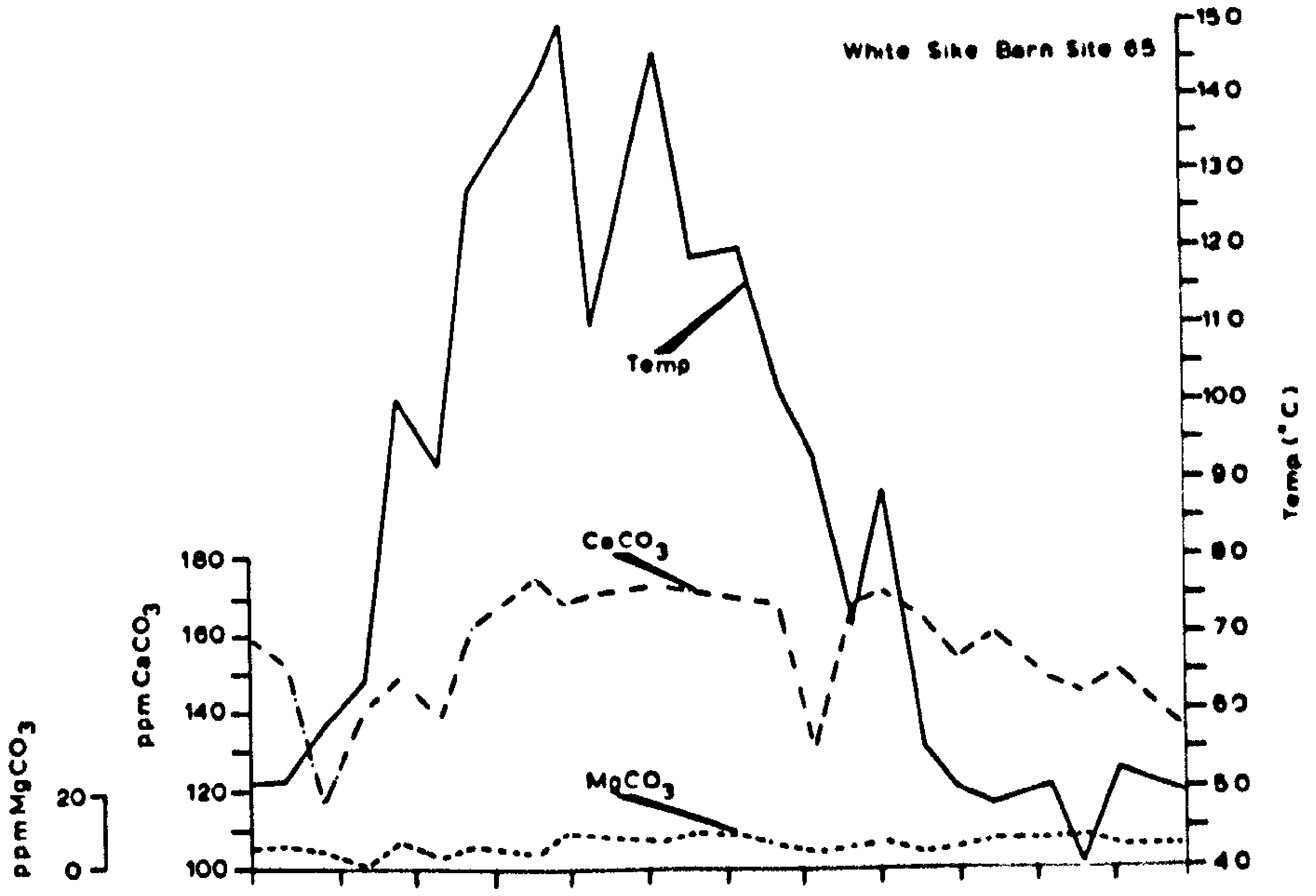


Fig.28b

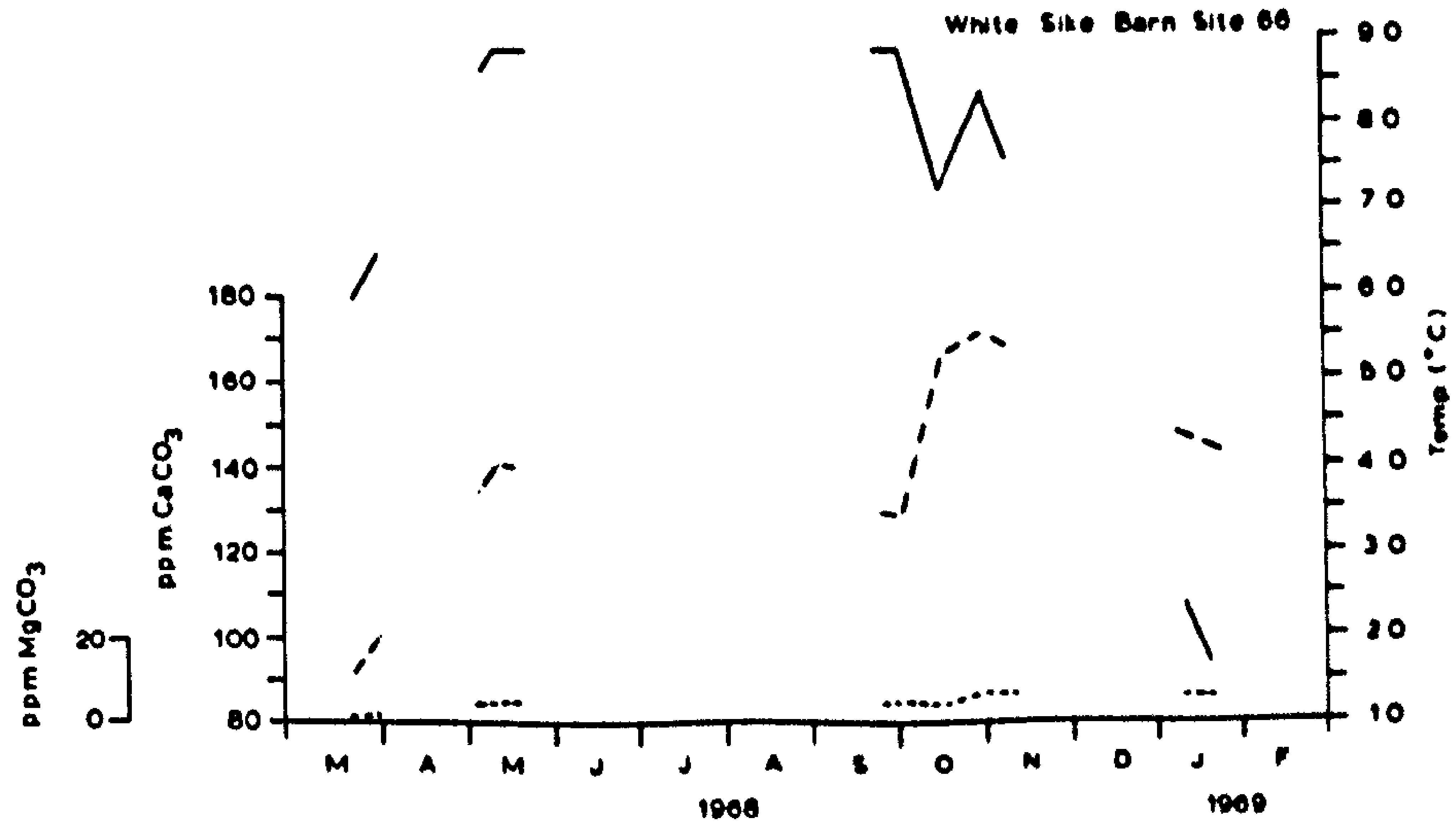


Fig.28c

Figs.28a-28c Dissolved calcium and magnesium carbonate and water temperature variations recorded at Cowside Beck (Skirfare) site 45 and White Sike Barn sites 65 and 66 (year I)

Fig.29a

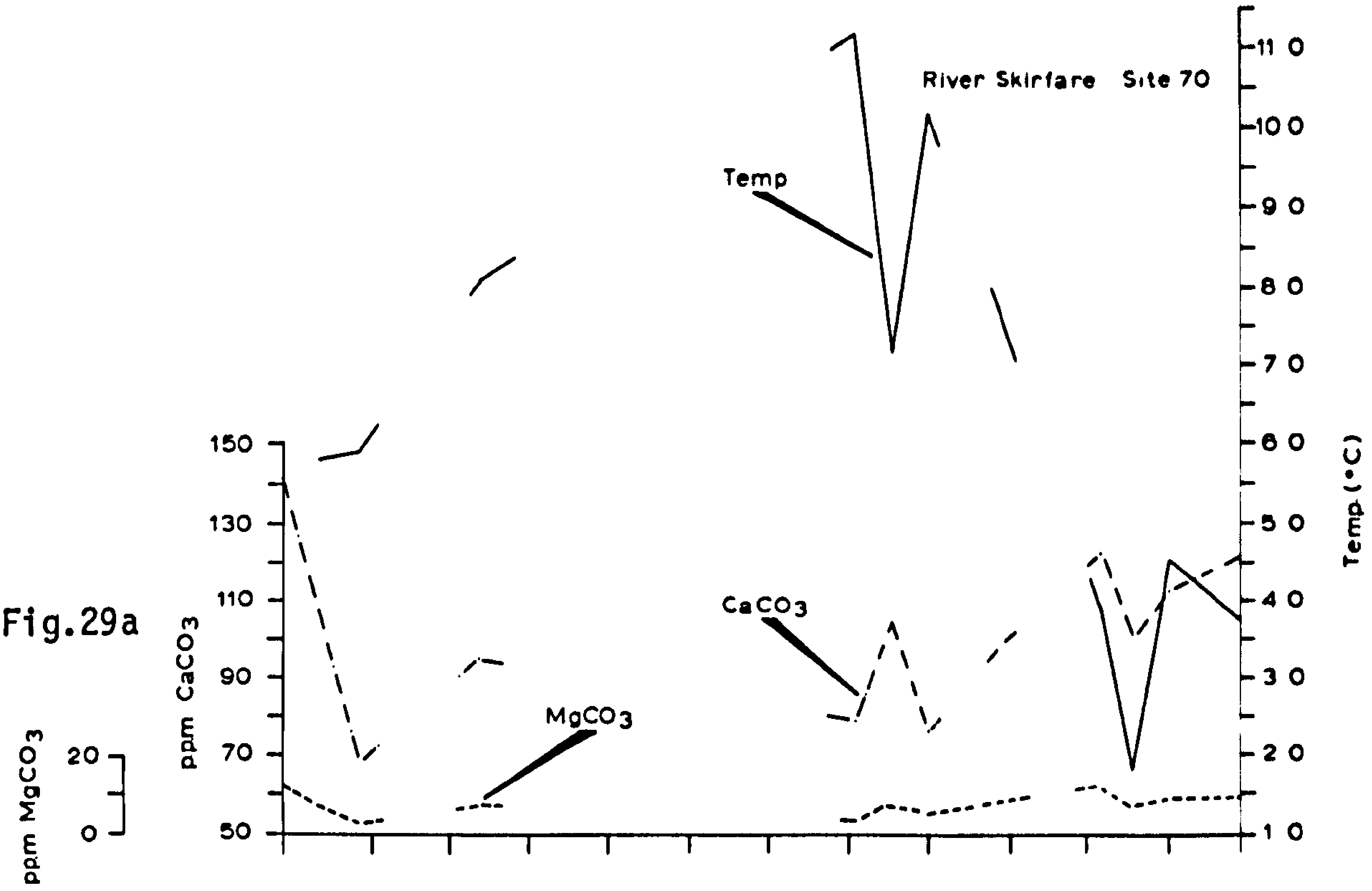
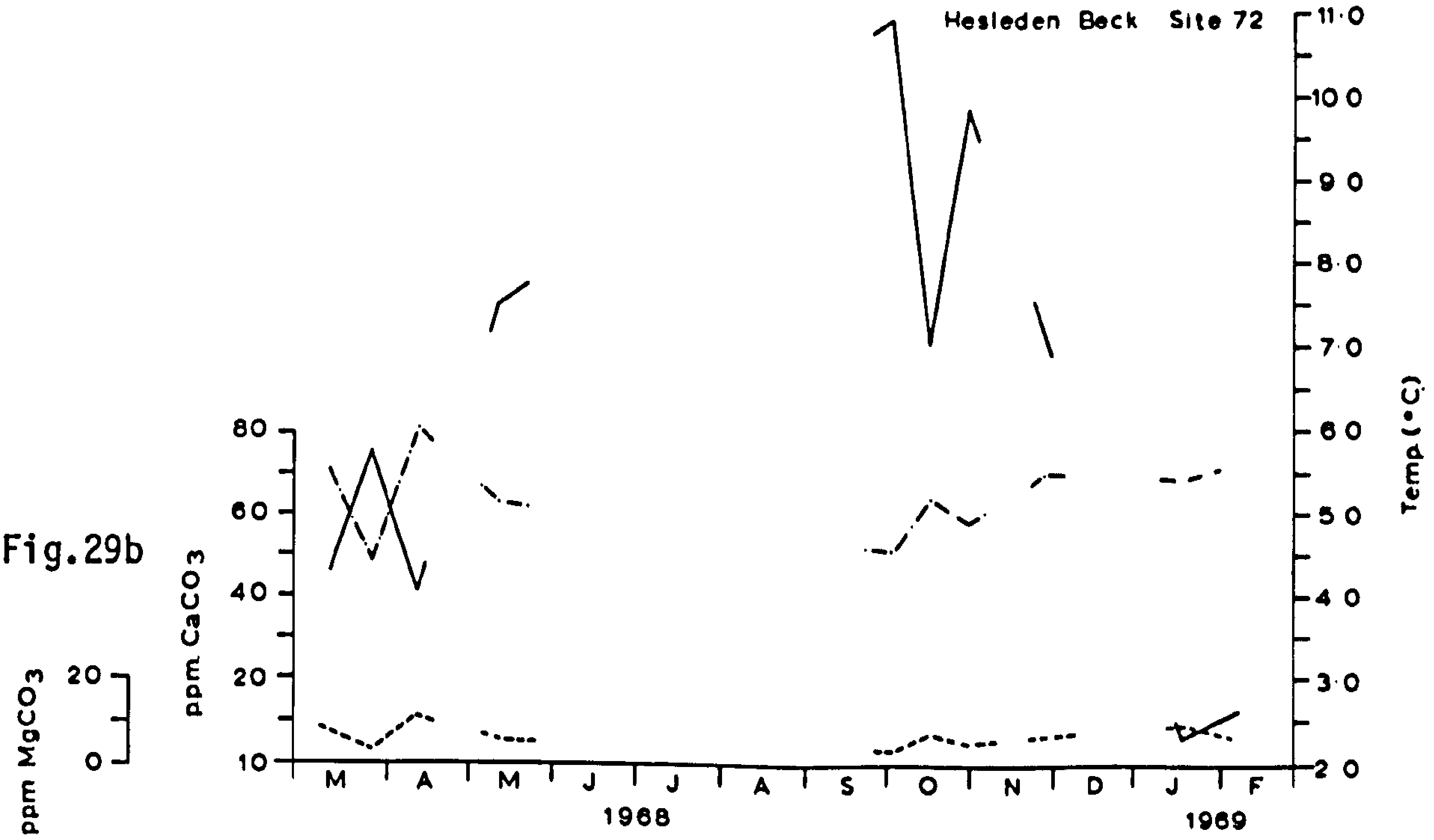


Fig.29b



Figs.29a & 29b Dissolved calcium and magnesium carbonate and water temperature variations recorded at River Skirfare site 70 and Hesleden Beck site 72 (year I)

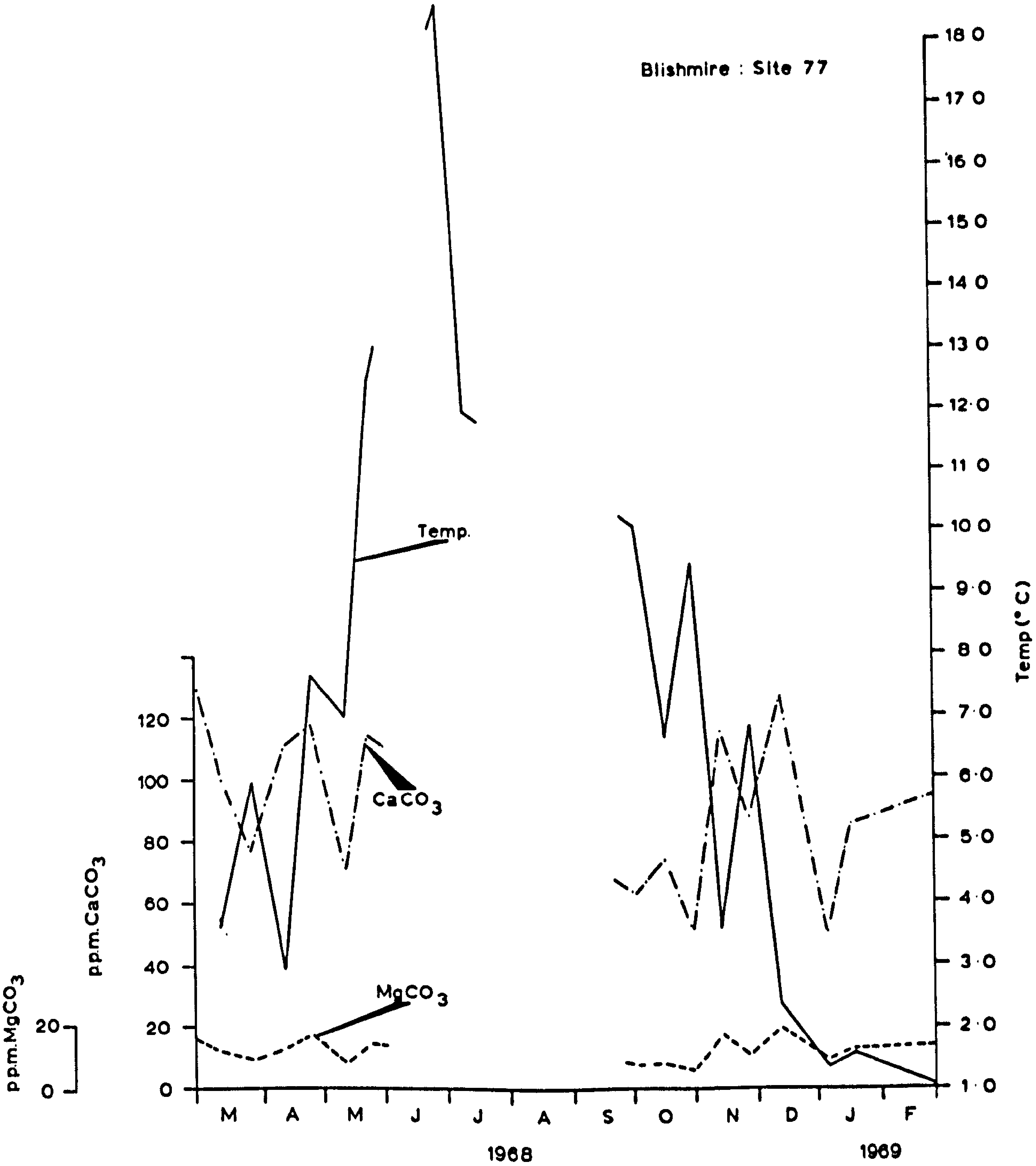


Fig.30 Dissolved calcium and magnesium carbonate and water temperature variations recorded at Blishmire site 77 (year I)

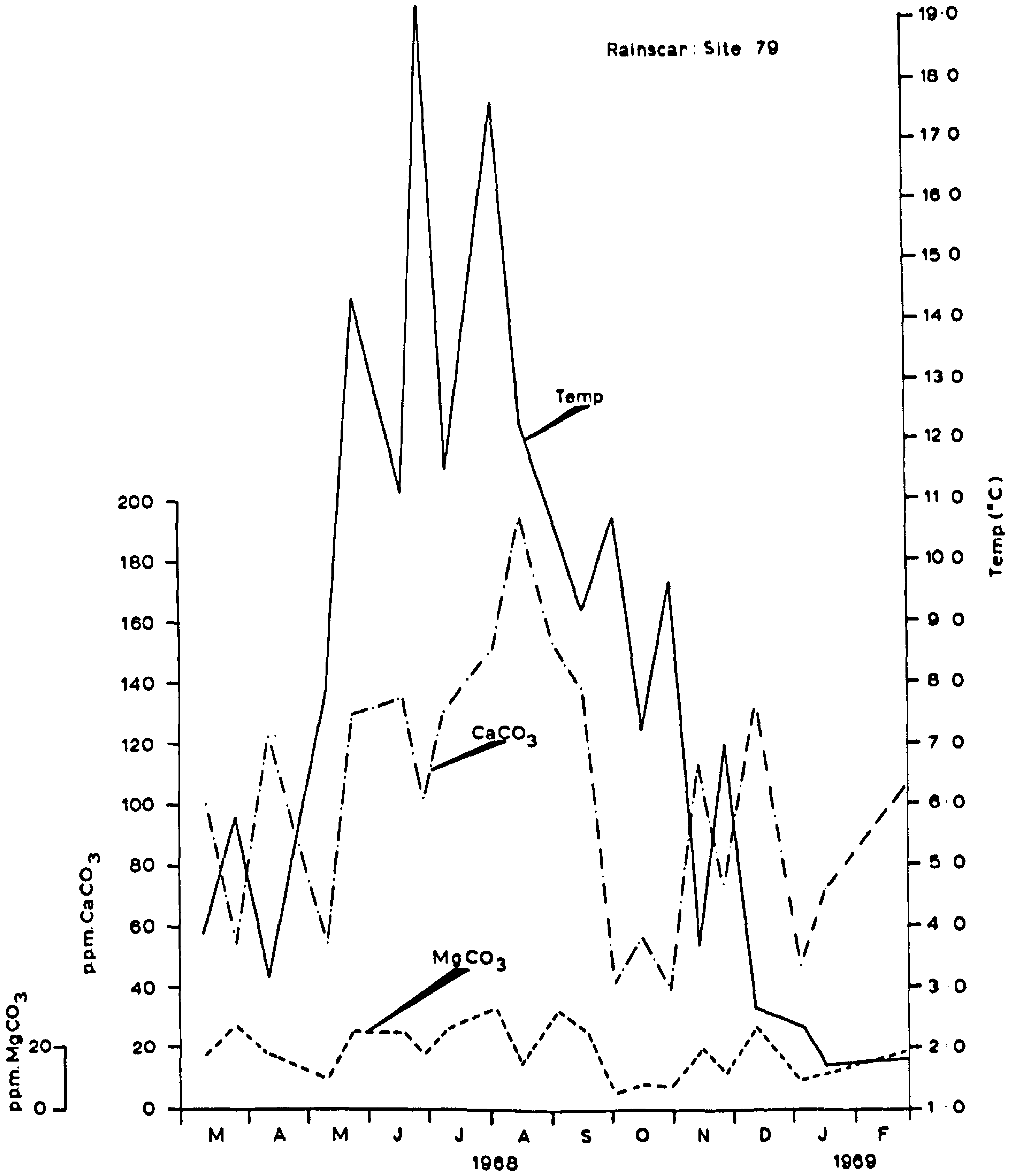


Fig.31 Dissolved calcium and magnesium carbonate and water temperature variations recorded at Rainscar site 79 (year I)

Fig.32a

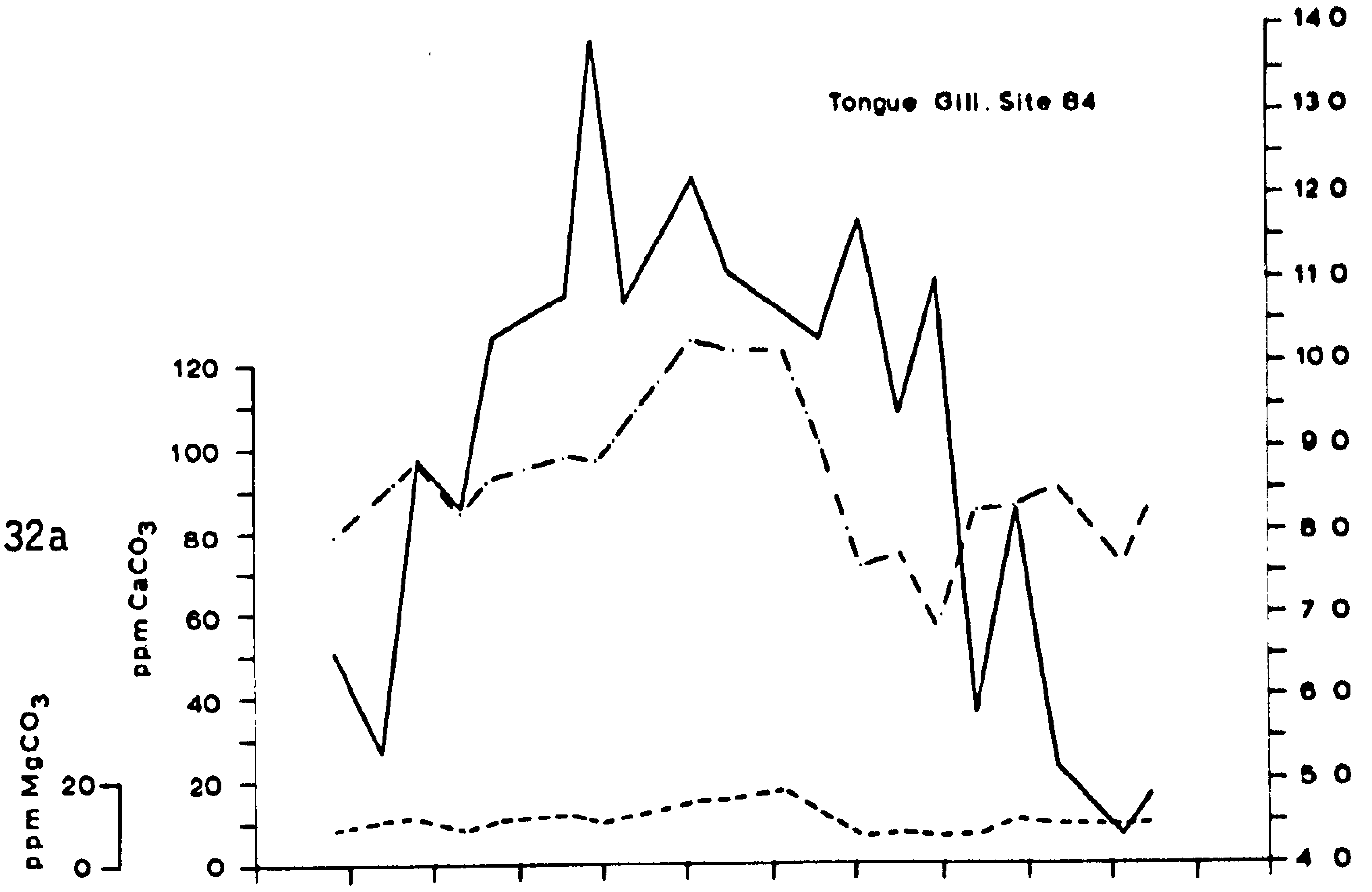


Fig.32b

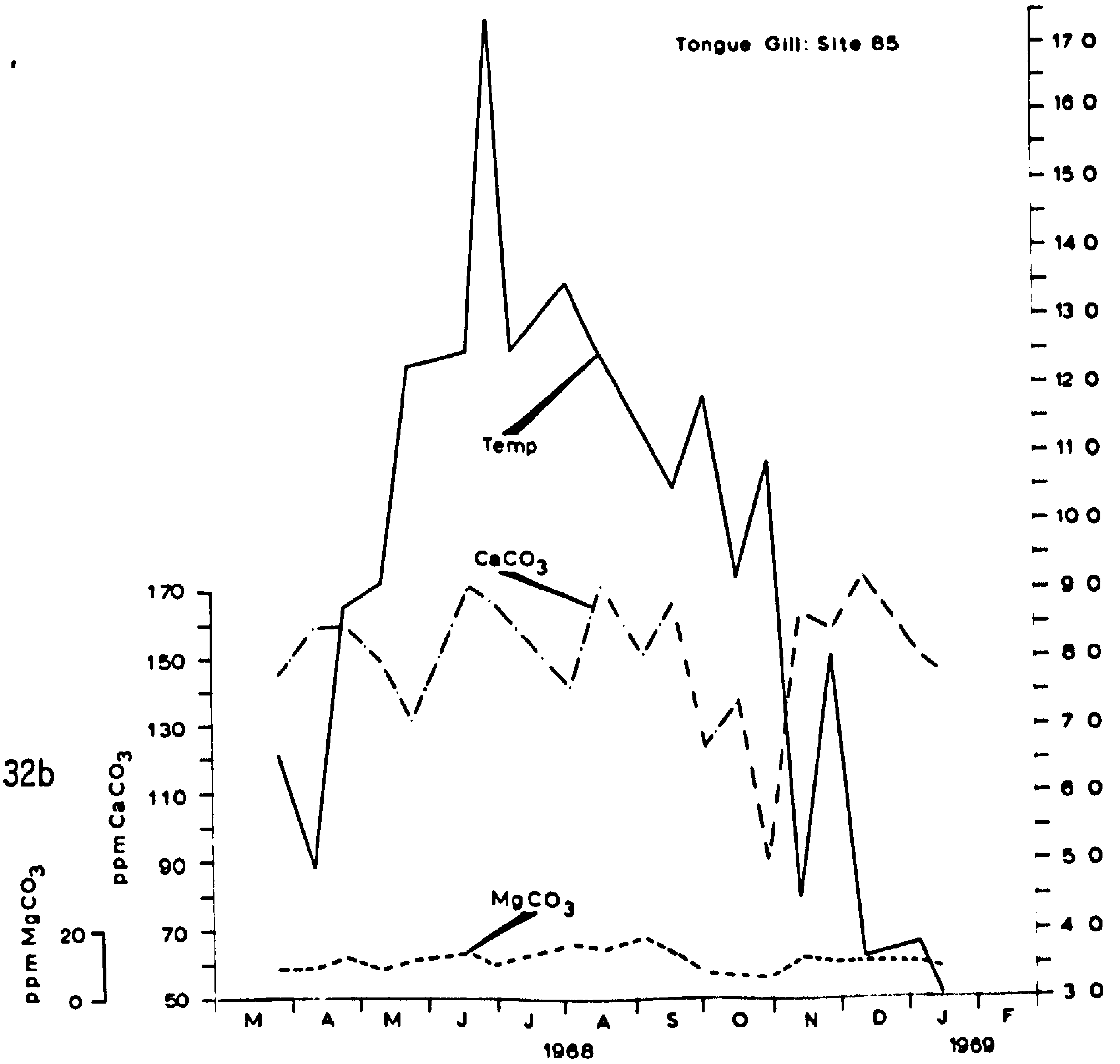


Fig.32a & 32b Dissolved calcium and magnesium carbonate and water temperature variations recorded at Tongue Gill sites 84 and 85 (year I)

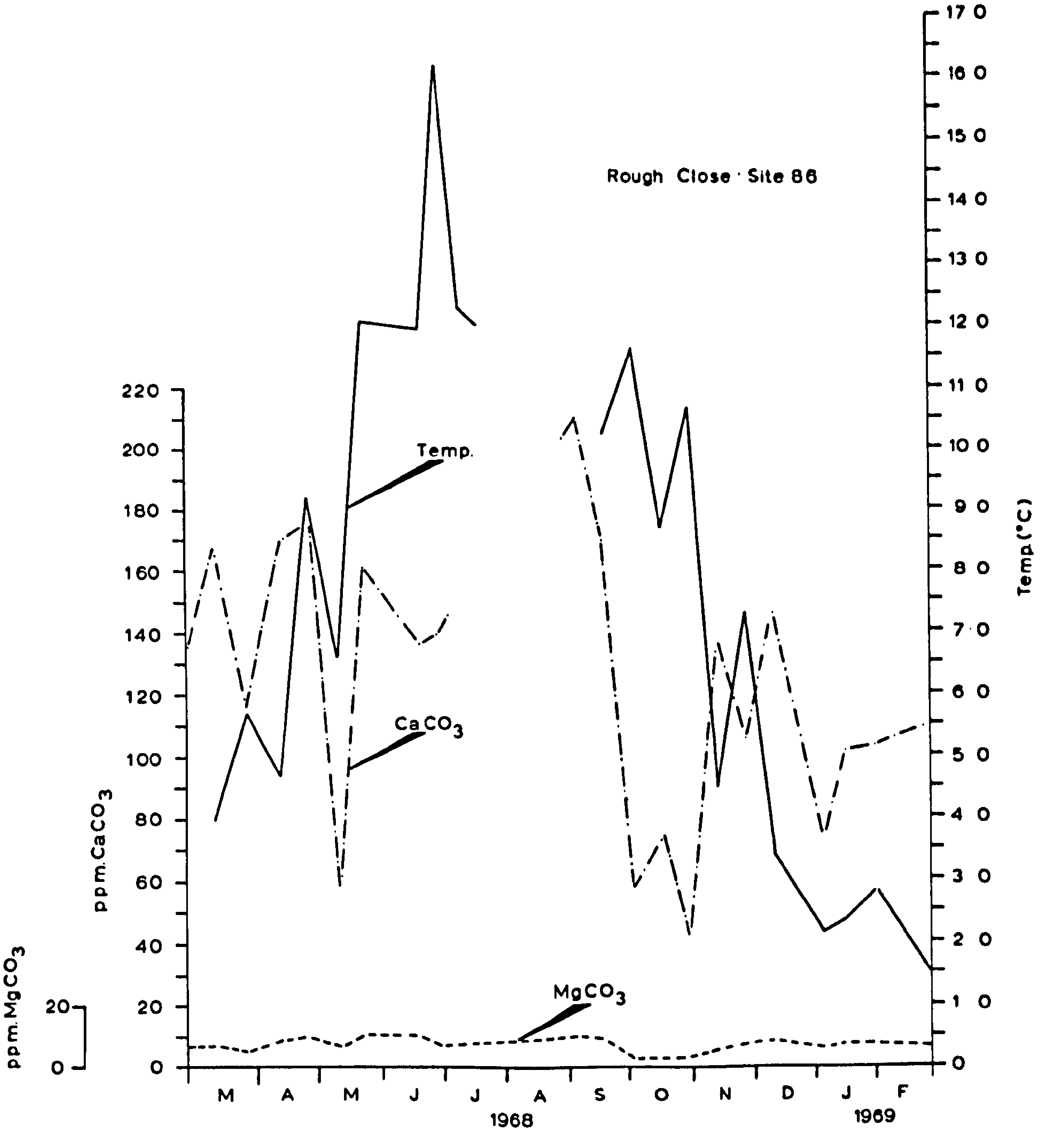


Fig.33 Dissolved calcium and magnesium carbonate and water temperature variations recorded at Rough Close site 86 (year I)

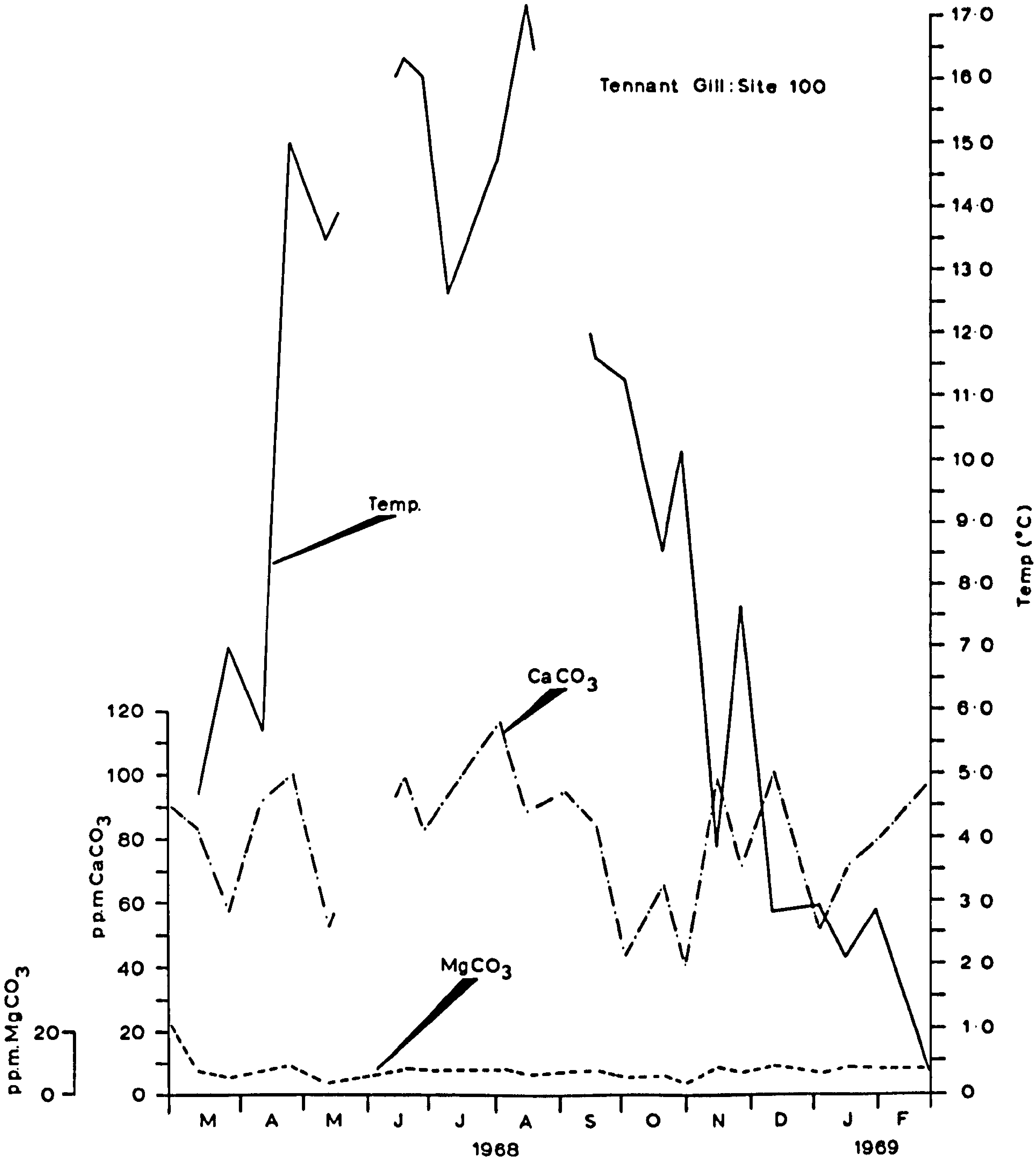


Fig.34 Dissolved calcium and magnesium carbonate and water temperature variations recorded at Tennant Gill site 100 (year I)

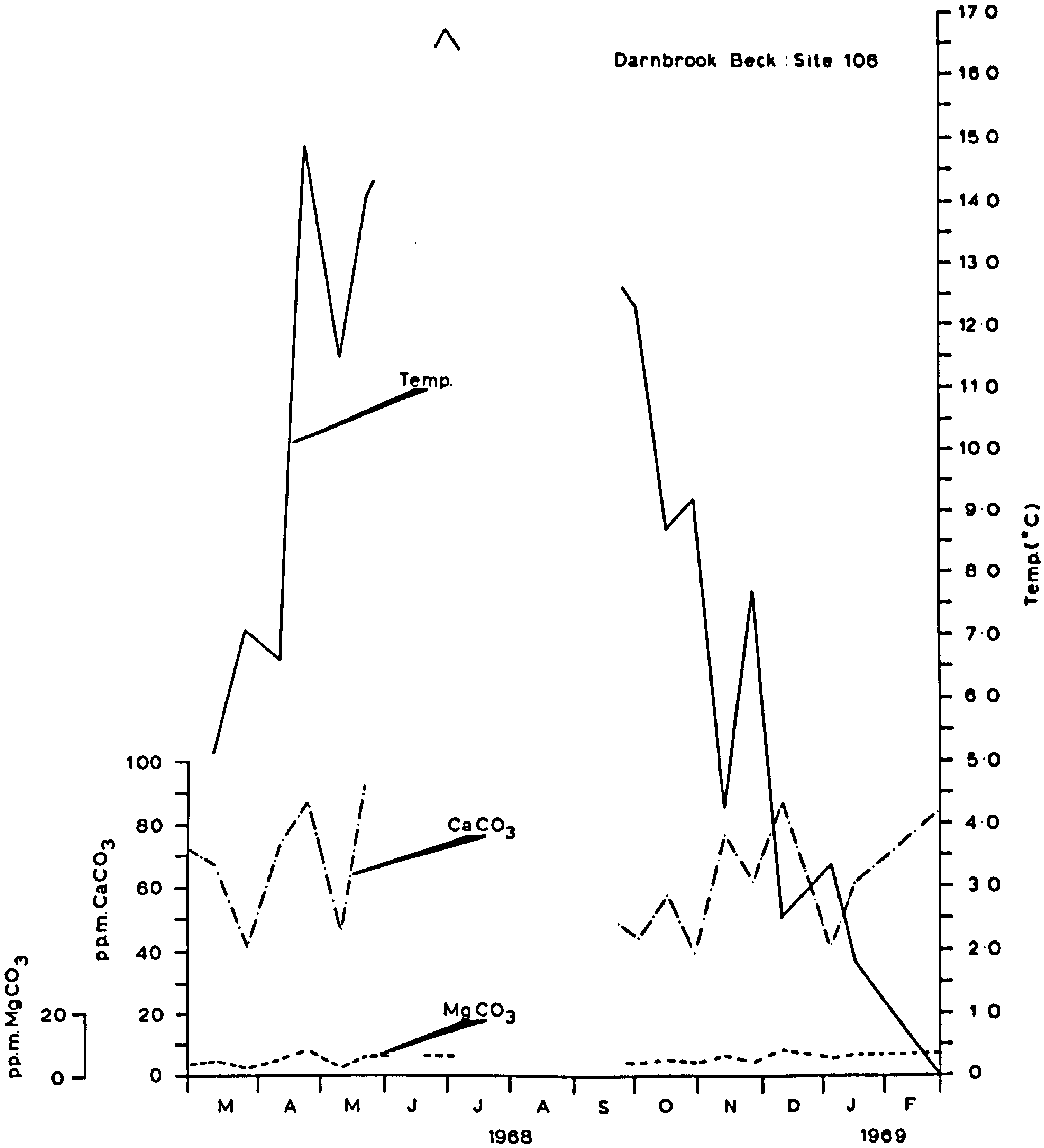


Fig.35 Dissolved calcium and magnesium carbonate and water temperature variations recorded at Darnbrook Beck site 106 (year I)

Fig.36a

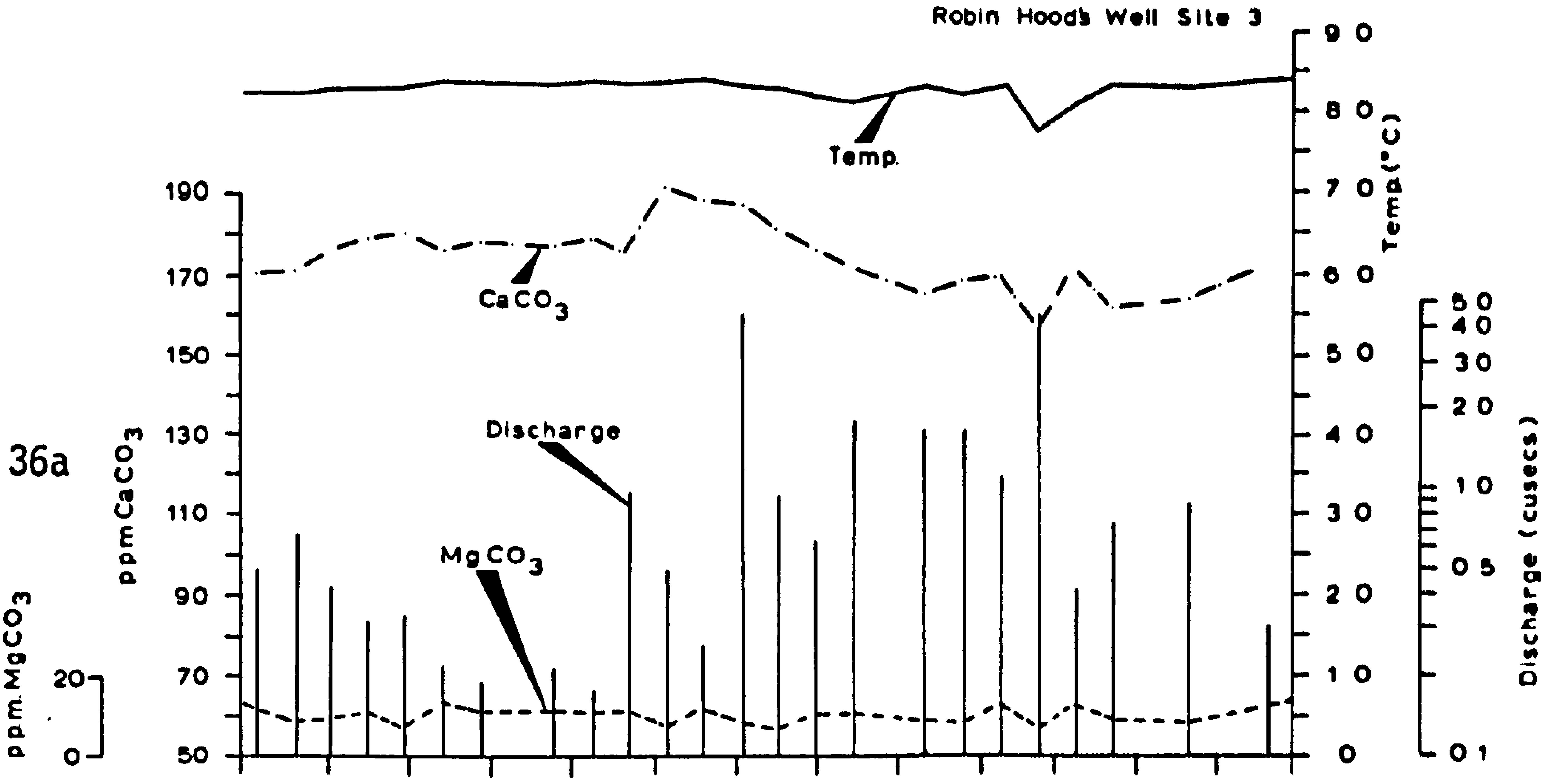
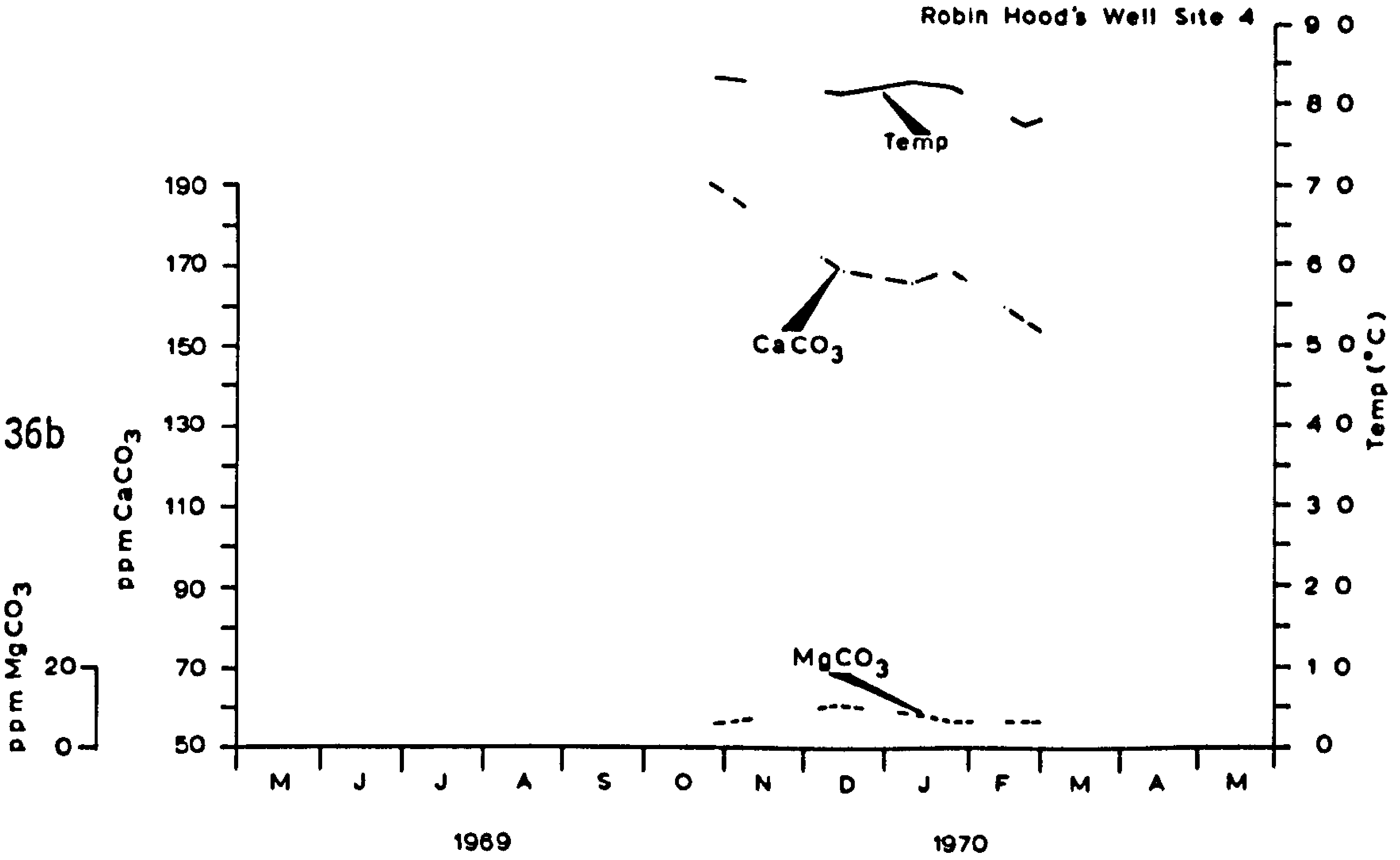


Fig.36b



Figs.36a & 36b Dissolved calcium and magnesium carbonate, water temperature and discharge variations recorded at Robin Hood's Well sites 3 & 4 (year II)

Fig.37a

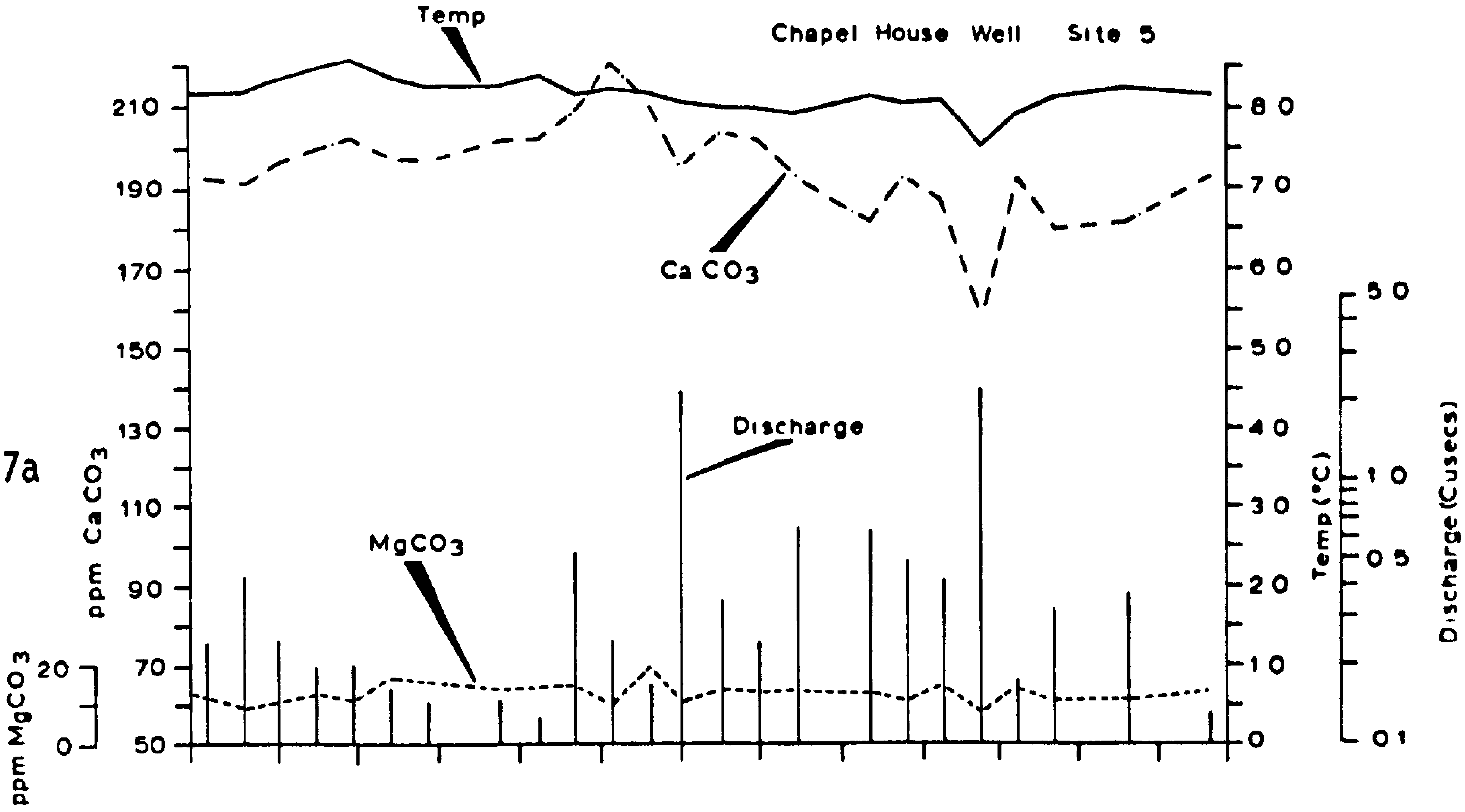
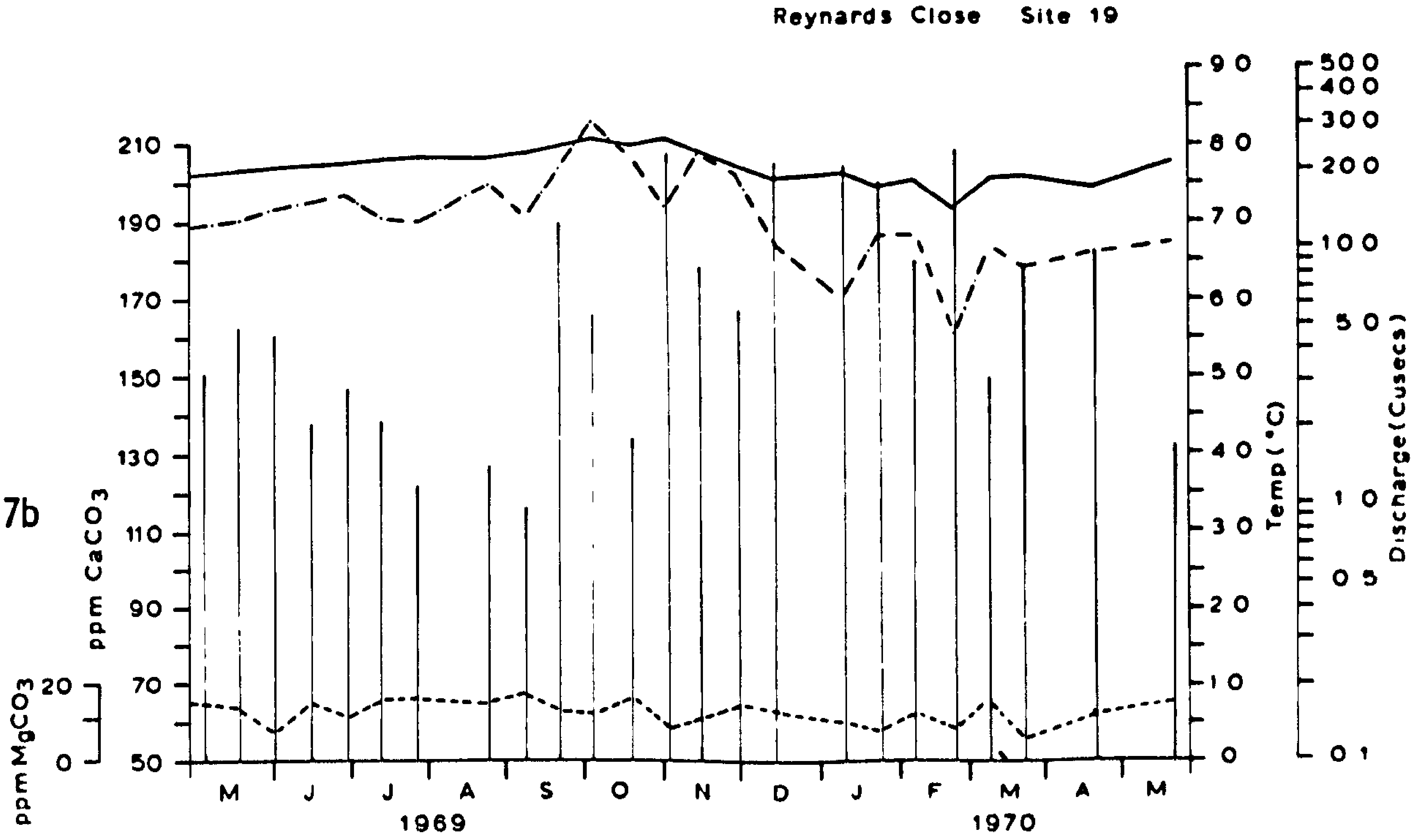


Fig.37b



Figs.37a & 37b Dissolved calcium and magnesium carbonate, water temperature and discharge variations recorded at Chapel House Wëll site 5 and Reynard's Close site 19 (year II)

Fig.38a

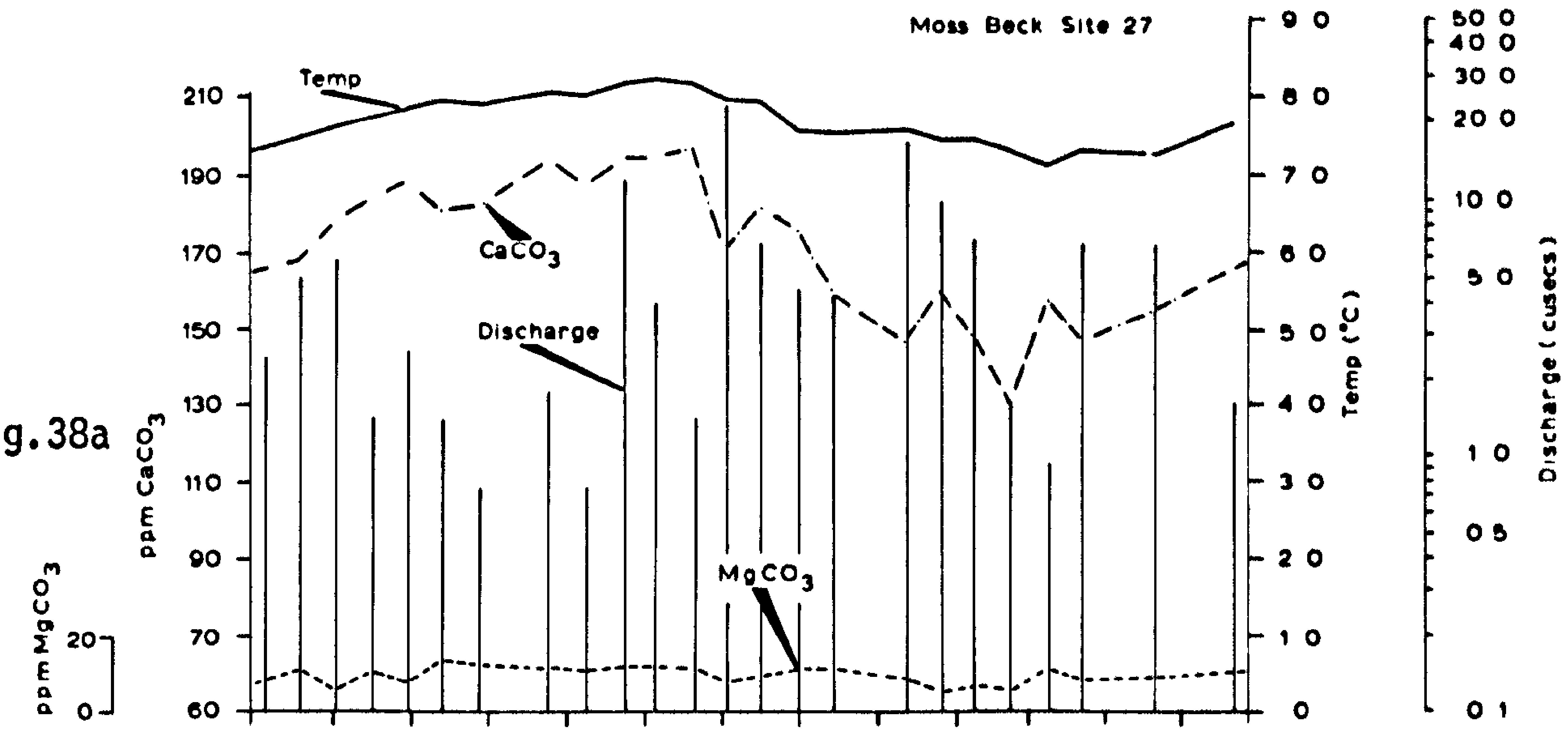
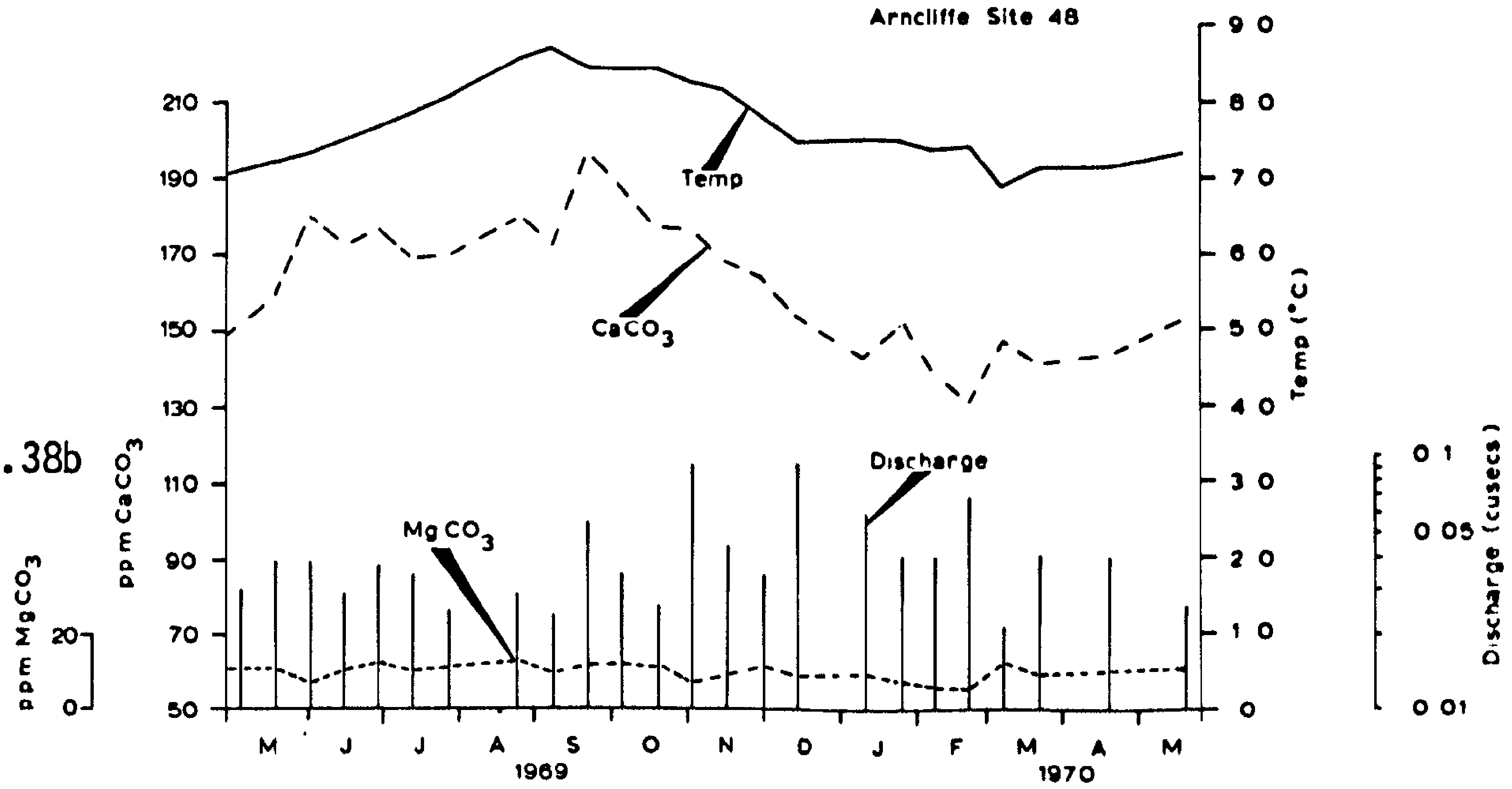


Fig.38b



Figs.38a & 38b Dissolved calcium and magnesium carbonate, water temperature and discharge variations recorded at Moss Beck site 27 and Arncliffe site 48 (year II)

Fig.39a

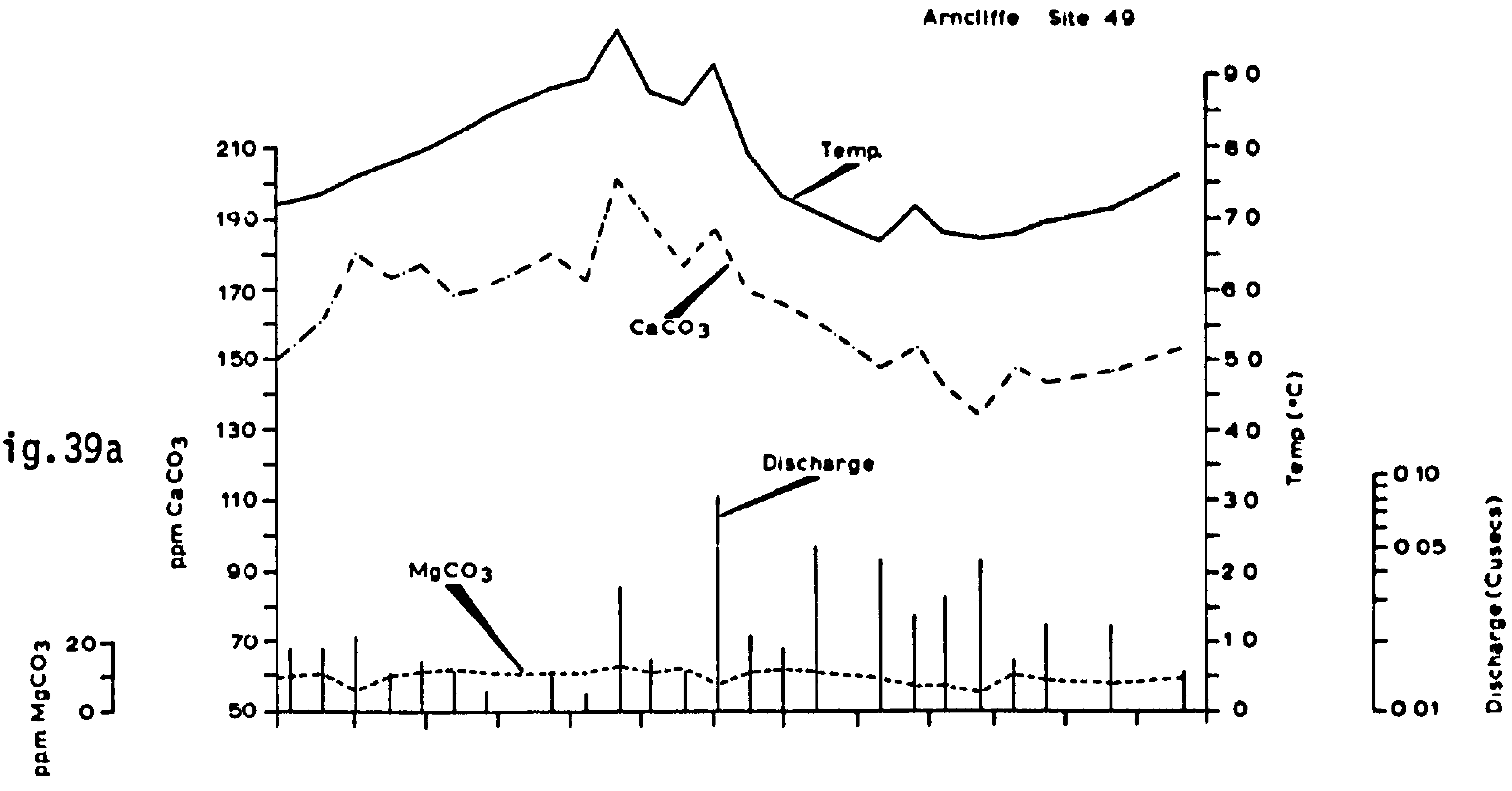
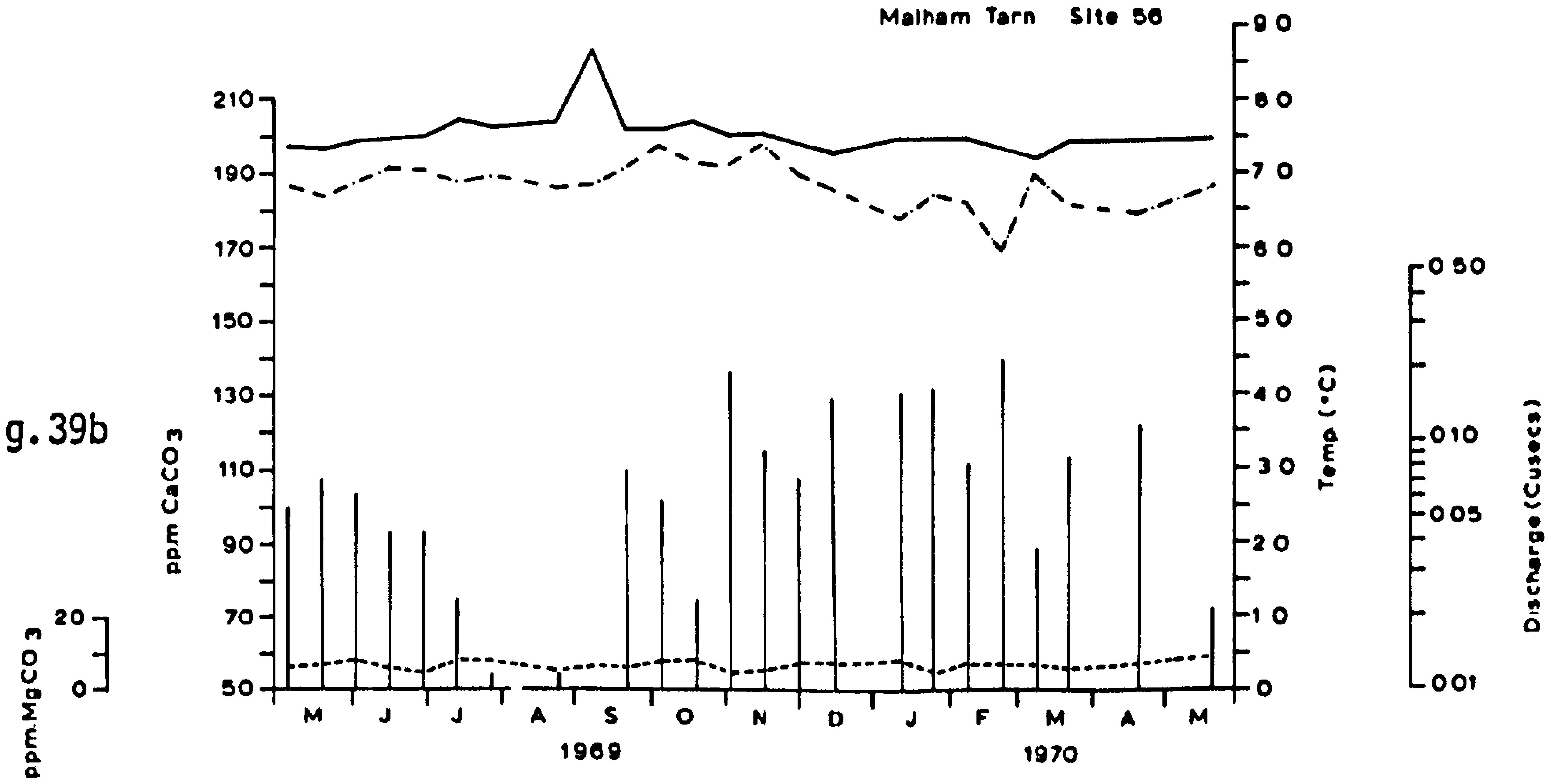


Fig.39b



Figs.39a & 39b Dissolved calcium and magnesium carbonate, water temperature and discharge variations recorded at Arncliffe site 49 and Malham Tarn site 56 (year II)

Fig.40a

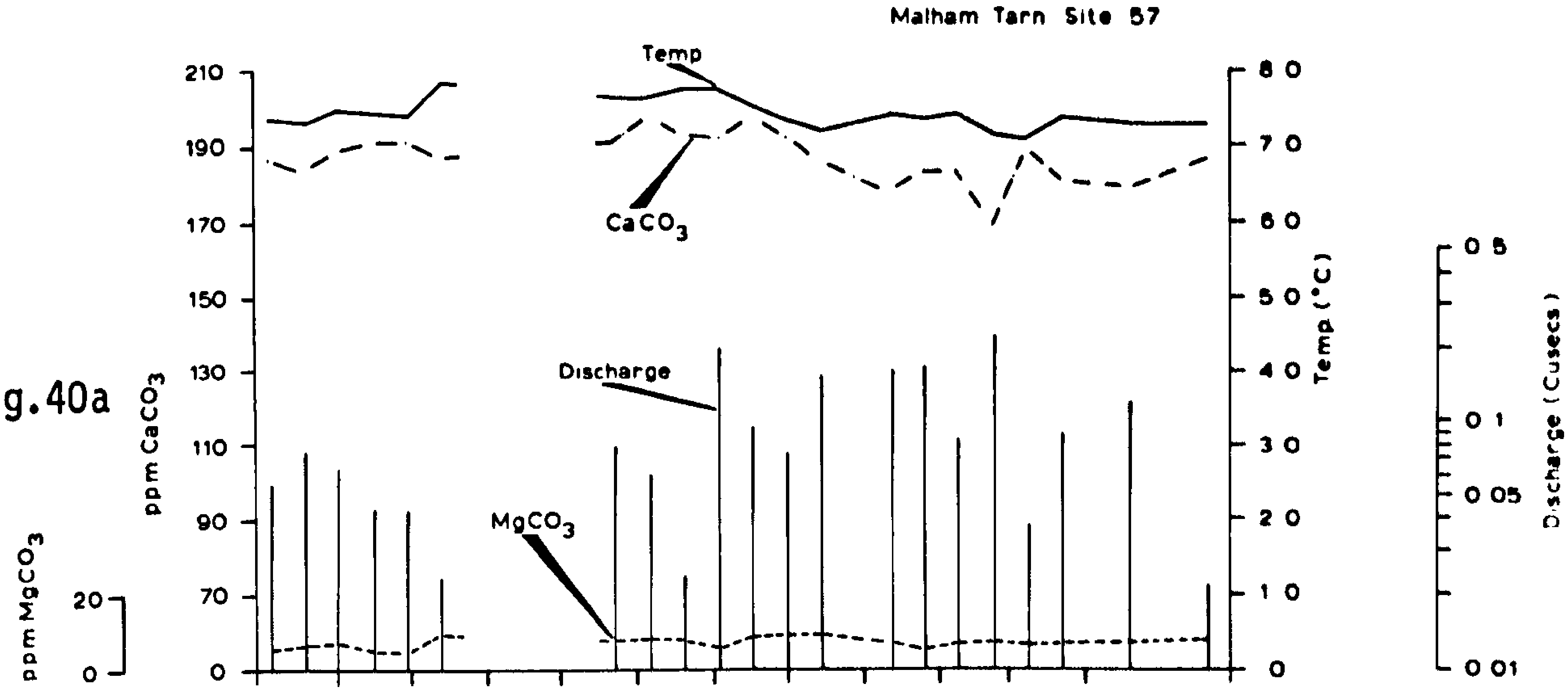
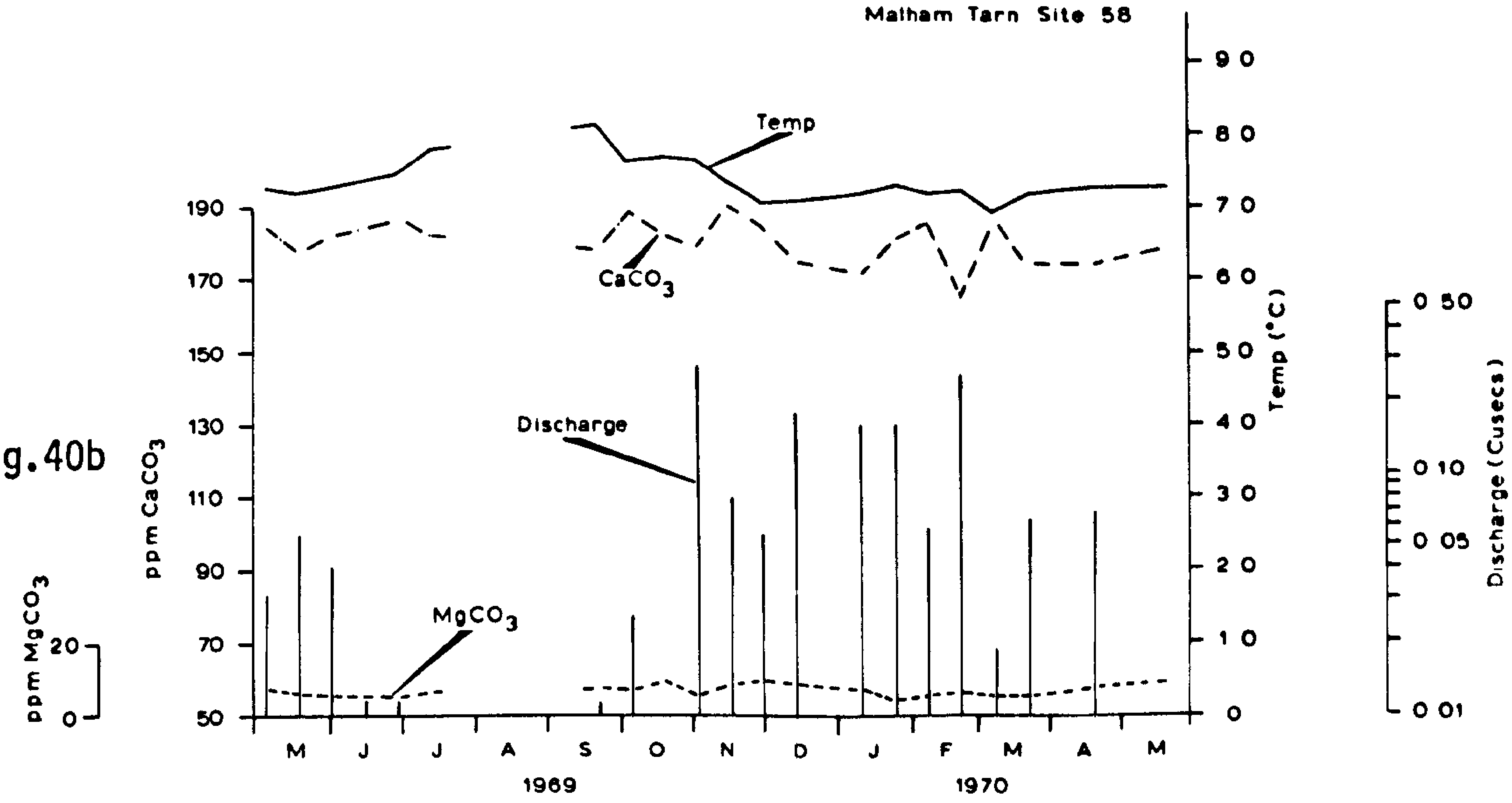


Fig.40b



Figs.40a & 40b Dissolved calcium and magnesium carbonate, water temperature and discharge variations recorded at Malham Tarn sites 57 and 58 (year II)

Fig.41

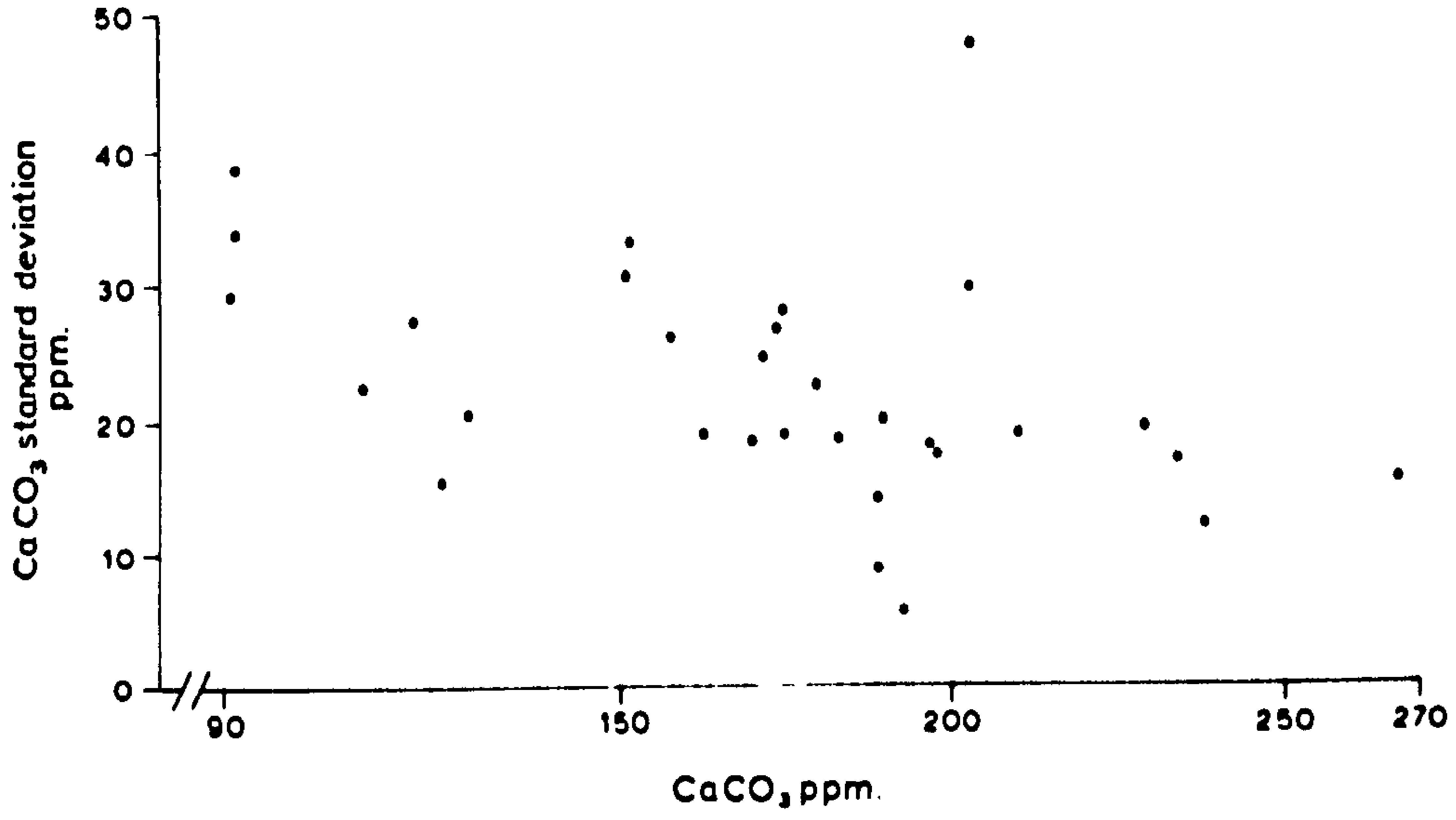


Fig.42

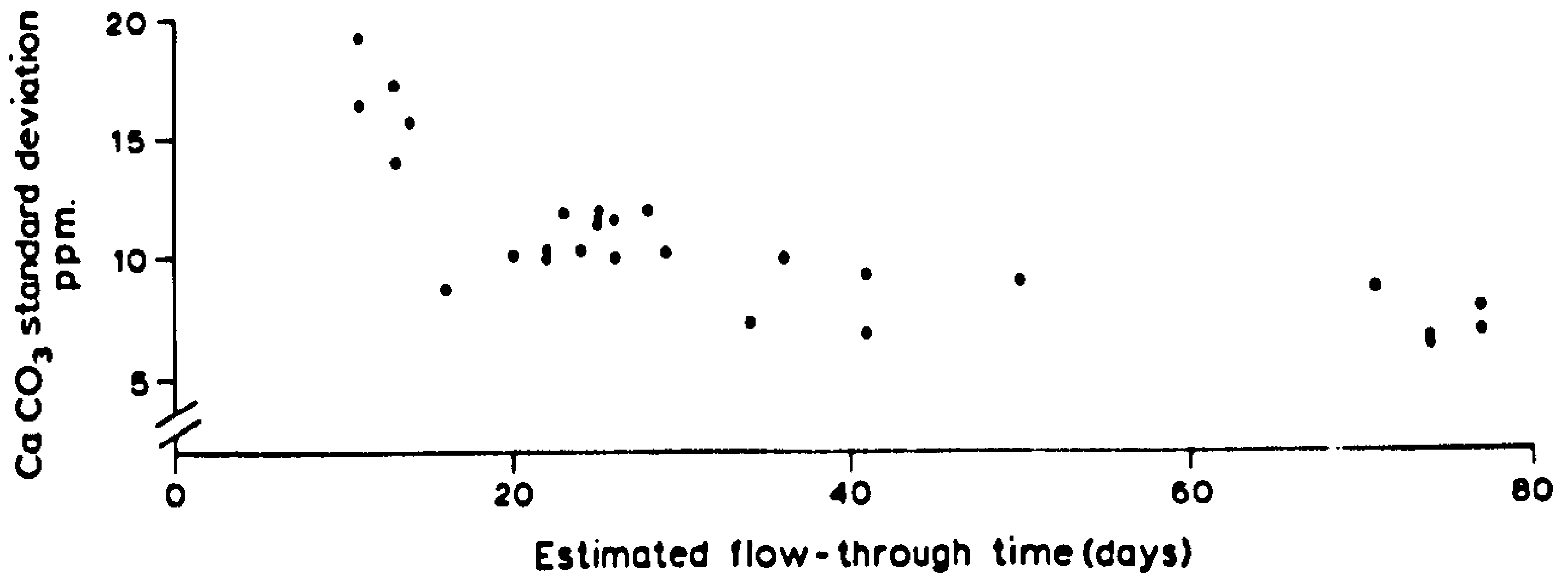


Fig.43

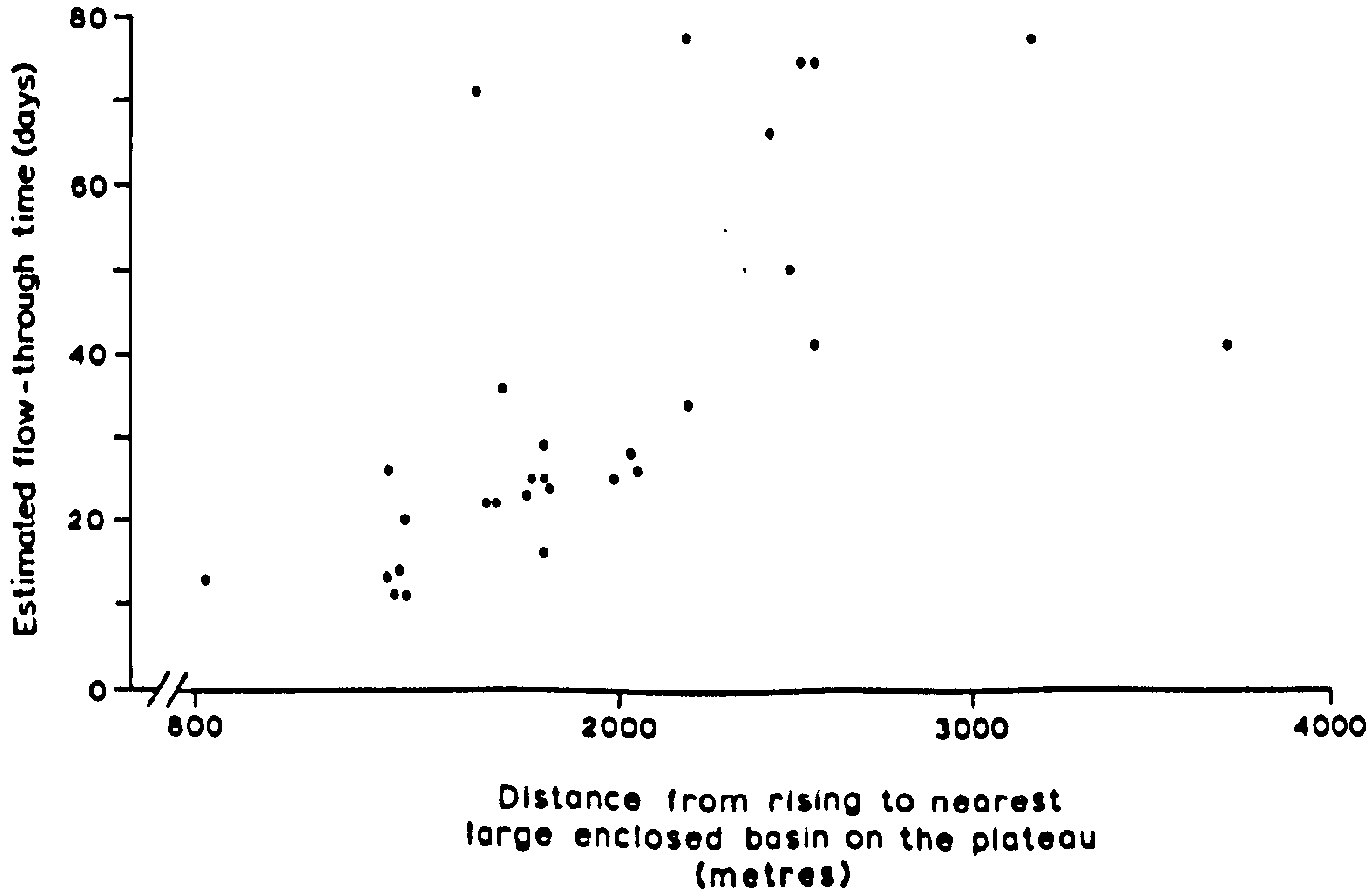


Fig. 41 The relationship between the standard deviation of dissolved calcium carbonate and mean dissolved calcium carbonate on Fountains Fell springs

Fig. 42 The relationship between the standard deviation of dissolved calcium carbonate and the estimated flow-through time of High Mark springs

Fig. 43 The relationship between the estimated flow-through time of High Mark springs and the distance to the nearest large enclosed basin on the plateau

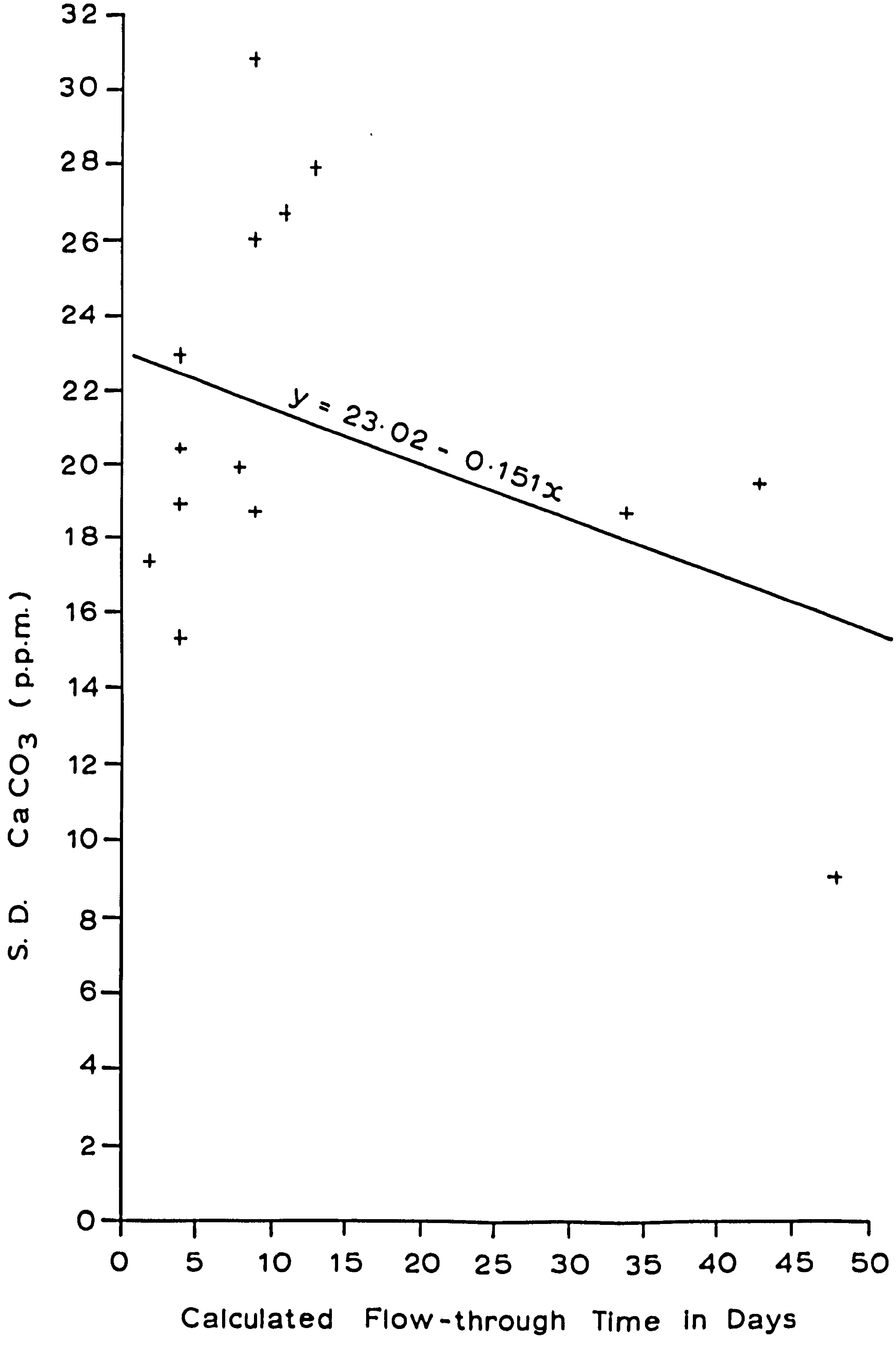


Fig.44 The relationship between the standard deviation of dissolved calcium carbonate and the estimated flow-through time of Fountains Fell springs

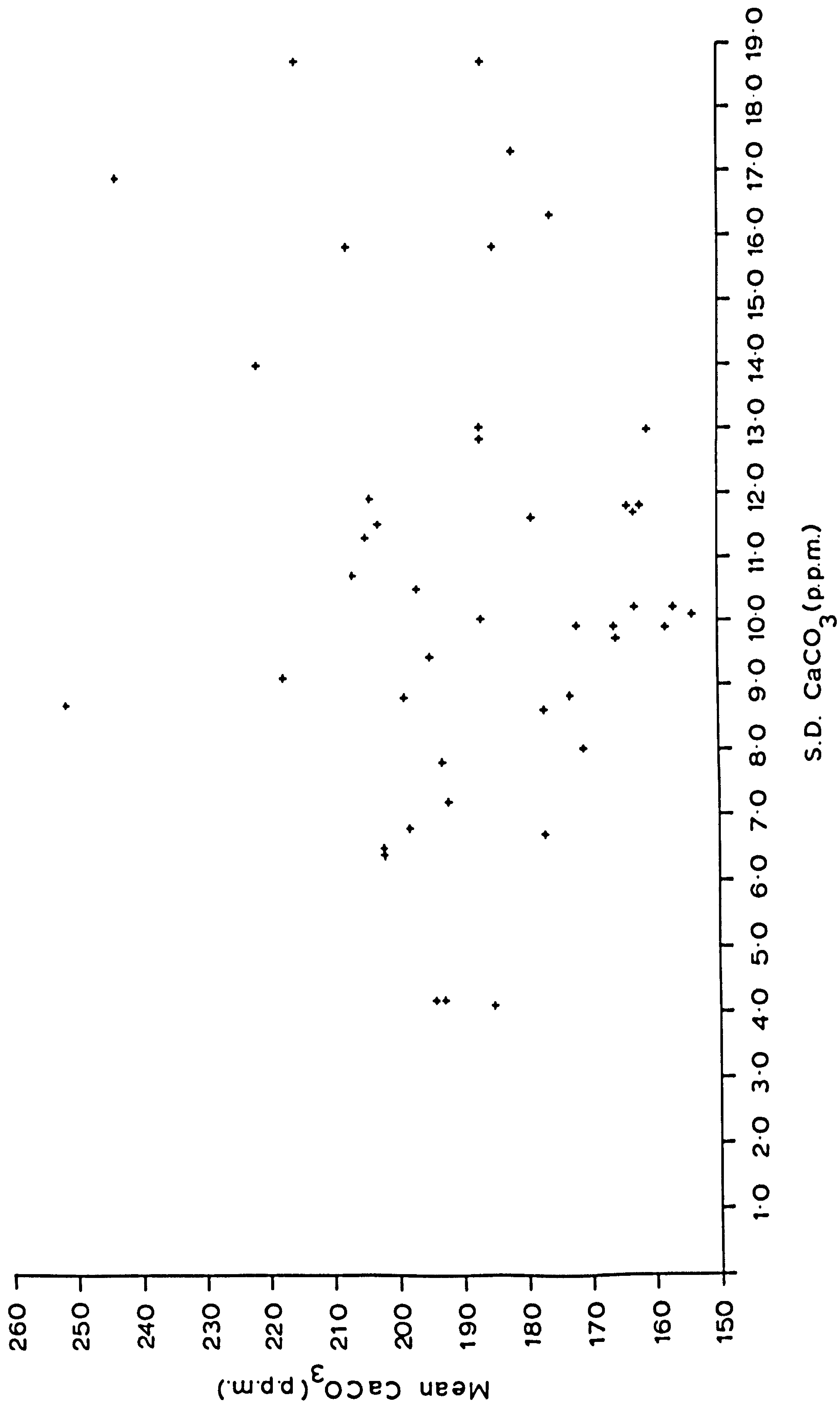


Fig.45 The relationship between the standard deviation of dissolved calcium carbonate and the mean dissolved calcium carbonate of High Mark springs

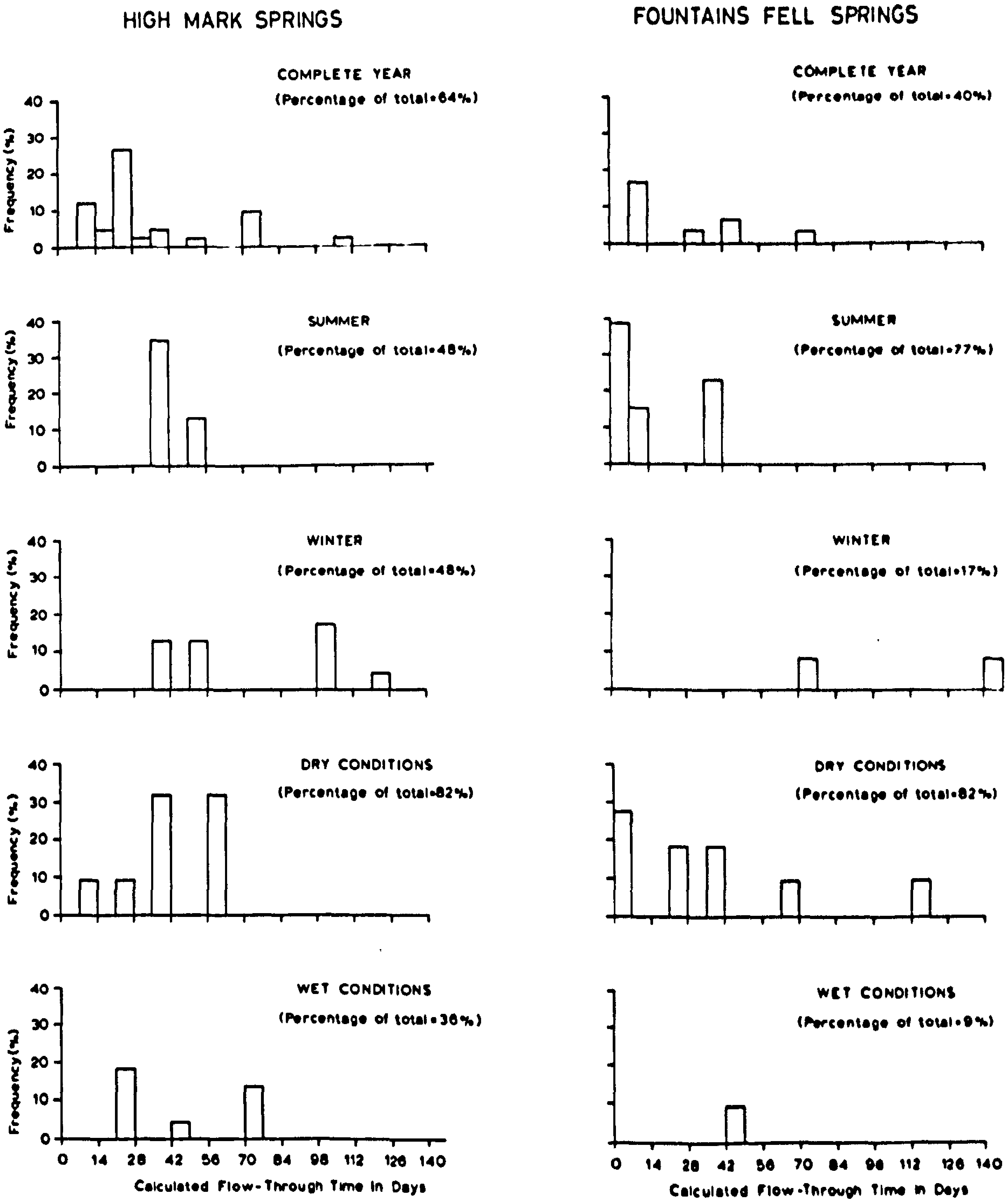


Fig.46 Histograms illustrating the estimated flow-through times of High Mark and Fountains Fell springs based on both the complete years observations and the seasonal observations. Only those springs with a correlation between dissolved calcium carbonate and the air temperatures of some period antecedent to sampling significant at the 0.01 level are included. The percentage this is of the total number of springs on which flow-through analysis was carried out is also given.

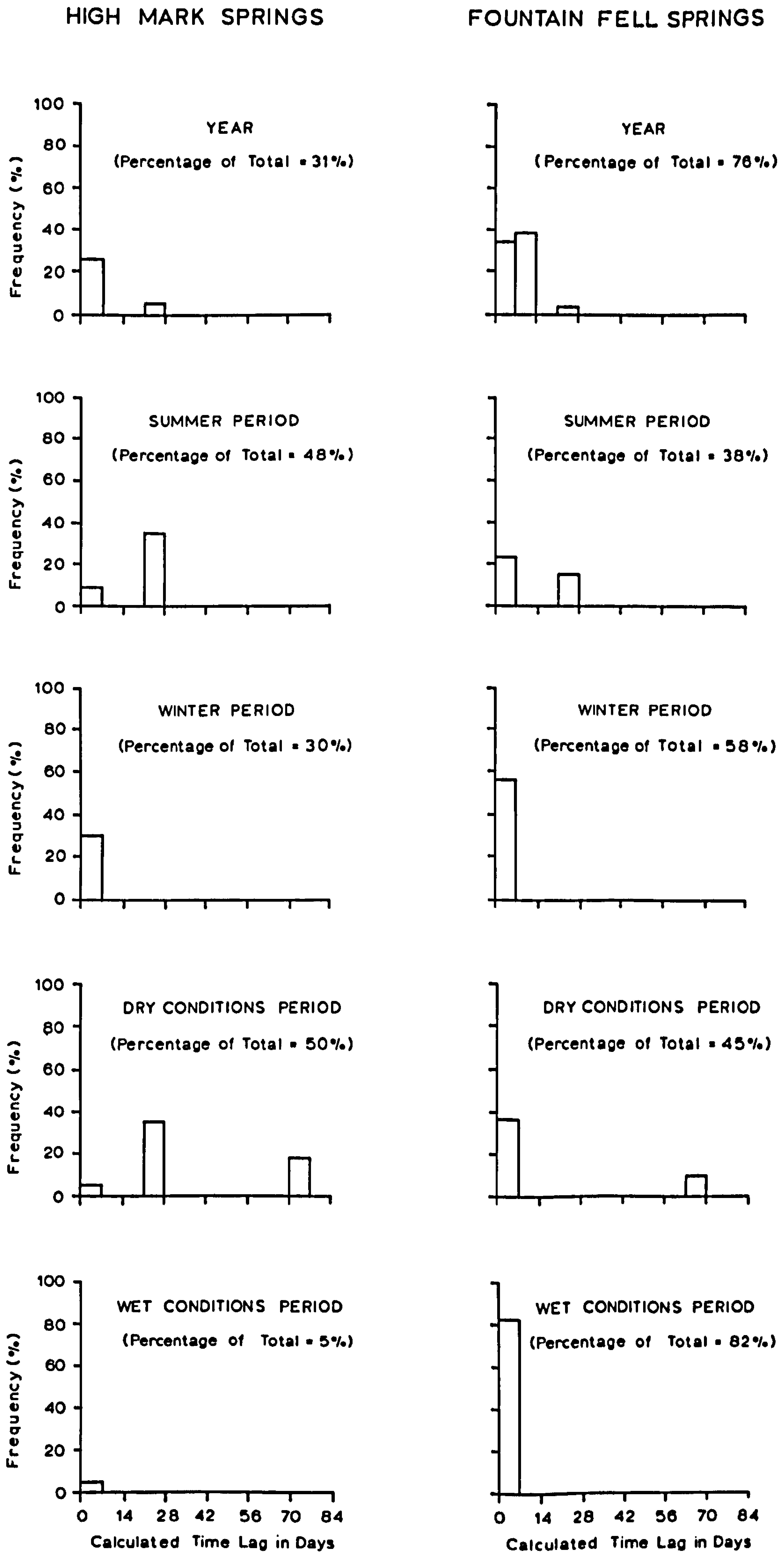


Fig.47 Histograms illustrating the lag of dissolved calcium carbonate fluctuation behind rainfall variations. Only these springs with a correlation between dissolved calcium carbonate and rainfall significant at the 0.01 level are included.

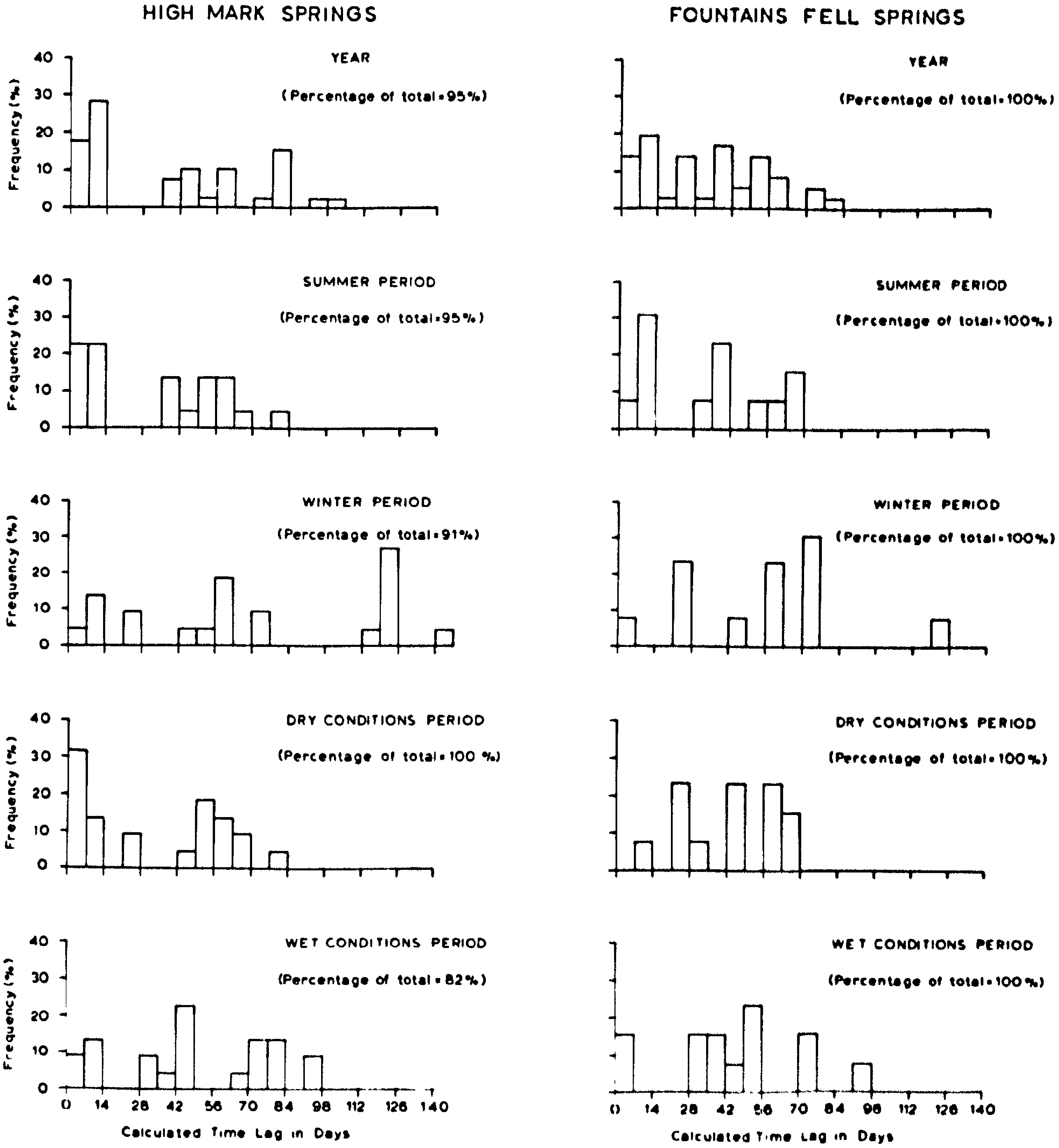


Fig.48 Histograms illustrating the lag of spring water temperatures behind air temperatures. Only those springs showing a correlation between water temperatures and antecedent air temperatures significant at the 0.01 level are included. The percentage this represents of the total number of springs is also indicated.

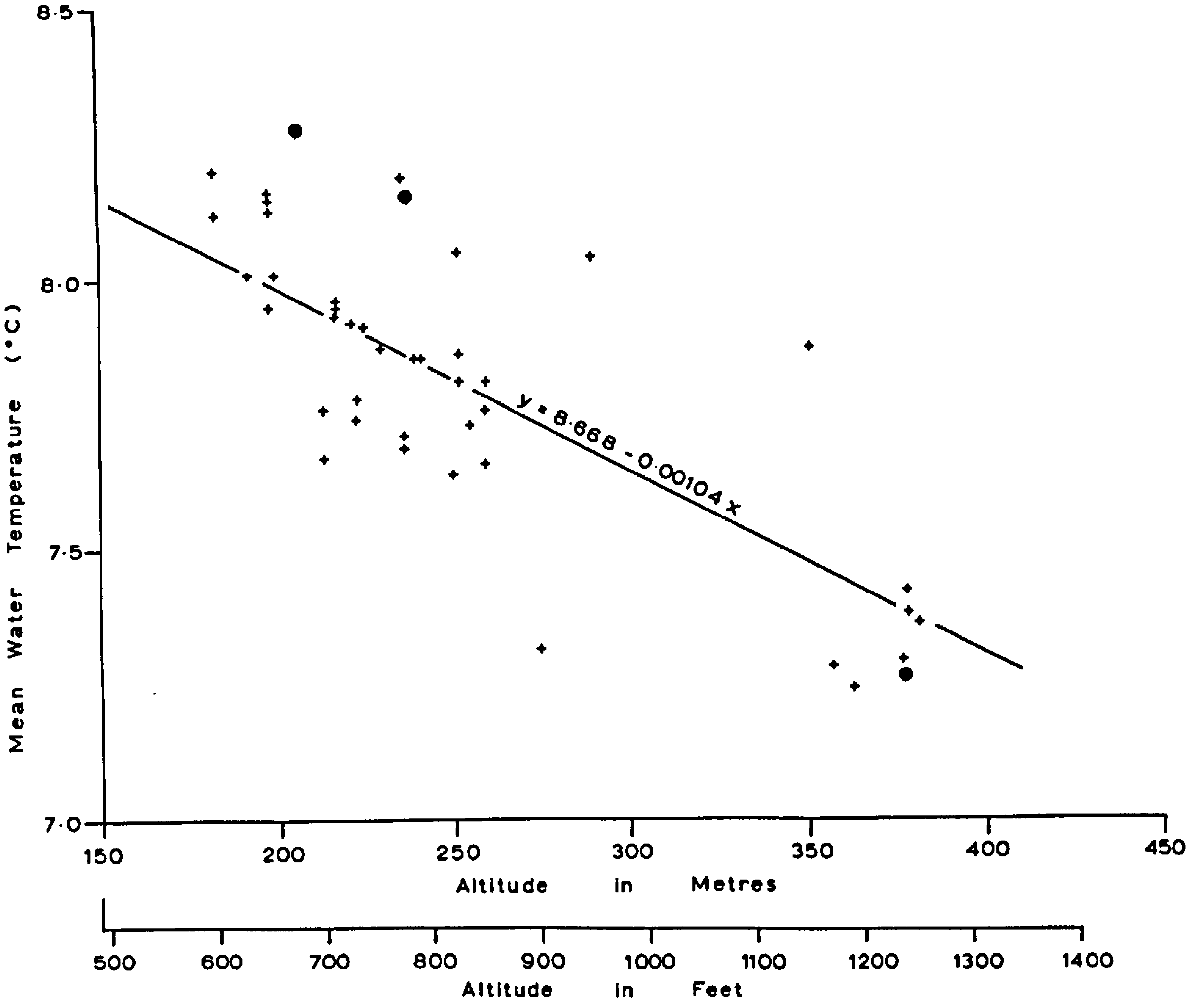


Fig.49 The relationship between the mean water temperature of High Mark springs and the altitude of the risings.

● Sites at which the air temperatures at the time of sampling may have influenced the recorded spring water temperature

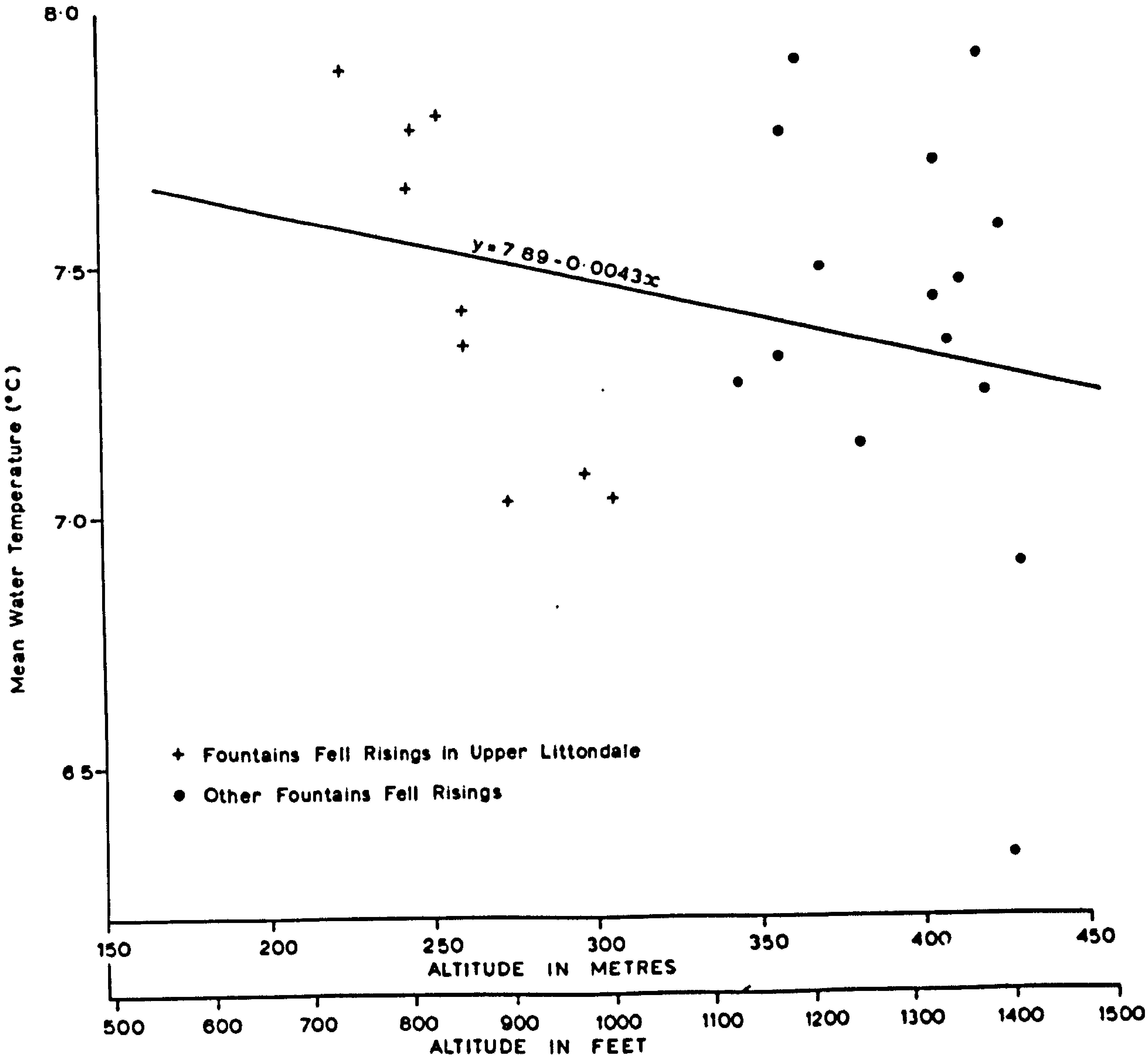


Fig.50 The relationship between the mean water temperature of Fountains Fell springs and the altitude of the risings.

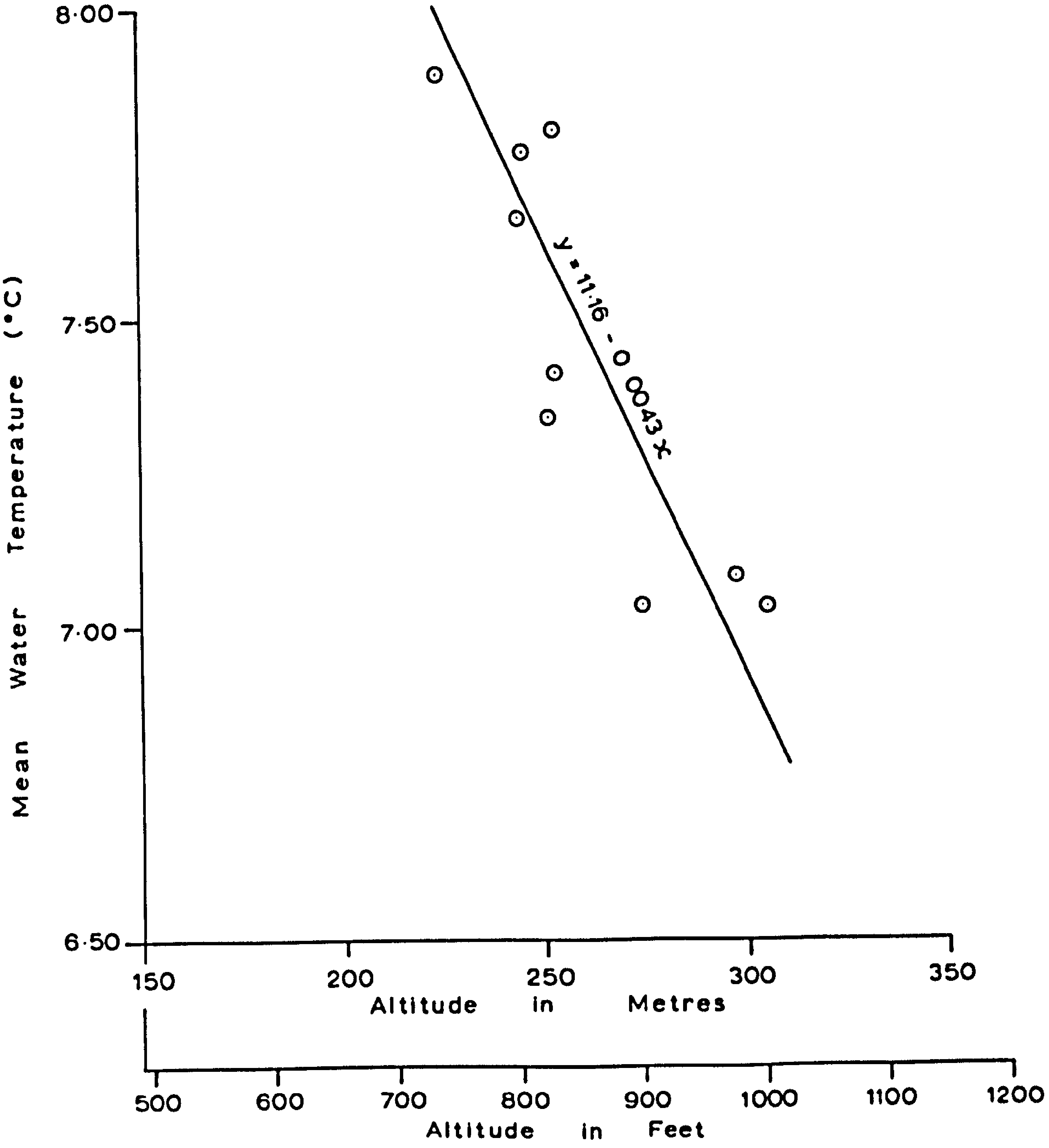
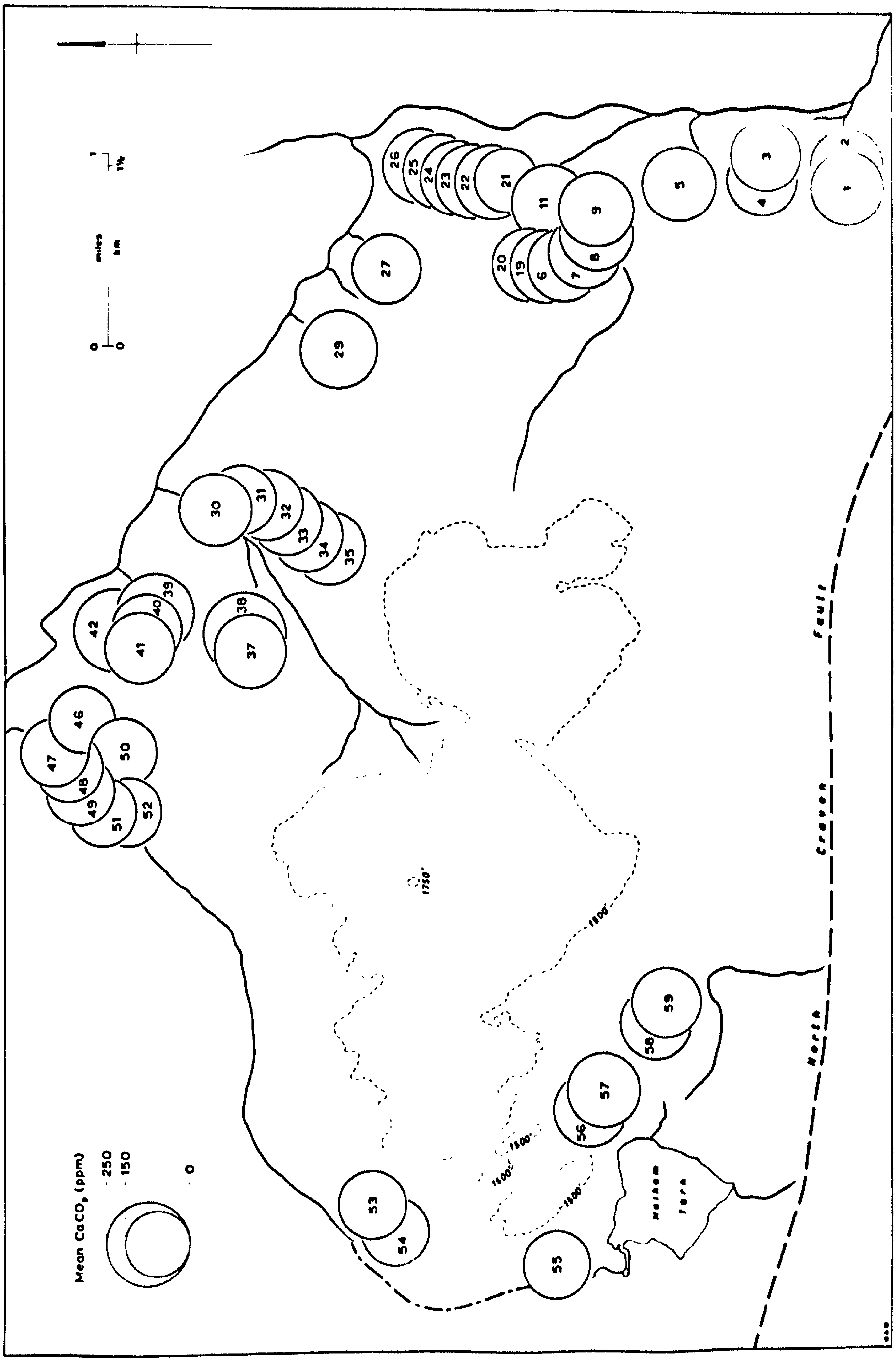
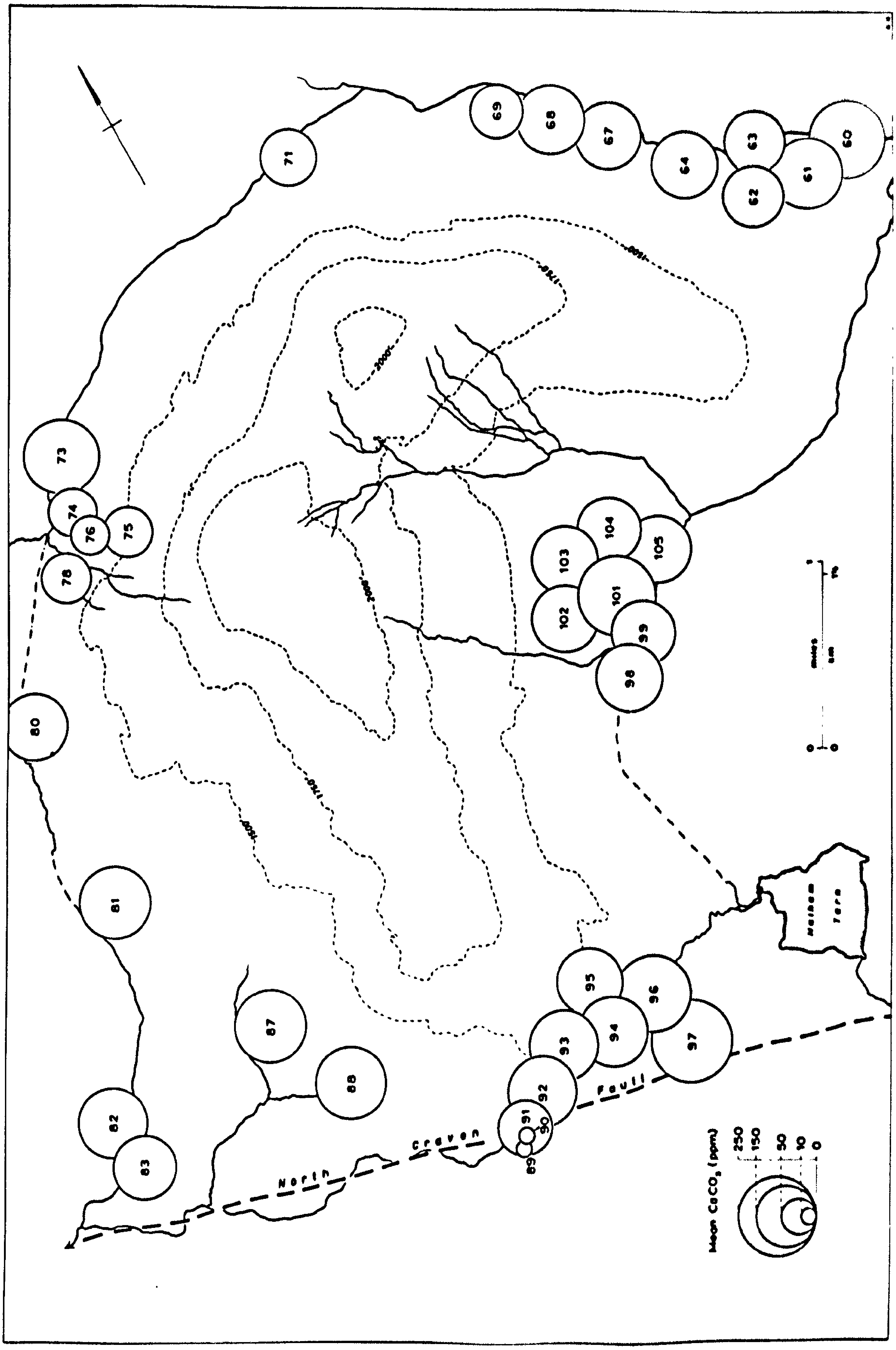


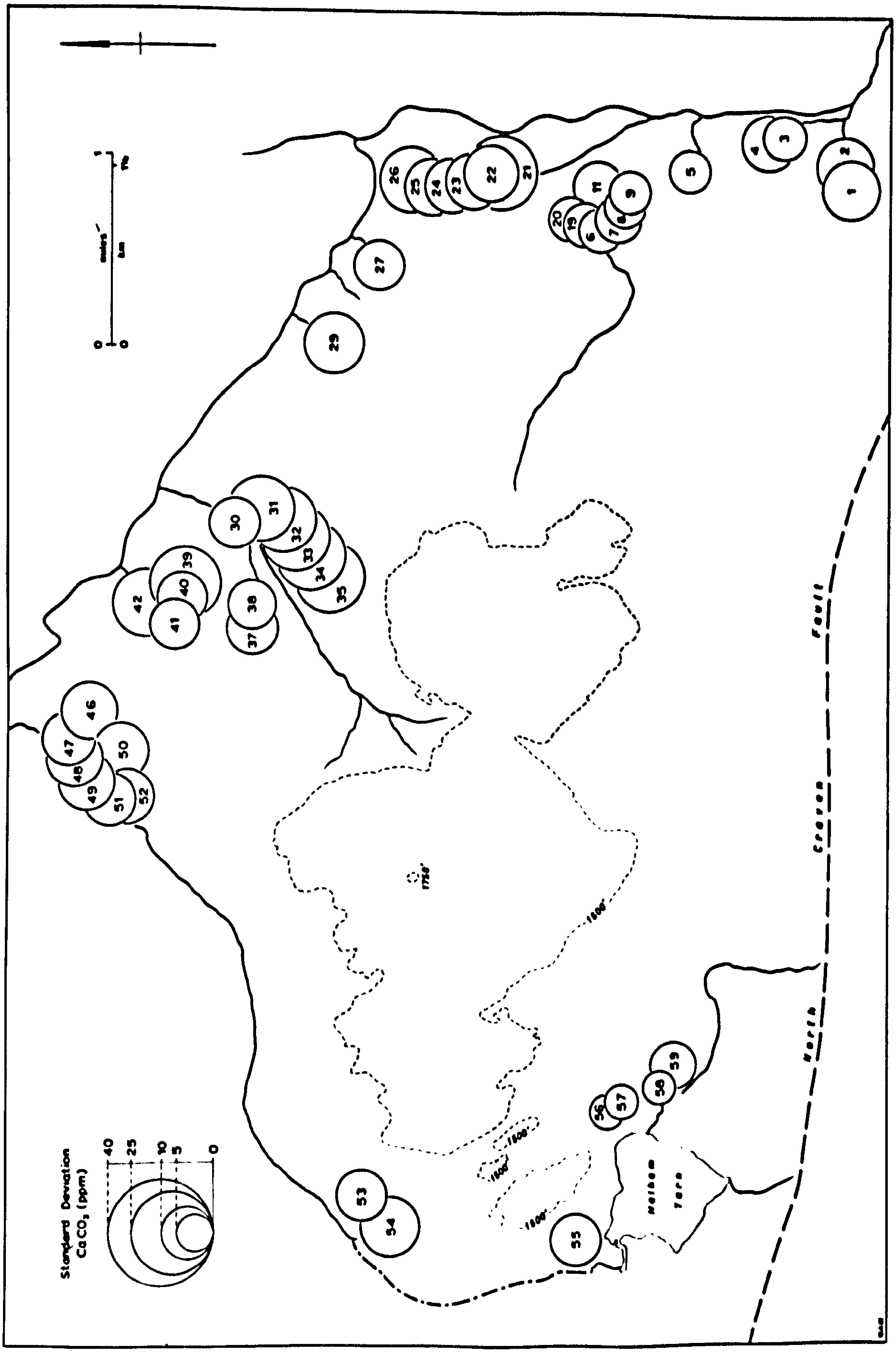
Fig.51 The relationship between the mean water temperature of springs in upper Littondale and the altitude of the risings.



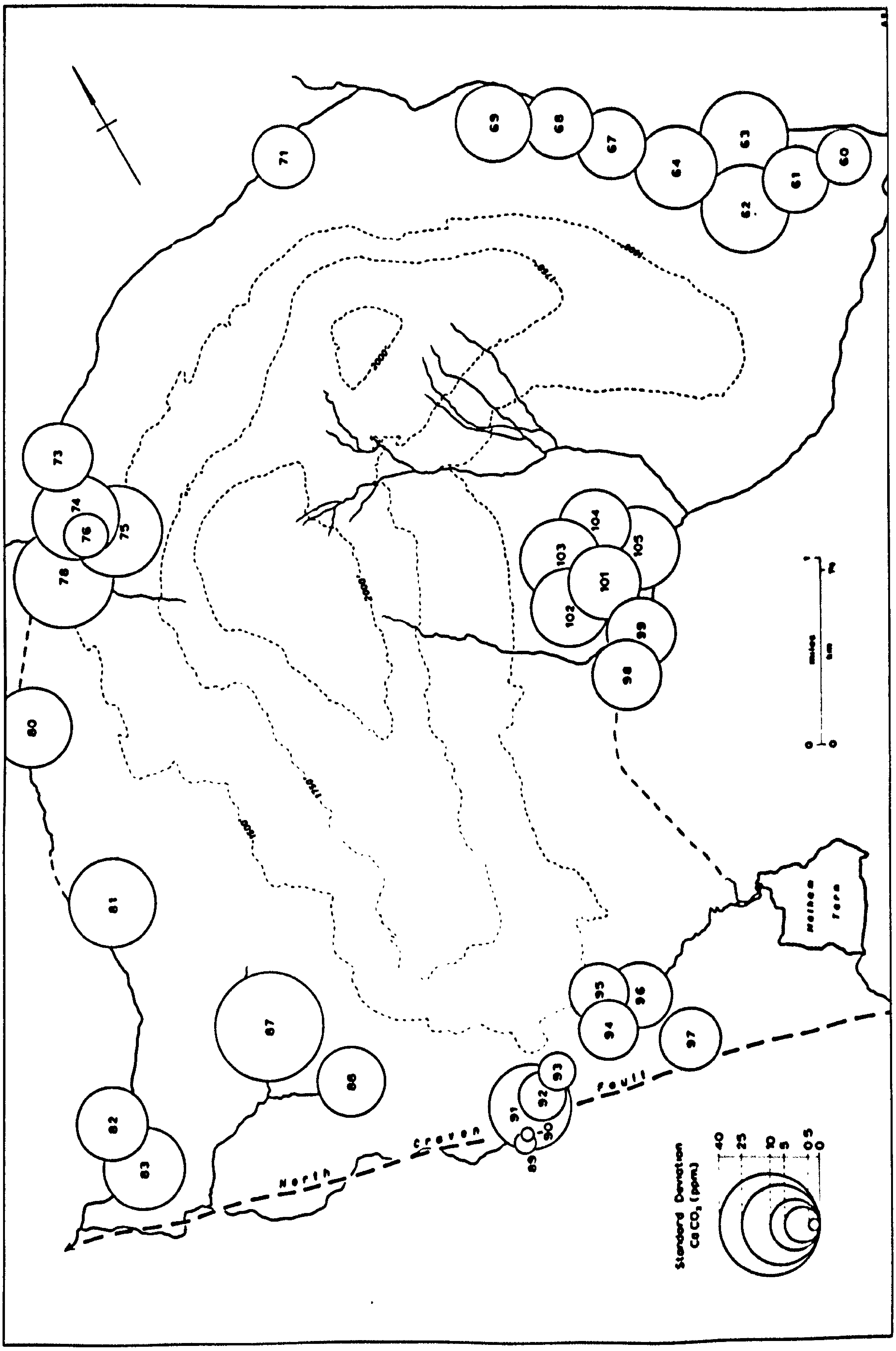
Map 12 Regional variations in mean dissolved calcium carbonate in the spring waters of the High Mark area



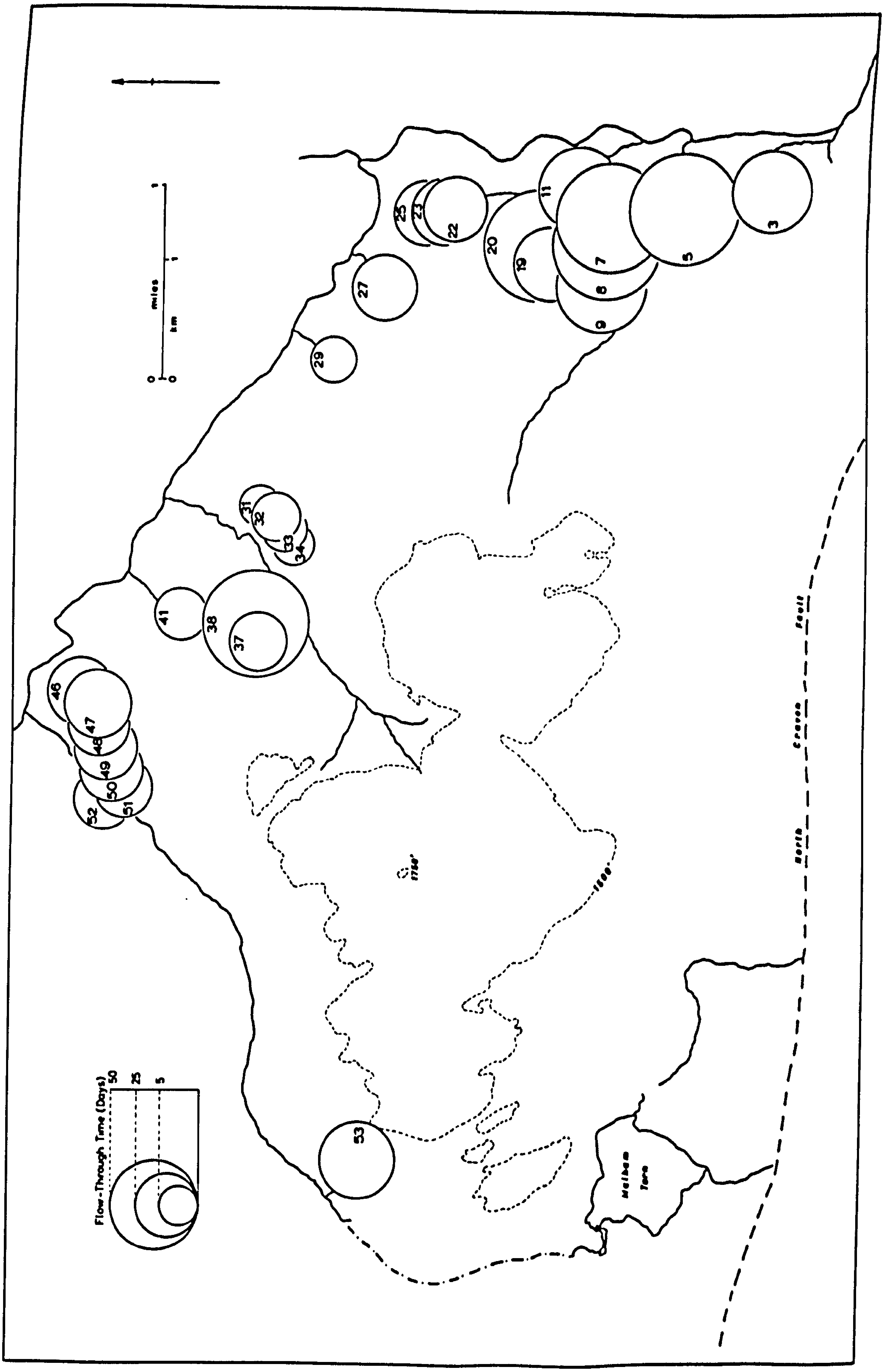
Map 13 Regional variations in mean dissolved calcium carbonate in the spring waters of the Fountains Fell area



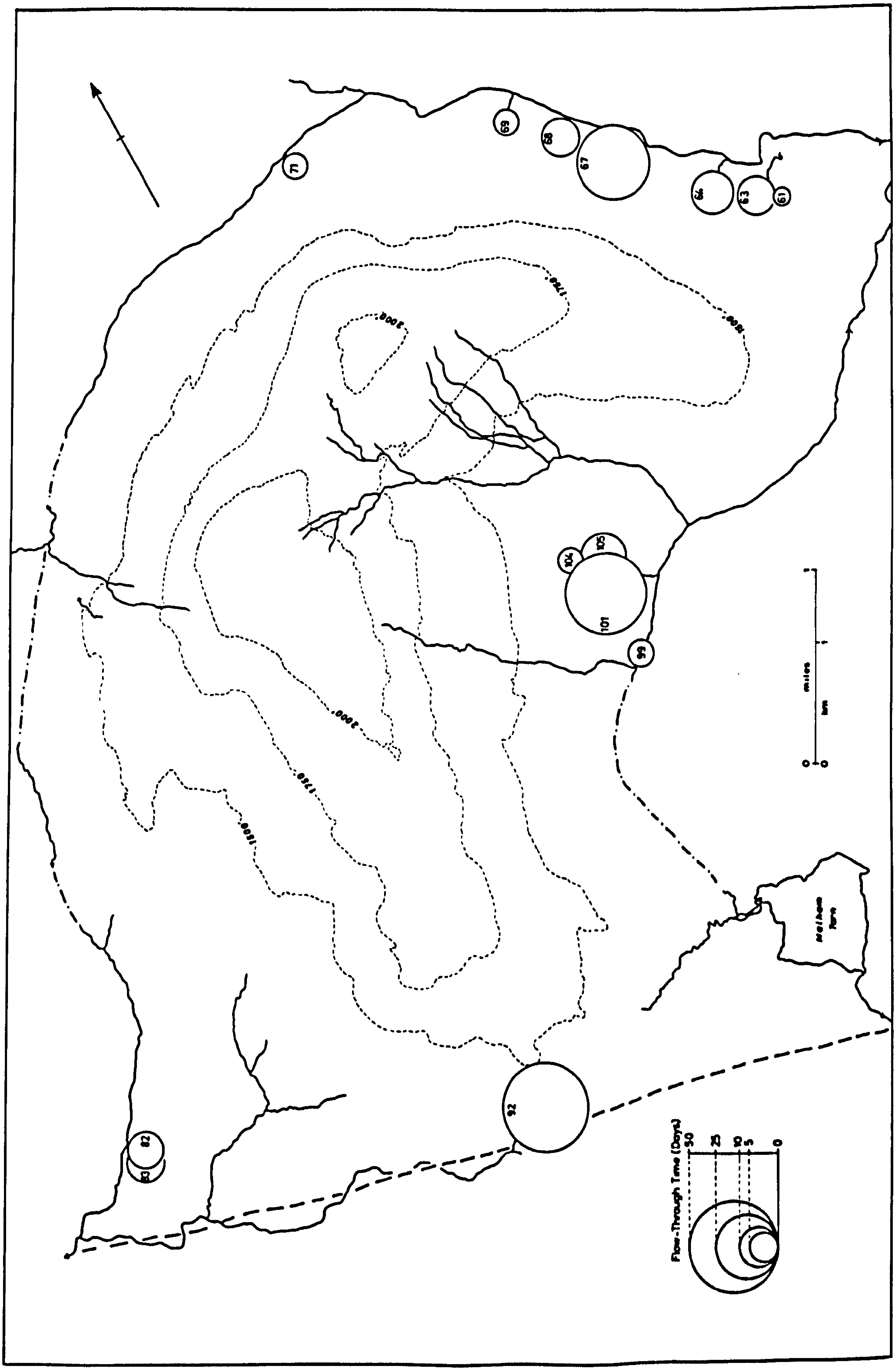
Map 14 Regional variations in the standard deviation of dissolved calcium carbonate in the spring waters of the High Mark area



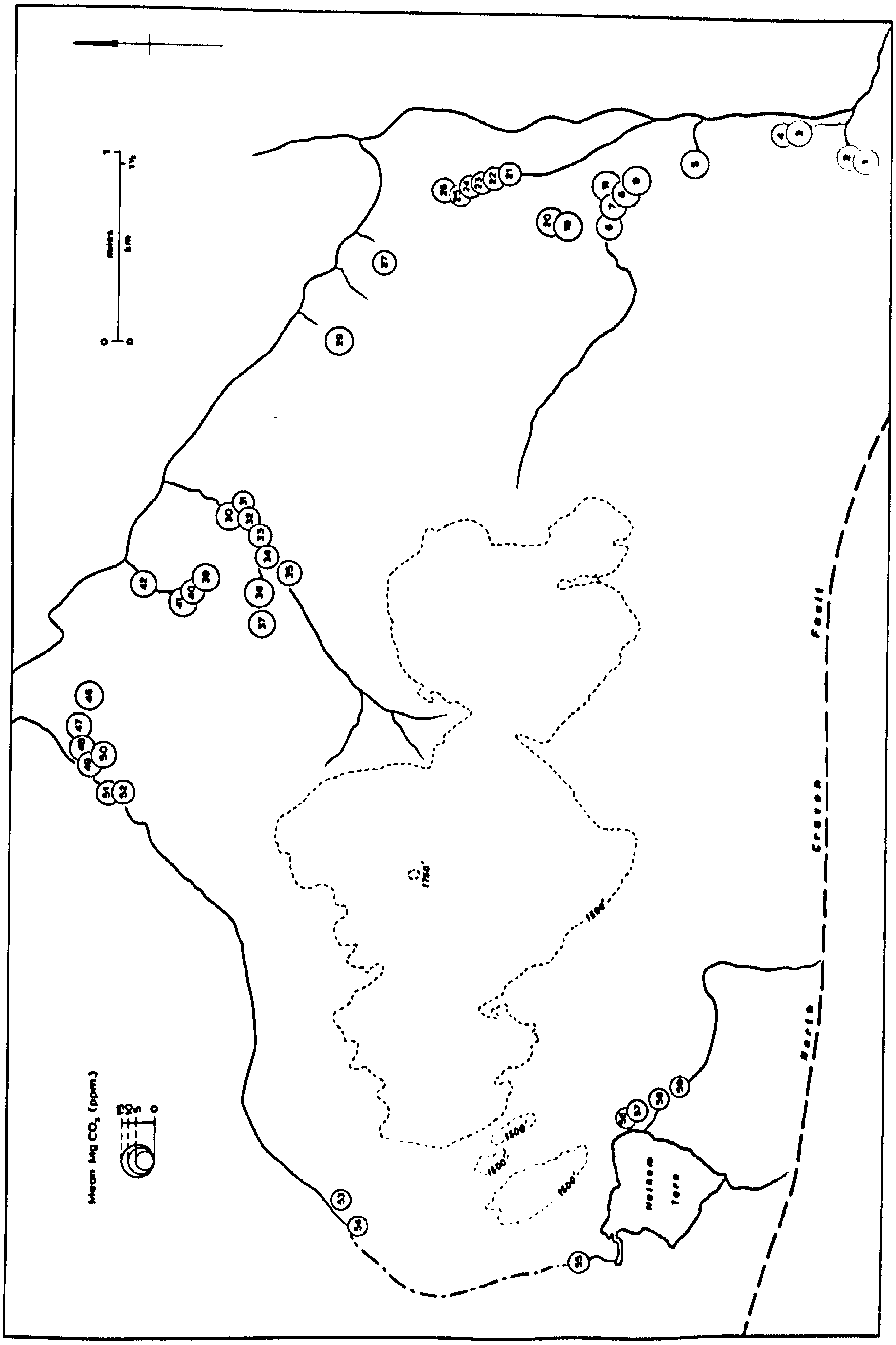
Map 15 Regional variations in the standard deviation of dissolved calcium carbonate in the spring waters of the Fountains Fell area



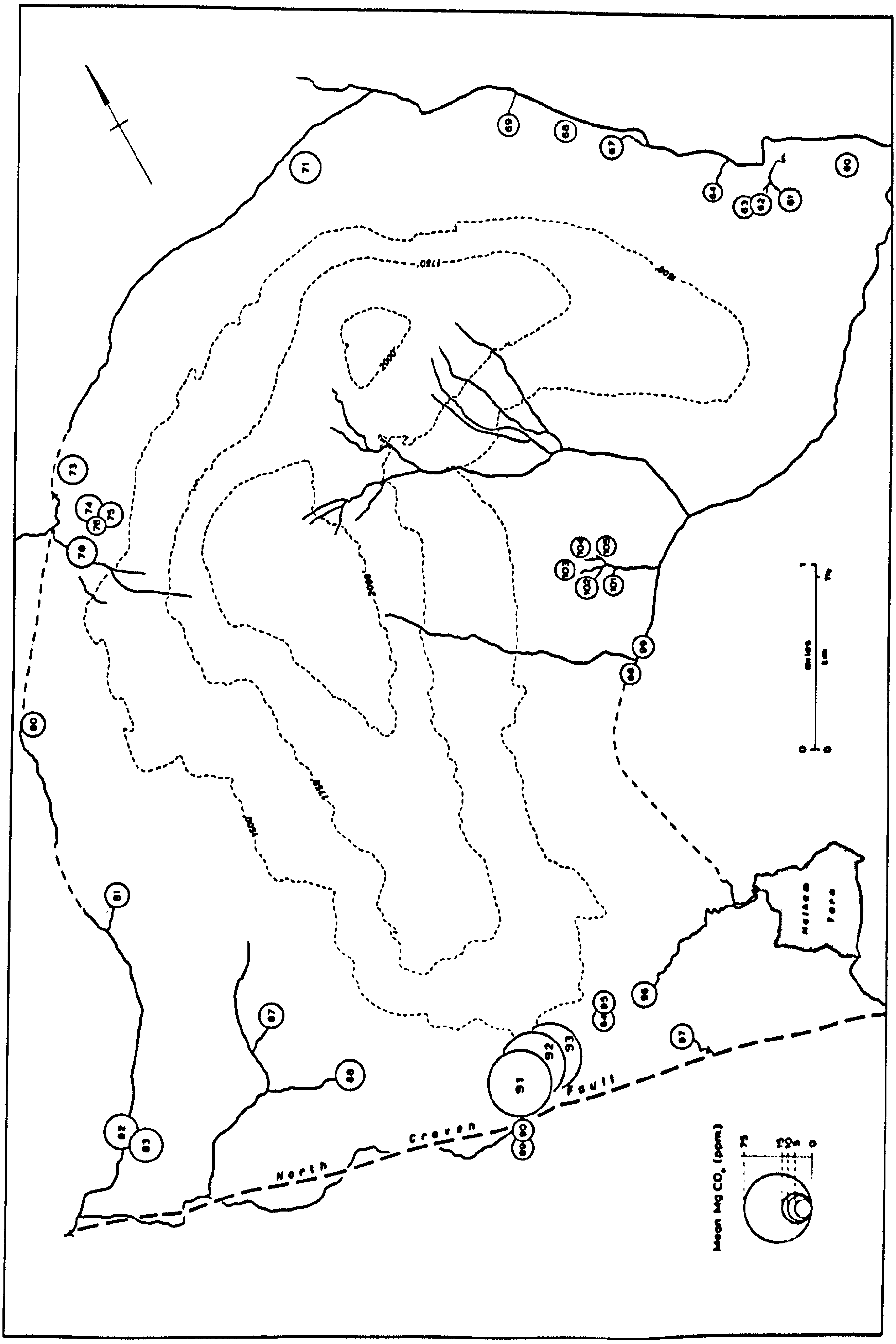
Map 16 Regional variations in the flow-through time of springs in the High Mark area



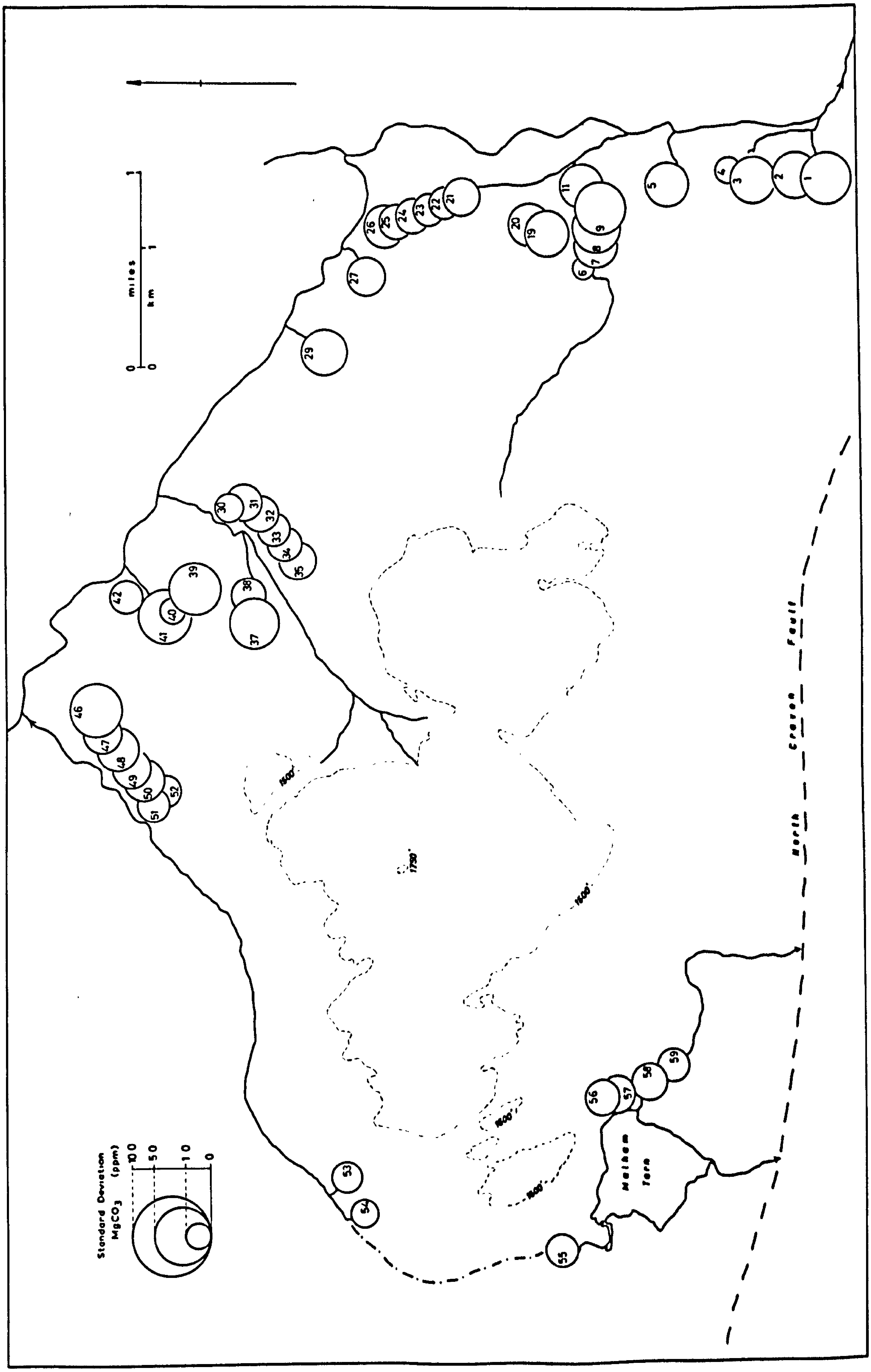
Map 17 Regional variations in the flow-through time of springs in the Fountains Fell area



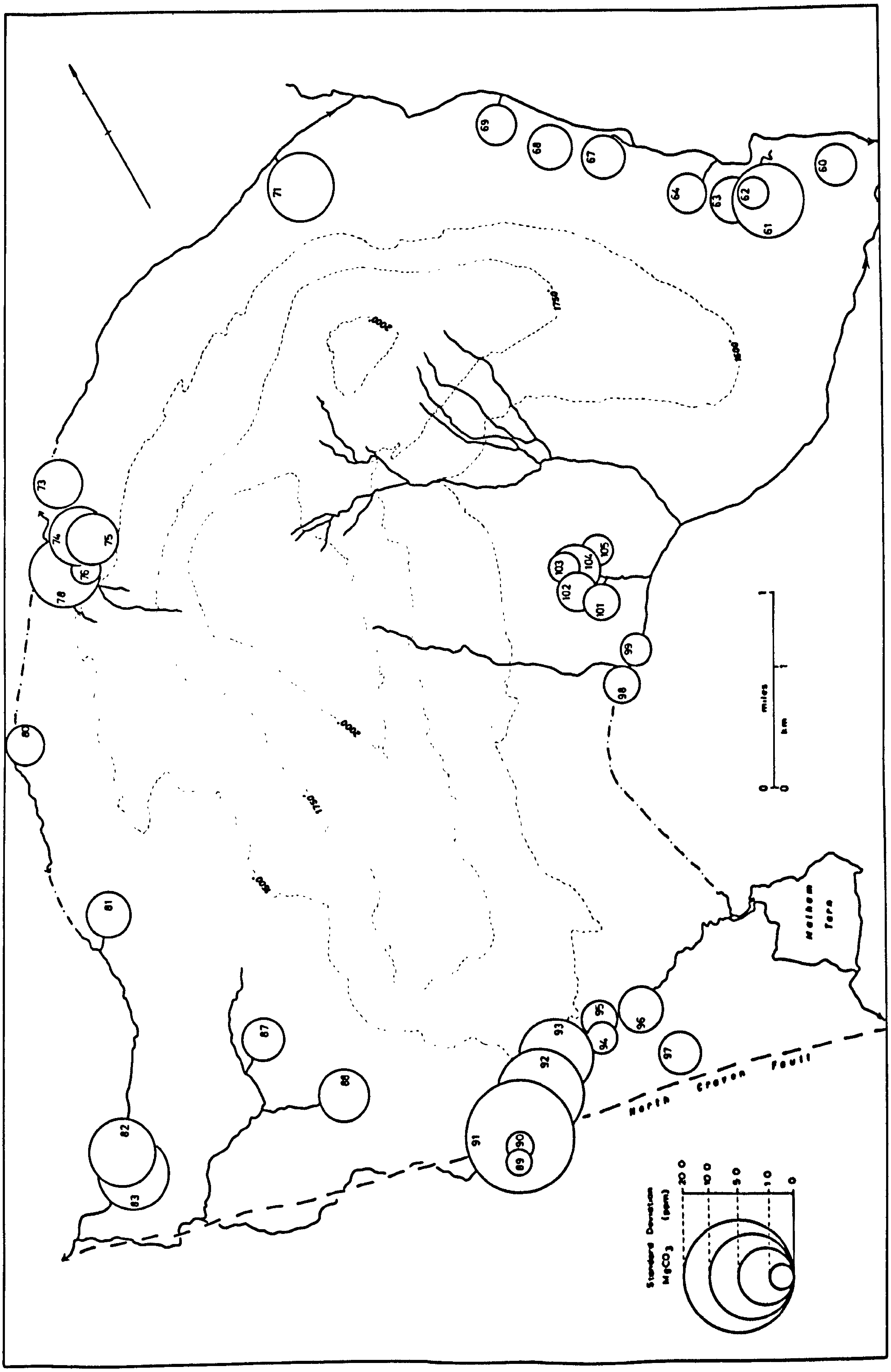
Map 18 Regional variations in mean dissolved magnesium carbonate in the spring waters of the High Mark area



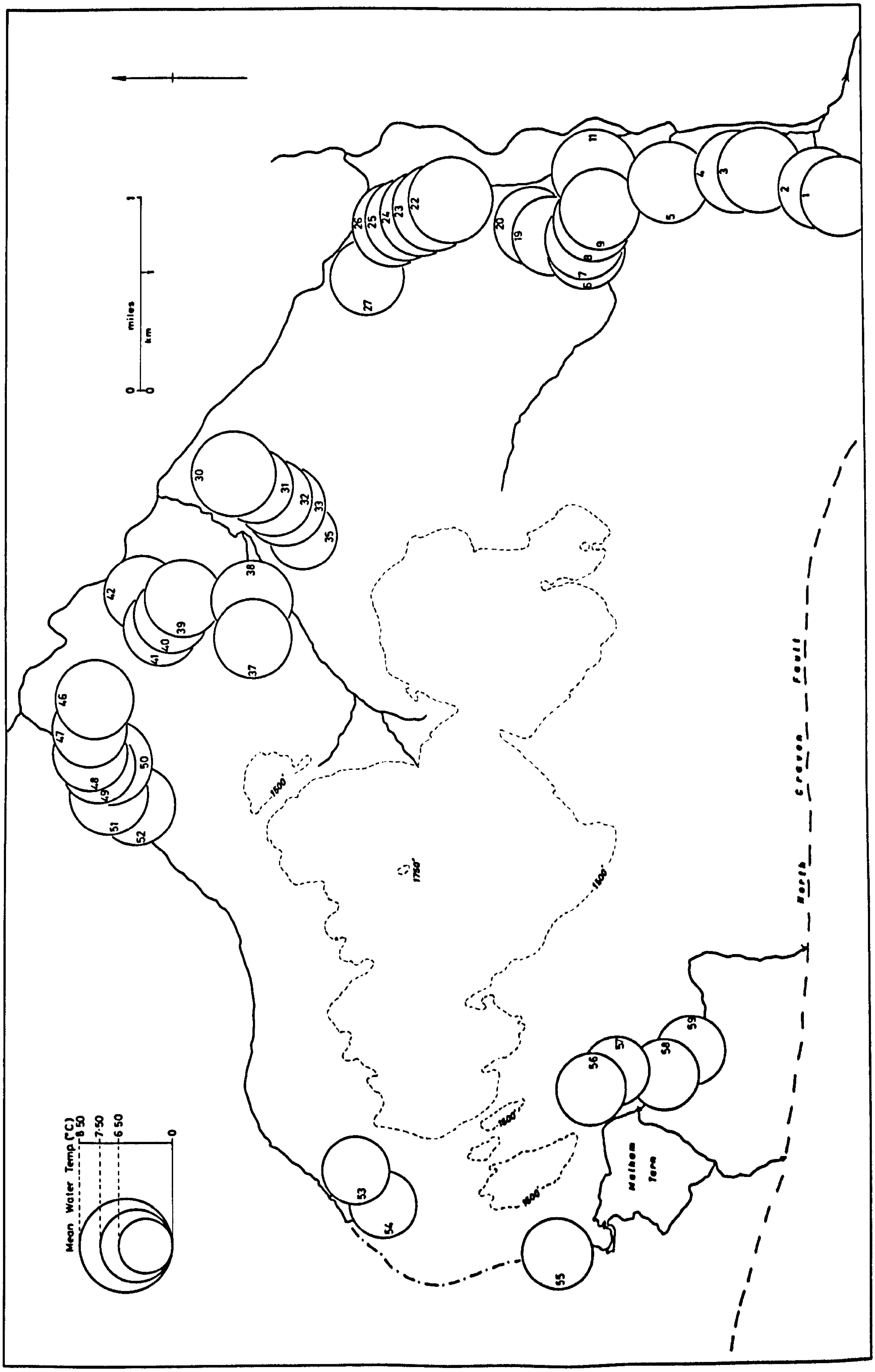
Map 19 Regional variations in mean dissolved magnesium carbonate in the spring waters of the Fountains Fell area



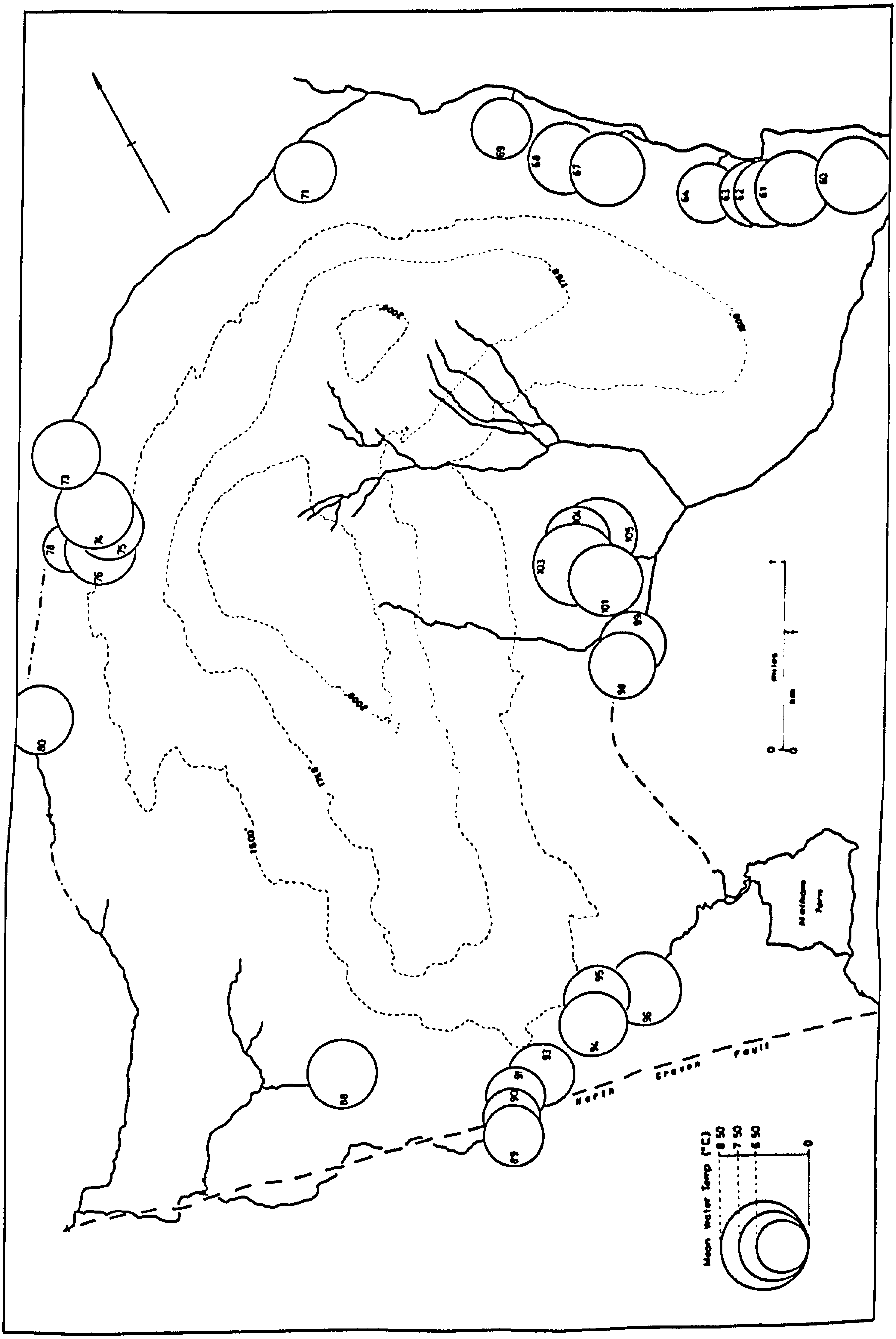
Map 20 Regional variations in the standard deviation of dissolved magnesium carbonate in the spring waters of the High Mark area



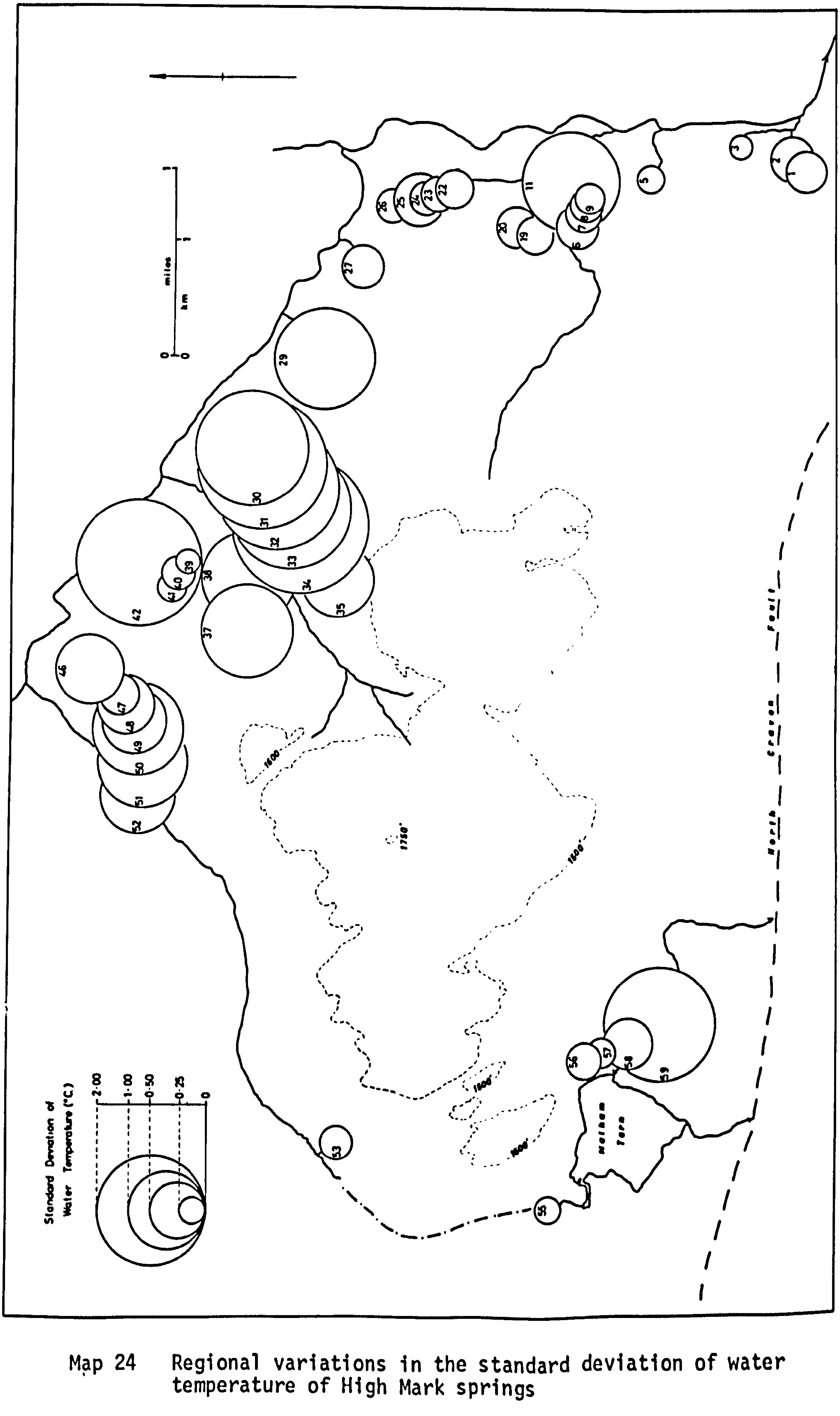
Map 21 Regional variations in the standard deviation of dissolved magnesium carbonate in the spring waters of the Fountains Fell area



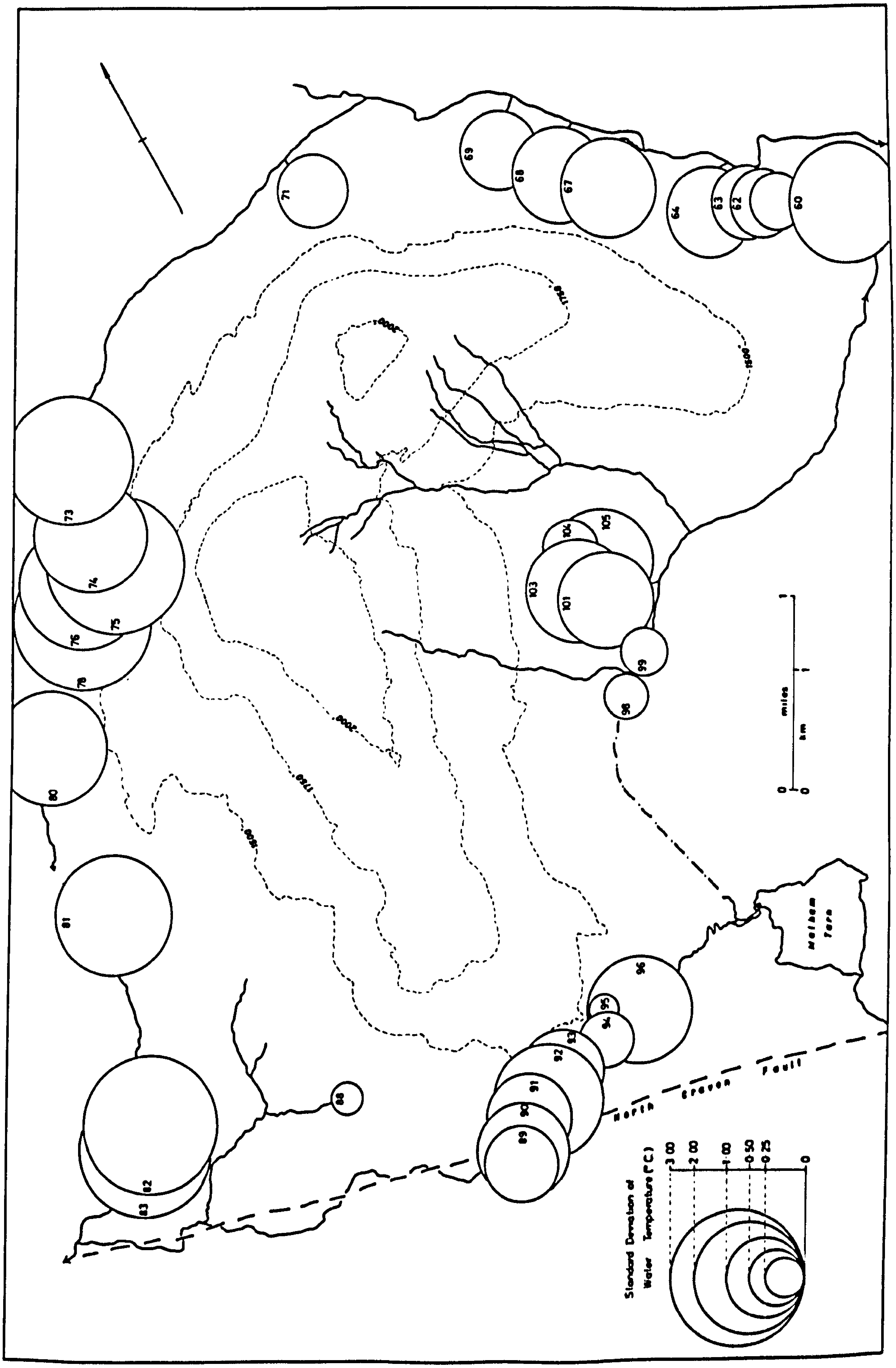
Map 22 Regional variations in the mean water temperature of High Mark springs



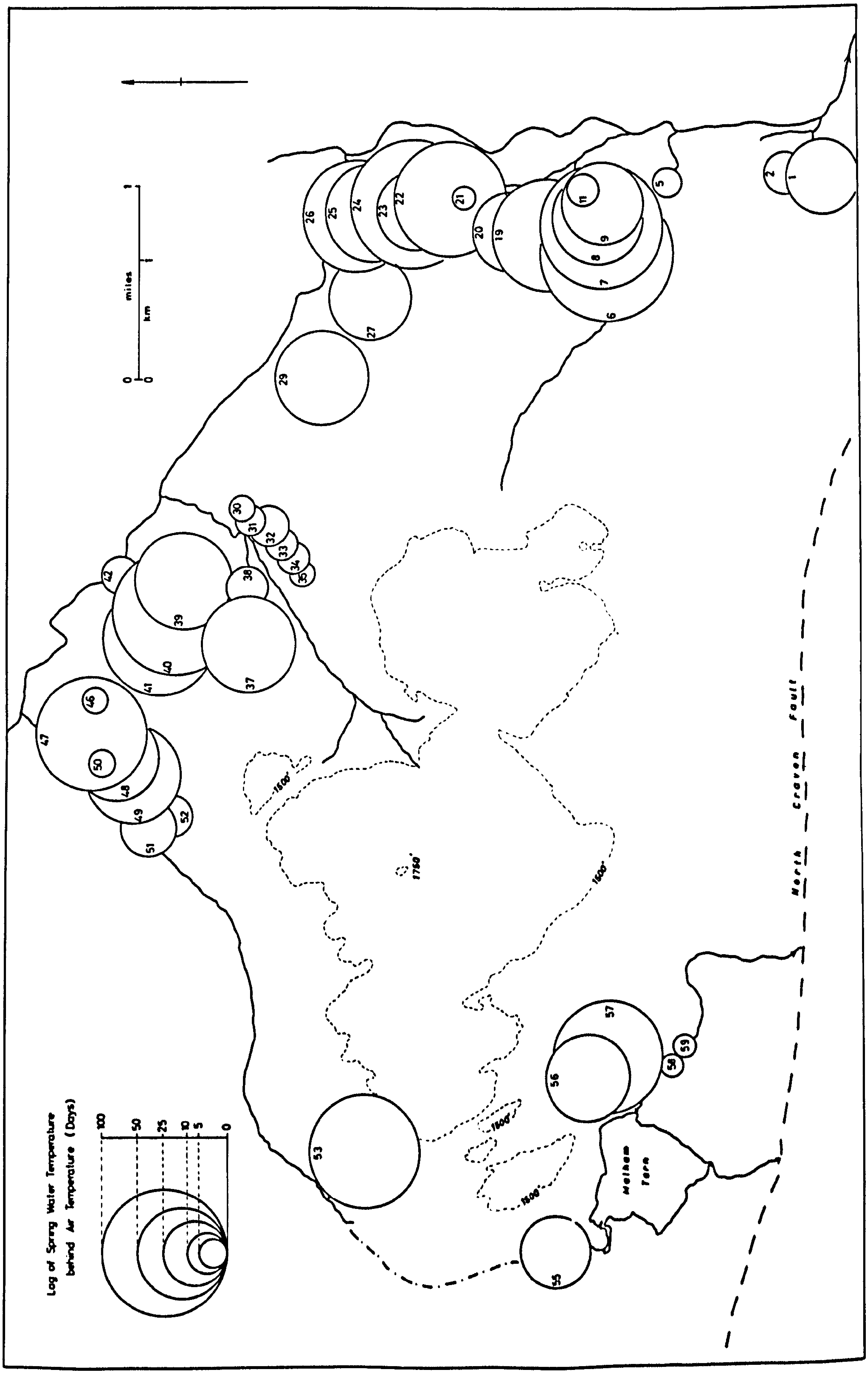
Map 23 Regional variations in the mean water temperature of Fountains Fell springs



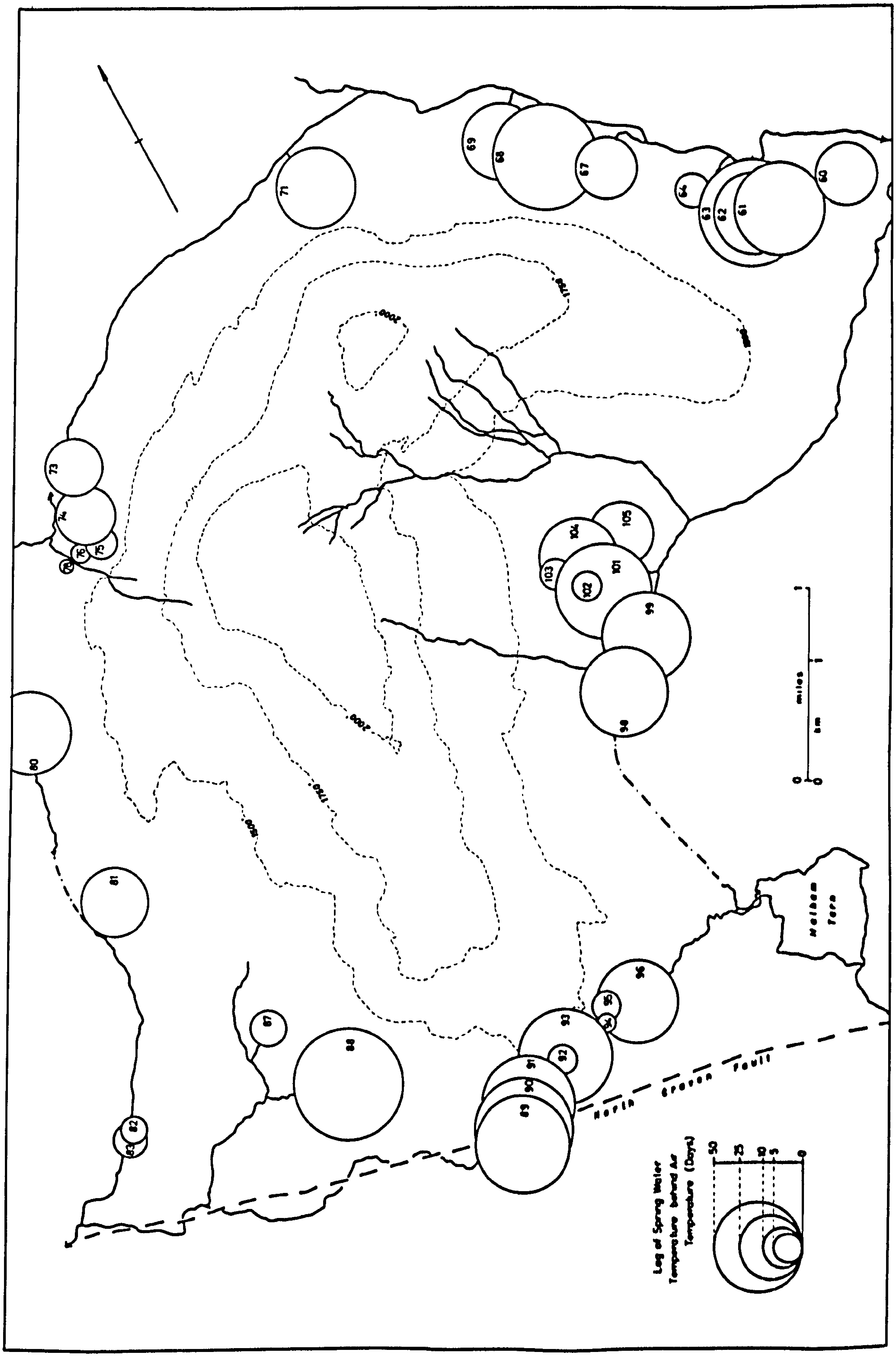
Map 24 Regional variations in the standard deviation of water temperature of High Mark springs



Map 25 Regional variations in the standard deviation of water temperature of Fountains Fell springs



Map 26 Regional variations in the lag of spring water temperatures behind air temperatures in the High Mark area



Map 27 Regional variations in the lag of spring water temperatures behind air temperatures in the Fountains Fell area

Plate 1 A large enclosed basin on the High Mark plateau near Parson's Pulpit

Plate 2 A dry valley in the High Mark area debouching onto the 396m (1300ft) erosion surface of Sweeting (1950)

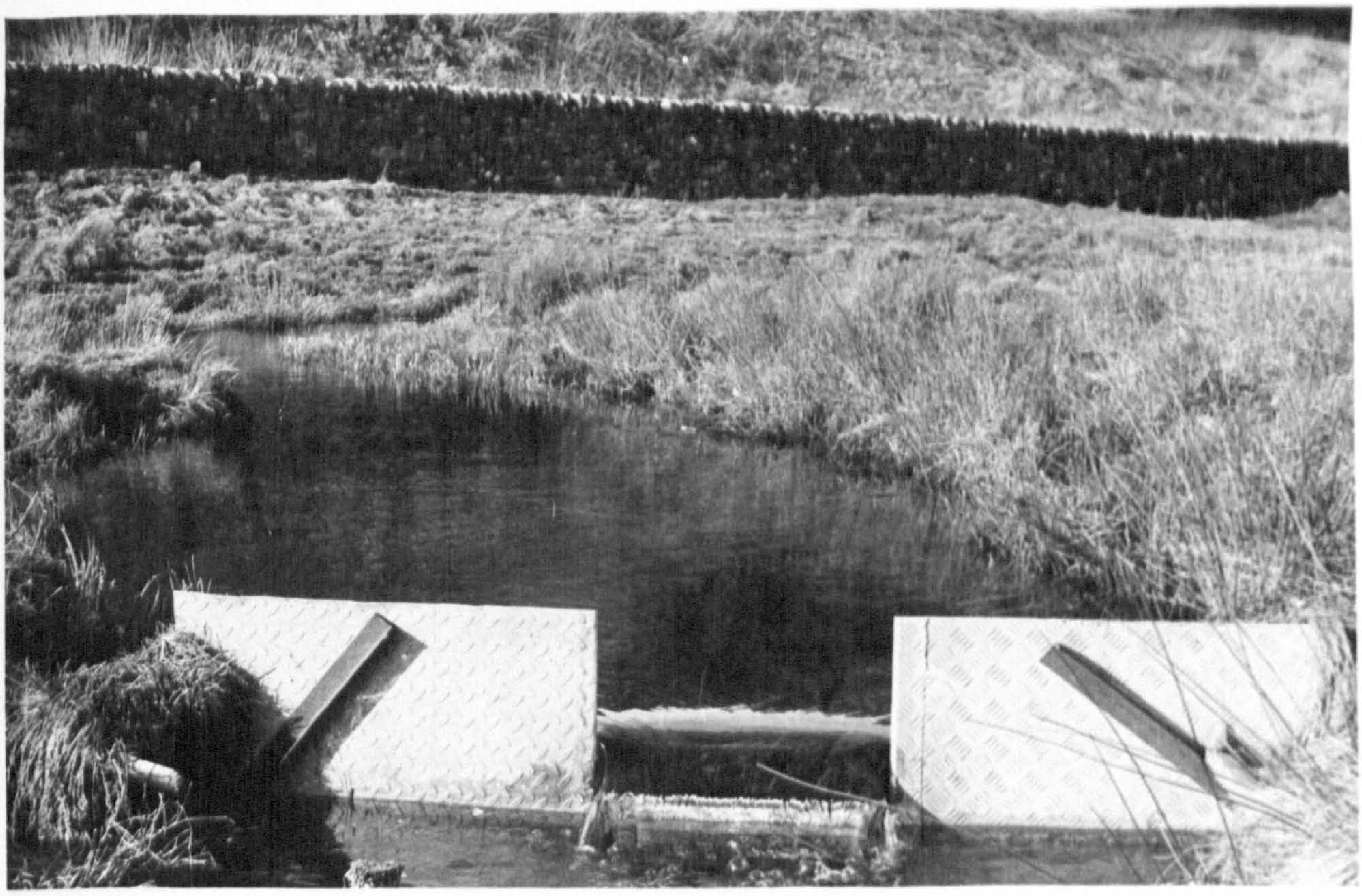


Plate 3 The thin plate square-notch weir at Robin Hood's Well under 'normal' discharge conditions

Plate 4 The weir at Robin Hood's Well submerged during severe flood conditions

Plate 5 The 'flood-rising' at Robin Hood's Well (site 4)

Plate 6 The spring at Outgang Hill site 8

Plate 7 The broad-crested square notch weir at Reynard's Close site 19 during flood conditions

Plate 8 The rising at Reynard's Close site 19 during flood conditions. The 'doming-up' of water at the spring is notable

Plate 9 The broad-crested square-notch weir at Moss Beck, site 27

Plate 10 The thin plate $\frac{1}{2}$-90° V-notch weir at Malham Tarn site 58

Plate 11 Seepage into an enclosed depression on the margins of Fountains Fell, occurring at root level on a slope of less than 5°

Plate 12 Calcareous tufa bar on Howgill Beck in Wharfedale