THE QUATERNARY ICE AGES IN NEW ZEALAND: A FRAMEWORK FOR BIOLOGISTS

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ABSTRACT

The methodology and nomenclature used to provide a framework of the major events in the Quaternary period of geologic time in New Zealand is introduced. The article is designed to be useful to biologists and others who have not specialized in geology.

INTRODUCTION

From about 2 million years ago to the present the long period of climatic fluctuations, known commonly as "The Ice Ages", has been the setting for the evolution of much of the New Zealand biota (as was discussed by Fleming 1962, Wardle 1963). It was a time of vigorous mountain building, vulcanism, construction of gravel plains and sand dune areas, alternation of long warm periods (interglacials) with cold periods (glacials) and the corresponding rise and fall of sea level. Such changes provided the impetus for adaptive radiation in some biotic groups and extinctions in others. In the latter part of the Quaternary the New Zealand landscape developed to its present form, giving rise to the modern range of habitats. During the latest part of the Quaternary the New Zealand biota came into violent contact with man, first Polynesian, then European, with their agents of disturbance and destruction, fire, the axe and plough and the alien plants and animals which they introduced.

Biologists have need to refer to the Quaternary time scale whenever it is relevant to their studies. The aim of this article is to outline a framework of the major events in the Quaternary of New Zealand, to describe, briefly, the criteria used to subdivide and differentiate periods of time and to describe environmental conditions which prevailed during them. The nomenclature is sometimes confusing and this article sets out to clarify it for the benefit of non-geologists. A glossary of technical terms, not covered otherwise in the text, is included at the end.

SUBDIVISION OF TIME: MATERIALS AND METHODS

The branch of geology known as stratigraphy (the science of study of rock strata) normally uses as its basic materials fossil-bearing rocks (see Holmes 1944, Dunbar and Roger 1957, Raup and Stanley 1971 for more detail). There is an assumption of superposition i.e. the oldest rocks will be found lowest in a sequence and the youngest at the top. The stratigrapher searches for the most complete vertical sequence of rocks possible, by using the overlapping, shorter sequences to synthesize an ideal "complete" stratigraphic column. He can then match unknown sections of strata against this, fitting them into their correct chronologic sequence by correlating with fossil assemblages, or some other attributes of the rocks. If there is continuity between vertically contiguous strata the sequence is conformable. If there are breaks in sedimentation (recognized by changes in lithology, fossils or signs of weathering, displacement or other kinds of time gap) the sedimentary strata on either side of the breaks are unconformable. Sections of sediment represent the elapse of time, but geologists prefer to keep time (chronostratigraphic or biostratigraphic) sequences and rock (lithostratigraphic) sequences separate, because there can be discrepancies between them. Later discussion elaborates on the distinctions between these. Usually it is possible to make inferences about environmental conditions which prevailed when particular rock strata were being deposited, from evidences in the materials of the rocks themselves or from their included fossils.

Meaningful boundaries of time periods, particularly before the Quaternary, are usually determined by fossil assemblages in the rocks (Table 1, 2). Boundaries lie where there are biotic changes, especially outgoings (preferably extinctions) of groups of fossils and incomings of new groups. The organisms which gave rise to the fossils have not always behaved in an ideal way so as to suit geologists. In some instances a species or group of species became extinct over a short time, but sometimes organisms disappeared in some areas but persisted elsewhere for a time so that a boundary based on their disappearance would be time transgressive. There is also the problem of facies differences caused by spatial habitat variation (and corresponding biotic differences) at any one time. Distinctive taxa which lived for relatively short periods of time, then became extinct and thus serve as "markers", are important for stratigraphic correlation. Ideally the organisms giving rise to the fossils should have occurred widely and have had good opportunities for fossilization. Marine organisms deposited in sedimentary basins are most useful in this respect. In recent years it has been possible to obtain radiometric absolute dates (discussed later) for such boundaries. In general, marine fossils are not as useful in this way in the Quaternary as in older rocks because, since the time is so short, suitable fossil extinctions and incomings are lacking. Many taxa have existed right through the period.

As much as is possible, however, the same general stratigraphic methodology is applied to describe Quaternary sequences. Thus the major time divisions in the New Zealand Lower Pleistocene (Table 2, 3) are based on changes in

TABLE 1: GEOLOGIC TIME SCALE

TIME (million years BP)	ERA	PERIOD	EPOCH
0	CAENOZOIC	Quaternary	HOLOCENE
0·01			PLEISTOCENE
2·0		Tertiary	PLIOCENE
5			MIOCENE
24			OLIGOCENE
40			EOCENE
			PALEOCENE
70	MESOZOIC	Cretaceous	
		Jurassic	
		Triassic	
220	PALAEOZOIC	Permian	
		Carboniferous	
		Devonian	
		Silurian	
		Ordovician	
		Cambrian	
550		Pre-Cambrian	

TABLE 2: LATE TERTIARY AND QUATERNARY TIME SCALE FOR NEW ZEALAND

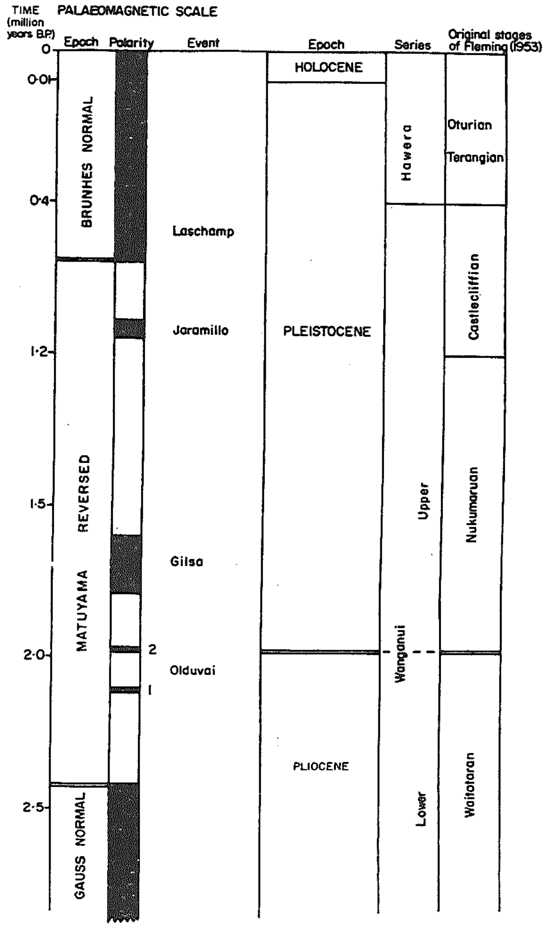


TABLE 3: TENTATIVE CLASSIFICATION OF THE PLEISTOCENE, NEW ZEALAND[1]

Time Scale (Million years BP)	Series / Stage[8]	STAGE (cold — warm)	Glaciation, Interglaciation	GLACIAL ADVANCES: Westland[2]	Waimakariri[3]	Rakaia[4]	Mackenzie Basin[5]	Hawea[6]	Te Anau[7]	Time Scale years
0	Hawera	Aranulan (warm)	Aranui	Waiho		Lake Stream	Birch Hill			14,000
	Hawera	Otiran (cold)	Otira	Kumara 3, Kumara 2	Poulter, Blackwater, Otarama	Acheron, Bayfield, Tui Creek	Tekapo, Mt John, Balmoral	Hawea, Albert Town	Marakura, Ramparts	?75,000
	Hawera	Oturian (warm)	Oturi							?130,000
	Hawera	Waimean (cold)	Waimea	Kumara 1	Woodstock	Woodlands	Wolds	Luggate	Whitestone	
	Hawera	Terangian (warm)	Terangi							?230,000
	Hawera	Waimaungan (cold)	Waimaunga	Hohonu	Avoca	? Glenroy	? part Wolds	Lindis	? Moat Ck	
	Hawera	Waiwheran (warm)	Waiwhera							
	Hawera	Porikan (cold)	Porika	Cockeye	? part Avoca		unnamed advance			
	Hawera	? unnamed interglacial (warm)	—							
	Hawera	? part Porikan (cold)	? part Porika							
0·4	Castlecliffian	Castlecliffian (= Putikian)								
	Castlecliffian	Okehuan					Glentanner Beds			
1·2	Nukumaruan	Maxwellan	? part Ross				Glentanner Beds			
	Nukumaruan	Nukumaruan (= Marahauan)					Glentanner Beds			
	Wanganui	Hautawan	Ross				Glentanner Beds			
2·0	Wanganui									

1 After Fleming (1953, 1962, 1975b), Gage & Suggate (1958), Suggate (1961, 1965a, b), Burrows & Mansergh (1973); 2 After Suggate (1965a); 3 Gage (1958); 4 Soons (1963); 5 Mansergh (1973b); 6 McKellar (1960); 7 McKellar (1973); 8 Fleming (1953). Dates for boundaries of the lower Pleistocene from Boellstorf & Te Punga (1977).

molluscan faunas in the shallow-water marine sequence in the Wanganui region (Fleming 1953, 1975a) but such deposits are uncommon in the Quaternary.

Deeper water marine sediments containing foraminifera (pelagic, marine protozoa with calcareous shells) are, at present, among the most widely-used kinds of materials for attaining a continuous record of the Quaternary. Although many of the taxa lived throughout the period, some are clear indicators of warm and cold phases. Some other marine protozoa and algae with siliceous or calcareous skeletons (silicoflagellates, radiolaria, dinoflagellates, diatoms and others) are similarly used (Kennett 1968, 1970, Kennett, Watkins and Vella 1971, Keanny and Kennett 1973, Berggren and Van Couvering 1974, Williams 1975). All of these groups of organisms are widespread through the oceans and, since the present latitudinal distribution of taxa in relation to ocean temperature conditions is well known, their time-transgressive occurrences have not proved to be too much of a hindrance in elucidating Quaternary environmental change (e.g. see Vella, Ellwood and Watkins 1975, and the references above).

If correlations with unique fossils (or fossil sequences) are not possible, other features of the rocks such as unique lithological characteristics or sequences may be useful "markers" for correlation. One of the most useful correlation tools because it is planet-wide, (though not present in all rocks), is palaeomagnetism. This method depends on the fact that the earth's magnetism has changed the direction of its polarity many times. In the Quaternary there were at least five changes in polarity. These have been dated in volcanic rocks, using a radiometric method, and can readily be recognized in continuous sedimentary sequences from the ocean floor (Cox 1973, Shackleton and Opdyke 1973, Berggren and Couvering 1974) (Table 2). Palaeomagnetism is also useful in terrestrial rocks (especially in some volcanic rocks which can be dated).

Quite different criteria for subdivision (but the same basic stratigraphic methodology) have been used for classification of the Upper Pleistocene and Holocene, where suitable terrestrial materials are abundant. In New Zealand the Lower and Upper Pleistocene sequences are separable because only in the Upper Pleistocene were the essential elements of the modern geography of the country (including the mountain ranges, river-valleys and coastline) present. Earlier the uplift of the Kaikoura orogeny was proceeding rapidly and the land had not attained its present configuration. Some Lower Pleistocene deposits were deformed by the crustal movements. The Upper Pleistocene deposits have had increasingly better chances of survival, in depositional contexts similar to those of the present day, the younger they are. The most usual materials upon which the classification of the Upper Pleistocene in New Zealand is based are glacial and associated fluvial deposits but unless they are interbedded with warm climate (interglacial) deposits or show some other clear-cut sign of interglacial climatic conditions, these are useful mainly to distinguish only the cold periods. Often there are gaps in the record, because of fluvial erosion, or destruction or burial by subsequent glacial events.

The intervening warm periods are identified from palaeosols and organic sediments, or inferred from weathered surfaces and deposits, or evidences indicating erosional intervals when supply of gravel did not exceed the power of rivers to carry it. One set of evidences used to distinguish interglacials includes shorelines and beach deposits indicating high sea levels and believed to represent eustatic response to melting of world ice during the times of interglacial maximum temperature. These evidences are not necessarily closely linked to the sites of the glacial evidences, though some, in Westland, are (Suggate 1965a). We should be cautious about use of raised shorelines as interglacial indicators in a country as tectonically active as New Zealand. It is desirable to have confirmation of the interglacial character of the deposits from other evidence, such as pollen data.

These general criteria for subdivision of the Quaternary are essentially climatic (though presumed also to be chronostratigraphic) as distinct from the biostratigraphic criteria used in subdividing older time periods.

Distinct problems arise in correlation of the terrestrial Quaternary deposits because often rock units of widely different age are composed of rather similar materials (glacial tills or fluvio-glacial outwash gravels). Also often there may be unconformities, sometimes difficult to detect. Deposits from early glacial activity are most likely to survive only if subsequent events are of lesser magnitude so, at best, the record is fragmentary. Unless there is a clear-cut, long and complete chronologic sequence of deposits present in one site (a rare occurrence), or unless there are distinctive features of the deposits of different age, the assignment of a deposit to a particular time period is very difficult. Absolute dating (discussed later) is one means by which glacial rock units may be fitted into their correct order. Weathering features and relative stratigraphic separation are the most commonly used criteria for relative dating in contexts where absolute dates are unavailable. However, degree of weathering is not an infallible guide to comparable age of two deposits, because of climatic effects which vary in intensity from place to place. Also, the linking of a moraine to its correct downstream outwash sheet is not always easy.

Widely used materials for correlation and cross-dating glacial deposits in North and South America, and Iceland are tephra (volcanic ash shower) deposits which are distinctive, relatively easily recognized, often occur over extensive areas and are frequently interbedded with other kinds of deposit. Further, many tephras have been deposited over very short time periods. Unfortunately virtually all the tephra deposits in New Zealand occur in the North Island and most of the glacial deposits in the South Island. The techniques of tephrochronology have been highly developed in New Zealand (Pullar, Birrell and Heine 1973, Vucetich and Pullar 1973, Topping 1973, Topping and Kohn 1973) and the results of the basic studies are now being applied to correlations of, for example, the late Pleistocene glacial sequence on Mt Ruapehu (Topping 1974), the history of vegetation (by pollen analysis) in the central North Island during and since the last glaciation (McGlone and Topping 1973, 1977) and vegetation history in the Chatham Islands (Mildenhall 1976). Some tephras have been used for dating Lower Quaternary events (Seward 1974). Others in deep-sea sediments, will probably be useful for marine stratigraphic correlation (Ninkovich 1968, Lewis and Kohn 1973, Watkins and Huang 1977). Table 4 includes information about some of the most important terrestrial tephra deposits (McCraw 1975). Other rock materials, usually of limited usefulness for correlation because they suffer from disabilities the same as, or greater than, those of glacial deposits are loess sheets and various fluvial, lacustrine and swamp deposits, dune sands and soil complexes.

TABLE 4. IMPORTANT NORTH ISLAND TEPHRA SHOWERS

Event	Date (Yr BP)	Volcanic Centre
Kaharoa Ash	950	Okataina
Taupo Pumice Formation (a complex)	c 1 800	Maroa-Taupo
Waimihia Formation	3 400	Maroa-Taupo
Rotoma Ash	7 300	Okataina
Waiohau Ash	11 200	Okataina
Rotorua Ash	13 000	Okataina
Rerewhakaaitu Ash	14 700	Okataina
Kawakawa Tephra Formation (a complex - includes Oruanui, Aokautere)	c 20 000	Maroa-Taupo
Mangaoni Lapilli Formation (a complex now divided into several Formations)	c 22 000 | c 40 000	Okataina
Rotoehu Ash	41 700	Okataina
Mt Curl Tephra Formation	230 000	Maroa-Taupo

All of the types of rocks described above can be used to build up a sedimentary stratigraphic column, when conditions permit, in much the same way as marine sediments but it is unlikely that it will be possible to establish something approaching a continuous record. Marine or lacustrine sedimentary basins potentially are the best kinds of site for attaining a continuous record of the Quaternary.

Pollen and spores are potentially useful fossils for subdividing the Quaternary and interpreting its environmental conditions. They are produced in large numbers by terrestrial plants, are widely dispersed, usually preserve well in aquatic and mire sediments and are readily recognized. Some long, pollen-bearing sedimentary columns have been studied (e.g. a 0.5 million year old column from Macedonia which clearly records a complex sequence of glacial and non-glacial conditions (Van Der Hammen, Wijmstra and Zagwijn 1971); and, an as yet incompletely studied column of, perhaps, 1 million years from Lake George in New South Wales (Dr Gurdup Singh pers. comm.).

No continuous New Zealand pollen studies of the greater part of the Pleistocene, nor even of the complete extent of the last (Oturian) interglacial or last (Otiran) glaciation are yet published, mainly because suitable materials have been difficult to find. A long core (with a discontinuous pollen record) was obtained from Petone near Wellington but the results of its study are not yet fully available (Mildenhall 1973). The core may extend through all of the Hawera series. However, some shorter pollen sequences, in unequivocal relationship with glacial, glacio-fluvial or other cold-climate deposits, are available (e.g. Suggate 1965a, Fleming 1970, 1972, McGlone 1973, Mildenhall 1973, Moar and Suggate 1973). New Zealand pollen assemblages do not reveal (except in the early Quaternary) extinctions which could be used in the same way as marine fossils in older rocks to define biostratigraphic boundaries (Mildenhall 1973). Interglacials are usually recognizable from the abundance of lowland forest pollens and glacials from the predominance of herbaceous or scrub pollens. Care is needed to interpret these because of the latitudinal extent of the country and the amount of unglaciated terrain. Forest which included the lowland species survived the glaciations in various places outside the ice limits.

Although unequivocal "marker" fossils may be absent in the later Pleistocene it is possible that unique fossil pollen assemblages or sequences can be found to assist in the identification of the deposits they are associated with. Workers in the palynology of the European Pleistocene have been fortunate in finding such unique occurrences, so that their interglacial sequences, each different, are well known (cf West 1968). We have insufficient data on our interglacials to know whether the same may apply here.

In Europe, North America and elsewhere, mammalian bones and human artefacts are used as "marker" fossils in terrestrial stratigraphy (West 1968, Flint 1971). In New Zealand there may be some potential for similar use of bird bone and perhaps marine mammal fossils (see Grant-Mackie and Scarlett 1973) but otherwise we must rely on invertebrate fossils, a field which is virtually untapped. Ostracods in lacustrine situations are likely to be useful (Dr T. Crisman and Mr D. Bell pers. comm.).

If suitable sediments containing pollen are found we may yet obtain a continuous record of the Quaternary of New Zealand, but they may have to be looked for in ocean cores from the continental shelf. The potential there for association of pollen and foraminiferal and other microfossil assemblages with dateable tephra horizons makes this prospect quite exciting. In all work using biostratigraphic indicators, time control using absolute dating methods is very important.

DATING OF QUATERNARY DEPOSITS

Correlation of stratigraphic sequences in the Quaternary is often very difficult unless absolute dating methods (using time-dependent change in some physical system) can be used. Some dating methods are applicable over long time periods and some for shorter periods. Those most commonly used are listed in Table 5. Among the most important are the potassium-argon, fission-track and radiocarbon methods. The techniques, materials and limitations are outlined fully in various publications (e.g. West 1968, Rafter 1975, Chappell 1978). NB, all radiocarbon dates cited in the present paper are according to the half-life for radiocarbon of 5 568 years (old T½ or "radiocarbon years") and are uncorrected for secular variation in radiocarbon formation (yr = year, B.P. = before "present", i.e. 1950 A.D.).

If suitable materials can be found the radiocarbon method will permit precise dating of events in the latter part of the Late Pleistocene and Holocene in New Zealand. Other methods are being applied to older deposits, e.g. fission track (Seward 1973, 1974, 1975). Absolute dating is especially useful when applied to particular distinctive "marker" horizons (palaeomagnetism, tephra) which can then be used to correlate and thus date rocks elsewhere.

TECHNIQUES FOR DEFINING PALAEOCLIMATE

A range of techniques is available for gauging the climatic conditions prevailing in the past (Table 6). For various reasons some (including certain of the biological indicators) lack precision. Other biological indicators have proved to be very sensitive indicators, however (Coope 1970, 1975). Few means are available for estimating precipitation. Summaries of methods are given in West (1968) and Flint (1971).

STRATIGRAPHIC NOMENCLATURE

Geologists use a set of internationally agreed rules when applying names to categories in the scheme for subdividing

TABLE 5. METHODS FOR DATING QUATERNARY EVENTS

Method	Brief Description of Basis for Chronometry	Time Span (Yr BP)	Statistical error	Type of Materials for Dating
Radiometric				
K^{40}/Ar^{40}	Decay of potassium^{40} to argon^{40}	50 000-unlimited	small	volcanic rocks
U^{234}/Th^{230}	Decay of uranium^{234} to thorium^{230}	50 000-250 000	large	coral, speleothems, bone
U^{238}/He^{4}	Decay of uranium^{238} giving rise to helium^{4}	>2 million	large	coral
Pa^{231}/Th^{230}	Decay of palladium^{231} and thorium^{230} causing change in ratio	5 000-120 000	large	marine sediments
C^{14}	Decay of radiocarbon after death of organism	200-40 000	small for good samples	peat, wood, charcoal, shell, bone
H^{3} (tritium)	Decay of tritium after deposition of water in glacier ice	50-100	small	water in ice
Fission track	Tracks in crystals caused by fission of uranium	100 000-1.5 million	large	volcanic glass
Other				
Amino acid racemization	Conversion of amino acids of L form to equilibrium mixture of D and L forms	to 400 000	large	organic materials
Varves	Deposition of sediments, with annual alternation of grain size, in proglacial lakes (unique sequences)	0-15 000	very small	laminated lake silts
Dendrochronology	Formation of annual growth layers of differing width (unique sequences)	0-1 000 (N.Z.) 0-8 000 (U.S.A.)	very small	long-lived, climate-sensitive trees
Lichenometry	Linear growth rate of lichen thalli on newly-formed rock surfaces	0-800 (N.Z.) 0-3 000 (Canada)	large	long-lived, slow-growing, regular shaped lichens

TABLE 6. METHODS FOR ESTIMATING CLIMATIC CONDITIONS

Method	Brief Description of Basis for Thermometry etc.	Parameter Estimated (Example of Materials Used)
Isotope ratio O^{18}/O^{16}	temperature-dependent changes in ratios of oxygen isotopes in calcium carbonate or water (ice), or various forms of organic material. (O^{18} enrichment with respect to O^{16} increases 0.02% per 1°C temperature fall).	ocean temp. (foraminifera, molluscs) cave temp. (speleothems) terrestrial temp. (tree rings, ice in ice sheets)
Geomorphic, soil	distribution of landforms, soils or related evidences outside their present latitudinal or altitudinal limits.	terrestrial temp. (periglacial, glacial, tropical landforms or weathering evidences) world temp. (high or low marine shorelines)
Sediment type	distribution of distinctive sediment types outside their present altitudinal or latitudinal limits.	terrestrial temp. (glacial sediments) ocean temp. (marine sediments)
Snowline	temperature-dependent position of glacier equilibrium line and assumed adiabatic lapse rate (0.6°C decline in temperature per 100 m rise in altitude).	terrestrial temp. (geomorphically-determined previous altitudinal positions of snowline)
Timberline	temperature-dependence of altitudinal position of timberline.	terrestrial temp. (evidences for change in altitudinal position of treeline)
Tree growth-layer width	dependence of tree annual ring widths in difficult environments on climatic conditions.	precipitation (arid sites) temperature (cold sites, treeline)
Closed basin lake shorelines	dependence of levels of closed basin lakes on precipitation.	precipitation (beaches, tree rings, human occupation sites)
Biological indicators	the modern known range of organisms, with respect to climatic parameters, is used as an index to infer past climate from fossil distributions outside the modern range.	ocean temp. (foraminifera molluscs) terrestrial temp. (molluscs, insects, especially beetles, plants, mammals, birds etc.) lacustrine temp. (ostracods)
Special biological attributes	sinistral coiling of some foraminifera in cold water, dextral in warm water	ocean temp. (foraminifera)

and describing time periods. A full account of the field in the Quaternary of New Zealand is given by Gage (1977). The work of Fleming (1953) (extended by his articles in 1962 and 1975a, b) and of Gage and Suggate (1958) and Suggate (1960, 1961, 1965a, 1973) may be used to exemplify the methodology (Table 5).

LOWER PLEISTOCENE

Biostratigraphy

The boundaries of rock units deposited during an interval of time are defined in terms of the distribution of fossils e.g., the Lower Pleistocene Castlecliffian stage (Fleming 1953, Table 15, p. 103) is a biostratigraphic unit encompassing a generally uniform molluscan fauna in the shallow-water, marine, sedimentary sequence near Wanganui and named from the locality where it is well developed. Two substages, Okehuan (lower) and Putikian (upper) were differentiated within it, according to the distribution of restricted fossil assemblages.

One faunal zone was recognized in the former and seven zones in the latter. A type section serves as a standard of reference for each biostratigraphic unit. The Castlecliffian stage, and two others (the Nukumaruan and Upper Pliocene Waitotaran), were grouped into a higher category, the Wanganui series.

The biostratigraphic units are regarded also as chronostratigraphic units, as it is assumed (generally validly), that fossils are perfect criteria of passage of geologic time.

Lithostratigraphy

Corresponding approximately with the Castlecliffian stage are three rock-stratigraphic groups, the boundaries of which do not accord with any of the biostratigraphic units. To avoid confusion the groups are not named here. They were each based on general similarity of lithology of the sediments. Within the three groups were some 24 formations, each individually named. The formation is the fundamental unit of sedimentary rock classification, possessing uniform lithology and absence of breaks in deposition. In turn, certain of the formations contain distinctive, minor subunits, members. Rock units are also named and defined on the basis of a type locality.

The rules of nomenclature in stratigraphy are similar to those in biology, but not quite as stringent (see Geological Society of New Zealand 1967, Hedberg 1976). All New Zealand named units are defined and described in a compendium, the local section of the Lexique Stratigraphique International (Fleming 1959) which is updated periodically.

In the main, the names of the rock units differ from those of the biostratigraphic units but if the boundaries of each coincide the same names could be used. Evidence for marine transgression between periods of low sea level, along with incomings of warmth-loving organisms, followed by their disappearance and replacement by cold-loving organisms, led Fleming (1953) (elaborated in his 1975b paper) to postulate alternating series of warm (interglacial) and cold (glacial) events. The sequence of river terraces in the Wanganui district was interpreted as indicating aggradation during glacials and down-cutting during interglacials (although crustal movements complicate the picture).

Fleming (1953) grouped the sediments indicating glacial and interglacial conditions into substages. Subsequently these have been raised to stage status and the names Nukumaruan and Castlecliffian used in a restricted sense (Fleming 1962, 1975a), (Table 3). Fleming's scheme extends into the Upper Pleistocene and correlations are assumed between it and the Westland scheme for the Upper Pleistocene, proposed by Suggate (1965a), which has been the basis for late Quaternary studies in the South Island. However, there is uncertainty about whether there is overlap in time of some of the upper Wanganui sediments and lowermost Hawera sediments, as recognized, respectively, near Wanganui and in Westland (Suggate 1973). Table 3 shows a separation between the two, but this is still tentative.

UPPER PLEISTOCENE

The Upper Pleistocene classification differs from that outlined above because of the differences in the kinds of materials.

Lithostratigraphy

As outlined by Gage and Suggate (1958) and elaborated by Suggate (1961, 1965a) (Table 3), the distinctive sedimentary deposits (mainly glacial till and fluvial gravel units representing cold events and beach deposits representing warm events) are classified, lithologically, as formations, with distinctive names (not listed here, to avoid confusion). In the mapping programme for the New Zealand 1:250 000 geological series, formations are used as the mapping units and, wherever appropriate, grouped into glaciations and interglaciations.

Climatostratigraphy

The cold events are designated as glaciations, the intervening warm events as interglaciations. Suggate (1965b) suggested that a Pleistocene glacial stage should be defined as a period of cooling and subsequent cold and the interglacial stage a period of warming and subsequent warmth, with the start of the former being the first indication of downturn in temperature before its rapid passage to glacial conditions and the start of the latter the first indication of upturn of temperature before interglacial conditions are reached. He suggested that the sole criterion for defining an interglacial should be that temperature rose at least to that of the present, regardless of duration. Other authors (Luttig 1965, West 1968) would not agree on these definitions and place boundaries at about mid-way between the interglacial high and glacial low temperatures. Duration seems to be important, also. As a working basis it may be suggested that, to qualify for glaciation status, a time period must have experienced extensive development of glaciers in temperate latitudes for a long period (say 10 000 yr) and mean temperatures must have been well below those of the present (at least $4^{o}C$ lower) for much of the time. An interglaciation must have been at least as warm as the present and at least 10 000 yr in length. The question of where to position boundaries is difficult to resolve and more discussion is needed before agreement can be reached.

Chronostratigraphy

Chronostratigraphic units corresponding to glacials and interglacials are termed stages, differentiated nomenclaturally by a different ending to their names (see columns 2 and 3 in Table 3). It is implied that the boundaries of the chronostratigraphic units are very similar to those of the lithostratigraphic units.

Because of the fragmentary nature of the evidences and the scarcity of absolute dates there are some very distinct problems of correlation from place to place (even between adjacent valley systems) and there are some uncertainties e.g. about the relationship of the South Island glacial record with the evidences for cold climate in the marine sequences at Wanganui. The framework presented by Suggate (1965a) has been widely used for the South Island glacial sequence and Fleming (1975b) presented a concordance of the South Island and Wanganui information.

Discrepancies (discussed in more detail later) occur when trying to correlate from east to west in the South Island. As noted in Table 3 the records of glacial events from valley to valley differ and considerable critical work is needed before general agreement can be reached. Gage (1977) outlined the problems lucidly and objectively.

One of the most confusing features, for the uninitiated, of nomenclature of Quaternary sequences in New Zealand is the custom of using local names to describe deposits in each major valley system (see Table 3). A framework of generally-agreed stage names and names of glaciations is available on a nation-wide basis as noted above but the uncertainty of correlation has led to the use of the local nomenclature and, as suggested by Gage (1977), it is probably best to retain it until unequivocal correlations are possible.

The last word on the correct position in time of even the larger categories (stages) of the Pleistocene classification is still to be written and some of the correlations shown in Table 3 are merely informed guesses. Changes will almost certainly have to be made on the basis of new evidence. For example the Tui Creek advance included in the Otira Glaciation by Soons (1963) was later found to consist of at least three separate advances, (Soons and Gullentops 1973) and may be a full glaciation. In this case all earlier glaciations in the Rakaia sequence will need to be placed another step back in time. The correct position of some glacial phases in the Mackenzie Basin and further south (Mansergh 1973b, D. Bell pers. comm.) is also uncertain. It is to be hoped that, in time, it will be possible to develop a better-integrated scheme, by drawing on many, diverse sources of information.

SUBDIVISION OF STAGES IN THE UPPER PLEISTOCENE

The field evidence, in the form of morainic landforms and corresponding outwash sheets, shows that, within each Upper Pleistocene glaciation (and most clearly discernible within the last), several phases of glacial activity and inactivity occurred. In North America or Europe each glacial phase would be referred to as a stadial (or stade) with intervening interstadials (interstades) (West 1968, Flint 1971). In New Zealand the cold phases are usually referred to as "advances" (Gage 1958, Suggate 1965b) but there is no general agreement as to what magnitude an event should be before qualifying as an advance. Suggate (1965b) briefly discussed a definition for an interstadial, namely that an interval should receive interstadial status if the temperature did not rise as high as that of the present day. An interstadial is, by a definition used by West (1968), a period of non-glacial activity either too cold or too short to qualify as an interglacial so that development of temperate deciduous forest in North-west Europe could not occur. We cannot be so categorical in New Zealand because there are distinct evidences for occurrences of forest types, generally regarded as indicative of mild, moist climate, during some parts of the Otira Glaciation (e.g. during an early Otiran interstadial *Dacrydium cupressinum* forest was developed near Waikanae (Fleming 1972) and in the middle Otiran *D. cupressinum* forest occurred near Hokitika (Moar and Suggate 1973, McGlone 1973). By the criteria outlined by Suggate (1965b) these intervals might well be given interglacial status.

There are no corresponding terms for brief cool periods within interglacials and in any case there is little information on details of climate variation in interglacials other than the present one.

There are some obvious problems in extending the concepts of glaciation and interglaciation to places nearer the equator than the temperate latitudes where climatic changes were very profound. It is probably best to define the boundaries of glacials and interglacials, on a world-wide basis, in an arbitrary fashion, because there are bound to be time-transgressive boundaries if local criteria only are used for definition. However, the difficulty will be to get international agreement on these matters.

All of the New Zealand land mass must have been influenced in some way by the glacial climates, but yet the warm temperate (in many cases quite cold intolerant) elements of our biota survived. The land was extended considerably by lowered sea levels during the cold periods (at least - 90 m at the maximum of the Otira Glaciation), so that there was some scope for expansion of biota onto the extended strand plains. The northern part of the North Island is the usual area proposed for survival of warm temperate biota (Fleming 1962, Wardle 1963). The evidence is growing, however, that unglaciated, hillier parts of the South Island served as refuges for some forest, which suggests that glacial climate outside the immediately glaciated areas was not as severe as some authors (Willett 1950, Fleming 1962, 1975a) have proposed. Gage (1965) and others have argued for less severe climate, on geological grounds. The same conclusion may be drawn from the occurrence of moa *(Emeus* and *Euryapteryx)* at Oamaru at 32 500 and 20 300 yr B.P., during the Otira Glaciation (D.W. Ives, C.J. Burrows, R. Scarlett, unpublished). However the Otira Glaciation, at least, was a time of very marked oscillations of mean temperature, ranging from at least 6°C below the present to temperatures very near, if not identical with that of the present. There is no reason to expect that earlier glaciations were not similarly complex and that comparable climatic variations occurred during each of the interglacials.

SUBDIVISION OF THE OTIRA GLACIATION

The subdivision of the last (Otira) Glaciation may be cited to exemplify both the complexity of climatic variations in part of the Quaternary and the problems involved in their description, with its resultant nomenclatural complexity.

Evidence in the discussion below is drawn mainly from the zone of intensive glacial activity in the central South Island. Gage (1958), in a study of the record in the Waimakariri basin, was the first to attempt a detailed description of the period, based on glacial geological criteria. This was followed by Soons (1963) on the Rakaia valley sequence and a description of the sequence in Westland by Suggate (1965a). In these studies it was recognized that there had been multiple events in the Otira Glaciation - glacial advances with non-glacial intervals between, representing numerous oscillations of temperature. When the separate classifications were placed side-by-side there were discrepancies, for certain of the main phases of glaciation recognized contained more episodes in one valley than in another.

The first absolute datings, for some of the episodes in the late Otira Glaciation, were published by Suggate (1965a). However, the dates come from places as far apart as the Buller valley, Maruia valley, Waiau valley, Grey valley and Lake Hawea and carefully reasoned inferences, based on geomorphic and weathering criteria, were used in correlating the events from one area to another. The accumulated data were summarized in a general chronology of the late Otira Glaciation (Suggate and Moar 1970). The study of the period has advanced, but there are still few dates, in widely scattered localities, and various problems have emerged. On the basis of glacial geology Gage (1958) could see no grounds for separating the Woodstock advance in the Waimakariri from the rest of the events in the Otira Glaciation. Suggate (1965a), however, proposed that, as the outwash from the correlative of the Woodstock in Westland (the Kumara 1 (K1) advance) was cliffed by the sea, with beach deposits at the base of the cliff indicating interglacial conditions, the K1 should have the status of a full glacial, which he named the Waimea Glaciation. Between this and the Otira Glaciation was an interglacial interval which takes its name, Oturi, from the Wanganui coastal sequence (Fleming 1953). Considerable information is beginning to accumulate about the nature of this interglacial (Grant-Mackie and Scarlett 1973, Mildenhall 1973).

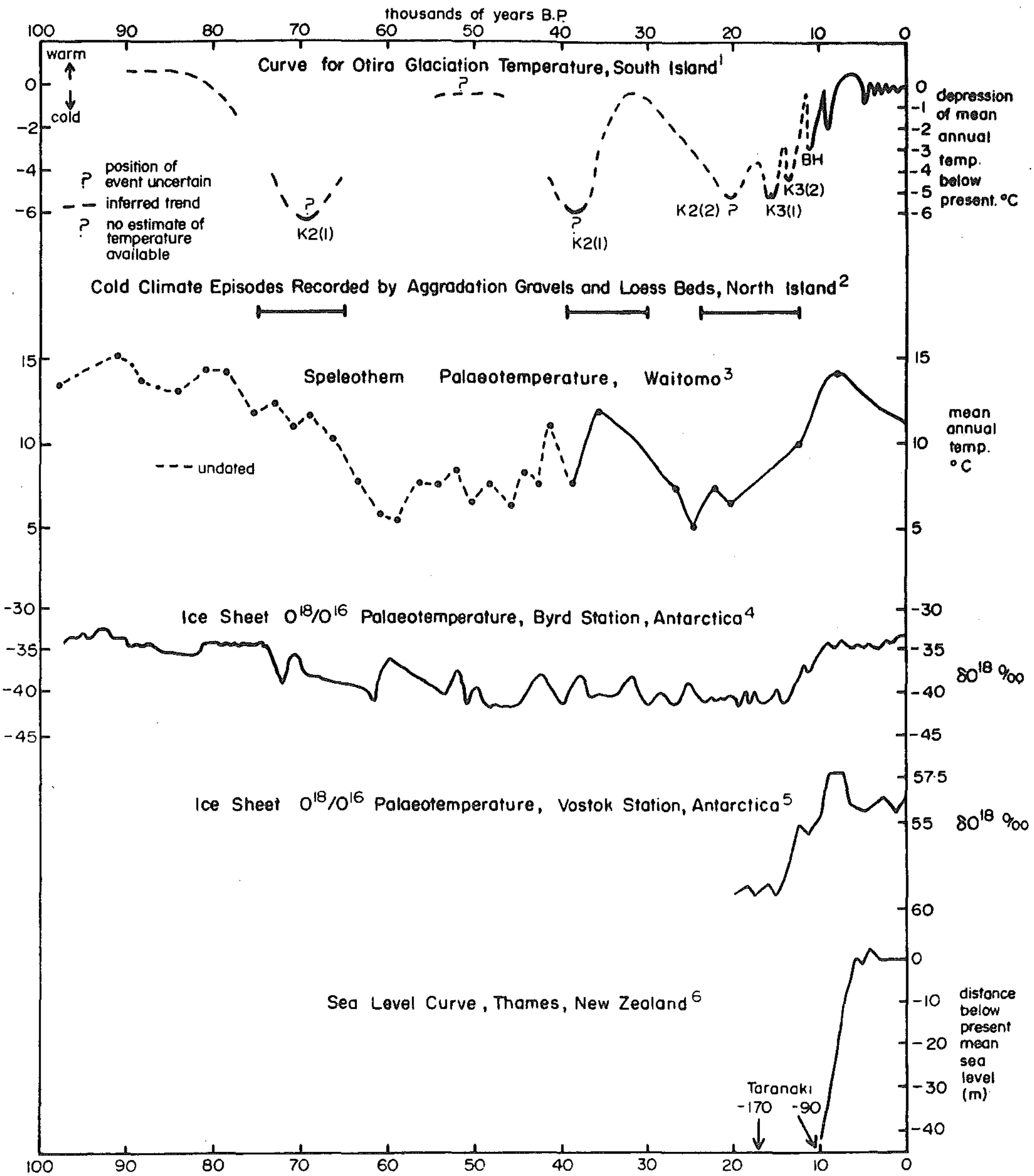
The detail of discrepancies between the number of events in the Westland scheme for the Otira Glaciation and those elsewhere were outlined by Burrows and Mansergh (1973), p. 29. Further problems have emerged, for example evidence from the Rakaia valley for an interstadial beginning earlier than 22 200 yr B.P. and finishing later than 19 200 yr B.P. This conflicts directly with the dates for the Westland Kumara $2_{(2)}$, ($K2_{(2)}$) stadial (Suggate and Moar 1970) of 22 300 - 18 000 yr B.P. and makes concordant correlation difficult. Several alternative explanations for this kind of problem are possible: (1) some of the dates are faulty, (2) the interpretation of either or both of the sequences is faulty for this time, (3) evidence for some events is missing at one or both localities, or (4) events happened at different times on different sides of the Southern Alps and correlation is not possible (which is unlikely).

All this is very confusing and hopefully will be resolved soon, because non-geologists need stable pegs on which to hang their information. Despite, or perhaps because of, the finer resolution with which we can perceive detail in the Otira Glaciation (than in earlier glacials) the story is by no means clear.

Based solely on glacial geological evidence the early part of the Otira Glaciation is not well defined chronologically, nor in terms of climatic conditions. Unfortunately the glaciation began at a time beyond the range of normal radiocarbon dating (though extension to about 70 000 years is possible, using special techniques). Table 7 presents an extended version of the general

TABLE 7. DATES FOR EVENTS DURING THE OTIRA GLACIATION

Stage	Westland Glacial Advances	Waimakariri Glacial Advances	Age (Yr BP)	Estimated Mean Temperature Depression Below Present °C
Aranuian	Aranui Interglacial			
	Waiho	McGraths Ck	c 11 900-10 000	-3.0
		interstadial	c 13 500-11 000	
Otiran	Late Kumara 3 ($K3_{(2)}$)	Late Poulter	c 14 500-13 500	-4.3
		interstadial	c 16 000-14 500	
	Early Kumara 3 ($K3_{(1)}$)	Early Poulter	c 17 000-16 000	-5.2
		interstadial	c 18 500-17 000	
	Late Kumara 2 ($K2_{(2)}$)	Late Blackwater	c 22 300-18 500	?
		interstadial	c 35 000-22 300	
	Early Kumara 2 ($K2_{(1)}$)	Early Blackwater	c 40 000-35 000	?
		interstadial	c?65 000-40 000	
	? part Early Kumara 2 ($K2_{(1)}$)	Otarama	c 73 000-?65 000	-6.3
Oturian	Oturi Interglacial			



1 Suggate (1965), Suggate & Moar (1970), Mansergh (1973b), Moar & Suggate (1973), Fleming (1972), Grant-Taylor (1964), Porter (1975); 2 Milne (1973b); 3 Hendy & Wilson (1968); 4 Johnsen, Dansgaard, Clausen & Langway (1972); 5 Barkov, Godiyenko, Korotkevich & Kotlyakov (1975); 6 Schofield (1963).

Fig. 1. Climatic variation during the Otira Glaciation

chronology of the Otira Glaciation (see Suggate and Moar 1970). It does not take into account the anomalies noted above between Rakaia and Westland sequences. The extension of the chronology to the early Otira Glaciation depends on a few radiocarbon dates near the normal limits of dating and on a chronology of cold-climate weathering and loess accumulation in the lower North Island presented by Milne (1973b) (calibrated with tephra markers and radiometric dating).

Temperature estimates in Table 7 depend on snowline depression information for the Mt Cook area (Porter 1975), but there are some uncertainties about correlations and to which particular phase of the glaciation some of the dates and temperatures should apply.

Fig. 1 is an attempt to summarize some diverse data which show temperature changes in or near the New Zealand area over the last 75 000 yr. Calibration of the South Island temperature curve during the glaciation is as for Table 7. The interstadial temperature conditions are inferred mainly from pollen analyses of deposits associated with the various warming events (see e.g. Fleming 1972, Moar 1973, Moar and Suggate 1973). Work on peat deposits with interbedded tephra layers, for which changes in pollen spectra indicate the colder and warmer phases, is beginning to elucidate the land chronology in the central North Island in considerable detail (M. McGlone pers. comm.). The detail in Fig. 1, with respect to the Kumara advances, is more complex than the scheme presented by Suggate (1965a). It accommodates evidence gathered recently from the Kumara and Rakaia areas (Soons and Burrows 1978, C.J. Burrows unpublished).

THE HOLOCENE PERIOD

The separation of the last piece of the Quaternary (Holocene) from the rest (Pleistocene) is somewhat illogical, on purely geologic or climatic grounds, for it is merely an interglacial phase within the Quaternary. Perhaps the outstanding "geologic" event which marks it as distinct is the vast expansion of man and his impact on natural systems (which includes causing extinction of many taxa). The Holocene is accorded the rank of epoch by some geologists and begins, somewhat arbitrarily, at 10 000 yr B.P. In Europe this is also regarded as the end of the last glaciation. Although several glacial phases, of lesser magnitude than those of the Otira Glaciation, occurred after 14 000 yr B.P., (Burrows, Chinn and Kelly 1976) the latter date is taken as the end of the last glaciation in New Zealand (Suggate 1961, 1965b). The subsequent time constitutes the Aranui stage, during which marine transgression occurred near Christchurch (Suggate 1958). Much detailed information exists about this period but will not be considered here. The essentials of broad climatic changes in the South Island and middle North Island are given by Moar (1971), McGlone and Topping (1973, 1977) (pollen analyses) and Burrows (1977) (minor glacial fluctuations).

POSTSCRIPT

There is no space to give an account of biological changes during the Quaternary. Brief summaries of some of the more important features are given by Fleming (1962, 1975b) and Mildenhall (1973).

GLOSSARY OF TECHNICAL TERMS

adiabatic lapse rate:	the regular decline in temperature with increase in altitude (0.6° C per 100 m).
eustatic:	relating to movements of mean sea level which are purely the result of changes in total water content of the oceans.
facies:	variations in space of fossil assemblages which lived in different habitats at the same time.
fossil:	the remains or form of a plant or animal which has been preserved in sediments.
fluvio-glacial:	phenomena related to streams issuing from glaciers.
glacier equilibrium line:	the position in the upper part of a glacier where there is balance of ablation (melting) and accumulation (representing a mean temperature of 0° C).
lithology:	relating to the kinds of materials of which rocks are composed.
loess:	wind-blown silt deposited in more or less thick sheets during periods of glacial activity.
mire:	a wetland ecosystem, often with peat accumulation.
moraine:	a landform in the form of a ridge deposited at the margin of a glacier.
orogeny:	a distinct period of uplift of land and mountain-building.

outwash:	gravels deposited by streams issuing from glaciers.
palaeosol:	ancient soil, preserved in some way (often buried by sediments such as tephra, loess, alluvium).
palynology:	the science of study of pollen and spores.
pro-glacial (lake):	a lake beside a glacier.
rock:	any material, consolidated or unconsolidated, of which the earth's crust is composed.
section:	A series of strata (usually exposed in a bank or cliff or borehole).
speleothem:	landforms (stalactites, stalagmites) formed in caves by accumulation of calcite from solution.
tectonic:	relating to forces which bend, warp or break the earth's crust, causing relative uplift and depression of adjoining portions.
till:	a distinctive sediment deposited by glaciers.
transgression:	flooding of land caused by rising sea-level.

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