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REGIONAL APPRAISAL OF THE POTENTIAL FOR STRATABOUND BASE-METAL MINERALISATION IN THE SOLWAY BASIN

This data package relates to work carried out by the British Geological Survey on behalf of the Department of Trade and Industry

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Regional appraisal of potential for stratabound base-metal mineralisation in the Solway Basin

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Summary

The Carboniferous Solway-Northumberland extensional basin covers an area of 6500 km^2 in northern England and southern Scotland (Figure 1.1). The basin, which is up to 7 km thick, developed due to N-S extension with major fault-controlled subsidence during the Courceyan-Holkerian (syn-extension phase), followed by more gradual post-extension regional subsidence during the later Carboniferous. It straddles the trace of the Iapetus Suture which marks the collision zone of the palaeo-North American and palaeo-European continents during Caledonian times. The major Irish lead-zinc deposits, including the world-class Navan deposit lie along the western extension of the Iapetus Suture. The basin is poorly exposed away from the margins and is covered by later Permo-Trias sediments. Much of the basin is also mantled with extensive drift deposits. Minor lead-zinc vein and replacement mineralisation occurs along the northern boundary of the basin, close to the contact with the underlying Lower Palaeozoic rocks of the Southern Uplands and vein style mineralisation carrying barite and minor base metals occurs along the southern margin at the contact with the Lower Palaeozoic rocks of the Lake District. More extensive syn-diagenetic mineralisation of Sedex style found in Ireland may occur adjacent to the major basin-controlling faults. Investigations of the regional geochemistry, geophysics and deep geology, together with Landsat imagery, show that the basin could be prospective for this style of mineralisation, but that the most likely rocks, in terms of chronostratigraphy, are likely to be at considerable depth on the southern margin. However, suitable conditions for the emplacement of this mineralisation may be found in several areas close to the northern margin and in the Bewcastle Anticline.

1. OVERVIEW

T. Colman

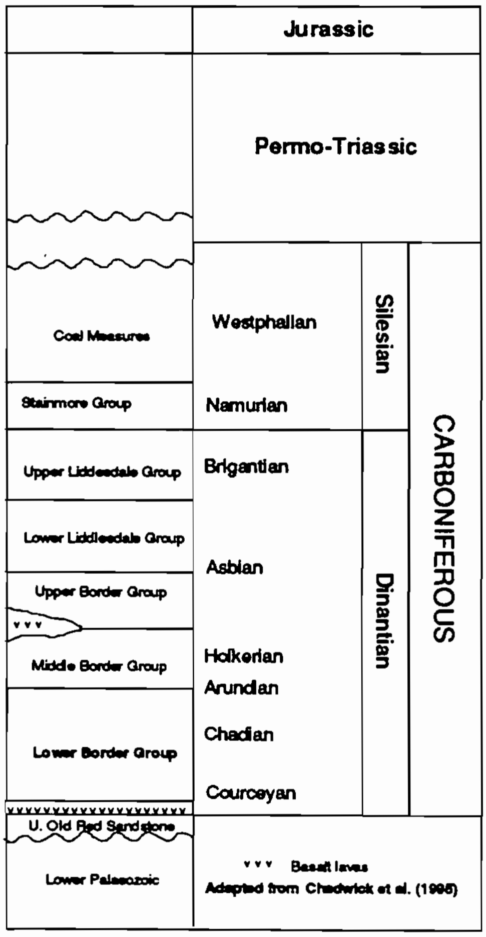
Introduction

This overview is intended to provide a summary of existing information and an appraisal of the most effective ways of continuing exploration of the Solway basin for stratabound base metal mineralisation. The Solway Basin is a loosely defined area trending ENE-WSW lying between Bewcastle in the east, where it continues as the Northumberland Basin, and the Solway Firth to the west where it continues as far as Abbey Head, south of Kirkcudbright. It is bordered by the Southern Uplands to the north and by the Lake District massif to the south (Figure 1.1). The basin also covers the trace of the 'Iapetus Convergence Zone' which developed in late Lower Palaeozoic times along the closure of the Iapetus ocean between the Laurentian and Avalonian continents. It was a major area of sedimentation during Carboniferous times, especially during the Lower Carboniferous (Dinantian). Part of the area is also covered by later Triassic sediments and a small outlier of Jurassic (Lias) clays around Carlisle. The geological succession consists of a basement of Lower Palaeozoic slates and greywackes with extensive granite intrusions. The rift-basin formation, accompanied by alkali-basalt extrusion, began in late Devonian - early Carboniferous (Courceyan) times with deltaic and coastal plain deposits covering a Devonian peneplain. The basin developed by N-S extension aided by E-ENE trending normal faults, probably accompanied at times by episodes of dextral transtension, locally interrupted by transpression (Plant et al, 1991). Interest in mineral exploration within the basin has developed since the discovery of the giant Navan Zn-Pb deposit in Ireland, close to the trace of the presumed extension along the Iapetus zone - the Navan - Silvermines lineament (Jones et al., 1994). This deposit, and others in Ireland, formed in early Carboniferous (Courceyan - Chadian) times by syn- or diagenetic deposition of mineralisation during fluid expulsion controlled by major faults (Andrew et al., 1986). The Solway Basin also has potential for hydrocarbon and coal exploration (Chadwick et al., 1995).

Geology

The Solway Basin developed on a folded and weakly metamorphosed basement of Lower Palaeozoic and early Devonian sediments by north-south extensional movement along ENE-trending basin margin faults during the early Dinantian. The main period of growth was during the deposition of the Lower Border Group in Courceyan to Chadian times (Table 1). Higher Dinantian, Namurian and Westphalian strata show progressively less evidence of growth faulting and an increasing tendency to onlap the basin margins, indicating the increasing importance of non-extensional thermal subsidence during later Carboniferous times (Chadwick et al., 1995). The major basin controlling faults are the en-echelon North Solway and Gilknockie Faults on the north side and the Maryport and Stublick Faults on the southern margin which have a maximum throw of between 4 and 5 km at the top of the basement (Figure 1.1). The syn-extension rocks are largely fault-bounded, confined to the basinal areas and are thickest close to the major basin-bounding faults (Chadwick et al., 1995). The unit of major interest from the point of view of early extensional mineralisation is the Lower Border Group which is up to 4 km thick adjacent to the major boundary faults such as the Maryport Fault. This consists of alternations of limestones, sandstones and shales reflecting repeated deposition of deltaic, lacustrine and shallow marine sediments at, or close to sea level. Beds are generally thin, now exceeding 10 m in any one unit, although one deltaic sandstone unit, the Whita Sandstone, is locally up to 600 m thick (Leeder 1974). The exact position of units within the Lower Border Group is often difficult prove due to the scarcity of outcrop and fossil evidence. Local syn-sedimentary soft sediment deformation has been recorded in the hanging wall sediments of the North Solway Fault in the Kirkbean area (Ord et al., 1988) which reflects contemporary dewatering of the sediments along the fault. N-S and NW-SE faults in the area are thought to be of Mesozoic age. There are only three deep boreholes in the area which penetrate the lower Carboniferous and seismic coverage is poor towards the west of the basin, especially at the margins. West Newton 1 is on the south side and Easton 1 and Archerbeck are on the north side of the basin (Figure 1.1). West Newton 1 25 km WSW of Carlisle ended in the Upper Border Group at 1400 m depth. Archerbeck BGS stratigraphic borehole 7 km south-east of Langholm ended in the Upper Border Group at 1400 m depth and Easton 1 10 km west of Bewcastle penetrated around 1500 m of the Lower Border Group (Courceyan) before ending at 2200 m total depth without reaching the base of the Lower Border Group. The Easton borehole revealed beds of massive anhydrite in the lower sections of the Lower Border Group below about 1200 m which may be the undissolved equivalents of the dissolution breccias mentioned below (Chadwick et al., 1995). The anhydrite is of probable sabkha origin and does not outcrop anywhere in the basin. The total thickness of anhydrite is over 150 m and is inferred to extend south-westwards to underlie the main Solway and Irish Sea Basins (Ward, 1995). A number of 'desiccation breccias' reported from the Lower Lynebank Beds of the Lower Border Group in the Bewcastle anticline (Day, 1970) may be dissolution breccias from anhydrite and gypsum solution. Their presence would not be unusual in this type of environment as the early sediments in the Lower Carboniferous Widmerpool Gulf in eastern England include the thick Hathern Anhydrite (Llewellyn and Stabbins, 1970).

Table 1. Summary of stratigraphy in the Solway Basin



Variscan deformation between Westphalian and Permian times has caused extensive inversion and folding of the Solway Basin into the major NNE-trending Solway syncline and complimentary anticline with regional upwarp and erosion leading to angular unconformity at the base of the Permo-Triassic. In the north-eastern part of the basin the asymmetrical Bewcastle anticline brings Lower Border Group rocks to the surface. The basin-margin faults show evidence of Variscan reversal which may, in places, have brought more prospective rocks close to the surface. The Variscan movements may have disrupted hydrocarbon-bearing structures, but would not have affected mineralisation.

Known mineralisation and previous exploration.

There are a number of minor mineral deposits in the area (Figure 1.2). The largest are numerous barite veins on the northern fringes of the Lake District which have been worked at several localities including the Cockermouth and Ruthwaite areas (Cooper et al., 1991). They commonly occupy faults normal to the basin margins. Lead-zinc and barite veins also occur along the northern margin of the basin, especially in the Langholm area, usually occupying N-S faults. A complex copper-lead-barite vein occurs at Threapland (NGR 3162 5394). Uranium mineralisation occurs in a small vein occupying a branch of the main North Solway Fault at Needle's Eye (NGR 2913 5561), on the southern margin of the Criffel Granite (Miller and Taylor, 1956). Parnell (1995) considers that the hydrocarbons associated with the uranium mineralisation formed during early Jurassic migration of hydrocarbons through the North Solway Fault system. A north-south striking massive barite vein north of Kirkbean at NGR 2973 5619 on the eastern margin of the Criffel Granite was briefly investigated during the current project. Initially recorded by Leeder (1970) it is only exposed in a stream section but can be traced as surface and wall float over a distance of at least 1.5 km.

Apart from searches for iron ore and coal along the north crop of the Cumberland coalfield in the Workington and Maryport areas the first modern search for base metal mineralisation in the Solway area was carried out by Consolidated Gold Fields Ltd in the early 1970s. They conducted a soil geochemical survey of the Carboniferous Limestone and underlying Cockermouth lavas around the northern margin of the Lake District. A number of mainly copper anomalies were found, the most interesting being in the Bothel area. This was investigated more intensively as the Torpenhow project at (NGR 3205 5378) with further soil and overburden sampling and IP geophysics. Five inclined holes were then drilled to investigate the Carboniferous / Lower Palaeozoic contact using a model of fault - controlled exhalative mineralisation similar to that recently (at the time) found in Ireland (Anon. 1973). No sulphides, apart from minor pyrite were found. The same area was later investigated by BP Minerals International Ltd. as the Bothel project in 1982 looking for a similar target. A small gravity anomaly, thought to be caused by sulphides at depth, coupled with soil geochemistry, was used to target a small drilling programme (Anon. 1983). Two vertical holes were drilled to 250 and 300 m respectively without success. The boreholes both failed to reach the Lower Palaeozoic and showed the rapid increase in thickness of the Dinantian sediments to the north of the Lower Palaeozoic contact due to the effect of the basin controlling faults.

The MRP carried out exploration over a 20 km strike length of the basal Carboniferous / Lower Palaeozoic contact in the Langholm area in the mid 1970s to investigate minor occurrences of base metal mineralisation around the contact of the basal Carboniferous Birrenswark lavas and the overlying 'cementstone' facies of the Lower Border Group. These occur within the Courceyan stage of the Dinantian. Regional stream sediment geochemistry over 200 km^2 and more detailed geochemical and geophysical investigations including deep overburden sampling together with magnetic and IP surveys over a 20 km^2 area were followed by the drilling of 13 cored boreholes from 20 to 60m depth in the Westwater area. Minor vein and disseminated stratabound galena and sphalerite mineralisation occurs sporadically within and above the basal Carboniferous lavas (Gallagher et al., 1977) over a 4 km strike length in the Westwater area. There are also a few small veins with a higher metal content. The mineralisation is thought to be partly syn-diagenetic although the fault-controlled vein mineralisation is probably Permian. The southern margin of the basin was examined in the Woodhall and Longlands areas near Caldbeck looking for 'Irish-style' mineralisation where the northwards extension of barite and copper veins in Lower Palaeozoic volcanic rocks intersected Carboniferous limestones (Wadge et al., 1977). Only weak geophysical anomalies were found; strong geochemical anomalies were attributed to contamination from the old workings. Reconnaissance stream sediment sampling was carried out in the Criffel area at the same time (Leake et al., 1978) and found barium and base metal anomalies over Lower Carboniferous rocks in the Langholm area caused by vein mineralisation. Similar sampling was completed over most of the Northumberland Basin in the late 1970s by the MRP but no substantial anomalies were found due to the thick glacial drift (Bateson et al., 1985). The MRP also carried out surface exploration along the southern margin in the late 1980s with a view to providing comprehensive information for a variety of exploration targets, including stratabound base metals and gold mineralisation associated with the Lower Palaeozoic volcanics at the northern edge of the Lake District (Cooper et al., 1991 & 1992).

Current work

A number of different data sets have been examined seeking information of relevance to the project. The main sources are the unpublished report (Plant and Jones, 1991) on exploration criteria for northern England generally, including the Craven, Stainmore and Solway-Northumberland Basins and the recently published report on the Solway-Northumberland Basin by Chadwick et al. (1995). Plant and Jones describe a number of major early Carboniferous planar faults which strongly influenced the development of the Solway Basin and hence its inferred syn-depositional mineralisation. Several of these may be prospective for Sedex-style base metal mineralisation though the basal Carboniferous target horizon may be at too great a depth for realistic exploration. The North Solway Fault cuts Courceyan rocks at depths of less than 500 m in the Kirkbean area. Mineralisation also occurs along the trace of the fault as uranium (with hydrocarbon, copper and bismuth) veins at Needle's Eye (Miller and Taylor, 1956) and barite and copper workings to the WSW. Variscan inversion along the Back Burn Fault has exposed upper Lower Border Group beds in the Bewcastle Anticline. The Maryport Fault and its extension into the Northumberland Basin (Stublick Fault) are not considered to be as attractive for mineralisation as the potential host rocks of the Lower Border Group occur at depths exceeding 2 km and are thus not a practical target for exploration.

The results of a regional investigation of the hydrocarbon potential of the Northumberland-Solway Basin (Chadwick et al., 1995) have been synthesised and these are presented in Section 2. Data from the Geochemical Survey Programme (GSP) for the northern margin of the Solway Basin has been acquired and is being used, together with MRP data, to investigate geochemical anomalies on the margin of the basin and along planar faults extending through the basin as defined in Plant and Jones (1991). This data is shown in Section 3. Regional geophysical data for the area has also been examined to indicate some of the main structural features of the area and in particular sites of intersection of major features which may be of importance in the location of mineralisation. This is shown in Section 4. Landsat imagery of the Solway area has also been acquired and interpreted for similar purposes. This is described in Tragheim (1994) which is included in this report as Section 5.

Potential sites for mineralisation.

1. Massive exhalative - Envisaged as similar to the Silvermines mineralisation in Ireland which were generated in part by mineralising fluids being expelled onto the seafloor (Andrew, 1986). The active tectonism in the Solway area would permit the transfer of fluids from depth up faults towards the surface. However, sediments in the Solway area have been laid down in conditions that may be too shallow, oxidising and with a high energy environment such that the preservation of this type of deposit, even if it formed, is unlikely..

2. Replacement. Formed where large volumes of rock are replaced and mineralised. They tend to form in reactive rocks, such as pure limestones. Some of the Irish deposits, such as Lisheen, are thought to have formed up to 5 Ma after the deposition of the Courceyan host rock during Chadian-Arundian times (Hitzman et al., 1992). The model used for locating this deposit was one where mineralisation formed at the base of the Waulsortian reef adjacent to feeder faults and close to a regional 'dolomitic front' which may have been a precursor of the metal-bearing fluids. Thus lithified sediments can be mineralised by this process. In the Solway area the sedimentary sequence is more argillaceous and thinner bedded than in Ireland as it is generally formed of a succession of thin beds of muddy limestone or sandstone separated by unreactive shales and mudstones. However, some of the sandstones such as the Whita sandstone are thicker and could be mineralised if they contained sufficient pore space or calcite/dolomite cements which could be dissolved by acidic mineralising fluids.. The cementstones in the Langholm area are dolomitised by syn- or diagenetic processes (Gallagher et al., 1977). Leeder (1975) records that the dolomite content of the Lower Border Group cementstones is no greater than 15%.

3. Breccia infill. The Harberton Bridge breccia deposit in Ireland extends through a 500 m vertical section of Dinantian limestone from the Waulsortian mudbank facies to the overlying Arundian limestone (Emo, 1986). Faults can cause porous breccias which may be infilled with mineralisation. Breccias can also be caused by the dissolution of gypsum and anhydrite. The Solway area does not have thick carbonate successions but does contain anhydrite at depth and probable dissolution breccias at surface in the Bewcastle anticline. Some dissolution breccias may be sufficiently porous to contain substantial amounts of mineralisation. The Gays River Pb/Zn deposit in Nova Scotia, Canada occurs on the margin of the Magdalen Carboniferous Basin (Ravenhurst et al., 1989). This basin is both larger (250 000 km^2) by two orders of magnitude and deeper (10 km) than the Solway Basin, and contains substantial thicknesses of evaporites, including anhydrite and halite. Mineralisation at Gays River, and other smaller Pb/Zn and barite replacement deposits, is thought to be caused by compaction-driven fluid expulsion from the basin to the margins under a seal of evaporites (Ravenhurst et al., 1989). The fluid movement may have caused dissolution and brecciation at the base of the evaporites, now seen as the Pembroke breccia. This may have parallels in the Solway area where evaporites are now known to be present, though the full thickness and extent has not been proved.

4. Veins. The typical Pennine veins form along semi-vertical fractures ranging from joints to faults with throws of tens of metres in strata of later Dinantian age (Asbian - Brigantian). Mineralisation tends to be concentrated in the more competent units such as sandstones and limestones and in fault breccias. Recent discoveries of fluorite mineralisation in the South Pennine Orefield have been made in replacement bodies in limestones adjacent to major veins (Butcher and Hedges, 1987). Numerous barite veins up to 4 m wide occur along the southern margin of the basin in the outcropping upper Dinantian (Holkerian - Brigantian) horizons which are thicker than their counterparts in the north of the basin and barite was produced from Ruthwaite, Woodhall and Longlands mines. Baryte veins also

occur along the northern margin of the basin eg. the n-S vein north of Kirkbean referred to earlier and numerous thinner veins in the Langholm area (Gallagher et al., 1975). None of these mines was large and the prospects for a major barite vein or series of veins appears to be low, although the outcropping, thicker limestones and sandstones on the south side of the basin would be the most prospective area.

Conclusions

1. The Solway Basin is prospective for stratabound base-metal mineralisation during early diagnesis because of the presence of major basin-controlling faults combined with active rapid sedimentation and dewatering during this stage. Traces of this style of mineralisation have been located in the Langholm area.

2. The areas most prospective for further exploration for exhalative mineralisation are those where Lower Border Group rocks are on or near surface and are close to major basin-controlling faults. These include the Kirkbean, Langholm, Newcastleton and Bewcastle areas. These areas are shown generally in Figure 1.2. Areas of suitable rocks on the southern side of the basin are at too great depths for practical exploration. as shown by the BP Minerals boreholes at Bothel (Anon., 1983) and the West Newton oil borehole.

3. Replacement mineralisation should also be sought adjacent to the basin margin faults, though the age range of potentially mineralised strata is likely to extend through the Chadian to Asbian stages when major extension and subsidence ceased.

4. Breccia-hosted mineralisation may occur in former evaporite horizons where anhydrite has been dissolved. Dissolution breccias can be found in the Bewcastle anticline and may occur elsewhere.

5. Vein mineralisation is more likely to be found in the massive limestones and sandstones along the southern margins of the basin, extending east towards the Alston Block.

6. Further exploration should include detailed overburden geochemistry, IP and VLF-EM geophysics to detect sulphide mineralisation and faults followed by drilling. Airborne geophysics (magnetic and EM) would be useful in locating the extent of the Birrenswark lavas and cross-cutting structures but may not be cost effective. Landsat imagery delineated the major NNE-SSW basin-controlling faults in the Criffel area but is not helpful in the drift covered lowland areas.

2. DEEP GEOLOGY OF THE SOLWAY BASIN

S.Holloway

Introduction

Together, the Solway Basin and Northumberland Trough form a Carboniferous sedimentary basin some 30 km wide and 140 km in length. A full account of the structure and evolution of the Northumberland/Solway Basin may be found in Chadwick et al. (1991). The term Solway Basin is generally used to refer to the western end of the basin, but, because it is essentially continuous with the Northumberland Trough, the eastern margin of the Solway Basin is not clearly defined. The area discussed here extends from a few kilometres east of the Bewcastle Anticline to the Solway Firth on the UK west coast (Figure 2.1). The Carboniferous succession is thought to be around 6-7 km thick in the centre of the Solway Basin. The Basin is bounded to the north and south by Dinantian growth faults.

Most of the Carboniferous rocks in the Solway Basin are concealed by Permo-Triassic strata. The strata which subcrop the Permo-Triassic rocks are shown in Figure 2.2. The contour overlay to Figure 2.2 shows the interpreted depth (below O.D.) to the top of the concealed Carboniferous rocks. The main features of the subcrop are:

1. Its strong NE trend.

2. The subcrop of Coal Measures in the middle of the Solway Basin. This is called the Solway Syncline (see also seismic line 1).

3. The subcrop of increasingly old Dinantian strata towards the crest of the Carlisle Anticline, which is immediately east of, and complementary to, the Solway Syncline.

4. The Brackenhill Thrust (see also seismic lines 2 and 3). This occurs at the base of the eastern limb of the Carlisle Anticline.

Sources and Limitations of Data

This compilation is based on an interpretation of a network of seismic profiles acquired by the oil industry for exploration of the Solway Basin and Northumberland Trough. The location of these profiles is proprietary unless specifically released by the oil companies.

The quality of seismic data is crucial to the quality of interpretation. Seismic data are very poor on the northern basin margin, the western margin of the Solway Syncline and on the southern basin margin between the Bank End Fault and the Stublick Fault (poor data areas are shaded grey on Figure 2.3). The reliability of the seismic interpretation is low in these areas. Control on the seismic interpretation is provided by the outcropping strata and by two deep oil exploration wells in the Solway Basin; West Newton (NGR 312300 543550) and Easton (NGR 344124 571694). Thus the level of control beneath the Permo-Triassic strata of the Solway Basin is very low.

Structural development

The Solway Basin initially developed by extensional movement on the ENE and NE trending basin margin faults and a set of NE trending intra-basin faults. These faults are identified on Figure 2.3.

Note that this figure shows their interpreted location at Base Carboniferous level, not where they subcrop or outcrop at the surface. All the growth faults imaged by seismic data show that the main period of growth was during deposition of the Lower Border Group. There is indirect outcrop evidence of later periods of less pronounced growth during the Dinantian (Ord et al., 1988), but lack of borehole or outcrop control makes these difficult to identify with certainty on seismic data shot over the concealed Carboniferous.

In broad terms, higher Dinantian, Namurian and Westphalian strata show progressively less evidence of growth faulting and an increasing tendency to onlap the basin margins, indicating the progressively increasing importance of non-extensional thermal subsidence during later Carboniferous times.

From Namurian times onwards, there is evidence of the beginning of compressional folding within the basin. The Solway Syncline (Seismic line 1) had certainly started to develop in Namurian times. On seismic there is clear evidence of Namurian and Westphalian strata thickening into its centre. There was also corresponding uplift on the Carlisle Anticline (Seismic line 1) at this time. Namurian and Westphalian strata thin over its crest. There is a possible unconformity within the Westphalian succession on its crest. These structures may be evidence of the earliest phases of the Variscan orogeny, which eventually ended the development of the Solway Basin. The main phase of the Variscan Orogeny occurred at end Carboniferous times and resulted in the folding and uplift of the basin and the subsequent peneplanation of the Carboniferous strata during earliest Permian times. These main Variscan movements undoubtedly increased the amplitude of the Solway Syncline and Carlisle Anticline and resulted in the development of many other folds and faults.

The Brackenhill Thrust (Seismic lines 2 & 3) is a complex structure which trends NNE across the Solway Basin. It is poorly resolved at depth, but at shallower levels it appears to be principally a Variscan structure related to the development of the Carlisle Anticline. In the centre of the Carlisle Anticline, immediately west of the Brackenhill Thrust, Lower Border Group strata are interpreted to subcrop beneath the Permo-Triassic. There is a very strong suggestion of strike slip movement along the line of the Brackenhill Thrust, though this is difficult to demonstrate directly. To judge from the NE trend of the subcrops and indications of strike slip motion on the Brackenhill Thrust, the main Variscan Orogeny resulted in the dextral transpression of the Solway Basin.

Permo-Triassic and Lower Jurassic strata unconformably overlie the Carboniferous succession. These are affected by normal faulting, inferred from regional evidence to be of Lower Cretaceous age. During deposition of the Penrith Sandstone there may have been a small syndepositional movement on two faults in the Silloth area. There are some indications that there may have been minor post-Triassic (?Alpine) compressive or transpressive movements on the Brackenhill Thrust.

Dinantian synsedimentary faulting in the Solway Basin

As indicated above, seismic interpretation and outcrop studies indicate that there were two major sets of Dinantian growth faults controlling basin development in Courceyan-Chadian times (Figure 2.3 - for surface locations see Figure 2.4):

1. An ENE and NE-trending set, forming the basin margins.

a. Southern Basin Margin Faults

These comprise the Maryport Fault, Bank End Fault and Stublick Fault, and probably the Gilcrux Fault. Locally, the Maryport Fault, Bank End Fault (Seismic line 4) and Stublick Fault are well imaged on seismic profiles.

The Maryport Fault is best imaged offshore, where it has a complex history (Chadwick et al., 1993). The age of Dinantian growth is not clearly resolved by the seismic data, due to lack of well control. Onshore there is a Variscan inversion anticline, the Crosby Anticline (Figure 2.4), in its hanging wall. This may represent a tightening of a pre-existing Carboniferous rollover anticline formed during Dinantian extension.

The Bank End Fault can be seen on seismic immediately south of the West Newton borehole (Seismic line 4). West Newton was drilled on a (Variscan) inversion anticline in its hanging wall. This tight anticline is unconformably overlain by gently northwards dipping Permo-Triassic strata, exactly as the Crosby Anticline is. The base of the Carboniferous is not imaged in its hanging wall and the age of any Dinantian growth cannot be demonstrated directly.

There is an area of very poor data between the Bank End Fault and the Stublick Fault, but it is clear that the southern margin of the basin is offset progressively to the southeast by a series of down to the northeast faults, seen on the northern margin of the Cumberland Coalfield (the Crummock, Baggrow, Allhallows Pit, Waverbank and Waver-Warnall Fell Faults).

The westward continuation of the Stublick Fault can be mapped on seismic for a few kilometres west of the Pennine Fault (Figure 2.3). Here it has been inverted (presumably during the Variscan orogeny) such that it throws down to the south at shallow subsurface levels (Figure 2.4). The main period of growth can be convincingly demonstrated to have been during deposition of the Lower Border Group. Maximum throw on this fault is about 3500 metres down to the north.

b. Northern Basin Margin Faults

On the northern side, in the extreme west of the area, the basin margin is formed by the North Solway Fault. It probably continues to the east along the NE trending Waterbeck Fault, a feature mapped by Nairn (1956), then transfers to the Gilnockie Fault. The Gilnockie Fault itself is poorly imaged on seismic profiles, though it is described in detail by Lumsden et al. (1967) where it forms the northern margin of the Canonbie Coalfield. Field mapping indicates that to the northwest of the Canonbie Coalfield the Gilnockie fault splits into the Kershope Fault to the south and the Kirk Hill Fault to the north. The Kirk Hill Fault eventually joins the Arnton Fault on the north side of Arnton Fell.

2. A northeast trending set of faults, mainly in the middle of the basin.

These include the Goat Island - Lyne Thrust and the Back Burn Fault (Figure 2.5). Seismic data convincingly demonstrates Dinantian growth across both these faults. There is also a major thrust fault parallel to these two faults concealed beneath the Permo-Triassic strata, here called the Brackenhill Thrust, because it appears to be the subsurface continuation of the Brackenhill Fault. Seismic data does not prove growth across this thrust. The Waterbeck Fault on the northern margin of the basin is subparallel to this set of faults and, as mentioned above, is a candidate for down to the southeast Dinantian growth.

a. Back Burn Fault

This fault shows convincing down to the southeast growth during deposition of the Lower Border Group (good borehole control is available from the Easton and Archer Beck wells). It was strongly inverted during the Variscan orogeny and now is represented by the monocline which forms the eastern margin of the Canonbie Coalfield (Figure 2.5).

b. Goat Island - Lyne Thrust

This fault forms the northwestern margin of the Bewcastle Anticline. It shows convincing down to the southeast growth during deposition of the Lower Border Group. It was strongly inverted during the Variscan orogeny to produce the Bewcastle Anticline. Breccias occur in the Lower Border Group in the Bewcastle Anticline. These can be seen in the stream sections, and also in Banks Quarry ((5558 7490) near Bewcastle. Extrapolating from the Easton borehole, these breccias are thought to be after anhydrite and thus indicate post-depositional fluid flow in the Lower Border Group (J. Ward, pers. comm.). Evaporitic brines provide a powerful mechanism for the dissolution and transport of metals such as Pb, Zn and Cu.

Prospectivity

During the early stages of the development of an extensional basin, the rate of subsidence is commonly high. This was certainly true of the Northumberland Trough, where vast thicknesses of Lower Border Group strata were laid down close to sea level. As these strata compact, fluid is expelled from them, and active extensional intra-basinal faults may well act as fluid conduits. So, intuitively, and by analogy with Irish-style mineralisation, it appears possible that the most likely sites for fluid exhalation or concentration during Courceyan - Chadian times might be the faults which were active in an extensional sense. That is, the North Solway Fault, possibly the Waterbeck Fault and the Gilnockie Fault and its continuations to the northeast on the northern basin margin, the Back Burn Fault and Goat Island-Lyne Faults in the basin centre and the Maryport, Bank End and Stublick Faults on the southern Basin margin. The best prospects are likely to be on the hanging wall side of these faults as the footwall would be too deep for exploration although this is where exhalative mineralisation is likely to located by analogy with Irish-style mineralisation.

However, it is worth bearing in mind that the basin was strongly deformed in the Variscan Orogeny, which culminated in latest Carboniferous times. The major compressive or transpressive folding and associated faulting which occurred at this time is bound to have altered dramatically the patterns of fluid flow within the basin.

Southern basin margin faults

The West Newton borehole (TD 2044.3 metres in Middle Border Group) would give a direct indication of any mineralisation occurring down to the Middle Border Group on the downthrown side of the Bank End Fault. Very deep drilling would be required to reach the Lower Border Group thereabouts.

The concealed Dinantian succession just north of the Stublick Fault, where it intersects with the Pennine Fault, is about 4600 metres thick. Base Dinantian hereabouts is estimated to be at about 4800 metres. This is the major fault intersection in the area studied.

Northern basin margin faults

The Lower Border Group is exposed in places (e.g. Kirkbean) along the hanging wall side of the North Solway Fault. However, there could well be a thick concealed Lower Border Group succession beneath the lowest exposed beds. There are no seismic data to confirm this possibility.

The outcrop around the Waterbeck Fault is heavily drift covered and the geology is poorly known, but see Nairn (1956) for possible outcrops of Lower Border Group. BGS is currently mapping this area.

As mentioned above, the Gilnockie Fault continues to the northeast as the Kirk Hill Fault and eventually joins the Arnton Fault on the northern side of the Arnton Fell Silurian inlier. If this fault system forms the northern margin of the basin, it seems possible, if highly speculative, that the Arnton Fault could be a reverse fault, which has had the Carboniferous succession stripped off its hanging wall side. Mineralisation is known on the southeast side of Arnton Fell.

Intra-basin Dinantian growth faults

The upper and middle parts of the Lower Border Group are well exposed in stream sections in the Bewcastle Anticline and should give a direct indication of the prospects associated with the hanging wall of the growth fault underlying the Goat Island - Lyne Thrust.

The upper part of the Upper Border Group is present (largely beneath drift) on the hanging wall (eastern) side of the Back Burn Fault. The concealed Dinantian succession is estimated to be around 3000 metres thick hereabouts. Depth to top Lower Border Group on the eastern side of the fault is approximately 750 m where the fault intersects the seismic profile shown in figure 2.5.

Sources of additional prospectivity data

The cuttings from the Lower Border Group in the Easton borehole (TD 2260 metres in Lower Border Group, NGR 344124 571694) might repay examination. This is located on the northern end of the Carlisle Anticline. It was drilled through a thick succession (>1500 metres) of Lower Border Group strata consisting mainly of interbedded anhydrites, limestones, shales and sandstones.

3. GEOCHEMISTRY

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Introduction

The regional geochemical stream sediment data described below is based on a subset of samples collected as part of the Geochemical Survey Programme coverage of Southern Scotland (British Geological Survey, 1993a) and the Lake District (British Geological Survey, 1993b). This information is supplemented by panned concentrate data collected during MRP reconnaissance surveys of the Criffel-Dalbeattie complex (Leake et al., 1978), the Ecclefechan-Langholm-Bonchester Bridge area, (described in part by Gallagher et al., 1977), and the Haltwhistle-Brampton area (Bateson et al., 1983). The panned concentrate samples do not provide complete coverage, but they include much of the area underlain by the Lower and Middle Border Groups of the Carboniferous along the northern margin of the basin, and a large part of the Bewcastle anticline.

Digital data for Ba, Cu, Zn, Pb, and Ni in a total of 3152 stream sediments and 2320 panned concentrates was retrieved from the Geochemistry Database together with locational information. In order to examine and evaluate geochemical changes across the Lower-Upper Palaeozoic boundary, the area selected for data retrieval includes the southern part of the Silurian greywacke belt (Hawick and Riccarton groups). Table 2 shows the summary statistics of this dataset.

Table 2. Summary statistics of the stream sediment $_c$ and panned concentrate $_p$ data.

	Ba_p	Ba_c	Cu_p	Cu_c	Zn_p	Zn_c	Pb_p	Pb_c	Ni_p	Ni_c
Minimum	10	172	0	0	0	0	0	9	0	0
Maximum	365394	12532	937	354	9680	3543	3061	822	186	262
Mean	2816.12	607.17	23.36	22.44	202.97	224.99	42.97	50.89	27.85	64.85
Median	355.5	554	9	21	83	178	18	43	20	64
Standard Deviation	12744.53	368.64	53.01	15.58	560.99	191.70	157.15	37.81	24.40	27.28
80th %ile	1445	719	30	31	174	282	40	62	50	87
95th %ile	10660	979	90	43	678	506	108	99	76	109

Examination of spatial geochemical patterns in relationship to geology, has been undertaken with the aid of colour scatter plots for the two sample media. The trace element data were initially sorted into ranked percentile values, and displayed using a PC-based graphics package (Stanford Graphics V4). Anomaly threshold was arbitrarily selected as the 95th percentile, and the top 5 per cent of values shown in red to enhance anomaly recognition. The principal geological boundaries and structures were digitised separately in AUTOCAD 12, edited in DESIGNER 4.0a and finally imported into the Stanford Graphics image.

Barium

Regional distribution

The entire northern margin of the Solway-Northumberland basin is characterised by high barium values in both stream sediments and panned concentrates (Figures 3.7 and 3.8). Most of the very high values in the two media are directly attributable to the presence of baryte mineralisation associated with sedimentary and volcanic rocks of the Lower, Middle and Upper Border Groups; zones of fracturing in the Silurian, and with the Silurian-Upper Old Red Sandstone unconformity. A threshold value of 1450 ppm, corresponding approximately to the 80 percentile of the data values delineates the anomalous population in panned concentrates, whereas stream sediments show a much smaller concentration range (Table 2), a more regular decline in values downstream of discrete sources of baryte and a wider distribution of low level anomalies (750-1000 ppm). As a consequence of the coarse primary grain size of baryte, heavy mineral samples nearly always display greatly enhanced contrast, increased sensitivity, and shorter dispersion trains more closely related to mineralised outcrop or overburden. They have the additional advantage of reducing the effects of Ba coprecipitation caused by secondary manganese and iron oxides which can lead to false anomalies in stream sediments.

Detailed distribution of anomalies

Four distinct groups of major Ba anomalies are recognised. These are described in relation to the principal lithostratigraphic units in which they occur and other known or inferred geological and stuctural controls.

1) Silurian: Prominent Ba_p anomalies ranging from < 1 % to > 5 % occur sporadically in the Silurian, usually within 4-5 km of the unconformable or faulted Upper / Lower Palaeozoic unconformity. In many instances the anomalous values can be traced to north-north-east trending streams following well defined shatter belts. The most conspicuous of these is located about 11 km north of Langholm in Glencreif Burn and the headwaters of Meikledale Burn where a 200 -400 m wide zone of sheared ochreous-weathering greywacke veined with quartz and baryte is intermittently exposed. Similar structures to the east and north east account for other high Ba_p values in the Fore Burn, Twislehope and Chapel Grain catchments. High copper values and the identification of chalcopyrite in the pan suggests an association with copper mineralisation. Down strike, to the south west of Langholm, Ba anomalies are less evident probably due to the increased thickness of drift. One notable exception occurs about 5 km north of Ecclefechan [3184 5802]. Here, a panned concentrate comprising almost pure baryte (36.5 % Ba) was collected from a stream containing abundant clasts of baryte-calcite-hematite veined greywacke. On the north side of the Solway, high levels of Ba_p and Ba_s are apparent over faulted Silurian rocks to the east of Rockliffe and between Kirkudbright and Black Stockarton Moor. Proximity to known Cu-U-Bi-Ba vein mineralisation (Miller and Taylor, 1966) in the former area and to porphyry-style Cu-Mo mineralisation in the latter area, partly account for the anomalies, although further, undisclosed sources are indicated beneath the drift cover.

2) Upper Old Red Sandstone: Many anomalies are clearly related to the Silurian-Upper Old Red Sandstone unconformity. Barium concentrations, typically of the order of percentage levels in panned concentrates, are common for example, in the south draining streams north east of Ecclefechan and on the north west flanks of the Arnton Fell Lower Palaeozoic inlier. Thin baryte veins have been noted in float boulders of red sandstone and basal conglomerates but are not seen insitu. Apart from a weak enrichment of Cu, there is no evidence of other base metal mineralisation.

3) Lower Carboniferous lavas: A high regional background concentration of Ba in stream sediments Figure 3.7) is evident over many of the Birrenswark lava outcrops, especially between Langholm and Ecclefechan where the lavas attain maximum thickness of *c.* 60-70 m. The data is consistent with the known enrichment of Ba (Rb, and Y) found in comparable suites of within-plate alkali olivine basalts (Pearce, 1982). Point source Ba anomalies in panned concentrates are also widespread (Figure 3.8) over the lavas of this area indicating numerous but, on the basis of short downstream dispersion trains, relatively minor baryte occurrences. The best evidence of baryte mineralisation is seen near the old lead trial [32926 58174] at Mine Sike, near Westwater. A vein (0.7 m wide) containing about 10 % baryte and abundant Pb and Zn-sulphides occurs at the faulted lava-sediment contact. Close by,

several more baryte veins and vesicle infillings, often associated with zones of intense brecciation, were discovered in recent exploration drilling (Gallagher et al., 1977). Other major Ba anomalies associated with lavas higher in the succession such as the Glencartholm Volcanic Beds, to the south of Langholm, suggest a similar style of mineralisation. Interestingly these rocks contain mugearites and trachytes comparable in composition to those hosting major baryte veins in the Misty Law trachytic complex in Dinantian rocks south of Glasgow (Stephenson and Coats, 1983).

4) Lower Carboniferous sediments: Very high values of Ba in both sample types form a prominent regional scale anomaly over Lower Border Group interbedded sandstones, siltstones and cementstones south east of Langholm. Irregular veins of baryte up to about 15 cm thick were noted close to the southern edge of the anomaly in the Tarras Water catchment [33886 58195], during revision mapping of the area (Lumsden et al; 1967). More recently, MRP follow up led to the discovery of a discontinuous zone of veining extending intermittently from the initial occurrence, northwards for at least 4 km. The veins lie within 1-2 km of the basin margin in an area affected by several major north east trending normal faults, but apart from weak Pb and Zn anomalies there is no direct evidence of associated base metal mineralisation. In contrast, Ba-Pb-Zn-Cu anomalies are well developed in the Black Burn-Green Burn catchment about 5 km to the east and on the east side of the Arnton Fell inlier have been traced to thin fracture-bound mineralisation in limestones and cementstones.

On the north Solway coast, a prominent Ba anomaly can be traced for more than 10 km, north-north-west from Kirkbean (Leake et al., 1977). A thick baryte vein is described by Leeder (1971) [2973 5619], close to the faulted contact between the Lower Border Cementstone Group and the Criffel granodiorite. Recent MRP exploration has extended the vein subcrop for at least a further 2 km northwards. Vein baryte with hematite and quartz breccia has also been observed in several stream sections within the zone. Other vein occurrences in the area are identified by high Ba values including the known veins east of Dundrennan.

South-eastwards away from the basin margin faults, Ba levels in stream sediments decrease sharply. Lower Border Group sediments exposed in the Bewcastle anticline for example, do not show the same level of enrichment observed in rocks of similar age in the Langholm and Solway areas. Panned concentrate data are sparse for the Bewcastle area, but the available information tends to confirm the generally low abundance of Ba except for a few scattered high values related to minor mineralisation mainly in faulted limestones. For example, localised fluid movement along the Antonstown Fault on the east flank of the anticline, has caused intense carbonate veining of algal limestones with associated enrichment of Ba (and Zn).

Copper

Regional distribution

Copper, like barium, shows a distinct increase in average abundance in both stream sediments and panned concentrates along the northern margin of the basin compared with its central and southern parts. Levels in sediments (Cu_c) are substantially lower than in panned concentrates (Cu_p), (Table 2 and Figures 3.5 and 3.6). This arises because copper is mainly present in drift and alluvium as coarse grains of chalcopyrite and cupriferous pyrite which are relatively resistant to oxidation under conditions of neutral to high pH.

A zone of north easterly trending high values extends with apparent continuity from the Hawick Group Silurian across the basin-boundary fault zone and into the Lower Border Group for a distance of 10-15 km. This anomalous zone in Cu is closely mirrored by the pattern of K_2O in stream sediments (British Geological Survey. 1993). It is truncated sharply on its south eastern side along a line broadly coincident with the Back Burn Fault and its continuation north-eastwards, the Kershope Fault. Very low Cu levels in both sample types, generally <15 ppm, characterise the Dinantian sedimentary sequence throughout the remainder of the basin.

There is no apparent relationship between the variation of Cu and either lithostratigraphy or structure. On palaeogeographic grounds though, it has been demonstrated by Leeder (1974), that two distinct fluvio-deltaic systems existed in Lower Border Group times, the marginal area between the delta fronts marking approximately the line of geochemical discontinuity. Adjacent to the basin margin, the Whita fluvio-deltaic system drained from Cu and K_2O enriched Lower Palaeozoic source lands in the Southern Uplands, depositing sediments containing a high proportion of potash feldspar and a suite of heavy minerals derived, in part, from erosion of the Birrenswark lava pile. Evidence from palaeocurrent studies in the Bewcastle anticline however, indicate persistent influxes of Cu-deficient sediment from the north east, containing very scarce amounts of magnetite and ilmenite and abundant subarkosic material from a possible acid igneous provenance, (Day, 1970).

Copper enrichment is a characteristic feature of the Lower Carboniferous sediments and lavas along the North Solway Fault and of the adjacent Hawick Group greywackes between Kirkudbright and Auchencairn. The anomalous pattern over the latter reflects not only the extensive, low-grade, disseminated Cu (Mo) mineralisation of the Black Stockarton Moor porphyry complex, but also the widespread presence of Cu-Ba minerals occupying fracture infillings in the greywackes. Several veins, which are exposed mainly in coastal sections around Rascarrel Bay, have been worked on a small scale for copper in the past. Because of the magnitude and continuity of the anomalies, it is possible that the veins extend inland towards the sub volcanic porphyry complex with which they may be genetically associated.

Detailed anomaly distribution

Many of the highest Cu_p (> 100 ppm) values occur in close proximity to the basin margin, in the area extending from the north side of Roan Fell south-westwards to the main Birrenswark lava outcrop near Ecclefechan. Detailed follow up investigations based on selection of the more promising anomalies revealed the presence of three distinct styles of mineralisation..

1) The most prominent Cu anomalies over the entire area are related to minor chalcopyrite-baryte veins in north-north-east trending zones of intensely shattered, sheared and brecciated greywacke. Several of these zones, described by Lumsden et al., (1967), as shatter belts, have been mapped in the Meikledale Burn-Glenreif Burn catchments. Numerous Cu_p anomalies (80-250 ppm) and variably elevated levels of Ba, Pb, and Zn, extend in a 15-20 km long, strike parallel belt, far outside the mapped limits of these zones,. In Braidley Burn, for example [347300 598400], one of the highest values in the data set of Cu (670 ppm), apparently unrelated to contamination, coincides with Pb (150 ppm) and Ba (0.77 %). Float boulders of veined, strongly haematised, micaceous greywacke containing rare grains of chalcopyrite at the vein margins were noted over a distance of several hundreds of metres along the stream channel.

Mineralisation of comparable style is presumed to be present in the Wormscleuch catchment near the north eastern edge of the project area. Highly sheared, strongly haematised greywacke is developed over a strike length of 200-300 m along the faulted eastern margin of the Arnton Fell Silurian inlier. Strong enrichment of Cu_p (and associated high Pb and Zn) related to the presence in the pan of abundant coarse grains of untarnished chalcopyrite, has been recorded from the headwaters of the catchment, but the anomaly train is short suggesting a local source of mineralisation obscured by drift.

Down strike to the south west of Roan Fell, the same element association, sometimes accompanied by enhanced Sb_p values (up to 35 ppm), was observed in Swin Gill (Cu_p 277 ppm at [336720 594960]), Back Burn, (Cu_p 250 ppm at [333470 584210]), Logan Water (Cu 223 ppm at [329980 587180]), Water of Milk (Cu_p 353 ppm at [324270 584530]), and the Winterhope catchment (Cu_p 600 ppm at [327740 583020]). At each of these localities, characteristically veined, and sometimes intensely sheared float boulders of greywacke siltstone or mudstone were observed and it is therefore suggested that additional sources of minor fracture bound Cu mineralisation exist in these areas.

On the north Solway coast a distinct zone of coincident Cu_p and Cu_c anomalies over Silurian greywackes and Birrenswark lavas near the faulted eastern margin of the Criffel granodiorite, have been interpreted by Leake et al. (1977) as potentially defining a 10-14 km long north-south mineralised structure. Evidence of secondary Cu minerals, baryte, and Pb-Zn sulphides in panned concentrates and of vein baryte, hematite and quartz breccia in float, support this suggestion.

2) Birrenswark Lavas: The main outcrop of lavas between Waterbeck and Ecclefechan is identified by high levels of Cu_p commonly in the range 80-100 ppm and Cu_c, 30-40 ppm. Chalcopyrite and pyrite are minor, but widespread constituents of panned concentrates in this area and are also present in samples from streams draining smaller lava outcrops on Roan Fell and along the south-east side of Arnton Fell. The lavas show little surface evidence of Cu mineralisation, possibly because they are frequently deeply weathered and oxidised. However, exploration drilling on soil and deep till anomalies located over Birrenswark lavas in the Callisterhall district [328100 581340] discovered intense zones brecciation and carbonate-dolomite veining containing abundant chalcopyrite (c. 0.5 % Cu over 0.5 m), marcasite and pyrite (Gallagher et al., 1977). The mineralisation is regarded as a late stage event, post dating brecciation and pervasive alteration which itself is likely to be a deuteric rather than a hydrothermal phenomenon.

3) Lower Border Group: Occasional, low to moderate amplitude anomalies (80-220 ppm) are associated with minor chalcopyrite on fracture surfaces or in thin carbonate veins in dolomitic cementstones and calcareous siltstones, and less frequently as rare disseminations of chalcopyrite and malachite in sandstones. Most of the Cu-occurrences are accompanied by small amounts of galena and sphalerite, in sedimentary rocks immediately overlying the Birrenswark Lavas (e.g. in the Westwater and Callisterhall area) or from the vicinity of faulted sediment-lava contacts (e.g. Black Grain [345450 859600]). Rarely, high Cu_p concentrations are related to major faults in Middle and Upper Border Group sediments such as the Kershope Fault or the parallel structure to the north-east, the Bloody Bush Fault. Although these anomalies have not been traced to source they are presumed to be related to thin carbonate veins observed in limestone float and, like the other styles of Cu mineralisation described above, are unlikely to be of economic significance.

Zinc

Comparison of the regional patterns for Zn in stream sediments and panned concentrates indicates that with the notable exception of the southern part of the Bewcastle anticline and the area north west of Newcastleton there is generally a poor degree of spatial correlation between the two sample media. In stream sediments Zn concentrations are influenced by sorption to hydrous oxides, clay minerals and organic matter often leading to difficulties in relating anomalous concentrations to mineralised outcrop or overburden. In contrast, panned concentrates provide a more direct indication of Zn mineralisation and also of metallic contamination, but can suffer from high sampling imprecision and anomaly exaggeration through over panning. Because the two sample types often reflect different geological and environmental features, they are described separately here.

Stream sediments

There is no evidence of a systematic difference in background Zn_c levels between the Lower Palaeozoic greywackes and Lower Carboniferous sediments. North east of Dumfries, concentrations in the vicinity of the unconformity do not show evidence of a significant increase suggesting that the fracture bound mineralisation in the Silurian which gives rise to the prominent zone of Ba and Cu anomalies, does not contain significant amounts of Zn. A stronger contrast is apparent between essentially low values (mainly <120 ppm) over the Permian sandstones of the Carlisle basin and higher values (mainly >200 ppm) over the dominantly marine, Lower Carboniferous sediments of the Bewcastle anticline. In the latter area, strong enrichment of Zn extends over a broad area affecting rocks ranging in age from Lower Border through Middle to Upper Border Group. The anomalous area comprises over thirty very high values ranging from 500 to 3543 ppm Zn, but their distribution does not coincide in any obvious way with structural features or with lithological variation. Coincident Pb_c anomalies (up to 318 ppm) in this area, accompanied by enrichment in Cd (up to 11 ppm) are indicative of suphide mineralisation although none is recorded in the area and no evidence of mineralised bedrock or float was reported at the time of sampling. An additional factor which complicates interpretation of the anomalies is their proximity to a large military training and heavy artillery area at Spadeadam [3610 5700]. Contamination from shell and cartridge casings and other associated metallic debris is scattered over a wide area, but there is no obvious correlation between Zn_p and contamination observed at stream sites, or with Sn_p which is normally a useful guide to the presence of substantial contamination. The anomalies are therefore regarded as genuine and merit further investigation.

Several prominent Zn_c anomalies are associated with cementstones and limestones of the Lower Border Group close to the faulted basin margin between Langholm and Newcastleton. Values are not as high (350-850 ppm) as in the Spadeadam area, but their distribution defines a distinct north-north-east trending zone parallel to several major, closely spaced, syn-depositional faults. On the north side of this zone the anomalies appear to terminate against the Skipper's Bridge Fault which forms the boundary of the Whita Sandstone and the overlying cementstones. On the south side the anomalies are truncated by the Kirk Hill Fault which is one of the few reverse faults in the area, down throwing to the north west. The anomalies thus show a close spatial relationship with the pattern of faulting, are clearly related to fracturing of basal calcareous sediments of the Lower Border Group, and do not extend into the fluvial sandstones of the Whita Sandstone Formation. Close similarity in the patterns exhibited by Pb_c and to a lesser extent Cu_c and Ba_c suggests the presence of base metal and baryte mineralisation extending in a discontinuous zone over an estimated strike length of about 10 km.

High Zn_c values identify the occurrence of disseminated Zn-Pb mineralisation near Callisterhall west of Langholm (1378 ppm at [328720 581670]) and the baryte-hematite-quartz breccia (Leake et al., 1978) at the south east margin of the Criffel granodiorite (519 ppm at [297520 560400]) although no Zn-mineralisation has been observed near Criffel. The only other significant group of high values occurs close to the north-west margin of the Criffel intrusion and at the southern end of the Black Stockarton Moor sub-volcanic complex where maximum values for the area (up to 730 ppm) appear to be related to hydrothermal alteration and the extensive development of disseminated pyrite in porphyrite dykes and hornfelsed greywackes.

Panned concentrates

Although analytical data for panned concentrates are not available for the entire area, it is evident from Figure 3.2 that Zn_p shows a closer relationship with geology than Zn_c. Mineralogical examination of about thirty anomalous samples mainly collected from catchments on the northern edge of the basin confirmed the presence of sphalerite in coarse (+500 -2000 μm), orange to brown, resinous fragments.

With the notable exception of two areas of lower Carboniferous occurring to the north-west of Newcastleton and east of the Arnton Fell inlier respectively, there is a distinct break from high average values over the Silurian to markedly lower values over Lower Border Group sediments. Away from the basin margin however, the area underlain by the Lower, Middle, and Upper Border Group and the Liddesdale Group south-east of the Whita and Larriston Sandstone formations, is characterised by variably high Zn_p (and, in the Spadeadam area, by high Pb_p) levels. This trend of increasing Zn levels south eastwards into the basin broadly corresponds with an increase in the proportion of marine limestones. In detail though, the relationship is complex since many of the thicker limestone units such as those exposed on the south eastern limb of the Bewcastle Anticline are not associated with high Zn values. Some of the more prominent anomalies are situated close to, or in, catchments following major structures which cut both limestones and sandstones, the former often showing signs of intense carbonate veining and brecciation. For example, the conspicuous cluster of high values occurring between the Goat Island-Lyne Fault and the Back Burn Fault is associated with a zone of fractured and veined sediments of Middle and Upper Border Group age.

The dominant north-east linear trend of other major anomalies including those in the Tweeden Burn catchment (up to 2040 ppm Zn_p at [351510 586440], Kershope Burn catchment (up to 7140 ppm at [355780 387030]), Green Burn/Black Grain/Black Burn catchment (2000 ppm at [345220 586500]), Thief Sike/Hartsgarth Burn catchment (3310 ppm at [349200 593450 ppm], Liddel Water catchment (up to 7040 ppm at [355680 594120], and Raven Burn/Wormscleuch Burn catchment (3710 ppm at [361890 602490] strongly suggests a structural control from major north-east trending faults. In every case Zn is the principal base metal present in the panned concentrates, but is often accompanied by elevated levels of Ba, Pb and, to a lesser extent Cu. In most instances the anomalies have been traced to minor fracture-bound sphalerite mineralisation concentrated in narrow calcite or dolomite veins in limestone/cementstone float and/or bedrock.

South west of Langholm, the recorded mineralisation in the basal Carboniferous cementstone group is identified by a single very high value near the faulted contact of the sediments with the underlying Birrenswark lavas (6720 ppm at [328710 581600]). Sphalerite forms a minor constituent of disseminated sulphide mineralisation in a 7 m thick sandstone unit, but is present in the Lower Border Group generally as isolated grains or clusters of grains in carbonate veinlets and fractures in limestones and cementstones. A unusual style of mineralisation only seen at this locality is represented by coarse crystals of strongly zoned sphalerite lining spherical sparry calcite-filled cavities up to 7 mm diameter [32869 58160].

Anomalous Zn_p values are very scarce in the area south-west of Ecclefechan. A few moderately high values define the north-south trending baryte-hematite-quartz breccia on the south east side of the Criffel granodiorite and are also present over Silurian greywackes in the vicinity of recorded U-Cu-Ba mineralisation near Needles Eye. In contrast to stream sediments there is no significant Zn_p enrichment over the porphyry-style mineralisation at Black Stockarton Moor (Brown et al., 1979), suggesting that the Zn is either present as a very fine grained sulphide or concentrated in rock forming silicates.

Lead

Overall the regional pattern of Pb variation is similar in stream sediments and panned concentrates although the former generally show a closer relationship with lithostratigraphy, are less influenced by contamination, and exhibit longer downstream dispersion trains from areas of known mineralisation. On the other hand, median levels of Pb are lower in stream sediments, geochemical contrast tends to be poorer and their ability to identify mineralisation in areas of high background, such as occur over and around the margins of the Criffel intrusion, is consequently very limited.

Stream sediments:
Stream sediments display relatively high background levels of Pb (40-65 ppm) throughout the Solway-Northumberland basin (Figure 3.3). This high background combined with low geochemical variability is probably reflection of the continuous supply of detritus from Lower Palaeozoic source lands to the north and north-west. Greywackes of the Riccarton and Hawick groups lying closest to the basin margin and therefore likely to represent an important source of Carboniferous sediment, are associated with comparable high background Pb levels (Regional Geochemistry, Southern Scotland). Lead levels in stream sediments tend to show a modest increase (59-99 ppm) over fluvio-deltaic sediments in the Lower Carboniferous, which are particularly abundant around the north edge of the basin and over parts of the Bewcastle anticline. The Whita Sandstone, which is typical of these dominantly arenaceous sediments, is also known to contain a higher proportion of microcline than plagioclase (Nairn, 1958).

Scattered high values of Pb (100-127 ppm) occasionally corresponding to anomalous Zn_c over the south-east margin of the Bewcastle anticline and the Upper Liddesdale limestones flanking the north margin of the Alston Block may be related to mineralisation. For example, the two largest anomalies in this area, (127 ppm Pb_c, 823 ppm Zn_c at [362480 568280] and 109 ppm Pb_c, 1164 ppm Zn_c at[362400 567650]) are from the same stream, contain low Sn_c and are not associated with observed contamination.

The most prominent and coherent groups of high Pb_c values are located over;

1) Lower Border Group sediments lying between the Skipper's Bridge and Kirk Hill-Arnton faults to the north and north-west of Newcastleton. The anomaly comprises 30-40 values exceeding 100 ppm (95th percentile) and ranging up to > 400 ppm. Zn_c displays a similar pattern, although the anomaly is less intense and more discontinuous than for Pb_c. Follow-up investigations in this area successfully identified small amounts of galena in cementstones, either as isolated crystals within thin carbonate veins or as plate-like blooms on fracture surfaces. The dominant north-easterly trend of the anomalous zone strongly suggests structural control from the syn-depositional basin margin faults and possibly lithostratigraphic control from Lower Border Group sediments which show evidence of marked facies change with fewer and thinner cementstone units to the south-west of the anomaly.

2) Silurian greywackes to the north-west and north-north-east, and Lower Border Group sediments to the south-west of Langholm respectively. The cause of these anomalies is uncertain since much of the area in the west and south west lies within a former military training area and evidence of corroded cartridge and shell casings was observed in some stream sections during the drainage survey. However, there is no association of high Pb values with enhanced Sn which would be anticipated if contamination was the principal cause of the anomalies. Also the known Pb-Zn mineralisation near Westwater [328520 581210] and several other minor occurrences nearby, are marked by similar high Pb (and Zn) values in stream sediments, but also lie within the area of military activity. Anomalous values in the Silurian north-north-east of Langholm are either related to shatter belts with associated zones of intense brecciation, haematisation and carbonate veining, or with unconformable (or

occasionally faulted) contacts between the Silurian and Upper Old Red Sandstone. The two highest Pb_c values in latter area (109 ppm at [341140 594410] and 116 ppm at [340680 593100]) may be derived from a mineralised source as Zn_c is markedly enriched (720 ppm and 874 ppm respectively) and, in both instances, brecciation was noted in bedrock upstream of the sample sites.

3) Over the Main Granodiorite of the Criffel intrusion high Pb_c values are frequently associated with high concentrations of Mn_c and Fe_c and are undoubtedly the result of feldspar decomposition and adsorption by secondary hydrous oxides. The pattern of broadly coincident Pb, Zn, Cu, and Ba drainage anomalies at the south-east margin of the granite suggests the presence of a possible mineralised structure affecting Silurian and Lower Carboniferous rocks along a strike distance of some 10-15 km. A component of igneous detritus is likely to have contributed to the high Pb content of these samples which are not clearly resolved from those within the granite.

Panned concentrates

The pattern of high Pb_p values (Figure 3.4) is broadly comparable to that of Zn_p, but, whereas anomalous values of the Zn have, almost without exception, been related to the presence of sphalerite, those of Pb are more difficult to establish and only rarely has galena been identified in panned concentrates. Mineralogical examination of 55 anomalous panned concentrates containing Pb varying from 140 ppm to >1000 ppm, and collected from streams close to the basin margin in the area between Ecclefechan and Bonchester Bridge, confirmed the presence of fresh galena at only four sites. Two of these were derived from the known mineralisation near Callisterhall (1640 ppm at [328710 581600] and 340 ppm at [329260 581740]), one sample from Glenshanna Burn draining the disused mine workings at Glendinning (2245 ppm at [331000 506820]) and the other from Green Burn (230 ppm at [345920 586920]). The latter has been traced to minor fracture bound galena in cementstones and forms part of a group of north-east trending high values overlying Lower Border Group sediments between the Kirk Hill and Skipper's Bridge faults (see section on Pb in stream sediments above). A similar high value (630 ppm at [297560 559160]) over the Kirkbean Cementstones in Kirkbean Glen clearly identifies the minor occurrence of coarse-grained galena in carbonate veined limestones (Craig, 1956). Other high values in the range 225-930 ppm occur along the east margin of the granite, but Sn is also elevated in these samples indicating that at least a proportion of the Pb is derived from contamination.

Several prominent Pb_p anomalies derived from basal Carboniferous sediments close to their contact with the Birrenswark lavas are caused by abundant bright green fragments and euhedral grains of pyromorphite considered to be alteration products of galena. The most notable of these occurs at Stoneybeck (3060 ppm Pb [32209 57706]), and near Westwater (2042 ppm at [330310 582520]) within an area of known Pb-Zn mineralisation. Grains of hematite separated from both of these samples were also found to be strongly enriched in Pb suggesting the basic lavas as the most likely source.

A few low-order Pb_p anomalies (100-400 ppm) apparently unrelated to contamination are also recorded from the vicinity of faulted lava-sediment contacts between Langholm and Ecclefechan. These are attributable to the presence of secondary Pb minerals of the plumbogummite-beudantite group which appear as rare, grey waxy anhedral fragments. The precise nature of the primary phase from which these minerals have developed is difficult to establish although in the streams draining the poorly exposed Birrenswark lava outcrop between Middlebie and Ecclefechan a few fragments showed good cubic cleavage indicating derivation by oxidation/alteration of galena.

There is little evidence of any substantial lead mineralisation in the Silurian and only three or four high Pb_p values are associated with anomalies in Ba, Sb, Cu and Zn, and unrelated to high Sn_p. These

4. GEOPHYSICS

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Introduction

This data package includes a number of maps and images derived from potential field (gravity and magnetic) data held by the British Geological Survey in the Regional Geophysics Databank. The displays were produced using Interactive Surface Modelling (ISM) package for contour maps and BGS COLMAP software for other the images; they represent a sample of the wide range of transformation and imaging routines that can be applied to digital potential field data to highlight structural features. Only a very limited qualitative discussion of the features revealed by these displays is included here.

Data sources and imaging methods

Gravity data

The area contains about 3600 gravity stations, representing an average station density of approximately 1 per 2 square kilometres. Most of the stations were established by the British Geological Survey, although the compilation does include some university data, for example surveys in the Dalbeattie area by Durham University. Data from the intertidal zone in the Solway estuary were acquired by BGS in 1974 using hovercraft transport. Elsewhere in the estuary there are no gravity determinations except for two sea-bottom stations measured by Bott (1964) in the south-western corner of the study area.

The gravity data have been reduced to Bouguer anomalies using a spatially varying reduction density based on the mapped geology (Williamson, 1993). This is to minimise the topographic distortion which can occur when an inappropriate Bouguer reduction density is employed (effects which can be enhanced when imaging methods are applied to the data). The data were gridded at 0.5 km intervals using the ISM minimum tension algorithm.

Figure 4.1 shows the gravity station distribution and Bouguer gravity anomaly contours at 0.5 mGal intervals (1 mGal = 10^{-5} m/s^2). In Figures 4.2-4.5 the data are displayed as grey-scale shaded-relief images illuminated from four different directions. A relief exaggeration factor has been selected which enhances the more subtle and shorter wavelength features within the data. A consequence of this is that broad gravity gradient zones which are inclined away from the illumination direction are very dark; features such as this are better resolved by the conventional contour map (Figure 4.1).

Aeromagnetic data

An aeromagnetic survey was flown over the area in 1959 by Canadian Aeroservices Inc. under contract to the BGS (then the Geological Survey of Great Britain). This formed part of the National Aeromagnetic Survey conducted in 1955-65. Flight lines were oriented north-south and spaced 2 km apart with east-west tie lines were at 10 km spacing; the magnetic sensor elevation was nominally 1000 ft (305 m) above terrain. The data were acquired in analogue form but have subsequently been digitised (Smith and Royles, 1989). The present study area contains approximately 3400 digitised points. The data were gridded on a 0.5 km mesh and slightly smoothed using ISM routines (ISM smoothing factor = 0.1).

Figure 4.6 is a contour map of total magnetic field which also shows the locations of the digitised data points. In Figure 4.7 the data are displayed as a colour shaded-relief image in which colours are assigned on an equal area basis and illumination is from the north. The aeromagnetic data contain anomalies with a wide range of wavelengths. Figure 4.7 illustrates one method of enhancing the short wavelength components. A residual anomaly has been calculated by subtracting a version of the field that has been upwardly continued by 1 km; the scalar horizontal gradient of this residual has then been calculated and is displayed as an equal area colour-shaded relief image in Figure 4.8.

Principal features of the geophysical images

Gravity data

In this part of the country, gravity features associated with local structures are superimposed on a long wavelength regional field which increases westwards and is probably due in large part to a decrease in crustal thickness (and/or increase in deep crustal density) beneath the Irish Sea (Bott, 1964; Lewis, 1986). This effect is not immediately obvious in the Bouguer anomaly map (Figure 4.1) because of the strong influence of shorter wavelength features, but it should be borne in mind when viewing the data as it does mean that changes in Bouguer anomaly values between one area and another do not necessarily reflect changes in upper crustal density structure.

A major Bouguer gravity anomaly low is associated with the late Caledonian Criffell-Dalbeattie granodiorite complex. This is a zoned intrusion with the most acid (and least dense) units towards its centre (Bott and Masson Smith, 1960; Stephens *et al.* 1985). Relatively low Bouguer anomaly values extend over the Bengairn complex (Phillips, 1956) immediately to the south-west of the Criffell pluton. Further pronounced Bouguer anomaly lows occur over the low density Permian rocks in the Dumfries and Lochmaben basins, while smaller amplitude lows occur over smaller basins at Thornhill and Moffatdale. The linear nature of some of the gravity gradient zones associated with the basin margins suggests fault control over these margins; in particular, the western margins of both the Dumfries and Lochmaben basins appear to be controlled by NNW-trending faults, and the northern margin of the Lochmaben basin aligns along a NE-trending lineament. A Bouguer anomaly low in the south-eastern corner of the study area is due primarily to the thick, low density Permo-Triassic sequence in the Vale of Eden basin. The eastern margin of this basin is controlled by the NNW-trending Pennine Fault system and it is interesting to note that an apparent lineament in the east-illuminated gravity image (Figure 4.4) extends along the projection of this fault system right across the Solway-Northumberland Basin.

The Permo-Triassic basins within the study area typically contain interpreted maximum sedimentary thicknesses of less than 2 km (e.g. Bott and Masson Smith, 1960), whereas the Carboniferous sequence within the Solway-Northumberland Basin reaches interpreted thicknesses of 5-7 km (Chadwick *et al.* 1995). The gravity expression of the Carboniferous basin-fill is, however, much less distinct than that associated with the Permo-Triassic basins, and this is probably due to the relatively high density of the early Dinantian rocks, in particular the Lower Border Group which contains significant quantities of high-density anhydrite at depth (Chadwick *et al.* 1993; Ward, 1995). A Bouguer anomaly low broadly aligns with the Solway Syncline and this is probably mainly due to the low density Silesian and Permo-Triassic rocks within the syncline. Elsewhere, there is a general spatial association between local Bouguer anomaly lows and outcrops of Dinantian rocks of `Yoredale' or arenaceous facies. For example, there are clear gravity signatures over the faulted margins between the arenaceous Dinantian rocks in the area north of Newcastleton and the Lower Palaeozoic basement, suggesting a relatively low density for the Dinantian rocks. densities, which has resulted in .

The grey-scale shaded-relief images (Figures 4.2-4.5) reveal a number of gravity lineaments over the Northumberland Solway Basin which probably reflect the pattern of faulting (or more specifically those occur to the north of Langholm in the Meikledale Burn catchment within a broad zone of intense shattering, brecciation and haematisation (e.g. 561 ppm Pb at [336720 594960]). Apart from minor fracture bound pyrite no sulphide minerals were observed in outcrop, however mineralogical investigation revealed that the principal source of Pb was hematite which constituted >80% of the total heavy mineral component.

Of the remaining mineralogically examined samples, the majority contain variable amounts of contaminant materials. Five distinct Pb-bearing phases have been recognised and optically confirmed; 1) flattened pieces of pale grey metal occasionally coated by white cerussitic overgrowths and resulting in some of the highest Pb values, 2) small spherulitic grains of lead shot, 3) coarse irregular fragments of dark grey slaggy metallic material often with microbotryoidal surfaces and associated with high concentrations of Sn, 4) angular fragments of orange and brown Pb-rich glass, 5) very fine powdery grains of cerussite and litharge (artificial lead oxide). The contaminants are widely distributed being generally more abundant over the lower, intensively cultivated ground, but also occurring in upland areas especially to the west and north-west of Langholm where very high levels of Sn_p are also evident.

Nickel

In comparison with panned concentrates, the Ni data for stream sediments show a wider range and higher average values, suggesting that a large proportion of Ni is held in fine-grained ferromagnesian phases and clay minerals than in spinels and hematite. Despite these differences, regional geochemical patterns are very similar in the two sample types.

High Ni levels in stream sediments (Figure 3.9) and panned concentrates (Figure 3.10) are essentially confined to, and widely distributed over Lower Palaeozoic greywackes, basaltic lavas in the Lower Border Group and quartz-dolerite sills and dykes associated with the late Carboniferous or early Permian, Whin Sill. The stream sediment data (Ni_c > 90 ppm)) is particularly effective in delineating the Upper-Lower Palaeozoic boundary over the entire 100 km strike length.

Uniformly high background levels characterise all of the area underlain by Lower Palaeozoic greywackes probably reflecting a significant component of mafic material during sedimentation. Contrasts between the Hawick Group (80-110 ppm) and the Riccarton Group (100-220 ppm) adjacent to the basin margin, correlate with the higher proportion of shales and mudstones in the latter, and thus reflect conditions of sedimentation rather than composition of the source material.

The highest Ni_c values are associated with vent agglomerates or volcanic necks and plugs which are numerous in the district between Langholm and Hermitage Water [34800 59600] and may have acted as feeders for the Birrenswark lavas and other basic volcanics in the Lower Carboniferous succession. Geochemically these vents are sometimes distinguished from their associated basaltic lavas by showing high Cr_c values (e.g. Ni 262 ppm, Cr 578 ppm at [347370 592990]). Blocks of serpentinized peridotite, a probable source of both Ni and Cr, have been recorded from the Black Burn vent agglomerate nearby [34580 58880].

There is little evidence of a correlation between high Ni and Pb or Zn suggesting that Ni is not directly associated with base metal mineralisation. However, along the south-east margin of the Criffel intrusion a north-south trending zone of high Ni_c may indicate the position of a mineralised structure in the Lower Carboniferous. Although the reason for the enhanced Ni is unknown, high levels of Cu, Pb, Ba and Zn are also recorded in stream sediments from this zone and a substantial baryte-quartz vein with a similar trend occurs in the vicinity.

Attenuation of anomalous Ni values is apparent in both sample media away from the basin margin. South-east of the lava-sediment boundary in the Ecclefechan-Waterbeck area, for example, stream sediment values diminish from an average of about 90 ppm to 60 ppm over a distance of 3-4 km. This pattern confirms the association of the early Carboniferous volcanism with the principal zone of major syn-depositional basin bounding faults and is consistent with eruption from a line of fissures distributed along a north-east lineament.

Conclusions

The stream sediment geochemistry is dominated by barium derived from veins along the basin margins. Copper is associated with some of the veins and also with the Birrenswark and Cockermouth lavas. Lead and zinc show broad, low amplitude anomalies in the Bewcastle anticline over Lower to Upper Border Group sediments, probably associated with veins. There are also several isolated, higher amplitude sample points which again may be associated with veins.

faults across which a detectable density contrast occurs). Apart from the possible extension of the Pennine Fault system, the dominant trend is north-eastward.

Magnetic data

There is a long wavelength magnetic high over the Southern Uplands in the north-western part of the study area. This has been interpreted in terms of magnetisation contrasts at depth within the basement underlying the exposed Lower Palaeozoic sequence (Kimbell and Stone, *in press*). A circular magnetic anomaly centred just to the north-west of Carlisle must also be due to a concealed source, in this case possibly a magnetic intrusive body underlying the Solway-Northumberland Basin (Lee, 1989).

The remaining conspicuous anomalies appear to relate to shallow igneous rocks of various ages. Pronounced magnetic anomalies are associated with the outer phases of the Criffell-Dalbeattie and Bengairn complexes. The Bengrairn feature extends west-north-westwards (as a linear feature) into the Black Stockarton Moor area, where ground surveys have indicated a complex magnetic anomaly pattern over a series of granodiorite sheets and porphyrite dykes (Brown et al. 1979).

Lavas of the Birrenswark Volcanic Formation are responsible for a belt of magnetic anomalies extending south-westwards from the Langholm area, although there is some divergence between the mapped unit and the magnetic anomaly towards the south-west. In the area east of Langholm (around and to the north of Newcastleton) there is a broad zone of magnetic disturbance which is in part due to the Birrenswark lavas, although there are also contributions in this area from magnetic igneous rocks of Permo-Carboniferous and Tertiary ages. The presence of a geophysically detectable unit at the base of the Carboniferous sequence could be very valuable in mineral exploration along the northern margin of the Solway-Northumberland Basin where exposure is generally very poor. It means that detailed magnetic surveys can contribute to structural mapping in this area and thus to the identification of potentially prospective targets. The resolution provided by the current, relatively sparse regional dataset is limited, particularly where the pattern is complicated by intersecting magnetic structures, and images of these data are subject to aliasing (undersampling of the magnetic field variations). To obtain more detailed structural resolution, either ground surveys (cf. Gallagher et al. 1977) or more detailed airborne geophysics are is required. If sufficient potential can be demonstrated in this region a high-resolution aeromagnetic survey spanning the northern margin of the basin would provide a very valuable foundation for future exploration in the area.

A zone of magnetic disturbance in the south-east of the study area is due to Permo-Carboniferous Whin Sill. Magnetic anomalies are also associated with the ENE-trending High Green Dyke echelon which is of similar age; this crosses the eastern boundary of the study area at about 590N.

Pronounced, narrow, south-eastward trending magnetic anomalies within the study area are due to Tertiary dykes. These have negative polarity because of the strong reversed remnant magnetisation of these intrusions. The most conspicuous is the Cleveland-Armathwaite Dyke, which passes through the south-eastern corner of the study area. There is evidence of changes in trend and offsets to the dyke in the Southern Uplands, perhaps because of deflection of the intrusion at pre-existing structures. There is also perhaps a `gap' in the near surface expression of the dyke in the vicinity of the Criffell-Dalbeattie complex. The limitations in data distribution need to be borne in mind when viewing the magnetic images: for example a NNW-trending segment of the dyke immediately to the north of the Criffell-Dalbeattie complex appears as a series of isolated anomalies in the shaded image (Figure 4.7) simply as the result of the oblique orientation of the dyke with respect to the flight lines. Further negative magnetic anomalies are associated with Tertiary dykes in the north-eastern part of the study area.

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Appendix 1
Solway Basin - Northumberland Trough mineralised localities

Number	Easting	Northing	Name	Type	Mineral 1	Mineral 2	Mineral 3	Mineral 4	Mineral 5	Direction	Dip	Sample Type	Host Rock
1	338860	581950	Tarras Water	Vein	Ba					320	90	Bedrock	Cementstone
2	338860	581920	Tarras Water	Fracture	Ba					320	90	Bedrock	Sandstone
3	346680	589120	Black Burn	Disseminated	Sph	Py						Bedrock	Sandstone
4	349210	592480	Hartsgarth Burn	Fracture	Sph	Py	Ca					Bedrock	Cementstone
5	345600	589120	Black Burn	Vein	Sph	Ga	Ca	Bit				Bedrock	Cementstone
6	339865	583140	Raegill Burn	Vein	Ba							Bedrock	Sandstone
7	361960	600905	Peel Burn	Cavity	Sph							Bedrock	Cementstone
8	361940	602170	Raven Burn	Fracture	Sph	Py	Ca					Float	Cementstone
9	361940	602210	Deep Sike, Raven Burn	Fracture	Sph	Py	Ca					Float	Cementstone
10	361930	602220	Raven Burn	Fracture	Sph	Py	Ca					Float	Cementstone
11	361890	602280	Raven Burn	Vein	Ba	Ca						Bedrock	Cementstone
12	361860	600865	Peel Burn	Cavity	Sph	Py						Bedrock	Limestone
13	339290	583400	Tarras Water	Vein	Ba							Float	Cementstone
14	339260	583450	Tarras Water	Vein	Ba							Float	Sandstone
15	341100	580600	Archer Beck	Vein	Ba							Float	Sandstone
16	355650	587470	Riding Grain	Fracture	Ba							Float	Chert
17	349200	593450	Thief Sike	Vein	Sph	Ca						Float	Limestone
18	349190	593470	Thief Sike	Vein	Ga	Ca						Float	Cementstone
19	349140	593550	Thief Sike	Vein	Sph	Ga						Float	Cementstone
20	349140	593550	Thief Sike	Vein	Ga	Ca				315	20(b	Bedrock	Cementstone
21	345820	586550	Green Burn	Joint	Ba					315	90	Bedrock	Cementstone
22	345742	586260	Green Burn	Vein	Ga	Ca				360	90	Bedrock	Limestone
23	345742	586260	Green Burn	Vein	Sph	Ca				360	90	Bedrock	Limestone
24	361881	602420	Raven Burn	Vein	Ba	Ca						Bedrock	Cementstone
25	350240	578450	Crook Burn	Vein	Sph	Ca						Bedrock	Limestone
26	350250	578450	Crook Burn	Vein / Cavity	Sph	Ca	Fe					Bedrock	Limestone
27	350260	578450	Crook Burn	Vein	Sph	Ca						Bedrock	Limestone
28	350290	578470	Crook Burn	Vein	Sph	Ca						Bedrock	Limestone
29	350300	578450	Crook Burn	Vein	Sph	Ca						Bedrock	Limestone

Appendix 1
Solway Basin - Northumberland Trough mineralised localities

Number	Easting	Northing	Name	Type	Mineral 1	Mineral 2	Mineral 3	Mineral 4	Mineral 5	Direction	Dip	Sample Type	Host Rock
30	350490	578460	Crook Burn	Disseminated	Sph	Fe						Bedrock	Limestone
31	358980	577040	Ashy Cleugh	Vein	Sph	Ca						Bedrock	Limestone
32	358980	577040	Ashy Cleugh	Vein	Sph	Ca						Bedrock	Limestone
33	358950	577110	Ashy Cleugh	Vein	Ba	Py	Ca					Bedrock	Limestone
34	358760	577000	Ashy Cleugh	Vein	Sph	Ca						Bedrock	Sandstone
35	358740	577000	Ashy Cleugh	Vein	Sph	Ca						Bedrock	Siltstone
36	349260	593320	Thief Sike	Vein	Sph	Ca						Bedrock	Cementstone
37	349630	576800	Sleet Beck	Vein	Ba	Hem						Bedrock	Sandstone
38	346580	589125	Black Burn	Vein	Ga	Ca						Bedrock	Limestone
39	346415	589110	Black Burn	Vein	Ga	Ca						Bedrock	Cementstone
40	350750	581900	Langley Burn	Vein	Ba	Ca						Float	Cementstone
41	349200	593460	Thief Sike	Vein	Ga	Ca						Bedrock	Cementstone
42	349130	593542	Thief Sike	Vein	Sph	Ca						Bedrock	Cementstone
43	349950	579000	Crook Burn	Vein	Py	Ca						Bedrock	Limestone
44	358280	577330	Hill Cleugh	Vein	Sph	Ba						Bedrock	Sandstone
45	357640	577140	Hill Cleugh	Vein	Sph	Ca						Bedrock	Limestone
46	357320	577180	Hill Cleugh	Vein	Sph	Py	Ca					Bedrock	Limestone
47	345520	585760	Black Grain	Vein	Sph	Py	Ca					Bedrock	Limestone
48	345500	585730	Dow Sike	Vein	Sph	Ca				100	85	Bedrock	Limestone
49	345480	585840	Thackie Sike	Vein	Sph	Py	Ca					Bedrock	Limestone
50	346290	589270	Hog Gill	Vein	Ga	Sph	Py	Ca				Float	Siltstone
51	346270	589350	Hog Gill	Vein	Ga	Sph	Py	Ba	Ca			Float	Cementstone
52	346240	589380	Hog Gill	Cavity	Ga	Sph	Py	Ca				Bedrock	Cementstone
53	346240	589380	Hog Gill	Vein / Cavity	Ga	Sph	Py	Ca				Bedrock	Cementstone
54	347530	589010	Black Burn	Vein	Ga	Sph	Ca					Float	Cementstone
55	355580	587040	Riding Grain	Vein / Cavity	Sph	Ca						Bedrock	Cementstone
56	355430	587030	Kershope Burn	Vein	Ba	Ca	Py					Float	Limestone
57	356040	587130	Riding Grain	Vein	Sph	Ca						Bedrock	Cementstone
58	346280	586600	Black Grain	Vein	Sph	Py	Ca					Bedrock	Cementstone
59	356860	606110	Wauchope Burn	Joint	Ba	Ca						Float	Cementstone

Appendix 1
Solway Basin - Northumberland Trough mineralised localities

Number	Easting	Northing	Name	Type	Mineral 1	Mineral 2	Mineral 3	Mineral 4	Mineral 5	Direction	Dip	Sample Type	Host Rock
60	330240	582520	Green Burn	Fault	Ba	Ga	Sph					Bedrock	Lava
61	349220	593400	Thief Sike	Vein	Sph	Ca						Bedrock	Limestone
62	345310	586290	Black Grain	Vein	Ba	Ca						Bedrock	Siltstone
63	361750	600840	Peel Burn	Vein	Sph	Ca						Bedrock	Limestone
64	345250	586300	Black Grain	Vein	Sph	Ca						Bedrock	Cementstone
65	328750	581820	Upper Pokeskine Sike	Disseminated	Ga	Sph				225	10	Bedrock	Sandstone
66	328690	581600	Upper Pokeskine Sike	Vein / Cavity	Sph	Ga	Ca	Py		210	8	Bedrock	Cementstone
67	328700	581630	Upper Pokeskine Sike	Disseminated	Ga	Sph	Py	Mar				Bedrock	Sandstone
68	328720	581920	Upper Pokeskine Sike	Vein / Cavity	Ga	Sph	Ca					Drillcore	Cementstone
69	331060	582490	St Bride's Hill	Vein / Breccia	Sph	Ga	Ca	Py	Py			Drillcore	Cementstn/Sa
70	329250	581880	Mine Sike	Vein	Ga	Ba	Sph	Cp	Py			Drillcore	Lava
71	329310	581840	Mine Sike	Vein	Sph	Ga	Ba	Hem	Ca			Drillcore	Lava
72	329050	581910	Mine Sike	Disseminated	Ga	Sph						Drillcore	Sandstone
73	328530	581890	W Pokeskine Sike	Disseminated	Sph	Ga	Cp					Drillcore	Sandstone
74	328530	581890	W Pokeskine Sike	Breccia	Cp	Ca						Drillcore	Lava
75	328100	581340	W Pokeskine Sike	Breccia	Cp	Ca						Drillcore	Lava / Sandstone
76	328240	580720	Lower Pokeskine Sike	Vein	Ga	Sph	Ca	Py	Dol			Float	Cementstone
77	327140	579840	Lower Pokeskine Sike	Vein	Sph	Py	Ga	Mar				Float	Cementstn / Sandstone
78	327150	579860	Lower Pokeskine Sike	Vein	Ga	Sph	Py	Cer				Float	Cementstone
79	330450	582480	Glentenmont Burn	Vein	Ga	Sph	Ca	Py				Bedrock	Cementstone
80	330440	582630	Glentenmont Burn	Fault/Breccia	Sph	Ga						Bedrock	Lava / Sandstone
81	330290	582530	Green Burn	Vein	Ga	Sph	Ca					Bedrock	Cementstone

Appendix 1
Solway Basin - Northumberland Trough mineralised localities

Number	Easting	Northing	Name	Type	Mineral 1	Mineral 2	Mineral 3	Mineral 4	Mineral 5	Direction	Dip	Sample Type	Host Rock
82	333170	582330	Wauchope Water	Vein	Ga	Sph	Py	Ca				F	Cementstone
83	317350	575250	Ecclefechan	Joint	Ga							Bedrock	Cementstone
84	318630	575820	Cowthat	Disseminated	Ga	Py	Sph?					Bedrock	Cementstone
85	345000	590600	Roan Fell: Newcastleton	Vein	Ga							Bedrock	Basalt
86	337400	581800	Broomholm: Langholm	Vein	Ga							Bedrock	Sandstone
87	316000	577000	Crawthwaite: Ecclefechan	Vein	Stib							Bedrock	Greywacke
88	312300	576000	Nutholm: Ecclefechan	Vein	Ga							Bedrock	Basalt
89	309280	537520	Rosegill	Vein	Ba							Bedrock	Limestone
90	309120	537410	Rosegill	Vein	Ba							Bedrock	Limestone
91	309000	531800	Broughton Crags	Vein	Ba							Bedrock	Limestone
92	311750	537690	Gilcrux	Vein	Ba							Bedrock	Limestone
93	311850	535590	Tallentire Hill	Vein	Ba							Bedrock	Limestone
94	312210	535350	Tallentire Hill	Disseminated	Cp	Mal						Bedrock	Limestone
95	313480	538320	Plumbland	Vein	Ba							Bedrock	Limestone
96	313650	537180	Wardhall Common (	Vein	Ba							Bedrock	Limestone
97	313280	536620	Plumbland	Disseminated	Ba							Bedrock	Limestone
98	314300	536300	Moota Qy	Vein	Ba	Ca	Cp			70		Bedrock	Limestone
99	316200	539420	Threapland	Vein	Ga	Cu	Ba					Bedrock	Limestone
100	317600	539000	Bothel Qy	Vein	Ba							Bedrock	Limestone
101	315850	536450	Clints Qy	Vein	Ba							Bedrock	Limestone
102	319700	538650	Torpenhow Qy	Vein	Ba							Bedrock	Limestone
103	320100	537630	Bird House	Vein	Ba	Cu						Bedrock	Limestone
104	323850	536850	Ruthwaite Mine	Vein	Ba							Bedrock	Limestone
105	297300	561900	Kirkbean	Vein	Ba							Bedrock	
106	297580	559121	Kirkbean Glen	Vein	Ca	Ga						Bedrock	
107	287600	554800	Halfmark	Vein	U							Bedrock	

Appendix 1
Solway Basin - Northumberland Trough mineralised localities

Number	Easting	Northing	Name	Type	Mineral 1	Mineral 2	Mineral 3	Mineral 4	Mineral 5	Direction	Dip	Sample Type	Host Rock
108	288500	554100	Brandy Cove	Breccia Vein	Qz	Dol	U			353	90	Bedrock	
109	289000	554600	Piper's Cove	Breccia Vein	Qz	Hem	U			335	80/E	Bedrock	
110	289100	554600	Sandyhills Bay	Vein	Dol	Qz	U			335	80/E	Bedrock	
111	289400	554800	Saltpan Rocks	Vein	U							Bedrock	
112	290200	555400	Powbrade Burn	Breccia Vein	U							Bedrock	
113	290400	555500	Marbruie Cove	Breccia Vein	U	Dol	Qz			315	80/E	Bedrock	
114	291000	555700	Lot's Wife	Vein	Dol	Qz	U	Hem	Cp	360	50/E	Bedrock	
115	291300	556100	Needle's Eye	Vein	Qz	Dol	U	Bit	Hem	350		Bedrock	
116	286900	552800	Man	Vein	Ca	Dol				110		Bedrock	
117	278600	547100	Barlocco	Vein	Ba					102		Bedrock	
118	278800	547300	Airyhill	Vein	Ba					92		Bedrock	
119	281800	548400	Aird's Point	Vein	Ba					69		Bedrock	
120	281300	548300	Rascarrel Bay	Vein	Qz					72		Bedrock	
121	283850	550350	Hestan Island	Vein	Cu					80		Bedrock	

Key

Ba - Baryte Bit - Bitumen Ca - Calcite Cp - Chalcopyrite Cu - Copper (Undifferentated) Dol - Dolomite Ga - Galena

Hem - Hematite Mal - Malachite Mar - Marcasite Py - Pyrite Qz - Quartz Sph - Sphalerite Stib - Stibnite U - Uranium (undifferentiated)

MRP (U) - MRP unpublished data

Dalbeattie Map - BGS 1:50K Scotland map sheet 5E (Dalbeattie)

Appendix 1

Solway Basin - Northumberland Trough mineralised localities

Cu	Pb	Zn	Ba	MRP Sample No	Reference		
39	8	10	123944	BFR6009	MRP (U)		
120	14	18	112354	BFR6010	MRP (U)		
37	156	150000	138	BFR6023	MRP (U)		
10	26	540	2713	BFR6037	MRP (U)		
8	75	339	41	BFR6048	MRP (U)		
18	9	14	37586	BFR6054	MRP (U)		
5	15	253	11	BFR6088	MRP (U)		
14	18	498	19	BFR6091	MRP (U)		
13	16	513	92	BFR6092	MRP (U)		
10	13	471	20	BFR6093	MRP (U)		
7	11	160	994	BFR6095	MRP (U)		
10	20	298	26	BFR6097	MRP (U)		
12	4	12	28708	BFR6106	MRP (U)		
16	25	13	20899	BFR6107	MRP (U)		
115	2	12	228158	BFR6113	MRP (U)		
7	0	4	37542	BFR6120	MRP (U)		
6	40	499	1071	BFR6140	MRP (U)		
11	502	340	104	BFR6141	MRP (U)		
11	336	557	99	BFR6142	MRP (U)		
6	178	125	121	BFR6143	MRP (U)		
6	12	8	3304	BFR6167	MRP (U)		
8	1618	1203	216	BFR6169	MRP (U)		
10	14	5681	257	BFR6170	MRP (U)		
18	3	30	6265	BFR6172	MRP (U)		
6	13	407	15	BFR7010	MRP (U)		
11	18	392	36	BFR7011	MRP (U)		
5	8	849	8	BFR7012	MRP (U)		
7	9	1657	26	BFR7015	MRP (U)		
6	7	1756	14	BFR7016	MRP (U)		

Appendix 1
Solway Basin - Northumberland Trough mineralised localities

Cu	Pb	Zn	Ba	MRP Sample No	Reference		
8	18	584	43	BFR7025	MRP (U)		
7	10	4001	224	BFR7026	MRP (U)		
9	19	1287	108	BFR7027	MRP (U)		
13	3	26	873	BFR7029	MRP (U)		
3	4	399	71	BFR7030	MRP (U)		
8	39	810	112	BFR7032	MRP (U)		
5	38	314	131	BFR7039	MRP (U)		
21	12	33	>5000	BFR7041	MRP (U)		
4	129	133	38	BFR7043	MRP (U)		
6	246	66	164	BFR7044	MRP (U)		
11	2	152	1739	BFR7045	MRP (U)		
5	1341	860	81	BFR7047	MRP (U)		
6	104	1469	331	BFR7048	MRP (U)		
201	12	14	108	BFR7056	MRP (U)		
18	7	1341	>5000	BFR7064	MRP (U)		
7	5	675	76	BFR7066	MRP (U)		
12	5	3332	278	BFR7069	MRP (U)		
6	40	438	79	BFR7070	MRP (U)		
4	20	799	569	BFR7073	MRP (U)		
8	83	799	21	BFR7075	MRP (U)		
	1149	1444		BFR4840	MRP (U)		
	336	1714	128000	BFR4845	MRP (U)		
	1105	727		BFR4846	MRP (U)		
	255	5577		BFR4847	MRP (U)		
	5659	5108		BFR5106	MRP (U)		
				BFR5219	MRP (U)		
		556	13000	BFR5221	MRP (U)		
				BFR5225	MRP (U)		
	121	2780		BFR5235	MRP (U)		
			8900	BFR5830	MRP (U)		

Appendix 1

Solway Basin - Northumberland Trough mineralised localities

Cu	Pb	Zn	Ba	MRP Sample No	Reference		
349	680	5773	5500	BFR5904	MRP (U)		
		1319		BFR5923	MRP (U)		
		214	806	BFR5924	MRP (U)		
		3556		BFR5925	MRP (U)		
	500	1380		BFR2507	MRP (U)		
0	12000	0		BFR1000	MRP 17		
10	180	550			MRP 17		
				BFR1003	MRP 17		
5	520	1140			MRP 17		
0	1500	1090			MRP 17		
560	10100	7820			MRP 17		
		1170			MRP 17		
22	1020	290			MRP 17		
260	660				MRP 17		
580					MRP 17		
5480					MRP 17		
10	10400	3500		BFR1014	MRP 17		
10	100	6300		BFR1008	MRP 17		
10	7200	3000		BFR1009	MRP17		
25	1600	1350		BFR3615	MRP 17		
170	550	12000		BFR3602	MRP 17		
10	8200	320		BFR3623	MRP 17		

Appendix 1
Solway Basin - Northumberland Trough mineralised localities

Cu	Pb	Zn	Ba	MRP Sample No	Reference		
10	33000	6500		BFR2592	MRP 17		
					A A McMillan Pers. Comm.		
					A A McMillan Pers. Comm.		
					Lumsden et al.,1967		
					Landless,1985		
					Landless,1985		
					Wilson,1921		
					MRP 118		
					MRP 118		
					MRP 118		
					MRP 118		
					MRP 118		
					MRP 118		
					MRP 118		
					MRP 118		
					MRP 118		
					MRP 118		
					MRP 118		
					MRP 118		
					MRP 118		
					MRP 118		
					MRP 118		
					MRP 118		
					Leeder (1971)		
					MRP (U)		
					Miller & Taylor 1966		

Appendix 1

Solway Basin - Northumberland Trough mineralised localities

Cu	Pb	Zn	Ba	MRP Sample No	Reference		
					Miller & Taylor 1966		
					Miller & Taylor 1966		
					Miller & Taylor 1966		
					Miller & Taylor 1966		
					Miller & Taylor 1966		
					Miller & Taylor 1966		
					Miller & Taylor 1966		
					Miller & Taylor 1966		
					Dalbeattie map		
					Shaw 1974.		
					Dalbeattie map		
					Dalbeattie map		
					Dalbeattie map		

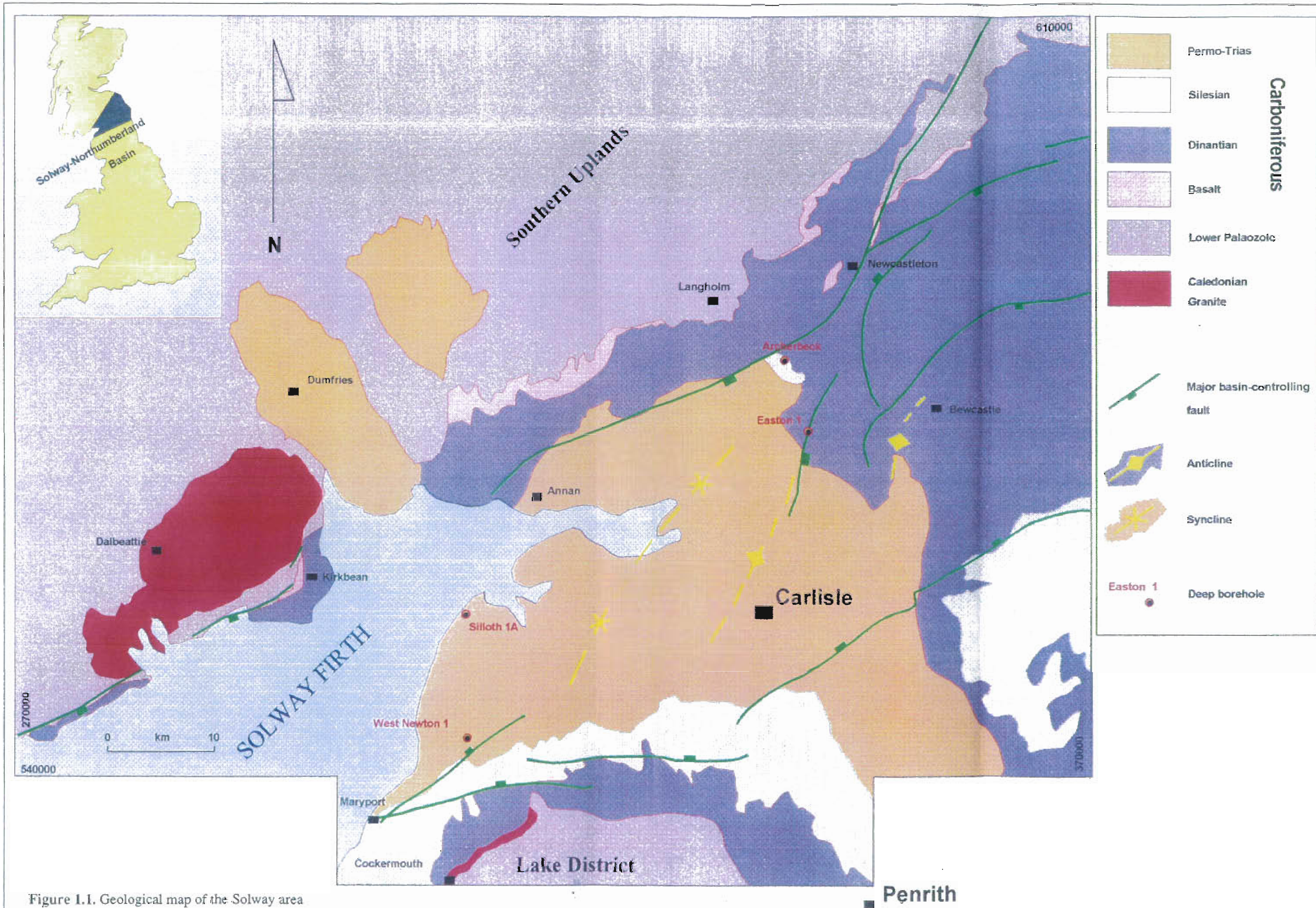


Figure 1.1. Geological map of the Solway area

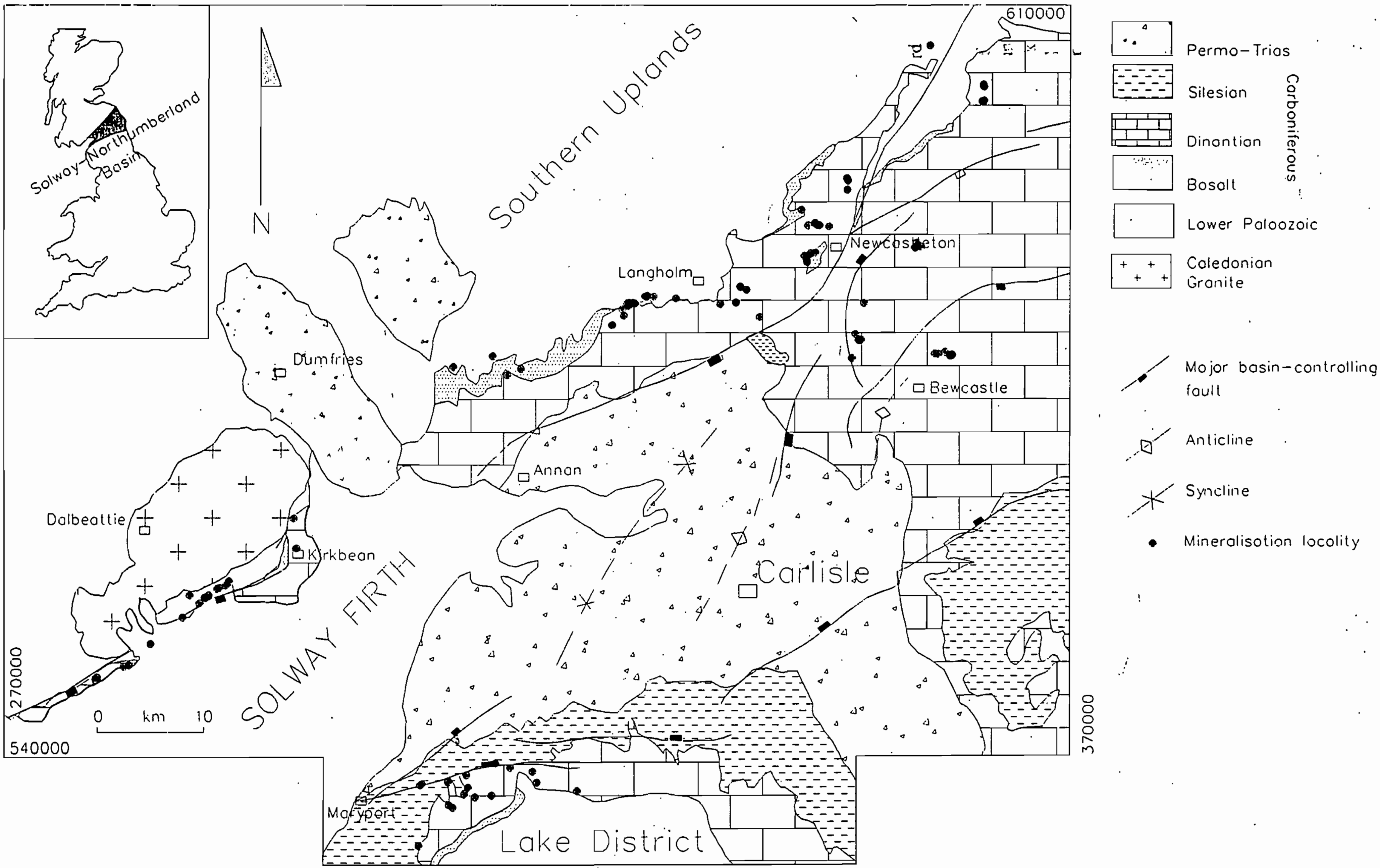


Figure 1.2. Mineralised localities in the Solway area

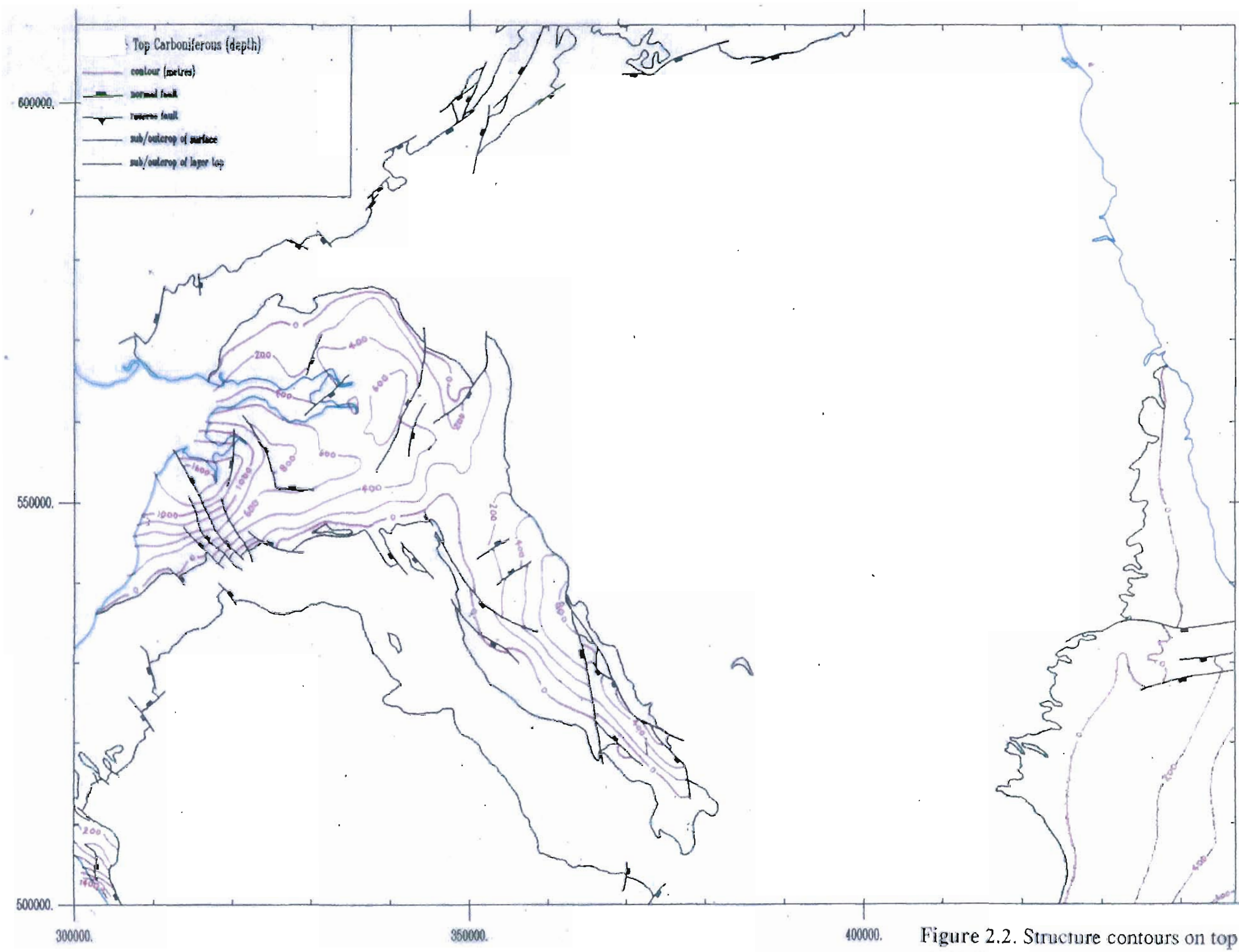
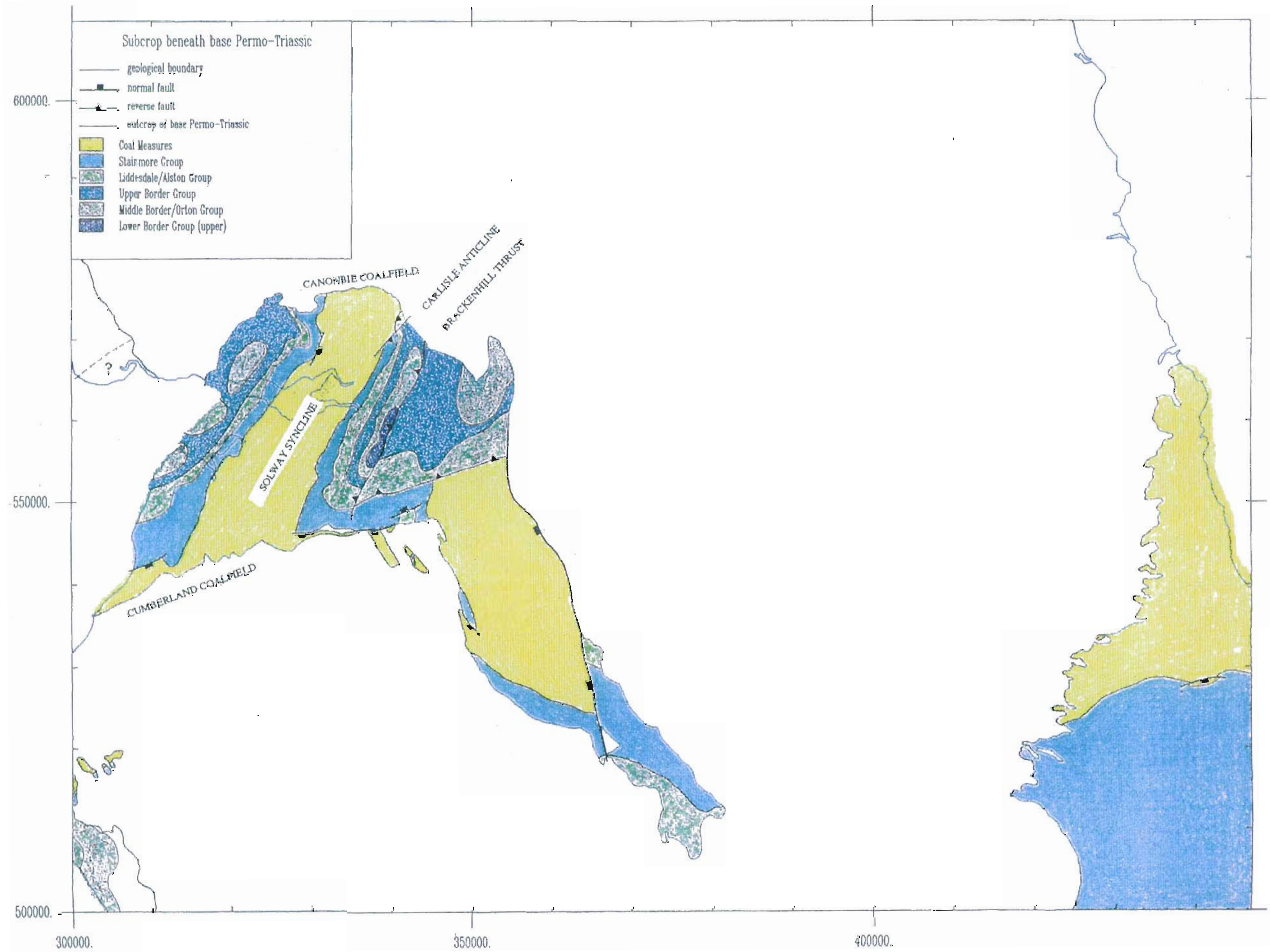


Figure 2.2. Structure contours on top Carboniferous



Subcrop beneath base Permo-Triassic
geological boundary
normal fault
reverse fault
outcrop of base Permo-Triassic
Coal Measures
Stainmore Group
Liddesdale/Alston Group
Upper Border Group
Middle Border/Orton Group
Lower Border Group (upper)
CANONBIE COALFIELD
CARLISLE ANTICLINE
BRACKENHILL THRUST
SOLWAY SYNCLINE
CUMBERLAND COALFIELD
?
600000.
550000.
500000.
300000.
350000.
400000.

FIG.

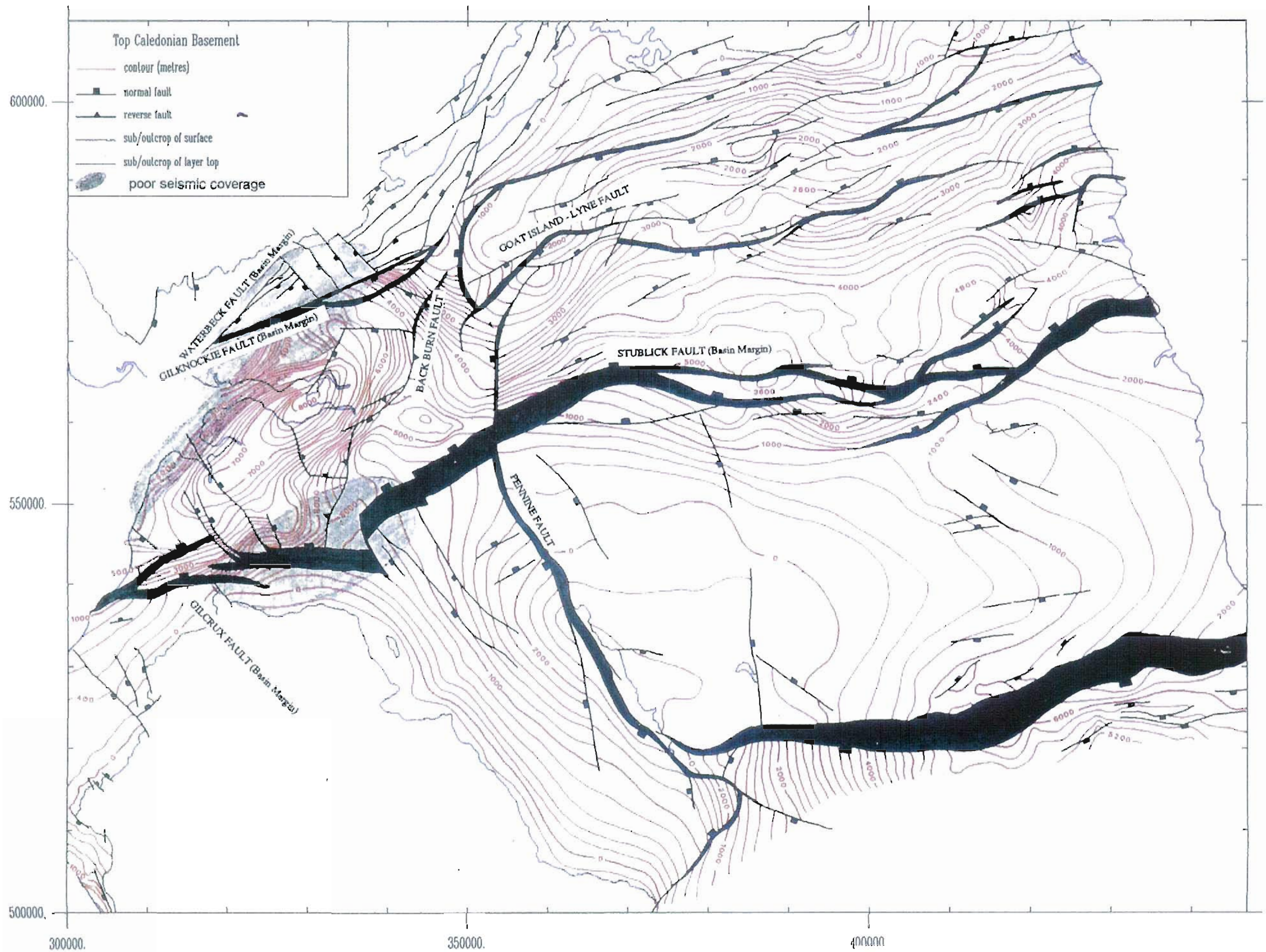


Figure 2.3. Structure contours on top Caledonian basement

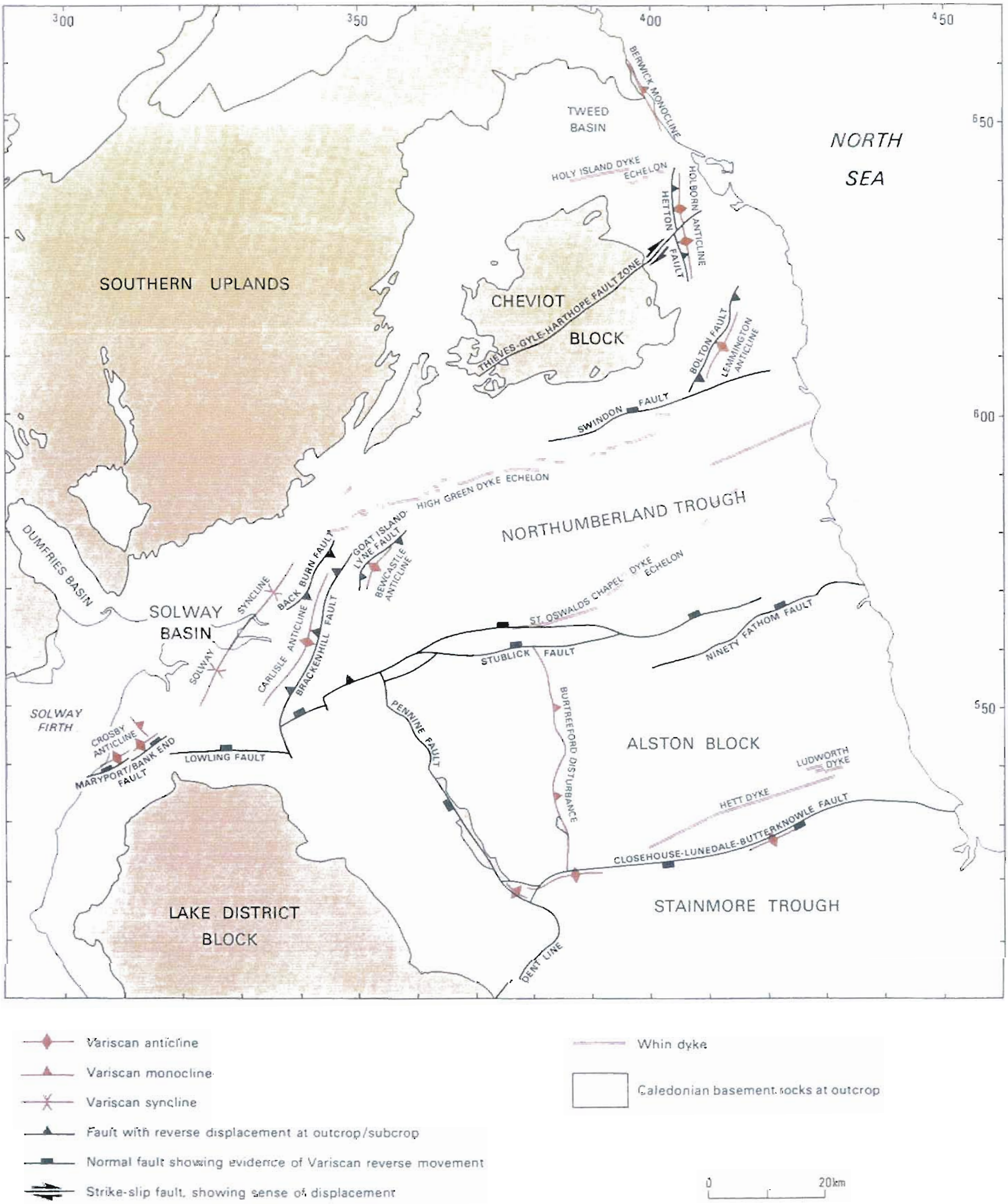


Figure 2.4. Main Variscan structural elements of northern England

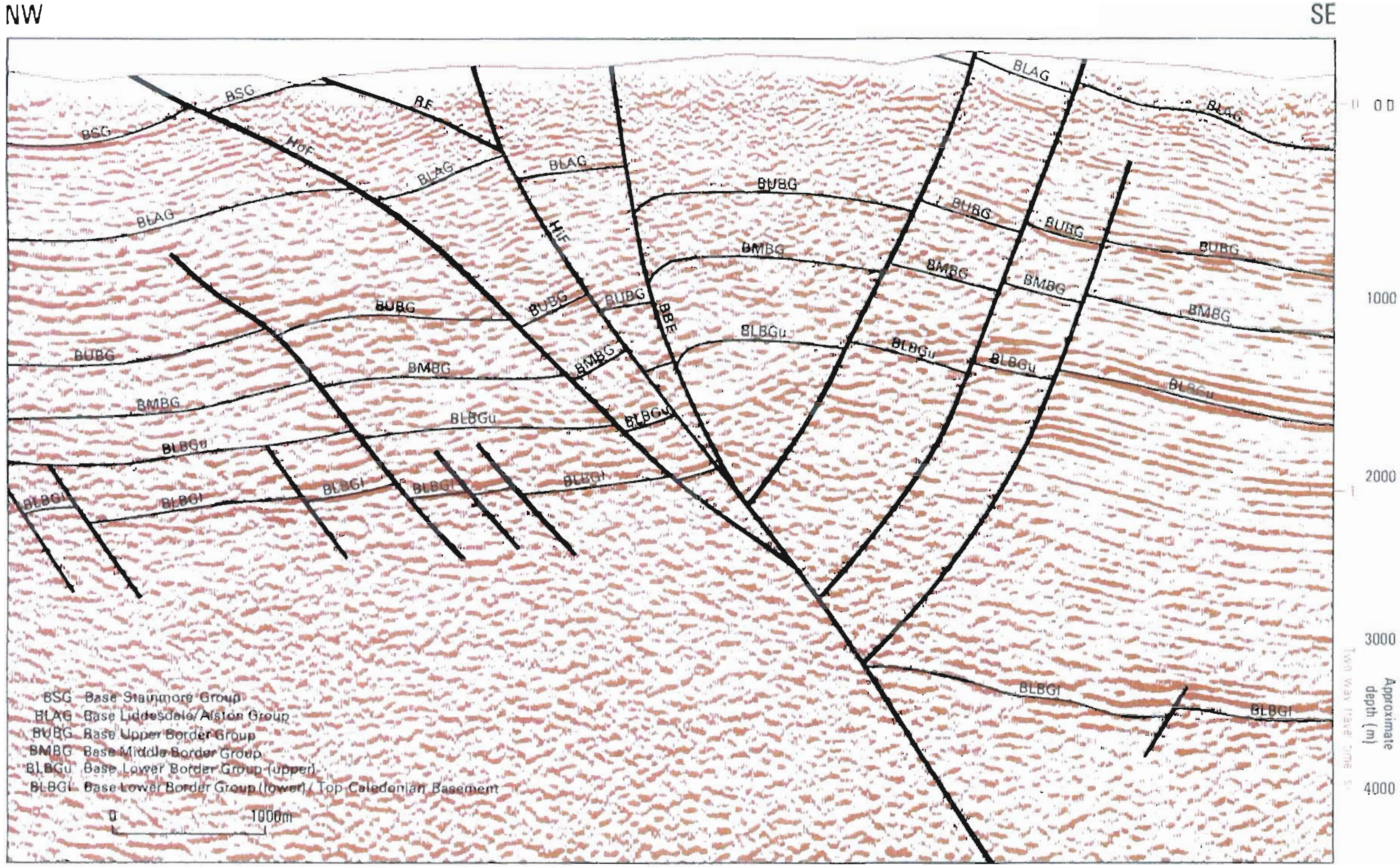


Figure 2.5. Seismic reflection profile across the Back Burn Fault (north-east Solway Basin), showing Variscan reversal of a Dinantian syndepositional normal fault. BBF Back Burn Fault; HoF Hogwash Fault; RF Rowanburn Fault; HiF Hilltop Fault.

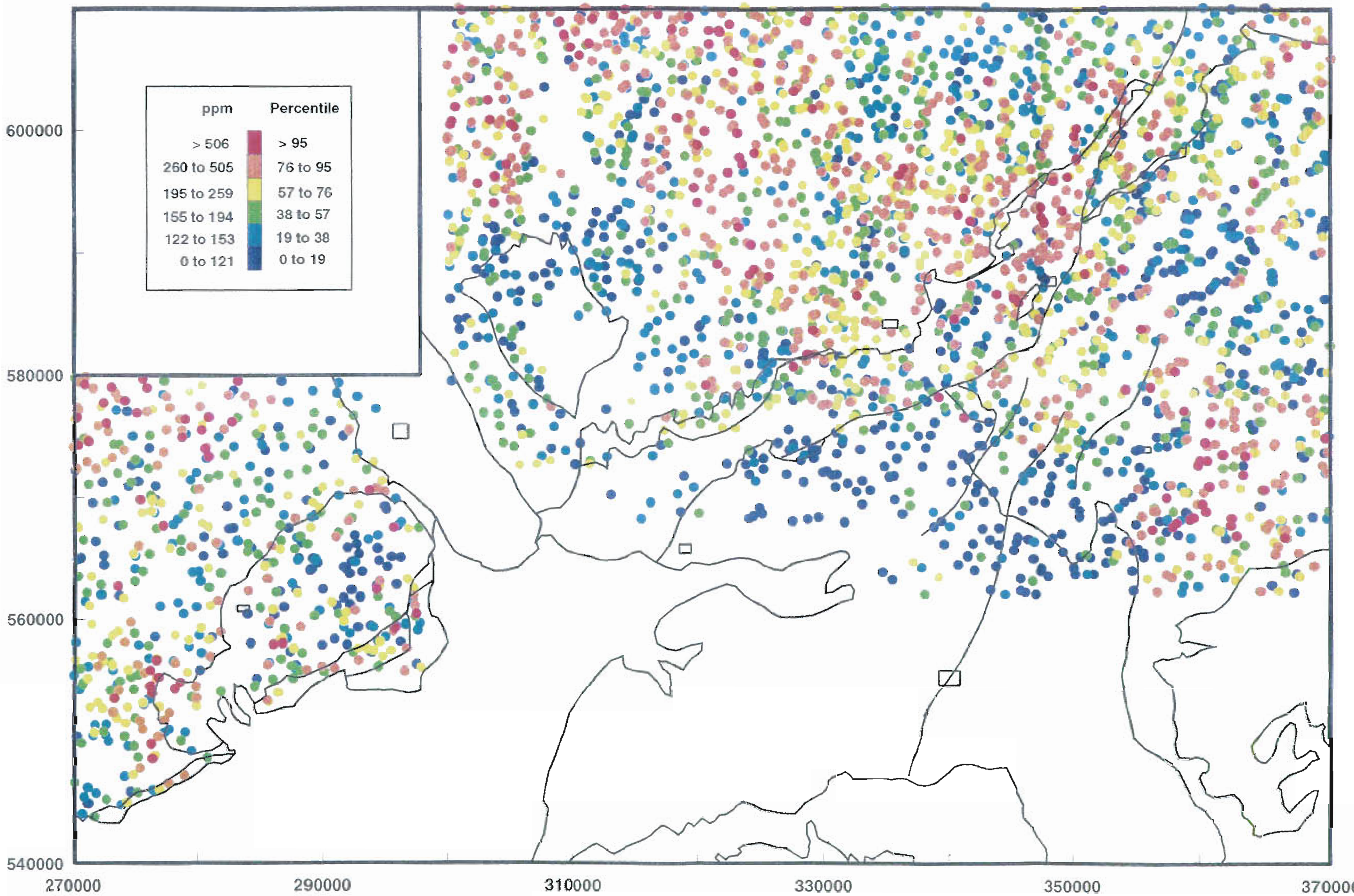


Figure 3.1. Colour symbol plot of Zn in stream sediments

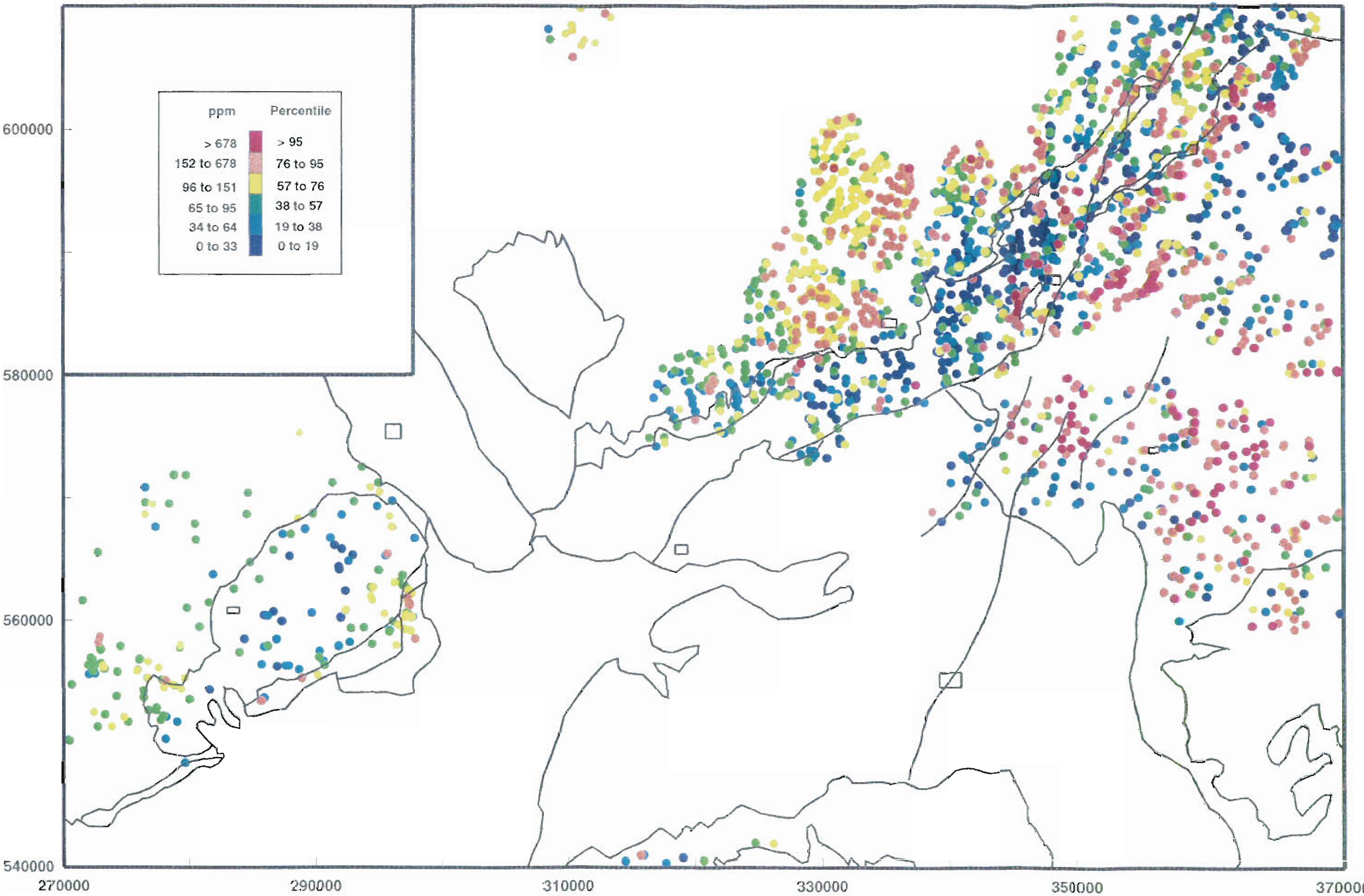


Figure 3.2. Colour symbol plot of Zn in panned concentrates

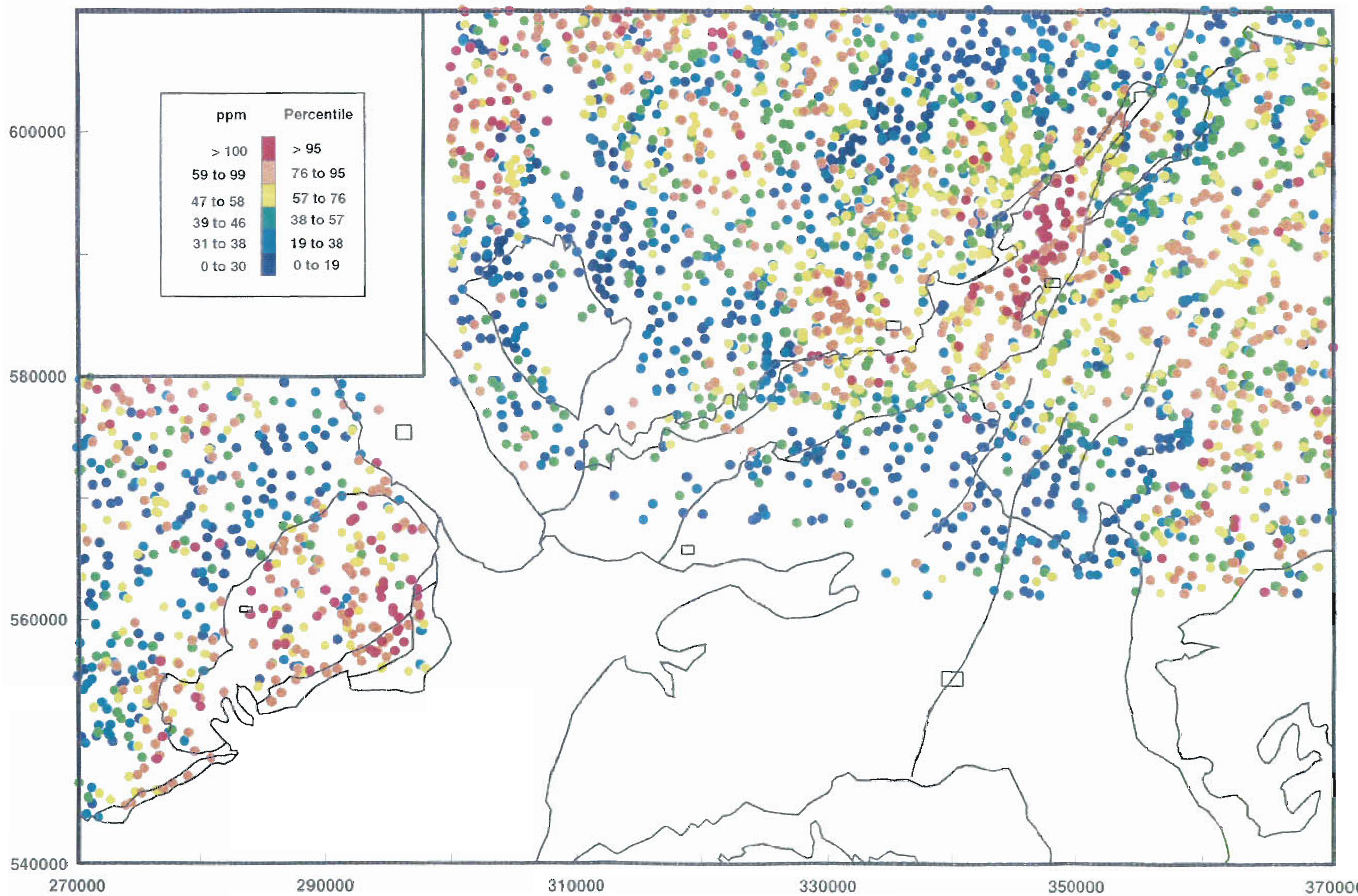


Figure 3.3. Colour symbol plot of Pb in stream sediments

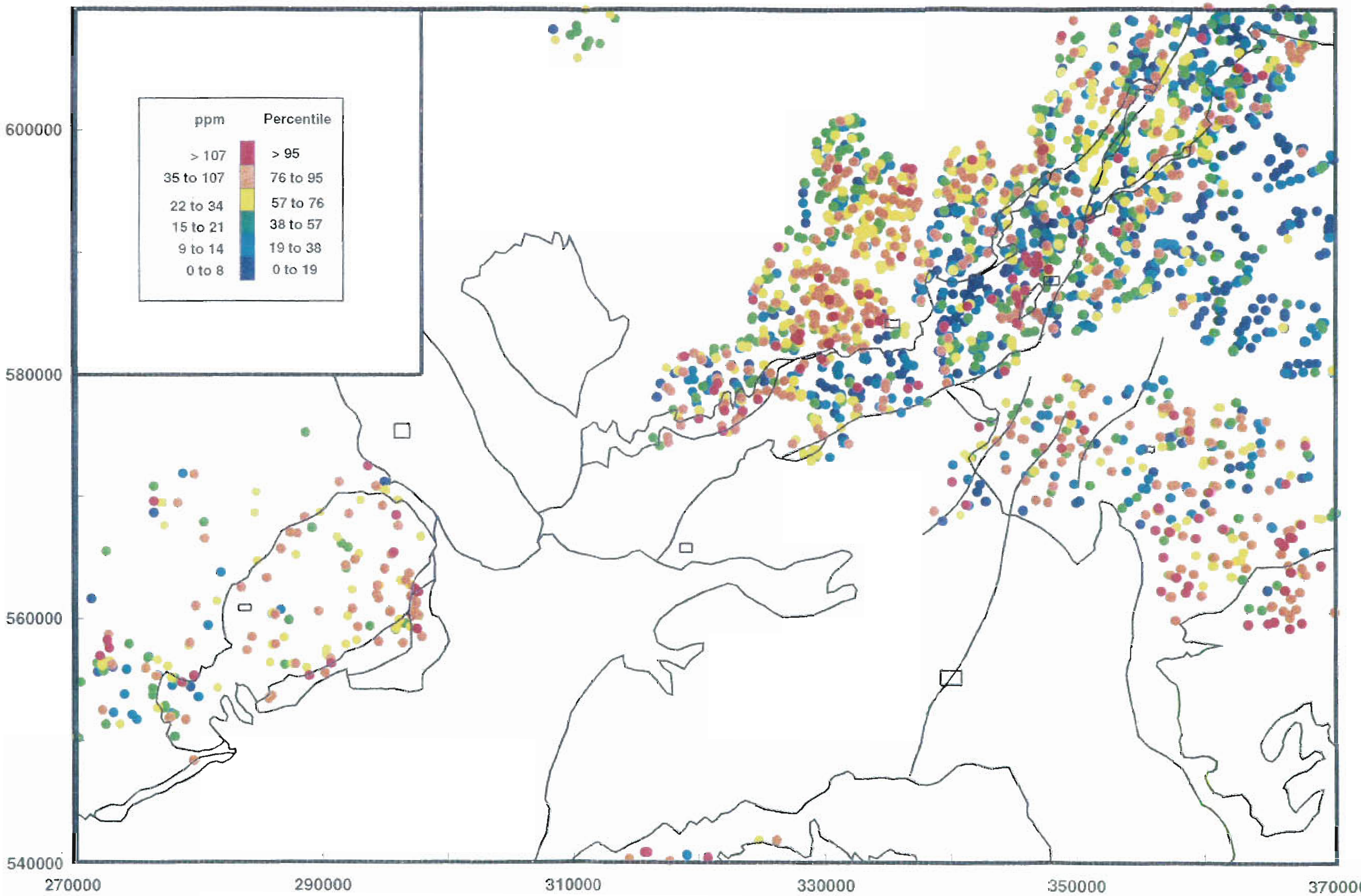


Figure 3.4. Colour symbol plot of Pb in panned concentrates

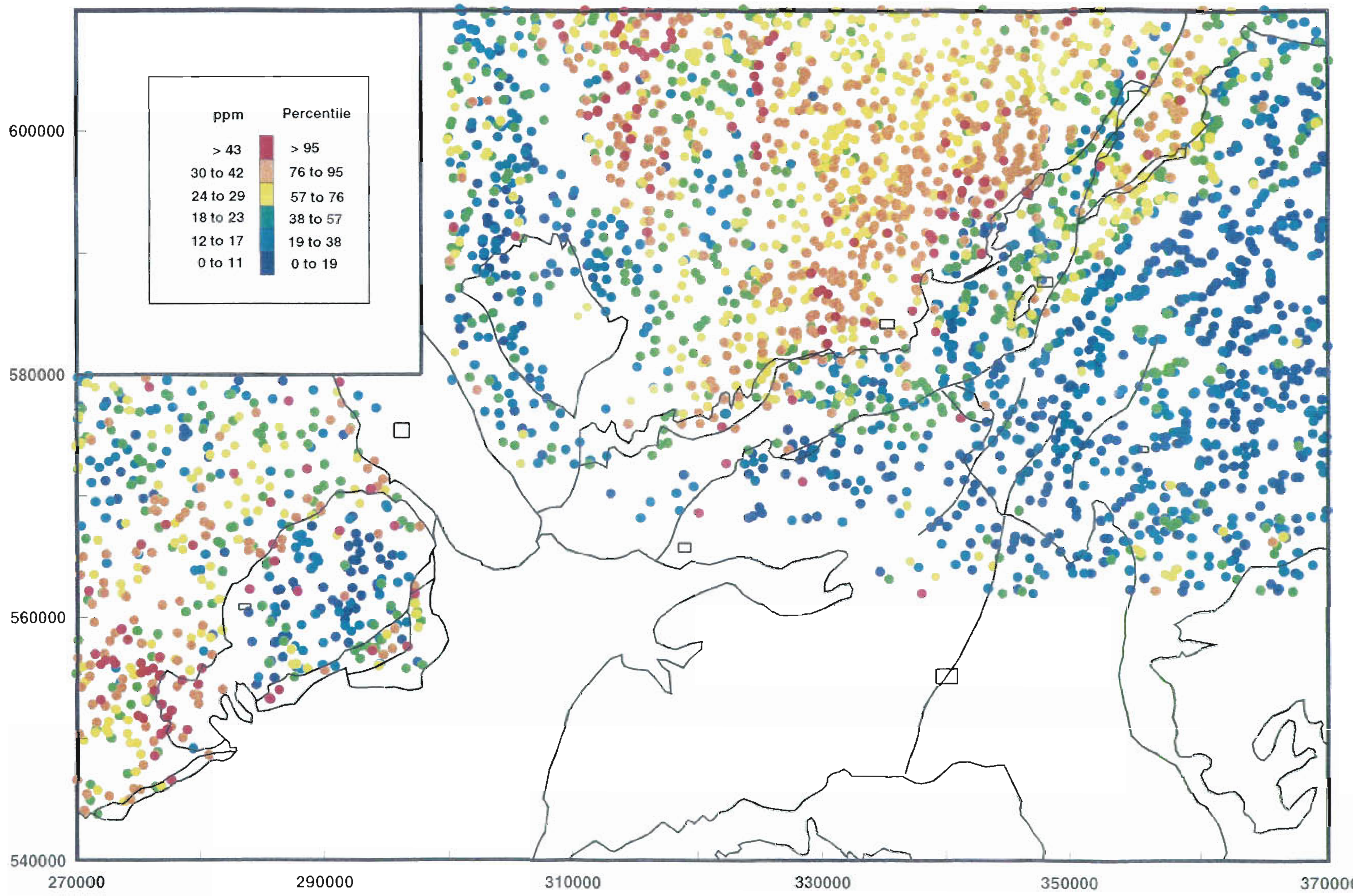


Figure 3.5. Colour symbol plot of Cu in stream sediments

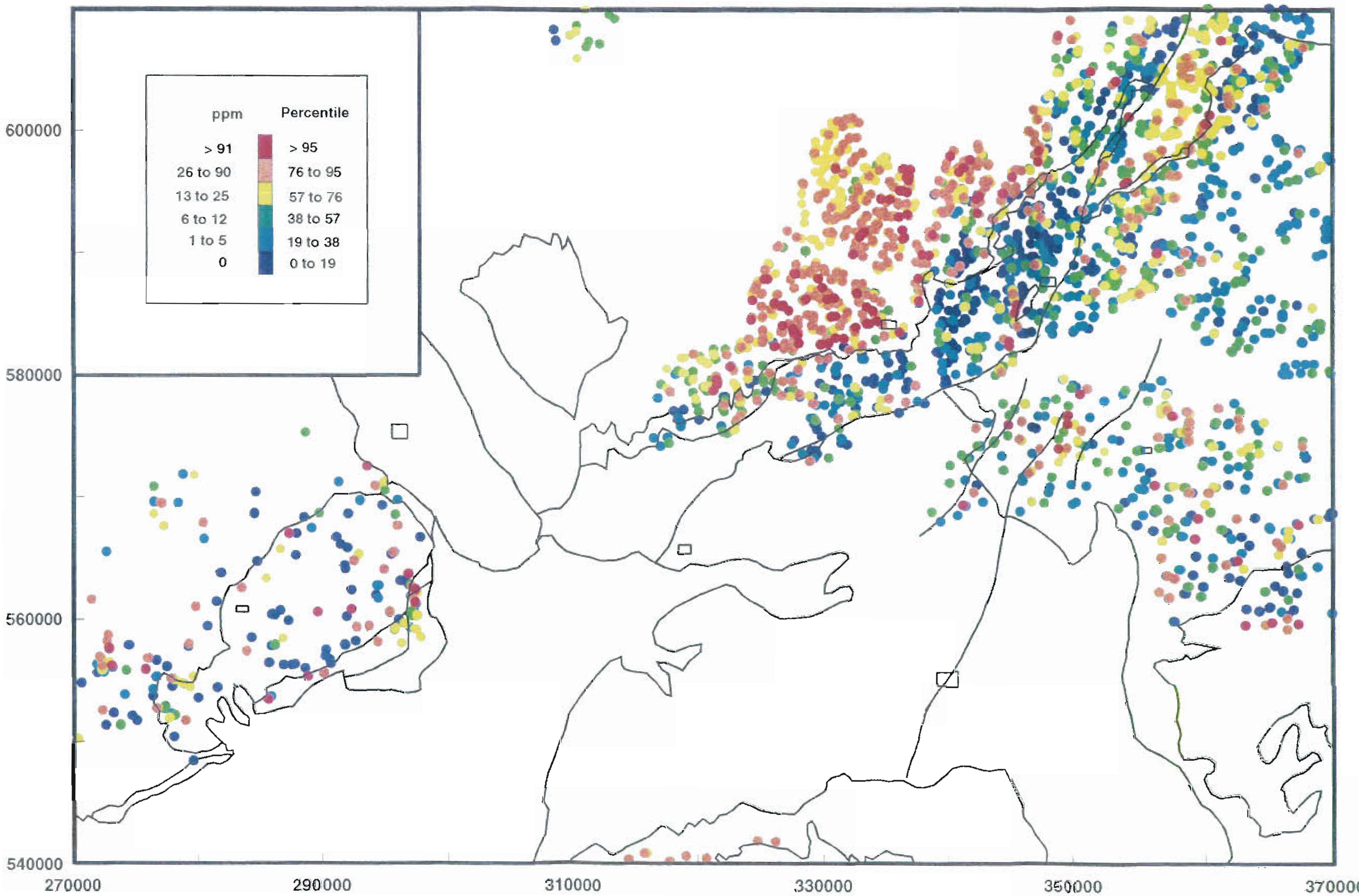


Figure 3.6. Colour symbol plot of Cu in panned concentrates

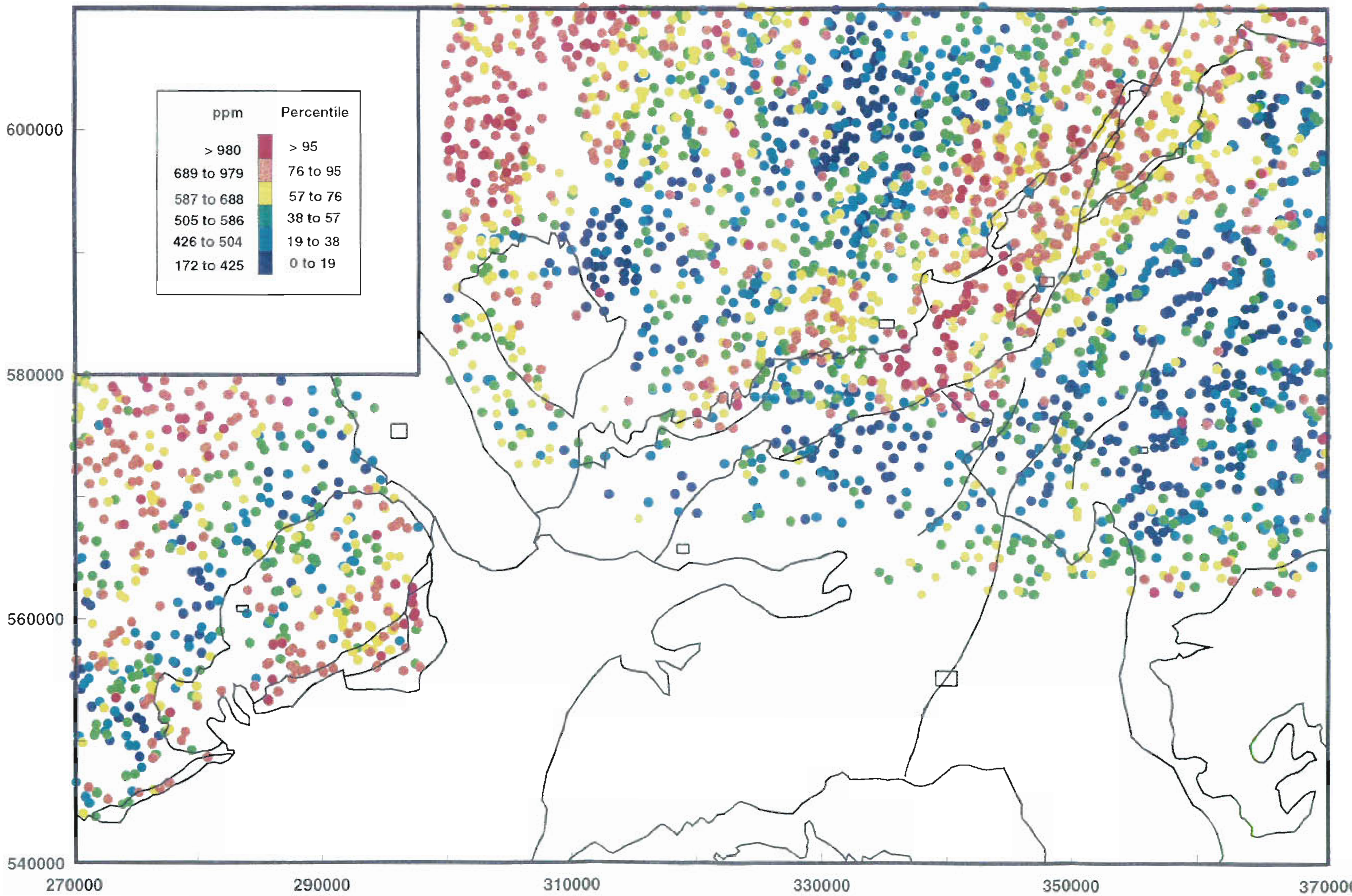


Figure 3.7. Colour symbol plot of Ba in stream sediments

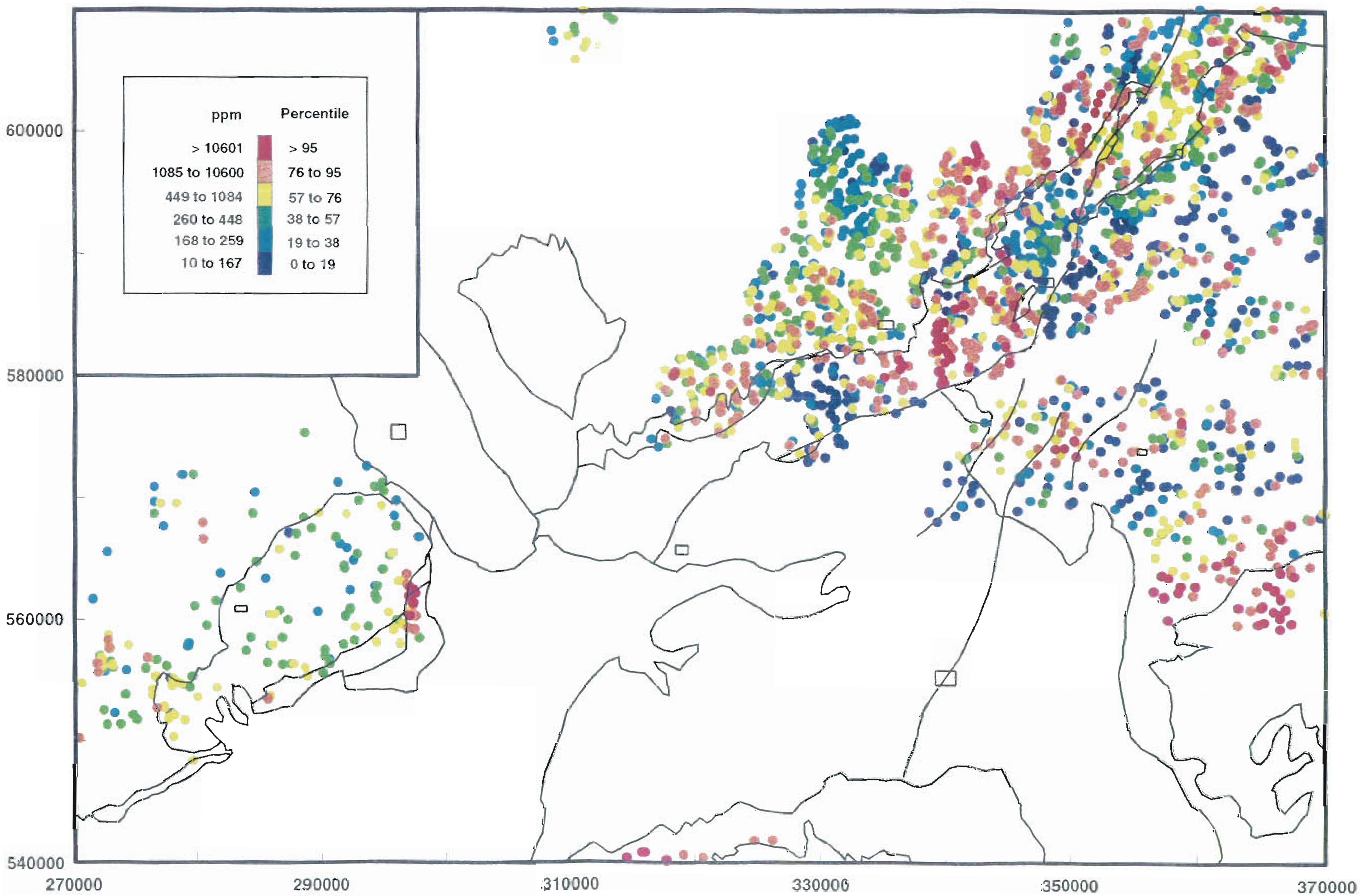


Figure 3.8. Colour symbol plot of Ba in panned concentrates

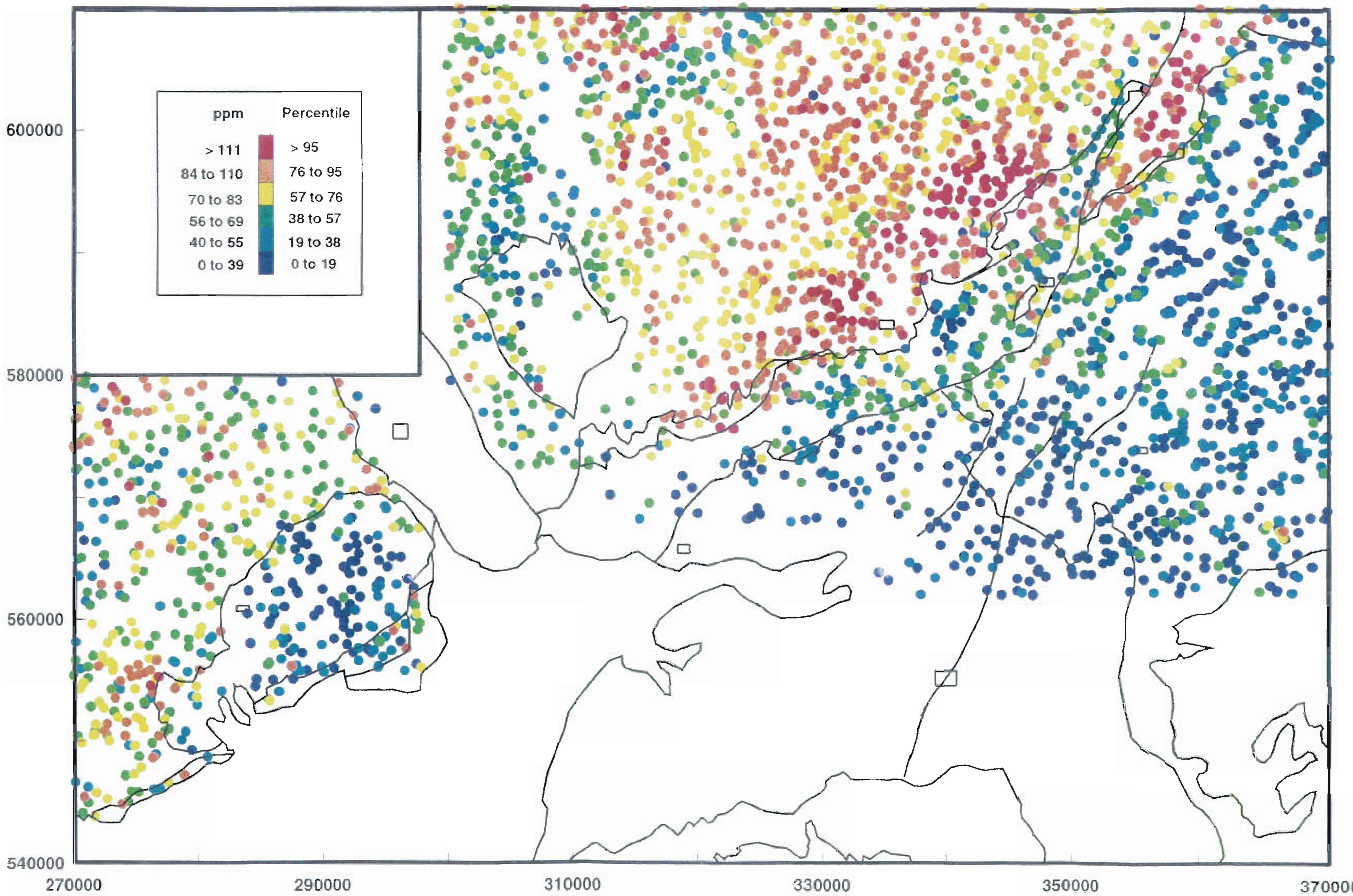


Figure 3.9. Colour symbol plot of Ni in stream sediments

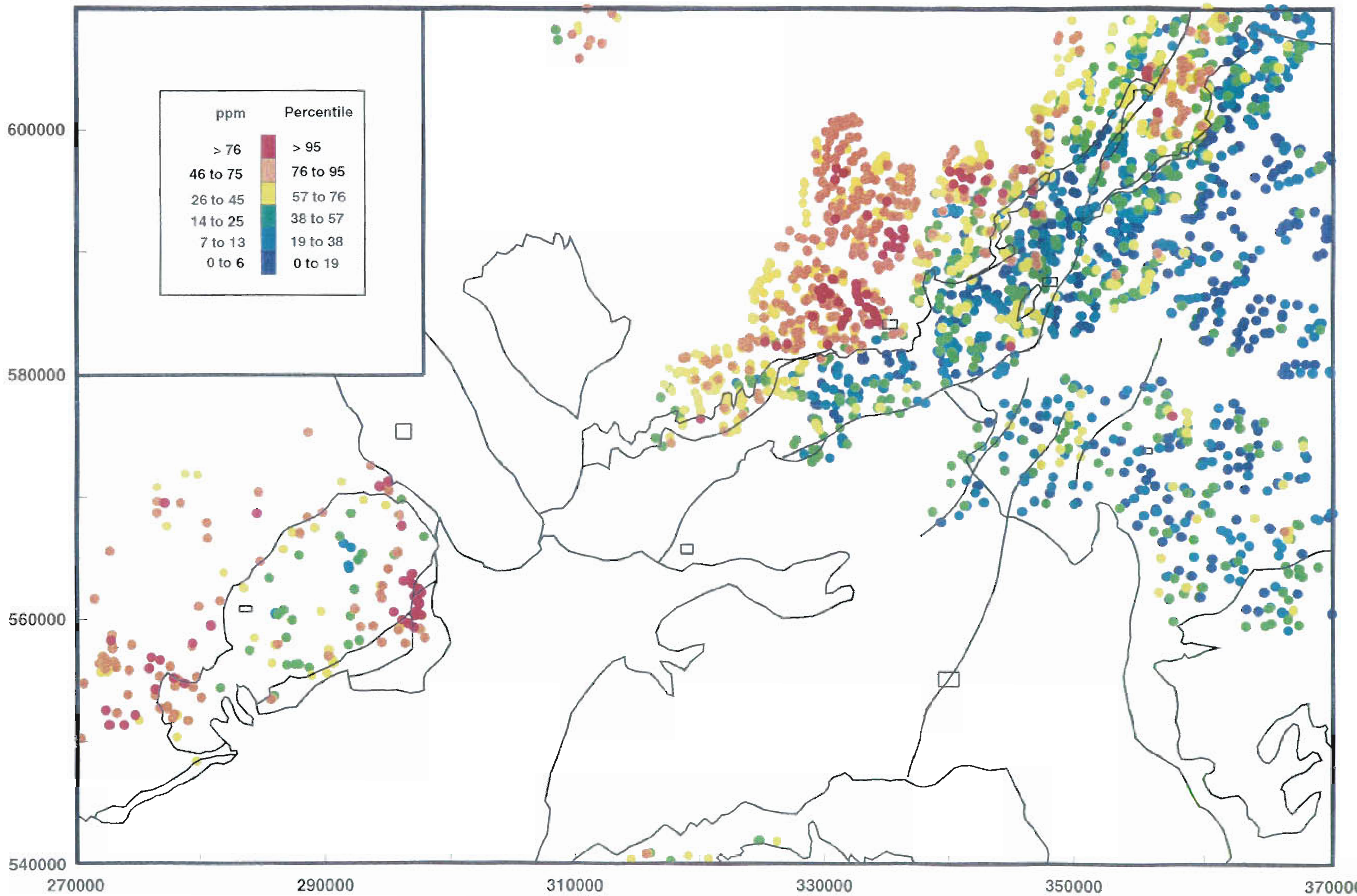
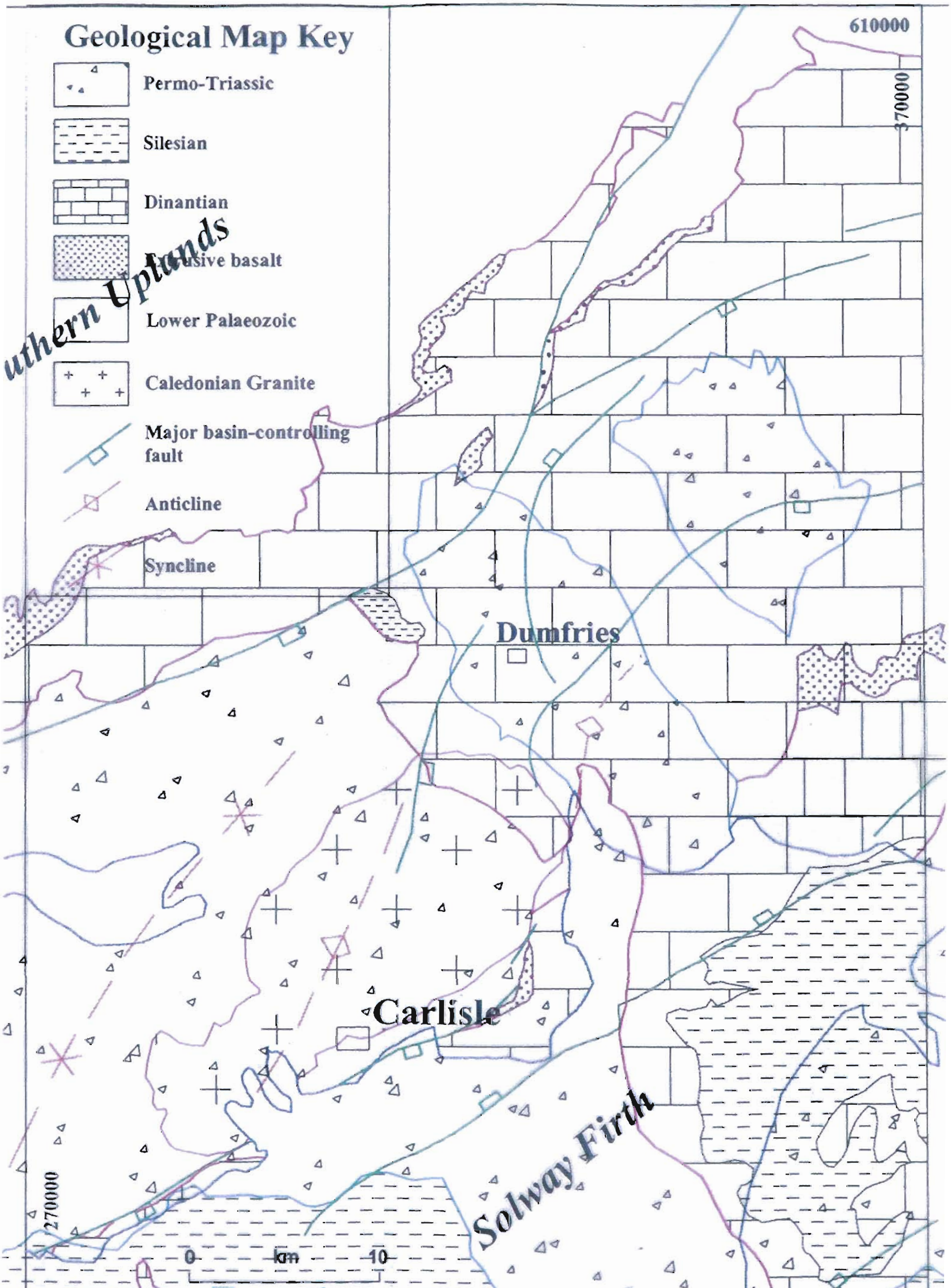


Figure 3.10. Colour symbol plot of Ni in panned concentratess



Geological Map Key
Permo-Triassic
Silesian
Dinantian
Extrusive basalt
Lower Palaeozoic
Caledonian Granite
Major basin-controlling fault
Anticline
Syncline
uthern Uplands
610000
370000
Dumfries
Carlisle
Solway Firth
270000
540000
0
km
10

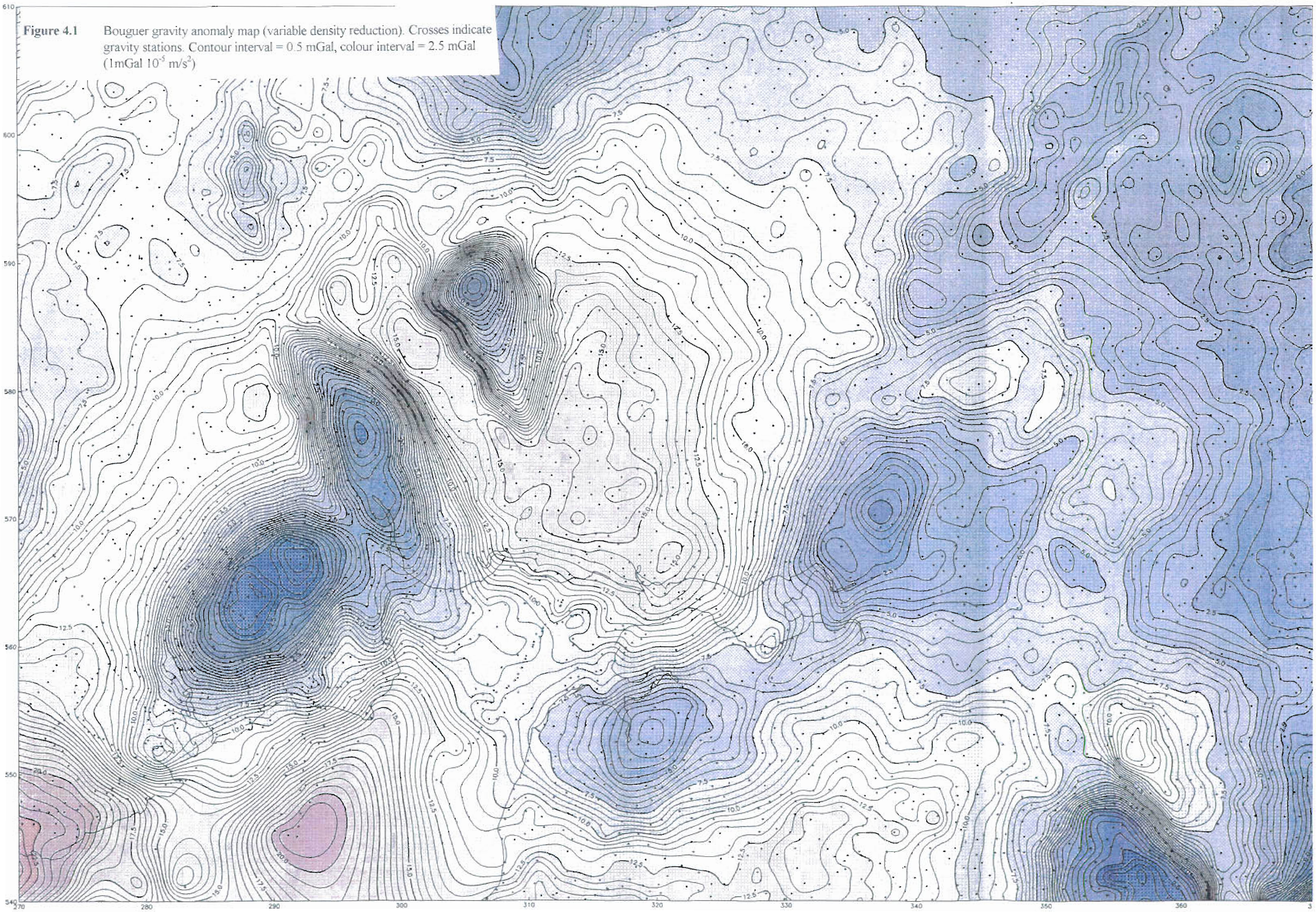


Figure 4.1 Bouguer gravity anomaly map (variable density reduction). Crosses indicate gravity stations. Contour interval = 0.5 mGal, colour interval = 2.5 mGal (1mGal 10^{-5} m/s^2)

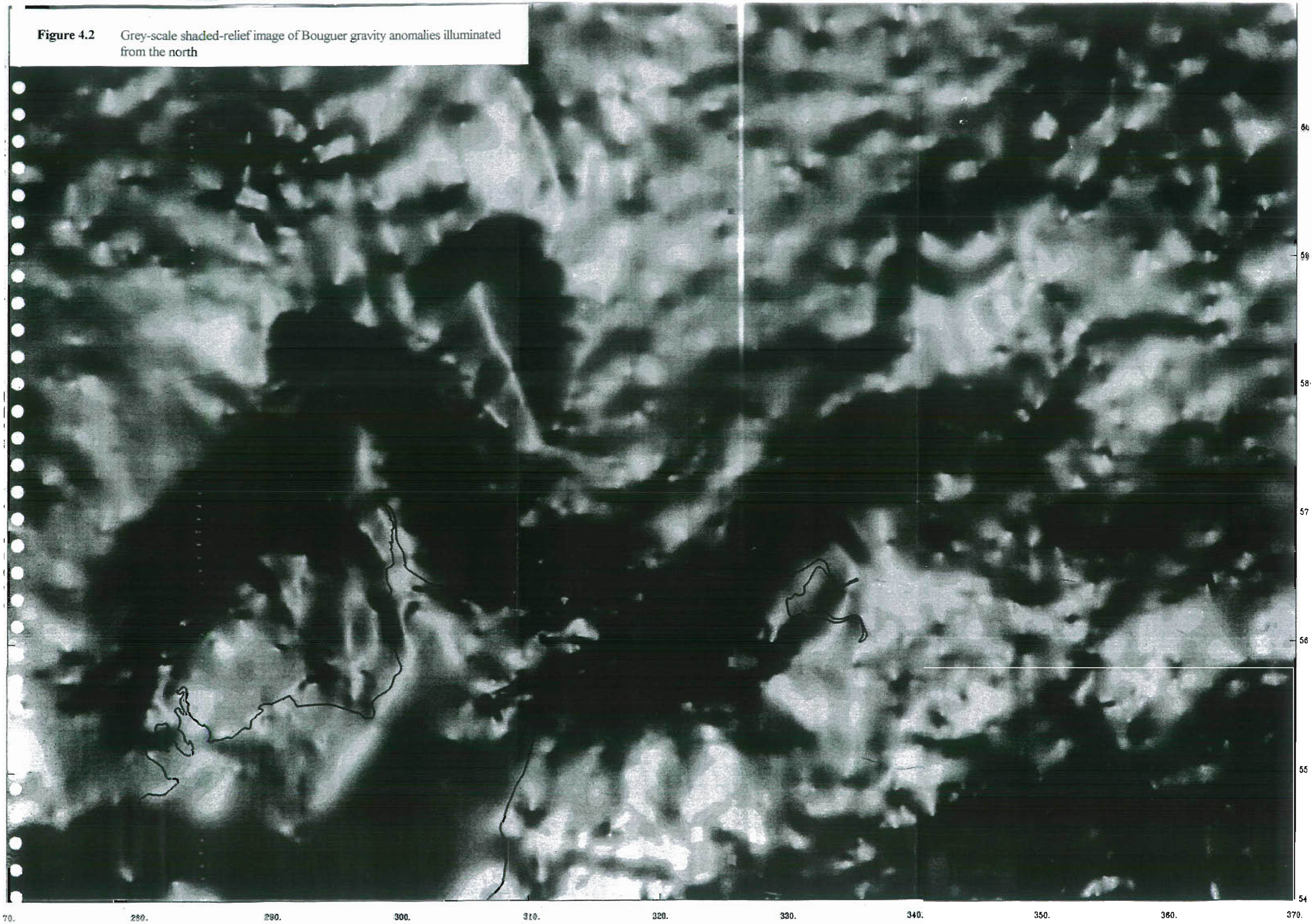


Figure 4.2 Grey-scale shaded-relief image of Bouguer gravity anomalies illuminated from the north

Figure 4.3 Grey-scale shaded-relief image of Bouguer gravity anomalies illuminated from the south

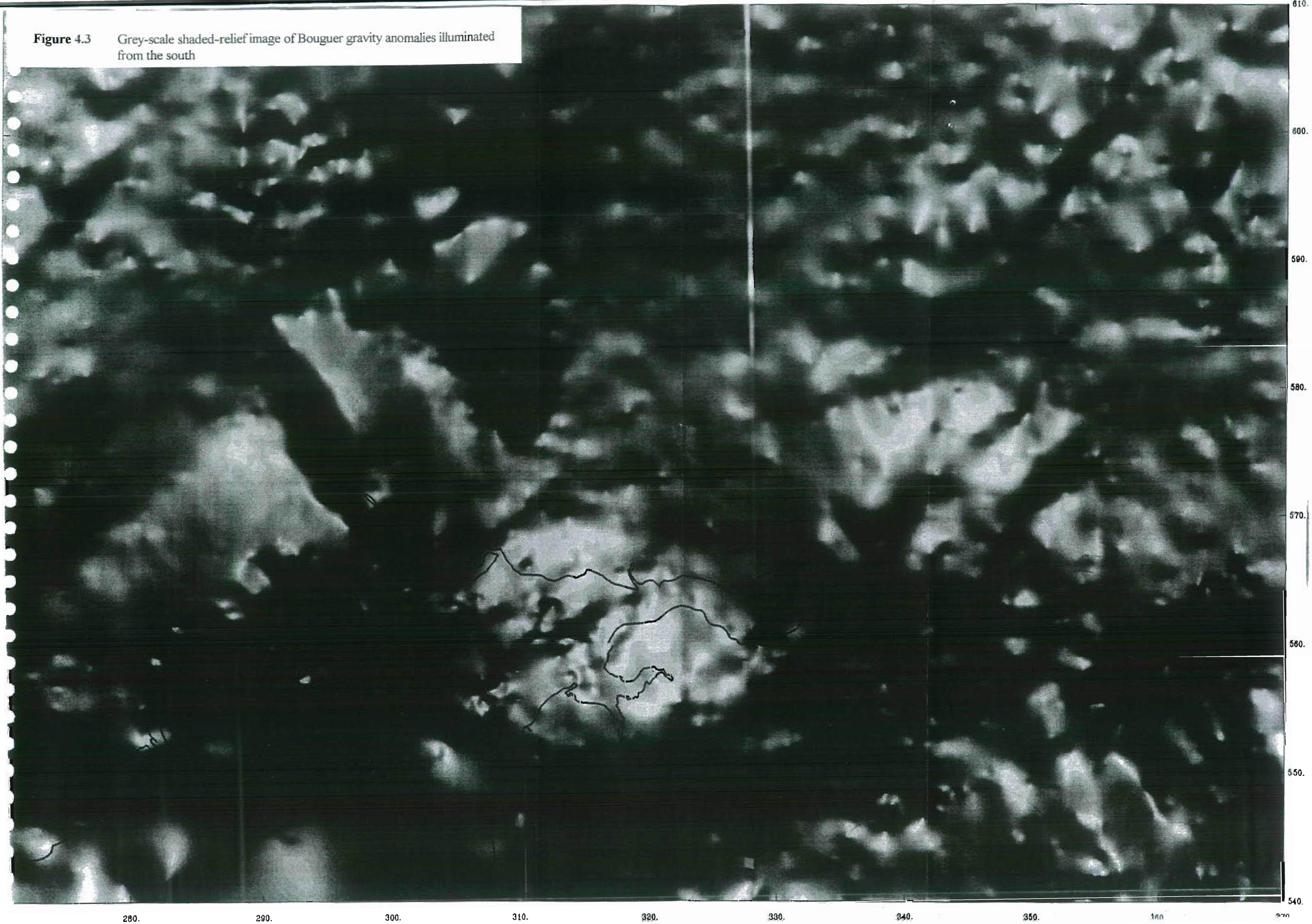
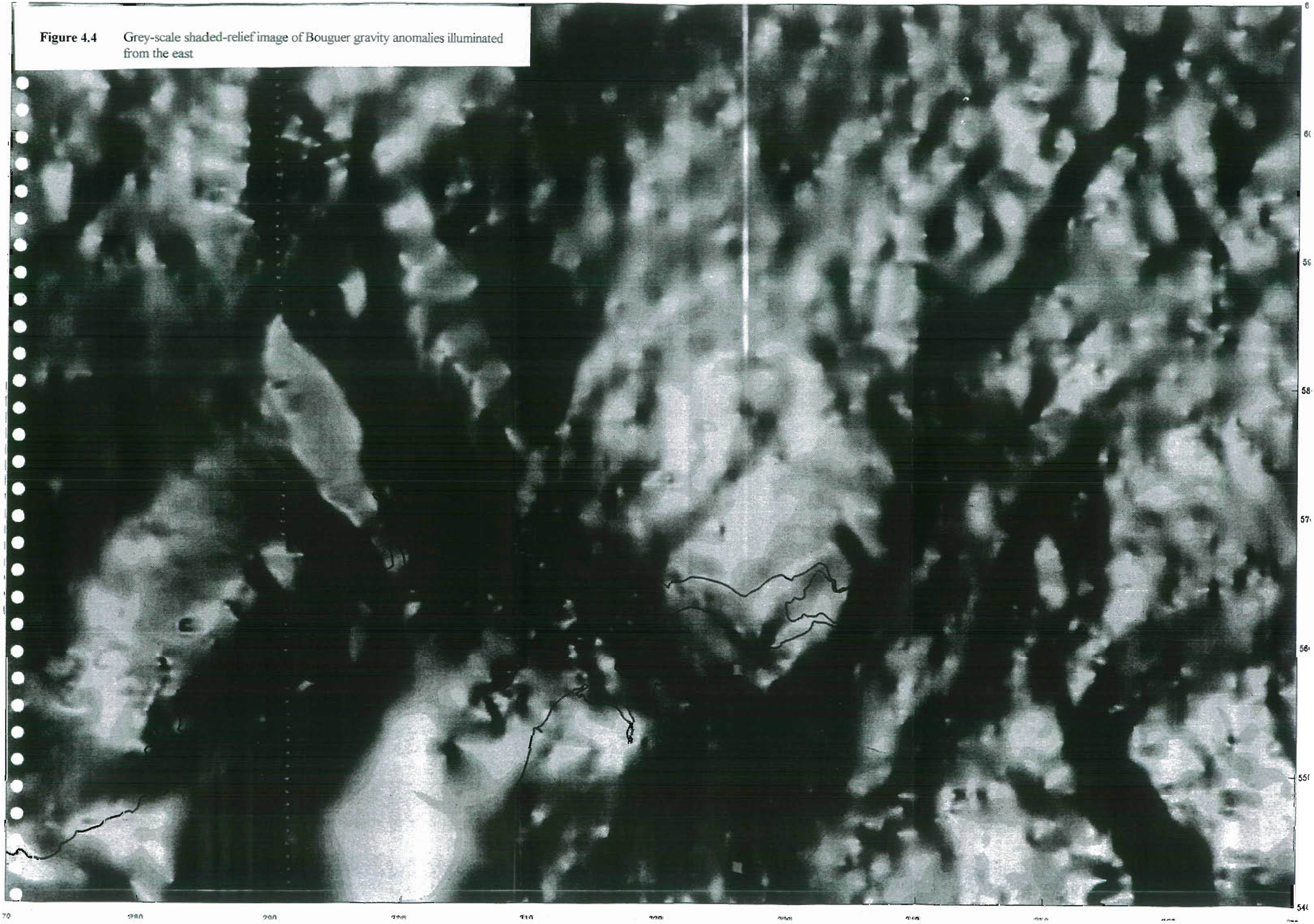


Figure 4.4 Grey-scale shaded-relief image of Bouguer gravity anomalies illuminated from the east



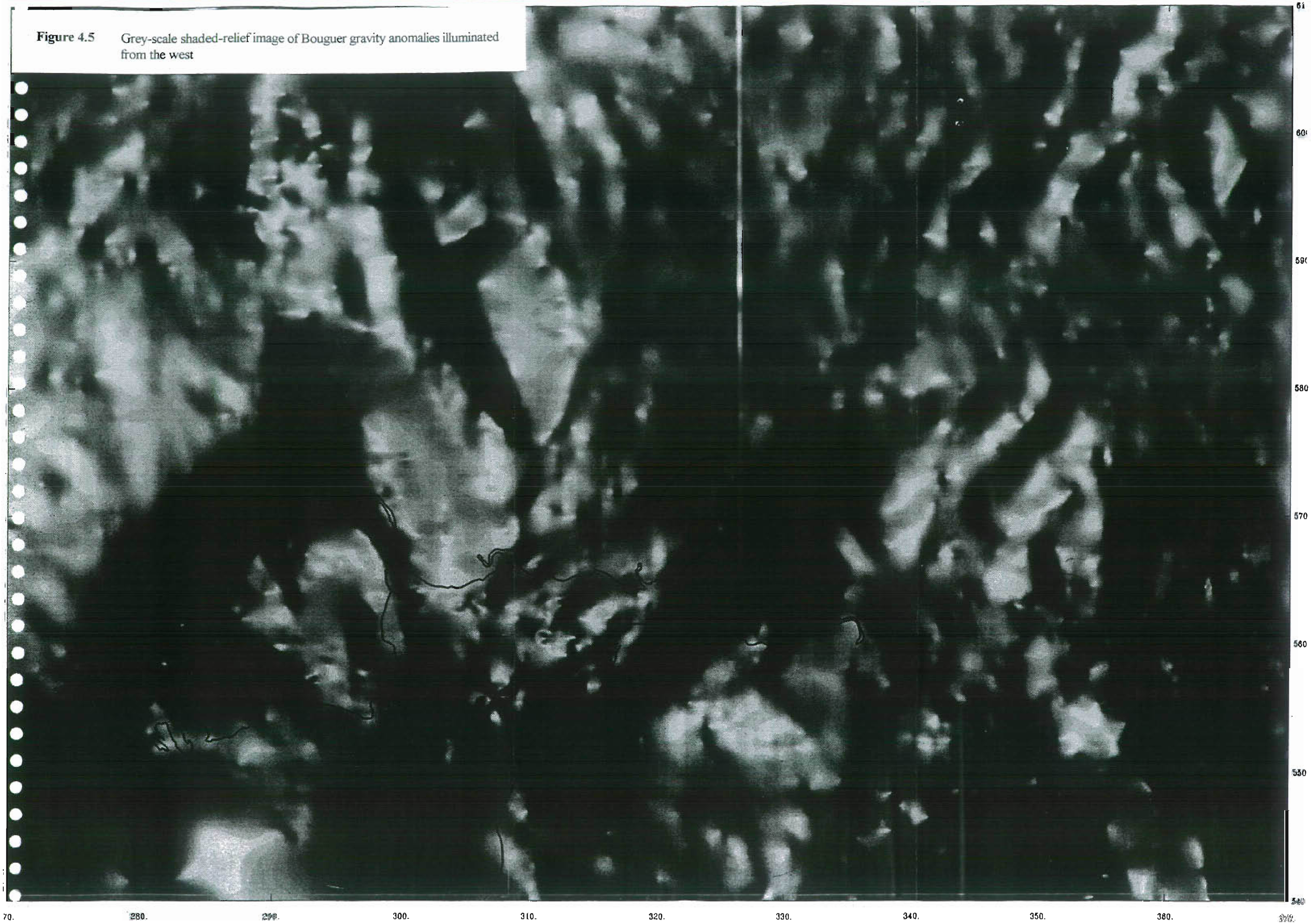


Figure 4.5 Grey-scale shaded-relief image of Bouguer gravity anomalies illuminated from the west

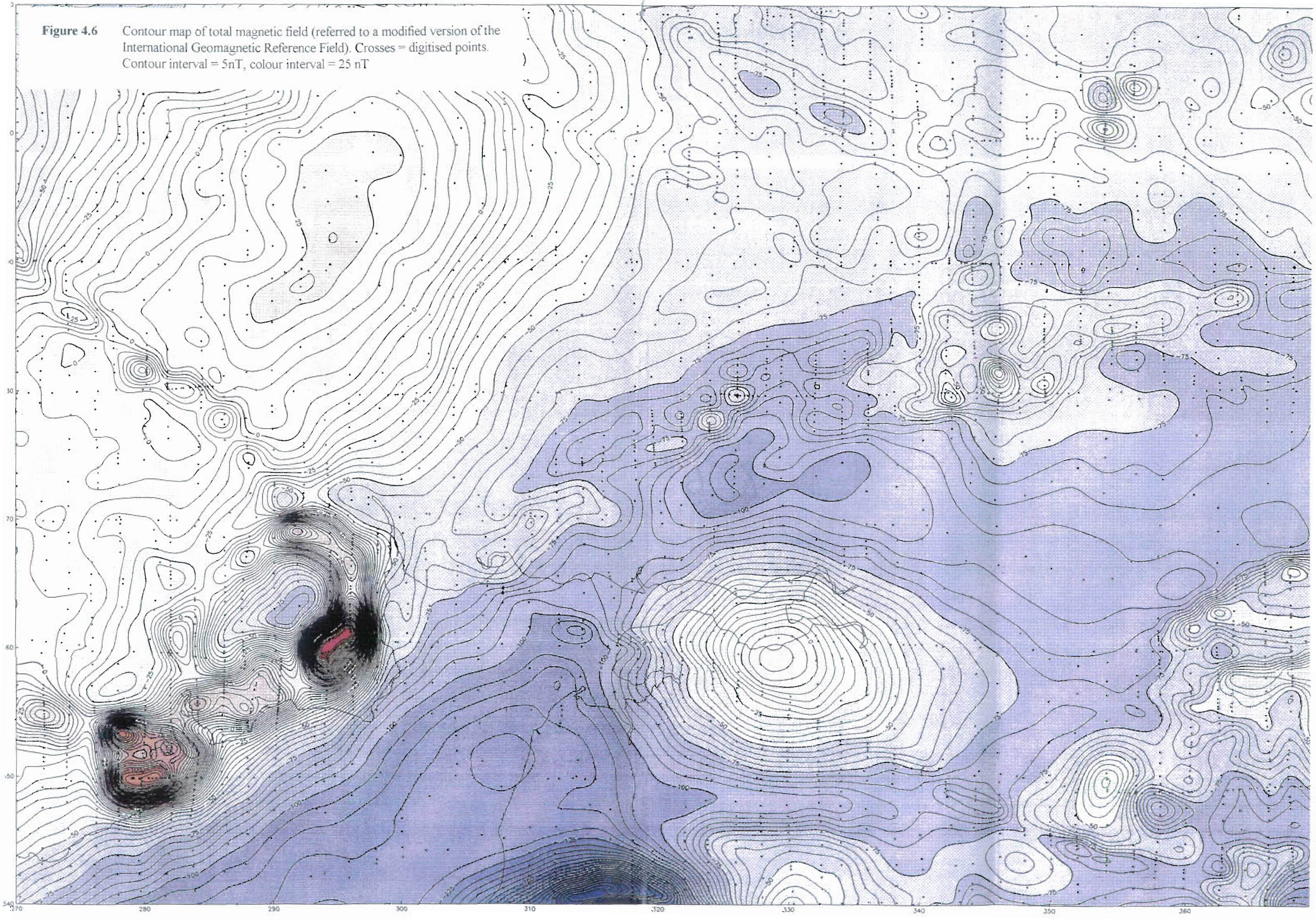


Figure 4.6 Contour map of total magnetic field (referred to a modified version of the International Geomagnetic Reference Field). Crosses = digitised points. Contour interval = 5nT, colour interval = 25 nT

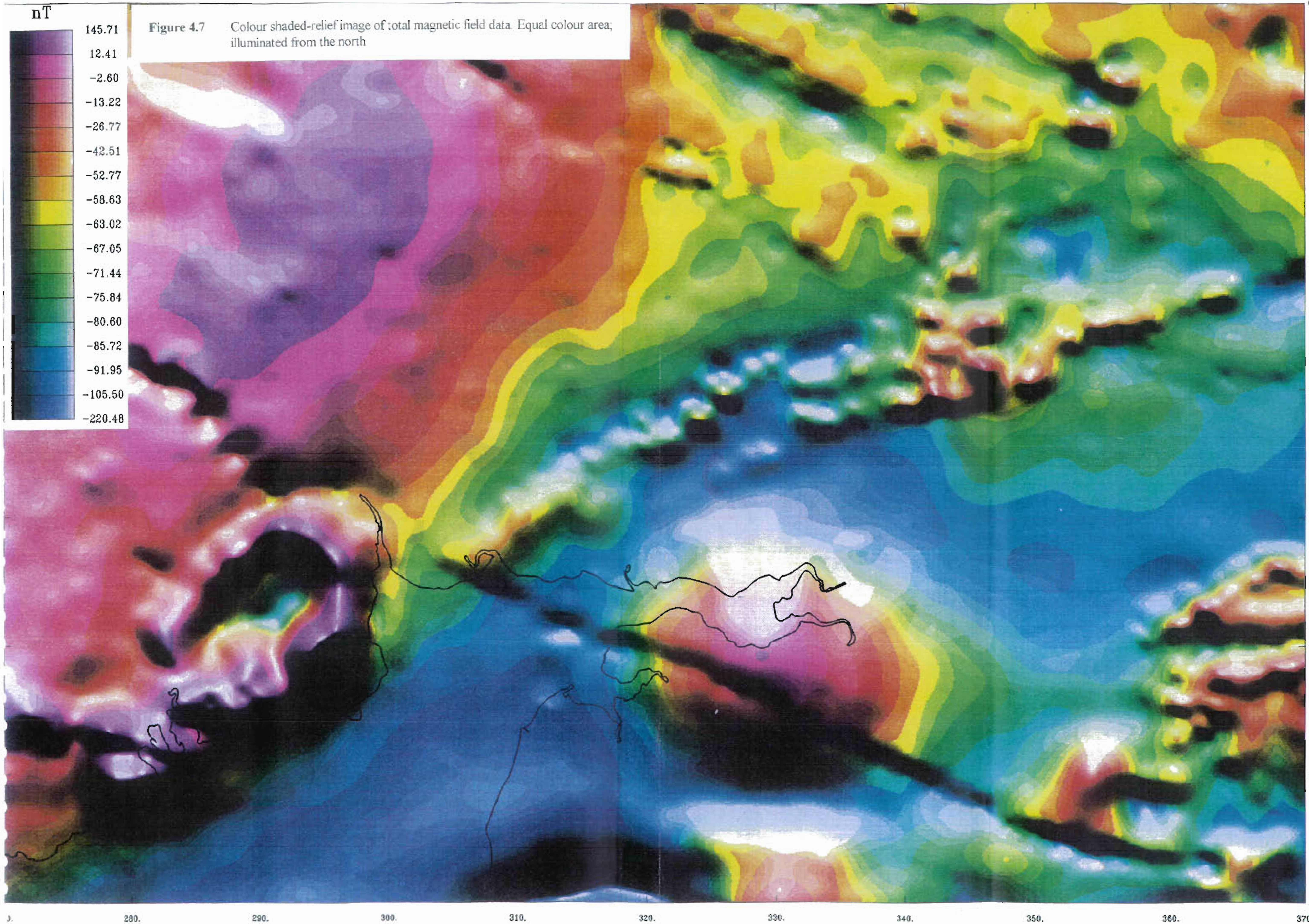


Figure 4.7 Colour shaded-relief image of total magnetic field data. Equal colour area; illuminated from the north

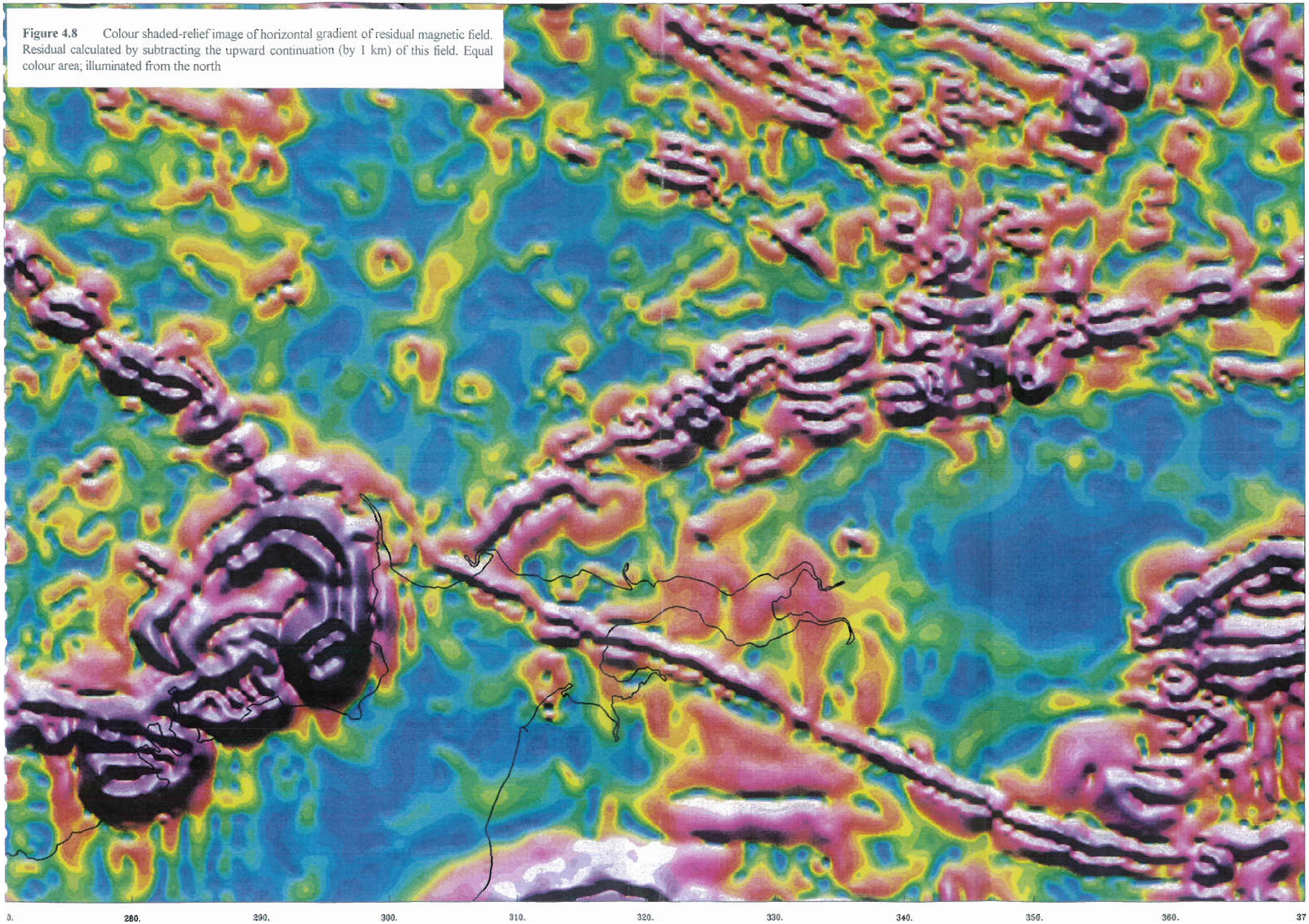


Figure 4.8 Colour shaded-relief image of horizontal gradient of residual magnetic field. Residual calculated by subtracting the upward continuation (by 1 km) of this field. Equal colour area; illuminated from the north

BRITISH GEOLOGICAL SURVEY

PROJECT NOTE RSG/94/2

Landsat TM Interpretation Notes: North Solway Region, Southern Uplands, Scotland

D.G.Tragheim

Remote Sensing Group

October 1994

Executive Summary

Two digitally enhanced, 1:50 000 and 1:250 000 scale, false colour Landsat Thematic Mapper images (path-row 204-022, bands 4-5-7, taken in November 1989) have been used to try and identify potentially basin-controlling lineaments and faults, which might influence the location of base metal mineral deposits in the North Solway region of the Southern Uplands, Scotland.

This interpretation is the result of a rapid study and forms a preliminary analysis subject to modification through field work and integration with other geophysical and geochemical datasets.

Using the Landsat imagery, it has been possible to define part of the North Solway basin boundary fault, near the southeastern margin of the Criffel-Dalbeattie granodiorite pluton. Although the position of the fault in this region was previously known, the lineament interpretation indicates that this NE-SW trending fault is probably composite in nature, and forms a zone up to 200 m wide. It was not possible to identify its north-eastwards continuation beneath the thick, glacial deposit lowlands of the north Solway region.

The main lineament trends on 1:50 000 geological map sheets 5E (Dalbeattie) and 6 (Annan) are: NW-SE, NE-SW, NNE-SSW, WNW-ESE and E-W. Most of these probably represent erosion along master joint sets, although some may be faults.

1. Background and aims

This project note contains details on an interpretation of two satellite Landsat Thematic Mapper (TM) images at 1:50 000 and 1:250 000 scales of the Solway Firth area, commissioned by T. Colman for the Minerals Group, Mineral Reconnaissance Programme Solway Project 63CS.

The main objective was to produce an interpretation of the TM data using topographic and tonal features, and indicate possible basin-controlling lineaments, particularly in the NE-SW, ENE-WSW and NNW-SSE directions. It is hoped that such lineaments, if faults, might also influence the location of base metal deposits whose delineation is the ultimate overall aim of the project. The specific aims were:

Aim 1. To delineate any features which might indicate the position of NE-SW, ENE-WSW or NNW-SSE basin-controlling faults.

Aim 2. To delineate any fault structures or stressed vegetation in an area where known barite vein mineralisation occurs in the Kirkbean region, to the south of Dumfries and east of Criffel.

Aim 3. To quickly look for similar fault structures in the Ecclefechan region, south-east of Locherbie.

2. Details of the data used

The imagery used in this study (path-row 204-022), was acquired by the Landsat 5 satellite on the 25 November 1989 at 10.42am (GMT). It had been previously processed by the Remote Sensing Group as part of the routine UK coverage. Subtle topographic features are highlighted by the low sun-angle for winter imagery, particularly where these are orthogonal to the illumination which is from the SE. Imagery acquired during the winter months also tends to have less confusing crop patterns, and more uniform vegetation growth.

The Landsat Thematic Mapper has a spatial ground resolution of 30 m at each instantaneous field of view (IFOV) for all bands except the thermal (band 6) which is 120 m. The TM is a line scanning instrument which records reflected radiation in 7 wavelength bands. These are:

Band 1	0.45 to 0.52 x 10^{-6}m blue-green
Band 2	0.52 to 0.65 x 10^{-6}m green-yellow
Band 3	0.63 to 0.69 x 10^{-6}m red
Band 4	0.76 to 0.90 x 10^{-6}m photographic infrared
Band 5	1.55 to 1.75 x 10^{-6}m near infrared
Band 6	10.40 to 12.50 x 10^{-6}m thermal infrared
Band 7	2.08 to 2.35 x 10^{-6}m short-wave infrared

These spectral bands have been carefully chosen to minimise the attenuation of surface energy by atmospheric water and also to provide information about certain natural phenomena listed below:

Band 1	Sensitive to chlorophyll and differentiations between deciduous/coniferous trees and also between soil/vegetation. Coastal water mapping.
Band 2	Sensitive to green reflectance by healthy vegetation.
Band 3	Sensitive to amount of chlorophyll absorption for differentiating plant species.
Band 4	Sensitive to infrared reflectance of healthy vegetation.
Band 5	Sensitive to vegetation moisture and snow/cloud reflective differences.
Band 6	Sensitive to thermal differences.
Band 7	Sensitive to vegetation moisture and also to hydroxyl ions in minerals.

The selection of the most suitable and informative bands for geological purposes has been the subject of much study, although less investigation has been done for temperate environments such as Great Britain, apart from Drury (1986). The BGS Remote Sensing Group has decided to standardise on two types of products. A Band 5 black-and-white image, and a false colour image combining Band 4 (in red), Band 5 (in green) and Band 7 (in blue).

In upland areas it has been found that this false combination of bands can provide a useful discrimination between natural vegetation associated with soils and their underlying Quaternary superficial deposits. Healthy green forest vegetation appears in shades of medium to dark reddish brown, with intervening areas of long tufted grass in bluish green. Sub-elliptical to elongate drumlins tend to have yellowish orange hues. Some areas of river alluvium are typified by smooth brownish orange colours while tidal flats have turquoise hues. Urban concentrations appear as irregular, coarsely textured bluish grey regions. In lowland areas, agricultural cultivation gives rise to a 'patchwork-quilt' mosaic of rectangles and polygons in various shades of orange and green. The latter colour indicating areas of relatively bare, moist soil.

The image processing consisted of geometric correction to the British National Grid (BNG), edge-enhancement, contrast stretching and the writing of colour and black and white negatives at a contact print scale of 1:600 000.

For this study, one colour print was produced at a scale of 1:50 000 from RSG negative RS/0027, covering sheets 5E (Dalbeattie), 6 (Annan), 9E (Thornhill), 10W (Lochmaben) and 10E (Ecclefechan). A regional overview colour print at 1:250 000 scale, was made from the whole of RSG negative RS/0027, which covers all of the Solway Firth region, including the northern part of the Lake District, Vale of Eden, and the western parts of the Alston Block and Northumberland Trough. Figure 1 shows the 1:50 000 geological sheet boundaries in relation to a 1:600 000 scale, colour photocopy of the processed Landsat image.

3. Method of interpretation

The interpretation was carried out on a clear overlay placed over the image, which was mounted on a light table to enable its study under transmitted light. Interpretation has been guided by previous experience gained in the adjoining Kirkudbright area to the west and north-west (Tragheim 1992), and also with reference to published and unpublished 1:50 000 solid and drift geology maps of the region.

The 1:50 000 interpretation was restricted to the region south and east of Dumfries. A fair copy of the 1:50 000 lineament interpretation has been produced on Ordnance Survey (OS) base maps for geological map sheets 5E and 6. The lineament interpretation is also presented as a single overlay to the satellite image so that the lateral persistence of features is clearly seen.

The imagery was checked against BNG using screened sepia overlays of the OS base maps and found to match the grid within reasonable limits. When transfering the interpretations to the base maps, small distortions can be accounted for by adjusting the position of the map overlying the enlarged satellite image to ensure a good local fit to the ground features. This was accomplished by using 20 by 10 cm rectangular grid blocks (10 km northing by 5 km easting).

The 1:250 000 interpretation of the North Solway region is presented as:

(a) an overlay to the satellite image.

(b) a colour photocopy of the lineaments overlying the satellite image.

(c) a colour photocopy of the lineaments overlying a digital versatec plot of the southern part of the 1:250 000 Borders geology map. It should be noted that the colour scheme for the geological units are non-standard.

As only 8 days were assigned to this study, no field checking component was available to the interpreter. The study should therefore be regarded as preliminary, and modified by later field investigation and with reference to detailed large scale 1:25 000 or 1:10 000 topographic base maps. Recent experience by the author in interpretating 1:50 000 satellite images in Leicestershire, has shown that many, if not most, lineaments in glaciated lowland regions are composite features such as drainage ditches, minor brooks, paths, tracks, fences and hedgerows, which are not displayed on the 1:50 000 Ordnance Survey base maps. The lineaments also sometimes mark geomorphological features associated with the drift and solid geological boundaries.

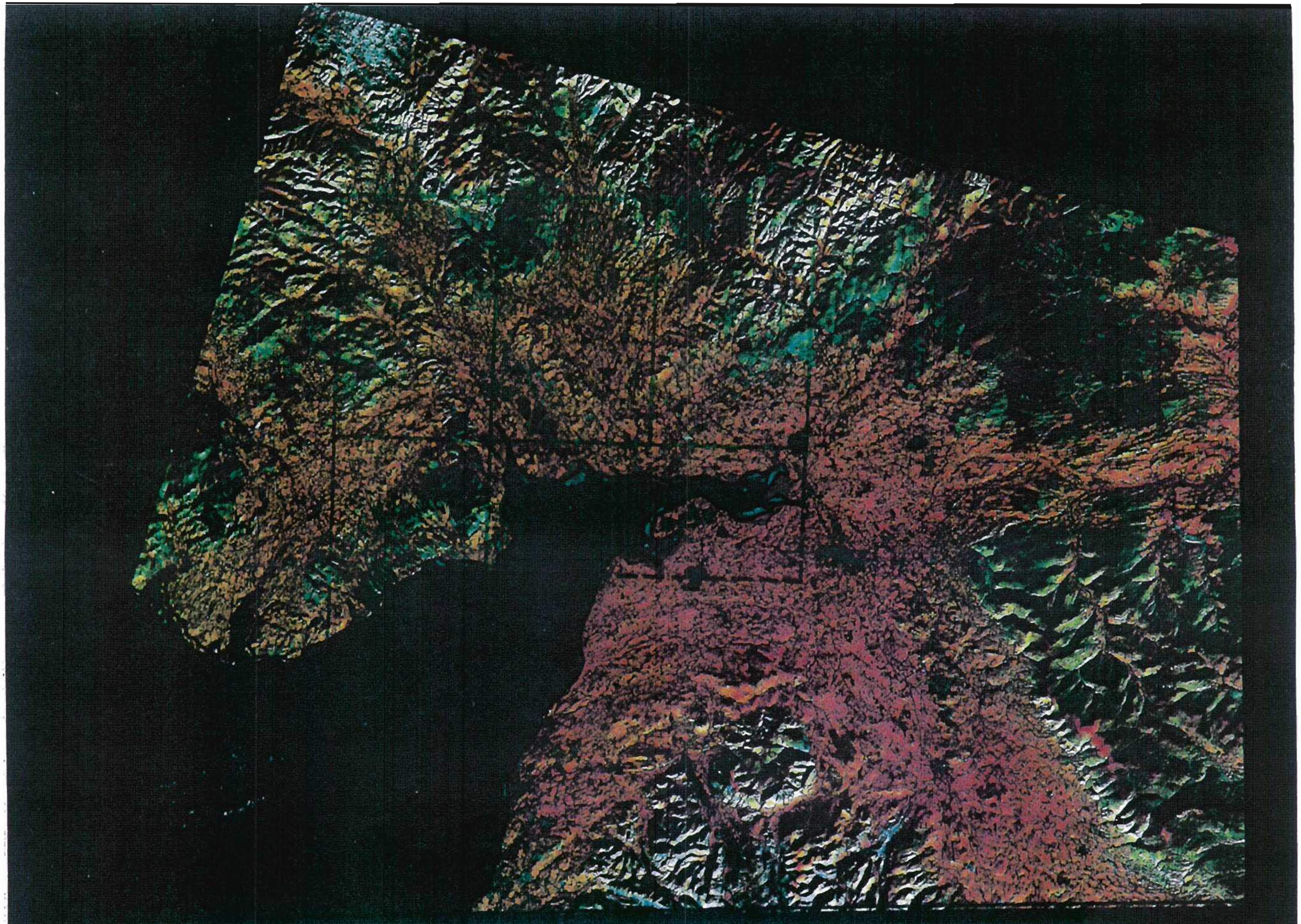


Figure 1 A 1:600 000 scale Landsat TM overview of the Solway Region, showing the position of 1:50 000 geological map boundaries.

4. Results

The landforms in the area result from a complex interaction between the solid geology and the effects of glaciation.

4.1 Geological setting south of Dumfries

Geologically this region mainly comprises the NE-SW trending, sub-elliptical, Criffel-Dalbeattie granodiorite pluton. It is bound to the west by the Silurian Llandovery, Carghidown Formation, consisting of calcareous greywackes and silty mudstones which are hornfelsed in the aureole of the granodiorite. To the east, the granodiorite intrudes and is partially faulted against a similar, but younger sequence of hornfelsed calcareous greywackes and silty mudstones belonging to the Ross Formation of Wenlock age. The main Solway Basin boundary fault trends NE-SW, but is cross-cut by later NW-SE trending faults, many of which extend well into the granodiorite pluton. It is also interesting to note that the granodiorite has a 3 km wide foliated zone along its eastern and northern margins. Further south, in the region of Rough Firth and Auchencairn Bay, this foliated zone curves north-westwards within the granodiorite and widens to about 5 km.

In the Kirkbean area, the Ross Formation is intruded by felsic rocks and microdiorite, and unconformably overlain by a discontinuous, very thin remnant of sandstones, siltstones and carbonate palaeosols of the Devonian Upper Old Red Sandstone. These rocks are overlain by olivine basaltic lavas of the Carboniferous (Tournasian) Birrenswick Volcanic Formation, which are thought to be related to tensional fracturing along the main basin faults (Chadwick et al. 1993) These lavas are in turn unconformably overlain by siltstones, sandstones and limestones of the Kirkbean Cementstone Formation, which form the upper part of the Lower Border Group of the Kirkbean outlier.

Just north of Mersehead Sands, undivided Lower Border Group lithologies have been downfaulted against the Ross Formation and Birrenswick Volcanic Formation, on faults trending E-W to ENE-WSW. From Southerness to Kirkbean, the Kirkbean outlier consists of a NNE-SSW trending and easterly younging sequence: the Southerness Limestone Formation, the Gillfoot Sandstone Formation and the Powillimount Sandstone Formation of the Lower to Middle Border Group. This is overlain by the Arbigland Limestone Formation from the Middle to Upper Border Group. To the west, this portion of the Kirkbean outlier is downfaulted against the undivided Lower Border Group and Kirkbean Cementstone Formation, on a curving, N-S trending fault. While to the north, the Southerness and Arbigland Limestone Formations, are downfaulted against the Kirkbean Cementstone Formation by an ENE-WSW trending fault. Within the Kirkbean outlier are minor E-W, WNW-ESE and NW-SE trending normal faults.

4.2 The 1:50 000 interpretation south of Dumfries

The lineaments of this area are shown on sheets 5E and 6, as enclosures in wallets 1 and 2 at the end of this report. They are divided into two main types, with broken lines denoting uncertainty:

(1) Topographic and tonal lineaments.

(2) Tonal lineaments.

The first category are thought to represent possible faults and master joints. The second category often occur as extensions of the first, and may thus represent their possible continuation. Occasionally, they also form sub-parallel features. None of these lineaments have been checked in the field, or screened for man-made cultural features using large scale 1:10 000 or 1:25 000 base maps.

The main trends of lineaments on sheets 5E and 6, in decreasing abundance are: NW-SE, NE-SW, NNE-SSW, WNW-ESE and E-W.

The **NW-SE lineaments** are most dominant within the Criffel-Dalbeattie granodiorite, and in an area to the north-west of Rough Firth and Auchencairn Bay in the Carghidown Formation region which contains part of the Black Stockarton Moor subvolcanic Complex. These lineaments are generally characterised by strong negative topographic features and are thus zones of weakness which erosion has preferentially exploited. They are thus interpreted as either master joints and/or faults.

When comparing a film overlay of the lineament interpretation with the recently published geology map sheet 5E & 6 (Dalbeattie 1993), there is a good correspondence with the 6 km long fault which occurs to the north-west of New Abbey. The Landsat interpretation suggests that this mapped fault might continue further south-eastwards, past the southern shore of Loch Kindar and on to Drumburn. In the region of Drumcow Burn, the present study has identified tonal lineaments along part of the northernmost of the two mapped, sub-parallel, NW-SE trending faults in the granodiorite. However a more prominent tonal/topographic lineament, which correlates with the forestry/arable land-use and a marked break in slope, suggests that the position of the northern fault may trend 060° instead of 045° from Redbank Hill to Boreland of Southwick. Compared with other NW-SW trending minor faults marked on the 1993 geology map, the Landsat lineaments either extend their possible continuation, or are sub-parallel to them. There are also more NW-SE trending lineaments than marked on the recent geology map. It is interesting to note that the dominant NW-SE trend of many of the small aplite dykes in the core of the granodiorite, and the porphyritic andesitic dykes in the foliated granodiorite south-eastern rim, correspond with the major Landsat lineament trend. This observation further strengthens the interpretation that these lineaments represent zones of weakness.

The **NE-SW lineaments** tend to occur in a 1-2 km marginal zone to the NE-SW trending granodiorite, and parallel the regional strike of the rocks. The main northern Solway Basin fault line, is well displayed on the Landsat image. From south-west to north-east, it occurs as the rectilinear coastline from Portling Bay to Southwick Water, and continues as a very strong negative break in slope from the Needles Eye at Mersehead to Caulkerbush. It then undergoes a 1 km right-lateral displacement (seemingly caused by WNW-ESE and NW-SE lineaments) to Hope Farm, and continues north-eastwards up Kells Burn to Kirkbean Burn where it is offset by a small NW-SE trending lineament. This section of the lineament is prominently displayed as a marked negative topographic break in slope and which also coincides with another distinctive land-use change from upland forestry to lowland agriculture. In contrast to the geological map which only shows a single, right-stepping, NE-SW trending fault line: the Landsat lineament interpretation suggests that the NE-SW trending Solway Basin fault line is a composite structure, and may have been reactivated during later Variscan N-S compression. In the Kells Burn to Kirkbean Burn area, the lineament pattern along the north Solway Basin fault, takes on the appearance of a sinistral strike-slip duplex, up to 200 m wide. The shorter interconnecting, slightly sigmoidal lineaments would thus correspond with R1 Riedal shears. There are also some smaller NE-SW trending lineaments in the Ross Formation, which might correspond with more resistent weathering greywackes.

There are also some weakly defined topographic but mainly tonal lineaments, which occur in a NE-SW trending zone, some 3-5 km WNW of Annan, on map sheet 6. Due to the thick boulder clay and glacial meltwater channel deposits in this region, it is uncertain if these lineaments have any structural significance.

The **NNE-SSW lineaments** are mainly confined to the granodiorite, although there are some N-S trending tonal lineaments on sheet 6, from the Kirkbean region northwards to Kirkconnell. The first group do not have any correspondences with the recent geology map (1993) and are thus probably master joints. Of the second group, there are only two minor fault correlations. There is a tonal lineament which corresponds with a N-S trending fault north of Cushot Wood. While south of Kirkbean, there is a NNE-SSW trending, 0.5 km long lineament which partially matches the fault which downthrows Southerness Limestone Formation against the undivided Lower Border Group. The significance of the other NNE-SSW trending lineaments is unknown.

The **WNW-ESE lineaments** tend to occur mainly within the south-eastern part of the granodiorite from Rough Firth to Southwick Water. These lineaments are characterised by well defined, rectilinear topographic depressions. However there are no marked faults with this orientation in this area, on the Dalbeattie geology map (1993). They may represent either master joints, or hitherto undiscovered, faults. From Caulkerbush to Loaningfoot, there is a 4 km long, discontinuous WNW-ESE trending lineament which coincides with the right side-stepping offset of the North Solway fault. The significance of this lineament is uncertain, as it trends 115° compared with the E-W to ENE-WSW trending continuation of the North Solway Fault, as depicted on the Dalbeattie geology map (1993). However this map does show that there are minor normal faults with a WNW-ESE trend in the coastal region of Arbigland.

The **E-W lineaments** are mostly confined to the coastal region of sheet 6, from Kirkbean to Drumburn. They range in length from 250 m to 2 km and tend to follow drainage depressions within the glacial drift. Their structural significance is dubious. However there are some longer E-W trending lineaments between northings 558000m and 559300m within the granodiorite, which also mark linear drainage depressions.

4.3 The 1:250 000 interpretation of the North Solway Region.

A rapid interpretation was undertaken of the North Solway region at 1:250 000 scale, in order to see if any major lineaments could help define the North Solway basin boundary fault. Unfortunately this was not possible, due to the thick mantling of glacial deposits in the northern coastal region from the river Nith to Gretna. Lineaments in the vicinity of Ecclefechan were also briefly noted.

Figure 2 shows the regional lineament interpretation overlying the Landsat false colour image of the Solway region. To the north of Langholm, the lineaments exhibit a complex network of curvilinear features which vary in azimuth from 010° to 040°. South of Langholm, they tend to curve south-westwards, with orientations between 050° and 060°. In the vicinity of Dumfries and Thornhill, the main lineaments trend either NW-SE or NNE-SSW. To the west of Ecclefechan the lineaments trend 355°-360° and also 010°-015°.

Figure 3 shows the lineament interpretation overlying a digital version of the 1:250 000 Borders geology map. (Please note that the colour scheme does not conform with the standard colours on the printed version of this map). The purpose of this is to show the correlations or otherwise, of the linements with the known chronostratigraphy and structure. Briefly, there is a moderate correlation of lineaments with the faults which trend 060° in the Lower Carboniferous, and that some of these might extend further southwestwards. There is also a moderate correlation of lineaments with NNE-SSW trending faults, north of Langholm, in rocks of Wenlock age. However the lineament interpretation suggests that there might be many more similarly oriented structures, west and north-west of Langholm. These lineaments also cross-cut the Llandovery-Wenlock boundary.

5. Conclusions and recommendations

Aim 1. This study has been partially successful in delineating NE-SW basin-controlling faults along the western margin of the Solway Basin, bordering the Criffel-Dalbeattie granodiorite pluton. Although the position of the main faults were already known in this area, the Landsat interpretation indicates that they are composite structures, forming a zone up to 200 m wide. In the Kells Burn to Kirkbean Burn area, the lineament pattern resembles a sinistral strike-slip duplex, with shorter interconnecting, weakly sigmoidal lineaments possibly representing R1 Riedal shears. This overall structural pattern might indicate reactivation along the main basin boundary fault during later Variscan N-S compression. It was not possible to identify the basin boundary fault beneath the thick glacial, drift-covered lowlands in the northern Solway region.

Aim 2. No stressed vegetation was detected in the Kirkbean area, in relation to known barite vein mineralisation. This might be due to the fact that each pixel of the Landsat TM imagery has a ground resolution of 30 m, while the known maximum vein thickness is of the order of 1 m. Two weakly defined, N-S trending topographic and tonal lineaments were identified in the region of known mineralisation from Cushot Wood to Drum Burn, 2 km NNW of Kirkbean. One of these corresponds to a mapped fault. There are other N-S trending lineaments in this general region, although it is uncertain if they are faults.

Aim 3. In the Ecclefechan region, the main lineament trends are 355°-360° and 010°-015°. Two of these correlate with mapped faults shown on the 1:250 000 scale Borders geology map.

It is strongly recommended, that prior to any field-checking of the lineaments interpreted in this study, they are checked against large scale 1:25 000 and/or 1:10 000 scale topographic maps, for any potential correspondences with cultural features.

6. References

Chadwick, R.A., Holliday, D.W., Holloway, S. & Hulbert, A.G. 1993. The evolution and hydrocarbon potential of the Northumberland-Solway Basin. In: Parker, J.R (ed). *Petroleum Geology of Northwest Europe: Proceedings of the 4th Conference,* 717-726.

Drury, S.A. 1986. Remote sensing of geological structure in temperate agricultural terrains. *Geol. Mag.* ***123***, 113-121.

Tragheim, D.G. 1992. Interpretation of 1:50 000 Landsat Thematic Mapper Imagery of the Kirkcudbrightshire Region, Southern Uplands, Scotland. *British Geological Survey Technical Report* WA/92/32/C, 45pp.

Geological Maps

1:50 000 solid (S) and drift (D) geological maps:

5E and part of 6 Dalbeattie (S) 1993 (versatec plot).
5E Dalbeattie (D) 1981.
9E Thornhill (S) 1978, (D) 1980.
10W Lochmaben (D) 1983.
10E Ecclefechan (D) 1982).

1:250 000 solid (S) geological map:

55N 04W Borders (S) 1986.

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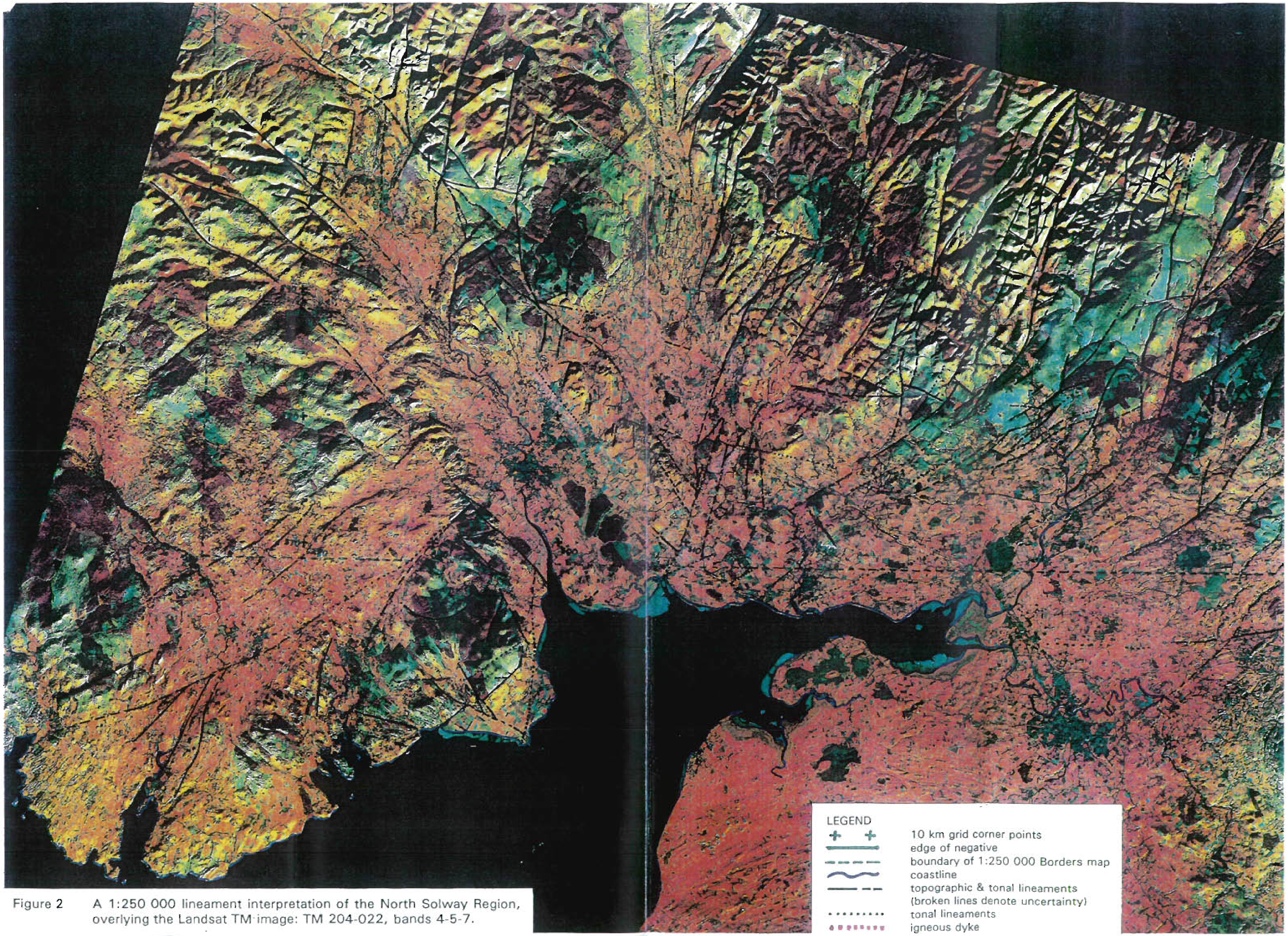

Figure 2 A 1:250 000 lineament interpretation of the North Solway Region, overlying the Landsat TM image: TM 204-022, bands 4-5-7.

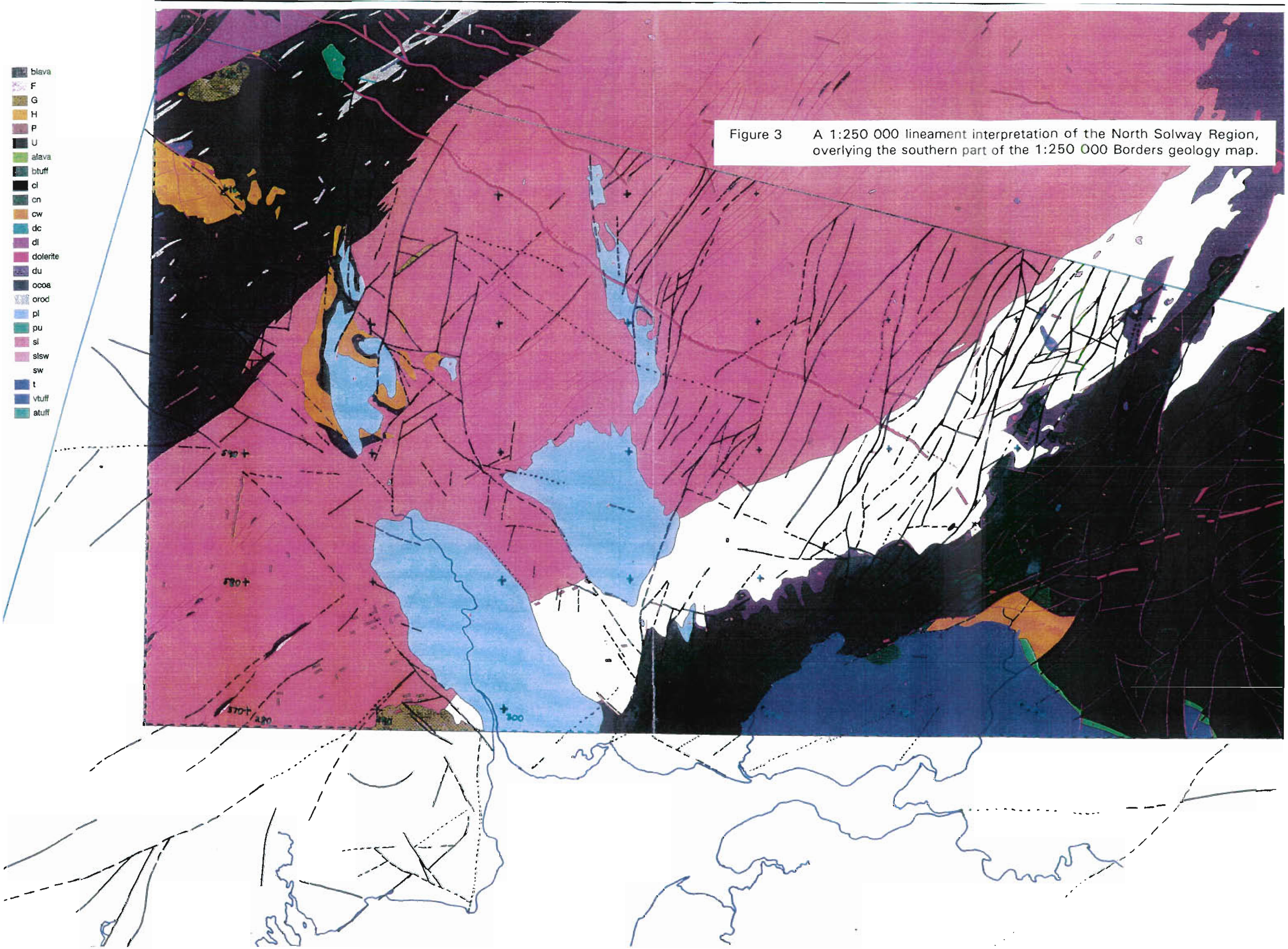

Figure 3 A 1:250 000 lineament interpretation of the North Solway Region, overlying the southern part of the 1:250 000 Borders geology map.

1:50 000 Series

ANNAN

SHEET 6

ORDNANCE SURVEY OF GREAT BRITAIN

Based on 1:50 000 First Series sheet 84 and 1:50 000 Second Series sheet 85 dated 1976

The representation on this map of a road, track or path is no evidence of the existence of a right of way.

LINEAMENTS INTERPRETED FROM LANDSAT THEMATIC MAPPER IMAGE TM 204-022, BANDS 4-5-7, NOV 1989

SHEET 6 - ANNAN

Scale 1:50 000

1 ¾ ½ ¼ 0 1 2 3 4 Miles

1 0 1 2 3 4 5 6 Kilometres

Contour values are given to the nearest metre. The vertical interval is, however, 50 feet

Heights are to the nearest metre above sea level.

LEGEND

——— – – – Topographic & tonal lineaments

.... Tonal lineaments

Broken lines denote uncertainty

Geological overprint ©NERC 1994

WF/MR/95/17