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Mineral Reconnaissance Programme

Exploration for carbonate-hosted base-metal mineralisation near Ashbourne, Derbyshire

Department of Trade and Industry

MRP Report 139

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G E Norton

Contributions by: N Aitkenhead and
N J P Smith

BRITISH GEOLOGICAL SURVEY

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Authors

J D Cornwell MSc, PhD
J P Busby BSc, PhD
T B Colman MSc, MIMM, CEng
G E Norton MA, PhD
BGS, Keyworth

Contributors

N Aitkenhead BSc, PhD, CGeol
N J P Smith MSc
BGS, Keyworth

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Keyworth, Nottingham NG12 5GG
☎ 0115-936 3100 Telex 378173 BGSKEY G
Fax 0115-936 3200

Murchison House, West Mains Road, Edinburgh, EH9 3LA
☎ 0131-667 1000 Telex 727343 SEISED G
Fax 0131–668 2683

London Information Office at the Natural History Museum, Earth Galleries, Exhibition Road, South Kensington, London, SW7 2DE
☎ 0171-589 4090 Fax 0171-584 8270
☎ 0171-938 9056/57

19 Grange Terrace, Edinburgh EH9 2LF
☎ 0131-667 1000 Telex 727343 SEISED G

St Just, 30 Pennsylvania Road, Exeter EX4 6BX
☎ 01392-78312 Fax 01392-437505

Geological Survey of Northern Ireland, 20 College Gardens, Belfast BT9 6BS
☎ 01232-666595 Fax 01232-662835

Maclean Building, Crowmarsh Gifford, Wallingford, Oxfordshire OX10 8BB
☎ 01491-838800 Telex 849365 HYDROL G
Fax 01491-25338

Parent Body

Natural Environment Research Council
Polaris House, North Star Avenue, Swindon, Wiltshire SN2 1EU
☎ 01793-411500 Telex 444293 ENVRE G
Fax 01793-411501

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Dr D C Cooper
Minerals Group
British Geological Survey
Keyworth
Nottingham NG12 5GG

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SUMMARY

Exploration has been carried out for lead-zinc-baryte mineralisation in Carboniferous (Dinantian) limestones to the south of the main mining district of the Peak District. Previous evidence from regional gravity surveys suggested the existence here of a ridge of limestones, the Snelston ridge, largely concealed beneath a thin cover of Permo-Triassic rocks. The structural setting suggests that the area could lie near the projected margin of the Staffordshire stable shelf area and at the northern margin of the Needwood Permo-Triassic Basin. Evidence provided by old mining activity in two small limestone inliers on the Snelston ridge encouraged the present exploration for concealed mineralisation either at the unconformity between these rocks and the overlying Permo-Triassic or, more importantly, hosted by limestones.

Interpretation of the improved regional gravity data sets and detailed traverses led to better definition of the location of the concealed limestone surface. Additional evidence on the concealed structure was provided by a commercial seismic reflection profile which became available during the project, and which clearly indicated the fault-controlled nature of the ridge. The gravity interpretation, supported by evidence from resistivity soundings, led to the siting of a borehole. This proved the existence of a shallow (60 m) Dinantian limestone ridge but found little mineralisation at the unconformity, apart from minor barium enhancement.

At the Limestone Hill inlier, previous mining history and limited evidence from exposures pointed to the existence of sulphide and baryte mineralisation in the exposed Chadian knoll-reef limestone. High barium, lead and zinc values were obtained from soils over the exposed limestone and geophysical surveys improved the interpretation of the near-surface geology. A borehole proved extensive replacement galena-sphalerite-baryte mineralisation with up to 10% Pb over an intersection of about 10 m near the top of the knoll-reef. The mineralisation is of replacive type in limestone which has been extensively dolomitised to leave a very cavernous rock. There is no evidence of fluorite, but baryte is common at the surface and occurs in the borehole core. Two further boreholes on the flanks of the knoll-reef showed that the mineralisation is associated with the dolomitised summit and does not extend laterally to any great distance.

The proven existence of the Snelston ridge provides a possible target in an otherwise unexplored area. A geophysical approach to further exploration would involve detailed gravity surveys and the application of methods capable of locating mineralisation at depths of 100 - 200 m.

INTRODUCTION

The Lower Carboniferous rocks exposed in the Derbyshire Dome (Peak District) have long been known to contain mineralisation and the area, the South Pennine Orefield, has a long history of mining. The main area of activity has been in the eastern part of the exposed Dinantian rocks (Figure 1), where veins have been mined for lead, zinc and fluorite. Outside this area, copper has been extracted from deposits at Ecton, to the west of the dome, and, to the south, there are a few occurrences of hydrothermal vein and replacement deposits in the limestone and mineralisation at the Carboniferous - Triassic unconformity. Included in the southern area are the two isolated occurrences of copper, lead and baryte in the small limestone inliers of Snelston and Limestone Hill within the outcrop of Permo-Triassic rocks at the northern margin of the Needwood Basin (Figure 1)[1].

The present interest in the Birchwoodpark - Limestone Hill area was initiated by examination of the regional gravity data (Figure 2) carried out in an assessment of the deeper geology of the Ashbourne district and summarised in the BGS memoir (Chisholm et al., 1988). The Bouguer gravity anomaly data for the area indicate that the two inliers probably form part of a concealed ridge of Lower Carboniferous rocks extending in a south-south-east direction from the main limestone outcrop (Figure 3). This suggestion was not supported by the limited borehole evidence available, which was interpreted to show the presence of an east-trending palaeo-valley at the base of the Permo-Triassic extending down at least to Ordnance Datum (O.D.) (Chisholm et al., 1988, fig. 20). However, the possibility that this ridge might contain economic mineralisation was supported by the gravity data suggesting that the structure could be fault-controlled, particularly on the south-west side, and that the fault could have been related to a growth structure controlling sedimentation during Lower Carboniferous times. A margin separating the stable area of the Staffordshire shelf from the 'mobile belt' to the north-east is inferred approximately along the line of the geophysically defined structure by Chisholm et al. (1988, fig. 28). In addition, the Carboniferous rocks at Limestone Hill form one of a series of Waulsortian knoll-reefs in the Milldale Limestones of Derbyshire whose growth-form have been compared with those in Ireland (Chisholm et al., 1988, p 19). A number of major lead-zinc deposits occurring in the Lower Carboniferous of the Irish Midlands are associated with normal faults which have permitted mineralising fluids to move upwards into Courceyan - Chadian carbonates, including Waulsortian reef facies (McArdle, 1990). Reef complexes at the margins of basins are therefore potential targets for mineral exploration. The presence of a shallow Carboniferous ridge would also raise the possibility of exploring for occurrences of mineralisation at the Carboniferous-Triassic unconformity, comparable with that at Snelston (Birchwoodpark).

Planning and development constraints

The southern extremity of the Peak District National Park lies 2 – 3 km north of Limestone Hill and, a few hundred metres to the north, there is a SSSI. Birchwoodpark Quarry is a municipal waste disposal site in a flat-lying area and there is a disused aerodrome close to this site. The area generally is agricultural with a large proportion of pasture land and is crossed by a network of minor roads.

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1 The Snelston inlier has been extensively quarried at Birchwoodpark Quarry and this more specific name is used frequently in this report to refer to the inlier. The Snelston ridge is used to refer to the concealed Dinantian feature postulated from the geophysical evidence.

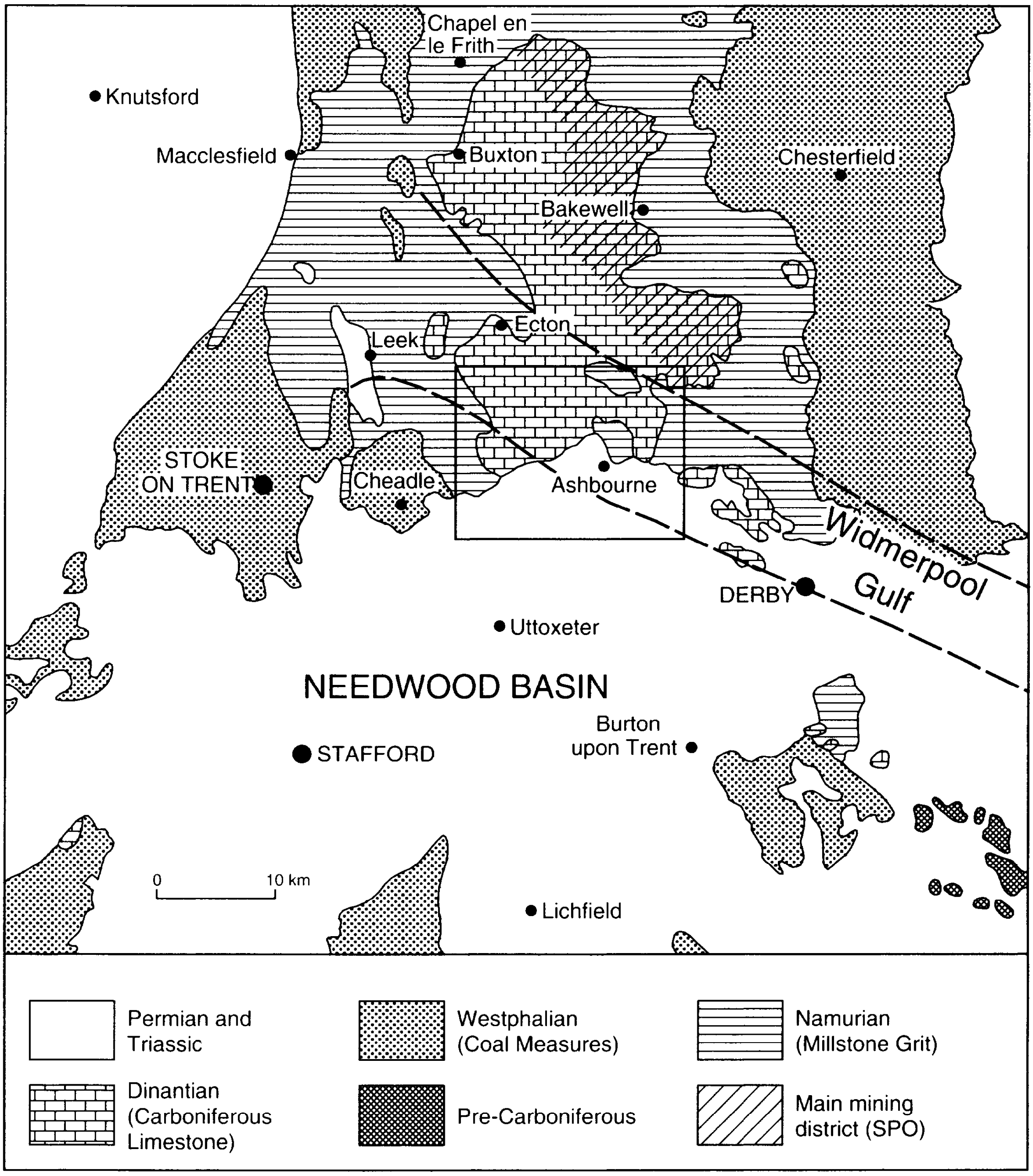

Figure 1. General geological setting of the Ashbourne district (based on Chisholm et al., 1988, fig. 1) including the main South Pennine Orefield (SPO). Rectangle indicates area of Figure 3.

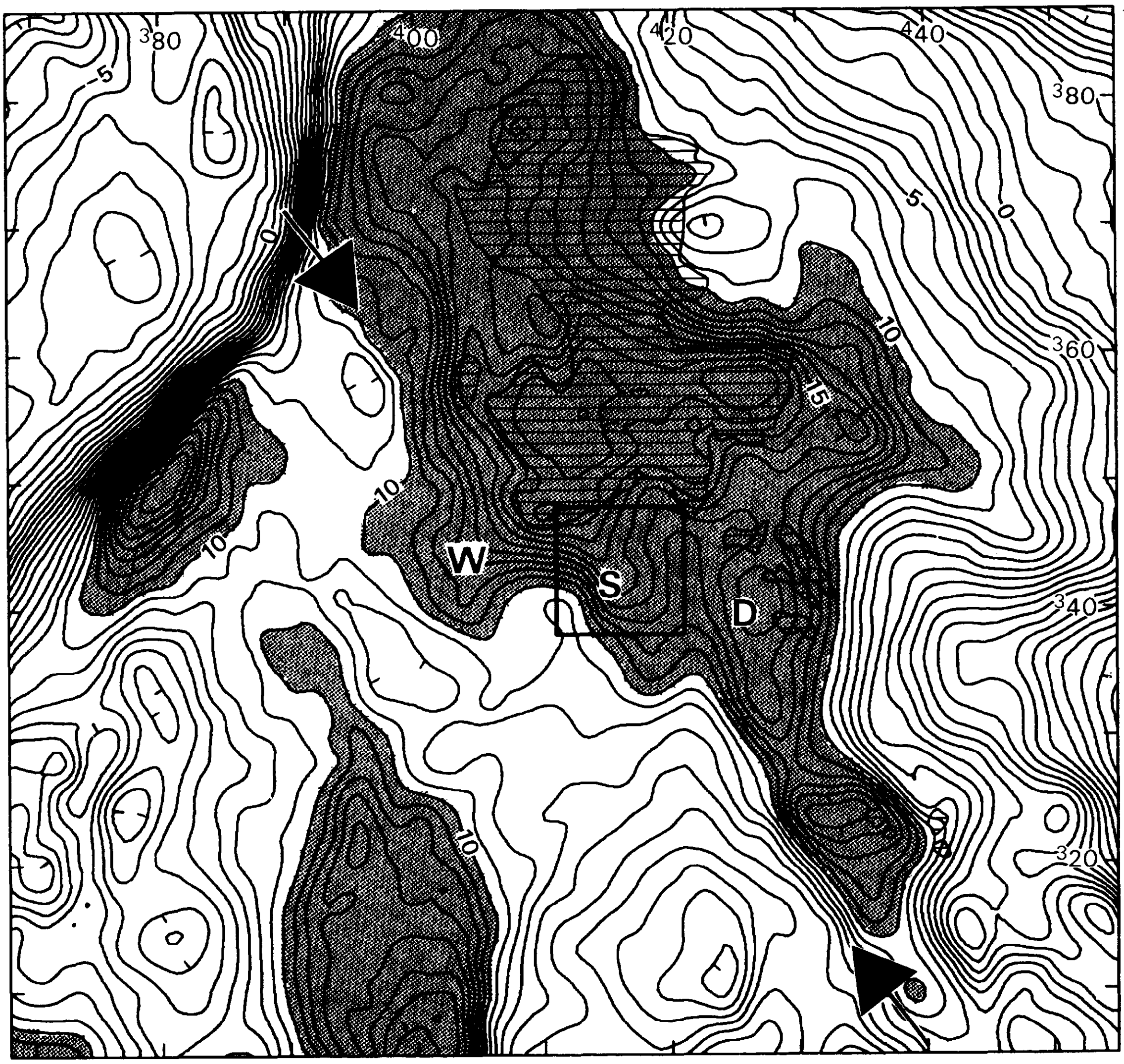

Figure 2. Bouguer anomaly map for the region shown in Figure 1 with locations of detailed gravity map (Figure 6), gravity highs referred to in text (D Derby, S Snelston and W Winnothdale), outcrop of Dinantian rocks (horizontal lines) and possible major lineament (arrows). Contours are at 1 mGal intervals and areas with values greater than 10 mGal are shaded. Bouguer correction based on variable densities.

Geology

The area of interest (Figure 3) lies within the Triassic outcrop at the northern margin of the Needwood Basin, to the south of the Dinantian rocks forming the central part of the Derbyshire Dome.

Carboniferous

The oldest Carboniferous rocks, of Dinantian age, are mainly marine limestones, ranging from late Courceyan/early Chadian to Brigantian and traditionally referred to as 'Carboniferous Limestone'. Their total thickness has been estimated to be about 1000 m (Chisholm et al., 1988) but the top of the pre-Carboniferous basement has been proved tentatively in the one deep borehole in the area (the Caldon Low Borehole; Figure 3), where it probably lies within the Redhouse Sandstones of Old Red Sandstone facies. The Dinantian sequences (Figure 4) comprise rocks recognised as belonging to two provinces; the shelf facies of the stable area of the Staffordshire Shelf to the south-west and the off-shelf facies of the mobile area to the north-east. The south-west margin of the mobile area has been defined in the Ashbourne district on the basis of the difference in structural styles and lithological facies and on the location of Asbian apron-reefs. The main rock units of interest lie mainly within the mobile belt and the near-surface sequence largely comprises the following formations:

> *Milldale Limestones (maximum thickness 470 m).* These, the oldest rocks at outcrop in the district, are a variable sequence of medium and dark grey well-bedded limestones with extensive knoll-reef limestone in places.
>
> *Ecton Limestones (260 m).* These are well-bedded limestone turbidites with a strongly diachronous boundary with the underlying Milldale Limestones.
>
> *Widmerpool Formation (250 m locally).* The main off-shelf rock unit, consisting of silty mudstones with limestone and, less commonly, sandstone turbidites. The Widmerpool Formation passes laterally into the Hopedale Limestones to the north of the area and, to the west, passes into the Ecton Limestones.

Although these rocks are likely to form the main part of the pre-Permo - Triassic basement in the area of interest, the projected boundary between the mobile and stable areas passes just to the east of the inliers. The projected south-easterly trending line of this margin lies close to the interpreted western margin of the Snelston ridge and also to part of a possible major geophysical lineament (Figure 2), suggesting that the ridge might have some major structural significance. The mobile area continues to the east-south-east as the Widmerpool half-graben, one of the many fault-bounded Carboniferous basins in northern England (Ebdon et al., 1990). These basins have been investigated as potential sources of mineralising fluids which moved out during compaction and tectonism into reactive carbonate host-rocks of the Pennine orefields (Plant and Jones, 1989).

Namurian rocks occur at outcrop north of the town of Ashbourne and probably at depth beneath the Permo-Triassic (Figure 5). Up to 1000 m thick, they comprise mainly interbedded mudstones, siltstones and sandstones.

Permo-Triassic

Following Variscan folding and faulting and a period of considerable erosion, Permo - Triassic rocks were deposited on an uneven Carboniferous surface. (Although only rocks of Triassic age have been proved in the area, the term Permo-Triassic is used to include any Permian in the deeper parts of the basin).

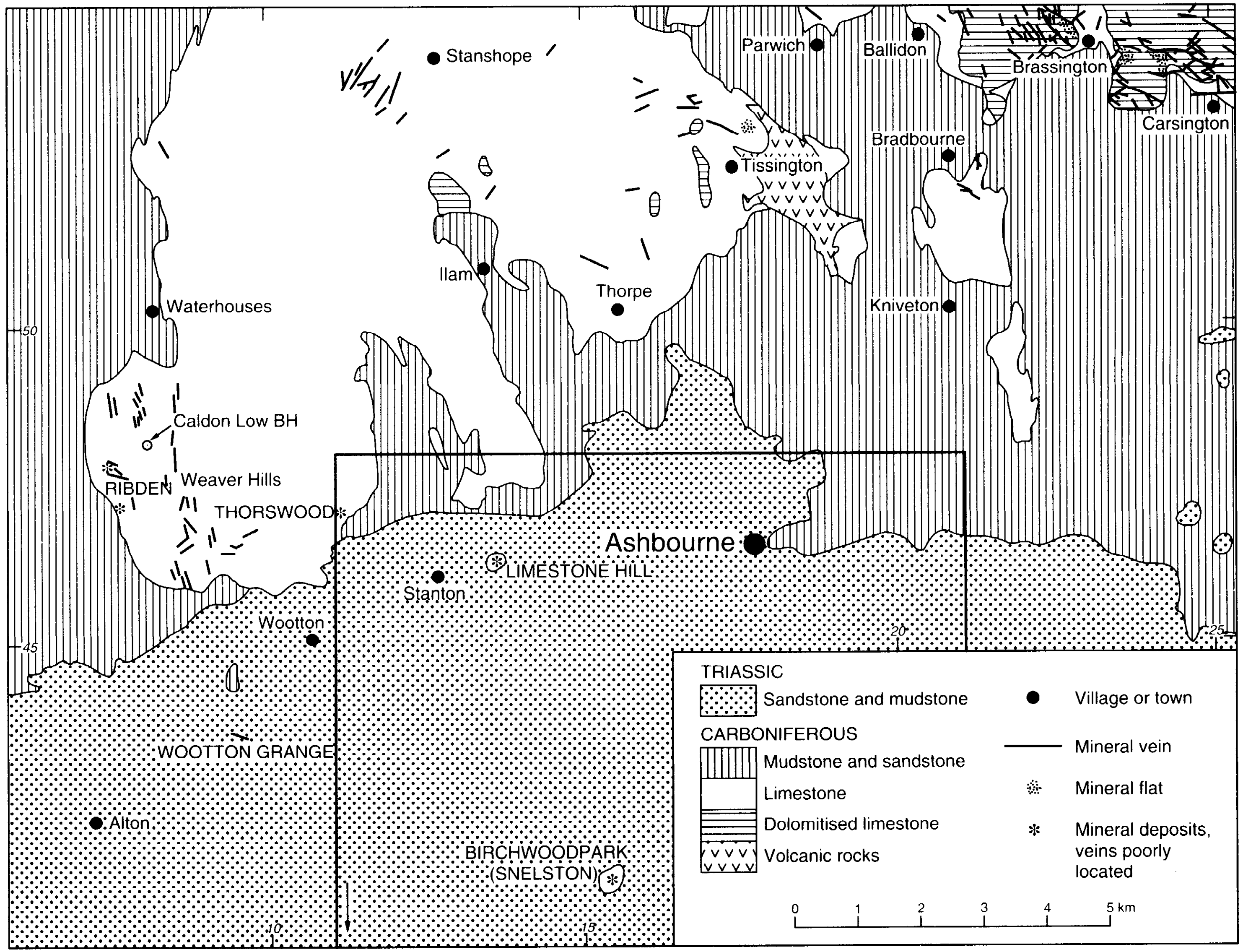

Figure 3. Geology and mineral deposits of the Ashbourne district (from Chisholm et al., 1988) with area of Figure 5 indicated.

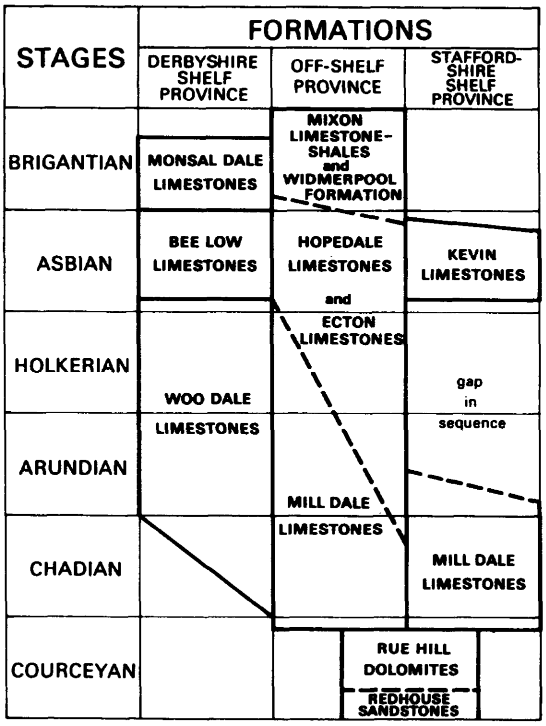

Figure 4. Age relations of the Dinantian formations of the Ashbourne district (from Chisholm et al., 1988).

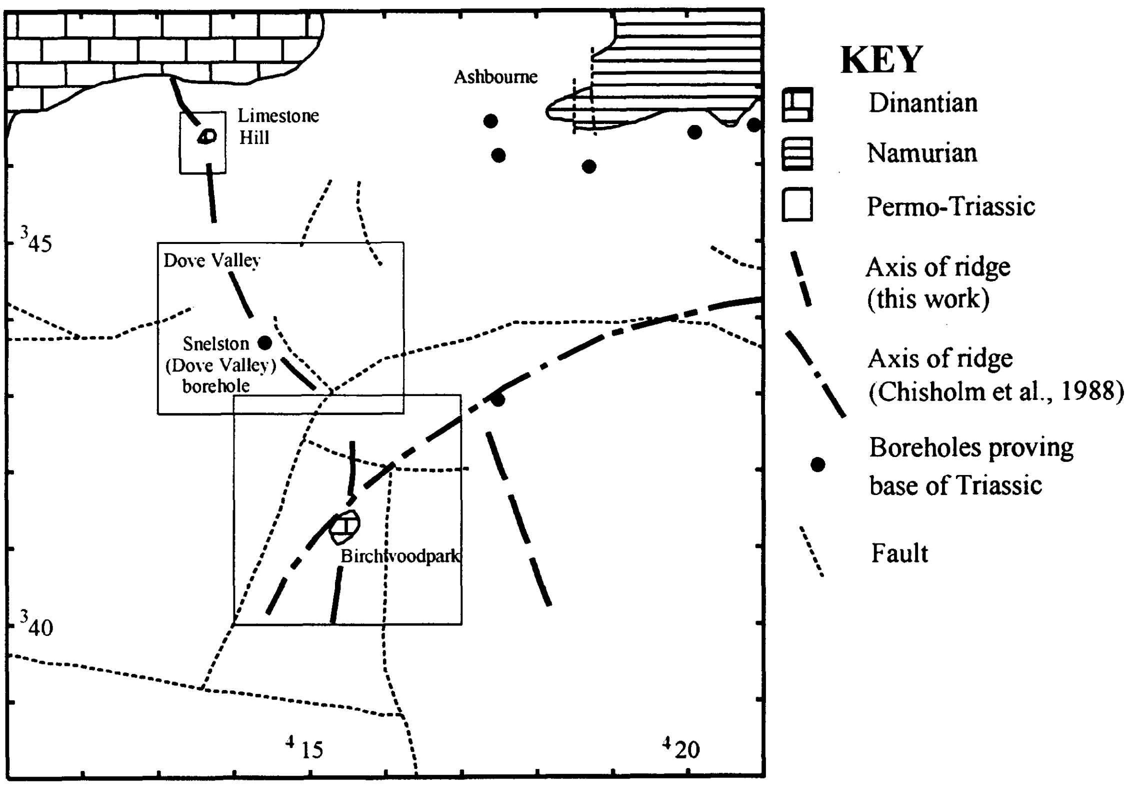

Figure 5. General map of the Snelston ridge area with simplified geology, boreholes and locations of detailed survey areas. Axes of concealed ridges are indicated as defined by gravity results in this study and by previous borehole evidence (Chisholm et al., 1988).

This surface dips generally to the south towards the centre of the Needwood Basin, but within the Ashbourne district it appears to be locally disrupted. Chisholm et al. (1988) suggest that the structure contour data for the base of the Triassic, based on limited borehole evidence, indicate two main valleys, one of which passes with an east–west trend between the Birchwoodpark inlier and the main Dinantian outcrop. In the area of interest, Triassic rocks belonging to both the Sherwood Sandstone and Mercia Mudstone groups occur (Table 1).

The Sherwood Sandstone Group comprises sandstones and conglomerates with minor siltstones and mudstones. Within the group, three formations have been recognised in the area of interest. The Huntley Formation is a distinctive but sporadic basal development of coarse-grained pebbly sandstone or conglomerate with locally-derived sub-angular pebbles. The overlying Hawksmoor Formation consists of cross-bedded pebbly sandstone with two conglomerates. At the top of the Sherwood Sandstone Group, the Hollington Formation consists of cross-bedded red-brown sandstones, often forming upward-fining units. The latter are commonly baryte-cemented (Chisholm et al., 1988) and 'chicken-feet' baryte crystals can be observed at numerous outcrops and in walls, as near the village of Upper Mayfield.

Table 1. Classification of the Triassic in the Ashbourne district (from Chisholm et al., 1988) with approximate thicknesses (in brackets) in metres.

Lithostratigraphic Subdivision			**Stage**
Mercia Mudstone Group (>150)	Undivided		Ladinian ?
	Denstone Formation (0 - 70)		Anisian ?
Sherwood Sandstone Group (360)	Hollington Formation (0 - 45)		Scythian
	Hawksmoor Formation (330)	Lodgedale Member (0-30) Freehay Member (0-55)	
	Huntley Formation (0-25)		

The Mercia Mudstone Group largely consists of mudstone and siltstone with subordinate sandstones. The lower part (the Denstone Formation) can be distinguished on the basis of fine-grained, thinly interlayed siltstones and sandstones with ripple-marks, pseudomorphs after halite and mudcracks.

Post-Hercynian structures include faults, with throws of up to 175 m, affecting Triassic rocks. The faulting partly reflects the rectilinear pattern in the underlying Carboniferous and is generally dominated by east–west trending normal faults.

Quaternary
Glacial deposits in the form of dissected remnants of 'older' (probable Anglian) till cover parts of the area. The tills are most extensive in the area around Birchwoodpark, where a thickness of 18.2 m was proved in a borehole at Darley Moor [4168 3414] [2]. Fluvial deposits in the valley of the River Dove include a few remnants of older terrace deposits.

Mineralisation

The mineral deposits of the South Pennine Orefield, which occur mainly on the eastern side of the exposed Dinantian limestone of the Derbyshire Dome to the north of the survey areas (Figure 1 and north-east corner of Figure 3), are largely composed of numerous elongate, narrow (<20 m), steeply dipping sulphide/fluorite/carbonate/sulphate oreshoots of limited vertical extent, confined to a small number of massive, competent limestone beds of Asbian or Brigantian age under a cover of Namurian shales. The oreshoots occur over an area of 400 km^2 within fracture-controlled veins which can extend to several kilometres in length. Semi-concordant replacement flats such as the major Masson Hill deposit near Matlock (Ford and Ineson, 1971) and manto-style horizontal pipe deposits also occur. More recently, large (up to 0.5 million tonnes) pipe and replacement fluorite ore bodies have been discovered and worked in the northern part of the South Pennine orefield (Butcher and Hedges, 1987). They occur marginal to some of the major east-north-east–trending vein deposits. The main ore minerals are fluorite and galena, with subsidiary, although locally important, baryte and sphalerite. The main gangue minerals are calcite and quartz. A comprehensive overview of the Pennine orefields is given by Dunham (1983) in which he characterised them as a fluoritic subtype of the Mississippi Valley type of Pb-Zn ore deposits. The mineralisation occurred in part after the dolomitisation of Asbian and Brigantian limestones which is believed to have taken place in Permian times (Dunham, 1952). Lead and potassium/argon dating has been used to attempt a more precise dating of the timing of mineralisation and a number of ages calculated, ranging from 270 to 160 Ma (Ineson and Mitchell, 1973; Walters and Ineson, 1980). Plant and Jones (1989) suggest that mineralisation occurred during a short time interval at the end of the Westphalian and the range of ages reported above may result from isotopic re-equilibration events. The mineralising fluids are thought to have been derived from Carboniferous basinal brines by catastrophic dewatering involving seismic pumping from the shale-dominated basins in the east into the regional fracture systems generated in the fringing carbonate platform to the west during Variscan tectonism (Plant and Jones, 1989). The known mineralisation is not extensive south or west of Brassington, some 10 - 15 km north-east of the Ashbourne area (Figure 3). There are a number of minor lead mines in the Weaver Hills to the north of the present area under study (Robey and Porter, 1971; Porter and Robey, 1972), and hematite also occurs in calcite veins in some of the limestone quarries in the Ribden area (Chisholm et al., 1988). The important copper deposits around Ecton Hill, on the south-west side of the Derbyshire Dome (Figure 1) occur 10 km to the north of the area (Figure 3). These are veins and semi-vertical pipes in Dinantian limestone

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2 British National Grid reference

containing calcite and chalcopyrite with minor galena, baryte and sphalerite (Critchley, 1979), which produced at least 60 000 tons of 'copper ore' at a reported grade of around 15% Cu (Dewey and Eastwood, 1925). The origin of the Ecton deposit is still controversial; the copper may have been derived from the Permo-Triassic Cheshire Basin.

The South Pennine Orefield mineral deposits were formerly worked for galena but fluorite has been the dominant mineral since the beginning of this century. Currently the main activity is in the north of the area where Laporte Minerals Limited operate underground and open-pit mines at Milldam, near Eyam, and along Dirtlow Rake, as well as treating feed from a number of tributor operations at their Cavendish Mill facility. The Pennine ore deposits are distinguished by having lead and fluorite as the dominant products; little sphalerite has been produced, the only substantial production of zinc being from the major Millclose Mine, north of Matlock, which produced over 500 000 tons of lead concentrates and 30 000 tons of zinc concentrates before closing in 1940 (Smith et al., 1967).

Previous mining activity in the Ashbourne area (Figures 3 and 5) is confined to the Snelston and Limestone Hill areas. At Snelston, Dewey and Eastwood (1925) describe the occurrence of copper and lead mineralisation at the unconformable contact of the Dinantian limestone and overlying Mercia Mudstone Group which consists of calcareous mudstone and thin beds of sandstone. The worked mineralisation consisted of malachite-cemented calcareous sandstone and galena, cerrusite and chalcopyrite nodules coated with malachite. Galena and cerrusite occur both in the Triassic calcareous sandstone and in clay-lined fractures and vugs in the underlying Dinantian limestone which is locally dolomitised. Limonite, baryte and fluorite also occurred and chalcocite was reported by King and Ford (1968). The mine was worked from an adit and two shafts up to 30 m deep. The only figures given are for 1869–1873 and 1909–1918. The total production probably amounted to around 1000 tons of copper 'ore' perhaps averaging 5% Cu, and about 600 tons of lead ore perhaps averaging 40 - 50% Pb. The mine was thus very small and few traces of it remain; workings to the west of the road have been destroyed by Birchwoodpark Quarry which is now being backfilled with refuse. Chisholm et al. (1988) recorded a 1.58 m wide vein complex trending east-south-east on the south-east face of the quarry [41543 34115] carrying calcite, baryte and fluorite. The Snelston occurrence is one of a series of mineral deposits in the East Midlands associated with the unconformity between the Carboniferous and the Triassic (King and Ford, 1968).

Limestone Hill is a small (100 m in diameter), approximately circular, poorly exposed outcrop of dolomitised knoll-reef limestone (Milldale Limestone) surrounded by Triassic Sherwood Sandstone Group. The remains of mining activity at Limestone Hill are confined to small surface depressions up to 1 m deep. Robey and Porter (1971) describe workings in 1859 on an outcropping 'large vein'; however, it seems more likely that the orebody is a highly irregular network of interconnecting replacement vugs. A shaft was sunk to 20 fathoms (about 40 m) and a cross-cut driven to intersect the vein to the east. Chisholm et al. (1988) record a shaft at [41369 34628]. This was another shaft sunk to connect with an old adit striking westwards towards the hill, possibly to intersect the surface mineralisation at depth as the adit apparently extended for 90 fathoms (approximately 180 m) into the hillside (Robey and Porter, 1971). This would place its western end about 50 m south of Limestone Hill No 1 Borehole drilled in the present programme. The adit was driven around 1820 and cleared out over its full length during the brief period of working in 1859. The surface and underground workings appear to have been little more than trials. No substantial production has taken place and no mineralisation was seen in the debris from the shaft which is now filled to the surface. The visible mineralisation at Limestone Hill consists of thin veins of galena and cerussite up to 1 cm wide, with larger scale replacement of the dolomitised limestone at the top of the hill by baryte in bladed crystals and more massive forms. A large block of dolomitised limestone about 2 m in diameter, extensively replaced by baryte and presumably from the shallow workings at the top of the hill, has come to rest half-way down the eastern side of the hill. Thin veinlets of galena, up to 1 cm wide, with baryte and malachite were observed in some of the exposures on top of the hill. The veinlets dip steeply south and strike east–west.

Geophysics

Gravity data formed an important part of the initial assessment of the Ashbourne area (Cornwell, in Chisholm et al., 1988) and are presented in a regional context in Figure 2. Gravity highs are very broadly associated with areas of Carboniferous rocks, while the lower values occur over lower density Permo-Triassic and younger rocks. The most notable high occurs over the Dinantian rocks of the Derbyshire Dome and three extensions to this continue to the south or south-south-east. These are referred to as the Derby (in the east), Snelston (centre) and Winnothdale (in the west) highs by Chisholm et al. (1988). The most pronounced of these, the Derby gravity high, extends over structural highs indicated at the surface by the inliers of Widmerpool Formation (Brigantian) in the Derby area and the Westphalian rocks of the Leicestershire Coalfield. A long seismic refraction profile recorded a high-velocity layer at depths of less than 2.1 km along the Derby high which was interpreted as possibly being Charnian rocks (Whitcombe and Maguire, 1981). Evidence that the adjacent Snelston gravity high is also associated with a structural high is provided by the Dinantian inliers at Birchwoodpark and Limestone Hill.

The interpretation of the regional gravity highs simply in terms of depth to the Dinantian is complicated by the presence of anomalies associated with deep basins of Dinantian rocks and the associated growth faults, and by the possible presence in places of concealed, lower density Westphalian and Namurian rocks. It has also been suggested on geophysical evidence that the Carboniferous rocks of the Derbyshire Dome are underlain partly by basement rocks with particularly high densities (Maroof, 1976). Several major geological structures are reflected in the gravity data by zones of steep gradients, notably the eastern margin of the Cheshire Basin. It is possible that lineaments indicated by other zones could indicate the presence of deeper structures. One of these, a north-westward extension of the Boothorpe Fault lineament in Leicestershire, could continue through the Ashbourne area along the western margin of the Snelston high (Figure 2).

SURVEY METHODS

Geophysics

The initial geophysical investigations consisted of in-fill gravity measurements and quantitative modelling to map the Dinantian limestone surface beneath the Triassic. From the results of this modelling, detailed gravity measurements, transient electromagnetic and resistivity soundings were made in an attempt to more accurately determine the depth to the limestone and to select a site for a borehole to confirm this and examine the possibility of mineralisation at the unconformity. The final phase of geophysics consisted of detailed surveys aimed at providing information on concealed mineralisation and geological boundaries at Limestone Hill. Induced polarization, electromagnetic and gravity methods were used for this purpose.

Gravity surveys

A total of 80 new in-fill gravity measurements were made to improve the definition of the Snelston ridge regional gravity anomaly, three of which coincided with previous gravity stations in order to check the consistency of the survey data. The measurements were taken relative to the gravity base station at the BGS headquarters at Keyworth, which is linked into the NGRN73 base station network. Gravity stations were located at Ordnance Survey bench marks or spot heights. The gravity coverage was increased from approximately 0.8 stations per km^2 to 1.6 stations per km^2. Some significant gaps still exist, however, as the bench marks and spot heights occur mainly along roads and tracks.

Detailed gravity measurements for two profiles were taken along roads, at stations 50 m apart. Heights were obtained by levelling, which incorporated all available Ordnance Survey benchmarks. A third, short detailed profile with stations at 25 m intervals was made on Limestone Hill.

Data reduction. The data were reduced to Bouguer gravity anomaly values using conventional procedures. The datum reduction surface was mean sea level at Newlyn (O.D.). The parameters used in the reduction were a free air gradient of gravity of 0.3086 mGal/m, a Bouguer constant of 0.041929 mGal/m and normal gravity calculated from the 1967 Geodetic Reference System (GRS 67). Terrain corrections were calculated from a Digital Terrain Model (DTM) constructed from Ordnance Survey digital vector data. The DTM was gridded at 50 m intervals for the inner zone corrections (out to a distance of 3 km from the gravity station) and 1 km for the outer zone corrections (out to a distance of 48 km from the gravity station).

After data reduction it was found that there was a consistent shift of 0.1 mGal between the old and new data at the three repeat stations, due probably to errors in the old base station network, and a datum shift was therefore applied to the old data. All the data have been reduced with a Bouguer reduction density of 2.60 Mg/m^3 and the resulting Bouguer gravity anomaly map, contoured at 0.4 mGal intervals, is shown in Figure 6. The Bouguer gravity contours clearly define the gravity high between Limestone Hill and Birchwoodpark indicated previously by the regional data. The gravity gradient to the west and south of the ridge is sharp, but it is less steep to the east.

Data interpretation. In order to derive depths to the Dinantian, an estimate had to be made of the gravity field due to the overlying, lower density Permo-Triassic rocks. This was achieved by computing residual fields after the observed gravity data had been represented by a series of polynomial surfaces. Polynomial surfaces of 2nd, 4th, 6th and 8th degree were fitted to the Bouguer gravity data and, as expected, the complexity of the residual field increased with the increasing order of polynomial. However, the main features of the Snelston ridge remained the same. This consists of an arcuate zone of higher values with maxima over Birchwoodpark and a region centred on [4145 3437] (see Figure 7). The absence of a maximum over Limestone Hill is due to the lack of data from the inlier iteself. The difference in gravity values between points along the ridge is similar for the residual fields computed using all the polynomial surfaces. As a result, the 2nd degree polynomial has been taken as defining the residual field because the gravity gradients defining the western and eastern margins of the ridge are the most compatible with the Bouguer anomaly map. The residual gravity anomalies calculated in this way indicated that over the Birchwoodpark Quarry inlier the value was not near zero but had a value of 1.66 mGal. This value has therefore been subtracted from the residual grid to produce a datum shift, resulting in zero residual gravity over the outcropping limestone. This residual gravity field is shown in Figure 7 and represents, at least in the region of the Snelston high, the gravity field which is regarded as being largely due to low-density Permo-Triassic rocks.

Interpretation of the gravity data, both regional and detailed, was carried out using the *Gravmag* program (Busby, 1987) in which the modelling is based on polygonal bodies of limited strike extent ('2.5 dimensions'). The Bouguer gravity data were first projected onto straight-line profiles with distances taken from the western end. The regional field removed was that defined previously which attempts to define the gravity field due to the pre-Permo-Triassic geology. Densities used in the modelling are listed in the figure captions.

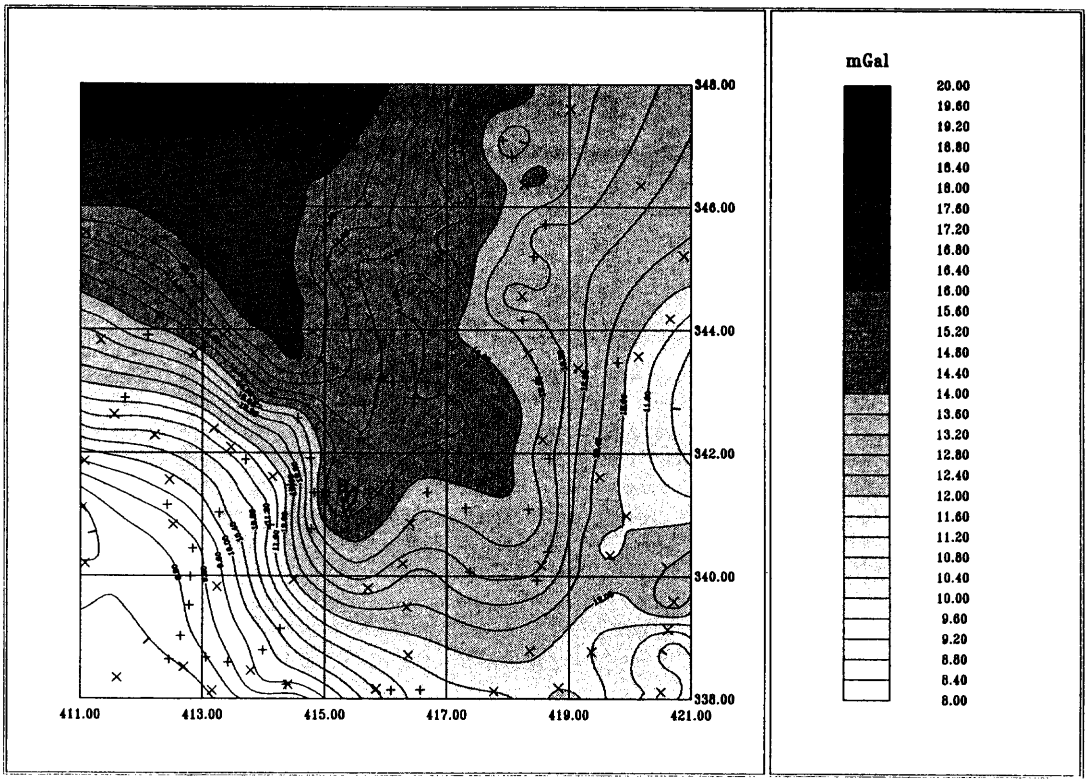


Figure 6. Observed Bouguer gravity anomaly map of the Snelston ridge area with contours at 0.4 mGal intervals. Gravity stations indicated by crosses (diagonal crosses for project in-fill stations). A, Limestone Hill; B, Birchwoodpark.

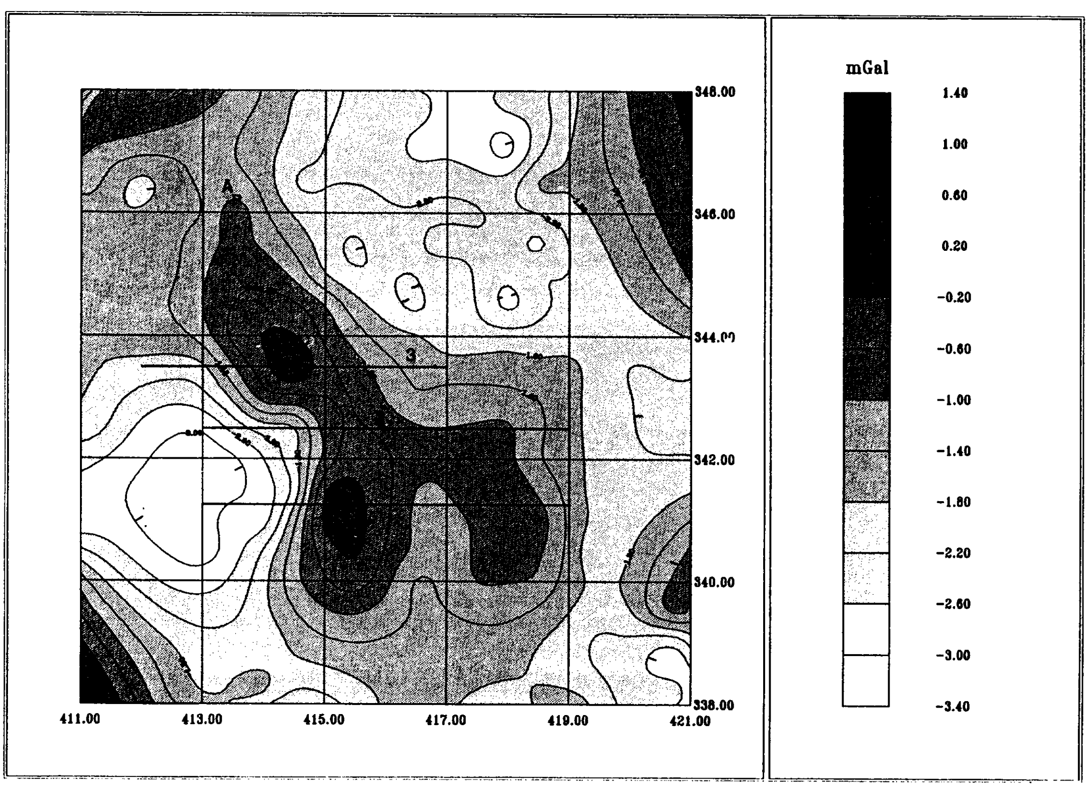


Figure 7. Residual Bouguer anomaly map and locations of interpretation profiles 1 to 3. A, Limestone Hill; B, Birchwoodpark.

Seismic reflection survey

During the course of the project a seismic reflection section became available for an east-west profile through the Snelston inlier (Birchwoodpark Quarry). The section had been acquired commercially by Horizon Exploration Limited for Clyde Petroleum plc using a *Vibroseis* source and a 40 m geophone interval.

Resistivity soundings

The Offset Wenner technique employing a multicore cable with spacings of 0.5, 1, 2, 4, 8, 16, 32 and 64 m, was used for the resistivity soundings. The apparent resistivity data were interpreted by one-dimensional layered models where the calculated apparent resistivity curve generated by the model is compared to the observed curve. The layers within the model are assumed to be homogeneous, isotropic and horizontal. They are defined in terms of a thickness and resistivity, with the bottom layer (the substratum) extending to infinite depth (Appendix 1). All of the resistivity interpretations are not unique and it is possible to produce alternative models. The aim has been to try to model the substratum as a consistent resistive layer.

Transient electromagnetic (TEM) soundings

Some soundings were also undertaken using a Geonics EM47 system with transmitter loop sizes of 10 x 10 m and 20 x 20 m. However, due to high levels of background noise these did not prove to be successful in the Dove Valley area.

VLF-EM

A VLF survey was carried out at Limestone Hill measuring both the magnetic and electric field components. Line 1 was surveyed from south to north utilising the VLF transmitter at Cutler Maine, USA, which transmits at 24.0 kHz and was on an approximate west-north-west azimuth. Thus anomalies might be expected from any conductive structures striking approximately west to east. Line 2 was surveyed from west to east utilising the VLF transmitter at Rugby, England, which transmits at 16.0 kHz on an approximate southeast azimuth and responses from northerly striking structures ought to be detected.

Induced polarisation (IP)

The IP method was used in the exploration for disseminated metallic mineralisation at Limestone Hill. The dipole-dipole electrode array was deployed utilising a dipole length of 25 m and dipole separations of n = 1 to 6. The station increment was also 25 m. The receiver used (Scintrex IPR-11) employed an on/off time of 2 seconds giving, a total cycle length of 8 seconds. IP results are plotted as chargeabilities for integration times between 90 to 120 ms after current cut-off. Apparent resistivity, in ohm m, is also presented.

Conductivity mapping

A limited amount of ground conductivity mapping was carried out using the Geonics EM31 meter to investigate near-surface (i.e. down to about 5 m) variations at Limestone Hill.

Physical property determinations

For the Ashbourne district, Chisholm et al. (1988) report the following densities for the main rock types based on values obtained elsewhere in the Midlands:

Trias	2.40 Mg/m^3
Westphalian and Namurian	2.50 Mg/m^3
Dinantian	2.65 Mg/m^3
Pre-Carboniferous basement	2.65 to 2.75 Mg/m^3

A few physical property determinations were made in the Engineering Geology laboratories at the BGS, Keyworth, to improve interpretation of the geophysical data. At an early stage typical samples of Sherwood Sandstone and Milldale Limestone were collected from [4155 3413] and Birchwood Park Quarry [4136 3429], respectively. Density and resistivity measurements (with a pore water resistivity of 14.1 ohm m) are listed in Table 2 for surface samples (a and d) together with densities for two core samples (b and c) from the Snelston (Dove Valley) Borehole.

These data demonstrate that there is a significant density contrast between the sandstones (although sample (a) could show weathering effects) and limestone and that the massive limestone is very resistive.

Table 2. Densities and resistivities of rock samples from laboratory measurements.

Lithology	Sample	Effective Porosity (%)	Density (Mg/m^3)			Resistivity (ohm m)
			Dry	Saturated	Grain	
Sherwood Sandstone	a	27.7	1.93	2.21	2.67	102
	b	13.9	2.29	2.43	2.67	–
	c	15.4	2.26	2.41	2.67	–
Milldale Limestone	d	1.5	2.67	2.69	2.71	2417
						4181

Geochemistry

The widespread Permo-Triassic cover of sandstones and mudstones restricted geochemical sampling to the immediate vicinity of the Carboniferous Limestone outcrops at Limestone Hill and Birchwoodpark. Soil, soil-gas and rock sampling were used to provide information on the geology and near-surface extent of the mineralisation.

Soil sampling

Soil samples were taken at 20 - 100 cm depth at 25 m intervals using a hand auger. Samples of 100 - 200 g were oven dried, lightly disaggregated and sieved at 2 mm and 150 μm. The coarse residual rock fragments were retained for visual inspection and the minus 150 μm fraction analysed by XRF for Cu, Zn, Pb, MgO, CaO, Fe_2O_3, MnO and Ba.

Soil gas radon was measured on two traverses at Limestone Hill using a Pylon AB-5 monitor with a zinc sulphide scintillation counter (Ball et al., 1991). The soil gas samples were taken from depths of 20 - 60 cm at 25 m intervals using a hollow spike. Radiometric (total gamma count) measurements were made over the same traverses using an Exploranium GR110 ratemeter.

Rock and drill cores

A number of surface rock samples were taken from Birchwoodpark and Limestone Hill. Drill core samples were taken from the Snelston Dove Valley drill hole and the three Limestone Hill drill holes. Only selected sections of the cores were sampled to provide information of the extent on the dolomitisation and mineralisation and to check areas of dark brown ferruginous limestone with calcite veining for anomalous levels of base metals. These samples were crushed to 2 mm and a 200 g split ground to 150 μm in a Tema mill. A 12 g subsample was mixed with 3 g Elvacite binder, ground for 30 minutes in a P5 ball mill and then pressed into a pellet for analysis by XRF (Phillips models PW 2400 and 1480) for Cu, Zn, Pb, Ba, CaO, MgO, Sr, Cd, Ag, Fe_2O_3 and MnO. Some samples were also analysed for F. Several highly mineralised samples, where Pb and Zn levels exceeded the maximum detection limit, were diluted by two or ten times with pure silica and then reanalysed to give levels within the normal operating parameters of the machine.

REGIONAL INTERPRETATION OF LIMESTONE SURFACE

Gravity evidence

The residual anomaly map based on the original and the in-fill survey data (Figure 7) shows the ridge to be more complex in form than indicated by the original survey, with two highs trending approximately northwards in the south, the more westerly, larger amplitude high containing the exposed limestone at Birchwoodpark Quarry. The form of this appears to be largely determined by the fault pattern mapped at the surface (Figure 5). To the north-north-west however, the continuation of the western high is probably also fault-controlled before it gradually disappears near the Limestone Hill inlier.

In the absence of any information facilitating a more complex interpretation model, the assumption was made that the residual anomalies were due to the variable thickness of the Permo-Triassic rocks and the main density contrast was between these and the underlying Dinantian basement. This assumption of a single density contrast is probably an over-simplification as it ignores, for example, the possible effects of lithologically controlled density variations within the Carboniferous and of the pre-Carboniferous rocks but errors are probably not significant within the relatively small area of interest.

The interpretation of the residual gravity anomalies was carried along the three, west to east profiles shown in Figure 8, assuming a density contrast of -0.25 Mg/m^3 between Permo-Triassic rocks and the underlying Lower Carboniferous.

Profile 1 runs from 413E to 419E along Grid line 341.25N, crossing the limestone outcrop at Birchwoodpark Quarry. The model shows the western margin to be sharply defined and therefore probably faulted, whilst the eastern margin is a limestone surface with a shallowing around 418E to a depth of around 50 m. An exact fit cannot be obtained over the inlier between observed and calculated curves because there is a slight negative residual field which has been assumed to be zero.

Profile 2, along Grid line 342.5N, crosses the Snelston high in a region where there is a negative residual field. Minimum Carboniferous depths are obtained between 415E and 416E of around 40 m. There is again a gently sloping eastern boundary to the ridge.

Profile 3 (343.5N) passes through the gravity high centred on [4145 3437]. The model indicates a distinct Carboniferous ridge which comes closest to the surface at easting 414.5E at the eastern margin of the flood plain of the River Dove.

There are three main factors affecting the accuracy of the modelled Carboniferous depths:

(i) The gravity data have been taken at bench marks and spot heights. Heights of bench marks are known to a centimetre, but those of spot heights are only accurate to a metre. This produces an error of ±0.2 mGal in the observed Bouguer gravity data.

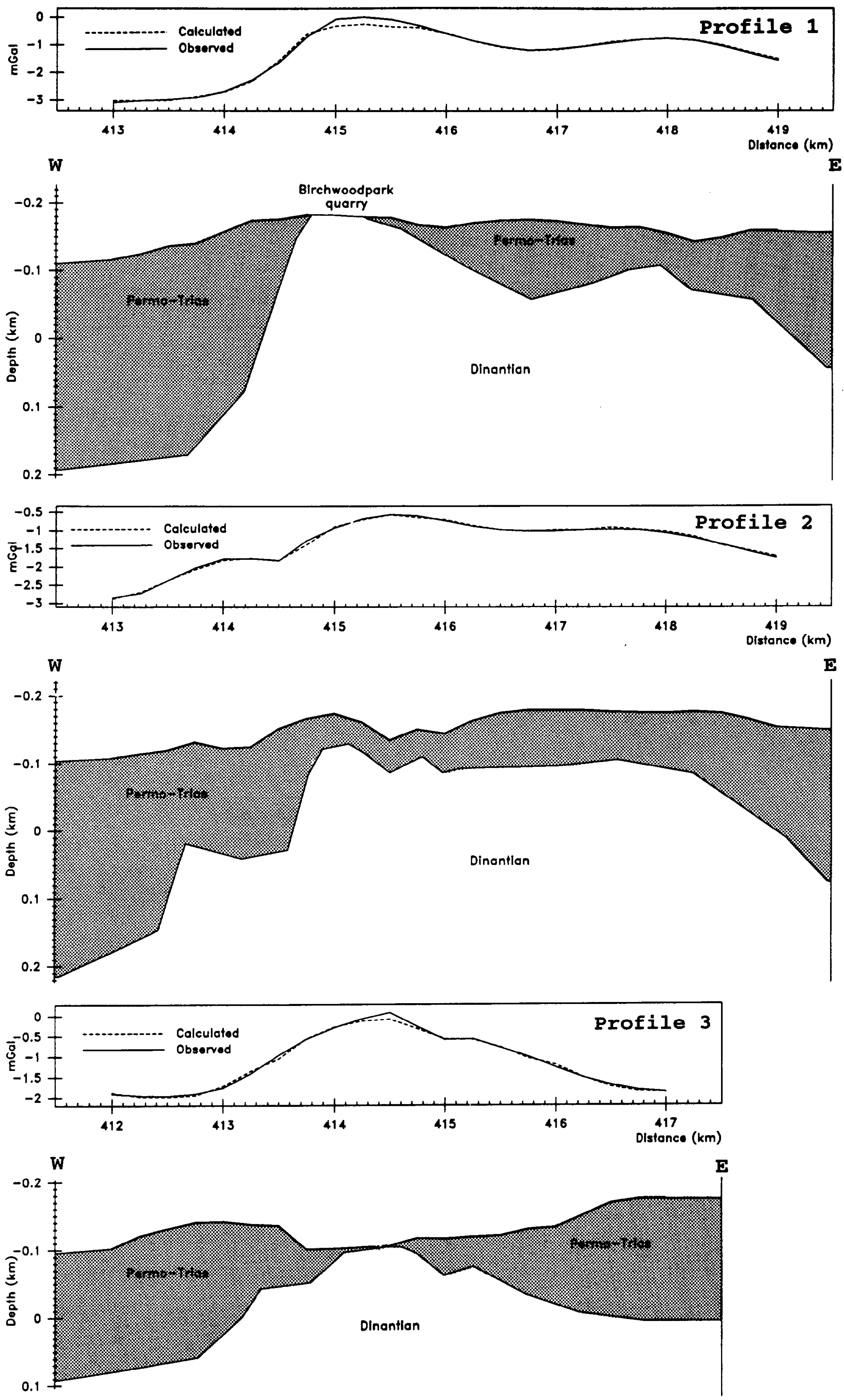


Figure 8. Residual Bouguer anomaly profiles 1 to 3 and interpreted models for Permo-Triassic rocks. Locations are shown in Figure 7. Horizontal distances refer to National Grid eastings. Densities: Carboniferous 2.65 Mg/m^3 and Permo-Triassic 2.40 Mg/m^3.

(ii) The polynomial surface which produces the residual field is a mathematical surface which will only represent the residual gravity due to the Permo-Triassic if it is well constrained. The constraints are the presence of the Carboniferous inliers and the ridge nature of the Snelston Bouguer high. It is clearly not possible to calculate the exact error in the polynomial fit, but a first-order approximation can be taken as the mismatch between calculated and observed gravity curves over Birchwoodpark quarry. This amounts to ±0.2 mGal.

(iii) The densities quoted in Chisholm et al. (1988) are general values obtained from various sources. The uniform density of 2.40 Mg/m^3 for the Permo-Triassic is incorrect in the area of interest because there is a contact between the Mercia Mudstone and the Sherwood Sandstone over the Snelston high. In addition the density of the Dinantian will depend upon the lithologies present. The error in the density contrast could be as high as ±0.1 Mg/m^3.

The error in the depths for each of the first two factors (calculated from the Bouguer slab formula) is 20 m, and is 2 m (assuming a depth of 50 m for the Bouguer slab) for the third factor. This produces a combined error of ±28 m.

The results presented above were obtained prior to obtaining evidence from seismic reflection interpretation (below) and drilling, which indicated that refinements were required to the gravity models.

Seismic reflection evidence

A provisional interpretation has been made of part of an east-west seismic profile (Figure 9a), acquired along public roads approximately along grid line 341N, and coincident in part with gravity profile 1. In the absence of any deep boreholes or any direct means of reflector identification in the area, the interpretation presented here is necessarily tentative. However, most of the main features of the profile are clearly defined and have particular relevance to the understanding of the structure of the Snelston ridge. Velocities of 3500 m/s and 3810 m/s have been used in the interpretation for the Permo-Triassic and Dinantian rocks respectively. The latter value will be too low if the Dinantian comprises thick, clean limestones.

The main feature of the part of the profile shown (Figure 9a and 9b) is the rise in the main reflectors to the surface near the location of the Birchwoodpark Quarry. Just to the west of the inlier a 0.5 km wide area with very thin or absent Triassic rocks is interpreted from the profile. Three faults downthrow the Carboniferous to the west, the westernmost of which is the north-north-east–trending fault shown on the Ashbourne geological mapsheet. The inlier is bounded on its eastern side by a fault, which is possibly the same fault reported in an adit to the north of Birchwoodpark Quarry (Chisholm et al., 1988, p 129).

In the west of the profile about 300 millisecond (ms) (equivalent to about 500 m) of Permo-Triassic rocks form a basin, floored by a reflector showing truncation of underlying beds. These beds are believed to be Namurian in age by comparison with results from a borehole off the profile to the west. A prominent reflector at about 200 ms beneath the unconformity is attributed to the top of the Dinantian limestones. This reflector rises sharply east of CDP (common depth point) 840 and is nearly truncated by the base Permo-Triassic unconformity at CDP 940, just west of the main west-downthrowing fault. The base of the Carboniferous is not known with certainty and a reflector at about 350 ms beneath the top Dinantian is taken to be the top Lower Palaeozoic reflector. Part of the zone above this reflector is thought to include late Devonian rocks, penetrated but not bottomed at the Caldon Low Borehole (Chisholm et al., 1988), and possibly early Devonian rocks. The deepest reflector picked is probably the base of the Silurian (Llandovery), although this interpretation has to be based on information extrapolated a considerable distance from the

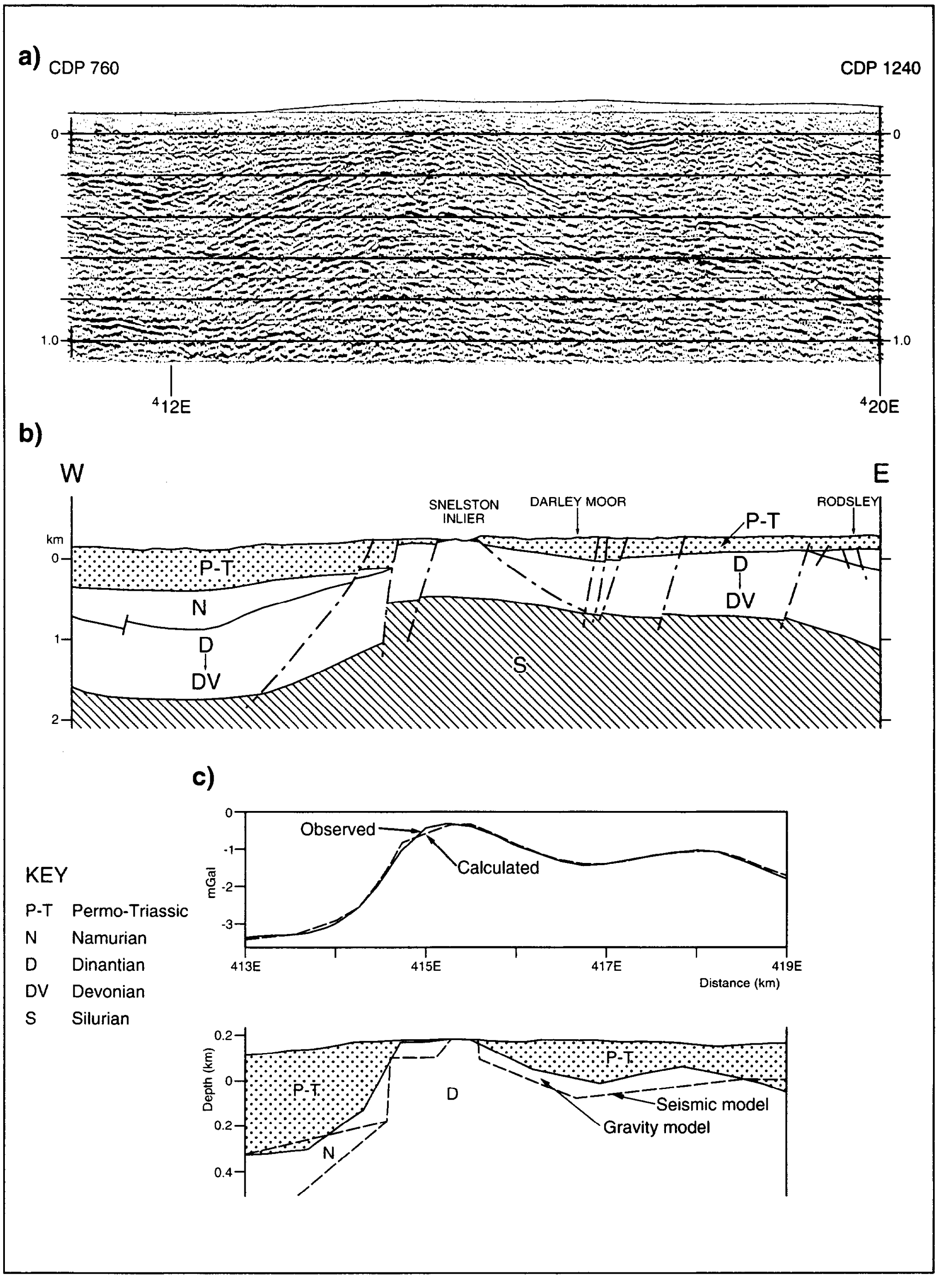


Figure 9. Seismic reflection evidence for the structure of the Snelston ridge.
a) Seismic reflection profile.
b) Interpretation of seismic data. Vertical exaggeration x 1.
c) Seismic model and re-interpretation of gravity profile 1. Vertical exaggeration x 2.5.

proven subsurface penetration and outcrop (Walsall) of these rocks. High amplitude reflectors just above the base Silurian are thought to be from the equivalents of the Wenlock Limestone.

In the east of the profile, truncated anticlines are evident, probably connected to the Madge Hill Anticline (Chisholm et al., 1988, p 118), with Namurian rocks in a syncline (CDP 1200–1250) corresponding to the Namurian outcrop north-east of Ashbourne. The Darley Moor Borehole failed to penetrate the base Triassic, but 2 km to the north the Edlaston Borehole confirmed the Dinantian subcrop at +133 m, beneath 10 m of Sherwood Sandstone. The Dinantian (and Devonian) sequence is here thicker than west of the Snelston Inlier but the top Dinantian reflector is of lower amplitude than that in the west. Taken together this suggests that the Dinantian rocks were thickening to the east and south against a syn-sedimentary fault bordering the Leicestershire Coalfield. A facies change from carbonate platform to basin turbidites and from relatively undeformed rocks (the stable area of Chisholm et al., 1988, fig. 28) to deformed rocks (mobile area) probably occurs south of Ashbourne, along the profile.

The relationship of the Carboniferous rocks in the Ashbourne area with the Widmerpool Gulf cannot be clearly established, mainly because of a gap between the end of present seismic line and the nearest with borehole control (BGS data at Duffield). A Dinantian basin depocentre has been interpreted beneath the Permo-Triassic Needwood Basin to the south of the interpreted profile. This basin has a different polarity to the Widmerpool Gulf, suggesting that the stable area extending from Caldon Low was tilted to the south-east, eventually forming another Dinantian basin controlled by faults, perpendicular to those controlling the Widmerpool Gulf. The late Dinantian basin facies extends from the Widmerpool Gulf, across the Derby High (Trusley Borehole), onto the eastern part of the profile line and into the Dinantian basin beneath the Needwood Basin. It is notable that the seismic profile includes no evidence that the structure associated with the Snelston ridge acted as a growth fault during the Dinantian.

A comparison of the seismic model with that obtained from the interpretation of the gravity data indicated that depths to the base of the Permo-Triassic could have been underestimated in the assessment of the gravity data. In the model shown in Figure 9c, the density of these rocks has been increased to 2.45 Mg/m^3, resulting in an increase in the estimated depths to the base Permo-Triassic. Further, more precise modelling would involve adjustments to both the densities and the velocities.

BIRCHWOODPARK AREA

Geophysics

Geophysical surveys in the Birchwoodpark area (Figure 10) were intended to more accurately define the surface of the concealed limestone and provide a control data set from the outcropping and near-surface rocks. The surveys comprised resistivity soundings and a detailed gravity traverse perpendicular to the strike of the ridge in the region of the gravity high. The greater resolution of the gravity field over the quarry achieved by the detailed traverse data (Figure 11) produced a positive anomaly over the limestone outcrop after the regional field had been removed. It was thus necessary to subtract 0.5 mGal from the profile to produce a near zero residual gravity field over the limestone outcrop. There is still a distinct residual gravity high over the outcrop, with a steep gradient to the west. Modelling indicates that this gradient is due to the steep western margin to the limestone ridge and a shallower eastern margin.

The resistivity soundings 1 to 3 (Figure 10 and Appendix 1) follow the thickening Mercia Mudstone Group sequence eastwards from the limestone outcrop at Birchwoodpark Quarry. A thin upper layer represents soil and drift, and the limestone substratum is modelled with resistivities in the range 250 ohm m to 300 ohm m (e.g. Figure 12a), considerably less than the laboratory measurement on limestone samples (Table 2). The

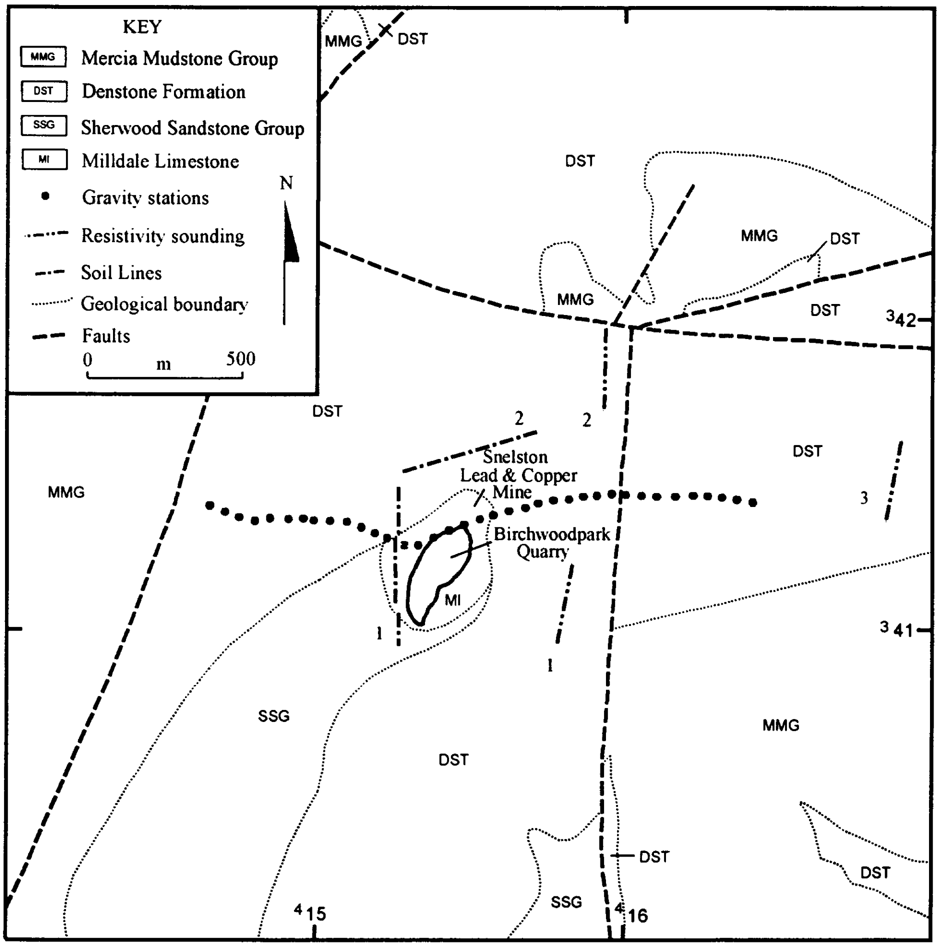


Figure 10. Location diagram for the Birchwoodpark area, with geology and locations of geophysical and geochemical surveys.

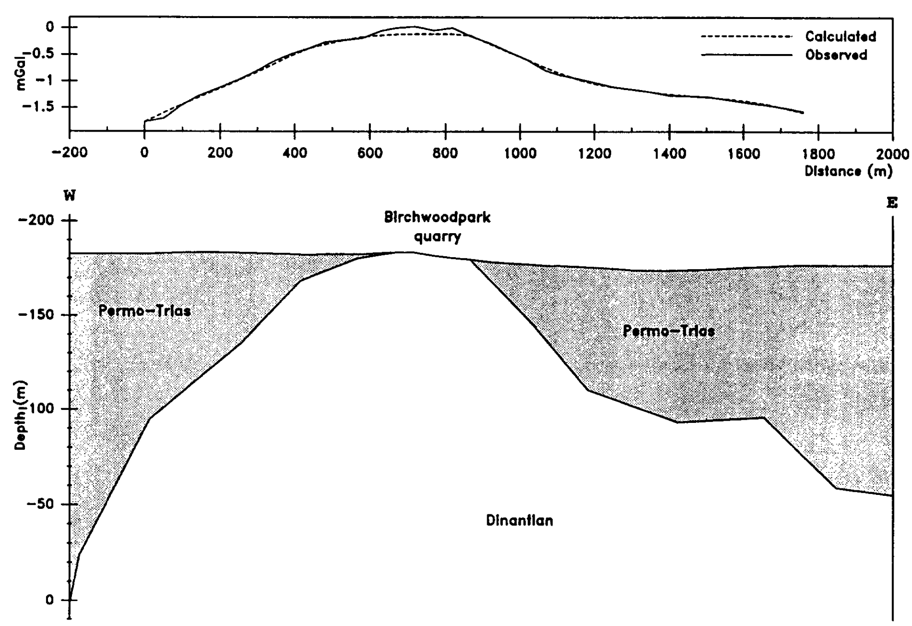


Figure 11. Detailed Bouguer anomaly profile along line of gravity stations (Figure 10) and interpretation.

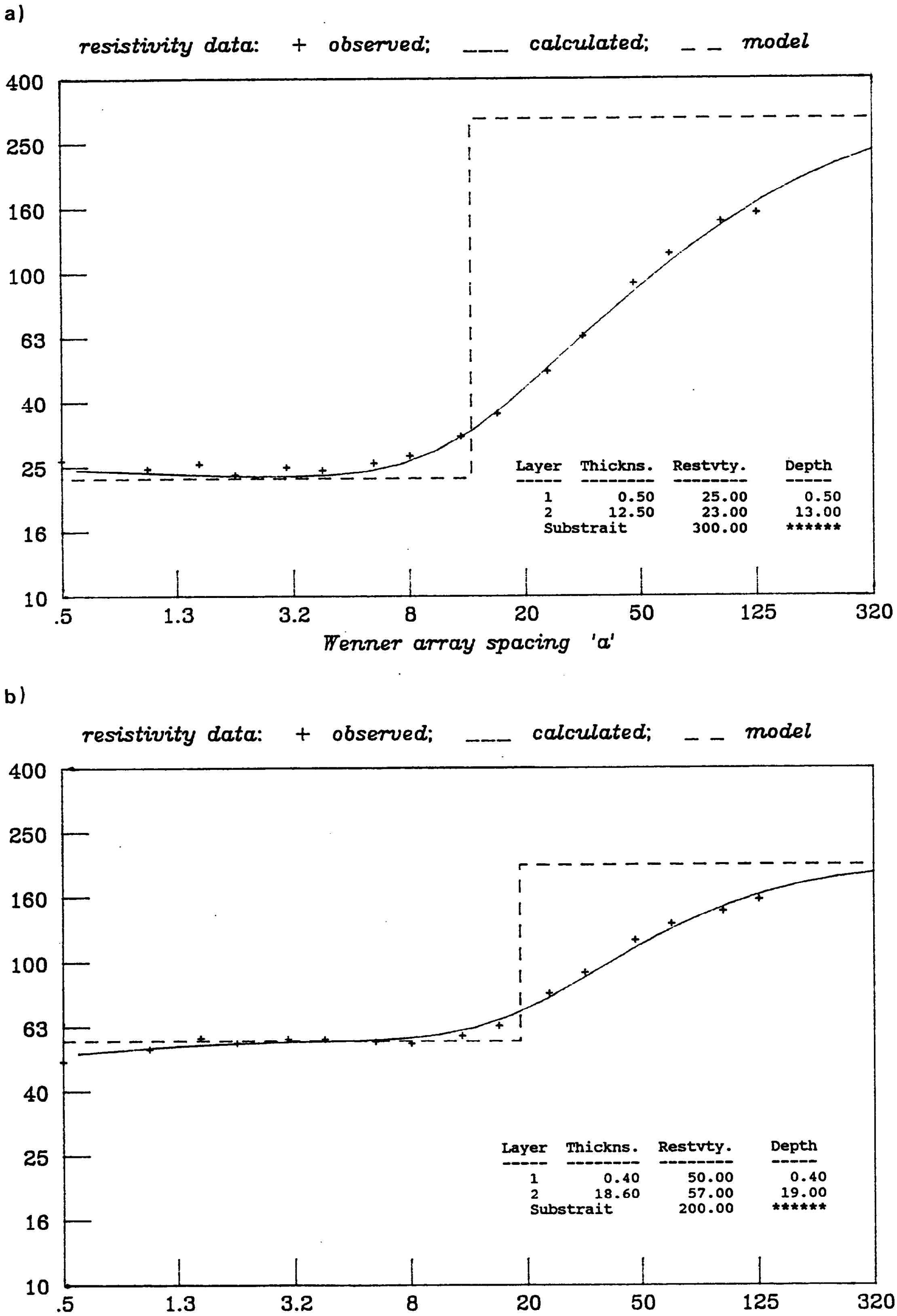


Figure 12. Examples of resistivity sounding data (crosses) and calculated curve for the horizontal layer models listed. a) Sounding 1, adjacent to Birchwoodpark Quarry, with Triassic rocks overlying Carboniferous and b) sounding 8 in the Derwent Valley, with drift overlying Triassic (Hollington Formation).

intervening layers with resistivities of about 23 ohm m are mudstones and siltstones and those in the range 35 ohm m to 43 ohm m are layers which incorporate sandstone, of which there is some evidence from the old mine at Birchwoodpark Quarry. Thus the limestone surface is estimated to extend from outcrop to a depth of 70 m at Darley Moor, over a distance of 1.5 km. Some in-situ resistivity measurements made directly on the outcropping limestone of Birchwoodpark Quarry indicated a very low value of 85 ohm m, suggesting extensive near-surface (i.e. a few metres) fracturing. It was therefore concluded that while resistivity values of 1000 ohm m, or more, could be interpreted confidently as massive Dinantian limestones, these rocks, if fractured or mixed with shale beds, might be indicated by values of a few hundred ohm m.

Soil geochemistry

Forty-two B-horizon soil samples were collected on two lines near Birchwoodpark Quarry from 50 to 100 cm depth using a hand auger. The lines ran approximately north–south and east–west to the west and north of the quarry (Figure 10). Line 1 runs over outcrops of Sherwood Sandstone Group, Milldale Limestones and Denstone Sandstone Formation, whereas Line 2 runs only over the latter formation. Summary statistics for the analysed elements are shown in Table 3 and profiles showing the concentrations of Cu, Pb, Zn and Ba are shown in Figure 13. Levels of all the base metals are low, although there is a perceptible variation in some elements that is related, in part, to the underlying lithology. For example, on Line 1, there are enhanced levels of MnO and Ba near both of the unconformable contacts between the Milldale Limestones and the overlying Triassic formations. MgO also shows a marked peak (to 2.5 wt%) over the northern unconformity. These higher values are probably related to the previously noted unconformity-related mineralisation at Birchwoodpark (Snelston). The two highest Pb values (165 ppm on the north–south line and 172 ppm on the east–west line) are not associated with enhanced levels in other base metals. Both lie over Permo-Triassic rocks and may be caused by contamination.

Table 3. Summary statistics for geochemical analysis of 42 soil samples from Birchwoodpark. Element concentrations in ppm, oxides in wt%.

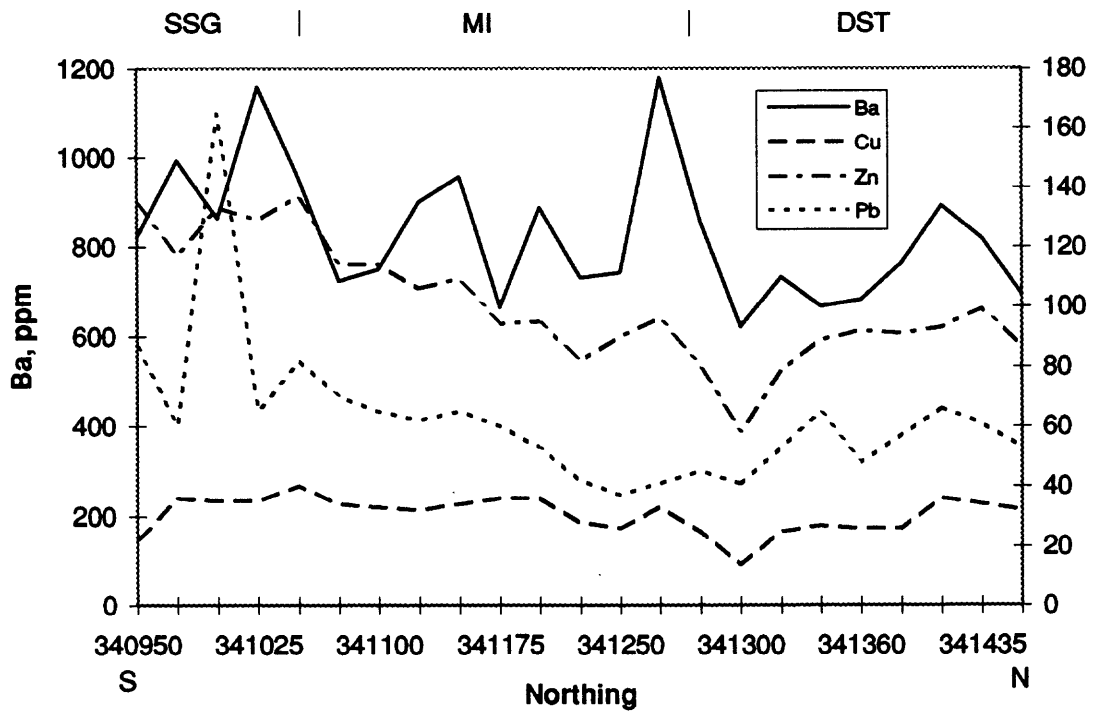
	Cu	Zn	Pb	MgO	CaO	MnO	Fe_2O_3t	Ba
Minimum	13	49	29	0.70	0.40	0.018	4.17	451
Maximum	40	137	172	2.50	7.85	0.312	7.85	1179
Median	29.5	92.5	60	1.20	0.68	0.099	5.79	729.5
Standard deviation	7.0	19.2	27.3	0.35	1.40	0.062	0.96	162.6

DOVE VALLEY AREA

The interpretation of the gravity data indicated that the shallowest part of the concealed Snelston high was likely to be beneath the valley of the River Dove, between the villages of Church Mayfield and Lower Ellastone. Further geophysical surveys were carried out to examine the area (Figure 14); geochemical surveys were not considered appropriate because of the masking effect of the alluvium in the valley bottom.

Geophysics

On the detailed gravity profile (Figure 15) along the Dove Valley, the Bouguer gravity high is located at [4146 3436], coincident with that indicated from the interpretation of the regional gravity data, and additional modelling showed that the limestone surface should be very shallow. The results of this modelling were followed up by a series of resistivity soundings along the valley floor of the River Dove (Figures 14 and 16). Soundings 4 and 5, to the north-east of the proposed shallow limestone ridge, indicate a higher a)



b)

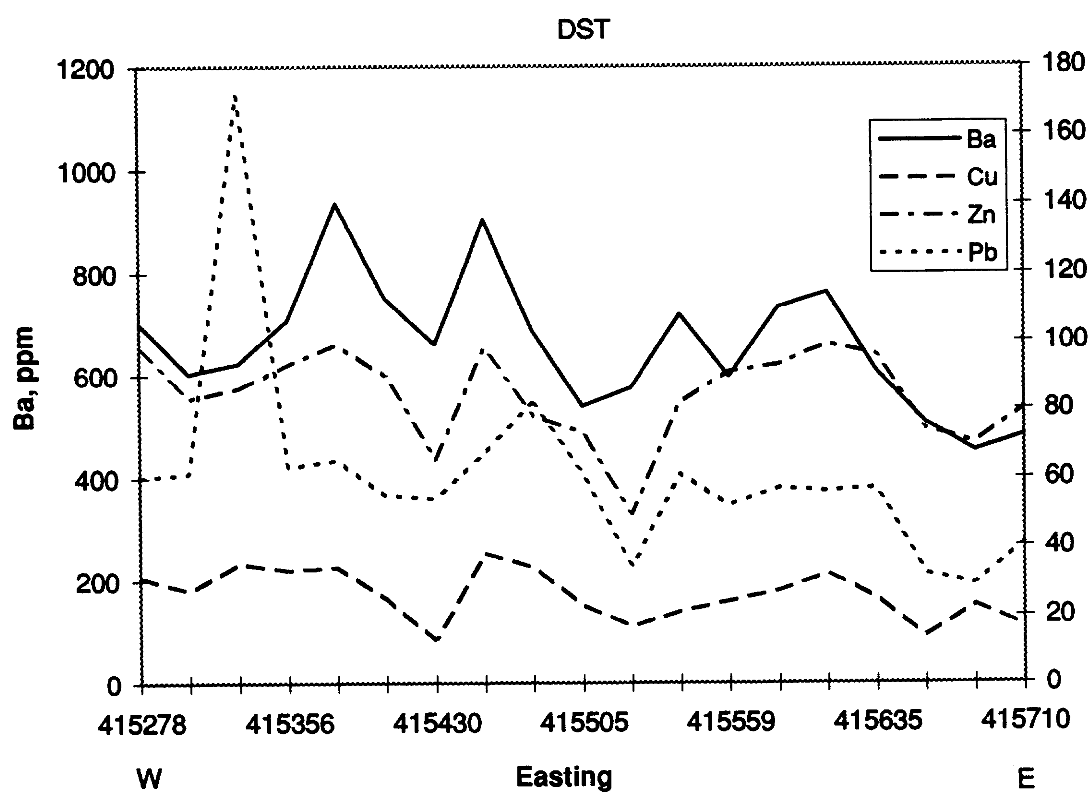


Figure 13. Soil geochemistry profiles, Birchwoodpark. a) north–south line, b) east–west line.

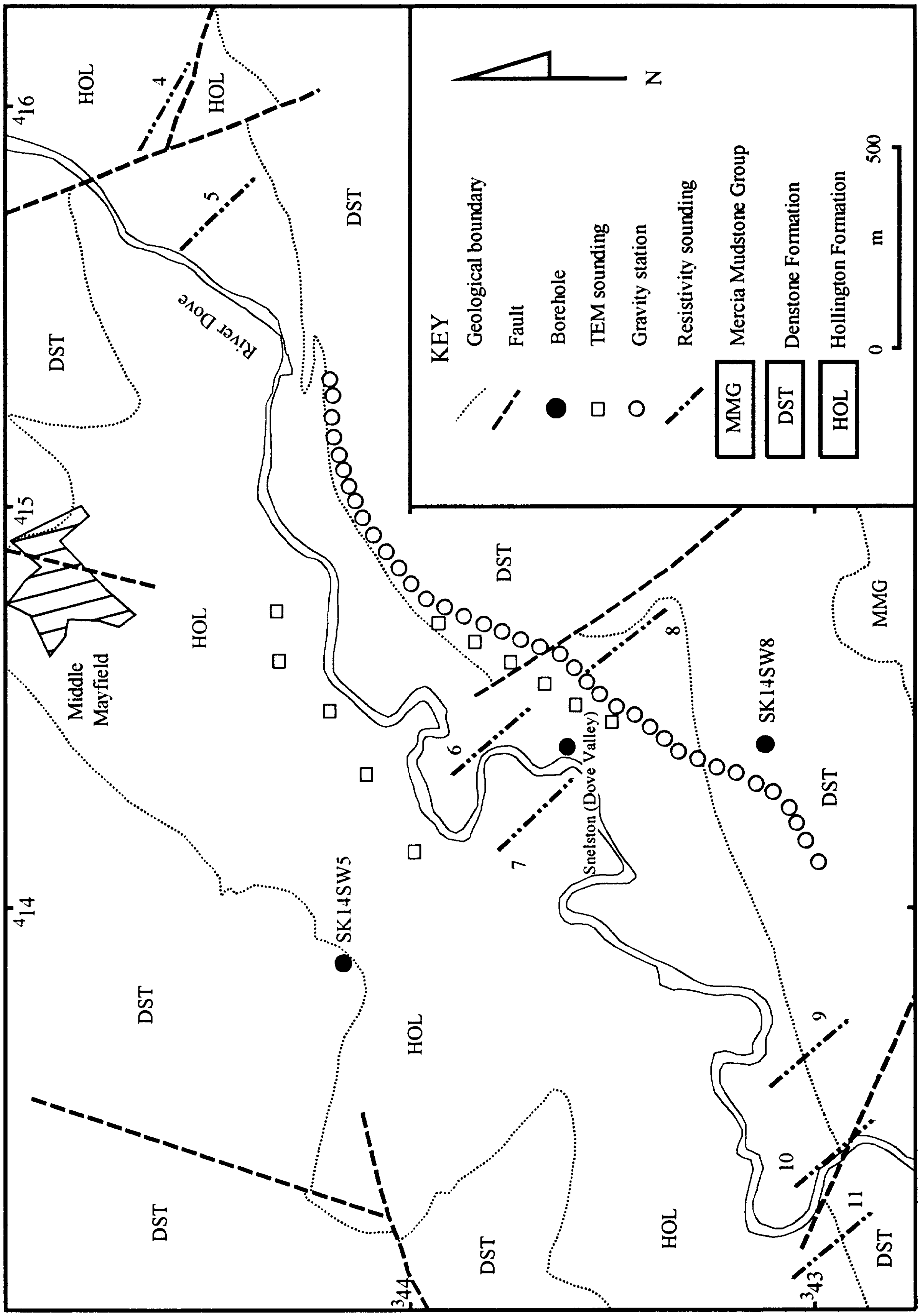


Figure 14. Location diagram for the Dove Valley area with geology and locations of geophysical surveys and boreholes.

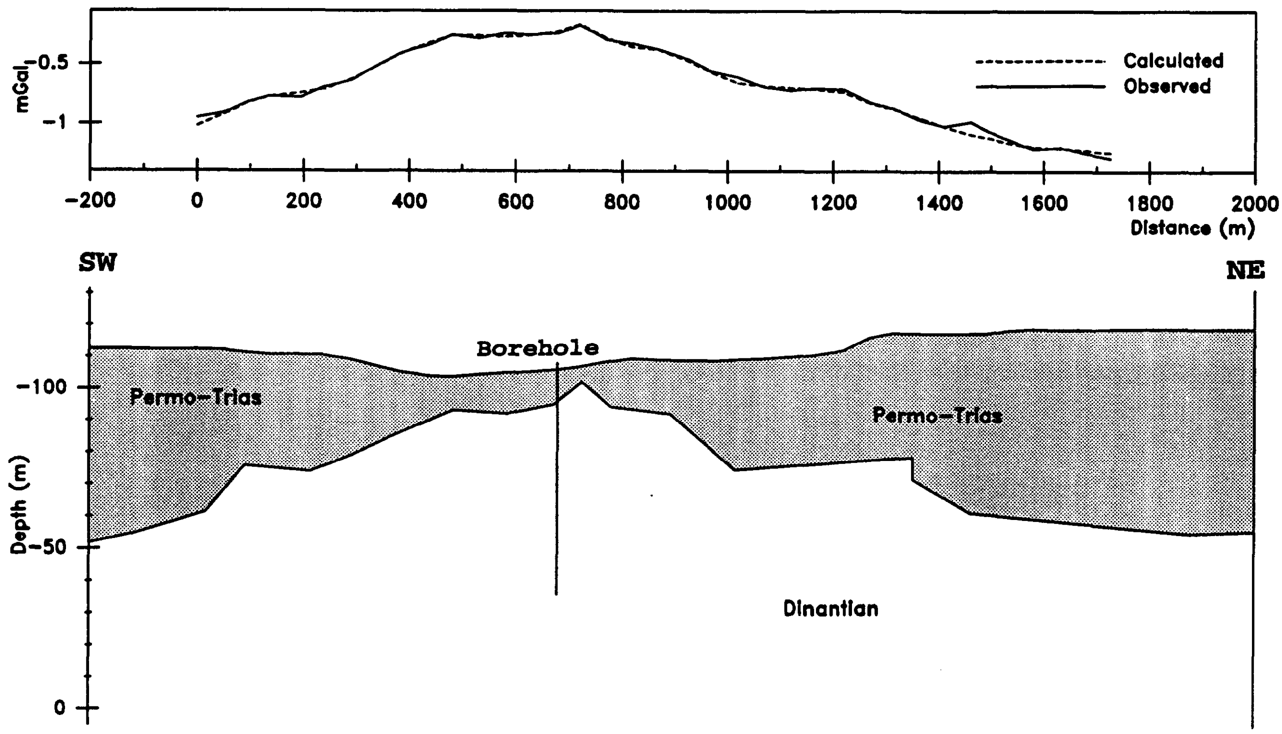


Figure 15. Detailed Bouguer anomaly profile and interpretation along the line of gravity stations shown in Figure 14.

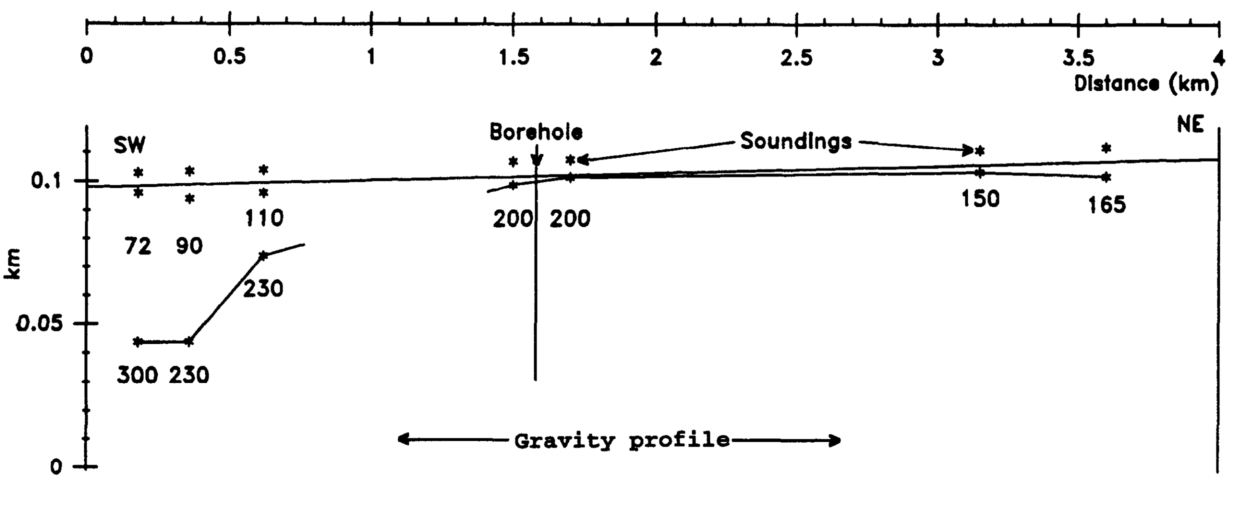


Figure 16. Composite section based on results of resistivity soundings.

resistivity lower layer (150–165 ohm m) at very shallow depth (2.5–5 m) which almost certainly forms part of the alluvial sequence, probably river gravels. Soundings 6, 7 and 8, located over the gravity high, produced upper layer resistivities characteristic of the alluvium or the underlying Triassic sandstone; all three soundings were modelled with a substratum resistivity of 200 ohm m (see Figure 16). At sites 6 and 7 this layer occurs at very shallow depths of 1.5–1.9 m, almost certainly within the alluvium. The 310 ohm m layer at a depth of 0.4 m at site 11, to the south-west of the gravity high is probably also due to river gravels but a deeper resistive layer is also indicated here and on the adjacent soundings (9 and 10). This resistive substratum (230–300 ohm m) increases in depth westwards from 25 m to 54 m and was originally regarded as possibly indicating the limestone surface beneath thickening Permo-Trias.

TEM soundings were carried out at a number of sites (Figure 14) to confirm the results of the resistivity soundings and also to check for the presence of any electrical conductors that might indicate mineralisation at the Carboniferous-Triassic unconformity. The data, however, were found to be badly affected by EM noise and satisfactory interpretations were not possible.

Drilling

Based on the geophysical evidence, a borehole was sited to prove the Dinantian limestone surface beneath the Permo-Triassic cover and to examine the possible presence of mineralisation at the unconformity near the crest of the concealed ridge. The vertical borehole (Snelston (Dove Valley)) was located [414396 34361] (Figures 14 and 15) on the Bouguer gravity anomaly high within the River Dove flood plain, where the geophysical results indicated that the limestone should be present at a shallow depth. The borehole was cored from 50.13 m to the final depth of 73.95 m and the core log is shown in Appendix 2. The Triassic - Dinantian contact was found at 61.20 m, confirming the prediction based on the gravity evidence that it would occur at relatively shallow depth, the discrepancy with the predicted depth being within the possible error discussed earlier. The interpretation that the very shallow, high-resistivity layers shown in Figure 16 must be gravels or Triassic sandstones, rather than Dinantian limestones, is confirmed.

The downhole lithological and geochemical plots for the borehole are shown in Figure 17 and a geological log is included in Appendix 2. The core shows subhorizontal Triassic sandstones overlying Carboniferous limestones dipping at 60°. The topmost two metres of the limestone are dolomitised but without visible mineralisation apart from minor calcite veining. Geochemical analysis of the Triassic sandstones from the borehole showed that samples contained slightly enhanced values of Ba (between 130 and 262 ppm); values in the underlying Dinantian limestone were $\geq$100 ppm. Pb and Zn values were very low at < 30 ppm, but Cu reached 88 ppm in one sample at the top of the Dinantian.

Two samples of Triassic sandstone from the Snelston (Dove Valley) Borehole provided a saturated density (2.42 Mg/m^3, with a porosity of 14.5%) typical of rocks of this age (Table 2).

LIMESTONE HILL AREA

Geophysics

The geophysical data at Limestone Hill (Figure 18) were collected primarily in order to provide additional information on the location and dip of the Carboniferous/Triassic boundary, the form of the knoll-reef and the extent of the base metal mineralisation.

During the VLF survey, both magnetic and electric field data were collected in order that the in-phase and quadrature data, arising from the magnetic field measurement, might detect any planar dipping mineralised structures, whilst the apparent resistivity and phase data, arising from the electric field measurement, would

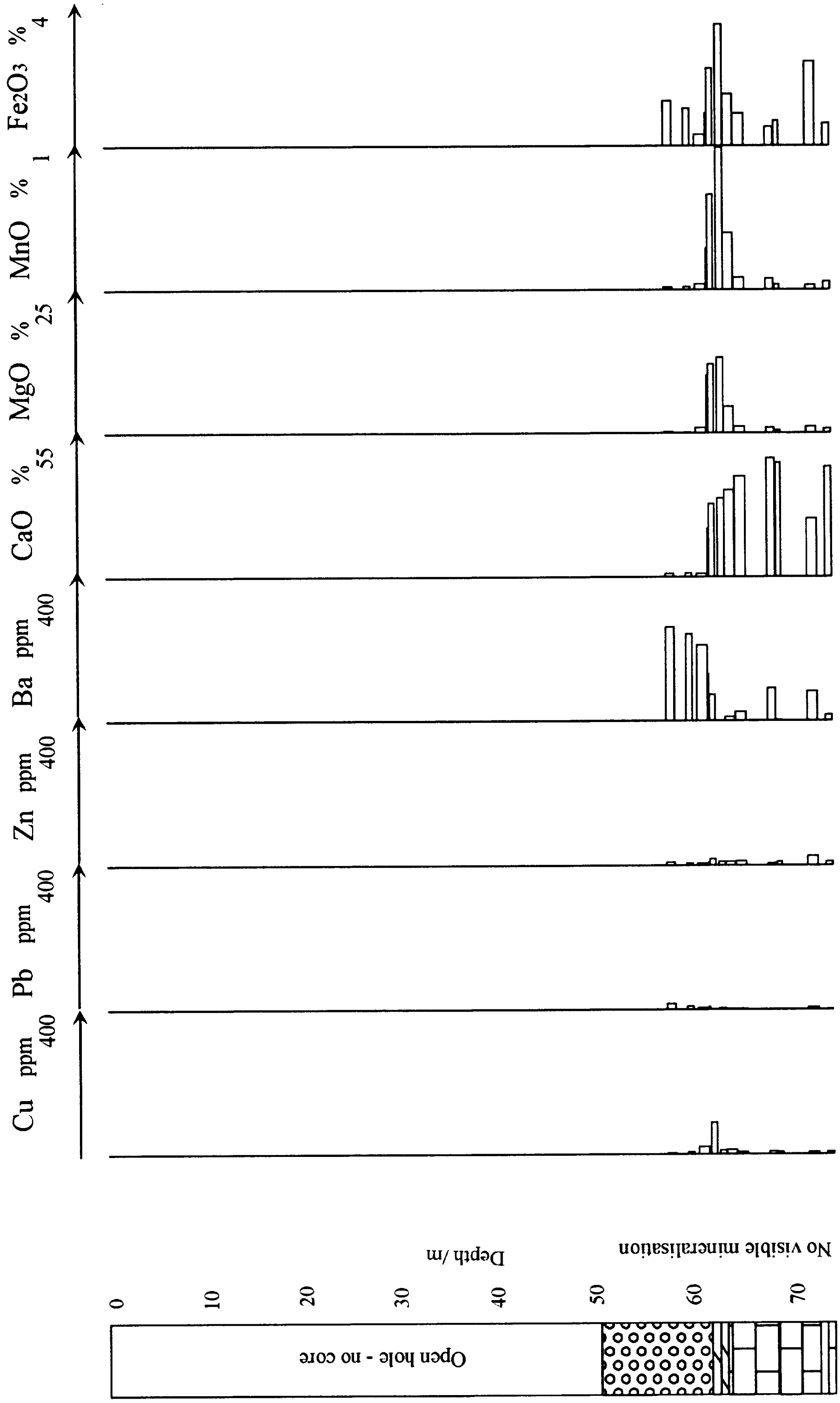


Figure 17. Lithology and geochemical results from Snelston (Dove Valley) Borehole. Cu, Pb, Zn and Ba in ppm; CaO, MgO, MnO and Fe_2O_3 in %.

outline the general extent of the mineralised zone. VLF magnetic field results for the two orthogonal lines 1 and 2 are shown in Figures 19 and 20 respectively. Along line 1 there was a cross-over type anomaly at about 70 m which was caused by a low tension power line. Higher in-phase values were recorded over the summit of the hill and these decrease progressively towards the northern end of the line, due to a weakening of the Cutler Maine VLF signal as the topography dropped into a valley. There were no VLF magnetic field anomalies along line 2. Resistivities obtained from the VLF electric field measurements (Figures 19 and 20) show background apparent resistivities of 100 - 300 ohm m for the Triassic and values in excess of 2000 ohm m over the Carboniferous rocks forming the summit of the hill. The extent of the (mineralised?) limestone is broadly indicated to lie north of 250 m; the northern margin was uncertain because of the lack of a distinct VLF anomaly, probably due to the degradation of the signal. On line 2 the resistive limestone was interpreted to lie at, or close to the surface between 70 and 215 m.

IP data were collected along three main survey lines (lines 3, 4 and 5, see Figure 18) which crossed the summit of, and lay to the west and east of the hill respectively. All lines were traversed from south to north. The results are shown in Figures 21 and 22 respectively. A chargeability anomaly occurs at the southern end of line 4 and implies a near-surface source located between 25 and 50 m, to the south-west of the hill summit. Additional lines 6 and 7 were surveyed to the west of the summit in order to investigate continuations of this anomaly but the most probable source of the anomaly is a concealed water pipe. Other chargeability highs are considered to be the result of noise and have no geological significance. The apparent resistivity data for line 3 again demonstrate that the summit of the hill, formed by mineralised knoll-reef, is associated with very high resistivities.

Detailed gravity measurements along profile 1 indicated an increase in values at about 150N to 200N, south of the contact shown by the VLF resistivity data. This implies a rapid thickening of Triassic to the south of the limestone outcrop but, to the north, the absence of a gradient suggests a gently dipping interface.

Conductivity variations were measured along three profiles using the shallow penetration EM31 mapping system to examine any near-surface variations. Along most of profile 1 the results were comparable to those from the IP survey, with intermediate values over the Triassic and very low values (i.e. very high resistivities) over the limestones. On the lower ground north of the hill, conductivity values increase progressively (to an equivalent of 30 ohm m), indicating the probable near-surface presence of clays, probably as thickening drift (Figure 23).

Geochemistry

Soil and rock geochemistry

A total of 34 soil samples were collected on two lines across Limestone Hill from 20–80 cm depth using a hand auger. The lines run approximately north–south and east–west over the top of the hill (Figure 18). The samples were generally collected from the B-horizon over outcrop of the Triassic but the soil cover is very thin over limestone reef C-horizon soils were taken there. These soils have a high content of residual dolomite fragments and occasional galena grains are visible. Summary statistics for the geochemical data for the traverses are shown in Table 4. The results show very high values for Pb and Ba (both >1%), together with anomalous Zn (to 1510 ppm) and Cu (to 439 ppm) values. Maximum levels of the base metals occur over the knoll-reef limestone outcrop (Figure 24) which is also clearly distinguished on the basis of higher CaO, MnO and MgO concentrations in soil. Two pits were dug to bedrock (at approximately 0.75 m) at the sites with the highest base metal values. Five rocks were sampled from the base of these pits together with two from surface exposures and selected analyses of these are shown in Table 5 (ARR 7081-7084). These clearly show highly anomalous levels of Pb, together with enrichments of Ba, Zn, Cu, Ag and Cd.

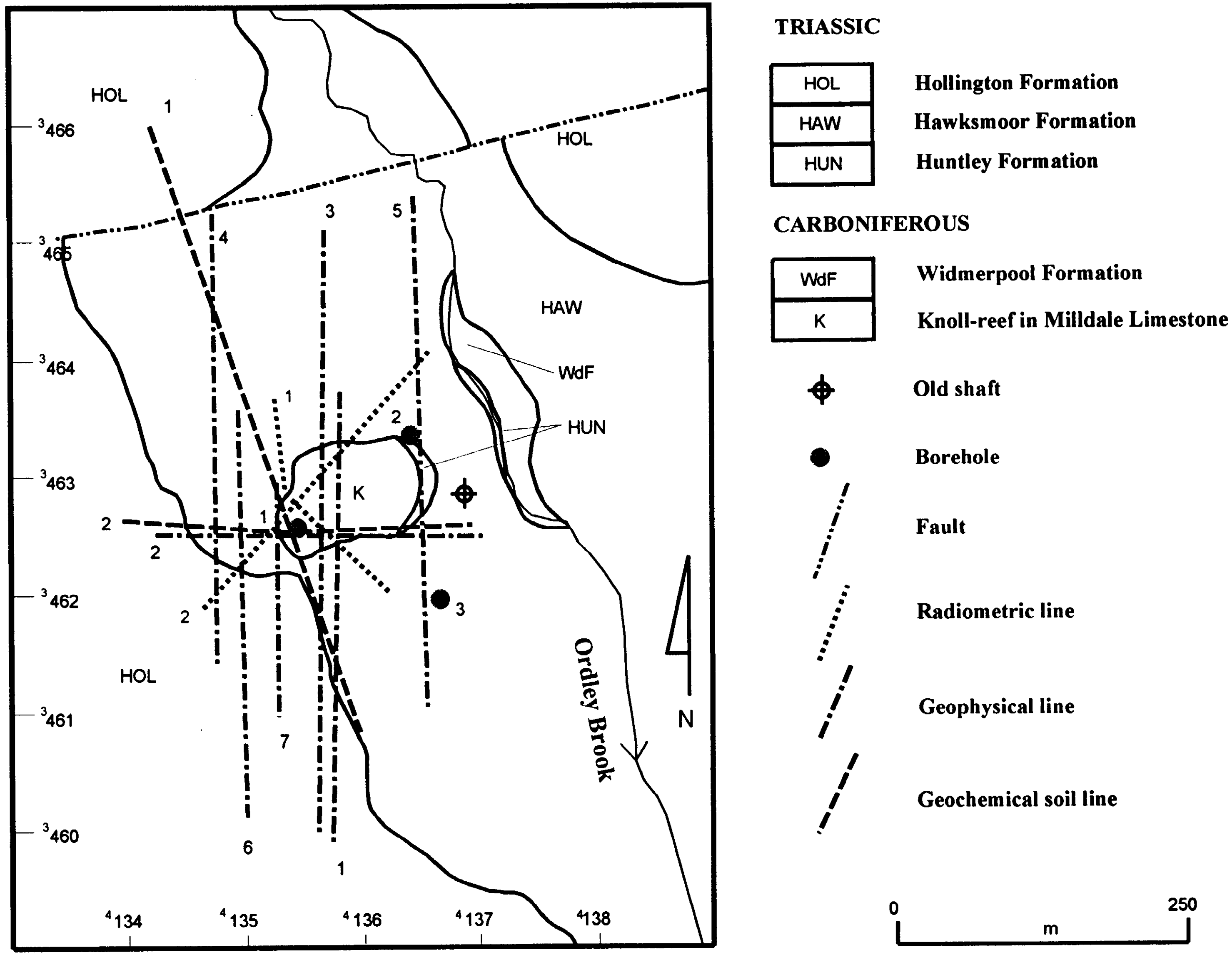


Figure 18. Location diagram for the Limestone Hill area with geology, locations of geophysical and geochemical surveys and boreholes.

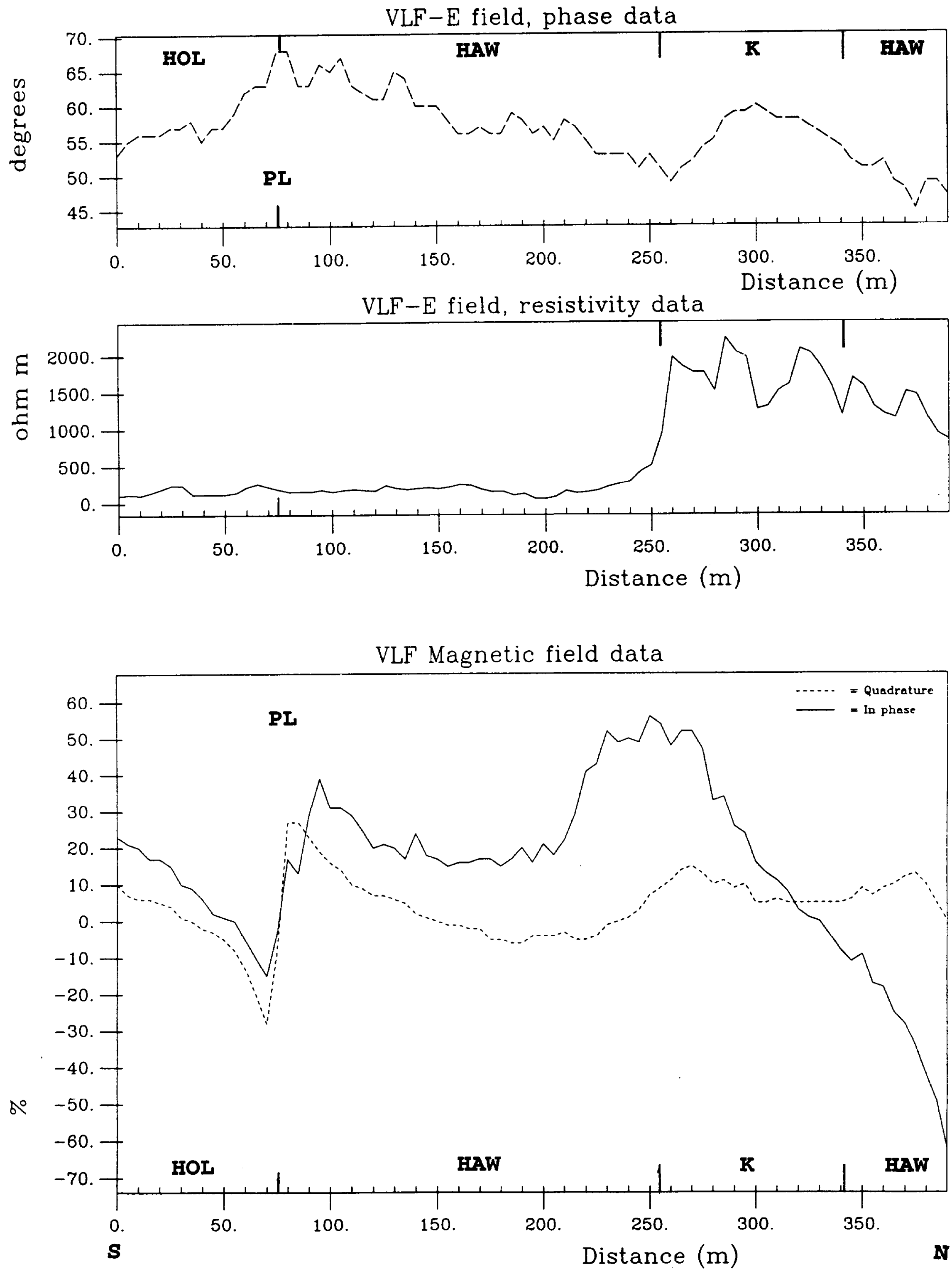


Figure 19. VLF electrical and magnetic field profiles for line 1.

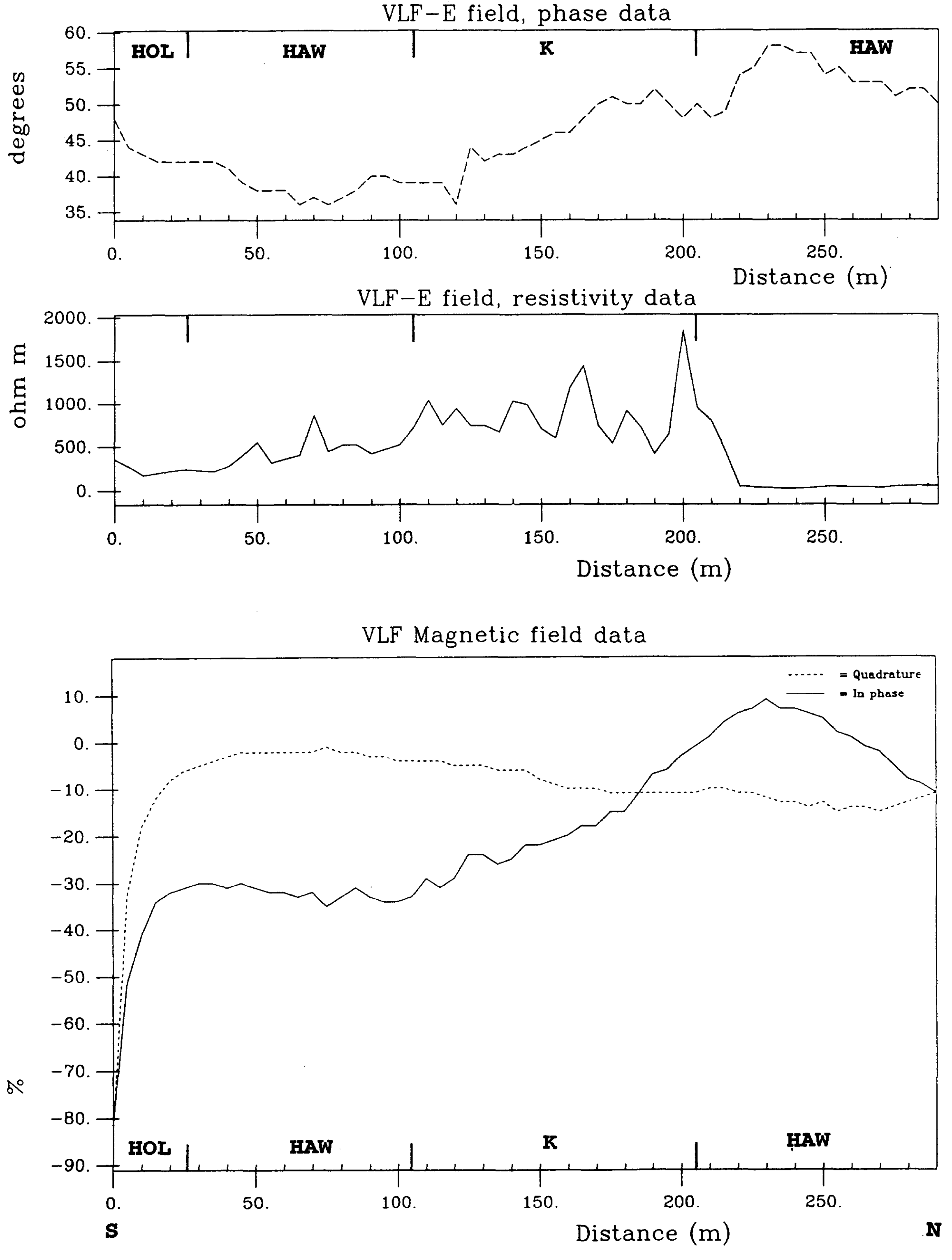


Figure 20. VLF electrical and magnetic field profiles for line 2.

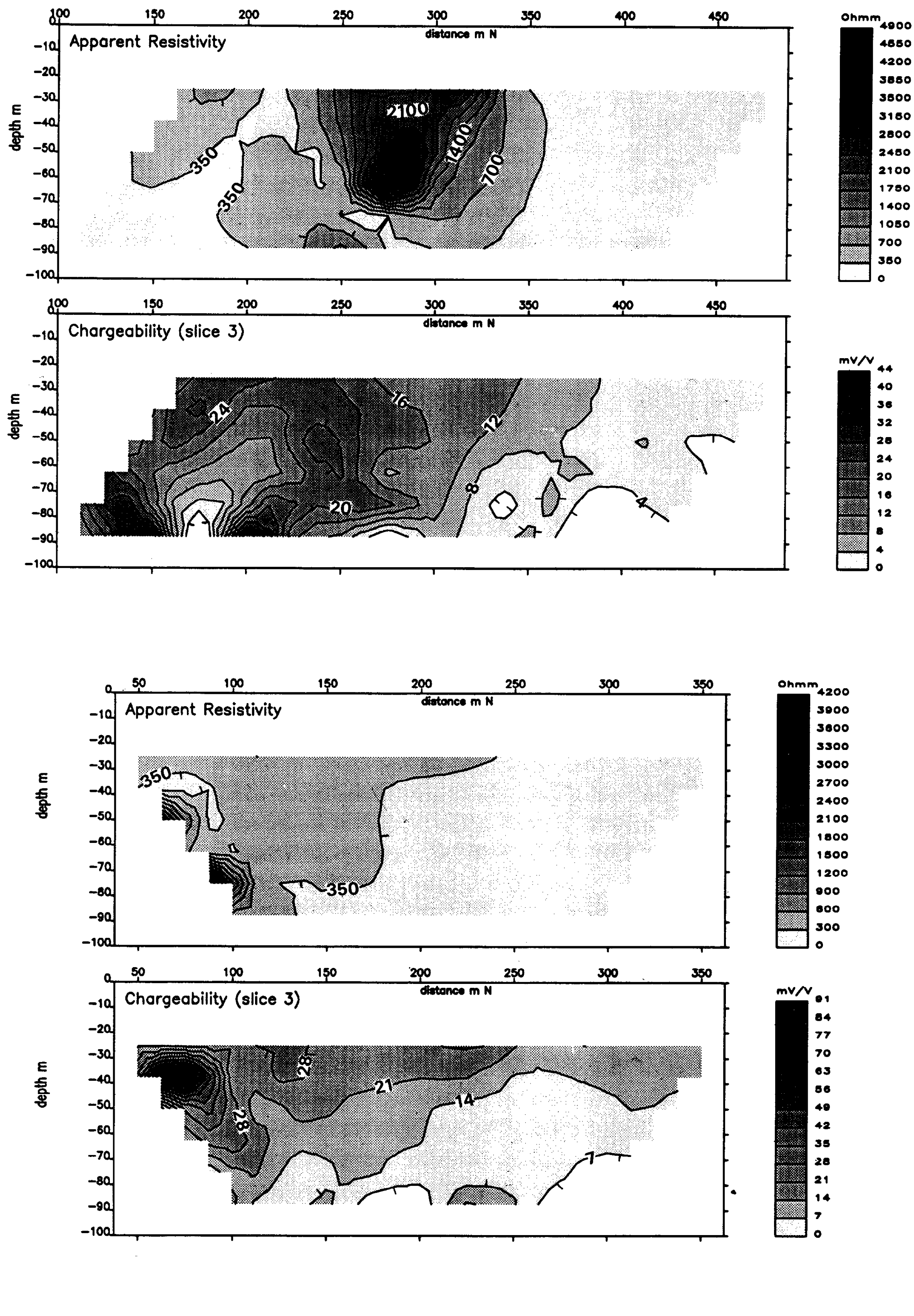


Figure 21. IP pseudo-sections for lines 3 (above) and 4 (below).

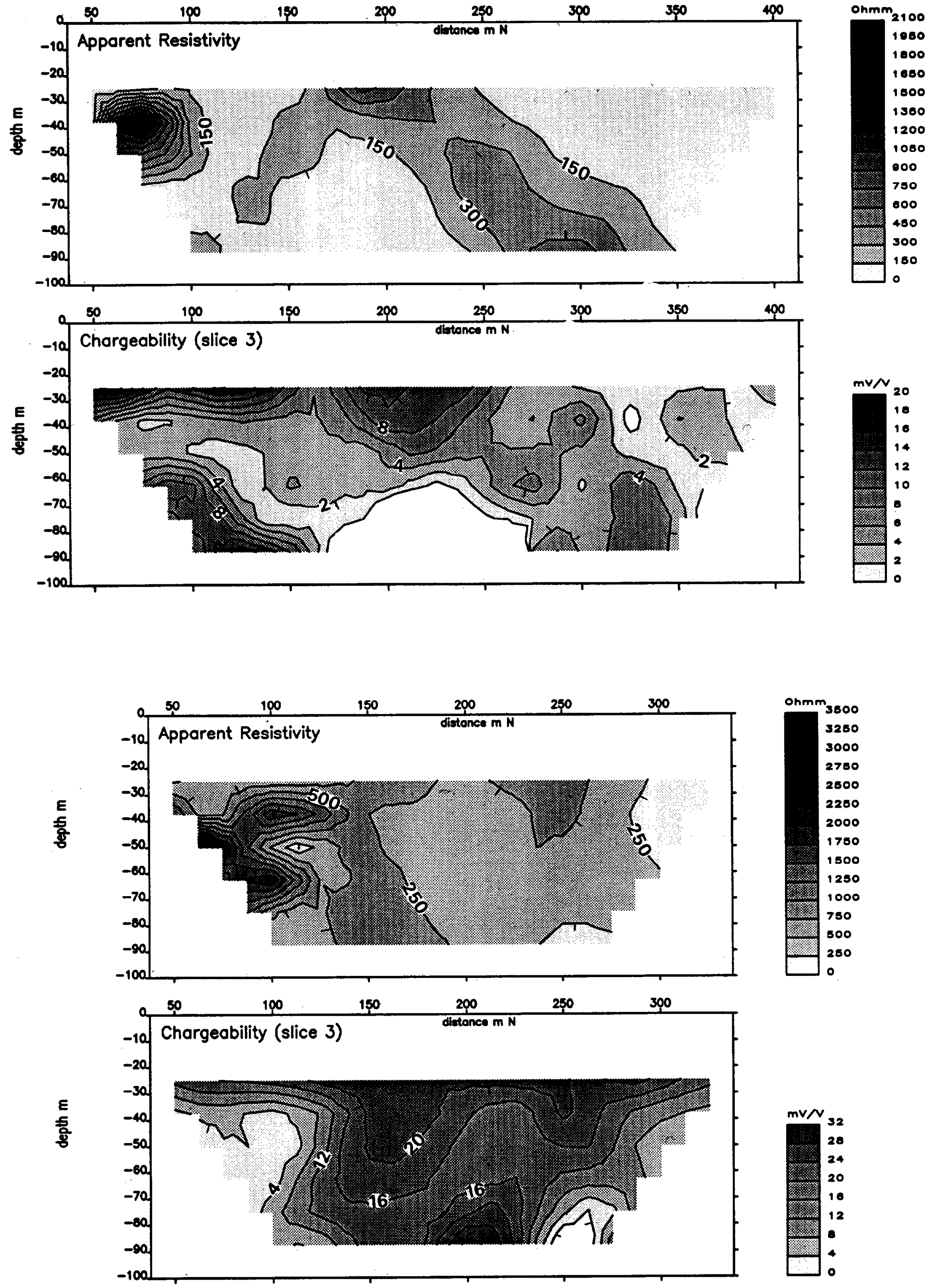


Figure 22. IP pseudo-sections for lines 5 (above) and 6 (below).

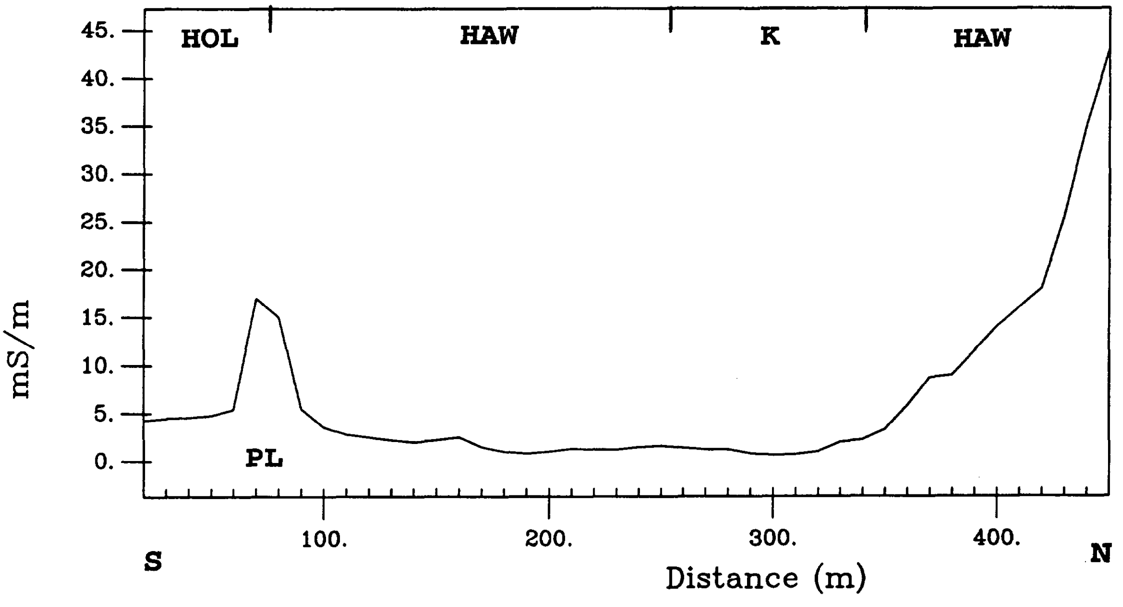


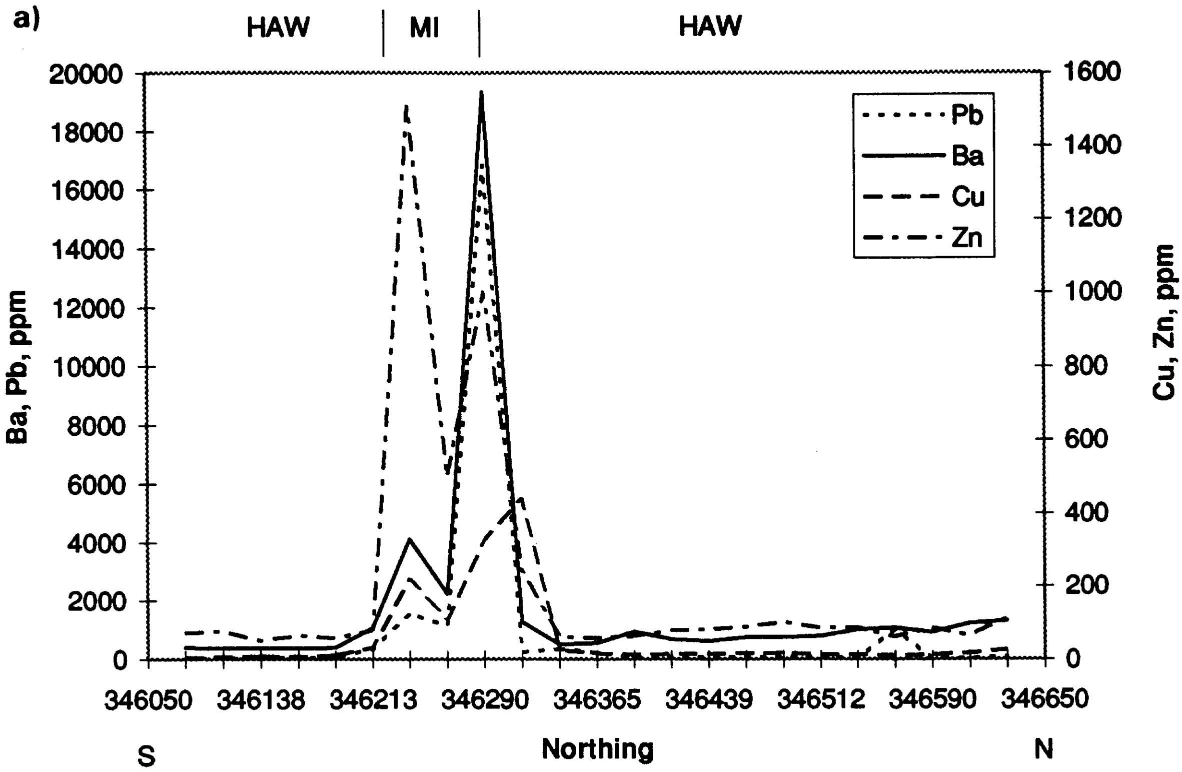
Figure 23. Shallow conductivity profile for line 3

Pb values in soil are generally greater than Pb and Cu over the limestone outcrop, and Pb and Ba anomalies are closely coincident. However Cu anomalies occur to the east and north of the limestone. This is probably due to temporal variation in the mineralisation as Ba shows two peaks coincident with both Pb and Cu on line 2 and is consistent with observations on the drill core which are suggestive of a minor Cu-Ba sandstone mineralisation event distinct from the Ba-Pb-Zn limestone mineralisation. The width of the Zn anomaly (to the east of the limestone outcrop) on line 2 is difficult to explain, but may be due to dispersion downslope caused by previous mining activity.

Table 4. Summary statistics for geochemical analysis of 34 soil samples from Limestone Hill. Element concentrations in ppm, oxides in wt%.

	Cu	Zn	Pb	MgO	CaO	MnO	Fe_2O_3t	Ba
Minimum	4	42	12	0.20	0.02	0.015	1.29	357
Maximum	439	1510	16862*	6.20	22.15	1.141	6.19	19340
Median	16.5	83	92.5	0.50	0.205	0.130	2.43	920
Standard deviation	110.5	379.4	2974.3	1.31	4.63	0.303	1.25	3564.5

* As the maximum calibrated analytical value for Pb is 1%, the maximum value is given as a guide only.



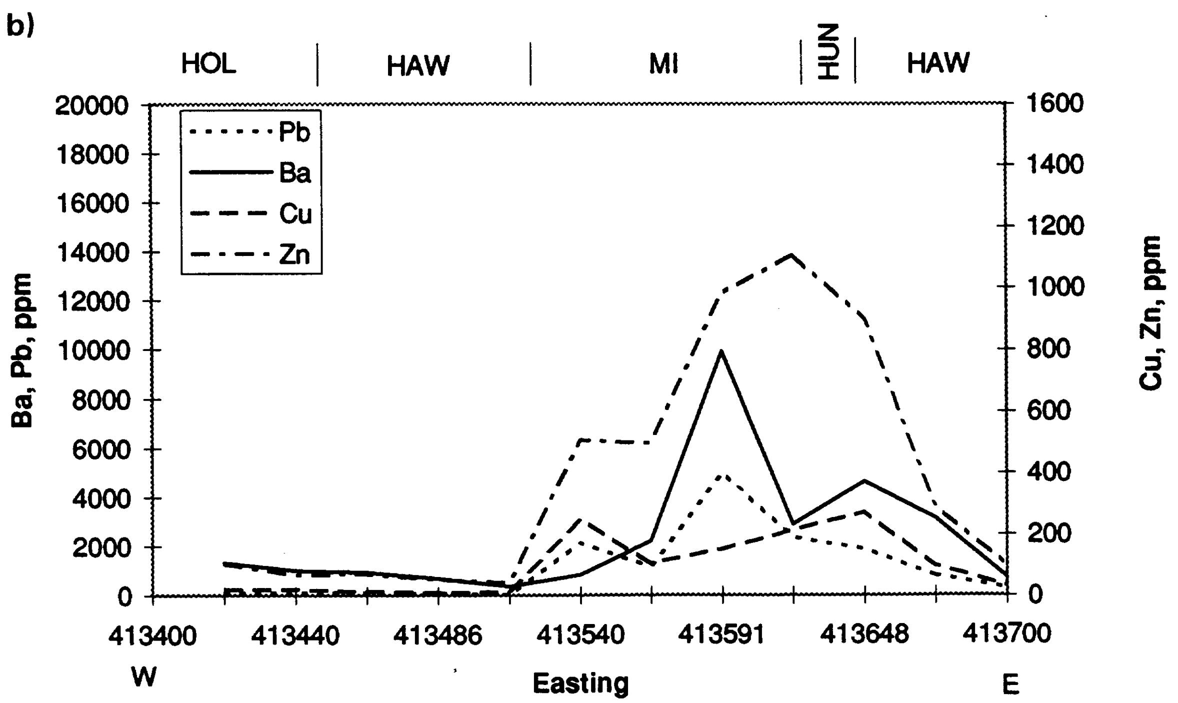


Figure 24. Soil geochemistry profiles, Limestone Hill. a) line 1, b) line 2.

Soil gas (radon and thoron) and ratemeter measurements were made along two lines approximately at right angles (Figure 18). On line 1 there is a large increase in surface gamma activity and radon at the Carboniferous - Permo-Triassic contact. This may be due to the contrast in rock types or could be a high permeability zone, such as a fault. It coincides approximately with the breccia and karst in-fill zones in Borehole No. 2.

Table 5. Selected analyses for dolomites from outcrop and drill core from Limestone Hill.
(n/a = not analysed)

	ARR7081	**ARR7082**	**ARR7083**	**ARR7084**	**ARD7109**	**ARD7110**
Lithology	Dolomite	Dolomite	Dolomite	Dolomite	Dolomite	Dolomite
Top depth m	Pit sample	Pit sample	Surface exposure	Surface exposure	14.74	15.35
Bottom depth m	0.75	0.40	-	-	15.35	16.7
MgO wt%	18.70	10.40	20.20	19.80	24.0	22.8
CaO wt%	35.81	35.91	30.58	31.48	30.70	33.86
MnO wt%	0.21	0.27	0.21	0.32	0.35	0.36
Fe_2O_3 wt%	0.48	1.06	0.38	0.44	0.60	0.46
Pb wt%	0.27	0.61	0.16	0.19	>10	>2
Cu ppm	38	128	50	22	200	68
Zn ppm	403	1300	336	420	28930	10594
Ba ppm	428	1739	434	1126	620	116
Ag ppm	7	12	14	4	interference	interference
Cd ppm	7	58	22	30	630	270
Sb ppm	11	12	26	0	n/a	n/a

Samples ARD 7109 and 7110 from Limestone Hill No.1 were diluted by 10 x and 2 x silica sand respectively to provide data on elements present in high concentrations.

Drilling

Three cored drill holes (Limestone Hill Nos 1-3) were sunk on and around the base of the hill (Figure 17). They were drilled to investigate the highly anomalous soil sample results and test extensions beneath Permo-Triassic cores in the vicinity of the hill. It was recognised that sphalerite and baryte are not very responsive to most electrical geophysical methods, especially if they are not massive, and thus drilling was the only effective method to test the extent of the poorly exposed reef limestone and the mineralisation therein. Three holes were drilled for a total of 175 m. Core recovery was excellent in spite of bad ground conditions in two of the holes and lack of water return. The core logs are given in Appendix 2.

The first hole was drilled on top of the hill to a depth of 60 m in 'knoll-reef' facies Milldale Limestone of Chadian age. An 11.2 m section from 8.5 to 19.7 m contained mineralised dolomitic limestone with coarse- and fine-grained galena in occasional clots and fracture fillings. A 0.61 m section from 14.7 to 15.3 m contained >10% Pb with about 3% Zn in cavernous dolomitic limestone (Table 5, ARD 7109). The following 1.35 m contained >2% Pb and ~1% Zn. Galena occurs as large crystals up to 2 cm in diameter and also in thin, sub-horizontal veinlets in a dolomitic matrix with a zebra-like texture in the section from 14.7 to 15.3 m. This texture is thought to be analogous to those described by Wallace et al. (1994) from carbonate-hosted sulphide deposits in Spain, Greenland and Australia. These authors suggest that the characteristic banding is a result of post-depositional fracturing followed by further dissolution of the carbonate and contemporaneous sulphide deposition during fluid fluxing.

Sphalerite was rarely seen but is thought to occur as a very fine grained pale brown variety. Ba values are generally < 1000 ppm except at 22.40 m where several thin pink baryte veins occur (Ba up to 2.3%). Cu values are low except for a single sample near the top of the hole at 8.5 m with 433 ppm Cu and one with 487 ppm Cu associated with the baryte veining at 22.40 m. Cd values reach 630 ppm in the Zn-rich sample at 15 m. Alteration and silicification, with the development of calcite veining and brecciation, was noted to around 40 m depth though dolomitisation is reduced below 20 m. The hole was stopped at 60.21 m in unaltered massive knoll-reef facies limestone. The downhole lithological and geochemical plot is shown in Figure 25.

The second hole was drilled to the north-east of the hill in a south-westerly direction. The downhole lithological and geochemical plot is shown in Figure 26. The borehole was collared in Triassic Huntley Formation sandstone and entered the knoll-reef facies Milldale Limestone at around 4 m depth. It passed through a 6 m zone of probable cave infill containing Triassic mudstone from 15.26 to 21.60 m. The probable cave infill sequence consists of three parts. From 15.26 to 17.50 m broken cores comprise mainly conspicuously and irregularly laminated microspar interpreted as having a cave-roof flowstone or stalagmitic material. Below this, from 17.50 to 21.30 m, is a red-brown calcareous claystone or mudstone breccia. The fragments of claystone are up to 8 cm across and in close contact with each other. They show a weakly developed fissility, variegated purplish red to pale green colour lamination and some discordant sheared features. The third and basal part of the infill sequence, extending down from 21.30 to 21.60 m, consists of red-brown earthy mudstone with dispersed indeterminate white debris, which may represent a cave floor deposit. A Triassic age is suggested for the infill. The hole was stopped at 35 m in unaltered knoll-reef limestone due to drilling problems. No sulphide mineralisation was observed though minor copper values (to 344 ppm) were associated with malachite staining at the Triassic / Dinantian contact. The topmost metre of the limestone was dolomitised, but the rest of the Dinantian contained no dolomite.

The third hole was drilled to the south-east of the hill in a north-westerly direction. It started in Triassic Hawksmoor Formation sandstone, passing into Huntley Formation pebbly sandstone at 6.89 m and entered Widmerpool Formation rocks at 8.09 m. The Milldale Limestones were intersected from 30.63 m. The hole was stopped at 79.43 m in unaltered massive limestone with minor pyrite mineralisation on joint surfaces. No other mineralisation is visible in the core or apparent from the geochemical analyses (Appendix 2 and Figure 27). Three facies are present:

> *Facies A 8.09–30.63 m.* This consists of thinly bedded red mudstone / claystone and limestone. The limestones appear largely dolomitised in the top 6 m and increasingly less so downwards. The limestone beds mostly show sharp bases and gradational tops and upwards-fining grading, each with a lower division, probably of fine-grained packstone, and thicker upper division, probably of wackestone. Deposition was probably from weak turbidity currents in a distal ramp environment. The facies is assigned to the Widmerpool Formation of Asbian age based on foraminiferal evidence (Riley, 1995).

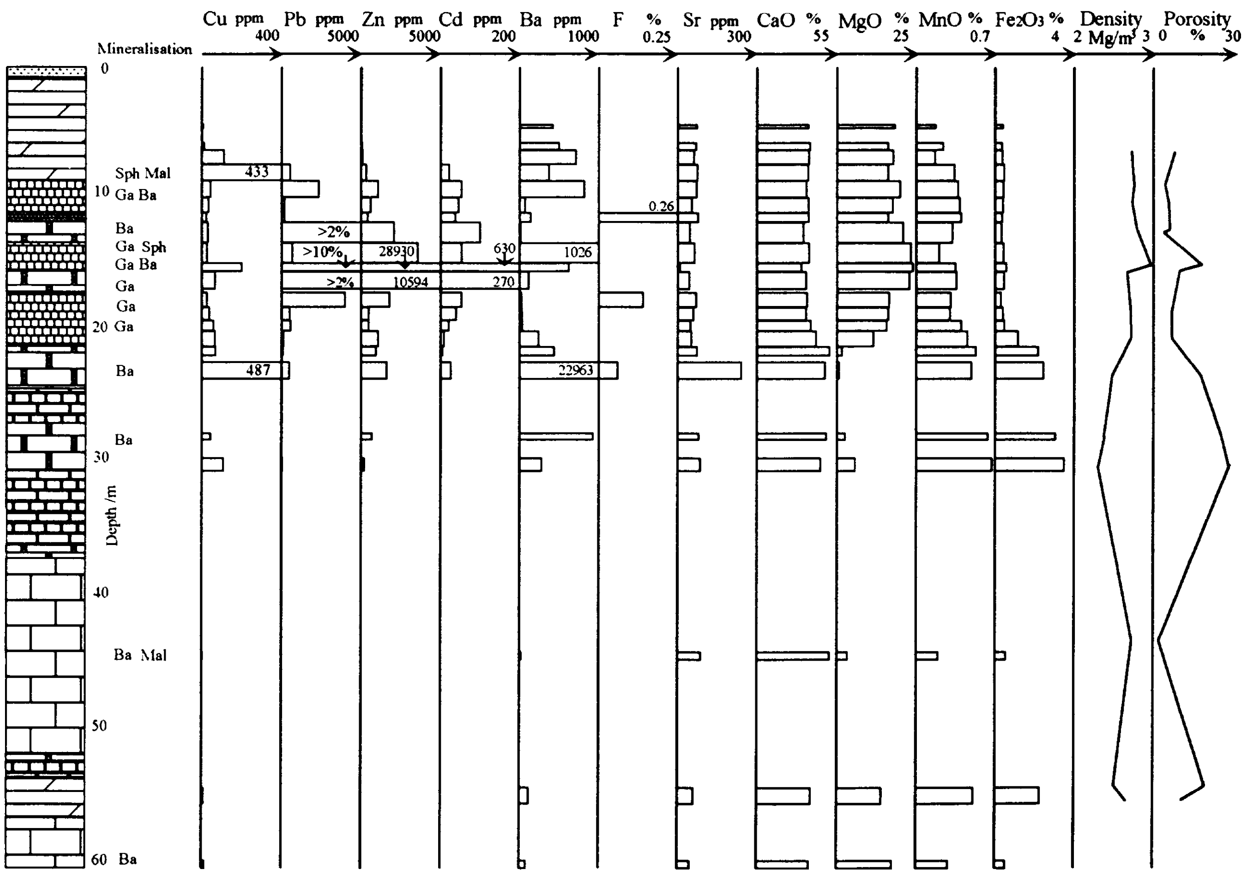


Figure 25. Geochemical results from Borehole 1, Limestone Hill, with density and porosity values. Key to lithologies in Figure 28.

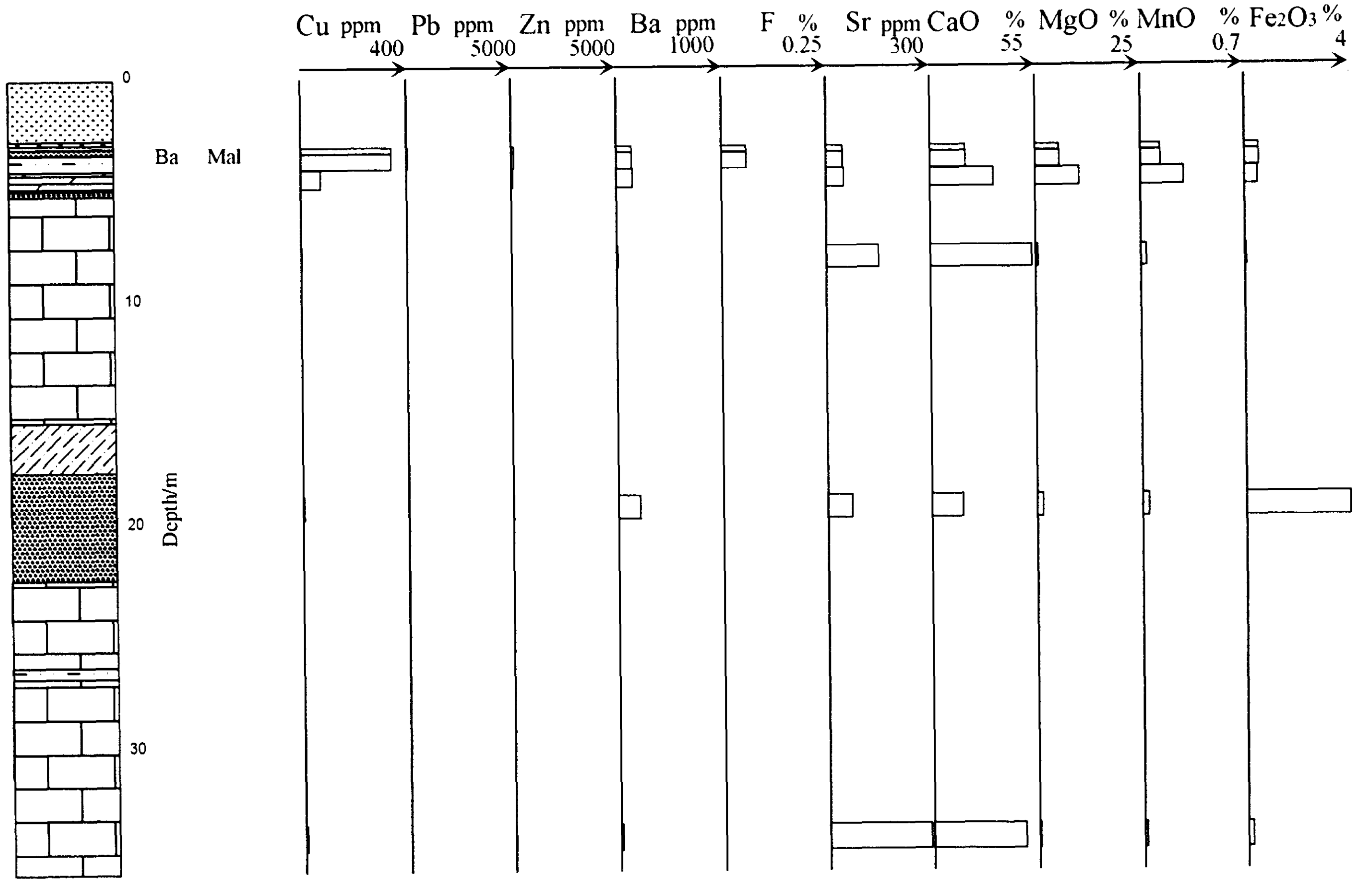


Figure 26. Geochemical results from Borehole 2, Limestone Hill. Key to lithologies in Figure 28.

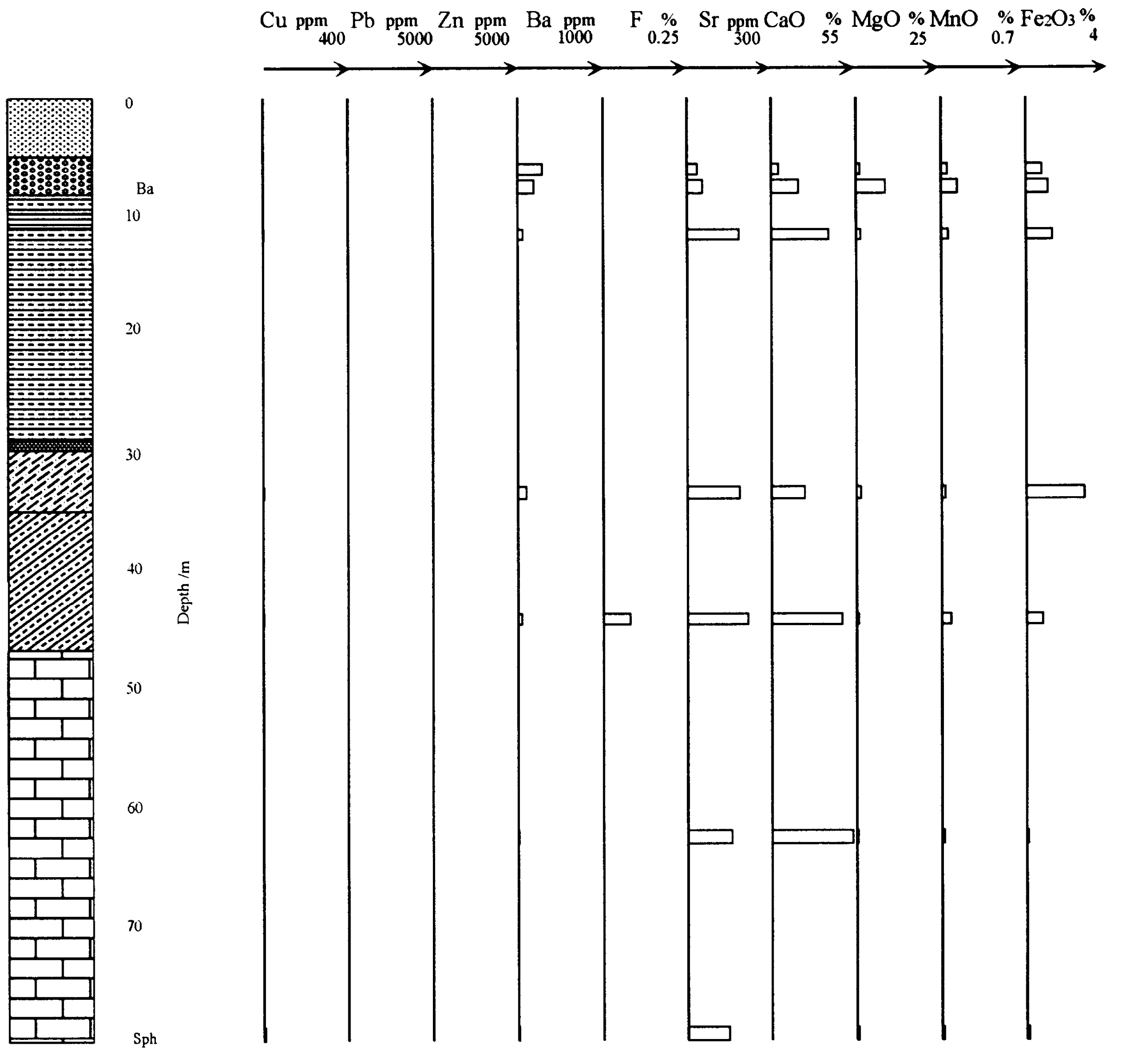


Figure 27. Geochemical results from Borehole 3, Limestone Hill. Key to lithologies in Figure 28.

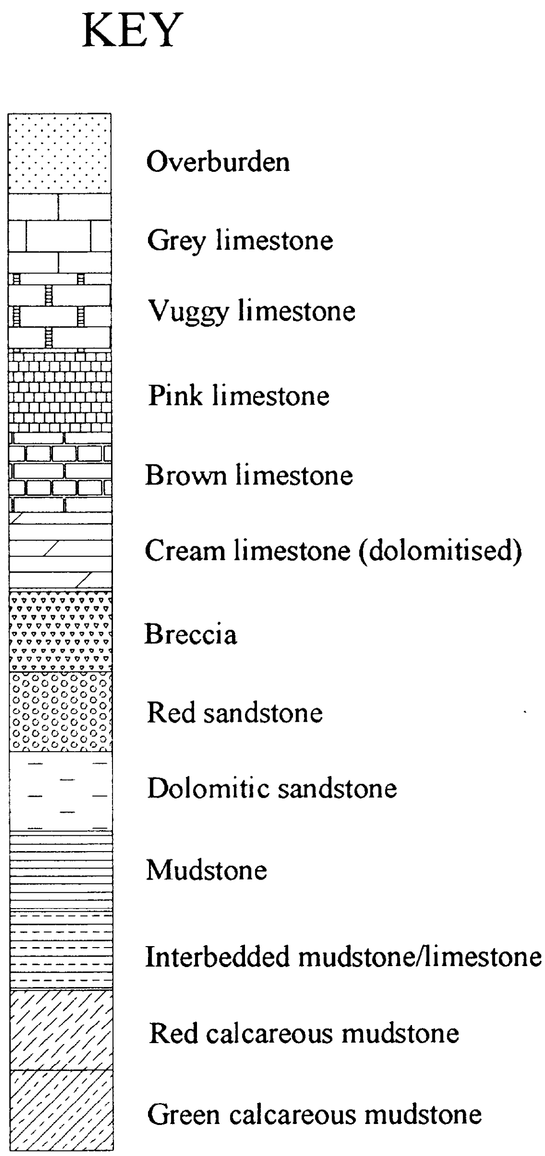


Figure 28. Key to lithological symbols used in Figures 25 to 27.

Facies B 30.63–46.37 m. This consists of relatively thickly interbedded red mudstone and limestone. In contrast to Facies A, the limestones consist entirely of wackestones (or calcilutites), and both tops and bottoms of beds are gradational. The facies represents a relatively deep water environment with little current activity and anoxic conditions hostile to marine animal life.

Facies C 46.37–79.43 m. This comprises the knoll-reef facies, as represented in boreholes 1 and 2, and is probably part of the same composite knoll which forms Limestone Hill. The top part of the reef from 51.99 to 52.09 m shows fissures filled with mudstone and in situ breccia, possibly as a result of early diagenetic processes prior to the submergence of the reef.

Facies B and C are separated from each other by a fault representing shearing and brecciation from 46.20 to 46.37 m. Such faulted contacts are the rule rather than the exception where the relatively ductile argillaceous bedded facies rests against or overlies (possibly unconformably) the rigid knoll-reef limestones.

In summary, the geochemistry of the drill core from Limestone Hill BH 1 indicates a replacement-style Pb-Zn-Ba mineralisation with Pb to > 10%, 3% Zn and enhanced Ba content in the upper part of the knoll reef. This is consistent with the soil results which show high levels of these elements directly over outcrop of the limestone. Slight enrichment of Ba and Cu in Triassic rocks immediately overlying the knoll-reef indicates a further type of minor mineralisation. Stream clasts in Ordley Brook and a large boulder on the eastern flank of Limestone Hill show barytic veining in Triassic sandstone which is more extensive than that encountered in the drill holes.

A diagrammatic section through Limestone Hill, based on surface mapping and drilling results, is presented in Figure 29.

Densities

The densities of fifteen samples from Limestone Hill Borehole 1 were measured, and mean values are listed below (with standard deviations in brackets) together with typical values for Carboniferous Limestone (Figure 25).

	Densities (Mg/m^3)		Porosity (%)
	Saturated	Grain	
BH 1	2.66 (0.17)	2.87 (0.15)	11.4
Typical limestone	2.69	2.70	1.0

The large variations indicated by the standard deviations reflect not only the presence of the dense mineral components (galena 7.5 Mg/m^3, dolomite 2.80 Mg/m^3) but also the variable number of large voids obvious in the core samples. Porosity values are generally high, reaching a maximum of 29%, especially in the barren limestones beneath the mineralised zone. The grain densities should reflect only the mineral composition and the highest value (3.42 Mg/m^3) is consistent with the presence of about 12% galena. More typical values of 2.80 - 2.85 Mg/m^3 could indicate dolomite or low percentages of galena. The average saturated density for the mineralised zone is high (2.78 Mg/m^3) but, because of the opposing effects of high grain density and high porosity, the borehole average is comparable with that for normal limestone.

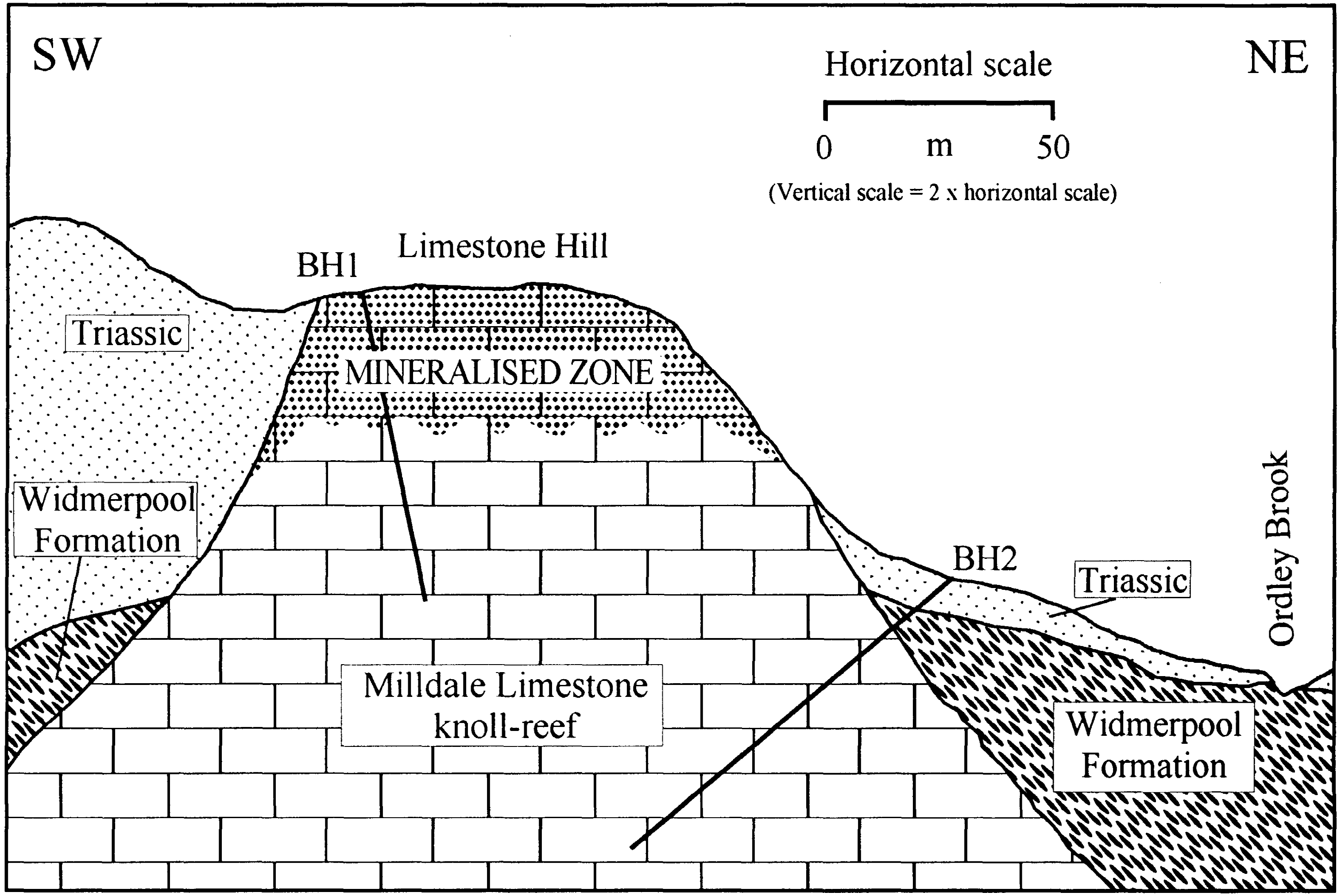


Figure 29. Diagrammatic section through Limestone Hill.

Magnetic susceptibility measurements were made on core from the entire length of the borehole using a hand held meter, mainly as a check on the presence of clay minerals. Although many of the values are low, the results indicate the presence of several clay-rich bands, particularly in the lower part of the borehole.

Origin of mineralisation

The mineralisation at Limestone Hill appears to be of limited extent (Figure 29) and differs from the vein typically developed in the South Pennine Orefield. Dolomitisation has strongly altered the top 20 m of the hill in borehole 1; limestone in the other boreholes, drilled in the base of the hill, are undolomitised. It is not clear whether the dolomitisation is as a result of knoll-reef being exposed during Permo-Triassic times or if it is associated with the mineralisation; no detailed mineralogical or petrological studies have been carried out. In either event, mineralising fluids have moved to the top of the knoll-reef and deposited Pb, Zn and Ba (with minor Cu) in vugs and as zebra-texture replacement.

The top of the knoll-reef appears to have acted as a structural and/or lithological trap for the mineralising fluids. Leakage of the fluids into the overlying Permo-Triassic may have been responsible for the baryte enrichment seen at Limestone Hill, in the Dove Valley Borehole and elsewhere. Baryte would form from the reaction with sulphate-rich groundwater; metal sulphides however would not be deposited. The copper-lead-zinc mineralisation at Snelston copper mine may have also formed by a similar process except that there was some reduced sulphur present to cause precipitation of metal sulphides. The source of the fluids could have been the Carboniferous Widmerpool Gulf to the east or deeper parts of the Needwood Basin to the south. The mineralisation fits within the general model for Mississippi Valley Type (MVT) mineralisation (Anderson and MacQueen, 1982) whereby acidic metalliferous brines are generated in sedimentary basins and pass laterally and upwards to the basin margins before depositing sulphides and sulphates in platform carbonates by fluid mixing or host rock interaction. Nothing is yet known about the fluid temperatures, salinities or isotopic compositions of the brines. Dolomitisation is a common host rock alteration, either preceeding or accompanying the mineralising process. Other features which may control the mineralisation include the presence of faults, changes in host rock lithology and development of karst solution structures. The limited mineralisation seen in the drill core is obviously of replacement style but there is insufficient information currently available to deduce controls on its deposition other than it occurs near the top of the knoll-reef.

CONCLUSIONS AND RECOMMENDATIONS

1. Previous geophysical evidence indicated the existence of a largely concealed ridge of Dinantian limestones which also appeared from old mining activity to be mineralised locally.

2. The existence of this ridge was confirmed by additional gravity data and subsequently a detailed profile was provided by the interpretation of a commercial seismic reflection line. Following detailed geophysical surveys, a borehole in the Dove Valley proved the presence of limestone at approximately the predicted depth and the existence of a 'Snelston ridge' was thus confirmed; however there was little indication of unconformity-related mineralisation at this site, apart from some enhancement in barium.

3. Detailed surveys at Limestone Hill, an isolated inlier of knoll-reef limestone, provided evidence from the geochemical results for the existence of near-surface mineralisation, but the geophysical surveys failed to indicate significant mineralisation at depth.

4. Drilling at Limestone Hill to determine the extent of the near-surface mineralisation proved extensive replacement-type lead-baryte mineralisation over an intersection of 10 m near the top of the knoll-reef, with a maximum content of more than 10% Pb. Two subsequent boreholes indicated that this does not extend at depth, or on the flanks of the knoll-reef.

5. While the observed mineralisation is not extensive, the replacive style is capable of generating larger deposits than the normal Pennine vein deposit. The proven existence of a concealed ridge of shallow limestone within reasonable depth for exploration opens up the possibility of further work on locating other, completely concealed knoll-reefs with similar, more extensive replacement mineralisation. A general target area is indicated by the geophysically defined ridges shown in Figure 5 but further work is recommended around Limestone Hill, concentrating on the detection of hidden knoll-reefs.

6. Geophysical methods recommended for further exploration in the area are gravity surveys and electrical techniques. The gravity surveys would be aimed at the recognition of local highs associated with knoll-reefs - the response expected would be largely due to the buried topographic highs formed since the higher density, mineralised rocks at Limestone Hill are associated with lower density, high porosity limestones. Although the lack of response at Limestone Hill was not encouraging, the presence of larger sulphide concentrations should be detectable using deep penetration methods such as IP for disseminated mineralisation or TEM for more massive sulphides.

ACKNOWLEDGEMENTS

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APPENDIX 1 RESULTS OF RESISTIVITY SOUNDINGS

Sounding		Model layers		
Number	Grid Reference	Number	Resistivity (ohm m)	Base (m)
1	41581 34109	1	25	0.5
		2	23	13.0
		3	300	-
2	41594 34184	1	30	0.3
		2	23	8.0
		3	43	45.0
		4	250	-
3	41687 34149	1	21	1.3
		2	23	12.0
		3	35	70.0
		4	300	-
4	41600 34461	1	40	0.7
		2	50	1.7
		3	75	5.0
		4	165	-
5	41573 34448	1	30	0.7
		2	60	2.0
		3	85	2.5
		4	150	-
6	41441 34380	1	35	0.7
		2	40	1.9
		3	200	-
7	41423 34369	1	40	0.3
		2	63	1.5
		3	200	-
8	41466 34347	1	50	0.4
		2	57	19.0
		3	200	-
9	41364 34302	1	40	0.3
		2	60	3.0
		3	110	25.0
		4	230	-
10	41339 34295	1	45	0.8
		2	110	5.0
		3	90	50.0
		4	230	-
11	41316 34269	1	45	0.4
		2	310	2.0
		3	72	54.0
		4	300	-

APPENDIX 2

BOREHOLE NAME	Snelston (Dove Valley)	BGS REG. NO. SK14SW13		PROJECT 63CA	
EASTING 414398	NORTHING 343612	1:10K SHEET SK14SW	AZIMUTH 0° DIP 90°	HEIGHT 102 m	
START DATE 18.11.93	FINISH DATE 25.11.93	DATE LOGGED 10.12.93	LOGGED BY T B Colman	FINAL DEPTH 73.95 m	DRILLED BY BGS Diamec 260 Alan Barnes Harry Wilson

DRILLING/m FROM	TO	RECOVERED metres	%	DESCRIPTION	ANGLE	MINERAL*	SAMPNO	INTERVAL/m
0.00	50.13	0	0	Open Hole. No core recovered. Red-brown and white Triassic sandstone fragments.				
50.13	59.70	9.57	100	Medium - dark red-brown even grained friable micaceous soft sandstone with pale grey bands to 13 cm - mainly around 3-5 cm. Bedding subhorizontal. Some thin red-brown mudstone bands and muddy sandstones (<10% of core length).	BCA~ 90°		ARD7085 ARD7086	57.00-57.86 59.00-59.69
59.70	60.16	0.46	100	Pink sandstone with white lenses to 5 mm (possibly baryte).		?Ba	ARD7087	60.10-61.10
60.16	61.20	1.04	100	Grey green sandstone. Bedding subhorizontal.	BCA= 90°		ARD7088	61.20-61.37
61.20	61.37	0.17	100	Yellow brown sandstone.				
61.37				Triassic / Dinantian contact				
61.37	62.24	0.87	100	Pale grey coarse grained limestone with rounded pellets to 1-2 mm. Fractured with red-green clay-filled fractures at 20-45° to core axis with some calcite.			ARD7089	61.37-62.00
62.24	63.11	0.87	100	Pale grey porous dolomitised limestone with fractures filled with dolomite crystals. Green clay at 62.9-63 m.			ARD7090 ARD7091	62.24-63.00 63.00-64.00
63.11	73.95	10.84	100	Massive medium grey limestone. Occasional brachiopods. Green clay at 63.25-63.44 m. Red clay at 64.1 m at 30° to core axis. Bedding flattens to 20° to core axis at 71 m. Breccia at 71.78-72.33 m with rounded to flat clasts of red-brown mudstone in calcite net veining.	BCA= 30°- 40°		ARD7092 ARD7093 ARD7094 ARD7095 ARD7096	64.00-65.13 67.33-68.13 68.19-68.70 71.30-72.39 73.18-73.95

* Ca/Mg carbonates omitted

SHEET 1 of 3

BOREHOLE NAME	Limestone Hill No 1	BGS REG. NO. SK14NW7		PROJECT 63CA
EASTING 413545	NORTHING 346250	1:10K SHEET SK14NW	AZIMUTH 45° DIP 80°	HEIGHT 215 m
START DATE 7.9.94	FINISH DATE 14.9.94	DATE LOGGED 17.10.94	LOGGED BY G E Norton / T B Colman	FINAL DEPTH 60.21 m
DRILLED BY	BGS Diamec 260	Alan Barnes, Harry Wilson		

DRILLING/m FROM	TO	RECOVERED metres	%	DESCRIPTION	ANGLE	MINERAL*	SAMPNO	INTERVAL/m
0.00	0.80	0.00	0	Overburden				
0.80	7.27	6.36	98	Light brown - yellow brown massive medium grained dolomitic limestone. Darker brown and cavernous from 1.80-2.60 m. Sparse black manganese dendrites. Sparse crinoids and corals - rather indistinct. 4 cm wide breccia (syngenetic / infilling?) at 6.20-6.40 m with angular squarish blocks of pale grey limestone in yellow-brown dolomitic sand. From 6.57 m rock is creamy brown dolomitic limestone with some manganese dendrites.			ARD7100 ARD7101 ARD7102	4.29-4.57 5.64-6.21 6.21-7.27
7.27	8.50	1.23	100	Creamy yellow-brown dolomitic limestone with extensive manganese dendrites growing into dolomitic sand infilling breccia as above. Dark red-brown sphalerite grain (2 mm) at 7.38 m. Sporadic grains of malachite to 1mm and in thin vein with white fibrous calcite at 7.57 m. Malachite only seen from 7.27-7.77 m.		Sp Mal	ARD7103	7.27-8.50
8.50	10.94	2.33	95	Light grey (with pinkish tinge) hard, coarser grained siliceous limestone (little reaction with acid). No manganese dendrites. Slightly vuggy - holes up to 1 cm sometimes folowing subvertical veins - usually random. Galena grains in vugs and along semi-vertical fractures. Overall <0.1% Pb. Grains to 5 mm usually associated with yellow-brown carbonate boxworks. Sparse pink baryte in thin veins associated with calcite around 9.51 m. No malachite seen. Coarse calcite in places. Denser at base with white baryte patches. Galena less common from 10.00 m onwards.		Ga Ba	ARD7104 ARD7105	8.50-9.76 9.76-10.94
10.94	11.62	0.62	91	Breccia. Pale grey-brown polymict breccia with pink areas. Angular fragments to 1 cm of dolomitic and siliceous limestone in a grey siliceous matrix. White clay along fractures from 11.30 m. Quite dense - possibly baryte.		Ba	ARD7106	10.94-11.62

* Ca/Mg carbonates omitted

DIAMOND CORE SAMPLE SHEET

SHEET 2 of 3

BOREHOLE NAME Limestone Hill No 1

DRILLING/m FROM	TO	RECOVERED metres	%	DESCRIPTION	ANGLE	MINERAL*	SAMPNO	INTERVAL/m
11.62	13.21	1.54	97	Light grey hard siliceous vuggy limestone with galena as from 8.50-10.94 m. More galena in coarser (to 2 cm) clots - less associated with carbonate boxworks, often in fractures. Resinous red-brown sphalerite with galena at 12.54 m. Direction of vugs at 30°to Core Axis around 13.00 m. Overall ~1% Pb.	Vugs 30°/ CA	Ga Sp	ARD7107	11.62-13.21
13.21	14.74	1.40	92	Massive pale grey-pink dolomitic limestone with manganese dendrites and a few vugs. A few grains and clots of galena from 14.10-14.35 m. Crinoid at 14.35 m. Increasing clay with trace baryte around 14.70 m. Vague ?bedding at 90°to core axis.	BCA= 90°	Ga Ba	ARD7108	13.21-14.74
14.74	15.35	0.56	92	Mineralised light grey-pink dolomitic limestone. Very distinctive replacive texture of subhorizontal, interconnecting galena veinlets in dolomitic matrix in a 'zebra-like' texture. Overall ~10% Pb. Creamy patches of sandy dolomite to 2 cm.		Ga	ARD7109	14.74-15.35
15.35	16.93	1.60	101	Light grey-pink siliceous vuggy limestone as from 11.62-13.21 m. Occasional crinoids. Galena in elongate vugs associated with brown carbonate boxworks as before. Overall ~0.1% Pb.		Ga	ARD7110	15.35-16.70
16.93	19.80	2.70	94	Light grey-pink limestone with white clay in fractures. Patches of pale grey-green calcite mudstone with sparse manganese dendrites and spots and some comminuted fossils. Galena clots in vugs around 17.70 m just above very fractured clay rich zone. Yellow brown dolomite 'sand' from 18.51-18.67 m with manganese dendrites at edges. Breccia zone with clay from 18.67-19.00 m with infill of yellow-brown dolomite with manganese dendrites - fractures at 0°to core axis. A few vugs with brown crystalline calcite infill at margins.	BCA= 0°	Ga	ARD7111 ARD7112 ARD7113	16.70-18.00 18.00-19.00 19.00-19.80
19.80	20.97	1.13	97	Light grey-pink limestone with increasing medium-dark brown iron carbonate. Some vugs infilled with white calcite. Few crinoids and brachiopods.			ARD7114	19.80-20.97
20.97	24.21	2.34	72	Dark brown vuggy limestone with ramifying network of thin calcite veinlets. Pink baryte veins (2-3 mm) at 40°to core axis at 22.40 m. Vugs at 40°to core axis in places.	VCA= 40°/ CA	Ba	ARD7115 ARD7116	20.97-21.65 22.13-23.46

* Ca/Mg carbonates omitted

DIAMOND CORE SAMPLE SHEET SHEET 3 of 3

BOREHOLE NAME Limestone Hill No 1

DRILLING/m FROM	TO	RECOVERED metres	%	DESCRIPTION	ANGLE	MINERAL*	SAMPNO	INTERVAL/m
24.21	26.80	2.52	97	Pale grey-yellow brown limestone, vuggy in places with dark brown patches. Creamy yellow brown calcite mudstone with manganese dendrites in synsedimentary infill from 25.23-25.45 m. Bedding at 80°to CA.	BCA 80°			
26.80	30.59	3.57	94	Dark brown vuggy limestone with ramifying calcite net veining as above. Calcite veining thicked near vugs which can be lined with black terminating dogtooth calcite crystals. Trace platy baryte around 27.60 m. Some patches of dark brown sandy iron carbonate infilling vugs. Vertical clay filled fracture with small fragments of brown wallrock at 28.25 m.		Ba	ARD7117 ARD7118	27.50-28.03 29.40-30.39
30.39	36.00	5.42	97	Pale grey-yellow brown limestone. Vuggy in places with dark brown patches. Vugs to 5 by 3 cm. Dark brown limestone around 34.20 m. Yellow brown calcite sand in fractures at 50°to CA at 34.50 m.	Fract 50°/ CA			
36.00	37.01	0.99	98	Medium brown vuggy limestone with ramifying calcite veinlets - not as intense as above.				
37.01	38.83	1.73	95	Light grey, cream and brown coarsely crystalline limestone. Matrix mainly grey with irregular patches of cream-brown sandy silt ?infill with manganese dendrites. Few vugs. Irregular calcite vein to 1cm.				
38.83	51.70	12.58	98	Light to dark grey limestone with minor cream layers and fossil fragments. Bedding? at ~30°to CA. Millimetre-scale baryte vein at 40.30 m at 30°to core axis. Vuggy infill at 43.98 m with malachite in calcite. Pink tinge in parts at 45.10-46.26 m. Brecciated zone at 46.26-46.57 m with cream material at 20°to core axis. Minor fracture at ~0°to CA. with calcite veinlet or calcite mudstone infill.	BCA= 30°	Ba Mal	ARD7119	43.98-44.57
51.70	52.20	0.50	100	Brown vuggy limestone with calcite netveining.				
52.20	53.43	1.23	100	Cream brown limestone with irregular light grey patches (30:70). ?Bedding at 30°to CA. Mainly light grey at 52.70-52.92 m. Abundant fossils.				
53.43	56.42	2.93	98	Cream to light brown limestone with irregular patches of calcite netveining and vugs. Calcite often has a rim of darker brown ?ankerite.			ARD7120	54.16-55.43
56.42	60.21 EOH	3.80	100	Light brown - pink - grey limestone with small 10-15 cm patches of dark brown carbonate and calcite veining. Baryte in calcite vein at 58.04 m. Breccia at 59.30 m with large vugs to 5 cm with calcite. Small subvertical breccia vein at 59.40 m.		Ba	ARD7121	59.65-60.21

* Ca/Mg carbonates omitted

BOREHOLE NAME	Limestone Hill No 2	BGS REG. NO. SK14NW8		PROJECT 63CA	
EASTING 413630	NORTHING 346330	1:10K SHEET SK14NW	AZIMUTH 220° DIP 60°	HEIGHT 180 m	
START DATE 16.9.94	FINISH DATE 21.9.94	DATE LOGGED 19.10.94	LOGGED BY G E Norton	FINAL DEPTH 35.49 m	DRILLED BY BGS Diamec 260 Alan Barnes Harry Wilson

DRILLING/m FROM	TO	RECOVERED metres	%	DESCRIPTION	ANGLE	MINERAL*	SAMPNO	INTERVAL/m
0.00	2.67	0.00	0	Overburden				
2.67	2.86	0.19	100	Light grey / light brown limestone with occasional fossils. Cream calcite mudstone areas with manganese dendrites. Some calcite veinlets and associated porosity.				
2.86	3.02	0.16	100	Light brown calciferous sandstone. Only rubble recovered.				
3.02	3.30	0.28	100	Light brown to cream dense polymict breccia. Minor malachite in calcite veinlets. Abundant manganese dendrites.		?Ba Mal	ARD7122	3.02-3.97
3.30	4.04	0.67	91	Light brown calciferous sandstone with larger clasts to base. Calcite vein to 1 cm at 3.9 m. VCA varies from 0 to 90°.	VCA= 0-90° at 3.9m			
4.04	4.91	0.54	62	Light brown to cream limestone with eroded top. Manganese dendrites and internal brecciation. 2 cm wide zone at 90° to core axis at 4.72 m with coarse calcite vein and brecciation with ?baryte. Manganese dendrites increase from 4.72-4.91 m.		?Ba	ARD7123	4.04-4.91
4.91	5.17	0.26	100	13 cm zone of sandy breccia followed by 13 cm of consolidated breccia.				
5.17	15.20	8.80	88	Light -dark grey massive limestone with abundant crinoids / corals /brachiopods. Bedding at 45° to core axis at 5.99 m with way-up structures. Red silty carbonate infill at 6.86m with mm scale clasts of grey limestone (to 15 cm width of core). Other fracture infills at 8.0, 8.56, 8.81, 9.97 and 12.94 m. Dark brown / yellow brown 'vein' at 11.04 - 11.20 m parallel to core axis with manganese dendrites. Similar at 13.72-14.03 m. Some large cavities, some with dissolved fossils infilled by calcite.	BCA= 45° at 5.99m		ARD7124	7.51-8.50
15.26	16.90	1.16	71	Light pink / grey carbonate mud. Grey limestone breccia infilled with layered pink / cream lime mud and then deformed. Some way-up structure but not consistent. Vug infilled with fluorite and calcite at 16.03 m.				

* Ca/Mg carbonates omitted

DIAMOND CORE SAMPLE SHEET

SHEET 2 of 2

BOREHOLE NAME Limestone Hill No 2

DRILLING/m FROM	TO	RECOVERED metres	%	DESCRIPTION	ANGLE	MINERAL*	SAMPNO	INTERVAL/m
16.90	17.50	0.60	100	Light pink banded calciferous mudstone with dark grey limestone clasts and orange brown later infill / vein material with manganese dendrites. Sequence at brecciation / infill / veining difficult to assess.				
17.50	21.30	3.57	94	Fault Gouge or Karst Infill. Purple / green clay and mud - like plasticene. Abundant clasts of limestone to 12 cm. Mud has carbonate content and many small clasts.			ARD7125	18.67-19.72
21.30	21.60	0.23	77	Breccia with clasts of grey limestone, pink banded carbonate mud and calcite to 1 cm by 5 cm in brown fine grained carbonate matrix with white chalky clay along fracture surfaces.				
21.60	22.30	0.49	70	Breccia with large clasts to 8 cm of light grey & pink banded carbonate mud and orange brown clay with manganese dendrites. In places breccia is composed of clasts of brecciated material similar to that above the purple clay.				
22.30	26.25	3.98	101	Dark grey / light grey limestone with abundant fossils and mm scale fractures. Fracture zone at 22.60 - 23.0 m with pink carbonate mud and grey limestone clasts to 1 cm. Clasts of light brown sandy material at 23.25 m.	BCA= 45°at 23.3 m			
26.25	26.73	0.48	100	Light brown - cream dolomite sand with brecciated clasts of light pink banded carbonate mud with calcite veining. Banded pink material at contact with grey limestone appears to be wavy. Possible algal growth / synsedimentary feature.				
26.73	35.49 EOH	8.25	94	Light - dark grey fossiliferous limestone with breccia bands at 30.10, 30.30, 30.50, 32.80, 33.53, 33.73, 34.00 & 35.30 m. Breccia as before with clasts of grey limestone in pink / white banded carbonate matrix. Variable dip. Some areas have brown / orange component in matrix. Red carbonate bands at 20-30°to CA at 28.93 m and 29.72 m.			ARD7126	33.38-34.50

* Ca/Mg carbonates omitted

APPENDIX 2 (continued)

Diamond Drill Core Log

SHEET 1 of 2

BOREHOLE NAME	Limestone Hill No 3		BGS REG. NO. SK14NW9		PROJECT 63CA	
EASTING 413665	NORTHING 346195	1:10K SHEET SK14NW		AZIMUTH 305° DIP 60°	HEIGHT 180 m	
START DATE 22.9.94	FINISH DATE 5.10.94	DATE LOGGED 21.10.94	LOGGED BY G E Norton	FINAL DEPTH 79.43 m	DRILLED BY BGS Diamec 260	Alan Barnes Harry Wilson

DRILLING/m FROM	TO	RECOVERED metres	%	DESCRIPTION	ANGLE	MINERAL*	SAMPNO	INTERVAL/m
0.00	4.92	0.00	0	Overburden				
4.92	8.09	2.13	67	Coarse grained red quarzitic sandstone with browner bands and becoming more brown with depth. Denser in places - ?baryte. Below 7.14 m, sandstone contains irregular clasts of red mudstone up to 2 cm across. Calcitic cement throughout with some calcite veining and associated vugs at 7.30-7.50 m.		?Ba	ARD7127 ARD7128	5.57-6.51 6.90-8.09
8.09	9.62	1.42	93	Alternating bands of red gritty mudstone (20 cm) and light grey-brown limestone/ sandstone (10 cm). Contact at 90° to core axis. Manganese minerals in parts of limestone. Coarse brecciated mudstone at 9.30 m.				
9.62	10.80	1.00	85	Red mudstone with breccia towards base. Breaks consistently at 90° to core axis.				
10.80	28.72	14.60	81	Alternating bands of light grey / pink limestone and red-green sandy mudstone. Partings / bedding about 90° to core axis. Many mm scale calcite veins at 0° to core axis throughout length, especially in limestone. No fossils seen. Limestone bands 10 - 60 cm (average 30 cm). Mudstone bands 2 cm - 30 cm (average 10 cm). Some shale bands brecciated, accommodating movement with limestone clasts to 2 cm. Breccias (<10 cm wide) at 11.49, 13.65, 18.20, 25.58, 27.93 and 28.31 m.	BCA= 90° VCA= 0°		ARD7129	11.04-11.93
28.72	29.59	0.76	87	Red brecciated mudstone with clasts to 2 cm of limestone and mudstone. Occasional green patches.				
29.59	34.75	4.84	94	Red - green shaley calcareous mudstone with clear partings at 80° to core axis. Breccias in 20 cm zones at 29.75, 30.70 and 34.60 m. Some calcite veins (1 mm - 1 cm). Veinlets at 0° to core axis, larger veins at 80-90°.	VCA= 0° or 80°		ARD7130	32.70-33.78

* Ca/Mg carbonates omitted

DIAMOND CORE SAMPLE SHEET

BOREHOLE NAME Limestone Hill No 3

DRILLING/m FROM	TO	RECOVERED metres	%	DESCRIPTION	ANGLE	MINERAL*	SAMPNO	INTERVAL/m
34.75	46.43	10.94	94	Red to grey-green calcareous <u>mudstone</u> with partings at 50°to core axis at 35.16m 70°to core axis from 39.56 m. Brecciated horizons at 35.41-35.64 m, 38.80-39.07 m, 36.10-36.18 m, 43.90-44.05 m, 45.54-45.67 m and 46.13-46.30 m. Light grey areas have less obvious layering ?more calcified. No fossils seen. Coarse calcite veins, often associated with brecciation especially at 35.56-36.47 m, 39.56-39.85 m, 43.58-43.71 m and between 45.64 m and 46.43 m. Calcite veins are about 5 cm across and can be slickensided as at 45.84 m. Calcite is variously Fe stained with one grain of ?sphalerite at 36.40 m. Soft sediment slumping at 41.08-41.38 m.		?Sp	ARD7131	43.43-44.37
46.43	79.43 EOH	32.75	99	Medium-grey <u>limestone.</u> Abundant fossils. Stylolitic in places at variable angles.Syn-depositional breccias with clasts of limestone to 2 cm with brown shale infill. Calcite veined to 2 cm across; no consistent angle. ?Bedding at 80° to core axis. Fractures at 80° to core axis from 79.20-79.43 m infilled with calcite and sand.	BCA= 80°		ARD7132 ARD7133	61.68-62.84 78.22-79.43

* Ca/Mg carbonates omitted