Natural Environment Research Council

Institute of Geological Sciences

Mineral Reconnaissance Programme Report

A report prepared for the Department of Industry

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No.60

Mineral investigations at Carrock Fell, Cumbria. Part 2—Geochemical investigations

INSTITUTE OF GEOLOGICAL SCIENCES

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SUMMARY

The underlying objective of investigations at Carrock Fell, under the Mineral Reconnaissance Programme, was the recognition of the most effective combination of surface exploration methods applicable to the discovery of new deposits in this type of geological environment. This second report deals with geochemical aspects of the investigation.

Soil samples were collected from 1199 sites in an area of 5 km^2 around the tungsten veins at Carrock, and were analysed for Ti, Mn, Fe, Ni, Cu, Zn, As, Rb, Sr, Zr, Mo, Sn, Sb, Ba, W, Pb, Th and U. The results are presented on geochemical maps. New areas of mineral potential, to the north-east of the mine, have been identified from the coincidence of geochemical anomalies with strong linear VLF features. High levels of W, Cu, Zn, As, Rb and Pb and low levels of Sr are evident in soils above the worked veins. These elements, with the exception of As, constitute a broad zone of anomalously high values to the north and east of the vein system, accompanied by low Sr values extending up to 1 km east of the worked veins over a distance of 1.2 km north-south. The distribution of As is exceptional in that a broad halo is apparent for some 800 m west of the main vein system. Patterns in the distribution of some elements not related to the mineralisation clearly reflect compositional changes of the underlying rocks. Gamma spectrometry demonstrates a distinct increase in the K/Th ratios over the main veins and delineates a potential area of mineralisation to the west of the mine, coincident with a strong VLF anomaly. Qualitative contoured maps of count rate for the U and K channels are effective in delineating the sub-outcrop of the granite. The geochemical results and previously reported geophysical results enabled three areas to be recommended for further detailed exploration.

INTRODUCTION

LOCATION

The area studied was centred on Carrock Mine (NY 3230 3295), approximately 20 km west of Penrith and 10 km north-east of Keswick, Cumbria (Figure 1). The mine lies within an area of high relief in the Grainsgill Valley, 3.5 km due west of Mosedale (Figure 2). Elevations in the area sampled are between 260 m and 620 m OD. The area, which forms part of the Lake District National Park, falls within the Ordnance Survey 1:50 000 Penrith and Keswick (90) Sheet and the Cockermouth (23) 1:50 000 Geological Survey Sheet.

PREVIOUS INVESTIGATIONS

During 1973, as part of the Mineral Reconnaissance Programme, a detailed drainage survey was undertaken over the Carrock Fell area, combined with a rock sampling programme (Appleton and Wadge, 1976). As the tungsten-bearing veins are associated with a greisenised cupola of the Skiddaw Granite, the objective of the work was to locate other similar cupolas, which might lead to the discovery of associated mineralisation. During the same period a supporting study was undertaken based on fluid inclusions, oxygen isotopes and K/Ar age determinations in order to obtain a better understanding of the Carrock Fell mineralisation (Shepherd and others, 1976). Examination of the analyses of stream sediments and heavy mineral concentrates resulted in the identification of an As halo (Appleton and Wadge *op. cit.*) which extended over 2 km west of the mine. Additionally, vein mineralisation of the quartz–wolframite–scheelite–arsenopyrite association was discovered within the headwaters of Wet Swine Gill (Figure 2). Analysis of a limited number of granite samples from Grainsgill Beck showed that the tungsten content was too low for the rock to be considered as a low-grade deposit.

Appleton and Wadge (1976) and Shepherd and others (1976) have suggested that the area to the west of the mine provides the best target for further exploration for tungsten mineralisation. However, Andrew (1976) suggested that the area to the east of the mine had the best potential, a view which was based on detailed geological mapping and the discovery of a tungsteniferous quartz vein close to Poddy Gill, some 350 m east of the Emerson Vein. As the major tungsteniferous sections of the veins are located in close proximity to the axial trend of the Grainsgill cupola, Andrew (*op. cit.*) proposed that future exploration should be concentrated towards the north-east of the mine between Brandy Gill and Poddy Gill (Figure 2).

More recently a detailed geophysical survey was undertaken over the Carrock Fell area

(Patrick, 1980) in conjunction with the investigation reported here. The survey produced two distinct sets of anomalies. The first, and possibly the most significant, was a set of VLF anomalies that may represent a series of north-south linear fractures possibly of favourable potential for mineralisation, the strongest anomaly occurring at Arm O'Grain (Figure 2). The continuation of the Emerson Lode and the structure in Poddy Gill were also detected by the VLF results. The second set of anomalies are coincident SP and magnetic features within the gabbro to the west of Brandy Gill, suggesting extensions of the Smith and Wilson Lodes, the geophysical signatures possibly being caused by pyrrhotite within a convergent set of fractures.

PRESENT INVESTIGATIONS

The immediate object of the geochemical study was to investigate the secondary dispersion of certain elements in overburden over an area of known tungsteniferous mineralisation and surrounding mine area.

A total of 1199 soil samples was collected along 11 east-west traverse lines 2 km in length and 200 m apart at intervals of 20 m (Figure 3), over a total area of 5 km^2. At the same time, a gamma-ray spectrometric survey was undertaken over the same traverse lines, readings being taken at 40 m intervals (Brown and Ball, 1979).

GEOLOGY AND MINERALISATION

GEOLOGY

The first major work in the area was undertaken by Ward (1876) and was followed by Harker's study of the gabbro (Harker, 1894) and the granophyre and greisen (Harker, 1895). Finlayson (1910) described the ore minerals and Scrivener (1916) the Grainsgill greisen. Later, a detailed study of the granite was undertaken by Hitchen (1934) and the area was re-mapped by Hollingworth (1938). The ore deposits have been described by Rastall (1942) and Thimmaiah (1956), and the hydrothermal alteration of the granite by Ewart (1962). A more recent detailed account of the geology of the area, including Carrock Fell, is documented in the Geological Survey Memoir covering the Cockermouth (23) Sheet (Eastwood and others, 1968).

The dominant rocks underlying the area are those of the Skiddaw Group, of Lower Ordovician age (Figure 1), consisting of turbidites which are mainly mudstone and silt but also include bands of greywacke-sandstone. The total thickness of the sequence is not known, but it must be several hundred metres. Upright open folding is evident, trending ENE, but complex minor structures produced by polyphase folding are also present (Roberts, 1971). North of the area sampled there is a thick succession of andesitic volcanic rocks (Figure 1), with tuffs and agglomerates, known as the Eycott Group. It was earlier thought to be equivalent to the Borrowdale Volcanic Group but is now considered to be older (Downie and Soper, 1972; Wadge, 1978). The Carrock Fell intrusive complex (Figure 2), which pre-dates the Skiddaw Granite, is composed of a lensoid mass of gabbro and related granophyric hydrids elongated parallel to the regional Caledonian strike.

The Skiddaw Granite (Rastall, 1910; Green, 1918; Hitchen, 1934) is intruded into the Ordovician sediments. It is poorly exposed, but exhibits an extensive metamorphic aureole indicating the prescence of a partially unroofed granite mass at shallow depth. The rock is a medium-grained biotite granite, showing varying degrees of greisenisation in a limited number of exposures. The northern margin of the granite, which is well exposed in the mine, is converted to a quartz-muscovite greisen. The greisen may be confined to the area of the tunsteniferous quartz veins (Ewart *op. cit.*) but the true extent is not known.

MINERALISATION

The known mineralisation is confined to a series of steeply-dipping north-south quartz veins cutting the northern margin of the Skiddaw Granite and extending northwards into the gabbro complex. The main veins, from west to east, are the Wilson, Smith, Harding and Emerson veins (Figure 2). They consist dominantly of quartz with, generally in decreasing order to abundance, wolframite, scheelite, arsenopyrite, pyrite and pyrrhotite. Other minerals recorded (N. Fortey *pers. comm.*, 1982) include molybdenite, chalcopyrite, bismuth, bismuthinite, galena, sphalerite, apatite, muscovite, biotite, rutile, tourmaline, fluorite, marcasite and columbite. Ferroan dolomite, ankerite and calcite are common in the quartz veins and in the wallrocks. The paragenesis is early wolframite followed by scheelite and Fe, As, Cu and Zn sulphide, and there is evidence of wolframite replaced by scheelite (Firman, 1978). Both wolframite and scheelite tend to be concentrated at either edge of the quartz veins, the scheelite being best seen using a short wave UV lamp underground. The veins vary in width between 0.1 m and 1.5 m and have sharp contacts with the wallrocks.

The north-south veins are cut by subsidiary, later east-west carbonate-bearing veins with associated Pb, Zn and Cu sulphides and little quartz, similar to the larger vein system a few km to the north. Although these later veins were exploited at Drygill Mine (NY 325 346) and Roughtongill Mine (NY 303 345) they have not been of any economic importance at Carrock Mine. Investigations by Kingsbury and Hartley (1956) at the mine have proved the occurrence of two lead-copper-bismuth sulphides and three lead-antimony sulphides and also the occurrence of stibnite. The

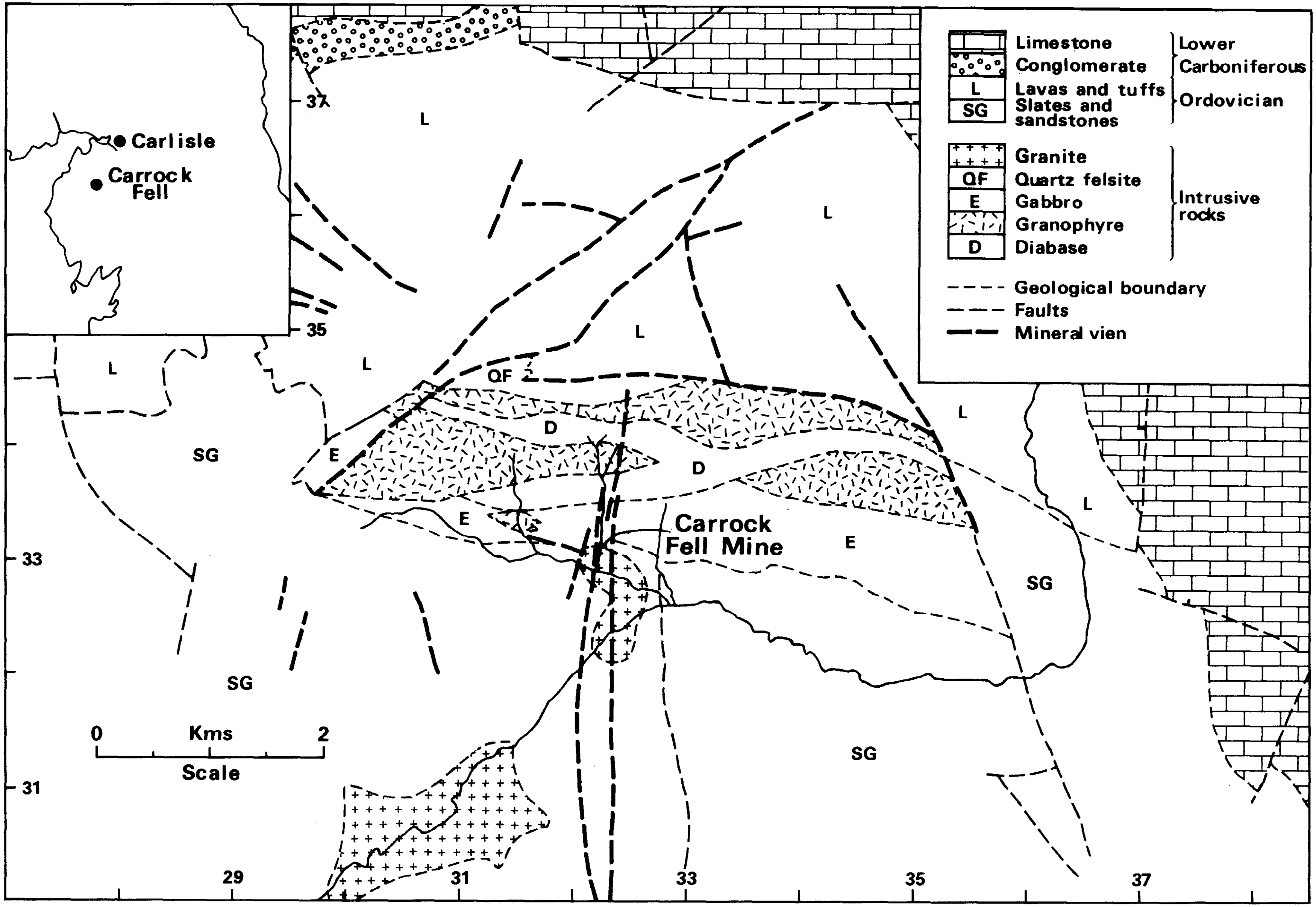

Figure 1 Location and geology of the Carrock Fell area

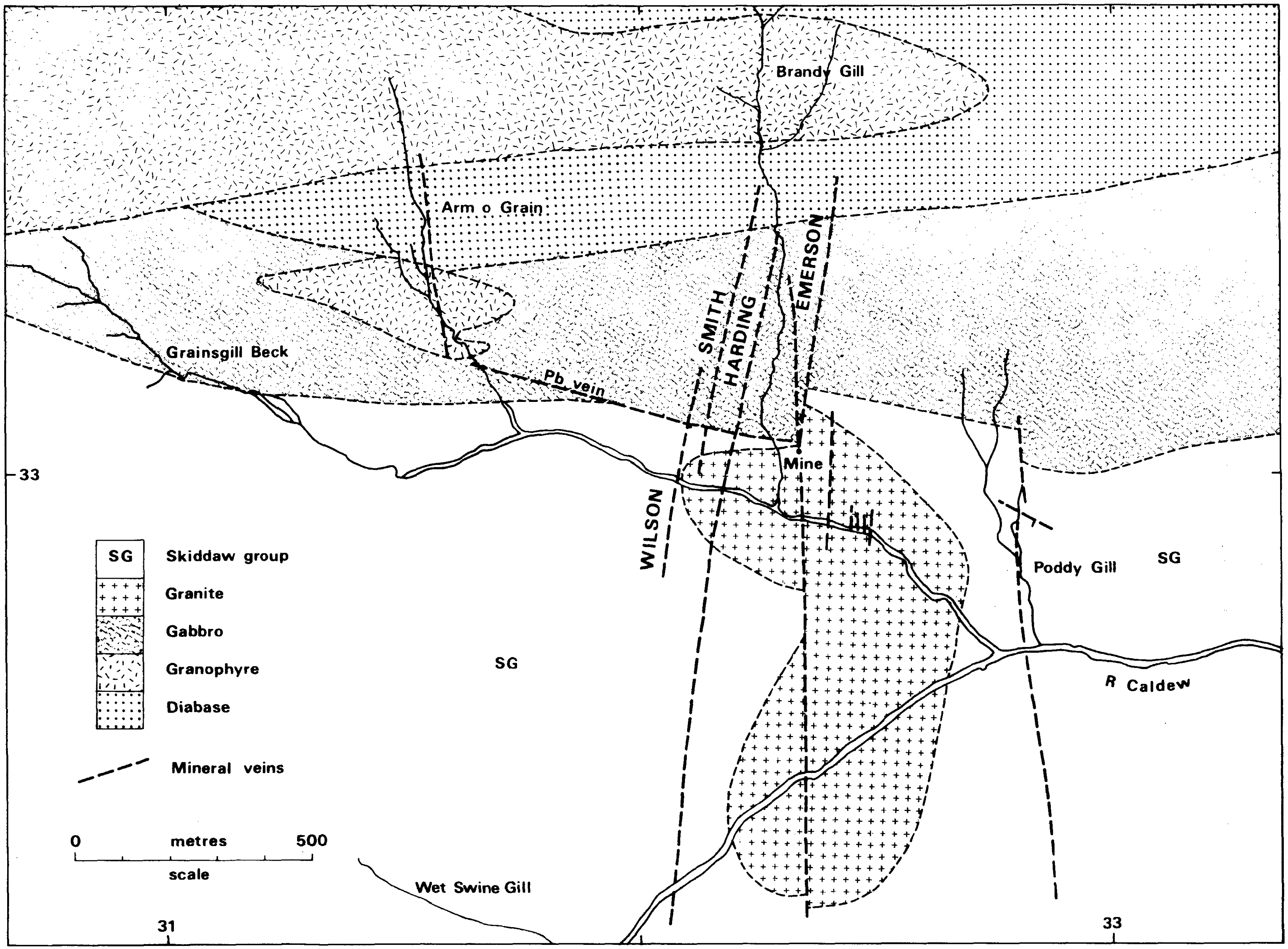

Figure 2 Detailed geology of the Carrock Mine area

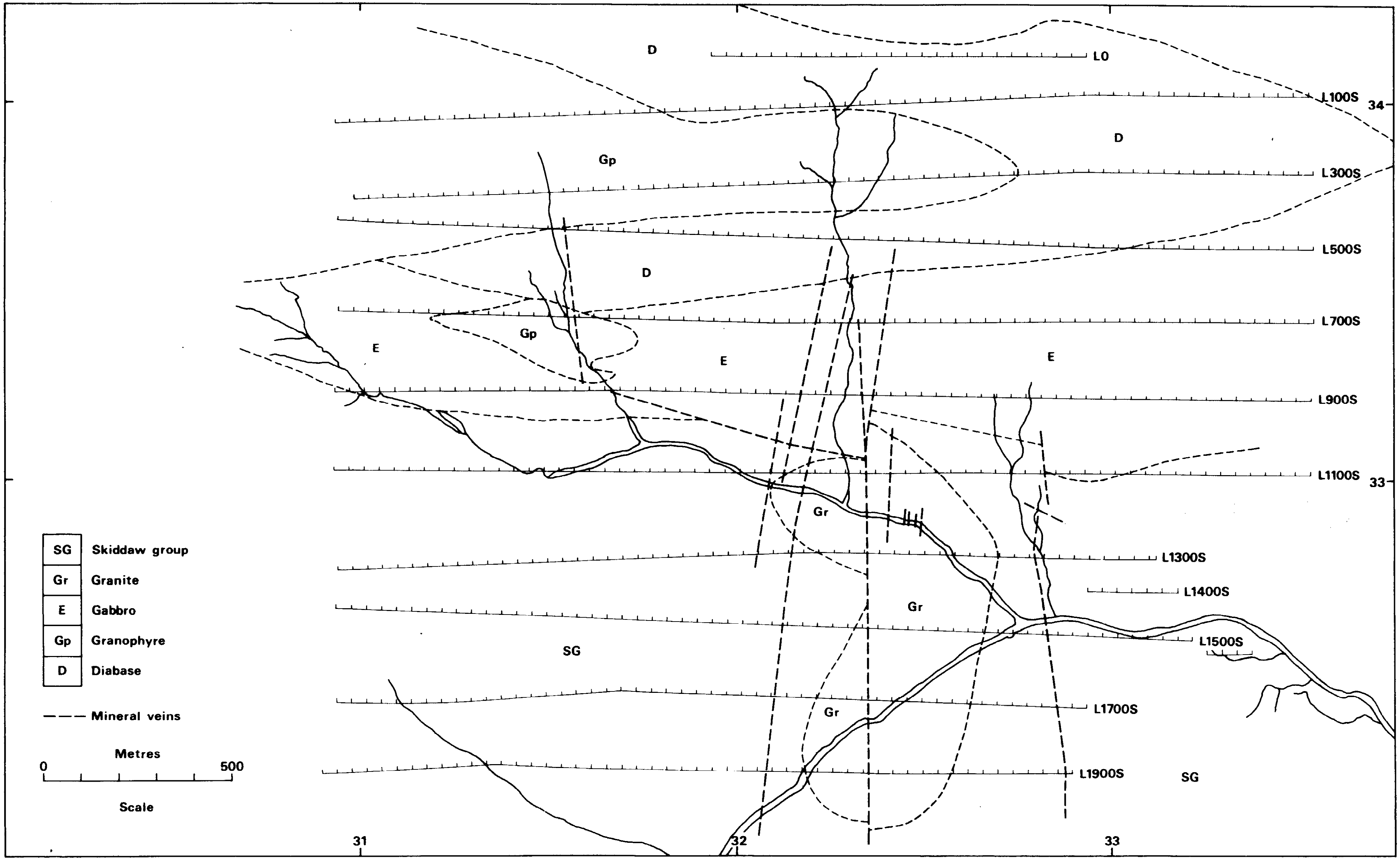

Figure 3 Location of the sample traverse lines

sulpho-salts have been identified as cosalite, aikinite, zinckenite, jamesonite and boulangerite. These minerals are considered to be from a series of low-temperature quartz-carbonate veins of later formation than the W mineralisation but younger than the east-west veins.

AGE AND GENESIS OF THE DEPOSIT

The age of the Skiddaw Granite has been reported by Brown and others (1964) to be 399 ± 6 m.y., based on K-Ar data from Miller (1961). K-Ar dating of hydrothermal muscovites from the Harding Lode and mica separates from the Skiddaw Granite and the Grainsgill Greisen have subsequently confirmed this date, within the limits of analytical error, although a mean age of 392 ± 4 m.y. has been suggested for the final cooling of the granite (Shepherd and others, 1976).

The genesis of the ore deposit has been discussed by Ineson and Mitchell (1974) who proposed an episodic model based on distinct isotopic events at 282, 231 and 197 m.y. These authors considered that the tungsten mineralisation was related to the 282 m.y. event while the two later events included the emplacement of the east-west cross courses. The latest event included a phase which formed the deposit at Roughtongill Mine (NY 303 345), suggesting hydrothermal activity continuing sporadically into Lower Jurassic times.

The results of fluid inclusion, oxygen isotope and K-Ar studies led Shepherd and others (*op. cit.*) to conclude that the mineralisation was contemporaneous with the extensive alteration of the granite soon after emplacement (390 m.y.). The data suggest that the mineralising fluids were moderately saline NaCl brines enriched in tungsten, periodically charged with CO_2 and depleted in ^{18}O relative to magmatic fluids, suggesting a major non-magmatic component. During the cooling of the granite, the fluids were drawn into the northern part of the intrusive rocks, through open north-south channelways, by convective flow from the adjacent volcanic country rocks. The mineralisation is confined to the greisen and the gabbro complex to the north, the surrounding Skiddaw Slates being impervious to mineralising solutions. Shepherd and others (*op. cit.*) suggested that the proposed model of ore genesis and associated alteration of the granite had many features in common with the water-rock interaction model for porphyry copper deposits (Sheppard and others, 1969), although there are differences in the geological setting.

GLACIAL AND POST-GLACIAL DEPOSITS

Three glaciations have been recognised in Cumberland: the Early Scottish, the Main and the Scottish Readvance (Eastwood and others, 1968). The boulder distribution over Carrock Fell indicates that the area was invaded by external ice from the south during the Main Glaciation. Abundant boulders of non-thermally-metamorphosed slate can be seen on the south-eastern spur of Carrock Fell and blocks of gabbro can be found on and beyond the Carrock Fell ridge, carried uphill by the northerly moving ice. Till covers much of the area and is exposed over a narrow zone on either side of the River Caldew and Grainsgill Beck.

To the south-east of the area sampled there is evidence of late glacial deposition (equivalent to the Scottish Readvance) where a large ridge of morainic material forms a dam enclosing Bowscale Tarn (NY 337 313) within a north-facing corrie. Relatively confined deposits of alluvium occupy the valleys of the River Caldew and Grainsgill Beck. Much of the area to the north-east of the mine and to the north, east and west of Arm O'Grain is covered by extensive hill peat. It is possible that peat formation commenced in depressions during the early post-glacial period, reaching maximum development during the relatively moist Atlantic and sub-Atlantic climatic phases (Eastwood and others, 1968) later than 5000 years ago.

MINING HISTORY

The history of mining at Carrock Fell is one of sporadic working from as early as 1854 (Shaw, 1970). A full account of the history of the mine is to be found in the Mining Magazine (1977) in addition to a summary by Eastwood (1959). Major development and assessment work was undertaken by Canadian servicemen during 1942–43 and a mill flowsheet was designed, but no building was started. More recently, in 1971, Weco Development Corporation of the USA purchased the mine and constructed a mill using 1943 figures of ore reserves as a basis for production. However, the mill produced tungsten concentrates for only a few weeks during 1972 before being put on a standby basis. During 1976 the mill was reactivated by the Carrock Fell Mining Company and production continued until 1981. At the time of writing the mine has been closed and placed on a care and maintenance basis.

GEOCHEMICAL INVESTIGATIONS

A total of 1199 soil samples were collected, using a hand auger, from a 5 km^2 area (Figure 3) and from a depth of approximately 0.8–1.0 m, after first removing the surface peat, where present, with a spade. Depths of overburden varied over the area sampled. It was very thin or absent near crags on lines 1100S to 1500S (Figure 3) and along valley sides, but elsewhere there were areas of deep peat where the depth to bedrock was uncertain.

Soil samples were dried and sieved to 80 mesh

(BSI), and a 12 g split of the undersize was ground with elvacite, to pass 300 mesh, using a Fritsh Pulverisette 5 equipped with agate mortars. The elements determined by X-ray fluoresence spetrometry were Ti, Mn, Fe, Ni, Cu, Zn, As, Rb, Sr, Zr, Mo, Sn, Sb, Ba, W, Pb, Th and U.

DATA INTERPRETATION

Summary statistics for the complete data set, compiled with the aid of a computer, are shown in Table 1. All mean values quoted refer to the geometric mean (the antilog of the mean log transformed data) and are identified as $\bar{x}g$ in each of the tables. The data were also sub-divided into classes based on the five geological units within the Carrock Fell Mine area, and summary statistics are presented for soils underlain by each unit in Table 2. As an aid to the interpretation of distribution patterns, for the total data set and for each of the five geological units, correlation coefficients were computed for the log transformed data (Tables 3–8).

The single-element maps (Figures 7–23, at end of report) were plotted using class-interval representation rather than a continuous function, since this illustrated more clearly the anomaly patterns attributable to the mineralisation and different underlying rock types. Class intervals were derived, in most cases, by plotting cumulative frequency diagrams and selecting the most obvious breaks in slope (Lepeltier, 1969). Most elements tend towards a multimodal distribution, with the exception of Mo, U and Sn; and Fe exhibits a normal distribution. Where breaks in slope of the cumulative fequency diagrams could not be identified, as for Mn, Cu and Zr, class intervals were based on the mean, the mean plus one and mean plus two standard deviation levels of the log transformed data. For those elements not exhibiting a log-normal distribution, the upper class-invervals were based on those values above the 95 percentile for Sn, and above the 97.5 percentile for Mo and U.

DISTRIBUTION OF ELEMENTS IN SOIL

The areal distribution of the 18 elements determined are discussed in atomic number order, with emphasis on identifying pathfinder elements to the mineralisation.

Titanium

The highest values of Ti occur over the basic igneous rocks (Figure 7) and the lowest over the granite, while soils over the sedimentary rocks exhibit intermediate levels (Table 2). Ti shows a good correlation with Fe, Mn, Cu and Ni (Table 3). Higher levels are expected over the more basic rocks, since Ti, mainly in the form of Ti^{4+}, is concentrated in the early stages of magmatic fractionation associated with Fe and Ca. Much of the Ti associated with the basic rocks occurs as ilmenite and sphene, the gabbro being particularly rich in these minerals.

Ti is chemically stable within the secondary environment, dispersion being mainly by mechanical transport. The Ti values that fall within the highest class plotted (>1.5%) are closely associated with the W anomaly (Figure 21) over the main area of mineralisation, with a marked distribution towards the east (Figure 7).

Soils contain higher levels of Ti than the underlying rocks because of the resistate nature of Ti minerals. Soils over the granite contain a mean level of 0.6% Ti (Table 2) which is higher than the mean level of Ti in the granite of 0.09% (T. K. Ball *pers. comm.*, 1982).

Manganese

High levels of manganese occur along line 1100S (Figure 3) and show a close association with samples of mainly alluvial material from Grainsgill Beck (Figure 8). Isolated anomalies within the highest class (>3500 ppm Mn) are found in valley bottom samples from Brandy Gill, Poddy Gill and Arm O'Grain. Under reducing conditions Mn-bearing minerals such as olivine, garnet, pyroxene and amphibole are weakly soluble but produce relatively high concentrations of Mn^{2+} in ground waters. Precipitation of hydrous manganese oxide occurs on mixing with surface waters, the result of an increase in both Eh and pH, and this action could explain the high concentration of Mn in samples collected close to stream courses. Mn is usually higher in mafic rocks than in granitic rocks. This is borne out by the soil geochemistry, lower Mn values being associated with the granophyre sub-outcrop. Mn shows a significant positive correlation with Fe, Ni and Ti, and with elements characteristic of the mineralisation including Zn and Cu and to a lesser extent Mo, As and W (Table 3). However, because of surface electronegativity of the precipitated Mn sesquioxide, adsorption of Zn^{2+}, Cu^{2+}, Ni^{2+} and Mo^{3+} can occur which may partly explain the correlation. Mn scavaging is particularly prevalent in glaciated terrain because of the reactive fine grained nature of glacial tills (Horsnail, 1975).

Iron

Fe is highly concentrated in soils over the area of known mineralistion (Figure 9), and high values also occur in a zone on the eastern side of the lodes. Values within the highest class (>10% Fe) are also found in the vicinity of Poddy Gill and Arm O'Grain. There is a significant positive correlation with Mn, Ni and Ti and to a lesser extent Zn, Cu and As (Table 3), the latter elements being clearly associated with the mineralisation. Fe can occur as either Fe^{2+} or Fe^{3+}, depending on the Eh and pH conditions. Fe^{2+} is stable under strongly reducing conditions which may exist below peat, which is present over a wide area. Under oxidising

Table 1 Summary statistics for total data set

Element	*Minimum*	*Maximum*	$\bar{x}g$	σ
Ti	0.6%	4.0%	0.9%	0.21
Mn	50	76610	891	0.40
Fe	0.7%	34.8%	6.6%	0.24
Ni	1*	148	11	0.57
Cu	2*	2230	48	0.46
Zn	19	2804	162	0.30
As	6	8647	214	0.52
Rb	1*	392	102	0.30
Sr	13	144	46	0.14
Zr	11	783	269	0.22
Mo	2*	151	1	0.58
Sn	7*	52	4	0.54
Sb	8*	39	3	0.63
Ba	13*	619	219	0.26
W	3*	13296	37	0.74
Pb	23*	4289	138	0.30
Th†	3*	315	12	0.31
U	3*	27	2	0.48

Values in ppm except where otherwise stated

*Detection limit n = 1199

†Interference from Bi and Pb

Table 2 Summary statistics based on geological units

Element	*Granite n = 84*				*Granophyre n = 176*				*Gabbro n = 262*				*Diabase n = 231*				*Slates n = 366*			
	Min	*Max*	$\bar{x}g$	σ	*Min*	*Max*	$\bar{x}g$	σ	*Min*	*Max*	$\bar{x}g$	σ	*Min*	*Max*	$\bar{x}g$	σ	*Min*	*Max*	$\bar{x}g$	σ
Ti %	0.09	2	0.6	0.24	0.18	1.9	0.7	0.18	0.06	4.0	1.3	0.23	0.20	3.2	1.1	0.19	0.37	3.0	0.8	0.11
Mn	70	76610	977	0.52	50	9050	417	0.32	60	8080	1096	0.34	70	5900	794	0.30	90	12420	1148	0.41
Fe %	0.7	30.4	5.4	0.33	0.7	13.6	4.5	0.24	1.0	19.8	8.1	0.20	1.0	19.9	7.2	0.21	1.0	12.8	6.7	0.18
Ni	1	148	12	0.46	1	141	2	0.75	1	48	16	0.32	1	118	11	0.59	1	74	18	0.34
Cu	14	2230	72	0.40	6	635	30	0.24	2	559	52	0.60	2	1093	76	0.46	11	268	44	0.24
Zn	31	2804	166	0.37	29	2456	145	0.37	25	873	166	0.23	34	1947	219	0.34	21	1017	151	0.24
As	17	8647	389	0.58	15	5911	214	0.55	12	2576	199	0.56	6	3074	190	0.63	22	1515	257	0.34
Rb	30	334	174	0.18	33	301	91	0.17	1	299	72	0.45	1	392	100	0.30	35	317	135	0.12
Sr	22	71	44	0.11	16	81	37	0.13	14	117	49	0.14	13	144	46	0.16	25	104	48	0.10
Zr	35	372	209	0.18	207	768	490	0.10	11	678	214	0.27	18	783	331	0.21	92	541	240	0.10
Mo	2	151	5	0.65	2	6	2	0.47	2	12	—	—	2	7	—	—	2	35	—	—
Sn	7	29	—	—	7	23	—	—	7	43	—	—	7	52	8	0.39	7	16	—	—
Sb	8	37	—	—	8	39	—	—	8	21	—	—	8	37	—	—	8	22	—	—
Ba	33	551	230	0.23	79	554	240	0.11	13	439	141	0.28	13	499	166	0.23	94	619	363	0.13
W	3	2646	87	0.79	3	474	12	0.61	3	3268	63	0.89	3	25500	54	0.76	3	1749	34	0.47
Pb	105	2940	240	0.27	29	4289	110	0.40	26	1648	126	0.29	23	2174	151	0.35	33	1161	129	0.20
Th	5	315	23	0.28	6	60	14	0.19	3	59	8	0.45	3	177	13	0.31	5	55	14	0.11
U	3	27	3	0.46	3	7	—	—	3	6	—	—	3	6	—	—	3	7	—	—

Values in ppm except where otherwise stated

Table 3 Correlation matrix for total data set (log-transformed data)

Element	*0.7–0.8*	*0.6–0.7*	*0.5–0.6*	*0.4–0.5*	*0.3–0.4*
Ti		Fe	Mn	Cu Ni	Sr W
Mn	Fe	Ni	Ti	Zn Cu Mo	As W
Fe	Mn	Ni Ti	Zn Cu	As	Mo W
Ni		Fe Mn	Zn Cu	Ti Sr	-Zr Mo W
Cu	W	Zn Rb	Ni Fe	Pb Mn Ti Mo As	
Zn		Cu	Pb Ni Fe	Mn As W	Rb Mo
As				Zn Cu Fe Rb	Ba Pb Mn Mo W
Rb		Ba Cu	W	As	Zn Mo
Sr				Ni	Ti
Zr					Ba -Ni
Mo				Cu Mn W	Pb Zn Ni Fe Rb As
Sn					W
Sb					
Ba		Rb			U Zr As
W	Cu		Rb	Pb Zn Mo	Zn Ni Fe Mn Ti As
Pb			Zn	Cu W	Mo As
U					Ba

Table 4 Correlation matrix for soils over the granite (log-transformed data)

Element	*>0.8*	*0.7–0.8*	*0.6–0.7*	*0.5–0.6*	*0.4–0.5*	*0.3–0.4*
Ti			Zr	Fe		Ba Sn Mn W
Mn		Fe Zn	As	Ni Sb Cu Mo	Pb W	Ba Sn Ti
Fe		Mn	Ni As	Zn Ti Mo	Ba Sb Cu W	Zr
Ni			Zn Cu Fe	Ba Mn	As	Sb Pb Sr Mo
Cu		Zn As W	Pb Ni	Mn Mo	Sb Fe U	-Sr
Zn		Cu Mn	Pb Ni	Fe As	Mo W	Sb
As	W	Cu Mo	Fe Mn	Sb Zn	Pb Ni U -Sr	
Rb					U W	-Sr Zr
Sr			Ba	-W	-As	-Sn -Pb -Cu Ni -Rb Zr
Zr			Ti	Ba		Fe Rb Sr
Mo		As	W	Cu Fe Mn	Zn	Sb Pb Ni U
Sn					Sb	Ti -Sr
Sb				Mn As	Cu Fe W Sn	Pb Zn Ni Mo
Ba			Sr	Ni Zr	Fe	Mn Ti
W	As	Cu	Mo	-Sr	Sb Pb Zn Fe Mn Rb U	Ti
Pb			Zn Cu		Mn As W	Sb Ni -Sr Mo
U					Cu Rb As W	Mo

n = 84

Table 5 Correlation matrix for soils over the granophyre (log-transformed data)

Element	*>0.8*	*0.7–0.8*	*0.6–0.7*	*0.5–0.6*	*0.4–0.5*	*0.3–0.4*
Ti		Mn	Cu Ni Sr	Zn Fe W	Rb Pb Mo	
Mn		Zn Ni Fe Ti	Cu Sr	Mo	Rb Pb As W	-Zr
Fe		Zn Mn	Cu As	Ni Ti -Zr Mo	Rb Pb W	Sr
Ni		Cu Mn	Zn Ti	Pb Fe Rb Sr	Mo W	Ba -Zr As
Cu	Pb Zn Rb W	Ni	Fe Mn Ti Mo	-Zr	As	Sb Sn
Zn	Cu	Pb Fe Mn Rb W	Ni	Ti Mo As	-Zr	Sn
As			Fe	Zn W	Pb Cu Mn Rb Mo	Sn Ni -Zr
Rb	Cu W	Pb Zn		Ni	Sn Fe Mn Ti Mo As	Ba -Zr
Sr			Mn Ti	Ni		Fe
Zr				-Cu -Fe	-Zn	-Pb -Ni -Mn -Rb -Mo -As -W
Mo			Cu	Pb Zn Fe Mn W	Ni Ti Rb As	-Zr
Sn					Rb W	Sb Pb Zn Cu As
Sb						Sn Pb Cu
Ba						Ni Rb
W	Pb Cu Rb	Zn		Ti Mo As	Sn Ni Fe Mn	-Zr
Pb	Cu W	Zn Rb		Ni Mo	Fe Mn Ti As	Sb Sn -Zr
U						

n = 176

Table 6 Correlation matrix for soils over the gabbro (log-transformed data)

Element	*>0.8*	*0.7–0.8*	*0.6–0.7*	*0.5–0.6*	*0.4–0.5*	*0.3–0.4*
Ti			Mn	Ni Fe		Rb
Mn	Fe		Ni Ti	Rb Mo As	Ba Zn Cu	
Fe	Mn			Cu Ni Ti Mo As	Rb	Zn
Ni			Mn Rb	Ba Zn Cu Fe Ti		Mo
Cu	Rb	W	Zn	Ni Fe	Ba Mn Mo As	
Zn			Cu Rb	Ba Ni As W	Pb Mn Mo	Sn Fe Zr
As				Zn Fe Mn	Sn Cu Rb Mo	Ba W
Rb	Cu		Ba Zn Ni W	Mn	Fe Mo As	Sn Ti Zr
Sr						Ba Zr -W
Zr		Ba				Zn Rb Sr
Mo				Fe Mn	Zn Cu Rb As W	Pb Ni
Sn					As W	Pb Zn Rb
Sb						
Ba		Zr	Rb	Zn Ni	Cu Mn	Sr As
W		Cu	Rb	Zn	Sn Mo	Pb -Sr As
Pb					Zn	Sn Mo W
U						

n = 262

Table 7 Correlation matrix for soils over the diabase (log-transformed data)

Element	*>0.8*	*0.7–0.8*	*0.6–0.7*	*0.5–0.6*	*0.4–0.5*	*0.3–0.4*
Ti		Mn	Ni Fe Sr		Cu	Mo W
Mn	Fe	Ni Ti	Cu Sr	Zn Mo W	Rb	Ba
Fe	Mn	Ni	Cu Ti	Zn Mo	Sr W	Rb
Ni		Fe Mn	Cu Ti	Zn Sr W	Rb Mo	Pb -Zr
Cu		Zn W	Ni Fe Mn Rb	Mo	Ba Sn Pb Ti	Sr
Zn		Cu	Pb Rb W	Ni Fe Mn	Ba Mo As	Sb Sn
As				Ba Rb	Sn Pb Zn	Sb Zr
Rb		Ba	Zn Cu W	Sn As	Pb Ni Mn Mo	Fe Zr
Sr			Mn Ti	Ni	Fe	Cu
Zr				Ba		-Ni U Rb As
Mo				Cu Fe Mn W	Zn Ni Rb	Pb Ti
Sn				Rb	Cu As W	Ba Sb Pb Zn
Sb						Sn Pb Zn As
Ba		Rb		Zr As	Zn Cu	Sn Pb Mn W
W		Cu	Zn Rb	Ni Mn Mo	Sn Pb Fe	Ba Ti
Pb			Zn		Cu Rb As W	Ba Sb Sn Ni Mo
U						Zr

n = 231

Table 8 Correlation matrix for soils over the Skiddaw Slates (log-transformed data)

Element	*0.7–0.8*	*0.6–0.7*	*0.5–0.6*	*0.4–0.5*	*0.3–0.4*
Ti					Zn Fe Mn W
Mn			Fe	Zn Ni -Rb	Ti
Fe		Ni	Zn Cu Mn As		Ti
Ni	Zn	Fe	Cu	Mn	
Cu		Zn	Ni Fe W	As	Mo
Zn	Ni	Cu	Fe	Mn	Ti
As			Fe	Cu	
Rb				Ba -Mn	Sr
Sr					Rb
Zr					W
Mo					-Ba W Cu
Sn					Sb
Sb					Sn
Ba				Rb -W	-Mo
W			Cu	-Ba As	Ti Zr Mo
Pb					
U					

n = 366

conditions Fe is precipitated as insoluble hydrous ferric oxide and is able to adsorb elements of high ionic potential such as As and Mo and divalent cations of the first row transition elements, which are related to the mineralisation at Carrock Fell.

As would be expected, Fe is more highly concentrated over the more basic gabbroic rocks (Table 2) when compared to the acid rocks.

Nickel

Ni appears to be of little use as a pathfinder element in this area. The distribution of Ni (Figure 10) shows no distinct patterns and cannot be related to the underlying geology or the mineralisation.

Ni is usually concentrated in mafic rocks but mean levels over each rock unit show little significant variation (Table 2) except for low levels of Ni in soils associated with the granophyre suboutcrop. There is a significant positive correlation with Fe and Mn (Table 3) characteristic of mafic rocks and sesquioxide co-precipitation. Ni is readily mobilised within the secondary environment but is co-precipitated with Fe and Mn which may contribute to the good correlation between these elements.

Copper

Much of the area shows background levels in soil up to 140 ppm, the mean level ($\bar{x}g$ = 48 ppm) lying within the range of average abundance for superficial material (2–100 ppm Cu; Taylor, 1966). Anomalous levels are associated with the veins, with a marked zone of high values towards the east (Figure 11). The pattern is similar to that of W (Figure 21). There is a significant positive correlation with W and to a lesser extent Zn and Rb (Table 3). There is also a correlation with Ni, Fe, Pb, Mn, Ti, Mo and As, some of which are clearly associated with the mineralisation. The correlation with W, Zn and Rb indicates an association with the mineralisation, making Cu an ideal pathfinder element in this area. Within the secondary environment the mobility of Cu is dependent on the pH and the adsorption by Fe, Mn, clay minerals and organic material. However, over Carrock Fell the dispersion appears to be directly related to the mineralisation, regardless of other forms of concentration.

Zinc

The distribution of Zn (Figure 12) is similar to that of Cu, but the extension of the anomaly towards the east is only evident on lines 0–500S (Figure 3). Other high values are confined to the strike of the productive veins. Much of the Zn anomaly is associated with an area of peat cover, where a decrease in the pH would tend to mobilise Zn in the form of Zn^{2+}. Under these conditions Zn^{2+} would be adsorbed by hydrous Fe and Mn oxides and may also be fixed in organic material in the peat. However, the close association of Zn with other elements associated with the mineralisation makes it a useful pathfinder element if interpretation takes account of factors producing other anomalous concentrations. There is a correlation of Zn with Cu and to a lesser extent Pb, Ni, Fe, Mn, As and W (Table 3). Sphalerite is certainly present in the north-south veins, providing a source of Zn.

Arsenic

Worldwide averages for arsenic in soil and peats are below 10 ppm (Boyle and Jonasson, 1973). Levels of As over the Carrock Fell area are extremely high ($\bar{x}g$ = 214 ppm) and can in places be directly related to the mineralisation. There is a distinct As anomaly (Figure 13) over the worked veins and a marked extension of high values towards the west, up to 600 m from Brandy Gill. All samples from above the veins fall within the upper class plotted (>1200 ppm As), and a majority of the values of the westerly extension fall within the second class (>700 ppm As).

A second distinct group of high values is apparent at the western end of lines 1700S and 1900S, in the vicinity of Wet Swine Gill (Figure 2), where the anomaly is not closed to either the south or the west. In the same area high As in stream sediment from Wet Swine Gill (1100 ppm As) was recorded by Appleton and Wadge (1976), where moderately high W values were also obtained. Overall, As shows no strong significant correlation with other elements associated with the mineralisation (Table 3), partly because the high values are concentrated to the west of the main vein system. Soils derived from the gabbro show a correlation of As with Zn, Fe and Mn (Table 6) and those from the granophyre with Fe, Zn and W (Table 5). For soils over the slates there is a reasonable correlation with Fe (Table 8). Granite-derived soils exhibit a significant positive correlation with W (Table 4) and also with Cu, Mo, Fe and Mn. There is also a close association of As and W over the main productive veins and in the area of Wet Swine Gill.

Where highly acidic conditions prevail and low levels of carbonate exist, As is relatively mobile and may migrate for considerable distances. Under weakly acid or alkaline conditions As is relatively immobile because of hydrolysis and co-precipitation with hydrous Fe oxide, Co, Ni, Pb and Zn in solution. Much of the anomaly between Brandy Gill and Arm O'Grain is over an area of peat, suggesting that the As halo has been formed mainly by hydromorphic dispersion. The marked difference in the distribution of As and W may reflect a zonation of the two elements within the primary environment. The element As has been used as a pathfinder for many types of deposit (Boyle and Jonasson, 1973) and proves to be a useful pathfinder at Carrock Fell.

The main source of As in the lodes is arsenopyrite, which was introduced at a late stage, selectively replacing micaceous aggregates during hydrothermal alteration (Ewart, 1962). Quartz and arsenopyrite increase slightly in amount in proximity to the vein.

Rubidium

Enrichment of Rb in soils is evident over the known veins, whether the host rock is granite or gabbro. A zone of high Rb (>200 ppm) lies to the east and north of the main vein system (Figure 14). Rb is characteristic of acid magmas, a fact which is reflected by high levels of Rb in soils overlying the granite. There is a distinct group of low Rb values (<60 ppm) in the east while the remainder of the area exhibits somewhat higher values (60–200 ppm). The wide distribution in soil of relatively high Rb may reflect the volatile nature and wide dispersion within the primary environment.

Good correlation with Cu, W and As (Table 3) indicates the association with other elements characteristic of the mineralisation. There is also a good correlation with Ba, both in the total population (Table 3) and in soils derived from the gabbro (Table 6), the diabase (Table 7) and the slates (Table 8).

Rb shows a similar behaviour to K because of similar chemical properties and ionic radius. Although K has not been determined in soils directly, the ^{40}K results of the gamma spectrometer study show a similar distribution pattern, particularly over the granite (Figure 4).

The volatile nature of Rb in the primary environment and its mobility in the secondary environment makes the element an attractive pathfinder for various types of mineralisation. Rb has been shown to be a good pathfinder for gold mineralisation at Ogafau Mine, Central Wales, exhibiting both a primary halo (Al Atia and Barnes, 1976) and a broad anomaly pattern in the overlying soils (Steed and others, 1976). Al Atia (1975) has also described an anomalous primary dispersion of Rb associated with Sn mineralisation at Wheal Jane Mine and with disseminated W mineralisation at Cligga Head Mine, Cornwall. At Carrock Fell, Rb can be considered to be a useful pathfinder for tungsten mineralisation, particularly during reconnaissance soil sampling, due to its wide distribution.

Strontium

There is a marked negative Sr anomaly in soils overlying the granite and the outcrop of the mineral veins, and also over an area to the east of the main mineralisation (Figure 15), coincident with a W anomaly. These results reflect data from wall-rock alteration studies (T. K. Ball *pers. comm.*, 1982), which show a marked depletion of Sr both within the vein and in the adjacent wall rocks, reflecting a decrease in the plagioclase content.

Sr and Ca are similar chemically and show similar migration patterns. Magmatic processes generally lead to the incorporation of Sr into the lattices of K, Ca and Ba minerals. The soil data indicate (Table 2) that both the granite and the granophyre are low in Sr compared to the more basic igneous rocks and the surrounding slates. Sr shows a positive correlation with Ba and a negative correlation with W and As over the granite (Table 4). Because of its marked depletion, Sr appears to be a good pathfinder element in locating the area of mineralisation in this region.

Zirconium

The distribution of Zr in soil (Figure 16) indicates that the granophyre is relatively enriched compared to the other geological units. There is a negative correlation of Zr with Cu, Fe and Zn and to a much lesser extent Pb, Ni, Mo, As, W, Mn and Rb (Table 5) for soils over the granophyre. There is no association of Zr with the mineralisation.

There is a limited amount of information on the weathering and transportation of Zr, but it generally tends to accumulate during weathering with much higher levels in overburden than the underlying rocks. Zr occurs mainly as zircon in acid rocks, and in basic rocks Zr can replace Ti in resistate minerals which are stable under most conditions. In soils Zr minerals are practically indestructable but under certain conditions of high alkalinity Zr can be partially mobilised.

Average levels of Zr in soils over the granite are 209 ppm (Table 2) compared to 69 ppm (T. K. Ball, *pers. comm.*, 1982) for the underlying unmineralised granite. Similarly, average levels for the Zr content of the gabbro are 76 ppm (T. K. Ball, *pers. comm.*, 1982) compared to an average value of 214 ppm (Table 2) in overlying soils. Degenhardt (1957) showed that Zr, determined in two sections of a weathering granite profile, increased from 195 ppm in the fresh granite to 306 ppm in thoroughly decomposed granite.

Molybdenum

Molybdenite, in minor amounts, has been recorded associated with the north-south vein system and wulfenite ($PbMoO_4$) is known from a Pb vein in Poddy Gill and from higher parts of Brandy Gill (Goodchild, 1885). However, the distribution of Mo in soils (Figure 17) appears to reflect higher background levels associated with the sub-outcrop of the granite. Soils over the granite show a highly significant positive correlation of Mo with As and W and to a lesser extent with Cu, Fe and Mn (Table 4).

During igneous processes Mo^{6+} tends to be concentrated in the late-stage residual fraction and may, therefore, be more enriched in granitic rocks. In the secondary environment the mobility of Mo increases with an increase in the pH with the formation of the soluble $MoO_4{}^{2-}$ ion. In tills in northern Scotland it has been shown that Mo is concentrated in the clay-grade basal till in association with fine-grained iron oxide (Smith and Gallagher, 1975).

Tin

Values of Sn in the upper class (>10 ppm) coincide with the mineral veins cutting the gabbro and extend to the north and west (Figure 18) showing a similar pattern to As. There is a weak correlation with As and W over the gabbro (Table 6) but none of the high values are associated with soils over the granite. Sn has been recorded in some assays of vein material from the mine (Eastwood, 1959) and at least two specimens of cassiterite are known to have been collected from the Mine area (B. Young, *pers. comm.*, 1982). Sn can be carried in common Ti accessory minerals such as ilmenite and sphene which are abundant in the gabbro and may contribute to the levels of Sn in soil to the west of the main veins. Sn is a common minor element in columbite, which occurs as minute crystals in the tungsten ore at Carrock, but electron-probe analysis of the columbite showed no detectable Sn (Beddoe-Stephens and Fortey, 1981).

Antimony

Higher Sb values (>12 ppm) are generally associated with soils overlying the veins, but dispersion is restricted compared to other elements characteristic of the mineralisation (Figure 19). No other patterns are recognisable, but isolated high values are scattered over the entire area.

Chemically Sb is closely related to As and Bi, being in the same group in the Periodic Table. There is no observed correlation with As (Table 3) except over the granite (Table 4) where there is also a correlation with Mn. Arsenopyrite, abundant in the veins, can contain between 170 and 1160 ppm Sb (Boyle, 1965). Similarly, both galena and sphalerite can contain high levels of Sb, and stibnite has been recorded from the mine (Kingsbury and Hartley, 1956). Another source of Sb may be ilmenite, abundant in the Carrock Fell gabbro, as it appears to be a favourable host (Esson and others, 1965). There is little information of average levels of Sb in soil, but it tends to be more highly concentrated compared to the underlying rocks (Handbook of Geochemistry).

Barium

The distribution of Ba in soil (Figure 20) shows no relationship to the area of mineralisation. Baryte has been recorded in association with the veins (Mining Magazine, 1977) but in minor amounts, and because it is relatively insoluble high levels are not expected to be reflected in the soil geochemistry. Relatively high levels of Ba (>400 ppm) in soil are coincident with the outcrop of the Skiddaw Slates to the south, which provides a contrast with lower levels associated with the igneous complex (Table 2). Ba shows a significant positive correlation with Rb in the total data set (Table 3), with Sr over the granite (Table 4) and with Zr over the gabbro (Table 6).

Tungsten

The distribution of W in soil shows a distinct anomaly above the worked veins, with an eastward continuation of high values for up to 1 km over a north-south spread of 1.2 km (Figure 21). The geometric mean for W in soil over the entire grid is 37 ppm (Table 1) but values over 1000 ppm are common within the anomalous zone. High values (200–1000 ppm) in the south-west corner of the grid, on line 1900S, are associated with high As values and coincide with high W and As in stream sediment from Wet Swine Gill (Appleton and Wadge, 1976).

There is a significant positive correlation with Cu and Rb, and to a lesser extent with Pb, Zn and Mo (Table 3). Mo is the most similar element to W, having a similar ionic radius and electronegativity and the same valence of +4 and +6 in natural materials. In the surface environment both elements are similar in that they form hydrated oxides on weathering and both form insoluble compounds with Pb, Cu and Fe.

There is little information on the weathering and distribution of W minerals, although it is recognised that wolframite and scheelite are fairly insoluble in the pH range of surface waters. However, tungsten minerals are slowly attacked by acid surface waters especially by the strongly acid waters of weathering sulphide deposits. Tungsten released by acid attack is probably partly dissolved as HWO_4^- and partly converted to some form of tungstic oxide. Work by Dekate (1967) suggests that climatic conditions play an important role in determining the formation of secondary W minerals. Doucet (1966) also claimed that organic matter would complex W at pH6–7 and therefore aid its movement into solution. If this is the case it would in part explain the high values over the area of peat cover to the east of the main veins.

It is considered that the large W anomaly in soil is a product of the mainly mechanical breakdown of wolframite and scheelite, with the possibility of some hydromorphic dispersion within the tills. Being fairly brittle, both wolframite and scheelite would tend to break down into very fine particles during incorporation into ground moraine. Chemical action may have contributed to the zone of high W values to the east of the main vein system, as both oxidising sulphides and the peaty environment would produce acid waters to carry the W in solution which would be subsequently adsorbed by Fe and Mn oxides and organic matter.

The W anomaly indicates a possible extension of the worked veins to the north and also a continuation of the mineralised structure evident in Poddy Gill (Figure 2). The presence of the mineral stolzite ($PbWO_4$), although rare, in the higher parts of Brandy Gill (Shackelton, 1966) also indicates that the W mineralisation continues to the north. Between the Poddy Gill structure and the veins of Brandy Gill there is the possibility of other undiscovered mineralised north–south structures parallel to the main veins. W anomalies in soil to the south of the mine are limited to a small group on line 1500S which are possibly due to the southerly extension of the Wilson and Harding veins. No other evidence exists to suggest a continuation of the mineralisation towards the south.

Lead

High Pb in soil is related to the north–south vein system, and moderately high values extend towards the east (Figure 22). The distribution of Pb is similar to that shown by W, but with the highest Pb values concentrated on lines 0S, 100S and 300S (Figure 3), suggesting a continuation of the mineralisation to the north. Pb shows a good correlation with Zn, Cu and W (Table 3). In the secondary environment Pb is relatively immobile except under near-surface oxidising conditions. The formation of secondary dispersion haloes associated with Pb deposits depends on the solubility of secondary Pb minerals such as anglesite ($PbSO_4$). At Carrock Mine much of the Pb that has been recorded as being present in the veins may be dispersed in part by mechanical means and chemical processes in a similar manner to the tungsten minerals.

Thorium

Although levels of Th in soil are shown in the summary statistics (Table 1), the values cannot be considered reliable because of interference by Pb and Bi during XRF analysis (T. K. Smith, *pers. comm.*), so no geochemical map was produced for this element.

Uranium

Higher levels of U (>6 ppm) in soil coincide with the sub-outcrop of the granite (Figure 23), with a few isolated high values confined to the area of granophyre. Enhanced levels of U in stream sediment also reflect the sub-outcrop of the granite (Appleton and Wadge, 1976). The distribution of U and Mo in soil appear to be a good indication of the granite sub-outcrop and, therefore, could be used in locating similar unexposed cupolas within the area. During igneous processes U^{4+} tends to be concentrated in the residual magmatic fraction and occurs principally in accessory minerals such as zircon, allanite, uraninite and monazite in late stage differentiates. Uraninite, which has been detected in the greisen exposed in Grainsgill Beck (Dawson and Harrison, 1966) and in fresh rock from the mine, is probably the main source of U (N. J. Fortey, *pers. comm.*, 1982).

ELEMENT DISTRIBUTION IN SOILS RELATED TO GEOLOGY

Examination of the soil data over each geological unit within the area sampled shows mean element levels (Table 2) characteristic of each rock type, although anomalies shown by some elements are superimposed and directly related to the mineralisation. Soils overlying the granite are enriched in As, Rb, Mo, Sb, W, Pb and U and are low in Sr, Ti and Zr in comparison with the other units.

Excluding elements that reflect the mineralisation, only Mo and U outline the granite sub-outcrop accurately.

The soils above the gabbro show higher mean levels of Ti, Fe and Sr and to a lesser extent Mn, Ni, Zn and W, with relatively lower levels of Rb and Ba.

Soils overlying the diabase and the granophyre, which for the most part lie outside the area of mineralisation, show a marked contrast in element distribution. Soils over the diabase are characterised by higher levels of Ti, Mn, Fe, Ni, Cu and Zn, whereas the soils above the granophyre exhibit a significantly higher mean level of Zr and to a lesser extent Ba. Compared to the other geological units, soils above the granophyre are low in Mn, Fe, Ni, Cu, Zn, Sr, W and Pb.

Soils overlying the Skiddaw Slates, which make up the largest proportion of the samples, show a significantly higher mean level of Ba and lower levels of Cu, Zn, Sn and W in comparison with those over the igneous complex. Many of the high Mn values are related to precipitation in stream courses particularly Grainsgill Beck (Line 1300S, Figure 3) probably due to high Mn levels within stream alluvium.

ELEMENT DISTRIBUTION RELATED TO MINERALISATION

Over the main north–south veins the soils are enriched in W, As, Cu, Zn, Rb and Pb, and are low in Sr. A broad zone of high W accompanied by high Cu, Zn, Rb and Pb is distributed to the east of the main vein system and high W, As, Pb, Cu and Zn and low Sr indicate a continuation of the mineralisation towards the north.

There is no evidence from the soil geochemistry that the mineralisation continues to the south of the granite into the Skiddaw Slates.

Anomalous levels of As (Figure 13) and W (Figure 21) in soils in the vicinity of Wet Swine Gill (Figure 2) suggest sub-outcropping tungsten mineralisation. During an earlier investigation (Appleton and Wadge, 1976) a quartz–manganese–arsenopyrite vein was recorded outcropping in the headwaters of Wet Swine Gill, and both wolframite and scheelite were identified in panned concentrates downstream of the vein. Unlike other elements associated with the main north–south mineralisation, the highest levels of As in soil are distributed in a broad zone to the west of the veins (Figure 13). It is unlikely that ice movement alone produced the W anomaly to the east, as the geochemical results reflect the composition of the underlying rocks accurately, suggesting the till to be locally derived. However, the evidence suggests that the ice moved from the south to the north during the Main Glaciation, and so the more resistant minerals may have been transported upslope towards the ridge of Carrock Fell and beyond. Downslope movement by mechanical means or hydromorphic dispersion to the east or west is not possible, as the veins outcrop in Brandy Gill (Figure 2). It is suggested that the pattern of W and As in soil reflects a primary zonation of the two elements in the underlying lodes. Analysis and mineralogical examination of lode material from the mine shows an increase of As away from the granite, whereas W minerals are more abundant both within and close to the granite (T. K. Ball, *pers. comm.*).

GAMMA SPECTROMETRY

The survey at Carrock Fell included a research element to assess the application of gamma-ray spectrometry in locating non-radioactive mineral deposits (Brown and Ball, 1979).

Instrument readings were taken at 40 m intervals along each of the east-west traverse lines (Figure 3) during the soil sampling programme. The instrument used was a 4-channel gamma-ray NUTMAQ Type 0928 spectrometer set to measure total gamma radiation and the 3 energy channels diagnostic of ^{214}Bi (U), ^{208}Tl (Th) and ^{40}K. Readings were taken with the sodium iodide detector unit held about 1 m from the ground. Two readings were taken at each station and the mean value recorded. The results for U, K and K/Th ratios were plotted (Figures 4–6) as difference count rates and contoured.

RESULTS

Potassium contours (Figure 4) show a well-defined anomaly immediately west of the confluence of Grainsgill Beck and the River Caldew, broadly coincident with the outcrop of the greisenised cupola of the Skiddaw Granite. Small isolated anomalies further up Grainsgill Beck may reflect more arkosic, gritty facies of the Skiddaw Slates. There is general agreement between the distribution of ^{40}K, as determined by the gamma spectrometer results, and that of Rb in soils (Figure 14), although anomalous Rb extends further north and east. This is to be expected as the two elements show similar chemical properties and ionic radii.

U contours (Figure 5) show a broad agreement with the sub-outcrop of the greisenised cupola of the Skiddaw Granite, with minor anomalies at the head of Brandy Gill and a north-south linear feature to the east of the granite. The latter anomaly may be associated with a north-south fault evident in Poddy Gill. There is good agreement between the gamma spectrometry results and the distribution of U in soil (Figure 23) for the granite area. However, the linear feature over Poddy Gill, evident from the plot (Figure 5) of values from the U channel, is not reflected by corresponding high values of U in soil.

The contoured plot of the K/Th ratios (Figure 6) depicts a strong, broadly linear anomaly along Brandy Gill extending in a northerly direction from its confluence with Grainsgill Beck. To the south, the anomaly extends some 300 m over the greisenised granite. The anomaly can be directly related to the major veins within the area due to an increase in K within the mineralised area, relative to the country rocks. A significant anomaly is observed over Arm O'Grain some 500 m west of Brandy Gill within an area where a small manganese vein has been recorded. The north-north-west extent of this anomaly corresponds with a pronounced VLF anomaly (Patrick, 1980) and merits further investigation, although the soil geochemistry provides no evidence of mineralisation.

CONCLUSIONS

1 Fault-controlled quartz-wolframite-scheelite mineralisation associated with a greisenised cupola of the Skiddaw Granite has given rise to geochemical anomalies in soils overlying bedrock covered with glacial till. Soil sampling is, therefore, an effective means of outlining areas of potential mineralisation and of delineating the extensions of known structures in this environment.

2 Soils above the main vein system are enriched in W, As, Cu, Zn, Rb and Pb and are low in Sr. The pattern of dispersion displayed by W and other elements in the soil suggests that similar mineralisation, possibly in the form of structures parallel to the main veins, exists to the north-east of Carrock Mine. An area up to 1 km east of the main lode system exhibits consistently high levels of W, Cu, Zn, Rb and Pb and low Sr which extend up to 1.2 km in a north-south direction. Soil anomalies suggest both a continuation of the Smith, Emerson and Harding veins to the north and a continuation northwards of the mineralised structure evident in Poddy Gill. Soil anomalies east of the vein system coincide with strong linear VLF anomalies, again indicating parallel structures.

3 The distribution of As in soil is exceptional in that the halo surrounding the mineralisation extends up to 800 m to the west of the main veins. An As anomaly in the same area was recognised in stream sediment samples (Appleton and Wadge, 1976) extending up to 2 km west of the main veins. It is suggested that the opposing distribution of As and W is related to a primary zonation of the two elements in the underlying rocks.

4 The distribution pattern of some elements not related to the mineralisation clearly reflects

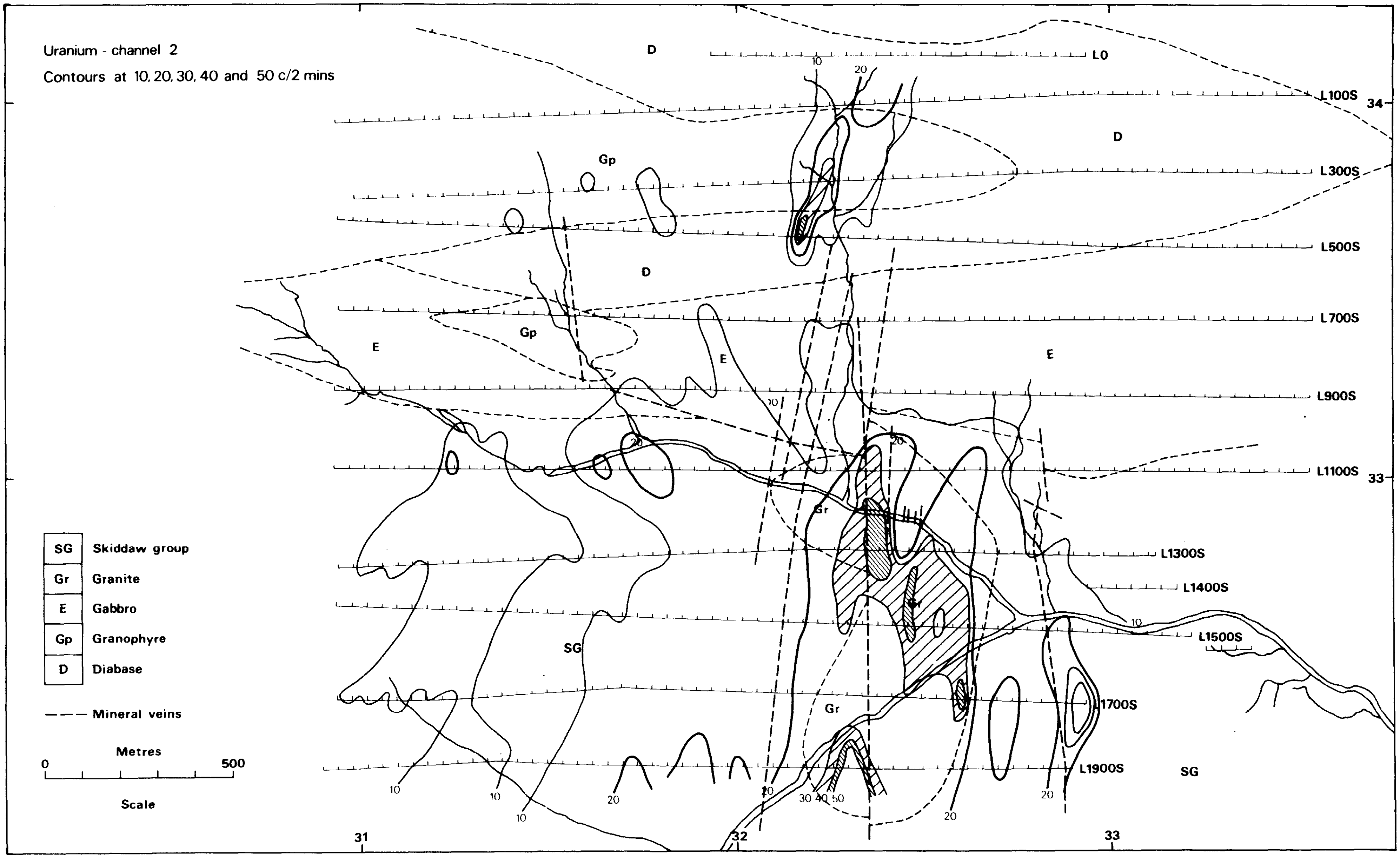

Figure 4 Qualitative contoured map of channel 3, potassium

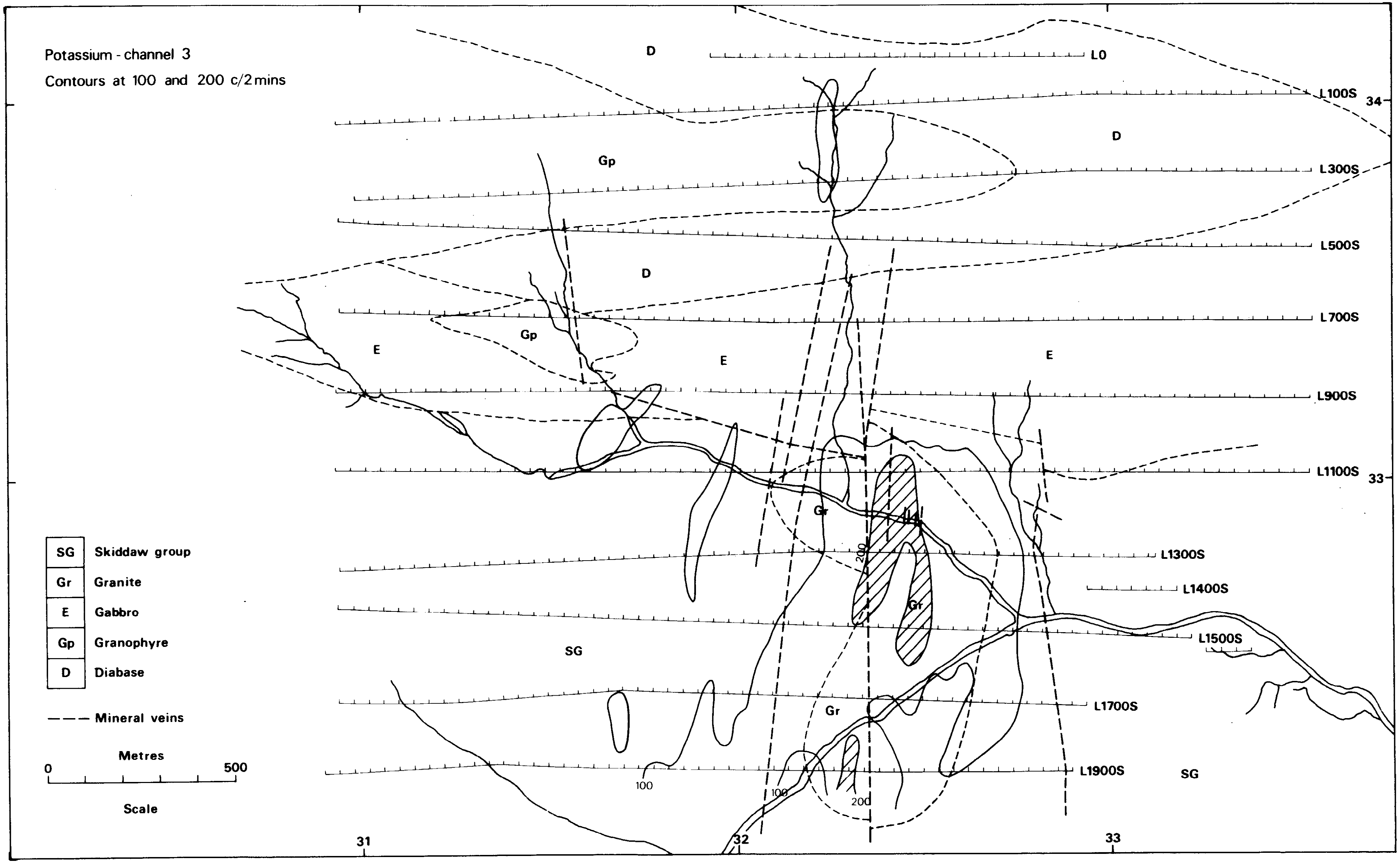

Figure 5 Qualitative contoured map of Channel 2, uranium

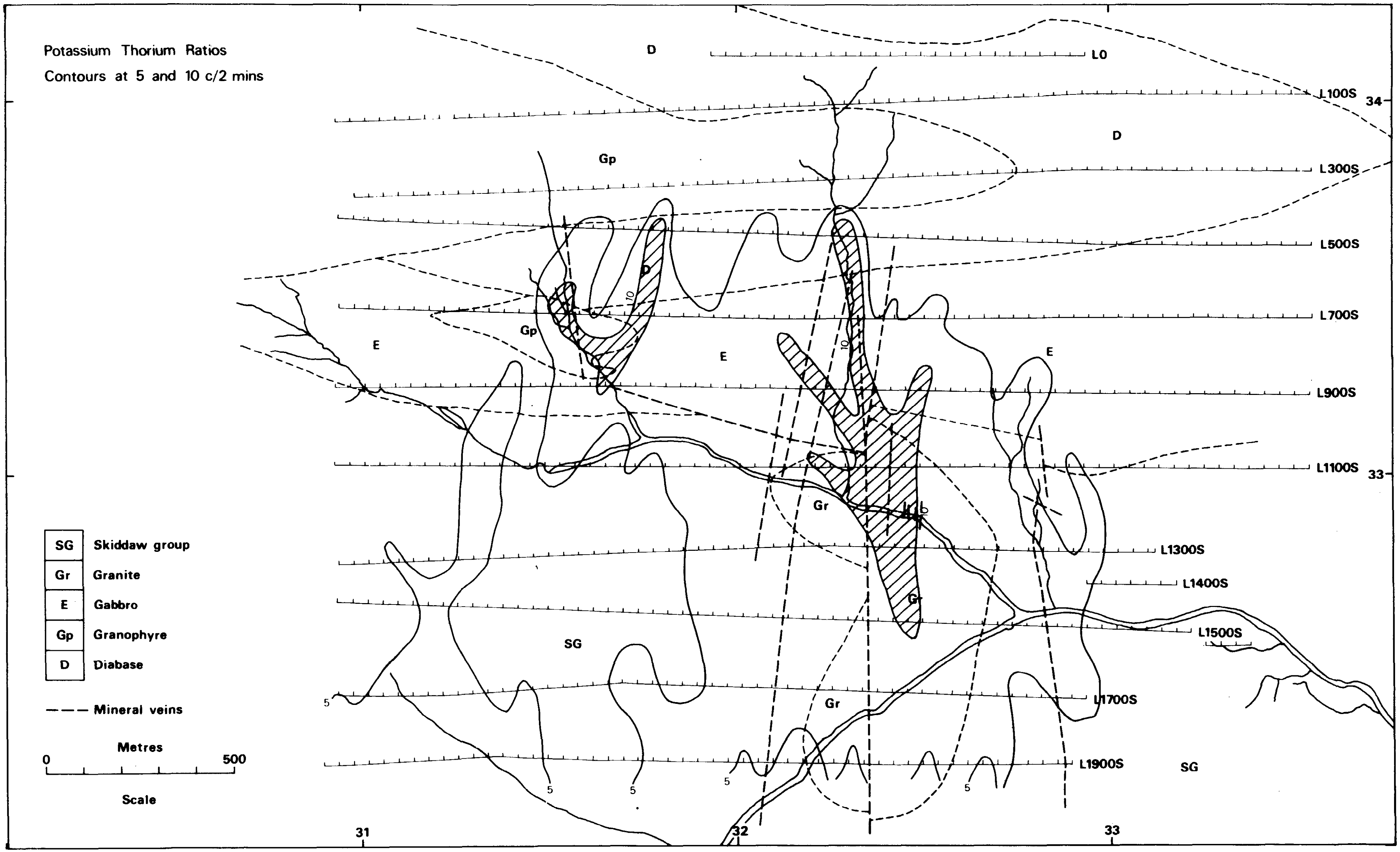

Figure 6 Qualitative contoured map of K/Th ratios

compositional changes of the underlying rocks. In particular, Mo and U in soil delineate the sub-outcrop of the granite and constitute a means of locating granite cupolas with which mineralisation might be associated. Higher levels of Ba associated with soils overlying the Skiddaw Slates exhibit a good contrast with lower levels over the igneous complex, and soils over the granophyre are relatively enriched in Zr compared to the other geological units. These elements, therefore, provide an effective means of mapping different rock types covered by glacial till.

5 Results of a gamma spectrometric survey demonstrated that the north-south tungsteniferous veins could be identified by a distinct increase in the K/Th ratios over background. A similar anomaly in the Arm O'Grain area is coincident with a strong VLF anomaly. Counts inthe U and K channels are effective in outlining the sub-outcrop of the Grainsgill Granite.

RECOMMENDATIONS

Geochemical results from the present study and results of the earlier geophysical investigations (Patrick, 1980) have demonstrated that the methods employed can identify targets for fuller detailed exploration, and three distinct areas are recommended for further work:

East of the worked veins

High linear VLF anomalies and coincident high levels of W and other elements in soil require further investigation by profile till sampling to bedrock, particularly in areas of deep peat cover, in order to confirm that anomalies in overburden reflect bedrock mineralisation. Rotary percussion drilling, on a grid within the anomalous area, is recommended to obtain bedrock material for analysis.

Wet Swine Gill area

Further soil sampling is required to the west and the south in order to close the anomalies exhibited by As and W. This should be followed by deep till sampling, detailed geological examination and rotary percussion drilling if considered necessary.

Arm O'Grain

Further investigation is required in the area around Arm O'Grain where geophysical work has outlined a strong VLF anomaly coincident with high K/Th ratios from the gamma spectrometer survey. Although the soil geochemistry does not indicate anomalous concentrations of either W, As, Cu, Zn, Rb or Pb the anomaly merits further geological investigation.

ACKNOWLEDGEMENTS

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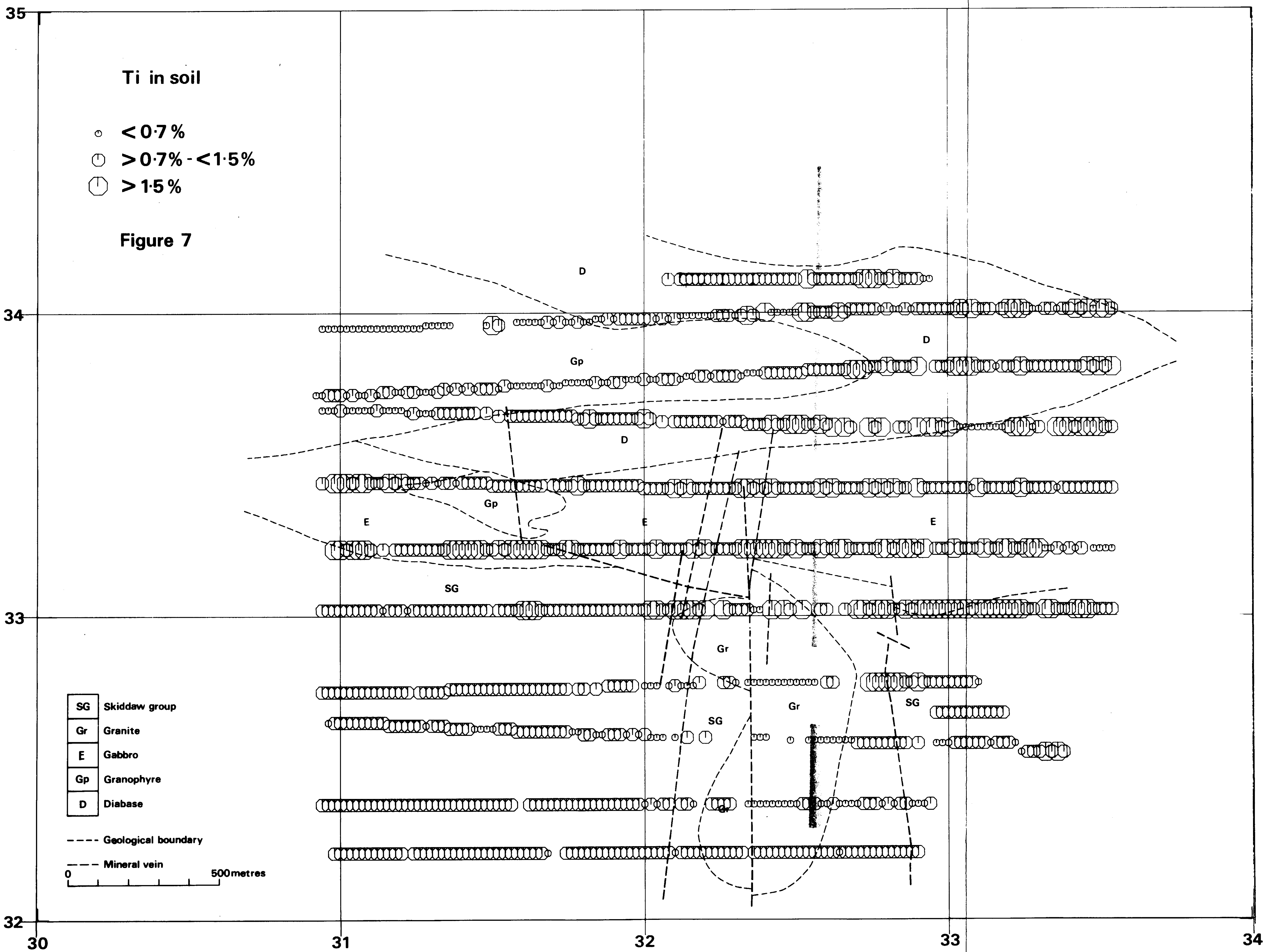
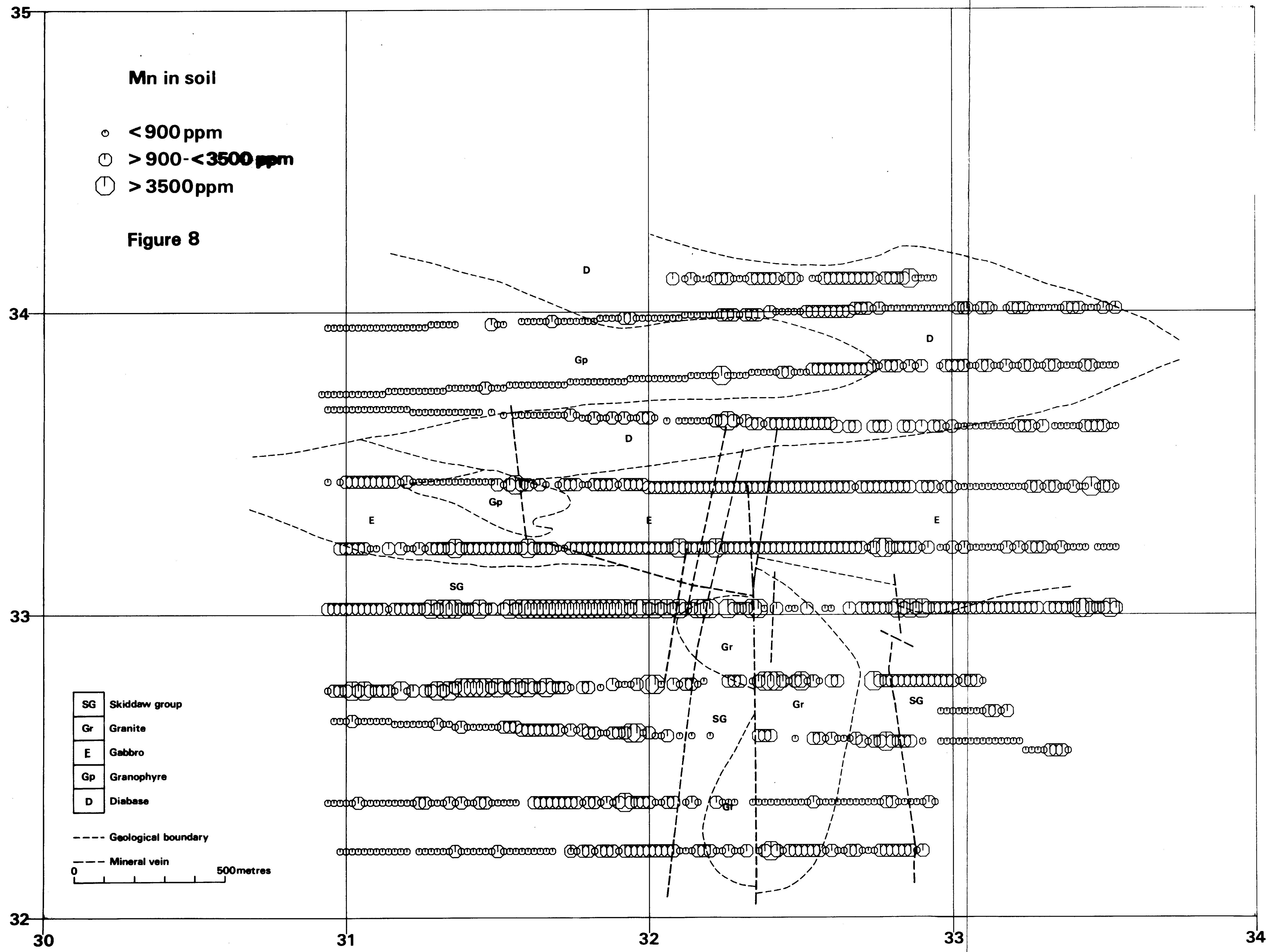


Ti in soil

Figure 7


Mn in soil
< 900 ppm
> 900-< 3500 ppm
> 3500 ppm
Figure 8
35
34
33
32
30
31
32
33
34
D
Gp
D
D
Gp
E
E
E
SG
Gr
Gr
SG
SG
Gr
SG Skiddaw group
Gr Granite
E Gabbro
Gp Granophyre
D Diabase
Geological boundary
Mineral vein
0
500 metres

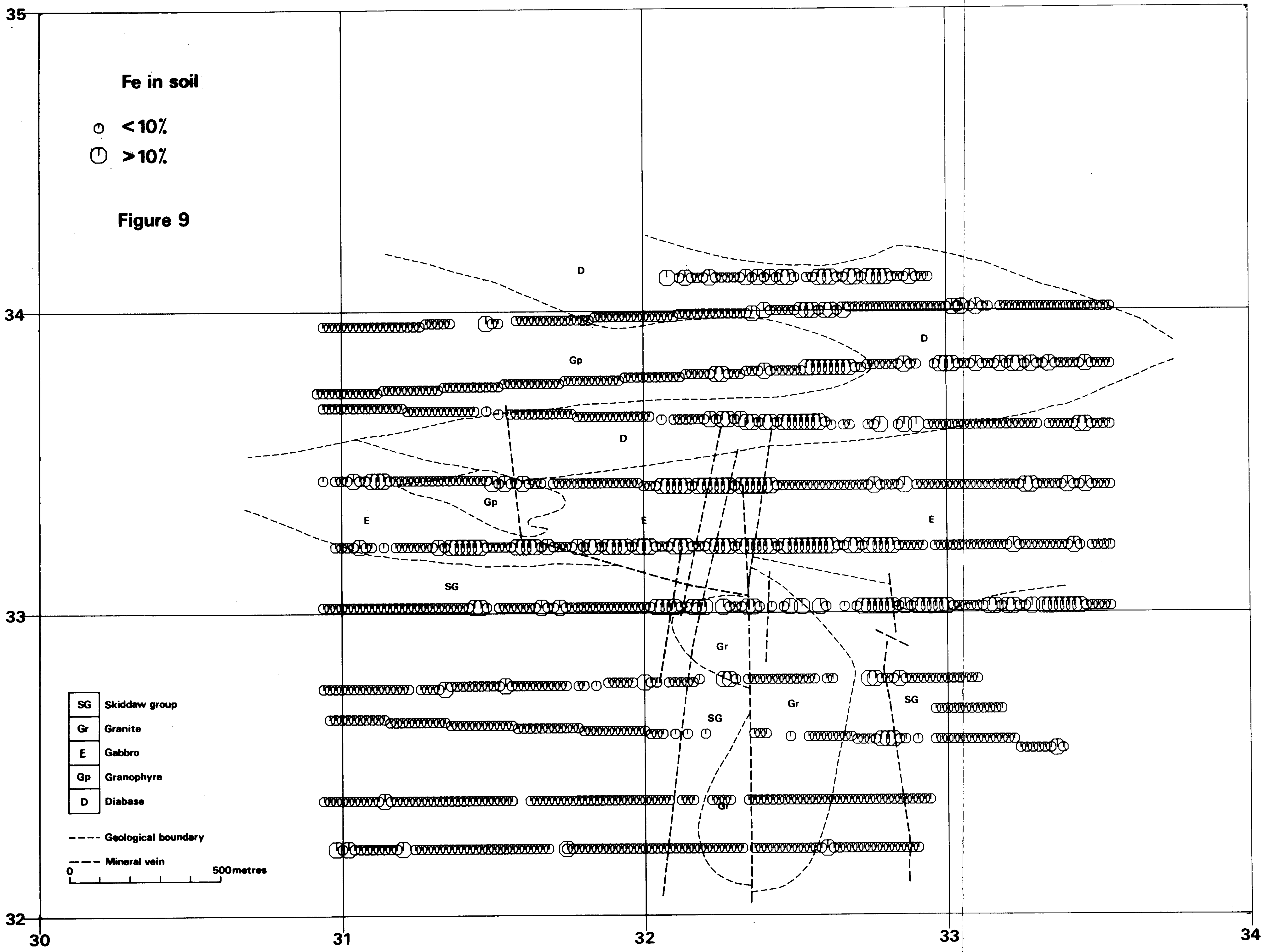
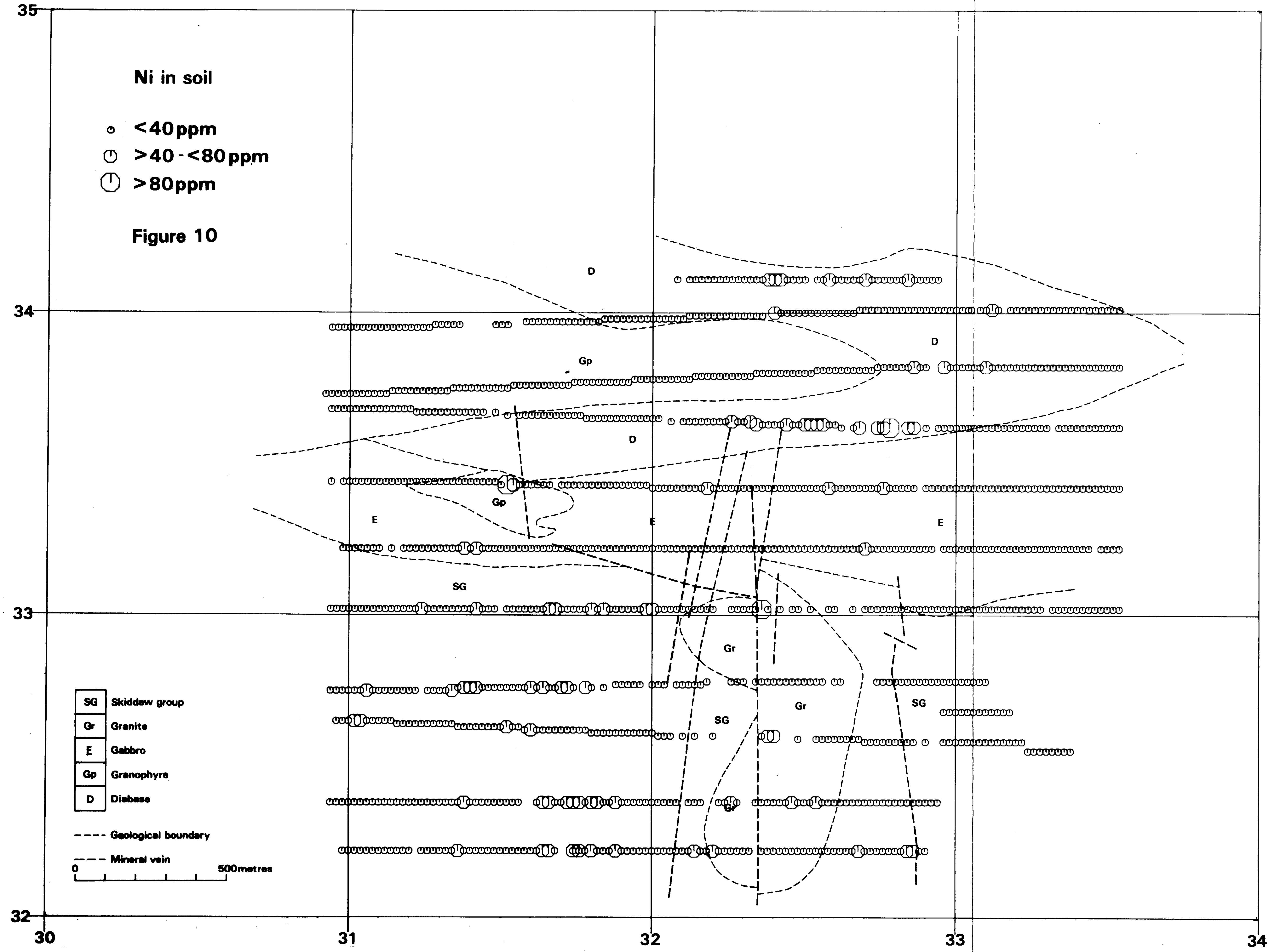

Fe in soil
< 10%
> 10%
35
34
33
32
30
31
32
33
34
D
Gp
D
D
Gp
E
E
E
SG
Gr
Gr
SG
SG
Gr
SG Skiddaw group
Gr Granite
E Gabbro
Gp Granophyre
D Diabase
Geological boundary
Mineral vein
0
500metres

Figure 9


Ni in soil
<40ppm
>40-<80ppm
>80ppm
Figure 10
SG Skiddaw group
Gr Granite
E Gabbro
Gp Granophyre
D Diabase
Geological boundary
Mineral vein
0
500metres
35
34
33
32
30
31
32
33
34
D
Gp
D
D
Gp
E
E
E
SG
Gr
SG
Gr
SG
Gr

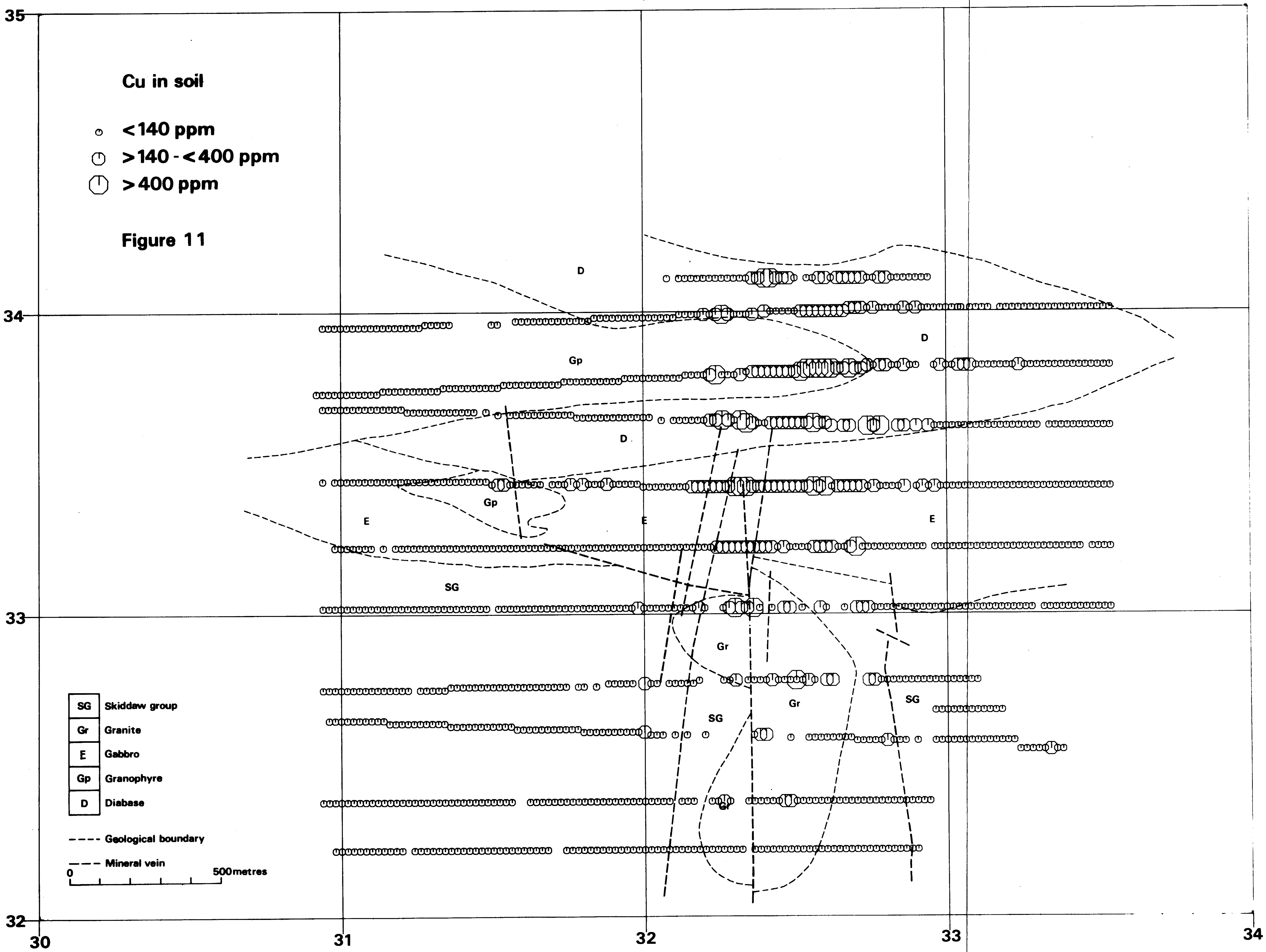


Figure 11

Cu in soil
<140 ppm
>140 - <400 ppm
>400 ppm
SG Skiddaw group
Gr Granite
E Gabbro
Gp Granophyre
D Diabase
Geological boundary
Mineral vein
0
500metres
D
Gp
D
D
Gp
E
E
E
SG
Gr
Gr
SG
SG
Gr
35
34
33
32
30
31
32
33
34

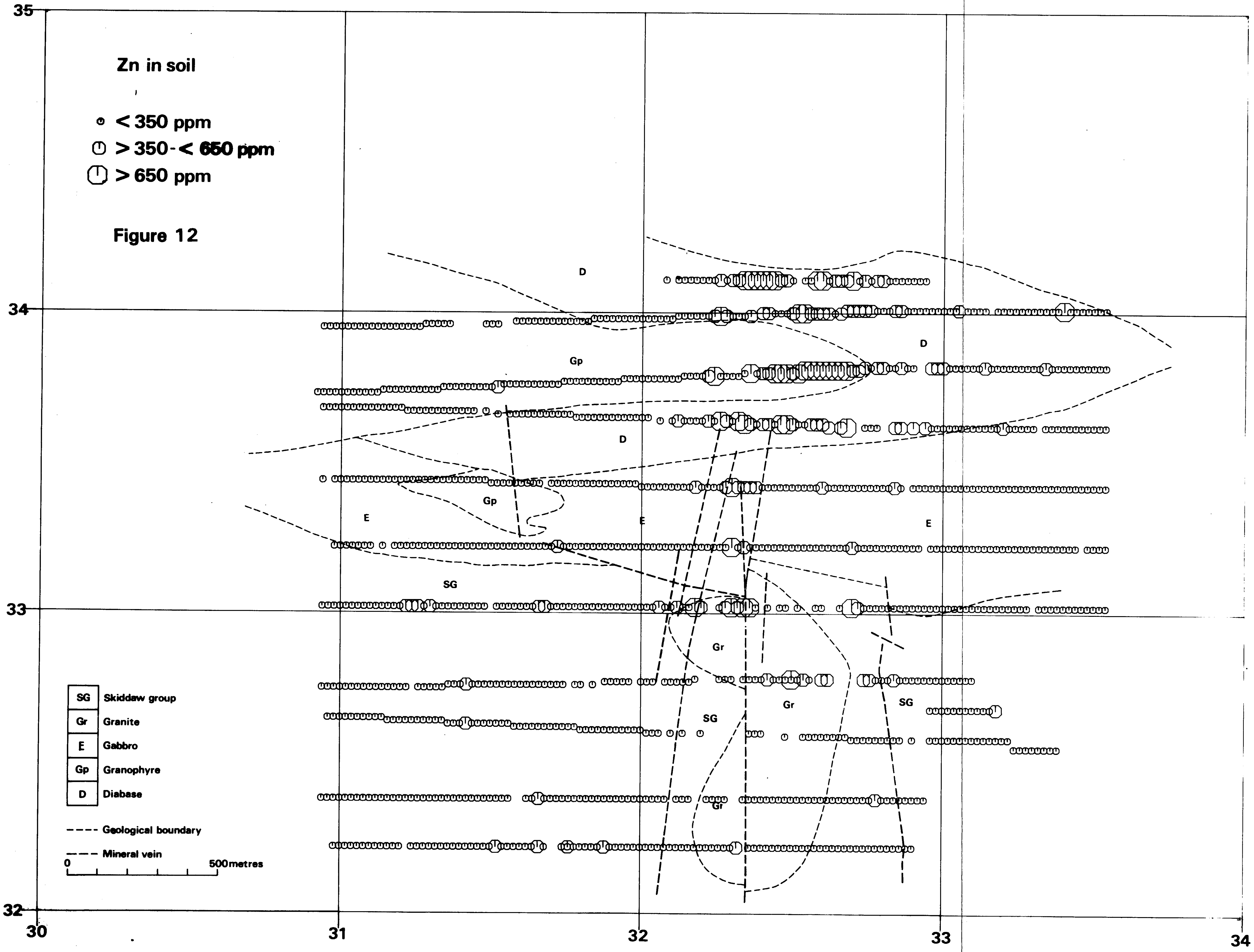
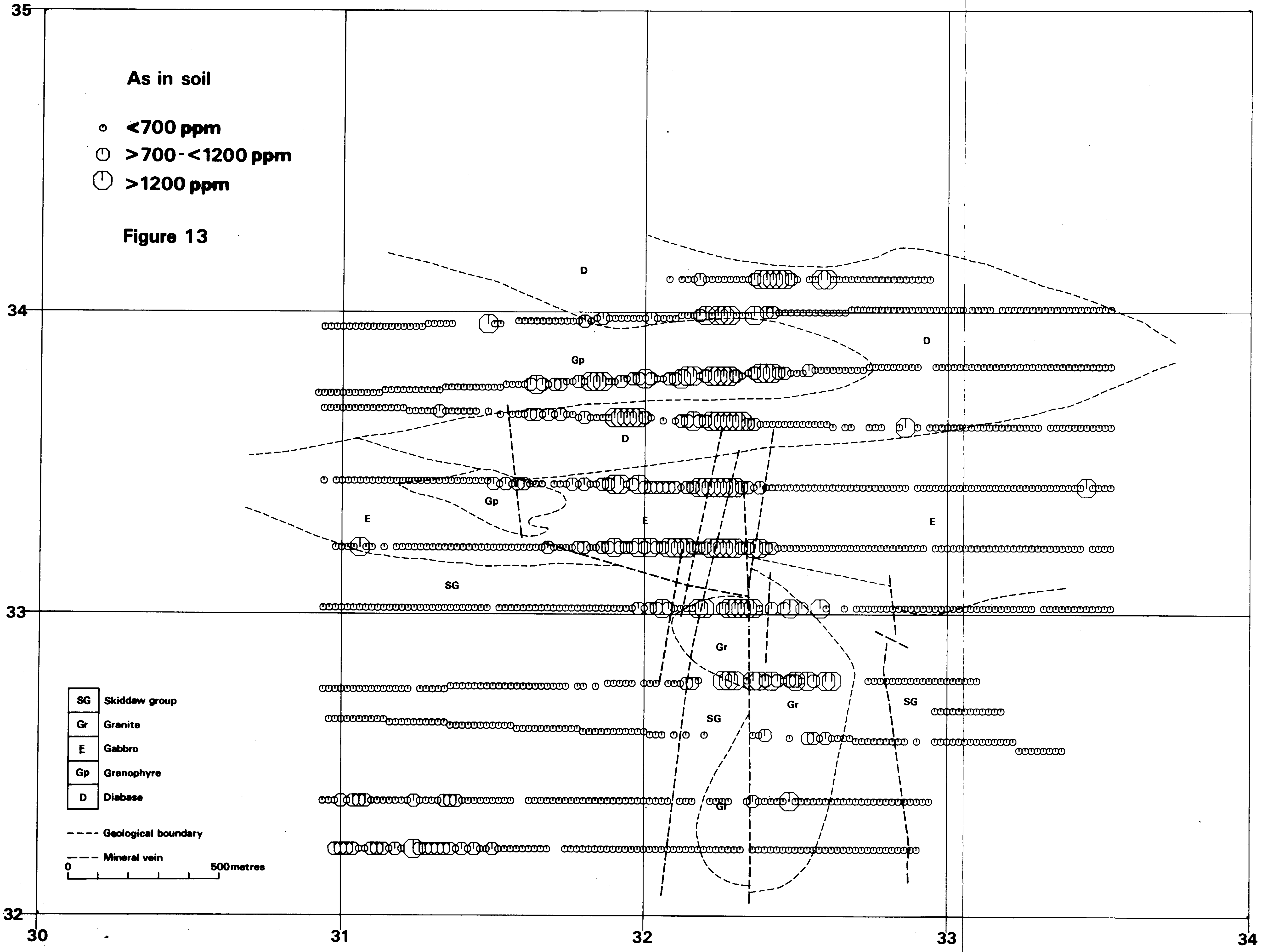


Figure 12

Zn in soil



As in soil
<700 ppm
>700 - <1200 ppm
>1200 ppm
Figure 13
SG Skiddaw group
Gr Granite
E Gabbro
Gp Granophyre
D Diabase
Geological boundary
Mineral vein
0
500metres
D
Gp
D
E
E
E
Gp
SG
Gr
SG
Gr
SG
Gr
35
34
33
32
30
31
32
33
34

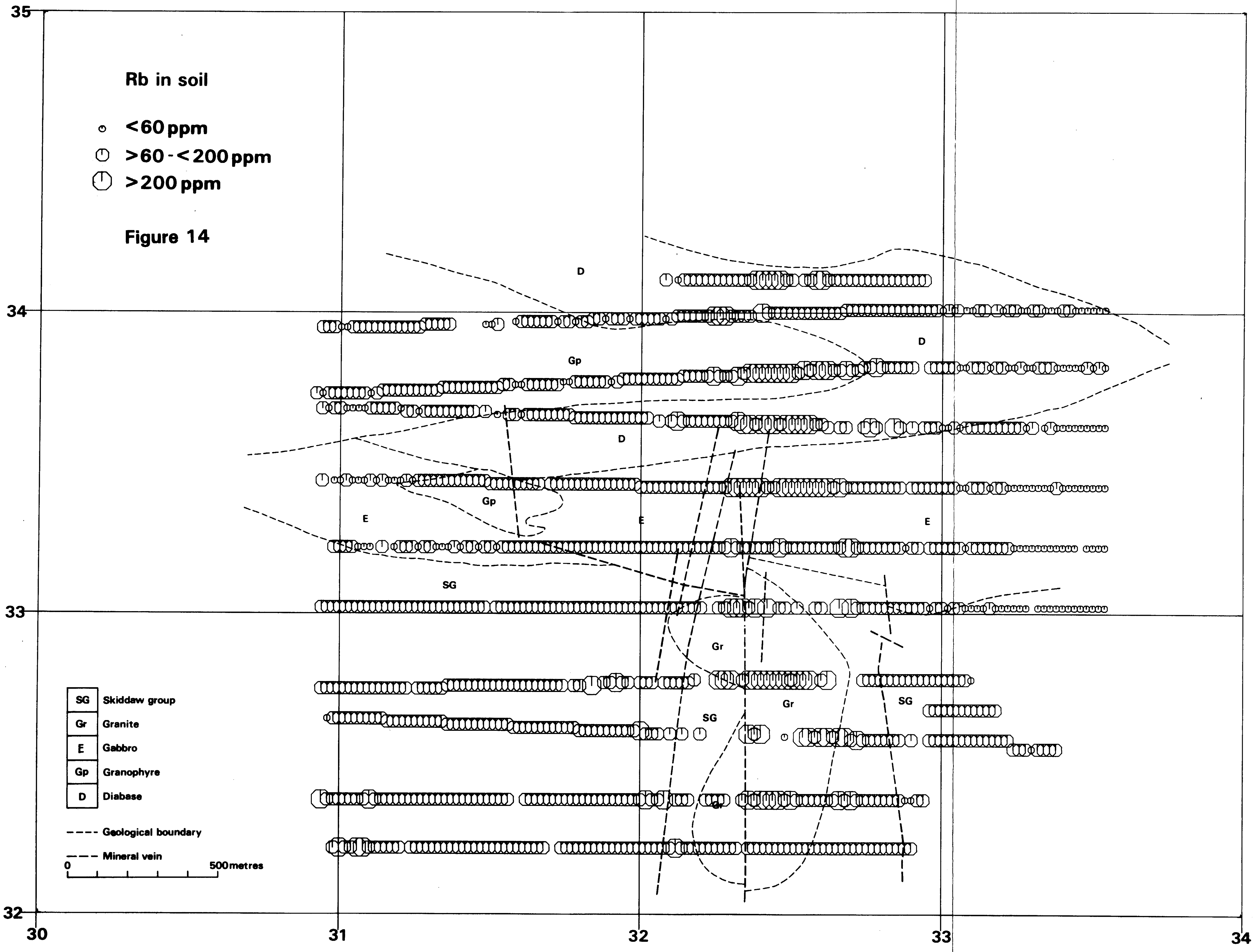

Rb in soil
<60ppm
>60-<200ppm
>200ppm
D
Gp
D
D
Gp
E
E
E
SG
Gr
Gr
SG
SG
Gr
SG Skiddaw group
Gr Granite
E Gabbro
Gp Granophyre
D Diabase
Geological boundary
Mineral vein
0
500metres
35
34
33
32
30
31
32
33
34

Figure 14

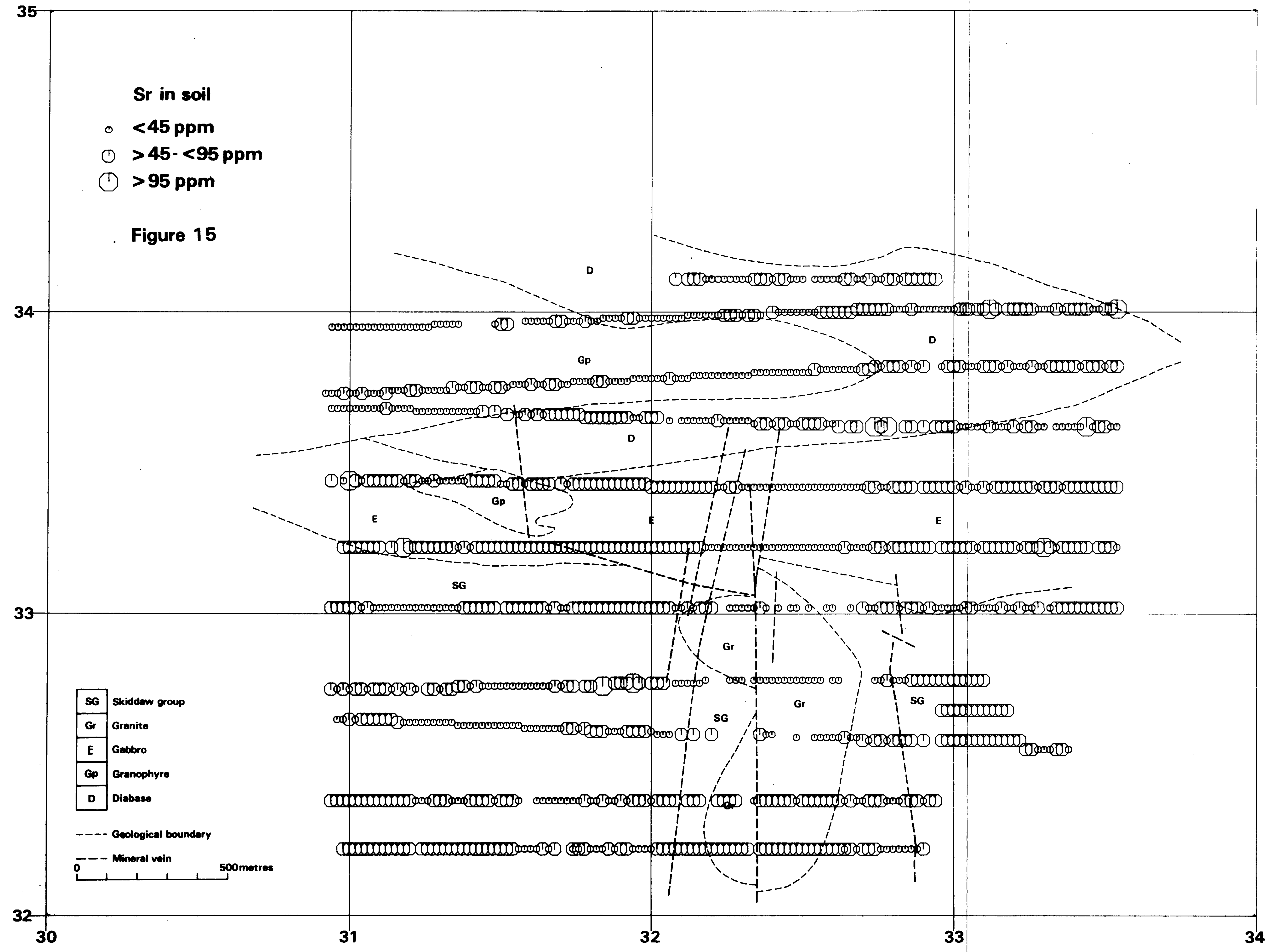
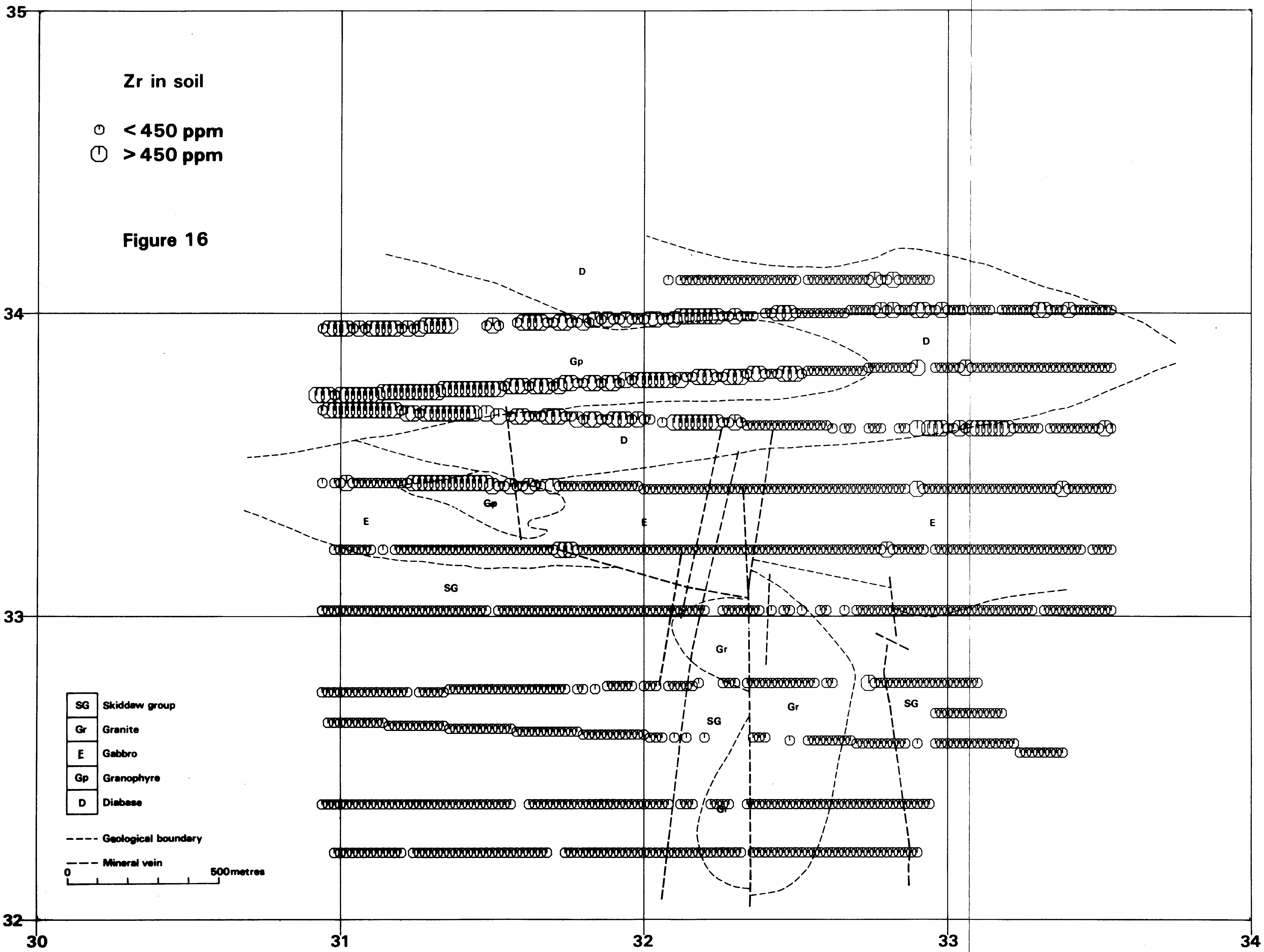

Sr in soil
<45 ppm
>45-<95 ppm
>95 ppm
SG Skiddaw group
Gr Granite
E Gabbro
Gp Granophyre
D Diabase
Geological boundary
Mineral vein
0
500metres
D
Gp
D
E
E
E
Gp
SG
Gr
Gr
SG
SG
Gr
35
34
33
32
30
31
32
33
34

Figure 15


Zr in soil
○ <450 ppm
◯ >450 ppm
Figure 16
35
34
33
32
30
31
32
33
34
D
Gp
D
D
Gp
E
E
E
SG
Gr
Gr
SG
SG
Gr
SG Skiddaw group
Gr Granite
E Gabbro
Gp Granophyre
D Diabase
Geological boundary
Mineral vein
0
500metres

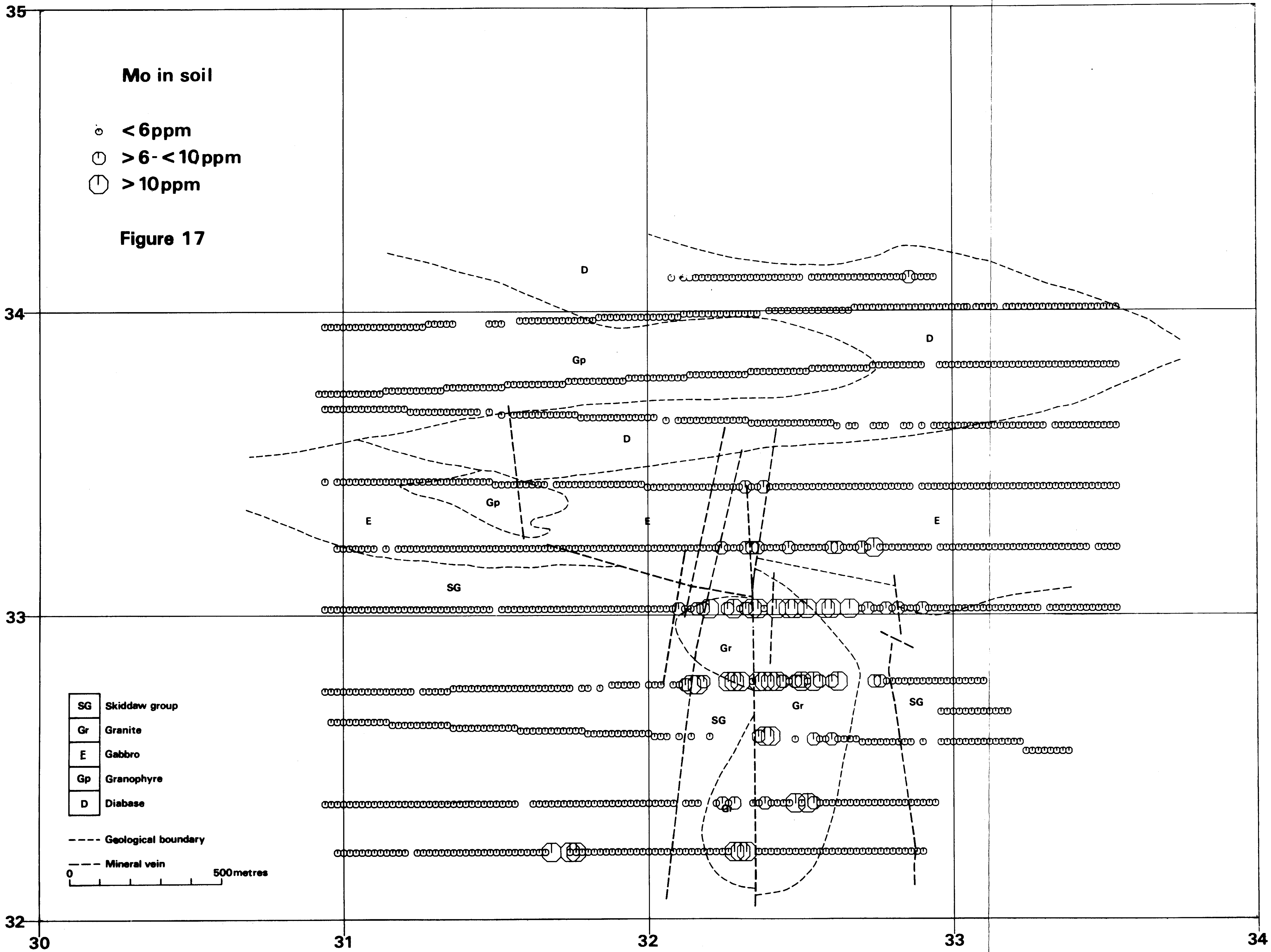

Mo in soil
< 6ppm
> 6 - < 10ppm
> 10ppm
SG Skiddaw group
Gr Granite
E Gabbro
Gp Granophyre
D Diabase
Geological boundary
Mineral vein
0
500metres
D
D
Gp
D
Gp
E
E
E
SG
Gr
Gr
SG
SG
Gr
35
34
33
32
30
31
32
33
34

Figure 17

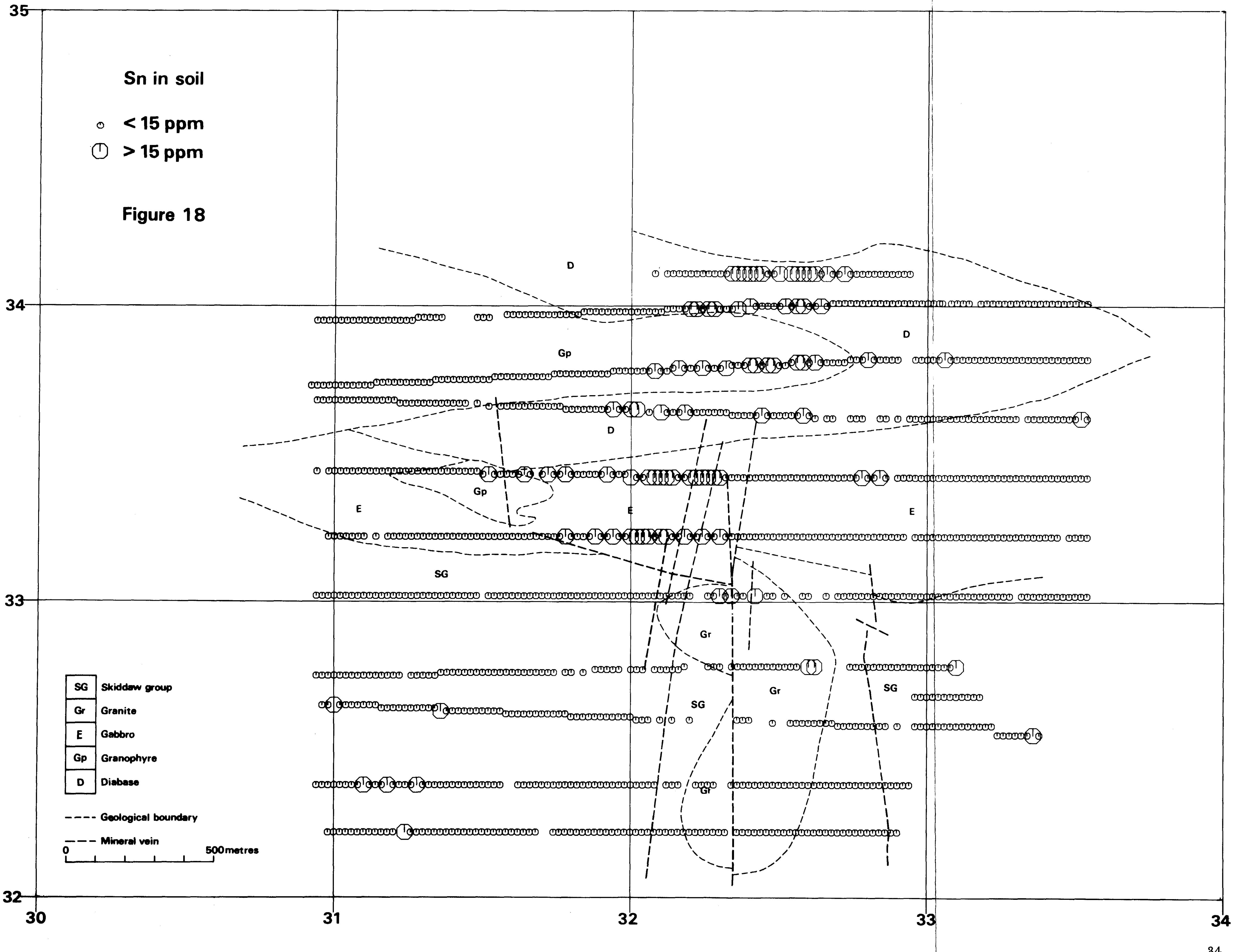
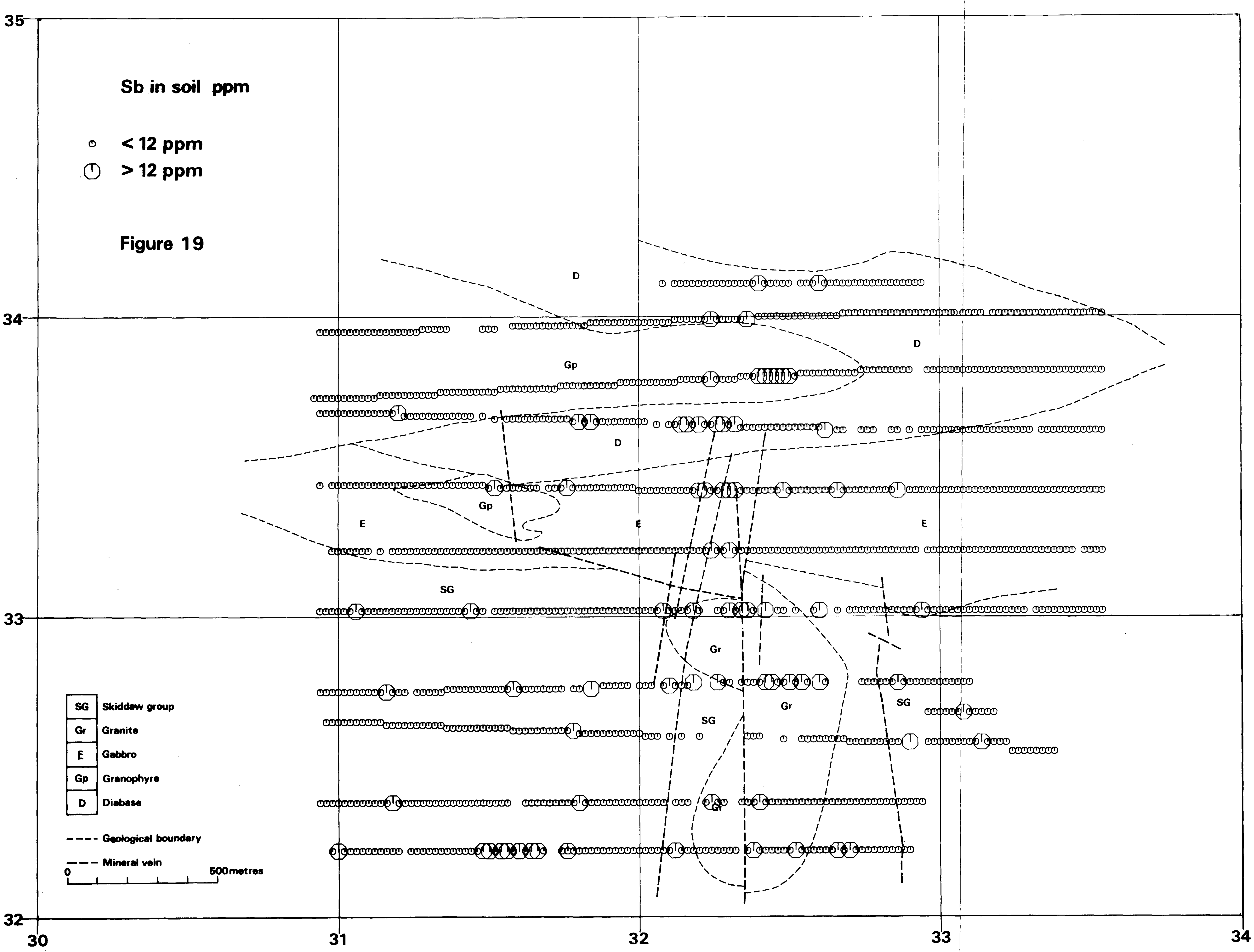

Sn in soil
< 15 ppm
> 15 ppm
SG Skiddaw group
Gr Granite
E Gabbro
Gp Granophyre
D Diabase
Geological boundary
Mineral vein
0
500metres
D
Gp
D
D
Gp
E
E
E
SG
Gr
Gr
SG
SG
Gr
35
34
33
32
30
31
32
33
34

Figure 18



Sb in soil ppm

Figure 19

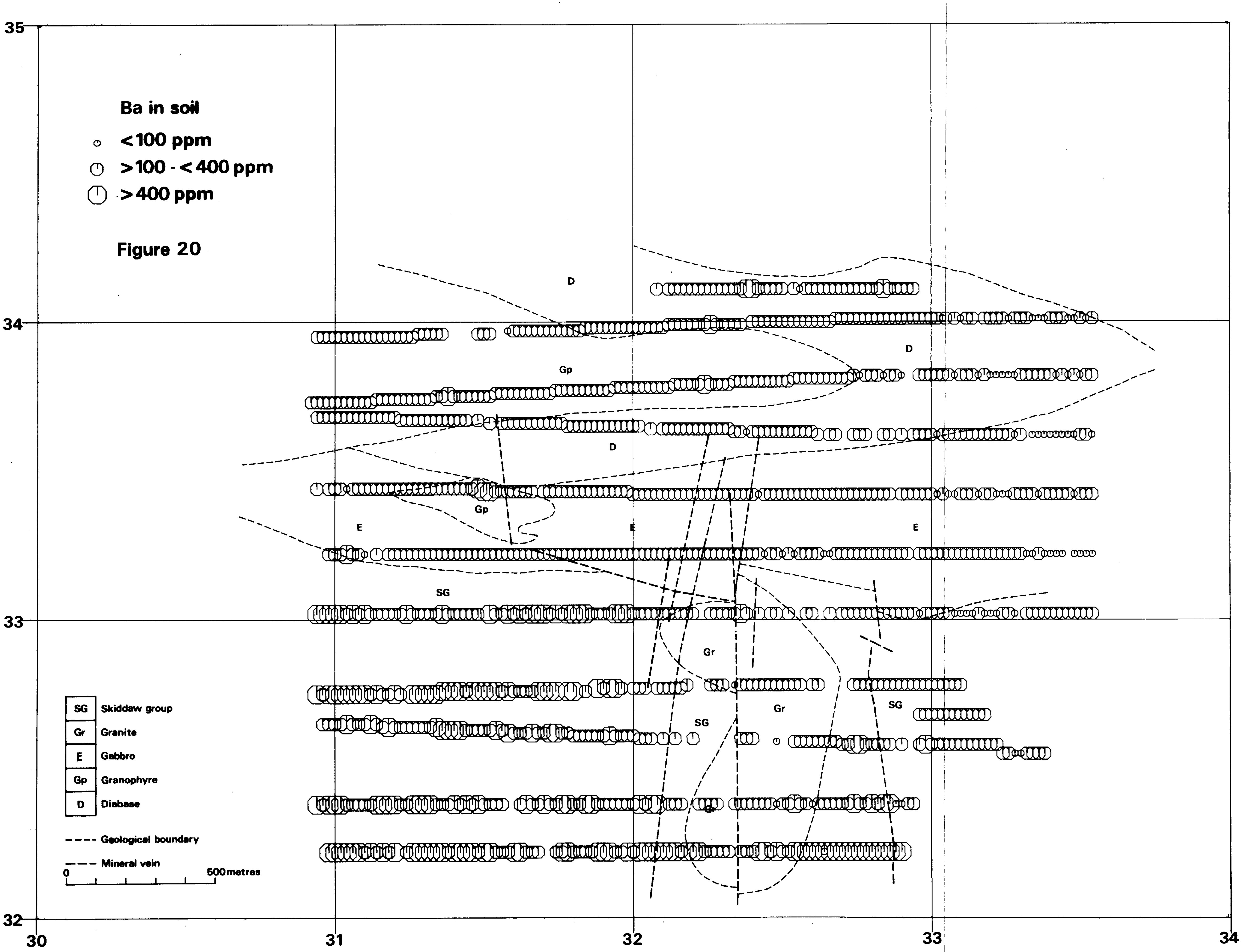
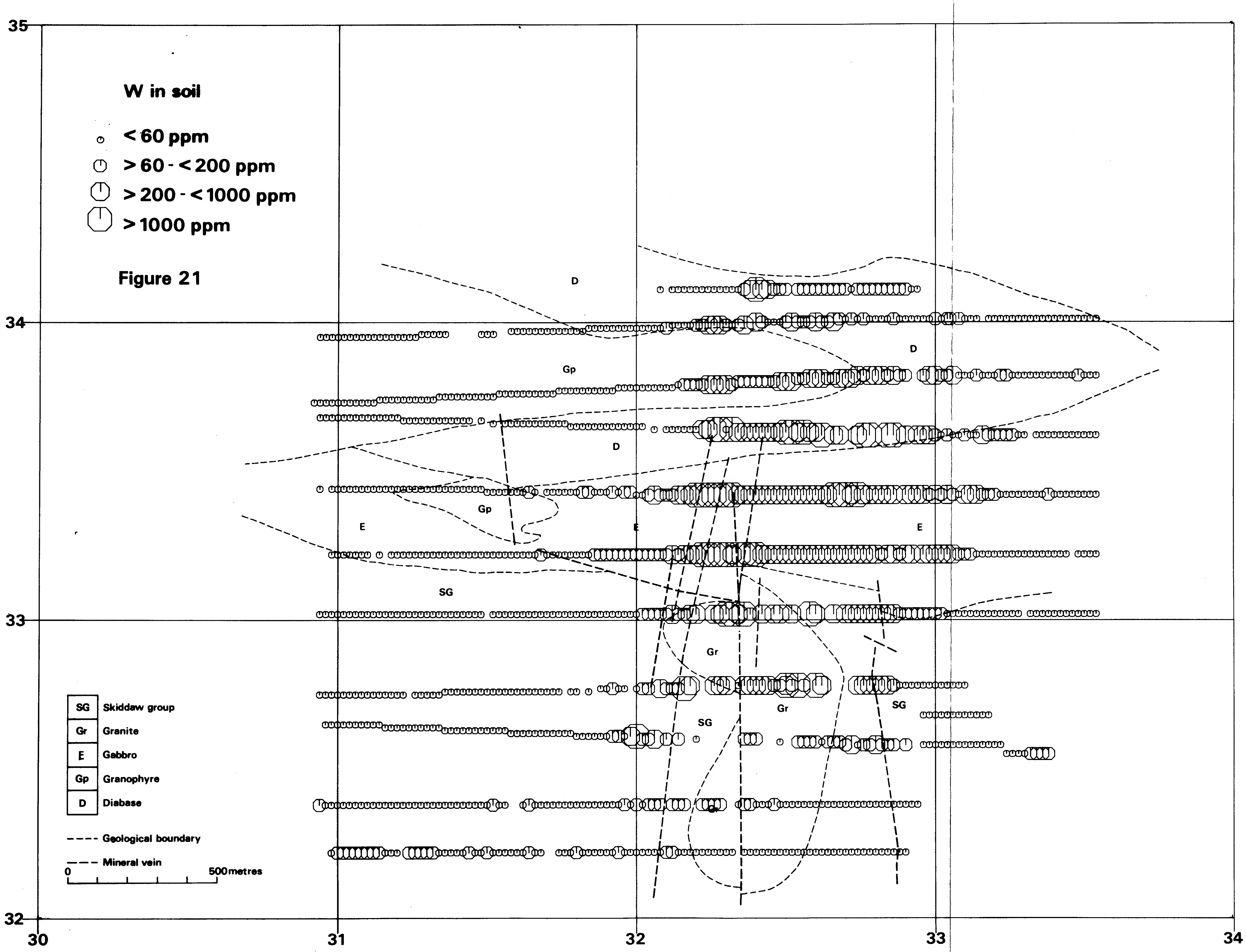


Figure 20

Ba in soil
<100 ppm
>100 - <400 ppm
>400 ppm
D
Gp
D
D
Gp
E
E
E
SG
Gr
Gr
SG
SG
Gr
SG Skiddaw group
Gr Granite
E Gabbro
Gp Granophyre
D Diabase
Geological boundary
Mineral vein
0
500metres
35
34
33
32
30
31
32
33
34



W in soil

Figure 21

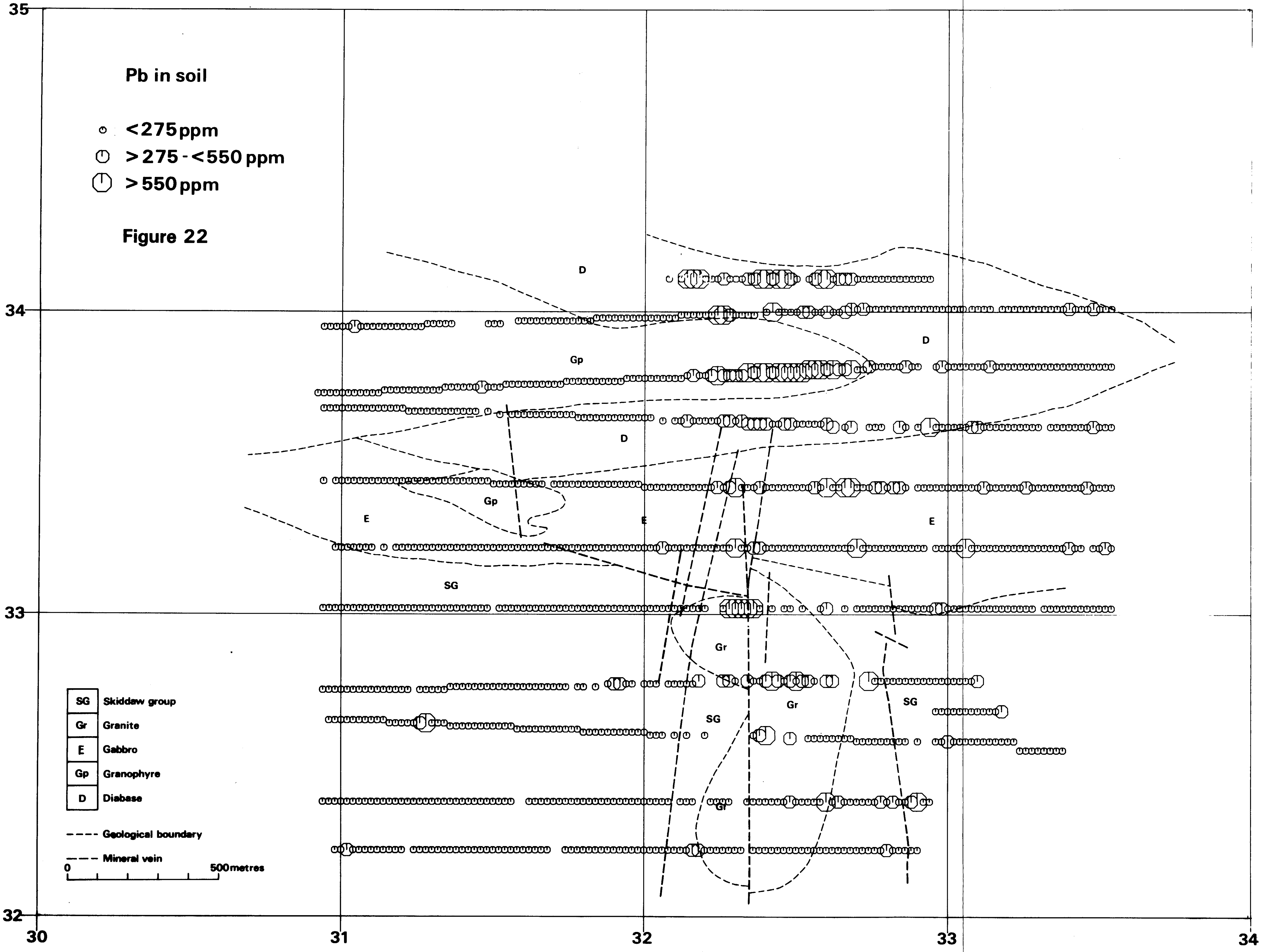


Figure 22

Pb in soil
<275ppm
>275-<550 ppm
>550 ppm
SG Skiddaw group
Gr Granite
E Gabbro
Gp Granophyre
D Diabase
Geological boundary
Mineral vein
0
500metres
D
Gp
D
D
Gp
E
E
E
SG
Gr
Gr
SG
SG
Gr
35
34
33
32
30
31
32
33
34

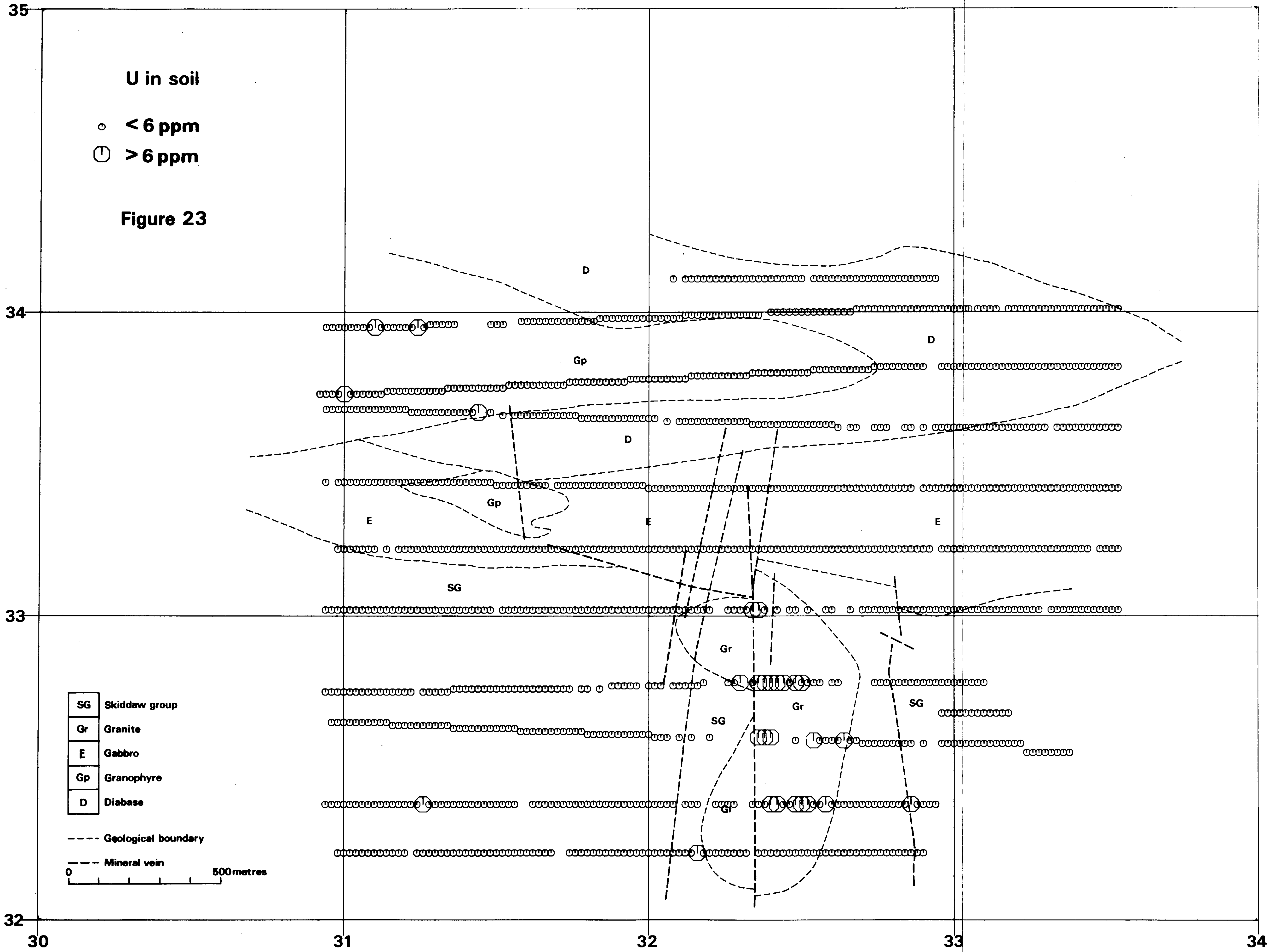

U in soil
< 6 ppm
> 6 ppm
35
34
33
32
30
31
32
33
34
D
Gp
D
D
Gp
E
E
E
SG
Gr
Gr
SG
SG
Gr
SG Skiddaw group
Gr Granite
E Gabbro
Gp Granophyre
D Diabase
Geological boundary
Mineral vein
0
500metres

Figure 23