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REDISTRIBUTION OF ELEMENTS BY METAMORPHISM

by

A.S. Joyce

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REDISTRIBUTION OF ELEMENTS BY METAMORPHISM

by

A.S. Joyce

SUMMARY

Some published studies have suggested that chemical redistribution within the earth's crust can take place during metamorphism. This concept is supported indirectly by a statistical study of chemical analyses of regionally metamorphosed rocks, and directly by a study of two contact metamorphic aureoles in the Canberra 1:250,000 Sheet area. Such redistribution provides an opportunity for segregation of original trace constituents of solid rocks, and should be taken into consideration as a possible source of ore in metamorphic terrains.

INTRODUCTION

It is commonly stated that stratiform base metal sulphide deposits occur in sedimentary environments. This is not strictly correct: very many, if not most, occur in regionally metamorphosed sedimentary rocks. Extreme contrasts of geological settings of stratiform sulphide deposits appear to be represented by those of the McArthur River deposits and the Broken Hill deposits. The McArthur River sulphides are enclosed in sediments which apparently have undergone little change other than that attributable to diagenesis; the Broken Hill deposits are enclosed in rocks so highly altered that their original nature can be deduced only very indirectly. Most stratiform sulphide deposits, however, are situated in environments intermediate between these extremes, commonly in rocks of the greenschist facies of metamorphism. Reasonable estimates of the pressure and temperature conditions prevailing during greenschist facies metamorphism are 3,000-8,000 bars pressure, and 300-500°C temperature. These pressures and temperatures can be expected to bring about considerable changes in the texture, probably in the mineralogy, and possibly in the location of minerals so readily deformed and recrystallised as sulphides. It is unlikely that the deposits in metamorphic rocks can be expected to retain much of their original character if they were deposited in a sedimentary environment, other than perhaps their stratiform distribution. Hence the controversy as to their origin: their present features can be explained as readily by exponents of a replacement origin as by exponents of a sedimentary origin.

Summarising a few pertinent observations, it is noted that -

(1) no appreciable base metal sulphide concentrations have been detected in present sedimentary environments.

(2) the problems of abstracting sufficient base metals from sea water in geologically reasonable time are considerable; no really satisfactory sedimentary environment has been postulated, and no present-day sedimentary sulphide ore-forming environment seems to have been recognised.

(3) all known stratiform base metal deposits occur in sediments which have undergone at least diagenesis, and more usually low-grade metamorphism, with one exception - a copper deposit in unlithified Tertiary strata in Bolivia (N.H. Fisher, verbal comm., 1967).

(4) the present textures of typical stratiform ores are recrystallised or metamorphic, not sedimentary.

Strictly, then, most of these deposits should be regarded as metamorphic, and the question arises as to whether they originated by modification of sedimentary accumulations of base metal sulphides or by metamorphic segregation of base metals from ordinary rocks of the stratigraphic sequence. This second possibility has been examined to see whether it is reasonable to discount it, as is usually done. If it is to be accepted as a possible origin of some deposits then it must be demonstrated firstly that appreciable migration of material through non-molten rocks can occur, and secondly, that localisation of such migrating material is possible.

In subsequent sections of this report, attention is not restricted to base metals because more data are available for the more common rock and ore forming constituents, and because any general patterns of element redistribution which emerge can probably be extrapolated, with care, to other elements for which data are scanty.

REDISTRIBUTION OF ELEMENTS BY REGIONAL METAMORPHISM

Many early petrologists favoured the view that most metamorphic changes take place without appreciable changes in bulk chemical composition. Subsequent workers have pointed out that rocks change their chemical composition at the very beginning of metamorphism by considerable losses of H_2O and CO_2, so that isochemical regional metamorphism in the strict sense does not exist. However, opinion differs widely regarding the degree to which the chemistry of rocks is capable of altering during metamorphic reconstitution. Some geologists consider that H_2O, CO_2, and similar "volatile" constituents are the only components capable of migrating appreciably under typical conditions of regional metamorphism. Others consider that some, or all, of the rock-forming constituents are capable of migrating in appreciable quantities and for significant distances.

Many French and Scandinavian workers were impressed long ago by a close field relationship between areas of high-grade metamorphism and the development of granitisation, and they suggested that granitisation is the result of chemical changes induced by regional metamorphism. This concept met with considerable opposition from other schools. Considerable confusion resulted also from early conceptions that the granitisation process necessitated expulsion of Mg, Fe, etc., which should be evident somewhere as a "basic front" adjacent to the theatre of granitisation. Read (1951) offered a solution to this problem by suggesting that these postulated "fronts" may in fact be basic "rears" concealed beneath the granitised terrain: that is, Si and alkalis migrate upwards from deep metamorphic zones which are left impoverished in these constituents.

Ramberg (1951) favoured a similar hypothesis, that granitisation ("quartzo-feldspathisation") is caused chiefly by upward migration of the chemical constituents of granites during regional metamorphism, and deduced that beneath such granitised areas should exist basified zones. He considered these basified zones would correspond to areas of maximum regional metamorphism, namely granulite facies. To test this theory Ramberg (1951) compared the chemical composition of the Isortoq granulite facies complex of West Greenland with that of the nearby Egedesminde amphibolite facies complex. The results indicate that the granulite facies area is distinctly more basic than the amphibolite facies area. Mg, Fe^{2+}, Fe^{3+}, Ca, Ti, and Mn are relatively more abundant in the former, and Si, Na, K, O, and H_2O in the latter.

Chemical studies of specific progressively metamorphosed regions by various geologists have yielded apparent examples of both isochemical and allochemical metamorphism, but few of these studies are based on sufficient chemical analyses for satisfactory interpretation. A study of the Grenville Series of the Northwest Adirondack Mountains, New York, by Engel and Engel (1953, 1958, 1964) is one of the best documented examples, and in this case the apparent transfer of material during metamorphism is considerable.

In a very generalised fashion, a sympathetic relationship exists between depth of burial and grade of regional metamorphism. Ramberg (1944, 1945, 1946, 1948), Barth (1948, 1962), Rosenqvist (1948), and Brewer (1951) have examined the question of radial diffusion and the equilibrium distribution of elements in the earth's gravitational field from a thermodynamic point of view. The results indicate that ideally the densest constituents will concentrate towards the core of the earth, and successively less dense material will concentrate towards the surface. Even a column of initially homogeneous rock is not stable in the gravitational field, and a tendency exists to initiate chemical migrations of various types directed towards attaining thermodynamic stability. In nature these simple theoretical trends of differentiation are modified to varying degrees by the chemical bonding energies of each element in each environment.

Lapadu-Hargues (1945, 1949) examined the question of chemical migration during metamorphism from a broad statistical approach. He collected analyses of metamorphic rocks thought to be derived sediments, and compared them with those of shales and granites, because he considered that sedimentary schists, crystalline schists, and granites form a continuous series corresponding roughly to depth zones. The analyses were arranged into seven supposedly progressive groups (viz. I. schistes sédimentaires, II. schistes à séricite et micaschistes à muscovite, III. micaschistes à biotite et muscovite, IV. gneiss à deux micas, V. gneiss granitoides, oeilles, à biotite seule, VI. granites, VII. granulites), and the average abundances of the various chemical components in these seven groups revealed an apparent migration of elements during metamorphism, especially alkalis, alkaline earths, and ferromagnesians. The tendency of this apparent migration is to create or stabilise a granodioritic composition.

The validity of Lapadu-Hargues' (1945) approach has been questioned by Mason (1958) because of the wide variation between individual analyses within each of the seven groups. On the contrary, probably the greatest weakness of Lapadu-Hargues' (1945) study lies in the undesirable subjectivity introduced by him in selecting analyses of metamorphic rocks derived from pelites.

In the hope of clarifying the question of whether regional metamorphism generally proceeds isochemically or allochemically, a new statistical analysis of metamorphic bulk rock analyses is presented, based on the concept of recognisable metamorphic facies.

COLLECTION AND TREATMENT OF DATA

Chemical analyses of regionally metamorphosed rocks were collected from readily accessible literature. The analyses were recorded as found, and no attempt was made to select or reject analyses on the basis of supposed parental rock type. The analyses were then classified into five groups appropriate to the greenschist facies, glaucophane schist facies, almandine amphibolite facies, granulite facies, and eclogite facies, as defined by Turner and Verhoogen (1960), as precisely as possible from the individual rock descriptions and general geological settings. Those analyses which could not be classified into a metamorphic facies with reasonable certainty were discarded.

The mean abundance of each oxide in each facies was calculated (Table 1), and a one-way analysis of variance was carried out (Table 2) to determine whether it is permissible to attach any significance to the observed differences between means. The method used follows that given by Crow, Davis, and Maxfield (1960).

It is important to note that the means calculated for P_2O_5, MnO, and CO_2 are probably higher than the true means. This is because the means were calculated using only those analyses in which a value is recorded for the particular oxide (including nil and below detection). Probably, in many, or most cases where rocks were not analysed for minor elements it was because their content of the element was expected to be very low.

The fundamental assumption for the analysis of variance used is that the observations are drawn from a normal population. The null hypothesis is made that the means of observations x_{it} for the r situations are all equal. It can be shown that if the null hypothesis is true, the variance (also called mean square) among situations (S_2^2) should be about equal to the variance within situations (S_3^2), so the statistic F, defined as $\frac{S_2^2}{S_3^2}$, should be approximately one. On the other hand, the null hypothesis is rejected at a specific significance level x if the quotient F exceeds a critical value, for which standard tables are available, for $f_1 = r-1$ and $f_2 = n-r$ degrees of freedom.

TABLE 1.

MEAN ABUNDANCE OF EACH OXIDE IN EACH METAMORPHIC FACIES.

	Greenschist Facies		Glaucophane Schist		Almandine Amphibolite Facies		Granulite Facies		Eclogite Facies	
	Mean	No. of Anal.	Mean	No. of Anal.	Mean	No. of Anal.	Mean	No. of Anal.	Mean	No. of Anal.
SiO_2	60.3	171	57.1	104	58.5	375	54.1	49	46.9	45
Al_2O_3	15.5	170	13.0	104	16.1	363	14.2	49	17.0	45
Fe_2O_3	3.5	145	4.3	100	2.1	357	2.2	49	3.3	45
FeO	4.8	143	5.4	98	5.5	358	7.5	49	7.5	45
MgO	3.4	169	5.1	104	4.1	375	7.4	49	7.9	45
CaO	3.7	192	6.8	103	5.5	375	7.2	49	12.3	45
Na_2O	2.4	191	2.9	103	2.7	360	2.6	62	2.2	45
K_2O	2.5	170	0.8	101	2.5	365	2.0	62	0.4	44
H_2O+	2.9	127	3.0	81	1.5	245	0.8	49	0.7	35
TiO_2	0.9	158	1.3	90	1.0	350	1.2	49	1.3	41
P_2O_5	0.2	145	0.2	68	0.2	303	0.3	48	0.2	33
MnO	0.1	136	0.2	90	0.1	320	0.2	49	0.2	27
CO_2	1.6	97	0.4	31	4.2	121	0.3	18	0.3	10

TABLE 2.

DESIGN OF ONE FACTOR ANALYSIS OF VARIANCE.

Source of Variation	Sum of Squares	Degrees of Freedom	Variance	F
Among facies	$(2) = \sum_i \frac{(\sum_t x_{it})^2}{m_i} - \frac{(\sum_{it} x_{it})^2}{n}$	$r - 1$	$S_2^2 = \frac{(2)}{r-1}$	
Within facies	$(3) = (1) - (2)$	$n - r$	$S_3^2 = \frac{(3)}{n-r}$	$\frac{S_2^2}{S_3^2}$
Total	$(1) = n \frac{\sum_{it} x_{it}^2 - (\sum_{it} x_{it})^2}{n}$	$n - 1$		

For SiO_2, Al_2O_3, Fe_2O_3, FeO, MgO, CaO, Na_2O, K_2O, H_2O^+, TiO_2, and MnO the null hypothesis that no significant difference exists between the means for the various metamorphic facies was rejected at all levels of significance (Table 3). For CO_2 and P_2O_5 the null hypothesis was rejected at the 0.05 level of significance but not at the 0.025 level.

The implication of these results is that the values for oxides in each of the five metamorphic facies cannot be considered to have come from the same populations, which would have equal means. There are several possible explanations.

NATURE OF THE CHEMICAL TRENDS REVEALED

To facilitate observation and interpretation of the apparent chemical trends revealed, the means of the analyses for each facies were plotted graphically. It is not possible to arrange the five facies considered into a single series in which both pressure (P) and temperature (T) increase progressively, so the results were plotted on two graphs (Figs. 1, 2).

Turner and Verhoogen (1960) suggested the following P-T ranges for the five metamorphic facies considered :

greenschist facies	300-500°C, 3,000-8,000 bars
glaucophane schist facies	300-400°C, very high P
almandine amphibolite facies	550-750°C, 4,000-8,000 bars
granulite facies	700-800°C, few thousand bars to very high P.
eclogite facies	400-700°C, 5,000-13,000 bars.

Using these values, the five facies were arranged into two series one increasing consistently in P (but not necessarily in T), and one increasing consistently in T (but not necessarily in P). These are :

(i) increasing P -

greenschist - almandine amphibolite - granulite-
glaucophane schist - eclogite

(ii) increasing T -

glaucophane schist - greenschist - almandine -
amphibolite - eclogite - granulite.

In plotting the graphs, the five facies have been plotted at arbitrary regular intervals along the axis. This is legitimate as the points on the increasing P graph are not independent of T, and vice versa, so the resultant curves can yield only qualitative information, and the absolute slope of the curve between adjacent control points is not important. Furthermore, the P-T conditions prevailing in the various facies belong to ranges which, especially in the case of P, are broad and not confidently or rigidly defined. From figs 1 and 2 it can be deduced that

SiO_2 tends to decrease in abundance with increasing P, but this trend is inhibited by increasing T;

Al_2O_3 tends to increase in mean abundance with increasing T, but increasing P opposes this;

TABLE 3.

ANALYSIS OF VARIANCE OF CHEMICAL ANALYSES OF REGIONALLY METAMORPHOSED ROCKS.

	Source of Variation	Sum of Squares	Degrees of Freedom	Variance	F
SiO_2	Among Facies	7348.60	4	1837.2	
	Within Facies	111173.20	741	150.4	12
	Total	118521.80	743		
Al_2O_3	Among Facies	959.19	4	239.8	
	Within Facies	16186.19	726	22.3	11
	Total	17145.38	730		
Fe_2O_3	Among Facies	487.43	4	121 .9	
	Within Facies	7699.10	691	11.1	11
	Total	8186.53	695		
FeO	Among Facies	448.96	4	112.2	
	Within Facies	7340.44	688	10.7	11
	Total	7788.40	692		
MgO	Among Facies	1272.27	4	318.1	
	Within Facies	12403.45	737	18.6	17
	Total	13675.72	741		
CaO	Among Facies	3009.42	4	752.4	
	Within Facies	23719.70	759	31.3	24
	Total	26729.12	763		
Na_2O	Among Facies	31.86	4	8.0	
	Within Facies	1510.60	756	2.0	4
	Total	1542.46	760		
K_2O	Among Facies	396.79	4	99.2	
	Within Facies	2035.99	737	2.8	35
	Total	2432.78	741		
H_2O^+	Among Facies	394.37	4	98.6	
	Within Facies	857.56	532	1.6	61
	Total	1251.92	536		
CO_2	Among Facies	699.65	4	174.9	
	Within Facies	18347.42	272	67.5	2.6
	Total	19047.07	276		
TiO_2	Among Facies	14.91	4	3.7	
	Within Facies	496.68	683	0.7	5.1
	Total	511.59	687		
P_2O_5	Among Facies	0.365	4	0.091	
	Within Facies	21.888	592	0.037	2.5
	Total	22.253	596		
MnO	Among Facies	0.391	4	0.098	
	Within Facies	12.832	617	0.021	4.7
	Total	13.223			

Critical F values from Table 5 of Crow, Maxfield and Davis (1960)

Significance level	$F(f_1=4,\ f_2=120)$	$F(f_1=4,\ f_2=\infty)$
0.10	1.99	1.94
0.05	2.45	2.37
0.025	2.89	2.79
0.010	3.48	3.32
0.005	3.92	3.72

FeO tends to increase in mean abundance with increasing P, but this trend is inhibited by increasing T;

Fe_2O_3 tends to decrease in mean abundance with increasing T, but this trend is inhibited by increasing P;

Total Fe tends to increase in mean abundance with increasing P, but increasing T inhibits this;

CaO and MgO show very similar trends, and tend to increase in mean abundance with increasing P. The trend is inhibited by increasing T;

Na_2O tends to decrease in mean abundance with increasing T, but to increase with increasing P;

K_2O tends to decrease in abundance with increasing P, but increasing T inhibits this;

H_2O decreases with both increasing P and increasing T;

TiO_2 tends to increase in mean abundance with increasing P, but increasing T inhibits this;

and MnO tends to decrease in mean abundance with increasing T, but increases with increasing P.

Thus, it appears that bulk chemical reorganisation of the crust does proceed during the mineralogical reorganisation accompanying metamorphism. As would be expected, pressure and temperature have opposing effects on the stable distribution of the individual elements, because high pressure favours the formation of dense mineral phases, but high temperature favours low-density phases. The common trends of progressive regional metamorphism (greenschist facies - amphibolite facies - granulite facies; and greenschist facies - amphibolite facies) appear to lead to basification in the highest grades relative to the lowest.

SiO_2, K_2O, H_2O, and Fe_2O_3, especially, are relatively decreased in the highest grades, and CaO, MgO, TiO_2, and FeO are relatively enriched. The other major oxides show less consistent variation.

Some doubt is cast on the validity of the inferences drawn from this statistical study by the possibility of crustal evolution with time (the most highly metamorphosed rocks exposed by erosion are usually also the oldest), and by the probability of sampling bias introduced by the frequency of investigation of abnormal rock types. Nevertheless, the trends implied by this study are in accord with the results of Ramberg's regional sampling study at Isortoq, and, if increasing grade of metamorphism is accepted as being very approximately a reflection of depth of burial, then the distributions deduced in this study also agree generally with the theoretical distributions deduced from thermodynamics. They are also in general accord with results by Eade et al. (1966) on a regional geochemical sampling programme of metamorphic rocks in Canada.

BEHAVIOUR OF TRACE ELEMENTS

As it seems that the major and minor rock forming elements are redistributed during regional metamorphism, it is probable that trace elements will undergo redistribution also.

Shaw (1952) studied the distribution of Tl with metamorphic grade in pelitic rocks from Dutchess County, New York. The rocks studied were representative of the chlorite, biotite, staurolite, and sillimanite zones of metamorphism, and were thought to have been metamorphosed isochemically with regard to major and minor elements. The results indicate that Tl increases with increasing grade of metamorphism in pelitic rocks. However, the distribution of Tl found by Shaw (1952) in rocks from Greenland indicates that Tl decreases in abundance in going from amphibolite to granulite facies. (Tl probably replaces K in silicate minerals).

Higazy (1952) studied the behaviour of many trace elements in skarn rocks and mica schists of the Malin Head district, Ireland, considered by Holmes & Reynolds (1947) to be metasomatically transformed epidiorite and quartzite, respectively. He found that the distribution of trace elements follows that of the major elements for which the traces can substitute. Rb and Ba, and probably Pb and Ag, follow the distribution of K. Sr and Y follow Ca and probably K. Ti, Cr, Ni, Co, V, Cu, Sc, Sn, and Mo follow Mg, Fe^{2+}, and Fe^{3+}. Ga follows Al.

Shaw (1954) examined the distribution of Ga, Cr, V, Li, Ni, Co, Cu, Sc, Zr, Y, Sr, Pb, Be, Mo, Sn, La, Ag, and Ba in 63 samples of the pelitic Littleton Formation of New Hampshire, representing all grades of metamorphism from shale to sillimanite gneisses. Most elements seemed to remain constant during metamorphism, but Ni and Cu appeared to decrease slightly and Li and Pb showed a well defined increase. The increase in Li and Pb is concomitant with K metasomatism.

DeVore (1955) working from analyses of individual minerals of various metamorphic facies concluded that conversion of one metamorphic assemblage to another would require redistribution and fractionation of both major and minor elements. For example, he predicted that metamorphism of a hornblendite from epidote amphibolite facies to granulite facies could release Cr, Ni, Cu, and Mg, and retrogressive metamorphism of a granulite facies hornblendite to an epidote amphibolite facies rock could release Pb, Zn, Ti, Mn, and Fe. Such apparent changes in trace element tolerance of rocks in going from one metamorphic facies to another provide a possible source of ore-forming elements in metamorphic terrains.

Engel and Engel (1958) published trace element as well as major element distribution from their studies of progressive metamorphism and granitisation of the major paragneiss of the north-west Adirondack Mountains, New York. With increasing grade of metamorphism in the least altered gneiss there is an increase in Cr, Ga, Ni, and V, together with Al, Fe^{2+}, total Fe, Mg, and Ca, and a decrease in Ba, together with K, Si, Fe^{3+}, and H_2O. Granitisation of parts of the gneiss of this region is accompanied by progressive increase in Ba and Pb, together with K, and a decrease in Co, Cr, Ni, Sc, Sr, Ti, V, and Y, together with Ti, Fe^{2+}, Fe^{3+}, Mg, Ca, and H_2O.

Overstreet (1960) examined monazite in relation to the metamorphic grade of its host rocks, and found both that monazite becomes increasingly abundant with increasing grade of regional metamorphism, and that the ThO_2 content of the monazite increases with increasing grade, ranging from about 0.5% ThO_2 in phyllites to 10-12% in granulites.

These results indicate two important points relating to the behaviour of trace elements during regional metamorphism. Firstly, the trace elements in metamorphic rocks tend to be distributed in sympathy with the major elements for which they can substitute (Hiyazy, 1952; Shaw, 1954; Engel and Engel, 1958). Secondly, the tolerance of particular minerals for the substitution of specific trace elements seems to be different in different metamorphic grades (Shaw, 1952; deVore, 1955; Overstreet, 1960).

Whether the trace elements are undergoing merely a redistribution along with the major elements, or whether they are being expelled because of decreased tolerance for them in the new metamorphic mineral assemblage, metamorphism theoretically could lead to generation of economically significant concentrations of specific trace elements provided some mechanism of localisation is operative.

In the case of lithophile trace elements, redistribution would be governed by the availability of suitable lattice sites in the common rock-forming minerals. Concentrations of lithophile trace elements are possible in rocks enriched in the particular major elements for which a lithophile element will substitute.

Typically, chalcophile and weakly lithophile trace elements also would redistribute themselves diffusely in suitable lattice sites of the common rock-forming minerals. However, if these elements encountered a source of S during redistribution, their ultimate distribution would be modified drastically because of their high affinity for S, new mineral phases would appear, and an orebody perhaps would result. Such a mechanism is one possible explanation of some metal sulphide deposits located in metamorphosed sediments stratigraphically associated with greenstones. Perhaps the chalcophile elements from the basic volcanic rocks were localised by adjacent sulphur-rich shales and limestones during metamorphism.

REDISTRIBUTION OF ELEMENTS BY CONTACT METAMORPHISM

Much of the preceding material presents indirect or partly subjective data. An attempt has been made to obtain some direct evidence by choosing single sedimentary rock units, reasonably presumed to have been fairly homogeneous before being progressively metamorphosed. This is the best method of approaching the problem, but it presents practical difficulties. Regional metamorphic isograds typically roughly parallel stratigraphy, so that it is difficult to locate a single stratigraphic unit which traverses several metamorphic facies. Secondly, regional metamorphic facies commonly extend over distances of miles, and this frequently poses a problem in confident recognition of a given stratigraphic horizon for sampling purposes, and so always casts serious doubt on any assumption of initial homogeneity of the unit, as depositional facies changes are very likely when dealing with distances of the order of a mile. Consequently, resort has been made to the special case of contact metamorphism in which situation it is not so difficult to locate transgressive relationships, and the changes involved are telescoped into distances which pose lesser problems in identification of the chosen unit, and in any assumptions of initial homogeneity.

Two suitable examples in the Canberra 1:250,000 Sheet area, one adjacent to the Jerangle granite, and one adjacent to the Urialla Granite, have been sampled, and subjected to extensive chemical examination.

THE JERANGLE GRANITE

Field Relationships.

At the northernmost tip of the Jerangle granite complex, about 8 miles south of Captain's Flat, N.S.W., steeply dipping Ordovician metasedimentary rocks strike towards the granite contact at a high angle. At this locality the contact is abruptly discordant, and the Ordovician rocks are hornfelsed up to about 100 yards from the granite. A single pelitic unit cropping out fairly continuously away from the granite for 300 feet was chosen for sampling. The unit is about 4 feet thick and nearly vertical, and strikes at 335° (Fig. 3). Three samples were collected within each 25-foot interval along strike for the first 100 feet, then 3 samples within each 50-foot interval for the next 200 feet. The location of the samples within each measured interval was determined largely by the availability of fresh rock.

Petrography.

The granite : The granite adjacent to the area sampled is a massive fine- to medium-grained leucocratic granite containing minor chloritised biotite. Its junction with the country rocks is abrupt.

The hornfels : The rocks nearest the igneous contact are entirely recrystallised to very fine-grained chlorite, muscovite, sericite, biotite, quartz, and opaque ores. The maximum grainsize is about 0.2 mm, but the typical size is less than 0.05 mm. Microscopically, the rock has a patchy appearance resulting from ovoid patches, about 0.3 mm in long diameter, of chlorite, sericite, muscovite, and quartz set in a matrix dominated by biotite and chlorite. The chlorite, sericite, and muscovite flakes within these ovoid patches display a preferred orientation parallel to the elongation of the patches. Subparallelism of the long axes of the ovoids themselves imparts a crude foliation to the rocks. The quartz grains are mildly strained. Most sections contain a few grains of greenish tourmaline.

No mineralogical changes were detected in the rock unit over the 300 feet sampled. However, unlike those nearest the igneous contact, the samples collected some distance away contain relict detrital quartz grains about 0.3 mm across. In outcrop the rocks closest to the igneous contact are dense, dark, and much more resistant to weathering than those progressively farther from the contact. The particular pelite unit sampled is not exposed outside the granite aureole, but comparable pelitic units typically consist of detrital quartz set in a schistose matrix of fine chlorite and sericite; brown biotite is rarely observed.

The petrography of the hornfels is summarized in Table 4.

Chemical composition.

Ten selected samples - one from each group of three samples - were analysed for major elements by the Australian Mineral Development Laboratories. The results are shown in Table 5 (a). All 24 samples covering the 300 feet sampled were analysed for trace elements; the results are given in Tables 5 (b), (c), and (d).

TABLE 4.

Modal Analyses of Hornfels adjacent to Jerangle Granite

Spec No.	chlorite	Biotite	Quartz	Opaque	Tourmaline	Muscovite and sericite
66420078	51.7	19.2	23.0	1.3	0.1	4.7
66420079	55.6	17.2	12.6	3.2	0.1	11.3
66420080	49.4	27.6	10.7	1.9	0.1	10.3
66420081	50.5	16.4	7.4	1.6	0.0	24.1
66420082	51.6	31.2	9.5	2.0	0.1	5.6
66420083	41.6	23.6	7.2	3.5	0.2	23.9
66420084	52.9	22.6	11.5	1.6	0.4	11.0
66420085	68.3	16.8	7.0	2.1	0.1	5.7
66420087	28.3	17.1	42.9	0.5	0.2	11.0
66420088	47.4	25.0	17.1	0.9	0.3	9.3
66420089	38.8	24.6	6.5	1.4	0.3	28.4
66420090	54.5	20.0	12.0	5.8	0.1	7.6
66420091	60.5	23.0	6.6	1.5	0.3	8.1
66420092	53.4	27.9	9.9	2.5	0.3	6.0
66420093	56.8	20.8	5.4	1.8	0.0	15.2
66420094	40.1	23.8	13.8	3.1	0.5	18.7
66420096	57.9	19.1	13.6	1.2	0.0	8.2
66420097	45.6	21.2	24.5	1.1	0.3	7.3
66420098	34.4	18.3	10.5	2.3	0.1	34.4
66420100	45.5	25.3	7.2	1.5	0.0	20.5
66420101	62.8	23.8	8.6	1.0	0.2	3.6

TABLE 5

ANALYSES OF JERANGLE HORNFELS

(a) Silicate Analyses - Australian Mineral Development Laboratories

	6642 0079	6642 0080	6642 0084	6642 0088	6642 0090	6642 0092	6642 0095	6642 0096	6642 0098	6642 0101
SiO_2	59.5	57.3	58.9	59.5	56.9	55.8	54.0	56.8	58.9	55.0
Al_2O_3	19.7	20.9	19.6	19.2	20.6	21.2	21.8	20.7	19.7	21.9
Fe_2O_3	0.46	1.40	0.82	1.40	0.85	1.44	1.33	1.60	1.90	2.20
FeO	5.45	4.45	5.65	5.05	5.65	5.15	5.60	4.80	4.30	4.30
MgO	3.15	3.00	3.25	3.25	3.40	3.25	3.40	3.10	3.00	3.05
CaO	0.29	0.14	0.17	0.14	0.16	0.14	0.17	0.14	0.17	0.19
Na_2O	0.45	0.32	0.33	0.31	0.28	0.67	0.36	0.36	0.29	0.47
K_2O	5.75	6.40	5.85	5.35	6.60	6.55	7.20	6.40	5.80	7.00
H_2O+	3.75	3.95	3.85	3.95	3.90	4.00	4.10	4.10	4.00	4.00
H_2O-	0.35	0.79	0.41	0.56	0.38	0.48	0.44	0.64	0.60	0.75
CO_2	0.06	0.06	0.06	0.01	0.07	0.03	0.28	0.38	0.04	0.06
TiO_2	0.81	0.73	0.70	0.72	0.67	0.77	0.80	0.70	0.71	0.75
P_2O_5	0.14	0.15	0.16	0.17	0.15	0.17	0.16	0.15	0.16	0.14
MnO	0.04	0.04	0.04	0.05	0.04	0.05	0.04	0.04	0.06	0.04
S	0.25	0.04	0.09	0.03	0.14	0.04		0.03	0.09	

(b) Semi-Quantitative Spectrographic Analysis (ppm) - Australian Mineral Development Laboratories

Sample No.	Sn	Bi	W	Mo	B	Li
66420078	6	2	20	1	25	200
9	10	3	"	2	30	200
80	4	2	"	1	10	100
1	10	3	"	2	20	200
2	8	3	"	1	3	150
3	10	3	"	2	15	100
4	10	2	"	1	25	200
5	10	2	"	2	25	200
6	10	3	"	2	40	100
7	8	3	"	1	20	100
8	20	3	"	2	20	200
9	8	3	"	1	25	200
90	6	3	"	1	25	200
1	6	2	"	1	25	200
2	10	3	"	2	25	200
3	8	3	"	2	40	100
4	10	4	"	2	30	200
5	10	2	"	1	25	150
6	10	3	"	2	30	150
7	5	3	"	3	40	50
8	8	3	"	1	50	200
9	6	3	"	2	10	100
100	8	2	"	1	20	150
66420101	10	3	"	1	40	150

(c) Atomic Absorption Analyses (ppm) -
Australian Mineral Development Laboratories

Sample No.	Pb	Zn	Co	Ni	Cd
66420078	99	134	15	40	<1
9	113	88	12	40	<1
80	54	132	18	45	<1
1	54	122	11	38	<1
2	142	161	15	51	<1
3	46	82	8	25	<1
4	113	111	8	35	<1
5	52	73	11	45	<1
6	59	70	6	29	<1
7	52	88	8	32	<1
8	82	103	11	40	<1
9	25	117	14	45	<1
90	109	115	15	45	<1
1	109	101	11	38	<1
2	25	71	11	32	<1
3	34	73	6	29	<1
4	20	88	8	32	<1
5	118	80	11	32	<1
6	132	86	8	32	<1
7	25	55	11	23	<1
8	25	91	11	25	<1
9	76	58	8	17	<1
66420100	59	132	15	38	<1
101	63	174	11	45	<1

(d) Spectrophotometric Analyses -
Australian Mineral Development Laboratories

Sample No.	% P
66420078	0.037
9	0.049
80	0.034
1	0.039
2	0.038
3	0.039
4	0.042
5	0.051
6	0.046
7	0.025
8	0.046
9	0.045
90	0.035
1	0.042
2	0.048
3	0.046
4	0.039
5	0.042
6	0.039
7	0.051
8	0.045
9	0.054
100	0.035
101	0.034

THE URIALLA GRANITE

Field Relationships

At the southern tip of the eastern mass of Urialla Granite a northerly trending ridge of Ordovician low-grade metasedimentary rocks (slate, sandstone, greywacke) intersects the granite contact nearly at right angles. The hornfelsed rocks have a low rubbly outcrop; their strike direction cannot be located with certainty, but measurements of the strike of slates to the east, outside the aureole, range from 015° to 365°. The crest of the ridge is flat, and so appreciable drift of rubble along strike seems unlikely. Samples of the hornfels on the ridge appear similar so a 10 feet wide strip was marked out in the estimated strike direction, and divided into seven intervals of 30 feet, commencing at the granite contact. Three samples were collected from each 10' x 30' area.

Petrography

Urialla Granite.

The Urialla Granite is a leucocratic medium-grained biotite granite which appears massive and fairly homogeneous. Its contacts with country rock are abrupt, but show no noticeable chilling.

Hornfels.

The rocks sampled are recrystallised fairly completely for about 120 feet from the contact, and partly recrystallized for about another 120 feet. In hand specimen the hornfels is a grey quartz-rich rock with some muscovite and chlorite. Narrow quartz veins are common. The hornfels grades outwards into grey labile sandstone. In thin section the most recrystallised samples exhibit a fine-grained allotriomorphic texture. Quartz ranges from 0.02 mm to 0.3 mm in mean diameter, and shows undulose extinction. Muscovite, much of which is strained, forms small laths, 0.02 to 0.1 mm in length, and sparse ragged porphyroblasts about 0.2 mm in diameter. Chlorite is ubiquitous. Both twinned and untwinned plagioclase is present. Opaque ores, brown biotite, tourmaline, and epidote are minor constituents. The least altered samples reveal a detrital texture partly modified by recrystallization. Many subangular quartz and feldspar grains about 0.3 mm in mean diameter are set in a fine matrix of quartz, chlorite, plagioclase, muscovite, and opaques. A few rounded siltstone fragments are present.

The modes of seven representative hornfels samples are presented in Table 6.

TABLE 6

Modal Analyses of Urialla hornfels

	Chl.	Qtz	Plag.	Musc.	Opaque	Biot.	Tourm.	Epidote
66420058	16.2	59.9	8.2	14.2	1.5	-	-	-
61	28.7	23.2	2.9	41.4	3.6	0.1	-	-
64	12.0	60.1	7.6	17.7	1.6	0.6	0.2	0.2
67	18.0	43.9	6.5	24.1	1.7	5.7	0.1	-
70	31.7	41.7	8.9	15.6	1.5	0.4	0.2	-
75	12.4	49.2	20.4	15.9	2.1	-	-	-
77	22.9	45.4	17.4	12.9	1.4	-	-	-

Chemistry.

Five representative samples of hornfels were analysed for major and minor elements, and all samples were analysed for selected trace elements. The results are presented in Tables 7a-e.

There are some unexplained discrepancies between duplicate analyses by Haldane (B.M.R.) and the AMDL (see graphical presentation, Figs 4a-c).

TABLE 7

Analyses of Urialla hornfels

(a) Major Oxides -
K. Bose,
Australian Mineral Development Laboratories

	66420 057	66420 060	66420 063	66420 071	66420 076
SiO_2	80.5	65.4	81.4	69.3	80.4
Al_2O_3	9.35	16.5	9.05	15.0	9.25
Fe_2O_3	0.84	0.85	0.35	0.58	0.50
FeO	1.93	4.50	2.30	3.75	3.15
MgO	1.33	3.40	1.31	2.70	1.56
CaO	0.21	0.07	0.28	0.18	0.21
Na_2O	1.16	0.65	1.83	1.05	1.13
K_2O	1.74	3.70	1.30	2.85	1.30
H_2O+	2.15	3.55	1.33	3.10	1.72
H_2O-	0.19	0.35	0.13	0.23	0.30
CO_2	0.03	0.06	0.05	0.18	0.09
TiO_2	0.49	0.74	0.45	0.69	0.47
P_2O_5	0.12	0.11	0.13	0.13	0.11
MnO	0.03	0.05	0.03	0.04	0.05
S	0.01	0.02	0.02	0.03	0.02

(b) Semi-quantitative spectrographic Analyses (ppm). - Haldane.

Sample No.	Ni	Co	Cu	Pb	Mo	V	Sr., Ca.
66420057	25	4	60	130	2	100	
58	25	6	60	180	3	130	
59	13	4	60	180	3	100	relatively
60	18	3	13	13	2	100	
61	18	4	25	18	3	80	low,
62	25	4	13	25	4	100	
63	18	4	13	25	4	100	
64	25	3	6	25	3	80	
65	18	3	4	25	3	80	
66	18	4	6	18	3	100	
67	25	6	10	10	3	100	
68	25	6	10	13	6	100	
69	30	8	13	13	3	130	
70	25	6	6	18	2	100	
71	18	4	13	13	2	100	
72	13	4	13	30	4	100	
73	13	4	10	13	4	100	
74	13	3	18	18	2	80	
75	25	6	13	13	2	80	decreasing
76	25	6	3	10	3	80	
77	25	6	10	10	3	80	

(c) SEMI-QUANTITATIVE SPECTROGRAPHIC ANALYSES - Australian Mineral Development Laboratories

Sample No.	Sn	Bi	Cr	V	W	Mo	Ba	B	Sr	Zr	Y	Ti	Li
66420057	40	1	40	15	<20	1	400	3	80	70	100	1500	20
8	80	2	60	100	"	2	1200	2	150	100	200	2000	20
9	60	2	120	20	"	3	120	2	80	<50	<100	500	30
60	150	2	100	150	20	2	1500	3	60	"	"	2500	50
1	120	2	100	25	<20	2	800	3	60	"	"	1000	20
2	70	3	100	60	"	3	800	5	150	"	"	1500	20
3	60	2	120	60	"	3	600	5	150	"	"	1200	20
4	40	2	100	30	"	2	600	5	60	"	"	700	20
5	50	1	100	30	"	3	600	5	80	"	"	700	20
6	25	2	100	25	"	2	600	15	50	"	"	700	50
7	20	2	100	25	"	2	800	20	80	"	"	700	5
8	20	1	100	25	"	2	600	10	80	"	"	700	25
9	250	2	120	25	"	3	800	12	100	"	100	1000	25
70	60	2	80	25	"	3	1000	15	200	"	200	1500	50
1	20	3	100	120	"	2	2000	20	300	150	200	1500	50
2	50	2	120	120	"	4	400	3	60	<50	150	800	20
3	40	2	120	40	"	2	500	5	100	"	150	1000	50
4	100	3	120	100	"	2	600	5	100	"	<100	1000	25
5	60	1	60	25	"	1	600	1	50	"	"	800	25
6	80	4	50	20	"	1	400	1	50	"	"	500	10
7	25	2	50	80	"	1	300	30	25	"	"	800	30

(d) Atomic Absorption Analyses -

Australian Mineral Development Laboratories

Sample No.	Pb	Zn	Co	Ni	Cu
66420057	76	42	6	19	11
8	76	60	6	17	19
9	89	34	6	17	7
60	194	81	6	23	17
1	46	60	6	17	23
2	24	67	6	23	13
3	142	46	6	25	17
4	29	53	6	23	7
5	58	43	6	23	7
6	20	21	6	19	11
7	58	21	6	13	11
8	24	22	6	13	15
9	222	50	6	25	19
70	46	49	6	19	11
1	104	45	6	13	13
2	66	48	6	13	10
3	46	27	6	10	10
4	128	27	6	13	15
5	46	29	6	17	7
6	46	27	6	17	7
66420077	38	67	6	29	15

(e)

Spectrophotometric Analyses - Australian Mineral Development Laboratories

Sample No.	% P
66420057	0.039
58	0.048
59	0.036
60	0.042
61	0.044
62	0.050
63	0.034
64	0.026
65	0.040
66	0.030
67	0.032
68	0.044
69	0.047
70	0.042
71	0.049
72	0.045
73	0.035
74	0.048
75	0.038
76	0.044
77	0.056

TABLE 8

SUMMARY OF SIGNIFICANT RESULTS

	JERANGLE					URIALLA				
	Mean Abundance Closest to contact		Mean Abundance Furthest from contact		Significance level of t test	Mean Abundance Closest to contact		Mean Abundance Furthest from contact		Significance level of t test
	%	ppm	%	ppm		%	ppm	%	ppm	
SiO_2	58.4		56.1		2%	75.7		74.8		)
Al_2O_3	20.0		21.1		1%	11.6		12.0		) Not
Fe_2O_3	0.99		1.69		5%	0.68		0.54		) Tested
K_2O	5.99		6.59		1%	2.27		2.07		)
H_2O^+	3.88		4.04		2%	2.34		2.41		)
B		22		30	2%		5		11	10%
Ni		39		32	5%		21		17	10%
Zn		107		94	N.S.		51		38	5%
Y		32		30	1%		NOT	ANAL.		
La		56		52	10%		NOT	ANAL.		

[redacted]

TABLE 8

a) RESULTS OF STATISTICAL TESTING OF CHEMICAL ANALYSES

	JERANGLE SAMPLES			URIALLA SAMPLES			
Constituent	mean Abundance Closest to contact	Furthest from contact	Significance level at which null hypothesis of t test rejected	Mean Abundance Closest to contact	Furthest from contact	Significance level at which null hypothesis of t test rejected	Source of data Tables:-
	% ppm	% ppm		% ppm	% ppm		
SiO_2	58.4	56.1	2%	75.7	74.8		5a, 7a
Al_2O_3	20.0	21.1	1%	11.6	12.0		5a, 7a
Fe_2O_3	0.99	1.69	5%	0.68	0.54		5a, 7a
FeO	5.25	4.83	N.S.	2.91	3.45		5a, 7a
MgO	3.21	3.16	N.S.	2.01	2.13		5a, 7a
CaO	0.18	0.16	N.S.	0.19	0.20		5a, 7a
Na_2O	0.34	0.43	N.S.	1.21	1.09		5a, 7a
K_2O	5.99	6.59	1%	2.27	2.07		5a, 7a
H_2O^+	3.88	4.04	2%	2.34	2.41		5a, 7a
H_2O^-	0.50	0.58	N.S.	0.23	0.27		5a, 7a
CO_2	0.05	0.16	N.S.	0.05	0.14		5a, 7a
TiO_2	0.73	0.75	N.S.	0.56	0.58		5a, 7a
P_2O_5	0.15	0.16	N.S.	0.12	0.12		5a, 7a
MnO	0.04	0.05	N.S.	0.04	0.05		5a, 7a
S	0.10	0.08	N.S.	0.02	0.03		5a, 7a

[redacted] (Table 8)

Constituent	mean Abundance Closest to contact %	ppm	Furthest from contact %	ppm	Significance level at which null hypothesis of t test rejected	Mean Abundance Closest to contact %	ppm	Furthest from contact %	ppm	Significance level at which null hypothesis of t test rejected	Source of data Tables:-
Sn		10		8	N.S.		70		66	N.S.	5b, 7c
Bi		3		3	N.S.		2		2	N.S.	5b, 7c
Mo		2		2	N.S.		2		2	N.S.	5b, 7c
B		22		30	2%		5		11	10%	5b, 7c
Li		163		155	N.S.		27		29	N.S.	5b, 7c
Pb		74		66	N.S.		75		75	N.S.	5c, 7d
Zn		107		94	N.S.		51		38	5%	5c, 7d
Co		11/34		10/31	N.S. N.S.		< 6		< 6		5c, 5e, 7d
Ni		39/45		32/41	5% N.S.		21		17	10%	5c,5e,7d
Cd		< 1		< 1							5c
P	0.041		0.043		N.S.	0.039		0.044		N.S.	5d, 7c
Cu		41		51	N.S.		13		12	N.S.	5e, 7d
Fe	4.6		4.6		N.S.						5e
Mg	1.6		1.6		N.S.						5e
Mn	0.033		0.029		N.S.						5e
Cr		10		108	N.S.		94		93	N.S.	5e, 7c
V		31		88	N.S.		52		55	N.S.	5e, 7c
Ti	0.366		0.396		N.S.		1230		936	N.S.	5e, 7c
Sr		51		60	N.S.		92		104	N.S.	5e, 7c
Ba		693		725	N.S.		722		727	N.S.	5e, 7c
Sc		16		16	N.S.						5e
Y		32		30	1%						5e
La		56		52	10%						5e
Zr		192		179	N.S.						5e

DISCUSSION

The chemical results were tested statistically for any significant differences between the samples closest to the granite contact and those farthest from it (i.e., between the highest and lowest grades of metamorphism). In the Jerangle example 9 of the 35 elements analysed yielded statistically significant differences in the means of the 12 samples closest to the granite contact compared with the means of the 12 samples farthest from the contact, when tested with the student's test (Crow, Davis and Maxfield; 1960). No statistically significant differences were detected in the modal data using the same test. In the Urialla samples, 3 of the 17 elements for which all samples were analysed yielded statistically significant differences between the means for the 10 samples closest to the contact and the 11 samples farthest from the contact.

The significant results are summarised in Table 8, along with the results for the equivalent constituents in the Urialla set of samples that have not been tested statistically because there are too few results. For 7 of the 8 constituents for which both sets of samples have been analysed, the pattern of variation is the same. Si, Ni, and Zn values are higher in samples close to the contact than in those away from the contact, and Al, K, H_2O+, and B are lower near the contact. In the Jerangle suite Y and Ca are also significantly higher in the specimens closest to the contact.

There are three possible explanations for these variations:

(1) They represent original variations in the sedimentary units.

(2) Exchange of material has taken place with the intruding granite magma.

(3) Original constituents of the sedimentary rocks have been redistributed in response to the thermal gradient imposed by the intrusive granite.

The first explanation is unlikely in view of the close similarity in the behaviour of the same elements in the two examples. Probably the true explanation lies in a combination of the second two alternatives, and the implication is that migration of material has taken place over considerable distances through solid metamorphic rocks.

CONCLUSIONS

Published studies and my own statistical study of published analyses indicate that notable changes in bulk chemistry of portions of the earth's crust are induced by regional metamorphism.

The fact that chemical migration can occur during metamorphism of rocks is supported by the two chemical studies of contact metamorphism that I have made.

Such mobilisation of elements would provide an opportunity for segregation of original trace elements into discrete mineral phases, which, under suitable localising influences, might form appreciable concentrations. Whether localisation is probable and what form it would take are problems yet to be studied.

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APPENDIX 1.

SOURCE OF CHEMICAL ANALYSES USED IN STATISTICAL STUDY OF REGIONAL METAMORPHISM

Greenschist Facies

Author		No. of analyses used
Banno	1964	11
Bayley	1955	5
Chapman	1952	2
Clarke	1915	78
Compton	1960	11
Henderson	1917	1
James	1955	24
Miyashiro	1958	7
Park	1918	1
Shagam	1960	5
Shaw	1956	5
Simonen	1953	9
Taylor	1955	17
Williamson	1939	15

Almandine Amphibolite Facies

Barker	1964	5
Buddington	1957	13
Chapman	1952	10
Choquette	1960	13
Clarke	1915	46
Crowder	1959	8
Engel and Engel	1953	6
Engel and Engel	1958	1
Evans & Leake	1960	33
Francis	1958	1
Friedman	1953	1
Green	1964	2
James	1955	3
Knopf & Jonas	1923	3
Leake	1958	17
Miyashiro	1958	12
Pitcher & Read	1960	10
Richey &Thomas	1930	4
Scotford	1956	9
Service	1937	6
Shaw	1956	11
Simonen	1953	55
Snelling	1958	7
Turner	1939	5
Wahlstrom & Kim	1959	12
Ward	1959	2
Weiss	1949	8
Wilcox & Poldervaart	1958	22
Wycoff	1952	22

Glaucophane Schist Facies

Author		No. of analyses used
Banno	1964	11
Bloxam	1959	4
Bloxam	1960	4
Borg	1956	4
Clarke	1915	2
Coleman	1965	3
Dengo	1950	5
Ghent	1965	10
Horikoshi	1965	4
Iwasaki	1963	12
Seki	1960	3
Suzuki	1952	15
Washington	1901	27

Granulite Facies

Compton	1960	4
Dearnley	1963	30
Green	1964	6
Kizaki	1965	8
Visser	1964	8
Ward	1959	4

Eclogite Facies

Alderman	1936	4
Angel	1957	4
Bloxam	1959	1
Briere	1920	11
Erdmannsdorffer	1938	1
Holway	1904	6
Lovering	1964	3
O'Hara	1960	2
Subramaniam	1956	10
Switzer	1945	3

Direct Reading Optical Spectrographic Analyses.*

* K.R. Walker, Bureau of Mineral Resources.
Fe, Mg, Mn, Ti in % : rest ppm.

Sample No.	Cu	Fe	Mg	Mn	Cr	Co	Ni	V	Ti	Si	Ba	Sc	Y	La	Zr
66420078	46	5.2	1.9	.038	124	22	46	97	0.42	50	740	19	37	62	232
79	43	4.7	1.8	.034	128	44	73	103	.45	61	790	18	30	54	182
80	57	5.2	1.9	.035	121	24	46	97	.40	61	960	18	32	64	168
81	49	4.8	1.7	.034	101	26	40	83	.37	56	770	17	32	60	178
82	37	4.6	1.5	.028	94	29	54	69	33	38	650	16	35	59	294
83	40	4.9	1.8	.033	116	36	56	98	40	49	790	18	30	51	159
84	62	5.2	1.7	.040	115	39	62	83	.40	52	710	17	32	52	187
85	39	4.7	1.7	.033	108	28	46	92	.39	59	810	18	33	57	175
86	21	2.5	0.86	.024	47	40	27	31	.20	47	278	11	35	61	239
87	28	2.9	1.0	.022	46	49	21	32	.20	31	373	10	29	50	229
88	35	5.1	1.8	.038	108	48	31	83	.40	58	750	17	32	52	193
89	31	4.9	1.7	.034	113	26	41	98	.43	47	695	17	29	53	172
90	46	5.5	2.2	.033	128	39	64	108	.44	58	860	18	30	44	155
91	29	4.5	1.5	.031	113	23	42	94	.40	56	750	17	29	60	185
92	50	5.2	2.1	.039	133	36	49	115	.52	70	865	18	29	48	168
93	44	4.7	1.9	.029	149	18	25	124	.48	100	1050	19	30	62	132
94	58	5.3	1.7	.028	96	26	38	81	.39	59	740	16	31	47	188
95	25	3.1	1.0	.025	56	46	27	41	.27	45	333	11	29	46	220
96	52	5.2	1.9	.026	110	21	39	90	.40	51	795	18	29	46	220
97	48	3.6	1.1	.021	68	33	32	46	.27	40	470	13	33	54	251
98	53	4.6	1.6	.025	115	34	61	98	.40	50	710	17	32	51	168
99	33	3.2	0.9	.020	51	36	26	38	.24	51	345	11	30	53	231
66420100	110	4.6	1.8	.029	130	30	34	113	.47	71	870	18	29	61	144
101	58	5.3	1.7	.026	150	24	55	112	.47	72	910	18	30	47	144

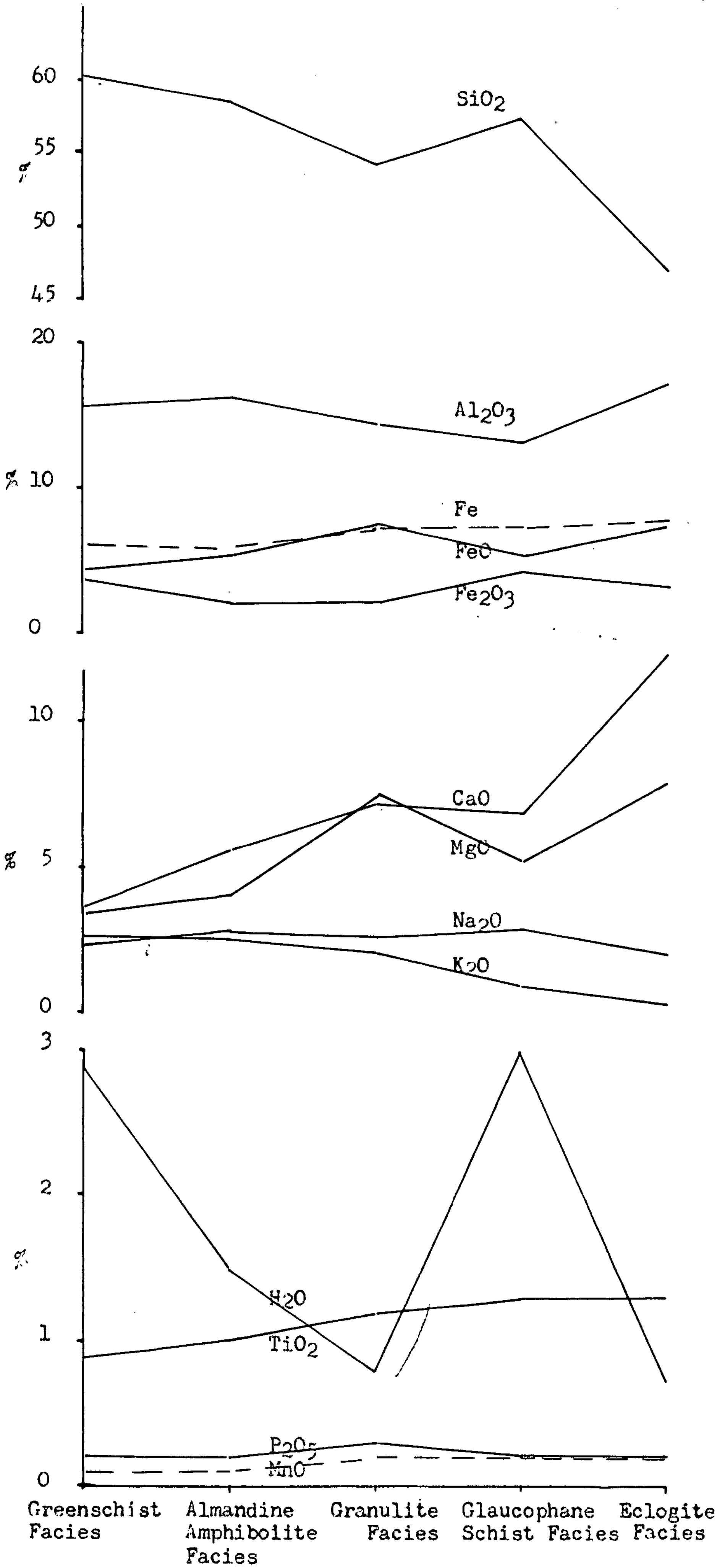

FIG.1 MEANS OF ANALYSES ARRANGED IN CONSISTENTLY INCREASING PRESSURE SERIES

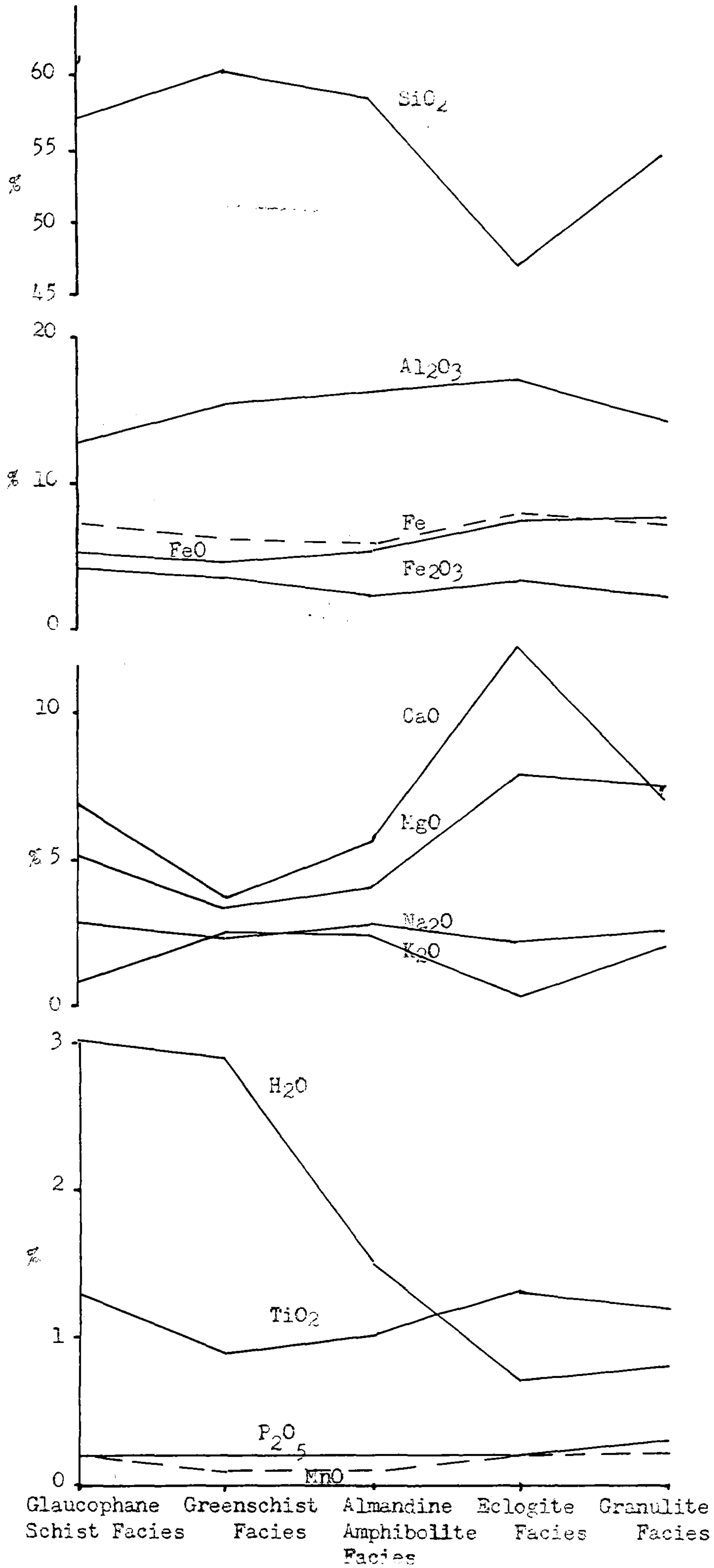

FIG.2 MEANS OF ANALYSES ARRANGED IN CONSISTENTLY INCREASING TEMPERATURE SERIES

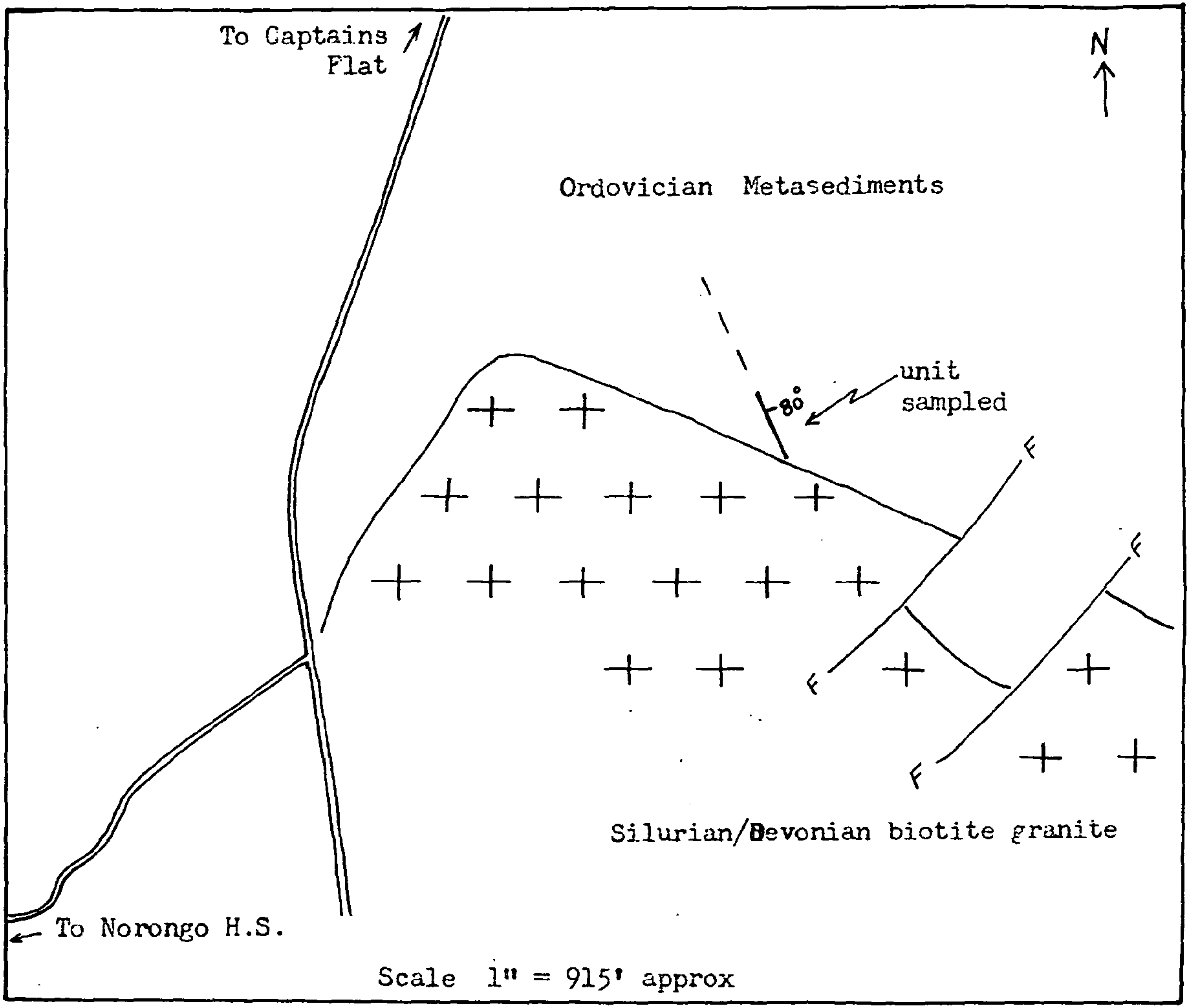

FIG. 3 FIELD RELATIONSHIPS OF JERANGLE SAMPLING AREA

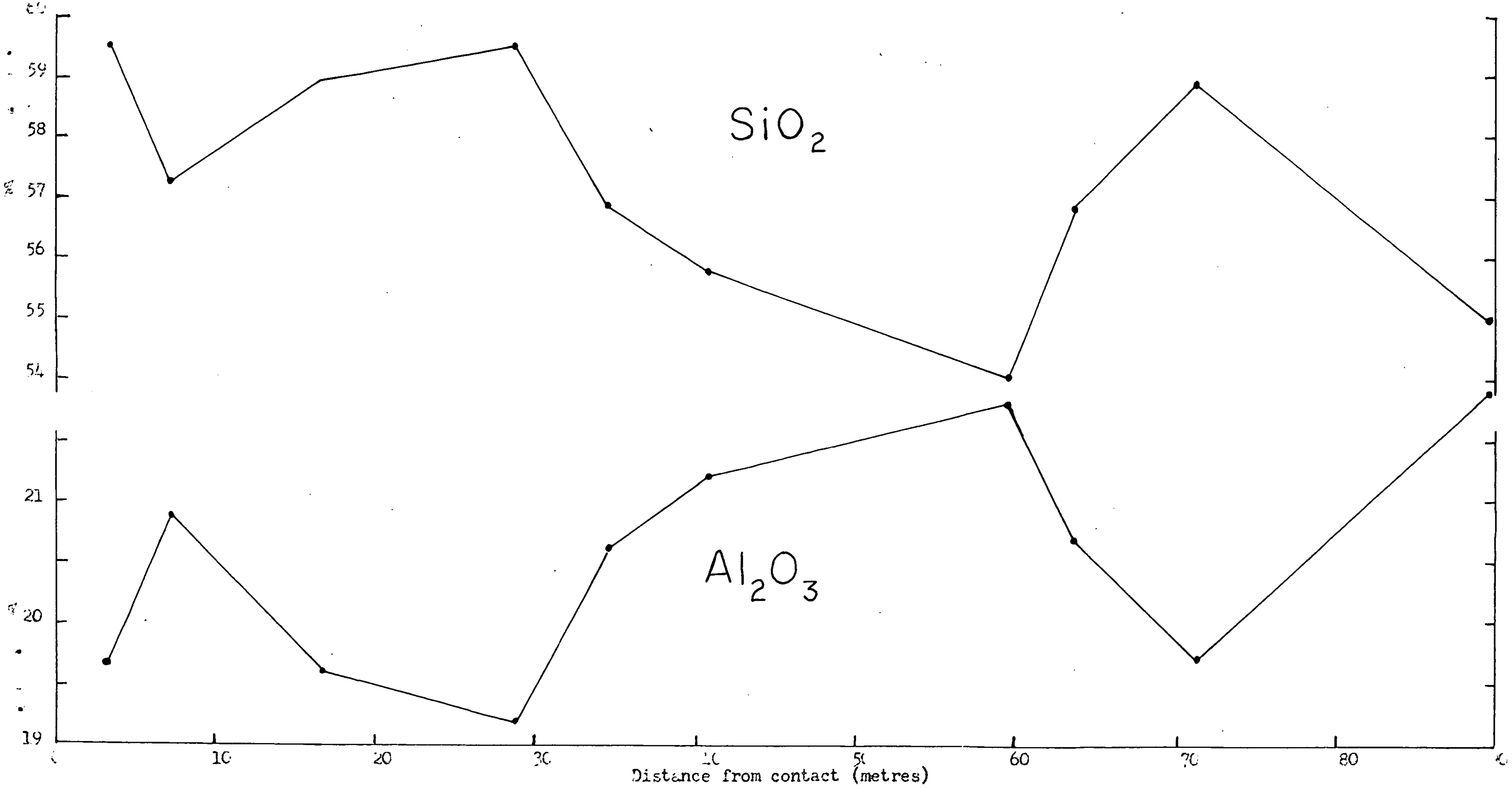

FIG 4a GRAPHICAL PRESENTATION OF SIGNIFICANT VARIATION IN THE JERANGLE HORNFELS

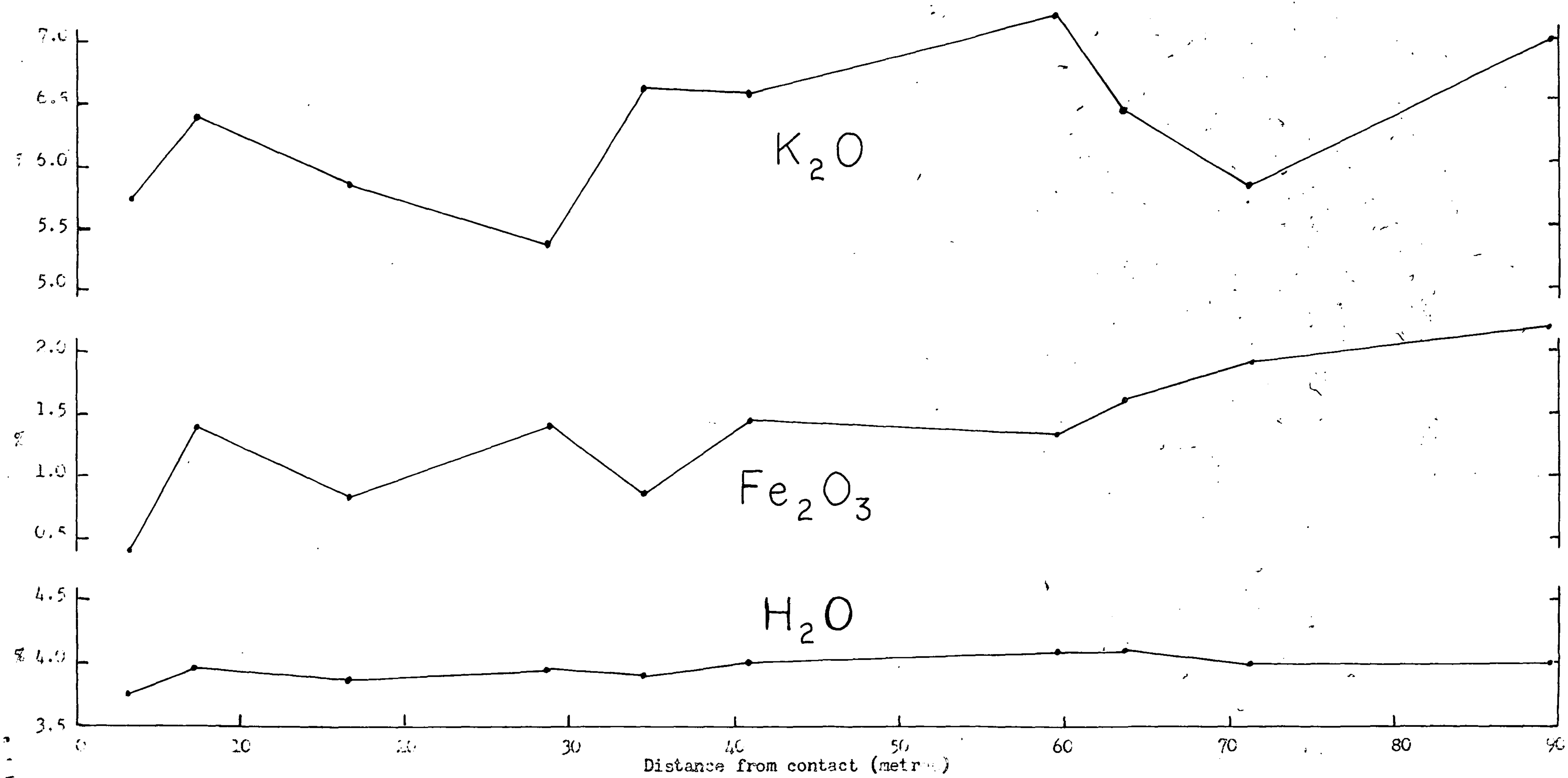

FIG 4b GRAPHICAL PRESENTATION OF SIGNIFICANT VARIATION IN THE JERANGLE HORNFELS

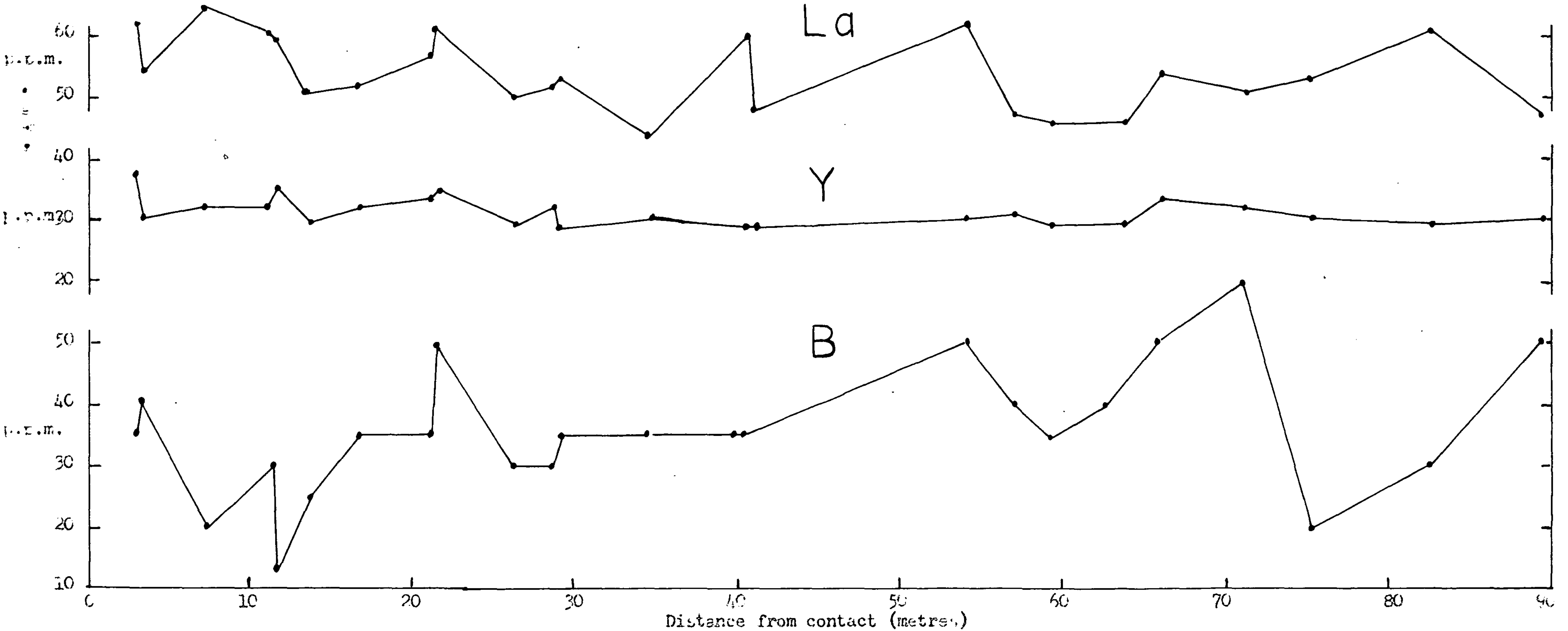

FIG.4c GRAPHICAL PRESENTATION OF SIGNIFICANT VARIATION IN THE JERANGLE HORNFELS

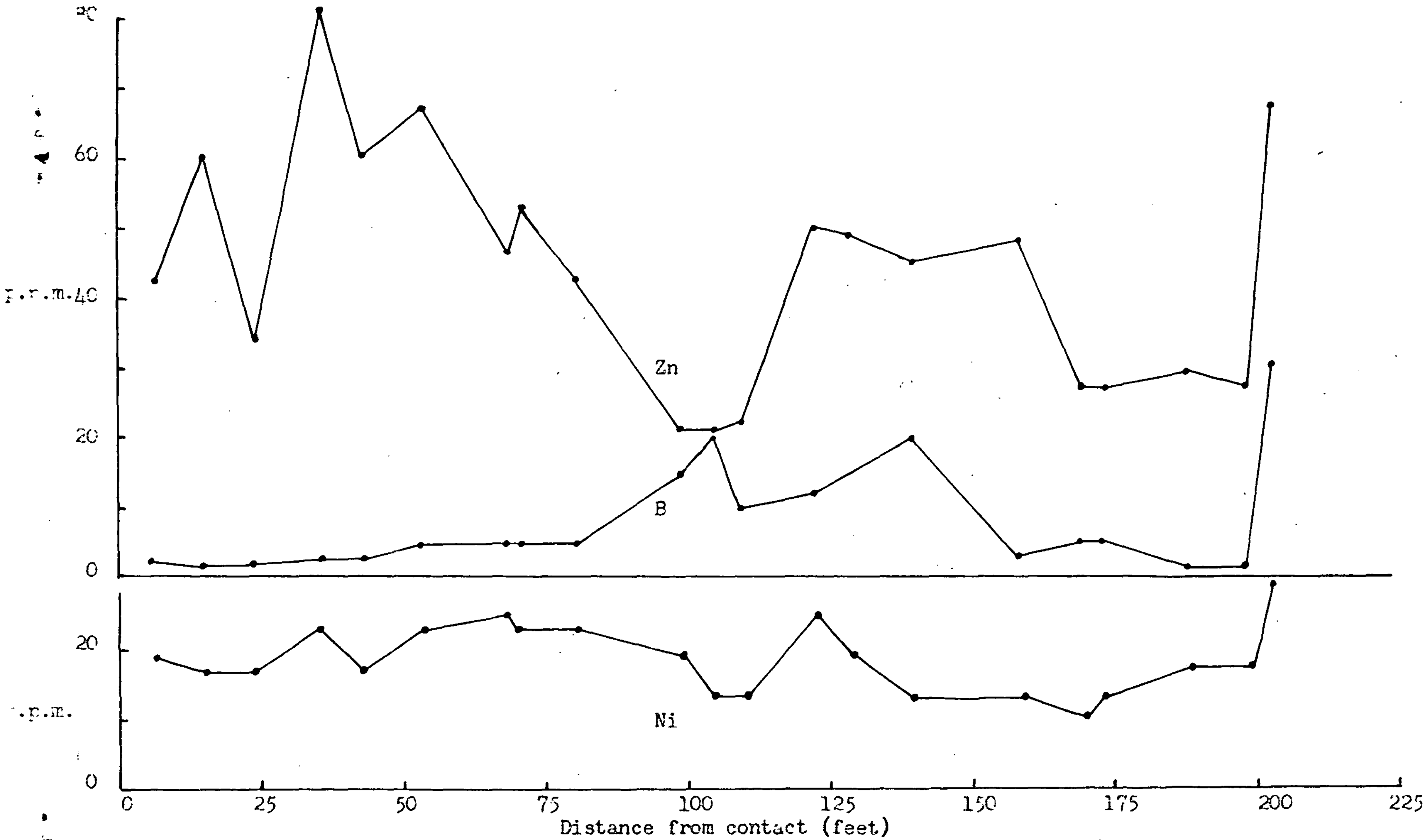

FIG.5 GRAPHICAL PRESENTATION OF SIGNIFICANT VARIATION IN THE URIALLA HORNFELS