SOME ASPECTS OF THE CHEMISTRY
OF THE BODMIN MOOR GRANITE

by

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Abstract

Attempts were made to sample the Bodmin Moor pluton, S. W. England, at grid intersections of a plan employing a 1.4 km spacing between grid lines. As a result of poor exposure the collection of material was extended to include sampling within a 0.5 km radius of the grid line intersections although even this could not be maintained at all the localities (circles about the grid intersections).

Major element determinations have been carried out on 34 samples, taken from three localities, to determine local and regional variations. Visual inspection reveals difficulties in locality classification of samples, although statistical analysis indicates a significant regional variation in FeO, CaO, Na_2O and K_2O.

Na, K, Li, Cu, Zn, Rb, Sr, Y, Zr, Sn, Cs, Ba, La, Ce, Nd, Pb, U and Th determinations have been carried out on 195 samples of granite and associated rock types collected, wherever possible, from the localities on the gridded sampling plan. Computerised process extraction techniques have been employed in the assessment of the analyses and the majority of elements are interpreted as following a "typical" igneous differentiation trend. The metallic elements and K, however, are considered to have been influenced by "post-magmatic" processes.

The Bodmin Moor granite is envisaged as having developed at a low crustal level and intruded at higher levels by passive upward emplacement and stoping. Subsequent tectonic activity, controlled by the regional setting of the S. W. England batholith, is regarded as having influenced the distribution of the metallic elements and K.

Contents

Introduction

The initial motivation for a geochemical study of the Bodmin Moor granite was multi-fold and whilst some of the original ideas were modified during the course of the research it is important that they should be recorded.

Previous work by Edmondson (1970) proposed a 'division' of the Bodmin Moor granite on the basis of differences in the structural state of the alkali feldspars and a logical continuation to this work was a verification, or contradiction, of the 'division' from chemical evidence. It was also hoped that the chemistry might lead to a better understanding of the history of the granite and its relationship with the other S. W. England plutons, as well as being of possible economic interest.

The Bodmin Moor granite is one of five, broadly similar major plutons and several smaller masses emplaced in the Upper Paleozoic sediments and basic rocks of S. W. England. The granites have been typified as post-kinematic high level plutons (Exley & Stone, 1964) of Hercynian age. Dodson & Rex (1971) give K-Ar dates of 260-280 my which equate with similar age figures quoted by Miller & Mohr (1964). Bott et al (1958), Bott & Scott (1964) and Bott et al (1970) have interpreted geophysical evidence as indicating that the granite masses form the surface expression of what is probably a continuous ridge of granite stretching from Dartmoor to the Scilly Isles. The axis of the gravity anomalies associated with the granites has also been shown, by Bott et al (1958), to closely follow the belt of mineralisation recognised by Hoskings (1950) as traversing the length of the Cornubian batholith.

A fairly comprehensive review of the geology of the S. W. England granites has been carried out by Exley & Stone (1964) and a summary of the previous research for the Bodmin Moor granite is given by Edmondson (1970). It is not intended, therefore, to re-iterate locality maps, history of research or details of petrography in this account as all are adequately covered in the previously mentioned summaries.

PART I

The Sampling Plan

As the results, from any survey, are no better than the data upon which they are based, it is essential to consider the criteria for judging the adequacy of the data before attempting to interpret them. In geochemical problems the investigator has some control over the analytical processes and evaluation of the results is basically dependent upon the validity of the sampling plan. Theoretically, therefore, the best assessment of regional chemical variation should be based on objective collection, preferably with some test of local variation, though in practice these requirements can rarely, if ever, be fully met.

For the Cornubian granites objective sampling is limited by poor exposure. Both Exley (1963), for the Bodmin Moor granite, and Booth (1966), for the Land's End granite, found that the outcrop pattern controlled hand specimen collection to the extent that a completely random sample could not be acquired. Similarly, surface relief is negligible when compared with the geophysical evidence for the granite depth (12 km, Bott & Scott, 1964) and, at its best, any interpretation of the results is only a reflection of the exposed part of the near-planar surface of the pluton. To what extent this can be extrapolated to the 3-dimensional form of the granite is a matter of personal reasoning.

Exley (1963) collected material from the Bodmin Moor granite based on a rectilinear grid having a 1.4 km (1500 yd) spacing, though irregularity of outcrop necessitated the collection of material from within a 0.5 km (500 yd) radius of the intersecting grid points (see

Fig. 1). It seemed logical to accept this gridding and attempt to carry out a similar sampling plan, particularly in view of Exley's (1963) statistical and economic considerations. During the course of collection, however, it became apparent that sampling on this grid could not be strictly adhered to and though in principle the ideals were maintained, sampling was inevitably controlled by outcrop distribution.

Although prior studies of major element chemical variability in igneous rocks (Baird _et al_, 1967; Morton _et al_, 1969) provided a general guide to sampling, a preliminary survey was considered appropriate for the Bodmin Moor granite in order to determine,

a) the variability in analyses of specimens from individual outcrops, i.e. optimum hammer collected sample size,
b) the variability in locality sampling, i.e. local variation,
c) the variability produced as a result of weathering.

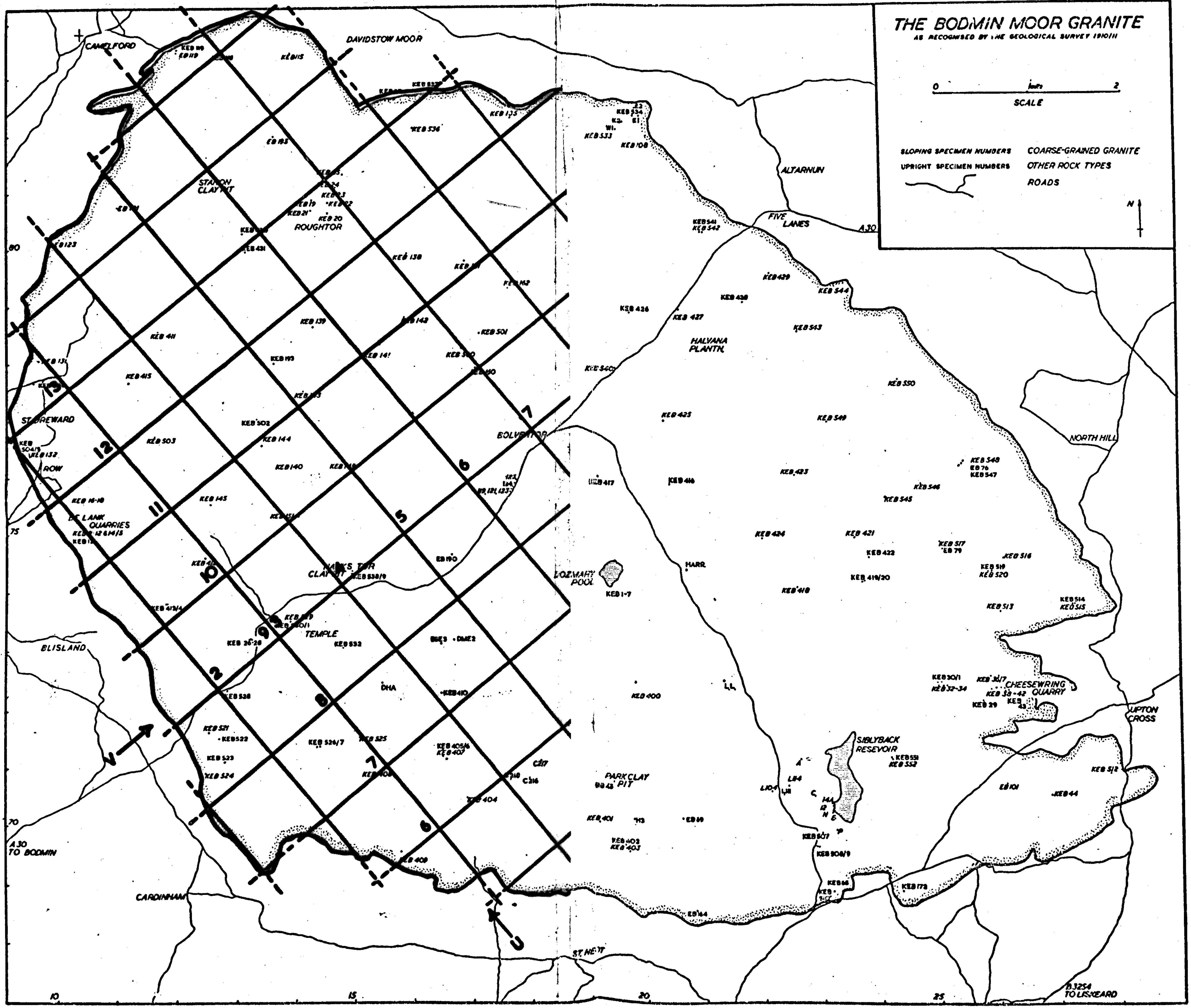
As a test four "circles" (subsequently to be termed "localities") were selected for initial sampling. These were the areas surrounding Dozmary Pool, De Lank Quarries, Cheesewring Quarry and Roughtor (see Fig. 1). These localities were considered not only to be areally representative but also to be a reflection of the various "divisions" of the Bodmin Moor granite that had been recognised by earlier workers (Reid _et al_, 1910, 1911; Ghosh, 1927; Edmondson, 1970).

Of the four localities, that at Dozmary Pool was somewhat of a failure in terms of exposure, there being only a small quarry to the south side of the pool. The quarry is important, however, for it represents the best exposure of Reid _et al's_ (1910, 1911) 'fine-grained granite'. Seven samples (KEB1-7) were collected from the quarry, the

__Fig.1__ __The Bodmin Moor granite__

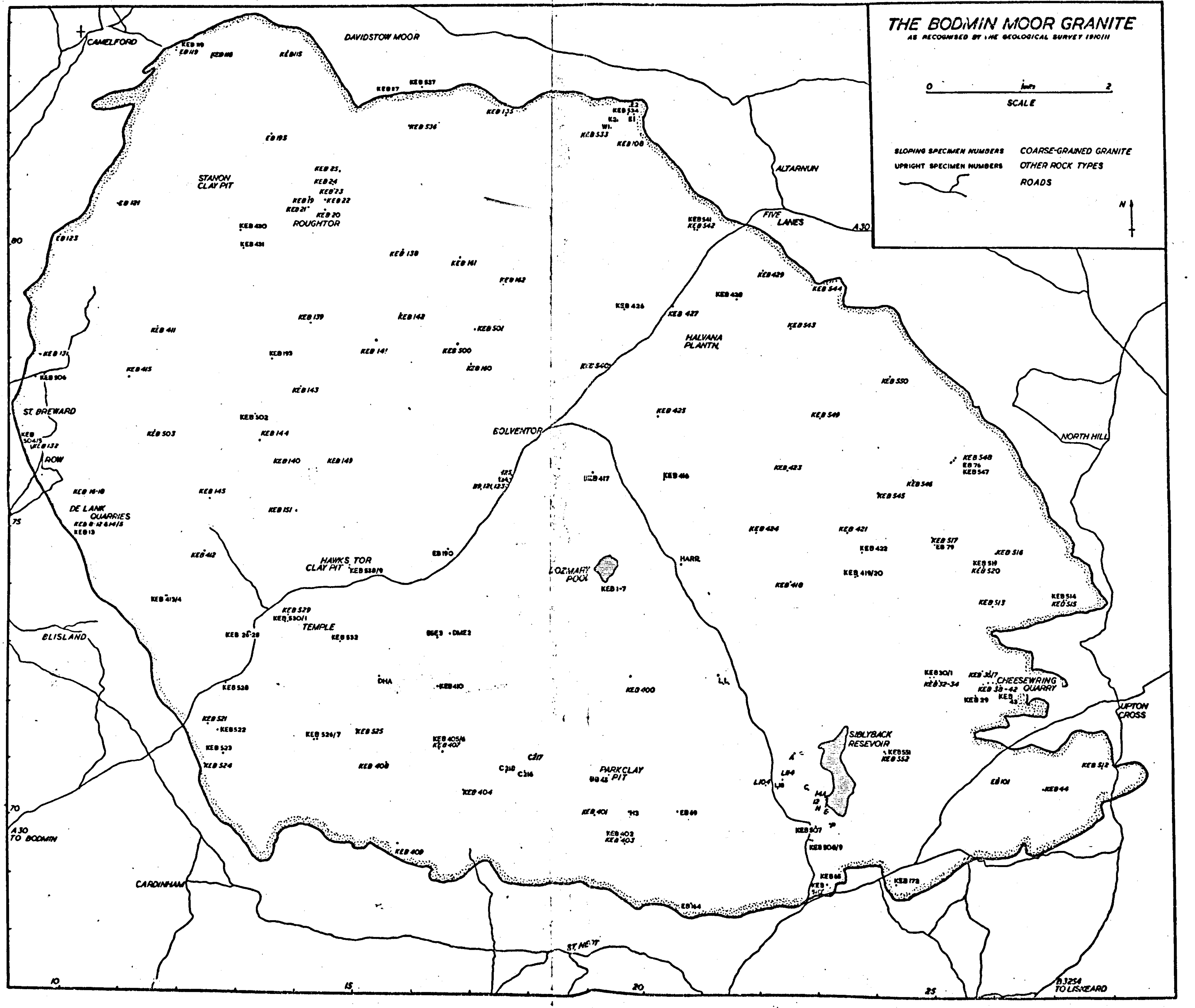
Specimen localities and partial overlay to explain the sampling grid and U, V co-ordinates.

(Some artistic amendment of overlay to overcome photographic distortion)



THE BODMIN MOOR GRANITE

AS RECOGNISED BY THE GEOLOGICAL SURVEY 1910/11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miles
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SCALE
SLOPING SPECIMEN NUMBERS
COARSE-GRAINED GRANITE
UPRIGHT SPECIMEN NUMBERS
OTHER ROCK TYPES
ROADS
N
CAMELFORD
DAVIDSTOW MOOR
ALTARNUN
FIVE LANES
A30
STANON CLAY PIT
ROUGHTOR
HALVANA PLANTN.
ST. BREWARD
BOLVENTOR
NORTH HILL
ROW
DE LANK QUARRIES
HAWKS TOR CLAY PIT
LOZMARY POOL
HARR
TEMPLE
BLISLAND
CHEESEWRING QUARRY
UPTON CROSS
SIBLYBACK RESEVOIR
PARK CLAY PIT
A30 TO BODMIN
CARDINHAM
ST. NEOT
B3254 TO LISKEARD
80
75
70
10
15
20
25
KEB 119
EB 119
KEB 118
KEB 115
KEB 117
KEB 537
KEB 135
KEB 534
KEB 533
KEB 108
KEB 536
EB 195
KEB 25
KEB 24
KEB 23
KEB 19
KEB 22
KEB 21
KEB 20
KEB 430
KEB 431
EB 121
EB 123
KEB 138
KEB 161
KEB 162
KEB 541
KEB 542
KEB 429
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KEB 139
KEB 142
KEB 501
KEB 411
KEB 131
KEB 193
KEB 141
KEB 500
KEB 160
KEB 540
KEB 415
KEB 506
KEB 143
KEB 550
KEB 502
KEB 425
KEB 549
KEB 503
KEB 144
KEB 504/5
KEB 132
KEB 140
KEB 149
KEB 417
KEB 416
KEB 423
KEB 548
EB 76
KEB 547
KEB 546
KEB 545
KEB 16-18
KEB 145
KEB 151
KEB 8-12 & 14/15
KEB 13
KEB 424
KEB 421
KEB 517
EB 79
KEB 516
KEB 422
KEB 412
EB 190
KEB 538/9
KEB 1-7
KEB 519
KEB 520
KEB 419/20
KEB 418
KEB 413/4
KEB 514
KEB 515
KEB 513
KEB 529
KEB 530/1
KEB 26-28
KEB 532
DME 3
DME 2
KEB 30/1
KEB 35/7
KEB 32-34
KEB 38-42
KEB 29
KEB 528
DHA
KEB 410
KEB 400
KEB 521
KEB 522
KEB 526/7
KEB 525
KEB 405/6
KEB 407
KEB 523
KEB 524
KEB 408
C 217
C 218
C 216
KEB 551
KEB 552
KEB 512
EB 101
KEB 44
KEB 404
KEB 401
KEB 402
KEB 403
KEB 507
KEB 508/9
KEB 409
EB 144
KEB 173

first five of these being spaced at 3 m intervals around the quarry and the remaining two being collected adjacent to a greisen vein. The specimens were all petrographically similar (Edmondson, 1970) and it was decided to analyse only KEB1/2 and 5 for major elements.

The De Lank Quarries area is marginal to the 'no microcline' and 'with microcline' divisions of the coarse-grained granites as recognised by Edmondson (1970). Specimens KEB8-12 were selected at 12 m intervals around the main quarry with KEB8, a large quarried block, coming from the base of the present workings (about 30 m depth). Other than KEB13, an elvan sample, the remaining specimens from the De Lank Quarries locality were taken from old workings to the N.W. of the main quarry (KEB14-16) and from the nearby Hantergantick Quarry (KEB17/18). Specimen KEB17 was taken from a surface exposure and KEB18 from the base of the main workings at about 30 m depth.

The Roughtor locality is representative of Edmondson's (1970) 'with microcline' coarse-grained granite. All the samples, KEB19-25, came from tor exposures.

The locality based on Cheesewring Quarry is included in Ghosh's (1927) 'normal granite' and Edmondson's (1970) 'with microcline' coarse-grained granite. The area also lies within the zone of mineralisation which follows the length of the S.W. England granites (Hosking, 1950). Of the material collected from the locality, however, KEB29 was the only specimen that could be regarded as mineralised, having been obtained from an old pit to the south of Cheesewring Quarry. KEB30-34 were taken from Goldiggings Quarry (Approx. $\frac{1}{4}$ km to the west of Cheesewring Quarry). The form of this quarry is like a figure of eight. At the linkage of the two circular quarry workings the rock appears quartz rich with an abundance of tourmaline crystals. Petrographically perhaps the most characteristic features are that orthoclase and plagioclase are present in almost equal proportions and tourmaline occurs as euhedral to subhedral bronzy pleochroic crystals, sometimes zoned, sometimes with blue pleochroic spots, and in proportions as much as four times as great as the coarse-grained granites from elsewhere in the quarry (see modal analyses, Table 4). The fact that this rock has not been quarried also suggests that it does bear some difference to the surrounding material. Further collecting, both in used and disused quarries, reveals that similar occurences of unworked rock often exhibit both unusual hand specimen and petrographic features. In fact, with only a little practice, it becomes quite easy to pick out "anomalous" rocks by observing the way in which the quarry has been worked. (Care must, however, be taken as the attraction of these features can be such as to mislead the collector from taking representative samples from the quarry.) Specimens were taken at 15 m intervals around Goldiggings Quarry and of these samples, KEB30 and 31 were from the vicinity of the "anomalous" linkage area. The relationship between the quartz and tourmaline rich granite and the coarse-grained granite is gradational and there appears to be no marked contact relationship. In fact it was thought on collecting, that KEB31 was representative of the coarse-grained granite and it was not until it was examined petrographically that it was found to be more comparable to KEB30 than the other specimens from elsewhere within the quarry. Other than KEB36 and 37 (from Stowes Hill Tor and Cheesewring Tor respectively) and one other exception, the remaining samples (KEB38-42) from the locality were collected at 15 m intervals around Cheesewring Quarry. The third exception, KEB43, represents the reddened, tourmaline veined, porphyritic potash feldspar rich rock of the quarry entrance.

The results of the major element chemical analyses of these samples is considered in Part II and the trace element analyses in Part III and suffice it to say now that further sampling, based on these results, was directed wherever possible to the collection of one large hand specimen from each of the "circle" localities based on the grid points of Fig. 1. A number of specimens from aplites, pegmatites and elvans were also collected when these rock types were encountered. In addition to the specimens collected by hammer a number of core samples were acquired from the East Cornwall Water Board (12, 14A, A, C, E, N, P), the Cornwall River Authority (C216, C217, C218, L104, L111, L114 - letter prefixes added personally to signify localities, L = Lamelgate, C = Colliford), Berk Ltd. (BSE3, H3, DME2, DHA), English Clays Lovering Pochin Ltd. (BB45) and The Institute of Geological Sciences (E1, E2, W1, K2). Six specimens, (117, 119, 121, 123, 124, 125), were collected from a road cutting at Minzies Down on the A30 road, this cutting being under construction during the period of sampling. Specimens with EB prefixes were kindly donated by Dr. C. S. Exley.

Each sample locality, with 'u' and 'v' co-ordinates, is recorded in the appendix and illustrated in Fig. 1. The samples are given an abbreviated rock type description based mainly on their field relationships and in some cases on petrographic features. Many of these prefixes are self-explanatory, for example Ap = aplite, Peg = pegmatite, Qv = quartz vein, FGG = fine-grained granite, CGG = coarse-grained granite. Of the remainder, WCGG (weathered), XCGG (contaminated), CCGG (kaolinised) MCGG (mineralised) and VCGG (veined) are somewhat loosely applied descriptions of the coarse-grained granite. "Altered" (ACGG) has been used for any rock which does not fall readily into any of the other groups and yet appears to deviate from the general description of coarse-grained biotite granite (Exley & Stone, 1964; Edmondson, 1970). In fact it is more than likely that all the rocks of the Bodmin Moor granite, if not all the S. W. England granites, could be described using one or more of these prefixes. Further discussion about these terms, and their appropriate usage, will be considered after presentation of all the chemical results though the use of the terms "weathered" and "contaminated" perhaps warrants further clarification.

In general "weathered" has only been applied to material which is very rotten and friable in the hand. Samples collected from tors rarely fall into this category. In some cases "contaminated" is undoubtedly a misnomer for, as will subsequently be shown, some specimens classified under this title have a chemistry intermediate between the coarse-grained and fine-grained granites rather than that which might have been expected from xenolithic material. No attempt has been made to amend the XCGG description and it should be borne in mind that there is some ambiguity in its use.

PART II

Major Element Chemistry

1) Variation in Composition

A) Some statistical considerations arising from the presentation of analyses as a constant sum

Prior to presenting the results of the major element chemistry of the Bodmin Moor granite and studying the possible variability, it is, perhaps, desirable that some consideration be given to the statistical interpretation of geochemical data. Some of the implications considered now will be referred to again throughout this work.

The major problem, both in the application of statistics and in visual inspection, with compositional data arises from the use of closed arrays in presenting results. Closed arrays are those in which the data from each sample has a fixed or constant sum, e.g. major element rock composition = 100%. In simple terms the problem can be expressed by considering a set of rock samples containing SiO_2, Al_2O_3 plus the remaining elements summed as one component. If any of these individuals remains fixed, say, the sum of the remaining elements, then any variation in SiO_2 will produce a variation in Al_2O_3 such that there is a perfect negative correlation between the two. This is not necessarily because of differences in geological processes but by the fact that the composition is expressed on an equal weight basis. By increasing the number of components the effect of the closed array is still present, albeit less pronounced.

Much of the work on the influence of closed arrays in geological studies has been considered by Chayes, and is summarised in Chayes (1971). To study induced correlations Chayes (Chayes & Kruskal, 1966;

Chayes, 1971) postulates a model in which an open array is defined having an equal number of variables to that of the closed array. The algebraic properties of the model allow the means and variances of the closed array to be obtained from the open array. If the calculated correlations from these means and variences differ from those observed from the original data, then it can be assumed that the element relationships are not merely a product of presenting the data as a constant sum. Certain limitations arise in the use of the model for which there is a marked deficiency of worked examples, not only by other authors but by Chayes himself.

The problem has also been considered by Vistelius & Saramonov (1961) who have shown that a known constant component among those being analysed can be used as a divisor of the other components to "open" the array, i.e. the sum of the components is no longer 100% but variable. In their study of ferromagnesium mica compositions they employed the oxygen content as a divisor, thus deriving the component correlation coefficients from the "opened" array. Miesch et al (1966) employed the SiO_2 content as their constant divisor in studies of the composition of tektites but preferred to consider the ratio produced as a property of the collected rock specimen rather than those of either an actual or a theoretical "open" system. Pearce (1968) has extended the use of the constant divisor, within certain limits, to include any independent constant within the system, regardless of whether it is an analysed component or not.

Whilst the effects of presenting data as a constant sum should not be ignored it is worth noting that Miesch et al (1966) found that the correlation coefficients produced by dividing throughout by SiO_2 varied little from those derived from the original data. Similarly

Webb & Briggs (1966) suggested in their use of principal component analysis to screen mineralogical data that the results of using uncorrelated variables did not vary appreciably from that obtained using the untransformed data.

In conclusion, therefore, whilst it appears logical to continue to present major element chemistry results, norms and modal analyses in the familiar terms of percentage proportions any implications with regard to component correlations should be treated with caution unless the data are transformed.

B) Variation in composition in specimens from individual outcrops

For quantitative analyses it is requisite that the rock specimen collected is of an adequate volume to include all the mineral phases in a proportion closely approaching that of the typical rock. These problems of variability in minimum sample volume and the influence of grain size on major element variation have been fairly comprehensively discussed by Baird _et al_ (1964, 1967a, 1967b) and Morton _et al_ (1969).

For the Lakeview Mountain tonalite, having a coarseness index of 15 - 28 (Chayes, 1956), Baird _et al_ (1967b) found that a 76mm (3") x 22mm ($\frac{7}{8}$") diameter core, weighing about 40g was satisfactory for suitably precise major element determinations. They also found that although the mean composition determined by analyses of a 2,000-3,000g hammer collected sample was not significantly different from the analyses determined from 76mm cores, there were greater differences in the means between sets of 2,000-3,000g specimens. This they attributed to additional errors arising from the inconvenience in handling a large specimen in sample preparation. For the Rattlesnake Mountain pluton (Baird _et al_, 1967a) having a coarseness index of 11-23, it was found that a 152mm (6") to 305mm(12") core of 22mm diameter was the minimum required size for major element analysis of appropriate precision.

The coarse-grained granite of Bodmin Moor, coarseness index of 14 - 22, is similar in grain size to the Rattlesnake Mountain pluton and whilst it may have been sufficient to have accepted Baird _et al's_ (1967a) conclusion that a 100-200g sample would be adequate, a test was made on the large quarried block collected from De Lank Quarries (KEB8). The block was split into a number of parts, each of about 500g. One of these parts was separated from the remainder and treated as an individual sample (KEB8 500g) whilst the other parts were similarly crushed and prepared as 500g specimens but then mechanically homogenised to give a bulk sample (KEB8 bulk). It was hoped that this later step would overcome any errors that might have arisen from handling the bulk sample as one large block. The single and bulk samples were then analysed in a similar manner, and the results are as follows:-

	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5
KEB8 (bulk)	72.83	0.21	14.45	0.28	1.47	0.05	0.44	0.94	3.66	4.88	0.24
KEB8 (500g)	72.91	0.20	14.86	0.24	1.47	0.06	0.44	0.92	3.40	4.83	0.25
S.Deviation	0.06	0.01	0.28	0.03		0.01		0.01	0.18	0.04	0.01

The analyses are similar, within the limits of experimental error (see appendix or Table 2), for the major element oxides and it is concluded that a sample of about 500g is adequately representative of an individual outcrop as well as being a convenient weight to handle during sample preparation.

Table 1 Major Element Analyses

Dozmary Pool (KEB1/2 & 5) Fine-grained granite

	KEB1	KEB2	KEB5
SiO_2	74.10	73.15	74.98
TiO_2	0.09	0.06	0.07
Al_2O_3	14.41	14.64	15.24
Fe_2O_3	0.31	0.14	0.11
FeO	0.92	0.86	0.80
MnO	0.04	0.02	0.02
MgO	0.18	0.19	0.17
CaO	0.55	0.37	0.41
Na_2O	3.35	2.32	2.54
K_2O	5.09	6.54	5.56
P_2O_5	0.27	0.25	0.24
H_2O	0.76	1.24	0.64
Total	100.07	99.78	100.78

De Lank Quarries (KEB8-12/14-18) Coarse-grained granite

	KEB8	KEB9	KEB10	KEB11	KEB12	KEB14	KEB15	KEB16	KEB17	KEB18
SiO_2	72.87	72.73	73.14	71.08	71.83	72.61	72.20	72.86	72.17	72.81
TiO_2	0.20	0.23	0.20	0.22	0.21	0.19	0.22	0.19	0.22	0.20
Al_2O_3	14.65	14.99	14.71	14.88	14.86	14.92	14.87	15.41	15.58	15.41
Fe_2O_3	0.26	0.34	0.24	0.29	0.69	0.24	0.39	0.18	0.43	0.17
FeO	1.47	1.55	1.50	1.58	1.27	1.51	1.61	1.48	1.40	1.46
MnO	0.05	0.05	0.04	0.05	0.04	0.03	0.04	0.03	0.03	0.04
MgO	0.44	0.47	0.43	0.49	0.43	0.42	0.45	0.40	0.46	0.40
CaO	0.93	0.82	0.80	0.95	0.89	0.74	0.92	0.62	0.74	0.95
Na_2O	3.30	3.16	3.27	3.19	3.15	3.08	3.21	2.51	2.70	3.54
K_2O	4.89	4.97	4.60	5.28	4.83	5.13	5.00	5.70	5.37	4.84
P_2O_5	0.24	0.28	0.21	0.25	0.27	0.24	0.27	0.24	0.29	0.26
H_2O	0.96	0.76	0.52	1.24	0.98	1.44	0.65	0.96	1.45	1.15
Total	100.26	100.35	99.66	99.50	99.45	100.55	99.83	100.58	100.84	101.23

Table 1 Major Element Analyses (contd.)

Roughtor (KEB19-25) Coarse-grained granite

	KEB19	KEB20	KEB21	KEB22	KEB23	KEB24	KEB25
SiO_2	71.56	72.45	71.82	73.40	72.45	72.70	72.96
TiO_2	0.25	0.24	0.23	0.20	0.24	0.24	0.25
Al_2O_3	15.10	15.02	15.17	14.74	14.62	14.99	14.99
Fe_2O_3	0.38	0.42	0.55	0.44	0.29	0.58	0.50
FeO	1.51	1.73	1.55	1.40	1.70	1.57	1.70
MnO	0.04	0.04	0.03	0.04	0.04	0.04	0.03
MgO	0.49	0.45	0.43	0.37	0.39	0.43	0.44
CaO	0.70	0.74	0.73	0.70	0.81	0.59	0.76
Na_2O	3.15	2.75	3.30	3.02	3.23	2.59	3.12
K_2O	5.20	4.72	5.06	4.89	4.62	5.48	4.88
P_2O_5	0.34	0.28	0.29	0.25	0.33	0.29	0.27
H_2O	0.65	0.89	0.67	0.83	0.79	0.67	1.29
Total	99.37	99.73	99.83	100.28	99.51	100.17	101.19

Cheesewring Quarry (KEB32-34/36-42) Coarse-grained granite

	KEB32	KEB33	KEB34	KEB36	KEB37	KEB38	KEB39	KEB40	KEB41	KEB42
SiO_2	72.28	71.64	72.67	71.75	73.27	72.96	72.44	71.58	72.69	73.62
TiO_2	0.23	0.23	0.25	0.19	0.23	0.28	0.27	0.22	0.19	0.24
Al_2O_3	14.92	15.55	15.27	15.01	14.85	15.23	15.14	15.05	14.58	14.04
Fe_2O_3	0.36	0.47	0.34	0.55	0.36	0.87	0.49	0.20	0.23	0.33
FeO	1.58	1.53	1.74	1.65	1.64	1.38	1.77	1.78	1.60	1.69
MnO	0.03	0.02	0.04	0.03	0.04	0.02	0.04	0.03	0.06	0.03
MgO	0.39	0.41	0.46	0.48	0.45	0.52	0.48	0.45	0.49	0.42
CaO	0.55	0.57	0.78	0.79	0.62	0.81	0.85	0.68	0.85	0.85
Na_2O	2.23	2.44	2.57	3.00	2.54	2.75	2.27	2.48	3.15	2.50
K_2O	5.86	5.51	5.40	4.90	5.48	5.28	5.23	5.80	5.29	5.08
P_2O_5	0.27	0.28	0.28	0.27	0.27	0.28	0.29	0.27	0.23	0.26
H_2O	0.64	1.25	1.03	0.87	0.80	1.05	1.18	1.61	0.75	1.49
Total	99.34	99.90	100.83	99.49	100.55	101.43	100.45	100.15	100.11	100.55

Table 1 Major Element Analyses (contd.)

Cheesewring Quarry (KEB29-31/43) KEB29 - MCGG, KEB30/31/43 - XCGG

	KEB29	KEB30	KEB31	KEB43
SiO_2	70.83	75.04	75.14	72.24
TiO_2	0.24	0.11	0.14	0.33
Al_2O_3	15.27	13.62	14.02	13.77
Fe_2O_3	0.72	0.37	0.32	0.60
FeO	1.46	0.80	1.10	2.67
MnO	0.01	0.04	0.02	0.07
MgO	0.45	0.17	0.23	0.51
CaO	0.24	0.57	0.55	0.63
Na_2O	2.80	2.42	2.40	3.41
K_2O	6.43	5.59	6.02	4.69
P_2O_5	0.17	0.28	0.27	0.22
H_2O	1.70	0.36	0.62	0.77
Total	100.32	99.37	100.83	99.91

Analyst K.Edmondson

Table 2 Summary of major element chemistry and standard deviations for the Bodmin Moor granite.

	1	2	3		4		5		6		7		8	
SiO_2	0.41	0.06	74.08	0.83	72.43	0.62	72.48	0.64	72.72	1.24	72.49	0.70	72.71	1.02
TiO_2	0.01	0.01	0.07		0.21	0.01	0.23	0.02	0.22	0.06	0.23	0.03	0.21	0.06
Al_2O_3	0.36	0.28	14.76		15.03	0.32	14.95	0.20	14.74	0.62	14.96	0.42	14.87	0.47
Fe_2O_3		0.03	0.19	0.01	0.32	0.15	0.45	0.10	0.44	0.19	0.42	0.19	0.39	0.17
FeO	0.05		0.86		1.48	0.10	1.59	0.12	1.60	0.41	1.64	0.12	1.50	0.34
MnO	0.02	0.01	0.03		0.04	0.01	0.04	0.01	0.03	0.02	0.03	0.01	0.04	0.01
MgO	0.03		0.18		0.44	0.03	0.43	0.04	0.42	0.10	0.45	0.04	0.41	0.10
CaO	0.07	0.01	0.44	0.01	0.84	0.11	0.72	0.07	0.67	0.17	0.73	0.12	0.71	0.17
Na_2O	0.21	0.18	2.74	0.29	3.11	0.30	3.02	0.26	2.64	0.34	2.60	0.30	2.87	0.38
K_2O	0.20	0.04	5.73	0.55	5.06	0.32	4.98	0.29	5.47	0.46	5.38	0.30	5.27	0.48
P_2O_5		0.01	0.25		0.25	0.02	0.29	0.03	0.26	0.03	0.27	0.02	0.26	0.03
H_2O	0.01	0.04	0.88	0.10	1.01	0.31	0.83	0.22	1.01	0.40	1.07	0.32	0.96	0.33

(Blank spaces indicate that results are insignificant to two decimal places)

1 Analytical errors (maximum standard deviation in duplicate analyses, see appendix; major element chemistry)

2 Standard deviations in analyses from one outcrop.

3 Means and standard deviations in locality sampling - Dozmary Pool.

4 Means and standard deviations in locality sampling - De Lank Quarries.

5 Means and standard deviations in locality sampling - Roughtor.

6 Means and standard deviations in locality sampling - Cheesewring Quarry

7 Means and standard deviations in locality sampling - Cheesewring Quarry, but excluding samples KEB29/30/31/43.

8 Means and standard deviations in major element chemistry of the Bodmin Moor granite from the data of Table 1.

C) Variation in composition in locality sampling

The results of the analyses of the samples collected from the four localities are given in Table 1 with the means and standard deviations summarised in Table 2.

As KEB29-31 and 43 reflect significant field, petrographic and chemical variations from the remaining samples from the Cheesewring Quarry locality the means and standard deviations have been calculated both by including and excluding these specimens (columns 6 & 7, Table 2). Exclusion lowers the standard deviation for each major element oxide, except Fe_2O_3, which remains unaltered. As a result of the obvious "anomalous" nature of KEB29-31 and 43 the Cheesewring Quarry locality is re-defined to exclude these four specimens in the following discussion. For similar reasons the Dozmary Pool locality can be temporarily disregarded.

Whilst it is possible to distinguish between certain samples merely by visual inspection and comparisons this is not always possible when dealing with larger quantities of data and it is necessary to turn to statistical tests to detect any significant variations. Such is the case in determining whether any meaningful variation exists between the major element chemistry of the De Lank Quarries, Roughtor and Cheesewring Quarry localities.

Although sample sizes are too large to compare visually they are too small to assess the nature of the population distribution. An underlying assumption in applying parametric statistics (F-test, t-test, etc.) is that the population is normally distributed, a fact which is all too frequently accepted and rarely proved. The observations are replaced by ranks, i,e. all the results from the k localities are combined and ranked in one series. It can be shown that if the k localities are from the same or identical population then H, the statistic defined in the Kruskal-Wallis test, is distributed as chi square with degrees of freedom (d.f.) = k - 1, provided that the sizes of the various localities are not too small. The statistic is

$$H = \frac{12}{N(N+1)} \sum_{j=1}^{k} \frac{R_j^2}{n_j} - 3(N+1)$$

where $N = \sum n_j$, the number of cases in all the localities combined

k = the number of localities

$\sum_{j=1}^{k}$ directs the sum over the k localities

R_j = sum of ranks in the 'j'th locality

and n_j = the number of cases in the 'j'th locality

For SiO_2 the null hypothesis (H_0) can be stated as being the condition in which there is no difference in the distribution of SiO_2 results between the three localities. The alternative hypothesis (H_1) is that there is a difference between the three localities. For a significance level of $\alpha = 0.05$ the region of rejection consists of all values of the statistic H which are so large that the probability associated with their occurrence under the null hypothesis is equal to or less than 5 in 100.

Thus, tabulating the data for SiO_2 gives the following:-

De Lank Quarries			Roughtor			Cheesewring Quarry		
Spec. No.	SiO_2	Rank	Spec. No.	SiO_2	Rank	Spec. No.	SiO_2	Rank
8	72.87	21	19	71.56	2	32	72.28	10
9	72.73	18	20	72.45	12.5	33	71.64	4
10	73.14	24	21	71.82	6	34	72.67	15
11	71.08	1	22	73.40	26	36	71.75	5
12	71.83	7	23	72.45	12.5	37	73.27	25
14	72.61	14	24	72.70	17	38	72.96	22.5
15	72.20	9	25	72.96	22.5	39	72.44	11
16	72.86	20				40	71.58	3
17	72.17	8				41	72.69	16
18	72.81	19				42	73.62	27

$R_1 = 141$ $R_2 = 98.5$ $R_3 = 138.5$

$n_1 = 10$ $n_2 = 7$ $n_3 = 10$

k

$K = 3$, $N = 27$

d.f. = k-1 = 2

and substituting into the Kruskal-Wallis statistic

$$H = \frac{12}{27(27+1)}\left[\frac{(141)^2}{10} + \frac{(98.5)^2}{7} + \frac{(138.5)^2}{10}\right] - 3(27+1)$$

$$= \underline{0.148}$$

For k - 1 = 2, degrees of freedom, the chi square value at $\alpha = 0.05$ is 5.99 (Siegel, 1956, Table C, p.249). Since H = 0.148 for SiO_2 is considerably smaller than 5.99 the null hypothesis is accepted. That is, there is no significant difference in the distribution of SiO_2 results between the three localities.

It should perhaps be noted that when a tie occurs between two or more scores, each score is given the mean of the ranks for which it has tied. In the example with SiO_2 there are only two ties and no attempt has been made to correct the value of H for the influence of ties. If required, Siegel (1956) indicates that the effect of ties can be corrected by computing the value of H and then dividing by

$$1 - \frac{\sum T}{N^3 - N}$$

where $T = t^3 - t$ (when t is the number of tied observations in a tied group of results).

Even by visual inspection of the major element results (Table 1) it is evident that there is a lack of variation in TiO_2, MnO, and P_2O_5 and for these oxides, plus H_2O, no attempt has been made to apply the Kruskal-Wallis statistic. For the remaining elements the test has been applied in a similar manner to that outlined for SiO_2 and the value of the statistic, H, is quoted below.

	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O
H =	4.5	8.0	2.0	6.0	11.9	8.0

(For MgO the value of H has been corrected for 9 ties)

At a significance level of $\alpha = 0.05$ the chi square value is 5.99 and it can be concluded from the test that the null hypothesis holds for SiO_2, Fe_2O_3 and MgO. For FeO, CaO, Na_2O and K_2O, however, it can be postulated that there is a difference between the three localities.

It should be stressed that this test makes no allowance for analytical or outcrop error and variation and whilst ranking may be regarded as an attempt to break the influence of the closed array such implications cannot be entirely dismissed. It is also notable that whilst this statistical test indicates that significant differences do occur for four of the major elements in the three localities it does not necessarily imply that these oxides viz. FeO, CaO, Na_2O and K_2O offer a method for classifying individual samples to one particular locality. In fact inspection of Table 2 reveals, in the case of the four oxides, that for a spread of one standard deviation about the mean of any one of the three localities there is an overlap with the mean of at least one of the other localities.

D) Variation in composition produced as a result of weathering

Although it implies some degree of atmospheric alteration, the geological application of the term weathering appears to vary from author to author. A number of attempts have been made to generalise mineral stabilities and define indices of weathering for silicate rocks; for example, Harris & Adams (1966) have indicated that plagioclase, biotite, K-feldspar, quartz comprise the common "least to most" stable mineral sequence in the weathering of granites and consequently sodium and calcium are more likely to be released during the early stages of weathering than potassium. Ruxton (1968) has considered several proposals for quantifying the degree of weathering and has suggested the use of the mole ratio of silica to alumina. More recently, Parker (1970) has offered an index of weathering based on the proportions of the alkali and alkaline earth metals present, using the bond strengths of these elements with oxygen as a weighting factor.

Whilst any of these attempts to classify weathering may be applicable to other igneous bodies, a certain difficulty arises in their use with the S. W. England granites. In addition to atmospheric effects chemical variations have arisen as a result of what may, at this juncture, be best described as "post-magmatic" processes and there is little doubt that weathering accentuates or is intimately related with these processes. Any attempt, therefore, to decide whether chemical variations between localities or particular hand specimens are solely a result of weathering may be inhibited by the fact that the present surface relief could initially have been influenced by "non-atmospheric" processes.

It seems logical, however, to compare the chemistry of a rock sample taken from a tor with one taken from an adjacent quarry to determine whether extensive atmospheric exposure produces any chemical change. A visual inspection of the major element chemistry of specimens KEB36 and 37, from Stowes Hill Tor and Cheesewring Tor respectively, with any of those from Cheesewring Quarry (KEB38-42), see Tables 1 & 2, suggests that any variation would be imperceptible within the limits of experimental and sampling error.

The use of the term weathering will be considered further in dealing with the trace element chemistry and as outlined in the preceding section on the description of the sampling plan (see Part I), its application in this text is confined to material that is friable in hand specimens. The majority of tor exposures yield material which is outside this physical description.

E) The conclusions of the major element tests of variation

The most significant conclusion from the three tests of variation in composition indicates that only four of the major elements - FeO, CaO, Na_2O and K_2O - appear to reflect detectable differences in chemical distribution between localities. In view of these results it was thought that the probable value of continuing with wet chemical analyses for the major elements for the remaining localities was fairly limited and certainly uneconomic in terms of the amount of time that would be required in carrying out the work. Attention was turned, therefore, to the trace element chemistry, although sodium and potassium were subsequently determined. The results of this work will be presented in Part III but having commenced with the major element chemistry it seems legitimate, at this point, to expand upon the data already obtained.

2) Composition of the granite

A) The coarse-grained granite

From a visual inspection of the analyses listed in Table 1 it can be seen that those rocks which fall outside the generally accepted petrographic and field descriptions of the coarse-grained granite also fall outside certain chemical limits. Though analyses are presented for only a small part of the Bodmin Moor granite, the means and standard deviations quoted in columns 4, 5, and 6 of Table 2 are regarded as a basis for defining these limits for the major element chemistry of the coarse-grained granite.

CIPW norms (computer calculated, after Morgan, 1968) for the analysed specimens are quoted in Table 3. Parslow (1969) has indicated that mesonorms, which account for the presence of biotite or muscovite, or both, are more significant than CIPW norms when granite rocks are reduced to three components and plotted on experimental diagrams. Such advantages, however, were found to be minimal in connection with the present work, the mesonorm values (calculation of which are described by Barth, 1959) being similar to the CIPW norm values. For this reason the mesonorm values are not tabulated.

When plotted on normative Q-Ab-Or and An-Ab-Or diagrams (see

Table 3 CIPW norms

Dozmary Pool (KEB1/2 & 5) Fine-grained granite

	KEB1	KEB2	KEB3
Q	33.85	33.63	37.90
C	3.04	3.67	4.87
Or	30.07	38.64	32.85
Ab	28.33	19.62	21.48
An	0.97	0.20	0.47
En	0.45	0.47	0.42
Fs	1.36	1.40	1.30
Mt	0.45	0.20	0.16
Il	0.17	0.11	0.13
Ap	0.64	0.59	0.57
Others	0.76	1.24	0.64
Total	100.09	99.77	100.79
Q	36.69	36.60	41.09
Ab	30.71	21.35	23.29
Or	32.60	42.05	35.62
An	1.63	0.35	0.85
Ab	47.72	33.56	39.20
Or	50.65	66.09	59.94

Q-Ab-Or and An-Ab-Or re-calculated to 100 for triangular diagrams. See Fig. 2

De Lank Quarries (KEB8-12/14-18) Coarse-grained granite

	KEB8	KEB9	KEB10	KEB11	KEB12	KEB14	KEB15	KEB16	KEB17	KEB18
Q	31.98	32.64	33.72	29.19	32.58	32.49	31.46	34.16	33.61	30.78
C	2.81	3.59	3.40	2.79	3.48	3.53	3.15	4.56	4.68	3.25
Or	28.89	29.36	27.18	31.20	28.54	30.31	29.54	33.68	31.73	28.60
Ab	27.91	26.73	27.66	26.98	26.64	26.05	27.15	21.23	22.84	29.94
An	3.05	2.24	2.60	3.08	2.65	2.10	2.80	1.51	1.78	3.02
En	1.10	1.17	1.07	1.22	1.07	1.05	1.12	1.00	1.15	1.00
Fs	2.25	2.28	2.30	2.39	1.49	2.32	2.35	2.31	1.91	2.28
Mt	0.38	0.49	0.35	0.42	1.00	0.35	0.57	0.26	0.62	0.25
Il	0.38	0.44	0.38	0.42	0.40	0.36	0.42	0.36	0.42	0.38
Ap	0.57	0.66	0.50	0.59	0.64	0.57	0.64	0.57	0.69	0.62
Others	0.96	0.76	0.52	1.24	0.98	1.44	0.65	0.96	1.45	1.15
Total	100.28	100.36	99.68	99.52	99.47	100.57	99.85	100.60	100.88	101.27
Q	36.02	36.79	38.08	33.41	37.12	36.57	35.69	38.35	38.12	34.46
Ab	31.44	30.12	31.23	30.88	30.36	29.32	30.80	23.83	25.90	33.52
Or	32.54	33.09	30.69	35.71	32.52	34.11	33.51	37.81	35.98	32.02
An	5.09	3.84	4.52	5.03	4.59	3.60	4.71	2.68	3.16	4.90
Ab	46.64	45.82	48.16	44.04	46.07	44.56	45.64	37.63	40.53	48.64
Or	48.27	50.34	47.32	50.93	49.34	51.84	49.66	59.69	56.31	46.46

Table 3 CIPW norms (contd.)

Roughtor (KEB19-25) Coarse-grained granite

	KEB19	KEB20	KEB21	KEB22	KEB23	KEB24	KEB25
Q	31.12	35.80	30.95	34.90	33.45	34.64	33.56
C	3.83	4.71	3.63	3.81	3.62	4.42	3.84
Or	30.72	27.89	29.90	28.89	27.30	32.38	28.83
Ab	26.64	23.26	27.91	25.54	27.32	21.91	26.39
An	1.25	1.84	1.73	1.84	1.86	1.03	2.01
En	1.22	1.12	1.07	0.92	0.97	1.07	1.10
Fs	2.12	2.51	2.07	1.95	2.56	2.08	2.35
Mt	0.55	0.61	0.80	0.64	0.42	0.84	0.72
Il	0.47	0.46	0.44	0.38	0.46	0.46	0.47
Ap	0.81	0.66	0.69	0.59	0.78	0.69	0.64
Others	0.65	0.89	0.67	0.83	0.79	0.67	1.29
Total	99.38	99.75	99.86	100.29	99.53	100.19	101.20
Q	35.17	41.17	34.87	39.07	37.98	38.96	37.80
Ab	30.11	26.75	31.45	28.59	31.02	24.63	29.72
Or	34.72	32.07	33.68	32.34	31.00	36.41	32.48
An	2.14	3.48	2.90	3.27	3.30	1.87	3.51
Ab	45.45	43.89	46.88	45.39	48.37	39.60	46.11
Or	52.41	52.63	50.22	51.34	48.33	58.53	50.38

Cheesewring Quarry (KEB32-34/36-42) Coarse-grained granite

	KEB32	KEB33	KEB34	KEB36	KEB37	KEB38	KEB39	KEB40	KEB41	KEB42
Q	34.86	34.39	34.33	32.86	35.20	34.42	36.39	32.33	31.08	36.80
C	4.56	5.21	4.45	3.98	4.26	4.19	4.90	4.10	2.68	3.51
Or	34.62	32.55	31.90	28.95	32.38	31.20	30.90	34.27	31.25	30.01
Ab	18.86	20.64	21.74	25.37	21.48	23.26	19.20	20.97	26.64	21.14
An	0.97	1.00	2.04	2.16	1.31	2.19	2.32	1.61	2.72	2.52
En	0.97	1.02	1.15	1.19	1.12	1.29	1.19	1.12	1.22	1.05
Fs	2.28	2.08	2.58	2.32	2.41	1.39	2.47	2.80	2.55	2.49
Mt	0.52	0.68	0.49	0.80	0.52	1.26	0.71	0.29	0.33	0.48
Il	0.44	0.44	0.47	0.36	0.44	0.53	0.51	0.42	0.36	0.46
Ap	0.64	0.66	0.66	0.64	0.64	0.66	0.69	0.64	0.55	0.62
Others	0.64	1.25	1.03	0.87	0.80	1.05	1.18	1.61	0.75	1.49
Total	99.36	99.92	100.84	99.50	100.56	101.44	100.46	100.16	100.13	100.57
Q	39.46	39.26	39.02	37.69	39.53	38.73	42.07	36.92	34.93	41.84
Ab	21.35	23.56	24.71	29.10	24.12	26.17	22.20	23.95	29.94	24.04
Or	39.19	37.17	36.27	33.21	36.35	35.10	35.73	39.13	35.13	34.12
An	1.77	1.85	3.67	3.82	2.38	3.87	4.43	2.83	4.48	4.69
Ab	34.64	38.08	39.04	44.92	38.94	41.06	36.62	36.89	43.96	39.39
Or	63.59	60.07	57.30	51.26	58.68	55.07	58.94	60.27	51.57	55.91

Table 3 CIPW norms (contd.)

Cheesewring Quarry (KEB29-31/43) KEB29 - MCGG, KEB30/31/43 - XCGG

	KEB29	KEB30	KEB31	KEB43
Q	28.47	38.42	36.69	31.17
C	3.68	3.22	3.20	2.47
Or	37.99	33.03	35.57	27.71
Ab	23.68	20.47	20.30	28.84
An	0.08	1.00	0.97	1.69
En	1.12	0.42	0.57	1.27
Fs	1.71	1.06	1.56	3.99
Mt	1.04	0.54	0.46	0.87
Il	0.46	0.21	0.27	0.63
Ap	0.40	0.66	0.64	0.52
Others	1.70	0.36	0.62	0.77
Total	100.33	99.39	100.85	99.93
Q	31.58	41.80	39.64	35.53
Ab	26.27	22.27	21.93	32.88
Or	42.14	35.93	38.43	31.59
An	0.13	1.84	1.70	2.90
Ab	38.35	37.56	35.72	49.52
Or	61.52	60.61	62.58	47.58

Fig 2 An-Ab-Or and Q-Ab-Or triangular diagrams

An-Ab-Or (top). The numbered lines represent approximate limits of the thermal troughs between 1 and 10kb water vapour pressure. (After Kleeman, 1965)

Q-Ab-Or (bottom). The numbered circles represent the positions of the ternary minimum from 0.5 to 10kb water vapour pressure. The line linking these points defines the trend of the minima; the thermal troughs containing these minima run parallel to the base and through these points. (After Tuttle & Bowen, 1958 and Luth, Jahns & Tuttle, 1964)

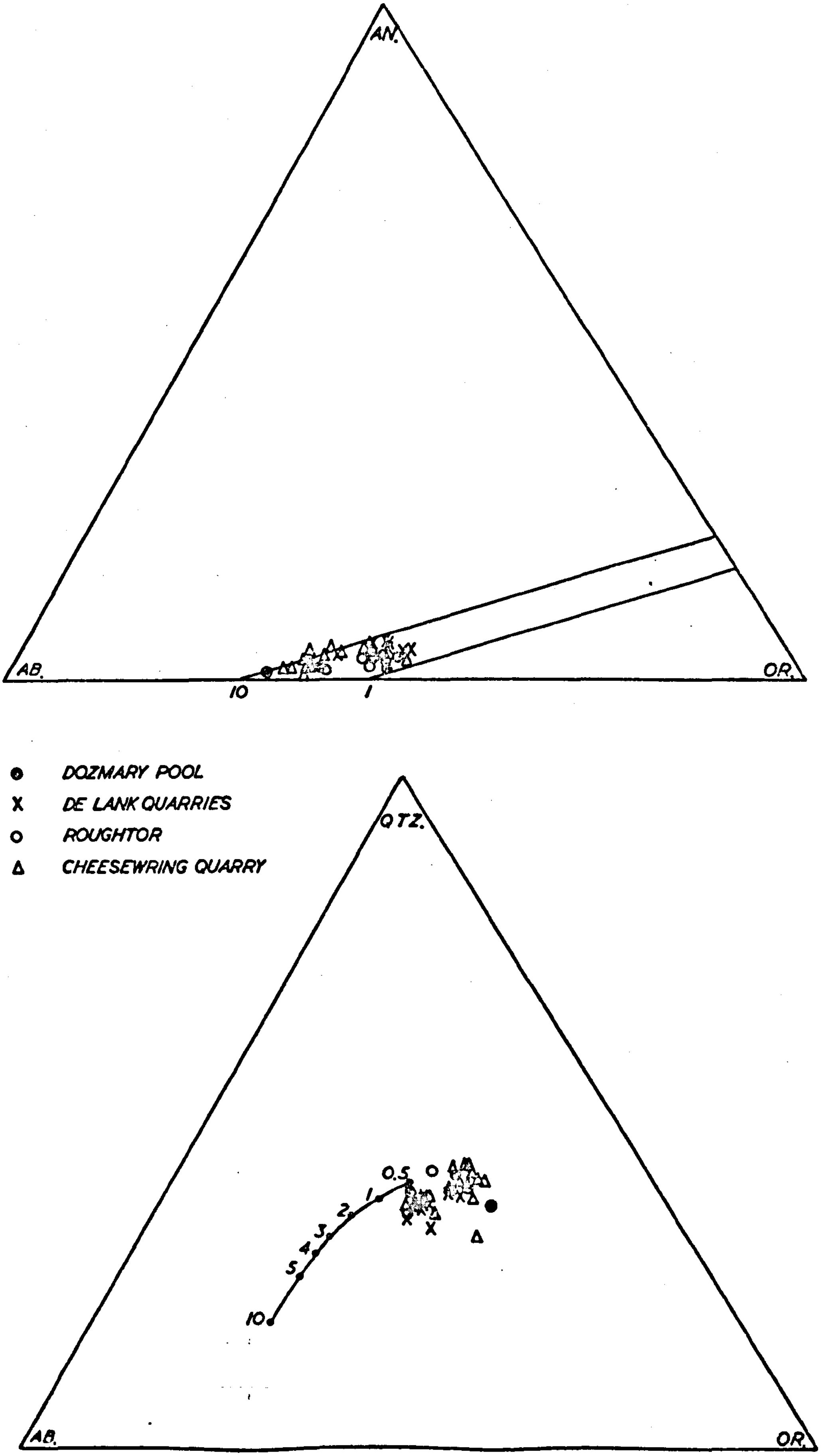

AN.
AB.
OR.
10
1
● DOZMARY POOL
X DE LANK QUARRIES
O ROUGHTOR
Δ CHEESEWRING QUARRY
QTZ.
0.5
1
2
3
4
5
10
AB.
OR.

Fig. 2) the three coarse-grained granite localities fall into a fairly compact group, though it is just possible to distinguish the Cheesewring Quarry locality from the other two localities. The plot of the norms on the Q-Ab-Or diagram fall in the field of the experimental 'ternary minimum' (Bowen & Tuttle, 1958) with an extension towards the quartz-orthoclase sideline. This is the case with similar Q-Ab-Or normative plots presented by other workers for S. W. England granites (Exley & Stone, 1964; Booth, 1966; Hawkes, in Edmonds et al, 1968; Hall, 1971). When plotted on the An-Ab-Or diagram the norms fall, as might be expected for granites, in the low temperature trough (Kleeman, 1965).

Hawkes (in Edmonds et al, 1968) has interpreted normative data from the Dartmoor granite as indicating that the coarse-grained granites from that pluton are 'adamellitic' in composition. If the clay mineral content of the modal analyses (Table 4) is added to plagioclase then both the normative and modal data of the present work suggest that the use of the term 'adamellite' would not be invalid for the Bodmin Moor coarse-grained granites as the K-feldspar and plagioclase proportions are almost equal in a number of specimens. The traditional use of the term "granite", however, is preferred here for the Bodmin Moor pluton and the plot of the normative data towards the orthoclase-quartz sideline in the Q-Ab-Or diagram and towards the orthoclase apex in the An-Ab-Or diagram are offered as sufficient evidence for its retention.

Modal analyses quoted in Table 4 were calculated from a minimum of 4,200 points from at least two large thin sections. The validity of using these counting ratios has been expressed by Booth (1966). Exley (personal communication, see Edmondson, 1970) has employed

Table 4 Modal Analyses

De Lank Quarries (KEB8-12/14-18) Coarse-grained granite

	KEB8	KEB9	KEB10	KEB11	KEB12	KEB14	KEB15	KEB16	KEB17	KEB18
Qtz	25.0	33.9	37.1	33.9	31.1	33.8	28.2	33.0	32.5	33.7
Plag	26.0	17.9	19.0	16.3	24.5	18.5	21.5	17.2	16.3	19.1
Ortho	32.7	30.7	30.5	30.5	23.4	34.4	35.6	28.9	27.9	36.0
Biot	4.9	3.9	4.4	5.4	6.1	3.1	2.5	5.3	2.9	1.7
Musc	4.4	8.0	3.8	6.1	6.0	5.5	5.8	7.2	11.7	3.5
C.Min	4.3	4.6	4.0	4.7	5.6	2.6	4.6	6.5	4.7	2.2
T'ne	0.1	0.0	0.3	0.6	0.4	0.0	0.2	0.1	1.0	0.9
2 Mic	2.4	0.8	0.7	2.5	2.5	1.7	1.1	1.7	2.6	2.7
Ap.	0.2	0.1	0.0	0.2	0.0	0.0	0.2	0.1	0.2	0.2
And	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ore	0.0	0.0	0.1	0.0	0.2	0.1	0.0	0.1	0.0	0.0
Total	100.00	99.9	99.9	100.2	99.8	99.7	99.7	100.1	99.8	100.0

Roughtor (KEB19-25) Coarse-grained granite

	KEB19	KEB20	KEB21	KEB22	KEB23	KEB24	KEB25
Qtz	32.3	40.0	23.6	36.4	31.9	37.8	48.2
Plag	21.2	15.4	20.1	19.8	26.1	24.1	15.6
Ortho	28.2	24.3	40.0	26.7	25.2	17.8	11.6
Biot	4.7	4.1	4.1	3.1	3.7	5.5	6.2
Musc	6.5	9.1	6.2	7.4	8.0	4.8	7.6
C.Min	4.9	3.8	4.7	6.1	3.5	8.4	9.6
T'ne	0.6	1.1	0.1	0.1	0.8	0.3	0.5
2 Mic	1.5	1.7	0.9	0.4	0.4	1.1	0.5
Ap	0.1	0.3	0.1	0.2	0.2	0.1	0.2
And	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ore	0.0	0.0	0.0	0.0	0.1	0.0	0.0
Total	100.0	99.8	99.8	100.2	99.9	99.9	100.0

Table 4 Modal Analyses (contd.)

Cheesewring Quarry (KEB32-34/36-42) Coarse-grained granite

	KEB32	KEB33	KEB34	KEB36	KEB37	KEB38	KEB39	KEB40	KEB41	KEB42
Qtz	34.5	27.3	28.9	34.1	43.9	29.6	51.1	31.9	40.2	38.1
Plag	15.2	17.7	18.8	18.9	13.0	14.4	14.0	14.8	8.3	14.9
Ortho	32.0	28.4	35.1	28.5	25.7	35.9	17.7	39.4	29.8	27.6
Biot	4.4	5.1	2.6	7.1	5.7	4.7	6.2	2.7	5.9	5.8
Musc	5.1	10.7	7.7	4.4	5.5	4.8	5.3	4.9	5.7	6.8
C.Min	5.9	8.6	4.8	5.7	5.7	8.3	4.5	5.2	8.1	4.7
T'ne	0.9	1.0	1.2	0.4	0.0	1.0	0.0	0.2	1.1	0.5
2 Mic	1.4	1.0	0.8	0.4	0.2	1.0	0.7	0.6	0.5	1.1
Ap	0.6	0.2	0.1	0.2	0.2	0.0	0.3	0.3	0.2	0.3
And	0.0	0.0	0.0	0.3	0.0	0.2	0.0	0.0	0.0	0.0
Ore	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.1
Total	100.0	100.0	100.0	100.0	99.9	99.9	99.9	100.0	99.8	99.9

Cheesewring Quarry (KEB29-31/43) KEB29 - MCGG, KEB30/31/43 - XCGG

	KEB29	KEB30	KEB31	KEB43
Qtz	22.6	34.5	36.0	33.4
Plag	19.6	29.9	20.5	13.7
Ortho	40.4	26.2	27.6	40.8
Biot	3.1	0.8	4.1	4.7
Musc	6.0	5.0	7.2	5.3
C.Min	6.2	0.6	0.9	0.9
T'ne	0.9	2.2	1.7	0.0
2 Mic	0.8	0.3	1.1	0.0
Ap	0.0	0.5	0.3	0.0
And	0.0	0.0	0.1	0.0
Ore	0.3	0.0	0.1	0.0
Total	99.9	100.0	99.6	98.8

Analyst K.Edmondson

similar techniques for the derivation of modal data from Bodmin Moor and the continued use of these methods may prove to be of value for future comparative purposes. The present modal results, however, merely indicate that a considerable mineralogical variation occurs both within and between localities and reliable relationships based on modal and chemical data are difficult to assess. For example, the high ratio of the means of K-feldspar to plagioclase for the Cheesewring Quarry could be used to explain the higher K_2O values associated with this locality but it does not satisfy any CaO or Na_2O variations and the former conclusion may be purely fortuitous.

	De Lank Quarries		Roughtor		Cheesewring Quarry	
	m.	st.dev.	m.	st.dev.	m.	st.dev.
K-feldspar	31.1	3.8	24.9	8.8	30.0	6.1
Plag.*	24.7	5.2	26.1	4.1	21.1	3.1
K-feld/Plag.	1.3		0.9		1.4	

*includes clay minerals

Averaged modal data from Table 4

Although the presentation of results in the form of a constant sum is intended to permit comparison with the results of other workers there is invariably an absence in publications of any degree of accuracy or precision associated with quoted analyses. In some cases it is possible to challenge the accuracy of another workers' results but in the majority of cases the validity of the analyses has to be assumed. Such assumptions may seriously bias interpretation but until evidence proves otherwise any possible inaccuracies will have to be regarded as contributing a negligible influence and have, therefore, been ignored in this account.

There are few other records of major element analyses from the

Bodmin Moor granite; only eight have been found in the literature and these are reproduced in Table 5. From the descriptions and localities quoted by the authors, analyses 1-5 (Ghosh, 1927) and 85 (Brammall & Harwood, 1932) are interpreted as being from coarse-grained granite samples. In the context of the proposed definition of the chemistry of the coarse-grained granite it is difficult to accept the validity of Ghosh's analyses. His specimen 1, which is recorded as being from Cheesewring Quarry, has a ten-fold increase in the MnO content compared with the mean of the samples analysed in this work for the same locality. In fact there is no evidence for such a high MnO value in any published analyses for S. W. England coarse-grained granites. There are similar discrepancies throughout the remaining samples and it is concluded that Ghosh's analysed specimens should be treated with caution. From this it follows that the authenticity of Ghosh's (1927) separation of the coarse-grained granite into 'normal' and 'Godaver' types might be invalid. A similar challenge to these divisions was made by Exley (in Exley & Stone, 1964) on modal analysis evidence and by Edmondson (1970) on the inferences of structural state distribution of the alkali feldspars. Although there are some minor variances, the analysis quoted by Brammall & Harwood (1932) for a specimen from De Lank Quarry (85, Table 5) is comparable to those quoted here for the same locality.

In Table 6 the results of analyses for the coarse-grained granites are presented for other S. W. England plutons, based on the available data of other workers. Column 5, Table 6 is perhaps out of place, for according to Booth (1966, p.177) "fine-grained later granites cannot be separated from the coarse on the basis of

Table 5 Major element analyses of Bodmin Moor granite quoted in other works.

	1	2	3	4	5	6	85	7
SiO_2	70.96	71.25	71.66	72.99	73.01	74.16	71.86	73.45
TiO_2	0.36	0.20	0.32	0.13	0.11		0.50	0.09
Al_2O_3	15.92	15.72	15.31	15.33	15.26	14.68	14.63	15.20
Fe_2O_3	0.20	0.16	0.19		0.29	0.26	0.15	0.30
FeO	0.84	0.86	0.84	1.09	0.73	0.65	1.26	0.99
MnO	0.30	0.21	0.28	0.06	0.07	0.07	0.06	0.01
MgO	0.49	0.32	0.25	0.28	0.06	0.18	0.66	1.85
CaO	1.11	1.42	1.21	0.64	0.68	1.01	0.87	0.57
Na_2O	3.53	3.56	4.31	2.96	3.18	2.51	2.92	3.47
K_2O	5.60	5.51	4.26	5.59	5.47	5.51	5.32	3.63
P_2O_5	0.03	0.32	0.32	0.18	0.21	0.27	0.42	0.14
$+-H_2O$	0.80	0.71	0.83	1.18	0.63	0.53	0.99	1.14

1 'Normal' granite, Cheesewring Quarry.
(Ghosh, 1927, analysis 1, p.307)
2 'Normal' granite, Fox Tor.
(Ghosh, 1927, analysis 2, p.307)
3 'Normal' granite, Notter Tor.
(Ghosh, 1927, analysis 3, p.307)
4 'Godaver' granite, N.Hill Tor.
(Ghosh, 1927, analysis 4, p.307)
5 'Godaver' granite, Godaver region.
(Ghosh, 1927, analysis 5, p.307)
6 'Fine granite', N.Dozmary farmhouse.
(Ghosh, 1927, analysis 6, p.307
85 'Granite', De Lank Quarry.
(Brammell & Harwood, analysis 85, p. 234)
7 'Fine leucogranite', Stannon Clay Pit.
(Exley, 1966, Table 2, analysis 7, p.366)

chemical composition, as a wide variation in the main granites completely overlaps the composition of the finer varieties". The results quoted for the Land's End granite by Wilson (1972), (column 6 & 7, Table 6) are probably more representative of the coarse-grained granite than that of Booth's. At present, the only available data for Carnmenellis are offered by Ghosh (1934) and both Chayes (1955), on modal evidence, and Austin (1960), on petrographic evidence, have challenged Ghosh's (1934) division of the Carnmenellis granite. As with the previously criticised Bodmin Moor analyses of Ghosh (1927) (p. 23) it seems possible that his Carnmenellis data may require caution in their reproduction and they are subsequently omitted from Table 6 and comparative considerations with the other plutons.

It is apparent, even by visual inspection, that analyses 2, 4 and 8 (Table 6) reflect a marked chemical variation when compared with their counterparts, 1, 3 and 7 respectively (Table 6), from the same pluton. Although all the granites in Table 6 are recorded, by their analysts, as coarse or medium-grained they are still subdivided for each pluton on field or petrographic features and as with specimens KEB29-31 and 43 from Bodmin Moor, recognisably distinct physical attributes are reproduced chemically. As analyses 2, 4 and 8 (Table 6) are similar to KEB30 and 31 further comment on these results is deferred until the Bodmin Moor specimens have been considered.

Analyses 1, 3 and 7 (Table 6) are comparable with the data of Table 2 for the three coarse-grained localities of Bodmin Moor. Any attempt to relate results from the different Cornubian plutons, however, is immediately beset with a multitude of problems; some of the statistical difficulties have already been covered and

Table 6 Major element analyses of 'granites' from S.W.England

	1	2	3	4	5	6	7	8
SiO_2	71.24	74.43	71.30	73.4	71.90	70.7	71.7	70.9
TiO_2	0.41	0.20	0.34	0.10	0.25	0.36	0.23	0.07
Al_2O_3	14.02	13.27	14.80	14.8	15.05	14.3	14.6	14.9
Fe_2O_3	0.55	0.44	0.25	1.32*	0.94	0.73	0.60	1.13
FeO	2.20	1.37	1.82		1.33	1.62	1.04	0.51
MnO	0.06	0.08	0.06	0.01	0.03	0.04	0.03	0.04
MgO	0.60	0.47	0.48	0.32	0.80	0.62	0.48	0.22
CaO	1.54	0.63	1.05	0.87	0.91	1.02	0.70	0.67
Na_2O	3.00	2.86	3.20	2.52	2.73	2.77	3.15	3.97
K_2O	4.85	4.86	5.15	4.63	5.24	5.34	5.61	4.81
P_2O_5	0.21	0.18	0.26		0.23	0.24	0.26	0.19
H_2O+	0.87	0.90	0.63		0.57	0.85	0.82	1.20
H_2O-	0.32	0.23	0.14			0.15	0.15	0.17

* Total Fe as Fe_2O_3

1 'Big-feldspar granite', Dartmoor, mean of 7 analyses.
(Hawkes, in Edmonds *et al*, 1968, analyses 1-7, Table 5, p.105)

2 'Poorly megacrystic granite', Dartmoor, mean of 5 analyses.
(Hawkes, *op.cit.*, 1968, analyses 8-12, Table 5, p.105)

3 'Porphyritic (big-feldspar) granite', Luxulyan Quarry, St.Austell, analysis of sample produced by combining equal portions of six separate specimens.
(Harding & Hawkes, 1971, Table 1, p.4)

4 'Porphyritic lithionite granite', St.Austell, mean of 3 analyses.
(Exley & Stone, 1964, Table 6, p.141)

5 'Granite', Land's End, mean of 25 analyses.
(Booth, 1966, p.290-294)

6 'Unaltered granite', Boscaswell, Land's End, mean of 15 analyses.
(Wilson, 1972, Table 14, p.126)

7 'Unaltered coarse-grained granite', Gt.Britain's Rock, St.Mary's Scilly Isles.
(Wilson, 1972, Table 15, p.127)

8 'Unaltered medium-grained granite', Porthloo, St.Mary's, Scilly Isles.
(Wilson, 1972, Table 15, p.127)

these are further complicated by considering results in which analytical accuracy is difficult to assess. Any of these problems could be impressively employed as an argument against any attempt at statistical comparisons of the results from the various plutons, though such arguments could equally be applied to any visual or intuitive judgments. The data from the Scilly Isles and St. Austell granite are limited but there are sufficient results from Dartmoor (Hawkes, in Edmonds _et al_, 1968, analyses 1-7, Table 5, p. 105), Land's End (Wilson, 1972, analyses 951-955, 959-960, Table 22 & 23, p. 160/1) and Bodmin Moor (analyses of KEB8, 9, 12, 14, 17, 25 & 34, selected at random from Table 1, p. 13) to be able to apply the Kruskal-Wallis test. As Wilson's (1972) results for silica and alumina are only quoted to the first decimal place these two elements have been ignored. Using the same significance level, $\alpha = 0.05$, as for the test of variability of the Bodmin Moor coarse-grained granite (p. 16), a value of 5.99 is offered by chi square for two degrees of freedom (k-1). The Kruskal-Wallis statistic, H, is tabulated for each element as follows:-

	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O
H =	11.0	9.3	12.0	15.0	4.1	3.3

It is concluded that Fe_2O_3, FeO, MgO and CaO reflect a meaningful variation between the three plutons. A visual comparison of the data suggests that the major cause of this variation can be explained by the relative enrichment of iron and calcium in the Dartmoor granite compared with the other plutons. A possible explanation for these differences is that there has been extra assimilation in the Dartmoor pluton, together with this granite being a slightly more basic differentiate than the other plutons. Certainly assimilation and differentiation have been advocated by Brammall & Harwood (1932) and Hawkes (in Edmonds _et al_, 1968) for differences in the chemistry of the Dartmoor granite and it is probable that these processes have been on a variable scale in the major S. W. England plutons.

B) KEB29-31 and 43

As already noted, specimens KEB29-31 and 43 from the Cheesewring Quarry locality reflect "anomalous" physical and chemical properties when compared with the other coarse-grained granite specimens from Bodmin Moor.

The field and petrographic relations of KEB30 and 31 have been described (p. 6) and their major element chemistry is presented in Table 1. Compared with the coarse-grained granite this chemistry indicates an apparent enrichment in SiO_2 and K_2O with depletion of Al_2O_3, TiO_2, Fe_2O_3, FeO, MgO and CaO. Obviously these are not all "real" variations; an increase in silica, for example, will produce a decrease in the other elements and conversely there will be similar reciprocal relationships (p. 9). Indeed, it is worth noting that when KEB30 and 31 are recalculated into three components and plotted on the Q-Ab-Or and An-Ab-Or diagrams their positions are comparable to other specimens from the same locality (Fig. 2), thus suggesting that there are compensatory relationships in recalculation.

The value of quoting all these apparent variations, however, is manifest in comparing analyses 2, 4 and 8 (Table 6) with their respective counterparts (1, 3 and 7, Table 6) from the other S. W. England plutons. In each case various authors have subdivided the coarse-grained granites on some physical attribute and although different names have been applied to the subdivisions a comparison of the chemical data reveals almost exactly the same variations as recognised above for Bodmin Moor, that is enrichment in SiO_2 and K_2O and depletion in Al_2O_3, TiO_2, Fe_2O_3, FeO, MgO and CaO. For Dartmoor, chemical variation in the 'big-feldspar granite' and 'poorly megacrystic granite' (employing the terminology of Hawkes, in Edmonds et al, 1968) was recognised by both Brammall & Harwood (1932) and Hawkes (op.cit.) and Hawkes actually states (op.cit., p.106) "that, compared with the poorly megacrystic material, the big-feldspar rock is richer in total iron oxides and CaO, but contains approximately 3% less SiO_2". Exley (1959) has also pointed to similar chemical changes in the St. Austell granite and whilst the silica variation is less emphatically displayed in Wilson's (1972) Scilly Isles results it is surprising that no previous author appears to have noticed that the same chemical trends occur in the coarser grained granites throughout S. W. England.

Though it is not suggested that the terminology of the different "coarse-grained granites" of the S. W. England plutons should be immediately changed, the chemical analyses so far carried out seem to indicate that each petrographic group has, at least in general terms, a similar chemistry. It would appear, therefore, that the petrographic terminology has a wider meaning than originally conceived and throughout the rest of this work the term "coarse-grained granite" will be used, as it has already been applied, with relation to the Bodmin Moor granite but with certain chemical implications and "medium-type granite" will be used for material similar in composition to specimens KEB30 and 31 from Bodmin Moor. The latter term is appropriate for most of the S. W. England plutons and in the light of the intermediate chemical nature of the "medium

-type granite", compared to that "coarse-grained granite" and the "fine-grained granite" (to be considered in the following section), its usage is justified. Subsequently, the 'big-feldspar granite' (Hawkes, in Edmonds et al, 1968) or 'giant granite' (Brammall & Harwood, 1923) of Dartmoor, the 'porphyritic (big-feldspar) granite' (Harding & Hawkes, 1971) or 'biotite-muscovite granite' (Exley, 1958) of St. Austell, and the 'coarse-grained granites' (Wilson, 1972) of Land's End and the Scilly Isles will now be expressed as "coarse-grained granite" having a distinct chemical range of composition and the 'poorly megacrystic granite' (Hawkes, op.cit.) or 'blue granite' (Brammall & Harwood, 1923) of Dartmoor, the 'early-lithionite granite' (Exley, 1958) of St. Austell and the 'medium-grained granite' (Wilson, 1972) of the Scilly Isles as "medium-type granite" also with a distinct range of composition, although a somewhat variable texture. Thus, while Exley & Stone (1964) preferred to consider the sub-varieties of various authors as one type, 'coarse, porphyritic biotite granite', in their summary of the coarser grained granites of S. W. England, it is clear that compositional differences are sufficient to introduce a two-fold division.

KEB29 and 43 are regarded as coarse-grained granites which have been chemically affected by "post-consolidation" influences. Exley & Stone (1964) have suggested that the use of "pre" and "post-consolidation", with regard to the Cornubian granites should be avoided as the exact nature of the granite magma is uncertain. For tourmalinization Exley & Stone (1964) prefer to use 'pre-jointing or primary' and 'post-jointing or secondary' though the implication of the meanings remains virtually the same as pre and

Table 7 Major element analyses of fine-grained granites from S.W.England

	1	2	3	4
SiO_2	74.68	73.16	72.5	75.5x
TiO_2	0.16	0.04	0.09	0.28
Al_2O_3	13.25	13.95	15.9	12.5x
Fe_2O_3	0.72	0.03	1.1*	1.70+
FeO	0.71	0.47		
MnO	0.02	0.01	0.01	0.04
MgO	0.25	tr	0.07	0.37
CaO	0.48	0.43	0.35	1.21
Na_2O	2.66	2.57	3.43	2.79
K_2O	5.42	8.16	4.70	5.50
P_2O_5	0.74	0.16		
H_2O+	0.93	0.31		
H_2O-	0.60	0.33		

*Total Fe as Fe_2O_3 +Total Fe as FeO
xEstimated

1 'Aplogranite, fine-grained granite' - intrusive below coarse-grained granite, Haytor Rocks, East Dartmoor.
(Brammall & Harwood, 1932, analysis 3, p.234)

2 'Aplogranite' - intrusive relation to coarse-grained granite, Wittabarrow, Dártmoor.
(Brammall & Harwood, 1932, analysis 8, p.234)

3 'Non-porphyritic lithionite granite' - St.Austell.
(Exley & Stone, 1964, Table 6, p.141)

4 'Microgranite' - Castle-an-Dinas, Land's End.
(Bowler, 1959, Table 6, opp. p.19)

post-consolidation. Little here seems to be gained in discussion of terms so long as their implication remains understood and it is assumed that the descriptions of "mineralised", for KEB29, and "contaminated", for KEB43, are sufficiently indicative of a chemical process which has locally affected part of the granite body after it has been emplaced.

C) The fine-grained granite

Although Reid et al (1910, 1911) mapped four areas of 'fine-grained granite' - near St. Breward, a little west of Bolventor, east of Dozmary Pool and on the hill top near Newel Tor - they are by no means easily distinguished in the field. In fact no evidence was found during the present work of the fine-grained granite at St. Breward or Bolventor and that at Newel Tor, as described by Reid et al (1911), is obscured and rather than being a continuous mass, appears as a group of veins which locally coalesce. As previously indicated in the introduction, the small quarry south of Dozmary Farm is the best exposure of the granite type.

The results of major element analyses of the three specimens from the Dozmary Pool locality are presented in Table 1 from which it is evident that even for such relatively closely associated samples there is a marked range of SiO_2 and K_2O concentrations. This is brought out in the high standard deviations for these elements in Table 2. Comparison with the coarse-grained and medium-type granites reveals that the general trend of SiO_2 and K_2O enrichment and Al_2O_3, TiO_2, Fe_2O_3, FeO, MgO and CaO depletion evident between the coarser granites is continued in the fine-grained granites. (It is for this reason that the use of the term "medium-type granites" is considered valid for KEB30/31 as these rocks lie between the coarse and fine-grained granites in composition, see p. 28). Exley (1966) presents a major element analysis of a leucogranite from Stannon Clay Pit (reproduced in Table 5) and whilst it is recognised that there is a compositional and textural range within the "fine-grained granites" the equality of Na_2O and K_2O and relatively high Al_2O_3 values suggest that Exley's (1966) leucogranite is perhaps more comparable to the aplites (in composition) (see, for example, Exley & Stone, 1964, analysis No. 3, Table 8, p.145) than the fine-grained granites.

There are relatively few fine-grained granite analyses for other S. W. England plutons. Four are presented in Table 7 and it is notable that each analysis, when compared to the respective coarse-grained and medium-type granite analyses from the same pluton (Table 6), reflects a similar trend in composition to that recognised in the coarse, medium and fine-grained granites of Bodmin Moor.

D) The major element chemistry - a discussion

In dealing with the coarse, medium and fine-grained granites it is appreciated that the evidence upon which deductions are to be made is minimal and in some cases insufficient to apply satisfactory statistical tests. Subsequently the conclusions that are to be made should be strictly limited to the few presented analyses and the inference that the conclusions are applicable to the granite as a whole can only be assumed.

The analyses of the major elements have shown that the coarse-grained granite of Bodmin Moor apparently exhibits a limited but nevertheless significant variation, though the results are insufficient to confirm or contradict any of the granite divisions implied by earlier workers (p. 1). It seems probable that similar variations could exist in both the medium and fine-grained granites, such variations reflecting a continuous "spectrum" in chemistry from coarse to fine-grained granite with the whole sequence following a typical magmatic differentiation trend. Some chemical changes would probably also arise from contamination and assimilation of country rock material. The field evidence suggests that the later fractions, i.e. the medium-type and fine-grained granites, may have punctured through the earlier coarse-grained granite so that the actual distribution of the rock types is complex and their relationships obscured by gradational boundaries. In other words, the pluton has probably been in a kind of "plastic" or "semi-mobile" state throughout these periods of injection. Such interpretations and conclusions will be discussed in further detail after consideration of the trace element chemistry.

From the available results it is possible to recognise similar variations for some of the other major S. W. England granites, though the granite types are not necessarily equivalent in chemical composition from one pluton to another, and a similar genetic history to that for the Bodmin Moor granite appears to be a legitimate assumption.

PART III

Trace Element Chemistry

1) Variation in Composition

A) Introduction

In considering the trace element chemistry of the Bodmin Moor granite the same general format will be followed as was used in dealing with the major element variability. Discussion about element concentrations and their relevance is deferred until all the results have been presented.

Although all the results are expressed as parts per million, the statistical implications which arise in presenting the analyses as a constant sum are less important than those that occur in major element chemistry. This is because there is a relative increase in the number of components, and despite the fact that not all of them have been determined, the influence exerted by one component on the remaining components, as a result of variation, is less apparent.

As there are few other recorded trace element analyses of the Bodmin Moor granite, or for that matter for any of the other S. W. England plutons, a few specimens were analysed for a number of elements spectrographically in an attempt to assess the range of chemical concentrations. On the basis of these results the spike series for calibration of the X-ray fluorescence spectrometer (XRF) were prepared (see appendix: XRF analysis). The spectrograph results are reproduced in Table 8, essentially for comparative purposes as all the data considered in the subsequent discussion are exclusively the product of XRF and rapid wet analysis (Na, K, Li).

Table 8 Results of spectrograph analyses

Specimen	Li	Sc	V	Rb	Sr	Y	Cs	Ba	La
KEB1	215			485	42	12	90	92	
KEB2	136			n.d.	34	21	81	119	
KEB5	140			490	56	25	53	119	
KEB8	345		12	440	90	14	70	234	
KEB9	300		12	446	138	24	41	277	
KEB11	243		13	382	93	18	40	404	
KEB12	343		10	454	74	12	61	162	
KEB17	238		11	481	85	22	40	227	
KEB19	330		9	574	73	12	44	125	
KEB21	324		11	569	70	16	54	106	
KEB23	329		16	550	93	18	52	135	
KEB25	228		12	524	84	18	37	136	
KEB32	232		16	652	97	17	40	200	
KEB34	529		22	508	105	26	84	259	
KEB37	295		18	664	135	22	47	294	
KEB40	264		10	688	90	16	50	260	
KEB43	658		22	n.d.	29		93	29	

All values in ppm

Analyst K.Edmondson

n.d. - not determined.

Blanks indicate that concentrations were below the level of detection.

B) Variation in composition in specimens from individual outcrops

Although a 500g hand specimen was found to be representative of an individual outcrop in terms of the major element chemistry of the Bodmin Moor granite, it cannot be assumed that this conclusion is so of the trace element chemistry. As a test, therefore, the two splits of KEB8 (see p. 12) were again analysed and the results are recorded below.

	Cu	Zn	Rb	Sr	Y	Zr	Sn	Cs	Ba	La	Ce	Nd	Pb
a)	0,0	69.4	422.2	89.7	37.5	115.9	18.7	37.1	211.0	29.0	35.4	32.9	43.6
b)	0.0	71.2	426.8	90.2	41.1	116.2	16.9	32.4	208.2	29.1	40.4	34.6	48.8
c)		1.3	2.8	0.4	2.5	0,2	1.3	3.3	2.1	0.1	3.5	1.2	3.7

All values in ppm

a) = KEB8 (analysis of greater part of large quarried block)

b) = KEB8 (analysis of 500g hand specimen from block KEB8)

c) = standard deviation

(Note:- In the subsequent Table 9, the results of all the trace element analyses from Bodmin Moor, KEB8 is represented by a) and not as an average of the two results as was the case in the major element analyses tables).

Other than for Rb, Y, Cs and Pb the standard deviations from the above test fall within the estimated limits of analytical error (see Table 10). Although there is a close affinity between the chemistry of Rb and Cs a conclusive reason for their relatively large variation in the two splits of KEB8 is not readily apparent. It would be convenient to suggest that as the greater concentration of these elements, and possibly also that of Pb, is incorporated in the alkali feldspars, a 500g hand specimen was not adequately representative of an outcrop in this mineral, particularly as the alkali feldspars predominantly occur as megacrysts. Within the

Table 9 Trace Element Analyses

Dozmary Pool — Fine-grained granite KEB1-7 — De Lank Quarries — Coarse-grained granite KEB 8-12/14; Elvan KEB 13

	KEB1	KEB2	KEB3	KEB4	KEB5	KEB6	KEB7	KEB8	KEB9	KEB10	KEB11	KEB12	KEB13	KEB14
LI	192	110	183	155	180	164	156	288	269	253	235	341	108	267
NA	24855	17213	16026	12613	18845	15210	16174	24484	23445	24261	23668	23371	13652	22852
K	42236	54268	43149	51862	46136	45389	47215	40577	41240	38170	43813	40079	59828	42568
CU	11.5	6.8	4.9	5.8	1.6	4.8	7.0	0.0	0.0	0.0	0.0	4.9	31.0	2.1
ZN	56.7	57.8	39.2	44.1	36.9	45.9	51.6	69.4	90.2	71.1	81.4	68.1	37.8	39.5
RB	414	453	459	471	411	423	440	422	450	371	372	428	452	422
SR	46	38	42	37	44	44	48	90	94	94	112	89	123	93
Y	39.5	44.9	42.9	43.8	38.2	37.1	34.6	37.5	42.9	37.1	40.5	46.5	42.4	38.2
ZR	33	32	31	35	38	36	33	118	138	106	138	117	151	109
SN	26.5	26.5	34.1	35.7	22.2	30.9	27.7	18.7	23.5	14.0	20.4	32.0	11.6	24.4
CS	52.5	45.0	57.0	53.5	38.3	44.7	46.0	37.1	30.2	17.1	22.5	42.2	13.8	29.3
BA	106	50	90	111	108	109	98	211	216	189	231	192	226	183
LA	11.6	11.2	12.0	12.3	11.4	12.0	12.3	29.0	32.0	28.0	33.2	34.6	33.6	28.9
CE	2.0	4.0	0.0	2.0	0.0	0.0	8.0	35.4	45.8	37.5	54.0	35.8	43.0	25.1
ND	20.5	20.0	23.2	19.6	15.2	19.1	20.7	32.9	36.1	37.8	41.8	41.8	37.4	33.6
PB	44.8	38.2	43.2	42.5	41.2	41.6	43.7	43.6	45.5	48.2	53.3	43.9	31.7	44.2
TH	5.0	3.7	4.0	6.9	8.5	6.4	5.8	17.5	21.5	19.6	24.1	22.4	23.8	18.2
U	6.8	7.2	2.6	2.4	3.8	2.2	4.0	11.1	13.1	8.1	8.5	11.0	8.2	5.1

De Lank Quarries — Coarse-grained granite KEB15-18
Roughtor — Coarse-grained granite KEB19-25

												ACGG	ELVAN	ACGG
	KEB15	KEB16	KEB17	KEB18	KEB19	KEB20	KEB21	KEB22	KEB23	KEB24	KEB25	KEB26	KEB27	KEB28
LI	254	133	250	291	257	193	237	221	234	110	166	201	225	108
NA	23816	18623	20032	26265	23371	20403	24484	22406	23565	19216	23148	16174	15581	16323
K	41489	47258	44560	40162	43149	39166	41987	40577	38336	45472	40494	48211	46551	53936
CU	0.0	10.3	0.4	0.0	0.0	2.7	0.0	0.0	0.0	8.4	0.0	4.9	32.5	13.2
ZN	48.0	36.7	50.7	66.2	49.3	71.2	52.8	46.9	50.6	61.0	59.3	39.1	48.4	46.9
RB	436	411	462	417	492	487	483	458	489	421	426	465	413	461
SR	89	55	87	89	68	53	63	68	57	63	59	81	110	72
Y	41.7	38.0	49.8	37.6	49.1	41.9	47.4	46.1	48.1	41.9	42.1	46.1	45.4	61.6
ZR	128	104	149	101	93	103	110	101	123	127	142	129	190	151
SN	24.6	24.8	27.3	24.1	19.4	19.3	19.7	12.8	16.1	18.5	13.3	13.4	6.9	15.7
CS	35.3	15.8	27.6	25.7	33.6	31.5	37.1	23.0	34.3	17.6	26.1	28.0	27.0	21.0
BA	170	204	198	183	110	86	97	127	98	130	70	176	288	225
LA	32.4	28.1	36.3	28.8	25.9	27.6	27.3	22.4	27.9	34.0	29.9	38.9	42.6	41.2
CE	37.4	32.0	45.4	32.9	24.2	37.4	33.4	24.5	32.5	38.5	34.1	49.4	60.9	53.1
ND	40.9	32.7	41.3	33.8	31.9	41.2	31.7	26.8	32.6	37.7	38.6	42.2	48.7	42.2
PB	45.9	43.8	48.1	48.4	40.9	44.6	39.1	41.3	37.5	37.1	35.8	30.4	36.7	31.1
TH	22.2	20.4	25.2	17.0	16.9	19.2	20.9	16.3	18.5	22.2	19.8	23.6	26.6	32.5
U	13.0	5.1	7.8	12.3	1.4	1.3	7.2	0.1	5.2	12.9	11.5	10.4	9.1	15.2

Cheesewring Quarry — Coarse-grained granite KEB32-42
'Contaminated' coarse-grained granite KEB30/31/43
Mineralised coarse-grained granite KEB29

	KEB29	KEB30	KEB31	KEB32	KEB33	KEB34	KEB36	KEB37	KEB38	KEB39	KEB40	KEB41	KEB42	KEB43
LI	222	136	238	180	282	450	215	230	411	217	268	198	243	372
NA	3710	17555	17806	16545	18103	19068	22258	18845	20403	16842	18400	23371	18548	25300
K	51530	46365	45953	48626	45721	44808	40660	45472	43813	43598	48128	43896	42153	38917
CU	384.5	25.3	102.5	22.0	3.5	248.1	6.7	4.6	5.6	17.1	348.6	17.6	7.4	1.8
ZN	129.7	60.4	55.9	91.0	70.1	181.3	58.8	52.6	67.2	52.9	235.7	50.9	62.3	80.0
RB	415	513	521	454	501	540	432	460	488	422	442	414	432	533
SR	87	33	34	85	79	80	85	90	50	77	87	91	79	22
Y	35.7	50.4	49.8	45.6	48.5	47.5	41.5	40.7	44.3	42.1	42.0	38.0	40.0	47.7
ZR	128	68	54	115	120	144	136	124	141	145	111	106	128	17
SN	24.2	20.5	17.3	15.4	17.4	18.3	13.7	13.0	18.0	18.9	16.3	13.1	17.0	20.8
CS	17.6	29.0	26.9	23.2	34.5	56.1	26.0	29.0	45.1	26.9	32.5	25.6	31.4	36.4
BA	267	19	45	200	177	135	135	163	172	182	202	199	155	36
LA	44.2	18.0	18.1	29.3	28.2	35.5	30.7	30.6	35.2	39.9	28.0	28.3	31.3	12.5
CE	63.0	11.7	7.0	32.6	29.8	43.0	44.5	42.7	42.2	55.6	34.4	35.8	40.0	3.0
ND	47.5	28.4	31.1	39.0	37.5	43.2	36.8	42.2	38.6	47.0	34.5	33.9	35.7	24.8
PB	33.1	26.2	41.2	44.8	38.9	42.3	38.4	35.6	40.1	30.9	52.2	38.2	33.2	28.9
TH	26.2	14.8	15.3	20.9	21.4	22.8	20.9	20.4	15.7	23.4	15.5	18.4	19.5	12.5
U	8.2	5.2	19.7	7.5	7.6	5.8	2.1	2.0	3.8	7.4	10.3	11.3	13.0	1.5

Table 9 Trace Element Analyses (continued)

	CCGV	CGG	CGG	YCGG	CGG	CGG	ELVAN	ACGG	CGG	CGG	CGG	CCGG	CGG	CGG
	EB45	KEB400	KEB401	KEB402	KEB403	KEB404	KEB405	KEB406	KEB407	KEB408	KEB409	KEB410	KEB411	KEB412
LI	332	152	229	51	89	219	89	168	216	114	103	215	120	319
NA	20597	14839	21813	13874	16026	19068	6232	21739	18548	20477	17139	742	20774	21145
K	43196	49123	43481	61570	42983	48377	46800	42734	45057	50783	43647	60657	31615	46468
CU	0.0	200.2	0.0	16.7	4.8	0.0	36.5	24.5	2.1	31.3	259.1	0.0	0.0	0.0
ZN	44.9	44.6	50.1	33.4	45.7	57.5	18.7	45.4	41.3	42.6	81.1	65.5	58.7	39.0
RB	532	585	462	477	402	493	335	478	455	441	409	761	338	521
SR	56	37	83	116	96	87	46	80	83	82	110	23	61	75
Y	45.2	55.7	46.9	44.9	41.0	49.5	33.7	50.0	46.8	50.7	55.3	80.0	37.7	48.3
ZR	56	70	146	165	181	144	90	148	125	165	116	78	164	122
SN	19.8	45.0	13.1	56.8	21.6	11.4	16.3	25.4	12.6	24.4	15.8	66.6	18.1	17.4
CS	52.1	47.1	30.3	13.5	14.9	23.1	16.6	27.7	28.5	22.5	12.5	52.5	14.5	30.6
BA	134	116	191	425	255	231	201	197	193	203	202	182	74	178
LA	18.1	17.2	35.0	52.9	52.2	34.0	26.5	26.8	26.1	38.1	32.7	17.7	38.5	26.6
CE	15.5	20.9	49.0	78.6	74.1	46.9	36.6	36.1	33.3	66.9	44.4	18.6	65.0	38.4
ND	26.4	21.3	42.0	50.8	52.9	40.1	35.5	35.2	32.9	43.6	34.0	24.0	42.8	33.4
PB	37.5	27.2	38.0	33.7	30.0	40.3	30.4	38.7	36.7	33.0	46.5	17.0	26.2	39.1
TH	12.3	13.4	26.8	33.4	35.3	29.4	16.9	21.6	18.5	32.3	20.5	18.0	25.3	20.1
U	11.9	16.4	6.5	11.9	10.4	9.8	8.0	5.6	5.0	16.5	10.9	5.8	10.6	5.1

	CCGG	XCGG	CGG	XCGG	WCGG	CCG	ACGG	AFGG	CCG	ACGG	CGG	WCGG	CGG	VCGG
	KEB413	KEB414	KEB415	KEB416	KEB417	KEB418	KEB419	KEB420	KEB421	KEB422	KEB423	KEB424	KEB425	KEB426
LI	197	98	339	472	270	298	86	211	135	160	278	361	344	263
NA	13058	15358	22110	22555	18994	20181	16990	15558	20597	8977	15803	20329	20923	1855
K	46219	51364	37008	42568	46883	41157	57338	50036	39830	64972	50534	46468	50119	62898
CU	15.5	14.0	0.0	0.0	0.0	0.0	4.9	0.0	2.4	10.9	0.0	0.0	0.0	46.1
ZN	87.1	43.9	54.2	51.1	51.1	57.6	32.9	65.9	41.5	44.3	47.7	47.7	47.7	37.5
RB	476	443	463	610	534	466	459	456	352	502	568	521	559	732
SR	89	89	68	35	59	67	66	110	55	80	45	66	59	79
Y	48.6	48.0	49.5	58.6	52.5	43.0	43.2	46.7	31.6	46.3	49.9	47.4	49.3	71.2
ZR	116	135	132	52	83	120	110	178	79	125	50	118	62	90
SN	24.1	23.8	15.5	44.2	44.2	16.0	24.1	8.9	10.6	40.8	19.9	20.3	8.5	523.4
CS	30.9	15.6	33.2	78.5	64.9	34.7	30.0	15.3	22.6	23.2	41.5	51.3	29.1	47.9
BA	254	244	104	65	123	142	217	271	81	276	112	72	113	221
LA	27.6	31.9	33.1	19.3	23.4	27.4	28.0	39.4	18.7	26.1	13.4	30.9	16.1	28.1
CE	38.4	54.9	51.9	14.9	28.9	33.9	34.3	60.7	15.1	33.8	8.2	35.9	13.6	35.3
ND	34.4	36.7	37.8	27.4	29.1	32.6	35.8	42.9	29.3	31.3	21.5	31.6	20.1	33.6
PB	49.9	35.7	41.1	29.0	29.0	35.7	31.4	37.9	36.2	42.4	31.9	41.0	39.0	31.0
TH	16.6	21.6	20.9	13.6	18.0	21.7	19.7	31.4	13.6	19.3	8.8	23.0	37.0	18.0
U	11.7	7.3	13.1	4.8	6.2	9.1	7.9	10.9	12.3	11.1	5.2	12.0	8.7	8.5

	CCG	CGG	CGG	WCGG	CV	ELVAN	PBG	ELVAN	CGG	CGG	CGG	CCG	ELVAN	XCGG
	KEB427	KEB428	KEB429	KEB430	KEB431	EB69	EB76	EB79	EB101	EB119	EB121	EB123	EB164	EB190
LI	187	193	171	169	207	0	48	157	277	87	72	93	63	376
NA	16471	20626	17658	22926	1113	1855	15358	16516	25077	17881	15506	22406	16694	28639
K	50783	43066	44145	41489	40908	82896	60077	45555	44311	45223	44311	42568	41987	36262
CU	0.0	0.0	0.0	26.0	27.4	0.0	0.0	0.0	0.0	1.5	0.0	0.0	79.5	0.0
ZN	63.0	46.5	41.7	81.1	45.7	14.6	8.9	66.2	53.3	105.6	41.5	39.9	42.4	52.5
RB	424	397	434	444	276	473	611	466	499	386	403	362	380	466
SR	77	75	79	65	27	63	70	76	72	97	85	102	129	35
Y	48.9	41.0	41.4	42.0	23.0	44.3	60.9	44.7	44.7	32.3	38.3	31.8	38.5	44.3
ZR	196	124	169	138	89	119	188	183	103	130	129	119	166	34
SN	15.7	19.5	9.9	15.9	15.2	14.6	33.5	22.4	17.4	15.0	25.5	12.7	41.5	28.1
CS	19.6	32.5	19.9	27.1	3.4	23.8	11.8	14.0	30.8	7.7	12.6	9.7	18.3	44.7
BA	181	155	149	103	279	193	448	98	152	245	174	164	181	94
LA	34.7	25.7	41.2	32.7	16.1	28.0	34.0	36.0	24.5	31.4	30.1	34.6	45.7	19.2
CE	47.5	35.5	71.1	47.3	0.0	38.9	50.2	52.7	22.9	40.2	32.9	45.2	68.9	6.0
ND	41.4	36.7	48.2	35.7	35.6	33.3	35.8	41.1	29.8	36.1	36.7	36.6	45.4	23.2
PB	49.2	39.0	38.9	39.6	21.4	12.6	20.6	21.8	38.4	62.7	44.3	48.8	32.7	24.0
TH	19.2	9.0	27.0	21.1	22.1	23.4	41.6	33.8	14.3	20.4	20.8	22.1	34.9	1.2
U	8.9	9.6	11.2	7.7	19.0	13.6	16.8	11.9	6.3	3.3	12.9	2.6	15.2	17.0

Table 9 Trace Element Analyses (continued)

	VCGG	CGG	CGG	XCGG	XCGG	XCGG	XCGG	XCGG	MCGG	ELVAN	ACGG	ACGG	CGG	CGG
	E8195	KEB500	KEB501	KEB502	KEB503	KEB504	KEB505	KEB506	KEB507	KEB508	KEB509	KEB510	KEB512	KEB513
LI	387	313	312	353	313	154	158	59	144	60	96	59	306	418
NA	28342	16100	17361	18548	15358	23742	24039	16323	18845	4674	19513	1484	18919	12242
K	33523	42734	42485	43647	42153	37091	27300	43730	43647	58168	48957	60989	41738	42319
CU	0.0	0.0	0.0	0.0	0.0	0.0	0.0	11.9	0.0	11.6	16.2	3.2	3.8	0.0
ZN	77.2	47.6	48.1	50.7	56.7	28.7	64.6	48.2	43.0	27.9	31.0	26.9	68.4	44.5
RB	520	455	453	473	507	441	374	349	423	700	494	480	482	486
SR	83	64	85	88	57	44	74	90	75	45	78	62	76	90
Y	48.8	45.7	44.5	48.3	44.3	37.1	32.6	31.5	44.1	65.0	46.6	55.0	47.3	45.9
ZR	149	124	126	133	152	36	145	40	176	31	155	153	109	118
SN	35.2	16.8	14.9	20.0	21.1	15.9	15.8	20.1	14.4	71.7	65.5	50.9	20.2	23.4
CS	56.9	35.7	17.7	56.7	37.1	13.8	11.4	12.0	15.7	29.4	34.2	14.6	40.3	63.4
BA	180	184	163	216	118	97	191	282	181	360	307	327	197	218
LA	25.3	26.8	26.5	31.4	31.9	11.8	29.4	11.9	38.4	10.3	37.5	48.0	25.0	24.9
CE	44.2	36.0	31.2	34.8	39.7	8.9	42.0	8.0	59.2	8.0	59.1	69.8	31.1	28.7
ND	34.4	31.7	32.9	32.9	39.7	19.2	40.3	20.6	41.7	21.6	41.3	58.0	35.2	29.6
PB	37.4	35.1	37.8	37.9	32.4	40.0	36.0	70.1	33.1	3.0	28.5	28.9	37.7	40.7
TH	22.1	5.9	10.8	12.6	18.5	1.4	18.3	1.8	22.4	1.6	20.2	22.9	9.7	11.5
U	5.4	7.1	4.0	8.4	10.5	19.0	17.7	15.3	14.2	13.6	21.9	36.1	21.8	13.0

	PEG	CGG	CGG	CGG	PEG	CGG	CGG	ELVAN	ELVAN	CGG	CGG	ELVAN	ACGG	VCGG
	KEB514	KEB515	KEB516	KEB517	KEB519	KEB520	KEB521	KEB522	KEB523	KEB524	KEB525	KEB526	KEB527	KEB528
LI	47	216	326	317	154	345	95	69	70	0	155	149	138	186
NA	4571	17806	18326	17510	22555	21442	17065	742	7419	21665	19290	11055	20774	742
K	75411	48708	46800	43232	46551	40743	51698	65138	61487	45638	41655	66964	52774	25474
CU	0.0	0.0	0.0	0.0	0.0	0.0	0.0	16.0	10.5	0.0	39.4	0.0	3.0	21.1
ZN	7.6	48.5	46.5	36.6	43.0	56.5	43.6	20.0	31.7	45.1	54.5	14.2	36.8	28.0
RB	541	456	473	463	377	426	456	574	630	477	522	521	501	433
SR	115	82	89	81	122	88	82	50	68	87	56	108	40	39
Y	45.2	42.5	44.7	44.6	35.9	41.3	46.8	50.6	60.3	40.6	48.5	40.3	44.3	33.7
ZR	80	102	132	131	138	140	184	176	139	123	71	146	62	190
SN	11.2	16.2	12.8	14.3	16.7	18.6	13.0	22.0	41.0	8.0	22.7	21.0	15.3	86.2
CS	12.9	18.7	37.3	30.7	17.7	34.5	14.9	29.6	39.2	26.9	34.0	25.9	26.9	24.0
BA	671	207	235	197	244	186	228	198	315	237	151	254	118	302
LA	35.5	25.4	29.4	25.4	22.5	30.1	41.5	33.3	37.4	30.5	17.6	35.8	17.2	34.5
CE	52.9	15.7	27.1	20.4	24.2	39.3	58.3	48.8	52.9	38.6	14.7	56.4	14.4	45.0
ND	38.0	25.6	35.8	37.0	31.5	36.3	47.2	35.2	46.3	38.0	28.4	43.0	25.4	39.2
PB	25.0	34.9	39.5	28.6	29.0	38.4	35.1	10.0	17.3	38.9	28.8	10.6	21.3	9.8
TH	10.1	14.3	7.1	6.3	14.3	11.3	22.7	21.8	16.9	12.6	5.0	16.9	4.0	30.7
U	13.5	15.4	7.3	11.6	15.6	14.6	14.2	13.6	15.1	17.5	20.5	4.3	6.7	4.1

	CGG	ACGG	ELVAN	ACGG	CGG	ACGG	CGG	MCGG	PEG	MCGG	CGG	XCGG	CGG	CGG
	KEB529	KEB530	KEB531	KEB532	KEB533	KEB534	KEB536	KEB537	KEB538	KEB539	KEB540	KEB541	KEB542	KEB543
LI	305	336	178	142	217	173	249	129	138	305	353	135	263	249
NA	21516	27155	17065	11648	21145	371	23519	742	742	1558	17213	21813	24113	22703
K	38336	38170	49372	59745	46385	56260	40660	39415	64806	48211	46883	39747	37589	43813
CU	0.0	0.0	0.0	0.0	0.0	185.3	11.3	5.9	4.1	17.7	0.0	0.0	0.0	0.0
ZN	43.4	35.5	49.3	25.6	79.2	39.7	67.6	44.4	43.0	47.0	47.2	62.3	70.3	45.7
RB	443	416	420	516	452	541	469	447	788	596	462	388	474	438
SR	75	76	108	78	90	38	87	67	65	49	87	48	71	88
Y	44.6	47.4	44.1	47.7	43.3	51.0	40.6	44.7	76.3	55.6	43.5	43.3	42.6	39.6
ZR	145	141	182	81	162	166	110	131	88	86	125	143	107	151
SN	12.6	14.1	7.8	17.9	10.6	87.8	20.5	35.2	36.2	24.3	16.6	11.1	15.1	9.4
CS	27.1	32.5	18.4	28.1	22.4	14.8	28.3	14.2	45.8	73.4	32.2	12.4	28.4	24.7
BA	177	154	312	292	218	249	216	405	364	171	203	107	176	229
LA	33.3	30.4	37.2	24.3	34.2	42.5	26.2	32.9	25.0	20.3	24.6	34.7	22.2	36.6
CE	45.3	33.6	49.1	22.3	45.2	67.4	33.7	40.5	22.6	13.6	30.3	46.6	22.8	42.7
ND	37.6	41.5	41.1	35.4	40.6	51.7	35.3	35.0	31.0	29.9	32.5	41.6	28.3	43.0
PB	36.2	37.7	44.5	37.6	38.9	21.0	48.2	83.1	21.2	34.0	35.3	31.6	43.9	39.2
TH	20.8	15.3	16.9	10.6	21.4	28.5	10.3	12.8	5.9	7.0	11.9	28.8	9.6	23.4
U	3.8	4.6	8.6	3.3	3.2	8.0	8.1	18.3	5.7	3.1	6.7	15.5	2.5	3.6

Table 9 Trace Element Analyses (continued)

	CGG	CGG	CGG	FGG	CGG	CGG	CGG	AP	CGG	CGG	MCGG	CGG	CGG	CGG
	KEB544	KEB545	KEB546	KEB547	KEB548	KEB549	KEB550	KEB551	KEB552	KEB44	KEB65	KEB108	KEB115	KEB116
LI	159	126	314	188	307	348	291	135	377	270	105	227	262	266
NA	20403	19365	20700	25226	24558	21590	22184	34574	21687	21071	1113	20997	22258	21071
K	46551	44808	45472	37672	36428	44394	41157	34187	43564	43730	49040	44145	41738	44311
CU	0.0	11.2	0.0	18.5	0.0	0.0	0.0	0.0	0.0	0.0	13.8	0.0	0.0	0.0
ZN	35.8	41.7	52.4	37.9	60.8	45.7	50.5	15.3	53.9	74.4	56.6	65.9	72.9	65.7
RB	440	475	475	498	511	468	449	469	480	472	454	463	420	412
SR	91	70	88	24	71	88	83	29	89	82	72	84	92	81
Y	40.4	44.0	44.0	42.1	52.9	44.5	44.1	29.8	42.9	44.3	44.0	40.4	34.9	39.1
ZR	161	87	131	53	181	120	170	0	146	112	144	144	132	147
SN	18.8	19.6	15.0	11.2	16.9	10.1	14.7	15.4	18.6	10.2	28.7	21.0	19.6	31.0
CS	15.1	17.6	36.4	19.0	38.0	25.7	24.1	18.7	39.0	16.8	14.6	19.1	20.4	21.7
BA	229	216	205	56	150	243	188	42	205	207	268	228	212	178
LA	39.8	28.8	29.6	15.5	38.7	27.5	36.7	5.6	29.3	24.3	48.9	31.1	30.5	35.6
CE	45.0	25.6	33.6	13.4	50.6	39.2	56.3	29.8	35.6	23.1	55.1	38.3	50.0	49.1
ND	50.7	34.1	38.1	28.2	43.6	30.8	40.4	17.3	36.7	34.8	44.7	36.0	39.5	33.4
PB	36.0	27.6	42.2	29.1	31.3	41.9	32.5	8.4	39.3	35.0	107.0	37.0	45.0	46.0
TH	20.6	9.1	13.1	4.6	26.2	18.0	26.7	2.6	15.5	8.4	15.0	15.0	13.0	16.0
U	8.1	5.9	3.2	6.1	1.9	9.2	5.9	1.4	6.1	7.2	0.5	2.1	9.4	6.2

	QV	MCGG	CGG	CGG	CGG	CGG	CGG	CGG	CGG	CGG	CGG	CGG	CGG	CGG
	KEB117	KEB119	KEB131	KEB132	KEB135	KEB138	KEB139	KEB140	KEB141	KEB142	KEB143	KEB144	KEB145	KEB149
LI	451	56	195	238	208	141	212	309	252	339	219	290	319	536
NA	16100	3784	23519	24855	20255	18623	21145	20700	22406	18326	21665	22184	23371	22926
K	48791	48128	41489	42485	44228	47713	47630	42583	43564	42236	52774	40411	41323	39332
CU	7.9	31.9	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ZN	45.3	47.1	101.0	67.5	59.1	131.3	46.6	50.2	44.8	60.6	37.1	57.8	124.9	43.5
RB	550	458	420	413	436	462	509	476	480	486	461	457	463	535
SR	59	88	90	95	82	75	80	80	91	71	101	84	77	52
Y	51.2	76.6	39.2	38.1	44.8	42.9	46.4	43.5	43.9	47.3	43.2	44.9	49.8	54.8
ZR	93	190	122	119	161	161	110	119	106	131	65	142	144	83
SN	33.1	16.7	18.5	18.3	11.4	15.3	16.8	20.9	15.8	20.1	14.0	15.0	13.0	28.7
CS	66.2	16.4	19.7	27.1	18.5	18.4	31.9	39.7	41.1	26.8	36.8	30.9	30.9	99.9
BA	70	276	210	209	191	198	197	168	216	184	242	188	175	105
LA	24.5	77.4	27.7	31.4	36.5	33.6	21.6	27.1	25.1	31.6	20.5	28.0	29.1	21.0
CE	29.5	112.0	31.2	38.7	49.8	41.1	20.7	22.8	21.6	41.3	14.2	38.9	41.4	14.7
ND	32.1	86.5	28.3	37.2	40.0	42.7	25.3	29.6	35.8	42.8	26.6	33.8	32.4	23.6
PB	28.0	40.0	41.0	44.0	38.0	35.0	41.0	37.0	41.0	44.0	48.0	33.0	37.0	33.0
TH	8.3	30.0	11.0	15.0	25.0	21.0	13.0	8.0	9.9	21.0	5.0	13.0	18.0	6.3
U	1.0	1.1	0.8	5.3	9.2	2.7	3.2	1.2	2.7	13.0	9.2	11.0	12.0	2.8

	CGG	CGG	CGG	CGG	ACGG	MCGG	CGG	CGG	CGG	AP	CGG	CGG	CGG	CGG
	KEB151	KEB160	KEB161	KEB162	KEB172	KEB153	A	C	E	N(40)	N(97)	P	12	14A
LI	230	412	171	336	203	275	313	117	.75	71	225	105	227	248
NA	19558	23565	18919	28490	16842	6084	19810	9348	19558	445	21145	17732	14913	23074
K	45289	39166	52940	40245	44726	41572	42651	54766	49289	3734	47713	51198	52526	48543
CU	1.3	0.0	0.0	0.0	108.9	2.4	0.0	82.5	0.0	21.2	1.2	2.6	5.3	17.5
ZN	52.9	42.5	127.0	53.0	65.5	70.5	55.6	44.7	41.6	32.6	44.2	32.4	34.0	50.0
RB	540	558	491	536	504	506	443	482	468	690	556	455	535	504
SR	54	52	51	51	105	54	95	74	91	56	60	83	74	77
Y	48.1	45.7	46.3	51.7	49.6	44.2	44.7	41.3	37.2	56.5	45.8	40.9	47.6	46.4
ZR	80	124	41	75	183	162	166	125	103	35	68	111	116	117
SN	29.7	17.9	21.2	22.0	19.6	12.4	16.2	17.9	18.0	47.0	16.9	18.5	25.0	18.0
CS	38.9	39.9	20.7	56.4	26.0	37.9	43.4	24.7	21.1	27.6	38.6	15.8	45.7	45.0
BA	130	129	159	119	244	158	113	237	114	253	154	217	164	182
LA	20.9	15.5	34.4	19.1	41.2	30.2	32.7	31.7	25.3	10.7	20.0	27.8	25.9	27.3
CE	21.2	6.7	35.4	16.7	56.0	42.9	41.6	39.0	31.2	2.8	20.5	36.1	34.4	38.6
ND	27.3	22.8	40.0	26.6	48.4	34.5	34.5	36.3	27.4	21.5	25.5	30.9	28.2	32.8
PB	131.0	31.0	30.0	30.0	24.0	51.0	32.3	32.5	36.0	6.4	25.8	29.0	30.6	36.1
TH	4.7	0.6	15.0	7.8	27.0	21.0	17.6	15.5	9.4	0.4	6.7	11.9	13.1	12.3
U	5.7	2.3	8.5	6.6	12.0	3.0	14.2	11.9	9.5	1.2	13.5	10.1	7.0	1.8

Table 9 Trace Element Analyses (continued)

	AP	MCGG	MFGG	MCGG	MCGG	MCGG	MCGG	XCGG	ACGG	CGG	ACGG	ACGG	CGG	XCGG
	E1(19)	E1(56)	E1(65)	E2(38)	E2(39)	E2(63)	W1	K2	C216	C217	C218(6)	C218(45)	L104(26)	04(40
LI	109	115	193	129	94	129	190	142	189	168	133	151	419	286
NA	148	0	0	668	742	668	0	668	17584	11426	18103	8235	17806	12474
K	45821	2406	23060	61487	61985	59081	30785	61985	46566	50617	45787	48294	35996	46385
CU	69.4	2136.7	146.1	101.9	61.9	53.6	55.6	1.7	16.3	296.0	0.0	0.0	0.0	0.0
ZN	98.7	127.5	90.5	30.6	39.1	23.5	34.4	88.1	70.2	56.8	107.1	105.2	60.6	44.8
RB	564	51	355	577	551	578	435	578	458	504	453	446	546	575
SR	17	49	72	49	54	38	23	42	76	71	85	85	72	43
Y	48.4	7.0	33.0	53.1	63.3	53.7	39.8	53.7	49.9	42.3	40.1	44.2	54.8	56.8
ZR	0	0	141	168	164	165	179	169	130	101	135	145	138	56
SN	41.3	36.0	98.8	51.6	43.7	80.0	56.6	31.9	21.0	22.4	13.1	10.4	27.5	22.9
CS	19.7	4.3	18.5	16.5	16.1	18.1	20.9	23.6	30.4	28.2	15.6	16.5	53.4	44.7
BA	129	0	107	260	295	278	33	295	166	204	242	244	198	78
LA	7.8	13.5	52.6	38.1	44.6	37.5	51.4	41.2	30.2	23.7	32.4	30.9	27.3	16.3
CE	0.0	83.4	88.7	57.5	66.4	50.0	74.2	63.5	46.4	33.4	44.7	41.4	40.0	12.2
ND	15.1	27.5	56.9	45.9	45.9	36.8	53.0	46.6	38.6	24.2	39.5	32.5	35.7	25.5
PB	24.9	54.0	48.0	26.0	29.0	14.0	8.1	23.0	35.0	39.0	40.0	45.0	30.0	31.0
TH	0.3	0.9	24.0	24.0	22.0	26.0	26.0	28.0	19.0	9.0	22.0	17.0	16.0	1.2
U	5.6	4.4	32.0	13.0	3.8	3.4	4.3	14.0	11.0	3.5	15.0	11.0	6.4	0.5

	AP	CGG	CCGG	XCGG	CCGG	CCGG	CGG	CGG	CGG	MCGG	CGG	WCGG	VCGG
	L111	L114	CHA	DPE2	BSE3	F3	119	121	123	124	125	HARR	LL
LI	94	429	324	386	369	242	116	376	481	265	384	349	165
NA	371	21368	74	18103	1410	668	17955	21739	19513	742	21516	16026	21887
K	66881	42817	13608	41987	46468	45721	49289	43315	45887	51281	47381	46634	44311
CU	0.0	0.0	4.1	23.7	35.0	5.2	0.0	0.0	0.0	5.0	0.0	11.1	2.6
ZN	29.3	59.1	67.4	56.9	51.9	45.5	37.1	66.1	50.1	40.0	48.9	42.9	80.4
RB	509	493	423	548	585	626	450	512	537	576	520	485	503
SR	81	58	53	67	48	43	101	56	59	43	60	45	61
Y	47.6	48.7	37.0	53.8	48.4	58.2	46.9	51.2	50.0	52.5	44.9	46.6	52.7
ZR	102	110	146	101	95	63	112	90	99	96	98	28	80
SN	13.0	22.6	24.4	23.5	30.4	31.7	19.1	20.7	31.0	37.7	30.9	33.4	17.9
CS	33.1	53.2	50.2	69.9	72.5	73.2	21.7	49.1	66.8	67.4	59.4	75.3	31.9
BA	255	115	71	163	142	156	213	109	119	140	88	73	34
LA	27.7	24.8	33.5	24.1	29.7	22.8	31.1	23.7	26.1	28.4	24.3	11.8	19.0
CE	34.7	28.2	45.2	26.8	32.0	10.6	37.7	28.5	32.6	36.0	27.5	5.2	17.8
ND	35.7	33.9	39.7	32.2	32.3	26.6	41.6	29.3	28.8	31.0	30.6	19.8	26.2
PB	24.0	36.0	32.0	27.0	28.0	28.0	29.0	33.0	35.0	32.0	33.0	46.0	32.0
TH	6.9	8.8	14.0	10.0	12.0	4.5	14.0	8.0	8.5	9.5	10.0	0.3	7.2
U	8.8	2.5	10.0	4.4	7.7	6.9	13.0	6.8	4.5	5.8	12.0	1.2	3.0

All values are quoted in ppm

Analyst K.Edmondson

To aid computer formating and print out of these tables, analyses are quoted to the first decimal place for those elements in which at least one value is less than 10ppm. For elements in which all the concentrations are higher than 10ppm the values have been rounded to the nearest whole number.

AFGG - Altered fine-grained granite
FGG - Fine-grained granite
ACGG - Altered coarse-grained granite
MCGG - Mineralised coarse-grained granite
XCGG - Contaminated coarse-grained granite
VCGG - Veined coarse-grained granite
WCGG - Weathered coarse-grained granite
CCGG - Kaolinised coarse-grained granite
PEG - Pegmatite
AP - Aplite
CGG - Coarse-grained granite
QV - Quartz vein
CV - Chlorite veined granite

Table 10 Summary of trace element chemistry and standard deviations for the Bodmin Moor granite.

	1	2	3		4		5		6		7		8		9	
Li			163	27	254	56	217	71	262	90	269	91	233	77	220	104
Na			20303	2149	23045	2223	22378	1927	19562	2519	19266	2223	21267	2186	16717	7706
K			47502	4559	41947	2653	41284	2404	45346	3813	44600	2487	43688	3979	45745	9411
Cu			6.1	3.0	1.8	3.4	1.6	3.2	86	136	68	123	33	90	30	161
Zn	2.1	1.3	48	8.6	62	18	56	8.5	93	55	92	64	70	39	55	27
Rb	2.5	2.8	444	31	419	29	465	31	469	46	458	40	451	41	477	77
Sr	1.8	0.4	43	4.0	94	7.4	61	5.2	73	24	84	5.2	71	23	72	22
Y	0.7	2.5	40	3.8	41	4.3	45	3.2	44	4.5	43	3.4	43	4.4	45	8.1
Zr	9.3	0.2	34	2.4	121	17	114	17	110	38	127	14	99	40	116	43
Sn	1.5	1.3	29	4.7	23	4.9	17	3.0	17	3.1	16	2.2	21	6.0	26	39
Cs	0.7	3.3	48	6.4	28	8.5	29	7.0	31	9.6	33	10	32	11	31	16
Ba	4.2	2.1	102	9.0	196	21	103	22	149	71	172	25	144	58	183	83
La	1.7	0.1	12	0.4	31	3.0	28	3.6	29	8.6	32	4.0	27	8.9	29	9.7
Ce	3.5	3.5	2.3	2.9	38	8.2	32	5.7	35	17	40	7.4	29	17	36	18
Nd	3.9	1.2	20	2.4	37	3.9	35	4.5	37	6.5	39	4.1	34	8.2	35	8.8
Pb	2.6	3.7	42	2.3	46	3.1	39	3.0	38	6.8	40	5.9	41	5.8	36	13

(Blank spaces indicate that results have not been calculated)

For Li analytical error see appendix; major element chemistry.

For Na and K analytical error see Table 2.

1 Analytical error (standard deviation based on 2x instrument relative deviation, as quoted in Tables XRF1 & 2, of KEB8, Table 9.

2 Standard deviation in analyses from one outcrop.

3 Mean and standard deviation in locality sampling - Dozmary Pool.

4 Mean and standard deviation in locality sampling - De Lank Quarries.

5 Mean and standard deviation in locality sampling - Cheesewring Quarry.

6 Mean and standard deviation in locality sampling - Cheesewring Quarry, but excluding KEB29/30/31/43

7 Mean and standard deviation in 3, 4, 5, & 6.

8 Mean and standard deviation in analyses quoted in Table 9

present limits of experimental error, however, Na and K for a 500g sample are typical of an outcrop and whilst it might have been anticipated that any inadequacies in the alkali feldspar content would also have been reflected in the standard deviations of these elements, this is not the case. Any shortcomings in outcrop sampling with regard to the alkali feldspar megacrysts, therefore, remains unproven.

C) Variation in composition in locality sampling

The results of the trace element analyses of the samples collected from the four test localities are given in Table 9, with the means and standard deviations summarised in Table 10. By expressing the standard deviations on a partitioned scale it is possible to see the contribution to the overall standard deviation of each element from the various levels of sampling. Thus, for Sn, Ce, Nd, Zr, Pb and La the analytical errors will predominate as the largest component of standard deviation in locality composition.

In the subsequent analyses of the other localities each sampling "circle" (see Fig. 1) is represented by a single specimen and even where it was possible to collect two or more specimens they have been treated individually rather than being bulked or averaged. Some patterns of regional variations, therefore, may be masked or obscured by the standard deviations arising from the scale of outcrop and locality sampling. Though it might have been logical to have collected and analysed several specimens per outcrop or per locality to reduce these errors, exposure is a limiting factor. There is little benefit in collecting and bulking, say, ten specimens from one locality when another locality can only be represented by one specimen at the most.

Tests to determine whether any meaningful variations exist in the trace element chemistry of the Bodmin Moor granite and associated rocks will be considered in further detail after discussion of the variability arising from weathering.

D) Variation in composition produced as a result of weathering

The problem implied in the use of the term "weathering" and the difficulty in its application to the Bodmin Moor and other S. W. England granites has already been discussed in dealing with the major element chemistry (see p. 18).

Although the term "weathered" has been employed as a field description for rocks which are regarded as friable in the hand specimen, it is the validity of the usage of the term in respect of possible chemical variation between quarry and exposed tor samples which is of interest at this point. If, as with the major element test of variability, the chemistry of KEB36 and 37 is compared with any of the specimens from Cheesewring Quarry (KEB38-42), see Table 9, then no apparent differences can be visually recognised. Although U concentrations are lower in KEB36 and 37 than in the quarry specimens, any conclusions about variation may be fortuitous in view of the inadequacies in detection of this element (see appendix; XRF analysis).

Fuge & Power (1969), on the evidence of Cl and F analyses from the Cornubian granites, have indicated that "alteration has an important effect on the distribution of chlorine in granitic rocks, and, as even a slight alteration can cause a large change in the chlorine content, care is needed in the interpretation of the apparent distribution of chlorine in granitic rocks where their alteration history is unknown". Fuge (personal communication) has suggested that weathering may also be included as alteration, though this is not directly specified by Fuge & Power (1969). A number of specimens from the Dozmary Pool, De Lank Quarries, Roughtor and Cheesewring Quarry localities were analysed for F and Cl by Fuge (see Fuge & Power, 1969, for experimental details) and though it was not intended that these elements should be determined purely as a test of weathering it is worth considering the results in this light.

It would be difficult to claim that Cl concentrations for KEB36 and 37 (see Table 11) were significantly different from those of KEB38-42, though there is a marked reduction in Fl content. For KEB8, from the base of the present workings in the main De Lank Quarry, the Cl content reflects a marked increase compared to the other specimens (KEB10-12) from upper parts of the quarry. This relationship is not apparent, however, in the Hantergantick Quarry specimens (KEB17 - outcrop exposure; KEB18 - base of present workings).

It is suggested, therefore, that although extensive atmospheric exposure may affect F and Cl concentrations the results of Table 11 are by no means conclusive and in the overall terms of major and trace element chemistry analyses carried out in this work, tor and quarry specimens are similar. A more detailed, statistically

Table 11 Fluorine and chlorine analyses

Dozmary Pool (fine-grained granite)

	KEB1	KEB2	KEB5
F	1013	946	800
Cl	124	95	74

De Lank Quarries (coarse-grained granite)

	KEB8	KEB10	KEB11	KEB12	KEB14	KEB15	KEB16	KEB17	KEB18
F	1805	1682	1575	2016	1432	1970	1006	1860	1762
Cl	718	249	238	350	263	171	113	334	274

Roughtor (coarse-grained granite)

	KEB19	KEB20	KEB21	KEB22	KEB23	KEB24	KEB25
F	1752	1522	1575	1393	1900	775	1388
Cl	227	165	151	295	239	56	217

Cheesewring Quarry (coarse-grained granite)

	KEB32	KEB33	KEB34	KEB36	KEB37	KEB38	KEB39	KEB40	KEB41	KEB42
F	1128	1956	6330	1261	1190	5080	5290	1611	2095	5590
Cl	71	286	245	200	133	276	220	153	172	259

Cheesewring Quarry (KEB29, mineralised coarse-grained granite)
(KEB30/31/43, contaminated coarse-grained granite)

	KEB29	KEB30	KEB31	KEB43
F	1598	2220	1561	5650
Cl	331	273	117	248

All values in ppm

Analyst R.Fuge

controlled, study of near-surface and fresh, deep quarried rock might help, however, to clarify the extent to which weathering is important.

2) The application of statistical methods

A) Introduction

Where large sets of chemical data are being considered, as in the present case of the trace element chemistry of the Bodmin Moor granite and associated rocks, the extraction of meaningful results is hampered by the sheer volume of analyses and use must be made of the computer in statistical and graphical methods for the breakdown of much of the data into more readily comprehensible terms.

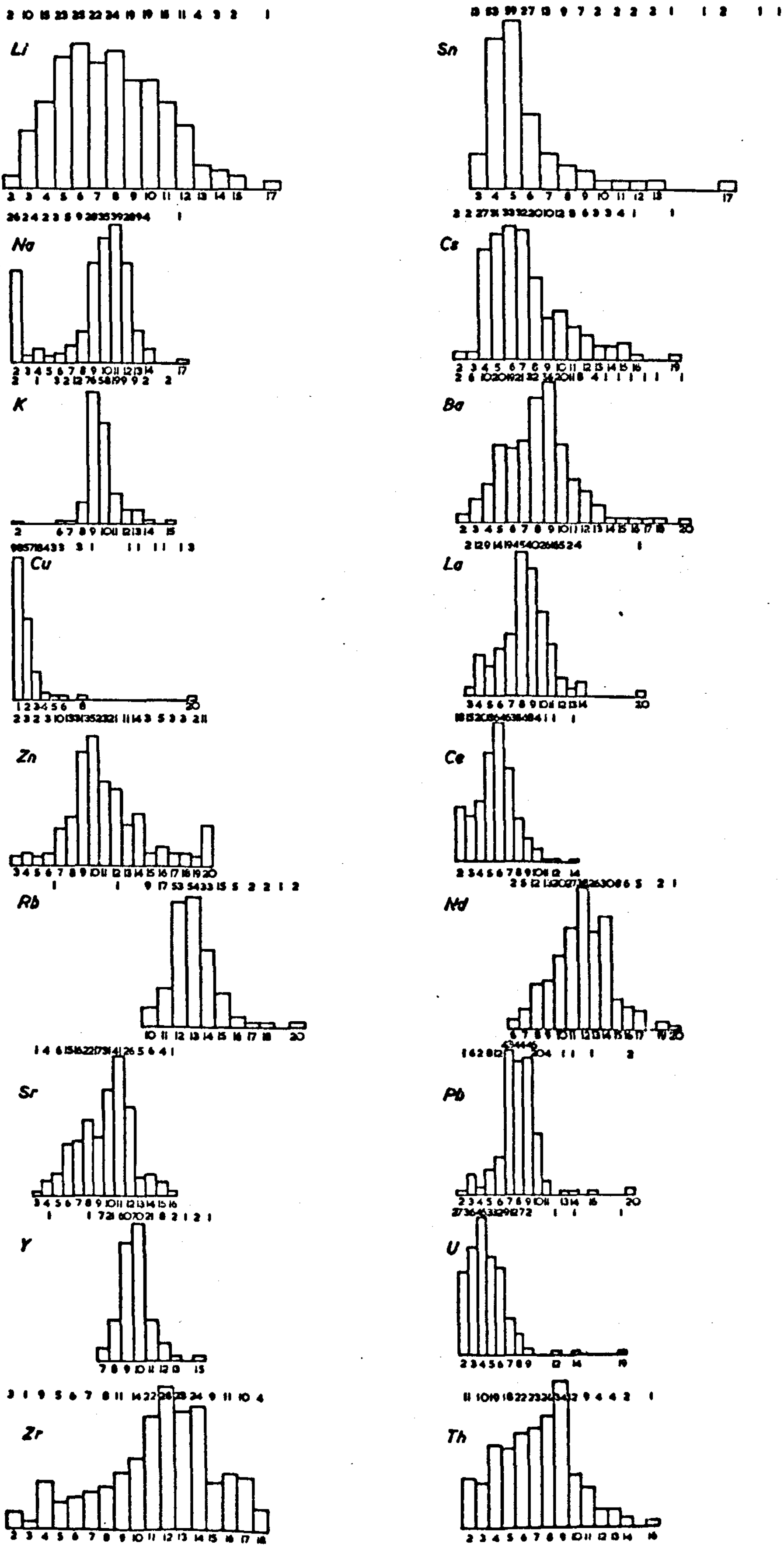
All of the following processing was carried out by Mr. E. Stephens at the Computing Laboratory of St. Andrews University on an IBM 360 computer. For brevity, only the sources of the programmes employed will be noted, though some relevant details of the basic aspects and usefulness of each programme will be considered. To some extent computer assessment often becomes cyclic with attempts at improving the output. For example, once a significant classification has been derived the next step could be to re-analyse the sub-groups, and so on, ad infinitum. For the present work, however, the computer has been used only for the initial requirements of assessment of the data and refinements have been minimised.

Fig.3 Frequency distributions

Computer calculated frequency distributions, top set of figures indicate the number of specimens falling within a particular class level. Lower set of figures indicate class number.

Each element distribution is accurately scaled but scale varies for each element.

See text for further discussion and interpretation


Li
Na
K
Cu
Zn
Rb
Sr
Y
Zr
Sn
Cs
Ba
La
Ce
Nd
Pb
U
Th
2 3 4 5 6 7 8 9 10 11 12 13 14 15 17
2 10 18 23 28 22 24 19 19 18 11 4 3 2 1
3 4 5 6 7 8 9 10 11 12 13 17
2 3 4 5 6 7 8 9 10 11 12 13 14 17
2 6 7 8 9 10 11 12 13 14 15
1 2 3 4 5 6 8 20
3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
10 11 12 13 14 15 16 17 18 20
3 4 5 6 7 8 9 10 11 12 13 14 15 16
7 8 9 10 11 12 13 15
3 1 9 5 6 7 8 11 14 22 28 28 24 9 11 10 4
2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 19
2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 20
3 4 5 6 7 8 9 10 11 12 13 14 20
2 3 4 5 6 7 8 9 10 11 12 14
6 7 8 9 10 11 12 13 14 15 16 17 19 20
2 3 4 5 6 7 8 9 10 11 13 14 16 20
2 3 4 5 6 7 8 9 12 14 19
2 3 4 5 6 7 8 9 10 11 12 13 14 16

Many statistical tests and procedures, including those to be dealt with in this account, are founded on the assumptions that the samples have been randomly drawn and come from a normally distributed parent population. Consideration of the latter point is undertaken in detail in the next section in dealing with the frequency distributions and to some extent the former has been dealt with earlier in the section outlining the sampling plan. It is, however, worth stressing that the granite has by no means been sampled randomly. For chemical mapping, or trend surface analysis, the effects of random sampling are not necessarily suitable as good areal distribution is required to prevent the trend surfaces from passing through unreal maxima and minima in regions of poor or even of no control. A partial sacrifice of randomly collected specimens for areally representative material would possibly be a suitable compromise but as stated earlier, exposure is the dominating influence and although inferences are made about the granite as a whole they are theoretically only applicable to the exposed granite that was sampled.

B) Frequency distribution

As noted in the preceeding section, statistical methods generally assume that the data upon which they are based is distributed normally, an implication which is not necessarily valid.

In the late 'fifties and early 'sixties the geochemical literature abounded with discussion and argument about element distributions, mainly as a result of a series of papers by

Ahrens (1954, etc) in which lognormal distributions were invoked for some trace elements. It is not intended to follow or summarise the details of these earlier works but to consider each element distribution for the Bodmin Moor granite as analysed in this work - an interpretation which Shaw (1961, p.117) also concludes as the most logical when he states that "theoretical distribution laws differ according to the situation" and "the errors of sampling, preparation and analysis are all reflected in the dispersion of a series of analyses".

All the 195 specimens recorded in Table 9 have been plotted by computer (Data Screen Programme, IBM Programmers' Manual, 1968) in the form of histograms for each trace element, Fig. 3. Sometimes it is possible to make general conclusions about the distribution of the data from histograms; for example if they are strongly bimodal the system is obviously complex. A visual inspection of Fig. 3 suggests that although a number of elements give the impression of being symmetrically dispersed some, such as Na, Zr, Sr and Ba, appear to be negatively skewed while others, such as Cs, Sn, Zn and Cu appear to be positively skewed.

A visual inspection of histograms is not, however, a rigorous test of frequency distributions and though presentation in other graphical forms may be an improvement a test of significance is required. The most suitable is the Kolomogrov-Smirnov (K-S) test which, being nonparametric, makes no assumption about the form of the population under consideration. In the present case this is an obvious requirement as there would be little value in testing for normality, etc., if this had to be initially assumed. The

K-S statistic is well documented in numerous statistical texts and is adequately explained by reference to geological applications by Miller & Kahn (1962, Appendix G). Basically the test involves the comparison of the cumulative frequency curve which occurs under a theoretical distribution (in the present case normal and lognormal distributions) with the observed frequency curve. The maximum point of divergence of the two distributions is then determined and reference to the sample dispersion indicates whether such a large divergence is likely on the basis of chance.

The results of the computer application (Kolomogorov-Smirnov Test, IBM Programmers' Manual, 1968) of the tests by comparison of the 195 samples of Table 9 with the theoretical normal and lognormal distributions are given below. The results are presented on a 0 to 1 scale of probability, the higher the probability value the more comparable is the sampled distribution to the theoretical distribution.

	Probability	
	Normal	Lognormal
Li	0.504	0.008
Na	0.000	0.000
K	0.007	0.000
Cu	0.000	0.000
Zn	0.000	0.013
Rb	0.059	0.001
Sr	0.204	0.001
Y	0.014	0.003
Zr	0.119	0.000
Sn	0.000	0.012
Cs	0.004	0.706
Ba	0.131	0.001
La	0.136	0.000
Ce	0.150	0.000
Nd	0.704	0.137
Pb	0.002	0.000
U	0.000	0.016
Th	0.661	0.000

The majority of elements are more comparable to a normal distribution than a lognormal distribution, although Cs, with the highest probability value is lognormally distributed. The failure of the metallic elements, Cu, Zn, Sn and Pb to follow a normal distribution could be logically explained by the fact that some mineralised specimens give high concentrations for these elements when compared with the majority of coarse-grained granite and associated rock specimens. The other two elements which fail to reflect a simple normal or lognormal distribution trend are Na and K. There is little doubt that the history of these two elements is complex, as will subsequently be shown, and as already shown by others for the Cornubian granites (Bowler, 1959; Exley & Stone, 1964; Stone, 1968; Hawkes, in Edmonds et al, 1968; etc.). The failure to conform to either of the theoretical distributions, therefore, is not entirely unexpected.

Having established that the majority of the elements are more likely to follow a normal, rather than lognormal distribution in the Bodmin Moor granite it appears valid to assume normality in the following statistical tests. The exceptions to this assumption will be considered when justified, though it is perhaps appropriate now to mention one consequence which has already arisen but has been overlooked. The mean and standard deviation values quoted in Table 9, for those elements whose distribution is not normal, may be slightly displaced as a result of assuming normality. For example, the geometric mean value for the lognormal distribution of Cs, for 195 samples, is 28 compared with the arithmetic mean of 31 quoted in Table 10. The effect on the standard deviation for Cs, however, is not significant.

C) Process extraction techniques

These techniques enable the investigator to extract information pertaining to those variables which work together, those which are opposed and those which are mutually exclusive within a particular system. In the present context they may be regarded as a means of characterising geochemical trends or processes within a set of analyses.

(i) Principal component analysis

If a number of variables are measured on a group of samples, then by linear transformation a set of new independent variables can be determined, generally fewer in number than those originally measured, to account for as great a part of the total variation as possible. These new variables are called "principal components".

The basis of principal component analysis can be explained in fairly simple geometric terms by considering a plot of all the samples in m-dimensional space, where $m =$ the number of variables. The cloud of points, thus formed, can be interpreted in terms of an ellipsoid, or hyper-ellipsoid if there are more than three variables. This hyper-ellipsoid can now be used to construct a set of axes to describe the variability within the samples. The major, or longest axis will represent the greatest amount of variability, the second longest axis the maximum of the remaining amount of variability and so on until all the variance has been accounted for by the constructed axes. If there are significant relationships among the original variables then the number of hyper-ellipsoid axes necessary to explain a greater part of the variance will be fewer than the original number of variables. Further details of the geometrical interpretation are given by Koch & Link (1971, Vol. II, p. 119-126).

In algebraic terms the analysis consists of a sequences of operations on a covariance matrix and it is perhaps of value to consider some aspects of the mathematical development in the transformation, albeit in very general terms. The covariance matrix represents a measure of underlying variability in multivariate data. The diagonal elements of the matrix are the variances and the off-diagonal elements are the covariances of the original variables. Being a square (m x m) matrix the roots, or eigenvalues, can be solved from the determinant equation

$$|A - \lambda I| = 0$$

where A = the covariance matrix, I = the identity matrix and λ is an eigenvalue. The solution leads to a polynomial in λ of the 'm'th degree for which the roots generally have to be found by iterative methods. Associated with each eigenvalue is a (1 x m) matrix or eigenvector. These matrices, of which there are 'm', are found by solving the equations that may be written as

$$X \quad |A - \lambda_i I| = 0$$

where X = a (1 x m) matrix and λ_i is one of the roots. If the eigenvalues of the covariance matrix are distinct, that is unequal, then the eigenvectors are independent and it is these vectors which are the required transformations and equivalent to the "axes" outlined in the geometric interpretation of the analysis.

It is relevant at this point to mention that the same procedures of analysis can also be applied to a correlation matrix. This matrix is constructed in a similar manner to the covariance matrix except that the original data are standardised so that each variable has an equal weighting and is independent of the magnitude of its concentration. This is done by making the means of the variables equal to zero and the variances equal to 1. Thus, instead of the transformed variables being based on the maximum amount of variance within the system they are based on the maximum amount of intercorrelation.

The trace, or sum of the diagonal elements, of the covariance or correlation matrix and the sum of the eigenvalues are equal and represent the total variance or the total correlation respectively. The eigenvalues are calculated in their order of magnitude and the percentage total of the variance or correlation can be calculated by dividing the eigenvalues by the trace. Generally the first few eigenvalues account for the majority of this total, or so it is hoped, and those in excess of an acceptable proportion can be disregarded. Similarly the squared values of the terms of the eigenvectors can be summed and the individual terms divided by the total to give an indication of the percentage contribution of the original variables to the principal component represented by that vector. If only a few of the original variables account for most of a principal component it may be interpreted by considering the nature of this combination and ignoring

Table 12 The principal component correlation matrix and the first seven "principal components".

```
CORRELATION MATRIX
                CU         ZN         SN         PB         TH         CE         U          CS         ND         LA

COPPER        1.000
ZINC          0.3314     1.000
TIN           0.5665E-01-0.9418E-01  1.000
LEAD          0.8457E-01 0.2778    -0.1108      1.000
THORIUM      -0.8648E-01 0.5084E-01 0.2995E-01-0.7537E-01  1.000
CERIUM        0.2262     0.7725E-01 0.4657E-01 0.1863E-02 0.7051      1.000
URANIUM      -0.2282E-01-0.3501E-01 0.2589E-01-0.1898E-01 0.1676      0.1201      1.000
CESIUM       -0.1414    -0.3755E-01 0.1145    -0.6762E-01-0.4109     -0.4358     -0.8315E-01  1.000
NEODYMIUM    -0.1588E-01 0.6645E-01 0.1281E-01-0.8297E-02 0.6564      0.8625      0.1023     -0.3559      1.000
LANTHANUM    -0.5693E-01 0.4358E-01 0.2947E-01 0.3381E-01 0.7434      0.9051      0.1216     -0.3686      0.4409      1.000
YTTRIUM      -0.3118    -0.1604     0.2981    -0.2621     0.3186E-01-0.2961E-01-0.1984E-01 0.3877      0.7071E-01 0.9526E-01
BARIUM       -0.1330    -0.1846     0.7689E-01-0.1639E-01 0.2723      0.3462      0.6345E-01-0.3608      0.3788      0.4123
RUBIDIUM     -0.2339    -0.1975     0.3323    -0.3444    -0.1741     -0.2840     -0.3348E-01 0.4844     -0.2221     -0.1828
STRONTIUM    -0.7105E-01 0.7203E-01-0.1129     0.2617     0.3464      0.4370      0.5312E-01-0.3152      0.4178      0.4775
ZIRCONIUM    -0.1718     0.6789E-02-0.5012E-01-0.2053E-01 0.7479      0.7661      0.5022E-01-0.3477      0.7772      0.8369
LITHIUM      -0.5549E-01 0.2037    -0.2011E-01 0.8610E-01-0.2052     -0.2632     -0.8123E-01 0.6701     -0.2116     -0.2082
SODIUM       -0.2342     0.1176    -0.3207     0.1969    -0.5771E-01-0.2256     -0.4580E-01 0.6146E-01-0.2055     -0.2158
POTASSIUM    -0.2888    -0.2488     0.1278    -0.1527     0.1357      0.3686E-01 0.4599E-01-0.3932E-01 0.7787E-01 0.1394

                Y          BA         RB         SR         ZR         LI         NA         K

YTTRIUM       1.000
BARIUM        0.1975     1.000
RUBIDIUM      0.8416     0.1349     1.000
STRONTIUM    -0.1654     0.4875    -0.3329      1.000
ZIRCONIUM     0.5295E-01 0.3878    -0.1629      0.5169      1.000
LITHIUM       0.1070    -0.3904     0.1617     -0.7648E-01-0.7639E-01  1.000
SODIUM       -0.2530    -0.3563    -0.2677      0.2590     -0.6658E-01 0.3668      1.000
POTASSIUM     0.4391     0.4795     0.4282      0.1044      0.9157E-01-0.3222     -0.2917      1.000

EIGENVECTORS

             NUMBER  1  NUMBER  2  NUMBER  3  NUMBER  4  NUMBER  5  NUMBER  6  NUMBER  7
COPPER        0.0054     0.2272     0.3130    -0.4646     0.1828    -0.0000     0.0552
ZINC          0.0110     0.2447    -0.1340    -0.3190     0.3922    -0.0874     0.5369
TIN          -0.0058    -0.2415     0.0782    -0.3342     0.1737    -0.1771    -0.7137
LEAD          0.0172     0.2605    -0.0794     0.1114     0.5784    -0.2213    -0.1261
THORIUM       0.3490    -0.0263    -0.1402    -0.0667    -0.2053    -0.0233     0.0577
CERIUM        0.3937     0.0257    -0.0408    -0.2325    -0.0316     0.0427    -0.0317
URANIUM       0.0722    -0.0196     0.0360     0.0090    -0.2626    -0.9413     0.1179
CESIUM       -0.2663    -0.1597    -0.4821    -0.1728     0.0716    -0.0455    -0.0489
NEODYMIUM     0.3908    -0.0238    -0.1286    -0.1493    -0.0525     0.0671     0.0159
LANTHANUM     0.4048    -0.0474    -0.1567    -0.1211    -0.0162     0.0328    -0.0027
YTTRIUM      -0.0237    -0.4679    -0.2141    -0.1012     0.1266     0.0065     0.1732
BARIUM        0.2431    -0.2213     0.1728     0.2611     0.3466    -0.0186    -0.0121
RUBIDIUM     -0.1368    -0.4748    -0.1359    -0.0663     0.0948    -0.0132     0.1432
STRONTIUM     0.2599     0.1196    -0.1590     0.3252     0.3328    -0.0550    -0.1990
ZIRCONIUM     0.3721    -0.0294    -0.2506    -0.0028    -0.0921     0.0728    -0.0207
LITHIUM      -0.1768     0.0629    -0.5680    -0.1624     0.0615    -0.0425    -0.0901
SODIUM       -0.0858     0.2749    -0.3737     0.3538    -0.1102    -0.0135    -0.0657
POTASSIUM     0.0818    -0.3734     0.1318     0.2717     0.2170    -0.0554     0.2464

EIGENVALUES   5.2432     3.1709     1.8552     1.5739     1.1523     0.9764     0.8021

PERCENT OF TOTAL CONTRIBUTION PER EIGENVALUE

             29.1284    17.6161    10.3064     8.7440     6.4018     5.4247     4.4556
```

The higher value the more significant the contribution of the element to the eigenvector. Minus signs indicate that there is a negative correlation with positive-signed elements.

the contribution of the other variables. Rather than consider the contribution of the original variables in terms of a percentage of the transformed variables they are presented here on a linear scale such that a loading close to ±1 indicates that a variable contributes significantly to the component and a loading close to zero signifies a negligible contribution. Further details and references to the mathematics are given by Wahlstedt & Davis (1968), whose computer programme was employed for the principal component analysis of the Bodmin Moor data.

Geological uses of principal component analysis have been presented by McCammon (1966), Webb & Briggs (1966) and Cann (1971) among others, with the latter two illustrating application of the analysis to geochemical data. Considerably more use has been made of factor analysis in the process extraction of geological data and this technique is, in fact, considered in the next sub-section of this account. As the first part of factor analysis is based on principal component analysis most of the literature cited in the following section is also applicable to this section.

Little is gained from a display of the principal component analysis of the covariance matrix for the Bodmin Moor data. The Na and K concentrations are so high, compared with the other elements, that they swamp the matrix and two principal components contain 99.9% of the total variation. The first of these components, accounting for 67.3% of the total variation can be attributed to K, with a small additional influence from Na (having a negative correlation with K). The second component, accounting for 32.6% of the variation is attributable to Na, with a small additional influence from K (having a positive correlation with Na). In other words, in terms of concentrations of those elements analysed the most significant variation arises in K and Na, a conclusion that might have been expected from studying the table of trace element results (Table 9).

Principal component analysis based on the correlation matrix for the Bodmin Moor data is presented in Table 12. Only the first seven eigenvectors are presented and these account for 82% of the total variation. The ideal situation would be to have a few variables contributing to each component, thereby simplifying a geological interpretation. Unfortunately this only happens in the sixth component where U has a very high loading. As this component accounts for only 5% of the total variation and the experimental detection level for U is unsatisfactory in the majority of samples (see appendix; XRF analysis) little significance can be attached to the result.

The first component, accounting for 29% of the total variation, is essentially controlled by Ce, Nd and La and to a lesser extent by Zr and Th. As the elements are normally distributed and mathematically independent a test can be applied to indicate the level of significance that can be attached to the correlation between the rare earth elements, Zr and Th. For the null hypothesis where two variables are independent let $p_{xy} = 0$ (where x and y are the two variables and p_{xy} is the correlation coefficient). If r_{xy}, which is an estimate of p_{xy}, is close to zero then the two variables are independent and if r_{xy} is far from zero then the two variables are significantly correlated. Thus for a significance level of $\alpha = 0.05$ for 195 samples the critical region is $-0.104 > r < 0.104$ (Dixon & Massey, 1969, Table A30a, p.569); that is if r lies between -0.104 and 0.104 the variables are independent and if r is greater than ±0.104 the variables are not independent. Taking the correlation between Ce and Nd as an example, the value of r_{NdCe} from the correlation matrix, Table 12, is 0.9409. Thus at the significance level of $\alpha = 0.05$ Ce and Nd are strongly correlated (not independent). A similar check indicates that for the same level of significance Ce, Nd, La, Zr and Th are all strongly intercorrelated. It follows, therefore, that the variation recorded by the first eigenvector of the principal component analysis can be assessed as significant.

The second component, accounting for 18% of the total variation, can be attributed to Y and Rb and to a lesser extent to K. The third component, accounting for 10% of the total variation, is influenced by Li and to a lesser extent by Cs and Na. Applying the same test as for the first component and at a level of $\alpha = 0.05$ then, the correlation coefficients between the variables in the second and third components are also significant, except those between Cs and Na.

The fourth, fifth and seventh components reflect variations that arise from the metalliferous elements though the actual amount of variation that accounts for each component is relatively small.

(ii) Factor analysis

For the purpose of this account factor analysis may be considered as an extension of principal component analysis as it attempts to highlight to a greater degree the variables that contribute to a particular principal component. It is convenient to explain the details involved geometrically, the reader being referred to Harman (1960) or Cattell (1965) for the full mathematical and statistical details. (There is also a number of works which consider the significances and interpretations of factor analysis with respect to the processing of geochemical data. Some of the more recent, in which references are made to earlier works, include Miesch et al (1966), Nichol et al (1969), Reeves & Saadi (1971) and Mottana et al (1971)).

If the orientations of the hyper-ellipsoid axes defined in the principal component analysis are significantly different from the original axes then interpretation of the results may be difficult. In an attempt to overcome this problem the principal component axes are "rotated" so that some of them lie as close as possible to the original axes. Thus, in the "rotated" components high variable loadings are maximised and low loadings are minimised. For the Bodmin Moor data an R-mode factor analysis has been applied (Factor Analysis, IBM Programmers' Manual, 1968), where R-mode indicates that it is the variables, rather than the samples, which describes the m-dimensional space.

The effect of "rotation" on the first eigenvector found in the principal component analysis merely enhances the loadings of Nd, Ce, La, Zr and Th. Similarly in the second component, Rb and Y are enhanced though K remains almost constant. Cs, however, also becomes a significant contributor. In the third eigenvector, although Li is slightly enhanced the factor analysis points to K and Ba, acting with a negative correlation to Li, as the most effective variables.

The loadings for the first three factor analysis components are shown in Table 13. A minus sign indicates that a particular variable is acting with a negative correlation to a positively-signed variable. Table 13 should be compared with Table 12 to identify the effects of factor analysis "rotation" on principal component analysis.

The statistical meaning in "rotating" the hyper-ellipsoidal axes is not satisfactorily known and there are no tests of significance that can be suitably applied to the results. Why, for example, Ba and K should become the high loading factors in the third component as a result of factor analysis is difficult to assess both mathematically and geologically. At a significance level of $\alpha = 0.05$, however, it is evident from the correlation matrix (Table 12) that Ba, Li and K are all significantly related, whereas Cs and Na in the third principal component are not. In theory, while it would be better if the implications of the process extraction techniques were confined to the results of the principal component analysis, the geological interpretations and element correlations are simplified by accepting the results of the factor analysis. As the third factor accounts for only 10% of the total variation and the first two factors are essentially those recognised in the principal component analysis little is lost in accepting what may possibly be a statistically inexplicable transformation. In the subsequent discussion of the trace element statistical tests, therefore, the simpler alternative of factor analysis is accepted.

D) Classification techniques

i) Cluster analysis

Cluster analysis is a method for grouping similar samples so that samples within one particular group are more comparable with each other than with the members of other groups. In the present context the technique permits a classification of the analysed samples based entirely on chemical data without being influenced by field or petrographic evidence.

The programme (Clustran II, Wishart, 1969, 1970) employed for the cluster analysis of the Bodmin Moor rocks is based on a measure of the Euclidean distance between two samples in m-dimensional space, where 'm' is the total number of variables. The shorter the distance between two samples the greater the degree of similarity, and vice-versa. Distance coefficients are thus built up for all the possible pairs of samples in a similarity matrix. The Clustran II programme allows one of a number of final classification techniques to be employed and Ward's (1963) method was selected. This inspects and reduces

Table 13 Factor Analysis Results (First Three Components Only)

Eigenvector (or component)	1	2	3
% of Total Contribution per Eigenvalue	29.1%	17.6%	10.3%
Cumulative % of Eigenvalue	29.1%	46.7%	57.0%
Li	-0.08383	-0.40428	0.68431
Na	-0.10837	0.21077	0.33588
K	0.03688	-0.41100	-0.70782
Cu	-0.03255	0.40016	0.21367
Zn	0.11819	0.12870	0.35180
Rb	-0.20281	-0.88370	-0.14394
Sr	0.50136	0.18851	-0.34620
Y	0.07508	-0.87794	-0.15302
Zr	0.90536	-0.01283	-0.09185
Sn	0.02811	-0.40740	-0.06147
Cs	-0.34664	-0.65388	0.45611
Ba	0.34306	-0.11687	-0.78757
La	0.95500	-0.00269	-0.14255
Ce	0.90597	0.15543	-0.07661
Nd	0.92269	0.04543	-0.10151
Pb	-0.01897	0.23772	-0.05108
U	0.15863	0.08514	-0.00648
Th	0.83367	0.06295	-0.06490

The higher the value the more significant the contribution of the element to the eigenvector. Minus signs indicate that there is a negative correlation with positive-signed elements.

the similarity matrix of the recognised groups (k) into k-1 groups by considering the union of all possible k(k-1)/2 pairs that can be formed and accepting the one with the optimum distance coefficient. The process is repeated until all the groups finally merge into one.

One of the problems of using Euclidean distances as the similarity measure is the fact that there is an underlying assumption that the variables are orthogonal, which in turn implies that they are not correlated. Some elements are, however, chemically related as it has already been shown in the preceding section and the effect of applying a cluster analysis classification is that these related variables are enhanced over the weakly correlated elements. Parks (1966) and Rhodes (1969) describe a number of methods of overcoming this shortcoming, though Rhodes (1969) finally ignored the orthogonal requirements when he found that weighting of the good discriminators produced results almost identical to those using the original data. In the Clustran II programme the first part of the analysis incorporates a principal components transformation of the standardised data, thus eliminating the effects of correlation of the original variables.

Although the objective of cluster analysis is to arrive at a meaningful grouping of the samples a difficulty arises as to the interpretation of "meaningful". In the present case this has been identified by inspecting the dendogram table (a listing of the distance coefficients between groupings) and noting the point at which the distance coefficients exhibit a marked discordance. This is perhaps explained in simpler terms by considering, say, eight samples of which four belong to one group and four to another. The first reduction will produce four sub-groups and the second the two groups which are already known. For these reductions the distance coefficients will be comparable but in the final step of reducing to one group the distance coefficient will be large because of dissimilarity. In other words these two groups are interpreted as "meaningful" because of the relatively large distance coefficient necessary to merge them.

The most "meaningful" grouping on this basis, for the Bodmin Moor specimens, gives five groups but as two of these groups contain only one sample and the reduction to three groups absorbs these two oddities it is perhaps more appropriate to consider these three groups together with their make-up. A sample listing of the groups is given in Table 14 together with the abbreviated notation of the field and petrographic classification outlined in the chapter dealing with the sampling plan. Although the cluster analysis is by no means equivalent to the field and petrographic classification a broad generalisation can be made. Group 1 contains the majority of the fine-grained and medium-type granites, aplites and kaolinised coarse-grained granites, Group 2 the elvans, and mineralised coarse-grained granites and Group 3 the coarse-grained granites. This last grouping is particularly strong, for going back as far as the clustering to 10 groups it has been virtually completed, whereas Groups 1 & 2 are still being formed from their sub-groups during the reduction from 10 to 3 clusters.

Table 14 Cluster analysis groupings

Group 1 Sub-Group A 26 Specimens

KEB1-7 (FGG), KEB30/31 (XCGG), KEB43 (XCGG), KEB400/421/423/425 (CGG), EB190 (XCGG), KEB504 (XCGG), KEB525 (CGG), KEB527 (ACGG), KEB547 (FGG), KEB551 (AP), KEB160/N(97) (CGG), E1(19) (AP), L104(40) (XCGG), HARR (WCGG), LL (VCGG).

Sub-Group B 19 Specimens

BB45 (CCGG), KEB410 (CGG), KEB416 (XCGG), KEB417 (WCGG), KEB508 (ELVAN), KEB538 (PEG), KEB539 (WCGG), KEB117 (QV), KEB149/162 (CGG), N(70) (AP), L114 (CGG), DME2 (XCGG), BSE3 (CCGG), H3 (CCGG), 121/123 (CGG), 124 (MCGG), 125 (CGG).

Sub-Group C 1 Specimen

KEB426 (VCGG).

Group 2 Sub-Group A 18 Specimens

KEB26 (ACGG), KEB27 (ELVAN), KEB28 (ACGG), KEB39/408 (CGG), KEB420 (AFGG), KEB429 (CGG), EB79 (ELVAN), EB164 (ELVAN), KEB507 (WCGG), KEB521 (CGG), KEB528 (VCGG), KEB544 (CGG), KEB172 (ACGG), E1(65)/W1 (MCGG), DHA (CCGG).

Sub-Group B 24 Specimens

KEB13 (ELVAN), KEB402 (VCGG), KEB414, (XCGG), KEB419 (ACGG), KEB422 (ACGG), EB69 (ELVAN), EB76 (PEG), KEB509/10 (ACGG), KEB514 (PEG), KEB522/523 (ELVAN), KEB524 (CGG), KEB526 (ELVAN), KEB532/534 (ACGG), KEB119 (WCGG), C (CGG), E2(38)/E2(39)/E2(63) (MCGG), K2 (XCGG), L111 (AP), 119 (CGG).

Group 3 Sub-Group A 106 Specimens

KEB8-12 (CGG), KEB14-25 (CGG), KEB29 (MCGG), KEB32-34/36-38/40-42 (CGG), KEB401/404 (CGG), KEB405 (ELVAN), KEB406 (ACGG), KEB407 (CGG), KEB409/411/412 (CGG), KEB413 (CCGG), KEB415/418 (CGG), KEB424 (WCGG), KEB427/428 (CGG), KEB430 (WCGG), KEB431 (CV), EB101/119/121/123 (CGG), EB195 (VCGG), KEB500/501 (CGG), KEB502 (XCGG), KEB503 (CGG), KEB505/506 (XCGG), KEB512/513/515-517 (CGG), KEB519 (PEG), KEB520 (CGG), KEB529 (CGG), KEB531 (ELVAN), KEB530 (ACGG), KEB533/536 (CGG), KEB537 (MCGG), KEB541 (XCGG), KEB540/542/543/545/546/548-550 (CGG), KEB552/44 (CGG), KEB65 (MCGG), KEB108/115/116/131/132/135/138-145 (CGG), KEB149/151/161 (CGG), KEB193 (WCGG), A/E/P/12/14A (CGG), C216 (ACGG) C217(CGG), C218(6)/C218(45) (ACGG), L104(26) (CGG).

Sub-Group B 1 Specimen

E1(56) (MCGG).

The Clustran II programme gives a diagnosis of the most powerful discriminators in the sample grouping. The statistic employed is based on the F-ratio test, the principles of which are described in most introductory texts on statistics (e.g. Dixon & Massey, 1969). In the present case the test is based on the ratio of the variance of the cluster samples to the variance of the total number of samples. The hypothesis that an element is a good discriminator is accepted when the calculated F-ratio value is less than that determined at a particular significance level from statistical tables. For a significance level of $\alpha = 0.05$ the $F_{\alpha}(N_1-1)(N_2-1)$ value is approximately 0.7 (Dixon & Massey, 1969, Table A-7c, p.483/4), where N_1 = the number of samples in the group (Group 1, $N_1 = 46$; Group 2, $N_1 = 42$; Group 3, $N_1 = 107$) and N_2 = the total number of samples (195). As N_1 is fairly large the F-ratio value is approximately constant for all the three Bodmin Moor groups. The calculated F-ratio values are given in Table 15 for the five-group level of the three recognised cluster groups. The reason for this is that in incorporating the two odd specimens from the five-group level to the three-group level there are marked changes in the F-ratio values for Sn and Cu in Groups 1 and 3. KEB426 has a very high Sn content (523ppm) and E1(56') a high Cu content (2138ppm) giving changes in the F-ratio values of 0.11 to 3.62 and 0.17 to 1.77 respectively. It can be seen from Table 15 that this would result in both elements being the worst discriminators in their respective groups whereas they are in fact among the best discriminators.

Table 15 F-Ratio values for the five-grouping level for the cluster analysis of the Bodmin Moor rocks.

Group1		Group2		Group3	
Element	F-ratio	Element	F-ratio	Element	F-ratio
Cu	0.04	Cu	0.07	Sn	0.02
Sn	0.11	Cs	0.23	Cu	0.17
U	0.29	Sn	0.37	K	0.21
Sr	0.30	Li	0.39	La	0.28
Nd	0.30	Zn	0.45	Nd	0.30
Ce	0.30	Zr	0.46	Ce	0.31
La	0.34	U	0.47	Zr	0.34
Zn	0.36	Pb	0.52	Rb	0.36
Zr	0.46	Rb	0.63	Ba	0.39
Pb	0.51	Ce	0.76	Y	0.39
Th	0.60	Th	0.82	Sr	0.44
Ba	0.68	La	0.90	Na	0.45
K	0.86	Y	0.96	Th	0.46
Rb	1.21	Na	0.99	Cs	0.51
Na	1.28	Nd	1.09	Li	0.66
Y	1.36	Sr	1.25	Pb	1.04
Li	1.38	Ba	1.53	Zn	1.21
Cs	1.41	K	2.01	U	1.48

The lower the F-ratio value the more significant is that element as a group discriminator. At a significance level of $\alpha = 0.05$ only F-ratio values less than 0.70 are significant.

When the results from the F-ratio test are considered in terms of the element means and standard deviations for the three groups (Table 16) it is evident that there is no distinctive relationship in Cu and Sn, the best element discriminators. Instead a spread of one standard deviation about the mean of any of the three groups gives an overlap of values such that it would not always be possible to "pigeon-hole" any particular specimen purely on the basis of its Cu or Sn concentrations. In fact only Zr appears to offer such a possibility for classification.

In terms of overall trace element chemistry, however, the three cluster analysis groups are adequately defined and although odd specimens appear to be incorrectly allocated there is a distinctive set of field and petrographic characteristics to each group. No attempt has been made to re-classify the apparently "anomalous" specimens.

When the results of the process extraction techniques are considered in the light of the three cluster analysis groups the variations accounted for by La, Ce, Nd and Zr are readily apparent from an inspection of the three group means (Table 16). For Cs, Ba and Li at least one of the three groups is distinctively defined but there is an overlap of values about the means of the other two groups. For Rb, Y and K a spread of one standard deviation from at least one group overlaps the mean values of the other two groups and similarly a spread of one standard deviation arising from some of the sampling localities (Table 10) also embraces the means of at least two groups. In other words variations in Rb, Y and K cannot be

Table 16 Mean compositions and standard deviations for the three cluster analysis groups.

	Group 1		Group 2		Group 3	
	mean	s.d.	mean	s.d.	mean	s.d.
Li	258	123	126	65	240	85
Na	16382	8967	10613	7748	19257	5478
K	45514	9117	52223	13466	43302	5832
Cu	15	34	28	43	37	215
Zn	50	16	41	18	64	30
Rb	540	89	481	62	448	58
Sr	47	13	78	25	80	15
Y	50	10	47	8.0	43	6.1
Zr	62	29	153	29	125	28
Sn	39	74	31	24	18	5.7
Cs	47	19	22	7.8	28	12
Ba	121	70	248	103	185	54
La	18	5.9	39	9.3	30	5.3
Ce	15	11	56	16	37	11
Nd	25	5.0	44	9.3	36	4.9
Pb	31	9.4	29	9.6	42	14
U	7.1	5.2	12	6.7	8.3	12
Th	8.2	6.6	24	7.5	17	5.8

All values in ppm

Note - If KEB426 is excluded from Group 1 the mean for Sn is 12. If El(56) is excluded from Group 3 the mean for Cu is 17. Standard deviations (s.d.) are also amended if these two samples are omitted, see text for further details and explanation.

adequately defined within any particular group.

(ii) Discriminant analysis

Discriminant analysis is another statistical method for classifying multivariate data and in the present case it has been employed as a basis for checking the field and petrographic groupings with the chemical data. Geometrically the analysis can be considered as a method of relating individual samples within a particular group, which defines a characteristic, hyper-ellipsoid, to the distance between the centres of paired hyper-ellipsoids. The closer a sample is to a hyper-ellipsoid centre the more closely it is related to the group defining that hyper-ellipsoid.

Briefly, in algebraic terms, the principle is to compute some linear combination of 'm' variables that define the recognised groups of samples in m-dimensional space so that the ratio of the between-groups' variance to the within-groups' variance is maximised. The linear function is specified for the variables (X) and a series of constants (λ) as

$$R = \sum_{i=1}^{m} \lambda_i X_i$$

The values of the constants are obtained by solving 'm' simultaneous equations based on the variable means and estimates of the pooled covariance of the variables within the recognised groups. Full mathematical details are explained in detail by Koch & Link (1971, Vol.II, p.102-117) who consider the distance concept between means from univariate through to multivariate data in readily comprehensible steps. Koch & Link (1971) also give examples of the use of discriminant analysis, as does Rhodes (1969), in terms of classifying geochemical data.

In the IBM programme (Discriminant analysis, IBM Programmers' Manual, 1968) employed for the discriminant analysis of the Bodmin Moor rocks the relationship of a sample to a group is expressed by the probability associated with the largest discriminant function on a 0 to 1 linear scale such that the nearer the value to 1 the more satisfactory the classification. In Table 17 the results of the discriminant analysis test of the grouping outlined in the sampling plan are presented. One point of note is that after the original sampling classification one or two samples were re-classified on further petrographic study and some samples in Table 17 may be included in groupings dissimilar to those referred to elsewhere. The incorrect location of these samples in running the discriminant analysis test is of minor consequence in view of the following conclusions.

The discriminant analysis does not offer a very satisfactory confirmation of the eleven recognised field and petrographic divisions. Discounting the fine-grained granite, because seven of the samples are known to be related by virtue of their field associations, only the kaolinised coarse-grained granite, pegmatite, aplite and mineralised coarse-grained granites can be considered as characterised from the chemical data. Even so there are "anomalous" samples within these groups; for example, KEB519 and L111 in the pegmatite and aplite groups respectively have a greater association with the elvan group though neither has the physical or mineralogical attributes of elvans. Similarly there are specimens in other groups which are more closely related to these fairly well defined four groups. KEB508, from the elvan group, and KEB402, from the veined coarse-grained granite group, are both classed as pegmatites though again neither is physically compatible with this description.

It is possible to test the significance between groups on the basis of the Mahalanobis' generalised distance (D^2) which is a measure of the distance between multivariate means. In the present case, however, such a test is of little value as the majority of the field and petrographic groups appear to be poorly defined chemically and there is no advantage in attempting to apply significances to groups which have inconclusive physical and chemical relationships.

In conclusion, whilst it is appreciated that classification "anomalies" do occur both chemically and petrographically, the three cluster analysis groups appear to satisfy the relationships between the chemical and physical attributes more adequately than the eleven field groupings. It has, therefore, been decided to adopt these three cluster groups. A consequence of this is that there no longer appears to be any justification for retaining the prefixed sampling descriptions (see p. 7) for the coarse-grained granite, that is apart from mineralised and kaolinised and possibly contaminated

Table 17 Discriminant analysis results

Division 1 Fine-grained granite (FGG)

Sample No.	Probability assoc. with the largest discriminant function	Largest function No.
KEB1	0.99581	1
KEB2	0.97991	1
KEB3	0.99583	1
KEB4	0.99737	1
KEB5	0.98461	1
KEB6	0.99570	1
KEB7	0.99127	1
KEB420	0.37230	3
KEB547	0.87107	5

Division 2 Elvan

Sample No.	Probability assoc. with the largest discriminant function	Largest function No.
KEB13	0.96076	2
KEB27	0.39584	3
KEB405	0.75632	1
EB69	0.99928	2
EB79	0.40606	2
EB164	0.74327	2
KEB508	0.59085	9
KEB522	0.99388	2
KEB523	0.70528	2
KEB526	0.99882	2
KEB531	0.48392	11

Division 3 Altered coarse-grained granite (ACGG)

Sample No.	Probability assoc. with the largest discriminant function	Largest function No.
KEB14	0.49361	3
KEB16	0.59807	3
KEB17	0.43245	11
KEB24	0.42731	3
KEB26	0.38692	7
KEB28	0.84474	3
KEB39	0.35685	3
KEB406	0.32424	3
KEB419	0.47144	3
KEB422	0.49407	2
KEB527	0.64327	5
KEB532	0.55829	3
KEB534	0.97219	4
KEB172	0.42742	3
C216	0.44258	7
C218(6')	0.41457	3
C218(45')	0.33213	7

Division 4 Mineralised coarse-grained granite (MCGG)

Sample No.	Probability assoc. with the largest discriminant function	Largest function No.
KEB29	0.96723	4
KEB537	0.99407	4
EB65	1.00000	4
E1(56')	1.00000	4
E1(65')	0.99448	4
E2([illegible]8')	0.38705	4
E2(39')	0.93618	4
E2(63')	0.89650	4
W1	0.99993	4
124	0.99574	8

Division 5 Contaminated coarse-grained granite (XCGG)

Sample No.	Probability assoc. with the largest discriminant function	Largest function No.
KEB30	0.47059	5
KEB31	0.70685	5
KEB414	0.48860	2
EB190	0.87995	5
KEB502	0.60213	11
KEB504	0.91595	5
KEB505	0.59719	5
KEB506	0.72229	1
KEB541	0.68906	5
K2	[illegible]	4
L104(40')	0.55722	5
[illegible]	0.412[illegible]8	11

Division 6 Veined coarse-grained granite (VCGG)

Sample No.	Probability assoc. with the largest discriminant function	Largest function No.
KEB43	0.85580	5
KEB402	0.68875	9
KEB426	1.00000	6
EB195	0.76065	11
KEB528	0.97965	6
LL	0.51407	5

Division 7 Weathered coarse-grained granite (WCGG)

Sample No.	Probability assoc. with the largest discriminant function	Largest function No.
KEB32	0.44809	3
KEB36	0.39487	11
KEB37	0.32347	3
KEB417	0.40465	7
KEB424	0.87204	7
KEB430	0.33255	7
EB119	0.47870	3
EB121	0.57205	3
KEB507	0.35066	7
KEB529	0.66973	11
KEB539	0.99295	8
KEB119	0.75812	7
KEB193	0.78600	8
C217	0.30160	3
119	0.46312	2
121	0.47744	11
HARR	0.95428	1

Division 8 Kaolinised coarse-grained granite (CCGG)

Sample No.	Probability assoc. with the largest discriminant function	Largest function No.
KEB410	0.99510	8
KEB413	0.52436	7
DHA	0.99991	8
BSE3	0.99676	8
H3	0.99958	8

Division 9 Pegmatite (PEG)

Sample No.	Probability assoc. with the largest discriminant function	Largest function No.
EB76	0.99999	9
KEB514	1.00000	9
KEB519	0.68388	2
KEB538	0.98543	9

Division 10 Apatite (AP)

Sample No.	Probability assoc. with the largest discriminant function	Largest function No.
KEB551	1.00000	10
N(70')	1.00000	10
E1(19')	0.99456	10
L111	0.99450	2

Division 11 Coarse-grained granite (CGG)

Sample No.	Probability assoc. with the largest discriminant function	Largest function No.
KEB8	0.65698	11
KEB9	0.66327	11
KEB10	0.43660	11
KEB11	0.41712	11
KEB12	0.55953	11
KEB15	0.41976	11
KEB18	0.70907	11
KEB19	0.45981	11
KEB20	0.41314	7
KEB21	0.37768	11
KEB22	0.35[illegible]49	11
KEB23	0.65318	11
KEB25	0.28412	5
KEB33	0.35203	3
KEB34	0.74094	11
KEB38	0.77819	11
KEB40	0.49201	11
KEB41	0.39338	11
KEB42	0.32549	11
BB45	0.33309	5
KEB400	0.31017	5
KEB401	0.36743	11
KEB403	0.69057	3
KEB404	0.47195	3
KEB407	0.27123	3
KEB408	0.33911	7
KEB409	0.50151	7
KEB411	0.51486	5
KEB412	0.64764	11
KEB415	0.40997	7
KEB416	0.44322	11
KEB418	0.43153	11
KEB421	0.64573	1
KEB423	0.40796	5
KEB425	0.68743	3
KEB427	0.30551	11
KEB428	0.35710	5
KEB429	0.61129	7
EB101	0.69355	11
EB123	0.51996	3
KEB500	0.44204	11
KEB501	0.63918	11
KEB503	0.41921	11
KEB509	0.30282	3
KEB510	0.30761	3
KEB512	0.40988	5
KEB513	0.46829	7
KEB515	0.36611	3
KEB516	0.75941	11
KEB517	0.58394	11
KEB520	0.71987	11
KEB521	0.49848	3
KEB524	0.38572	3
KEB525	0.72885	5
KEB530	0.67688	11
KEB533	0.53582	11
KEB536	0.69137	11
KEB540	0.62793	11
KEB542	0.63730	11
KEB543	0.51151	11
KEB544	0.60378	3
KEB545	0.33419	5
KEB546	0.70063	11
KEB548	0.74823	11
KEB549	0.78514	11
KEB550	0.67658	11
KEB552	0.82960	11
KEB44	0.58539	11
KEB108	0.69481	11
KEB115	0.69232	11
KEB116	0.74690	11
KEB131	0.63518	11
KEB132	0.67175	11
KEB135	0.43279	11
KEB138	0.41693	3
KEB139	0.51321	11
KEB140	0.76661	11
KEB141	0.64702	11
KEB142	0.52079	11
KEB143	0.45604	11
KEB144	0.65536	11
KEB145	0.47040	11
KEB149	0.47584	11
KEB151	0.77678	7
KEB160	0.90926	11
KEB161	0.72874	5
KEB162	0.51139	11
A	0.41672	7
C	0.461[illegible]5	3
E	0.30122	11
N(97')	0.44291	11
P	0.31335	3
12	0.34634	7
14A	0.59645	11
L104(26')	0.61004	11
L114	0.66338	11
123	0.71760	11
125	0.53106	11

Largest function number indicates the "division" a sample is classed and the larger the probability figure the more closely associated is the sample with that "division".

when this term refers to the medium-type granite. When the petrographic prefixes were first introduced it was admitted that they were loosely applied (p. 7) and as the discriminant analysis classification reveals that they are not chemically verified their use can be discontinued.

E) Multiple regression

Multiple regression enables the change of the mean of one particular variable to be followed in terms of the other variables. Its use is perhaps more applicable in economic geology where, for example, in one area the behaviour of a particular geological property can be found to vary in accordance with other, more readily measurable, properties. By assuming a similar relationship of properties in another area the benefits of the test are immediately apparent.

Both geometrically and algebraically the principles of the mathematics in multiple regression analysis are similar to those of trend surface analysis (to be considered in the following section). Geometrically the aim of regression analysis is to plot multivariate results and fit a plane or curved surface to the observations in order to minimize the sum of the squared distances from the fitted surface to a reference plane, the squared distance being measures perpendicularly to this reference plane. In other words it may be considered as an extension of the techniques of linear regression of one independent variable. Thus one variable is selected as a dependent while the other variables are independent such that the following equation relates the variables

$$w = \alpha + \beta_1 x_1 + \beta_2 x_2 \quad \ldots\ldots\ldots + \beta_k x_k + e$$

where,

w = the dependent variable,

α = the general coefficient,

$\beta_1, \beta_2, \ldots \beta_k$ = the coefficients for the independent variables,

$x_1, x_2, \ldots x_k$ = the independent variables and

e = the random fluctuation.

The correlation can then be estimated between the dependent and independent variables by a least squares solution of the parameters representing the general and independent variable coefficients. Further mathematical details are given by Koch & Link (1971, Vol. II, p.87-89) and programme computation details given in the IBM programmers' manual (Multiple Regression, IBM Programmers' Manual, 1968).

The results of the regression for each element in all the samples and then in each of the three cluster-analysis defined groups are tabulated, here, in terms of the standard error of the estimate of the dependent variable (Table 18). It is possible to determine the significance of the fitted surface, and hence that of the standard error of the estimate, from an analysis of variance test on the ratio of the mean for the sum of squares "explained" by the fitted surface (regression sum of squares) to the mean of the sum of squares "unexplained" by the fitted surface (residual sum of squares). The null hypothesis is accepted when this ratio is less than or equal to a theoretical value at some particular significance level. Taking Li, therefore, in all the samples as an example, at a significance value of $\alpha = 0.05$ the theoretical F-ratio value $F_{1-\alpha}(N_1-1)(N_2-1) = F_{0.95}(17, 177) = 1.75$ (Dixon & Massey, 1969, Table A-7c, p.485), where N_1 = no. of elements (18) and N_2 = no. of

Table 18 Multiple regression results

	All Samples		Group1		Group2		Group3	
	SEE	F	SEE	F	SEE	F	SEE	F
Li	62	22	62	8.4	50	2.8	48	14
Na	4873	18	4672	8.1	5144	4.1	3195	13
K	7092	9.7	7614	2.1	7335	6.7	3066	17
Cu	98	20	31	1.6	37	1.8	90	31
Zn	23	4.6	13	2.4	14	2.6	27	2.6
Rb	31	59	25	31	28	10	25	29
Sr	13	21	7.8	5.7	17	4.0	9.5	9.9
Y	3.9	40	3.3	23	4.2	7.1	3.4	15
Zr	20	44	15	9.0	17	5.4	16	13
Sn	35	3.1	64	1.8	17	3.4	4.7	3.9
Cs	8.9	26	10	7.3	6.5	2.0	5.9	19
Ba	51	19	34	9.3	73	3.4	34	11
La	2.1	222	1.6	34	2.1	42	2.2	31
Ce	5.6	113	5.3	8.6	5.8	18	5.2	24
Nd	2.9	97	2.6	8.1	3.1	21	2.7	15
Pb	12	4.3	5.4	6.2	6.7	3.6	12	2.1
U	9.9	0.4	4.6	1.8	6.6	1.0	12	0.7
Th	4.9	21	6.5	1.0	4.8	4.6	4.0	8.2

SEE = standard error of the estimate (in ppm).

F = F-ratio value.

The hypothesis that the standard error of the estimate is significant is accepted when the F-ratio value of the analysis of variance is greater than that derived from statistical tables (Dixon & Massey, 1969, Table A-7c, p.485). For $\alpha = 0.05$ the F-ratio values are

	All samples	Group1	Group2	Group3
D.freedom	(17,177)	(17,28)	(17,24)	(17,89)
F-ratio	1.75	2.01	2.11	1.75

Thus the higher the F-ratio value the more significant the standard error of the estimate.

samples (195) - N_1. The calculated value for the regression for Li is 21.8 and, therefore, the alternative hypothesis is accepted. In other words the fitted surface "explains" more of the variance than the residual and from this it can be assumed that there is a 95% chance that the Li value of any sample can be detected to ±62 ppm on the basis of measurements of the other elements. The importance of this can then be considered in terms of the means and standard deviations for the element in Table 10 and for the three cluster groups in Table 16. (Note that N_2 for the cluster analysis groups ceases to be 177 and becomes a lower figure depending upon the number of samples in the cluster group. The effect on the theoretical F-ratio value is noted in Table 18).

While the implications of the various statistical tests will be considered together in the conclusion, it is of interest to note at this point that although Cu and Sn are found to be good discriminators in the cluster analysis grouping their concentrations cannot be significantly assessed by multiple regression techniques. This inability to assess concentrations of Cu and Sn, and also Pb and Sn, on the basis of the other elements that have been analysed in this work implies that the present statistics and chemistry would be of little assistance in the economic exploration for these metallic elements.

F) Trend surface analysis

Of the numerous statistical tests that have been applied to geological data in recent years that of trend surface analysis is perhaps the most familiar. Although Grant (1957) is generally accepted as introducing the term 'trend surface' Krumbein &

Graybill (1965, p.321) offer what is probably a more comprehensible explanation of the process when they write "..... trend surface analysis may be defined as a procedure by which each map observation (chemical observation, in this case) is divided into two parts: some associated with the 'large-scale' (regional) systematic changes that extend from one map edge to the other and others associated with 'small-scale' (local) apparently nonsystematic fluctuations that are superimposed on the large-scale pattern".

As with the other analysis techniques it is not intended to review in detail previous results or applications of trend surface analysis, though references to such work will be made when appropriate. Although the algebraic computations in the analysis could be covered, such details are adequately expressed in other texts (e.g. Krumbein & Graybill, 1965, p.319-357) and as the methods involved are applicable to most trend surface procedures there is little point in reiterating these basic concepts.

Geometrically the analysis can be considered as an attempt to "fit" a planar or curved surface to a set of areally distributed points in order to assess variations within the results. By increasing the complexity of the mathematics the shape of the fitted surface can be amended in an attempt to account for a greater percentage of the variation. The criterion for obtaining the best fit or "explanation" is to reduce the sum of squares of the departures of the data from the computed surface. In other words the principles are very similar to those expressed earlier in multiple regression analysis except that each element is treated individually and it is the "geography" of the geological trend, rather than the predicted concentration which is being assessed.

As the fitted surface rarely corresponds exactly to the actual observations there is a residual variation, measured as the vertical distance between the sample point and the fitted surface. This residual variation may represent random "noise", such as sampling or analytical error, or it may contain geologically significant information. Whitten (1959), for example, in the trend surface analysis of the Donegal granite interpreted the residual variation as 'ghost stratigraphy'. Thus the removal of a general trend surface may emphasize local departures of significance and both the trend surface and residuals may have meaningful geological implications.

When observations can be made on a rectangular grid the algebraic computations of the trend surface are generally derived by orthogonal polynomial analysis but when the observations are limited and irregularly distributed over an area, as with the Bodmin Moor samples, a form of non-orthogonal analysis is necessary. As the height for the Bodmin Moor samples appears to offer little chemical variation, in terms of the 3-dimensional form that can be sampled, the trend surface for the granite was computed in two dimensions, U and V, for which the polynomial relationship may be expressed as

$$w = \alpha + \beta_{10}U + \beta_{01}V + \beta_{20}U^2 + \beta_{11}UV \;\ldots\ldots\; \beta_{pq}U^pV^q + e$$

where,

w = the trend surface estimated from a polynomial of the degree (p,q) that fits the observed data

α, β_{pq} = the parameters

e = the random fluctuation.

In the present work the co-ordinates U and V were based on the grid lines employed for the sampling of the granite (see Fig. 1). For non-orthogonal points the method of computing the polynomial expression is that of least squares, this being based on a conventional method of analysis in matrix algebra.

The method of trend surface computation applied to the Bodmin Moor granite results (all elvan, aplite, pegmatite and fine-grained granite samples having been discounted for the purpose of this test) was that of Cole (1968, 1969). Although the initial part of this programme is similar to others the final stage involves an "iterative-fit" technique the purpose of which is to "smooth-out" any discontinuities or irregularities in the initial "overall-fit" surface. The methods involved in this "smoothing" technique are described by Cole (1968, 1969) with the mathematics expressed in further detail by Cole & Davis (1969). The iterative stages are repeated until either the maximum correction at any grid point has just failed to exceed some initially stipulated value or until a specified number of iterations has been carried out. In the present work it was found that for most elements ten iterations were necessary in order that the "iterative-fit" surface accounted for at least 90% of the total variation and in order to maintain a consistency throughout, ten iterations were applied to each "overall-fit" surface. On the "overall-fit" trend surface print-out, triangular markers are placed at data points where the calculated value differs from the real value by some chosen percentage. 25% of the standard deviations of the original value was selected here as a suitable percentage as this figure was thought to be large enough to allow for any sampling or analytical error but small enough to permit detection of "anomalous" samples.

These markers, therefore, reveal any abrupt "anomalies" in the observed data which would result in contour gradients too steep to be accurately represented on the final "iterative-fit" surface. For clarity, however, the triangular markers are not reproduced on the trend surface diagrams for the Bodmin Moor granite (Figs. 4-12), though details of the "anomalous" specimens are given in the tables accompanying each figure. The computer programme also plots "difference-maps" showing the difference between the "iterative-fit" and the "overall-fit" trend surfaces and when the final fit is good, i.e. better than 90%, the "difference-map" can be considered as being similar to the traditional residual map.

Cole (1969) indicates that some of the advantages of employing the "iterative-fit" technique are

1) that the "overall" trend surface fit is not critical, in other words it is purely a guide for the computer construction of the "iterative-fit" surface,
2) that as the initial data are used at every iteration there is no "round off" error to accumulate,
3) that the data points after the "overall-fit" surface has been applied are not interdependent and "anomalous" points do not affect the entire map as they may do in some other trend surface techniques, and
4) that the statistical fit is generally good, quickly achieved and does not incorporate any preconceived ideas of the user.

Use of the "iterative-fit" trend surface technique in the assessment of geological data is well illustrated by Read et al (1971) in which the Cole (1969) programme is employed.

As with all other mathematical tests, trend surface analysis requires thoughtful use in order that any interpretations are geologically, rather than statistically influenced. Being one of the more familiar statistical tools the implications of these analyses have received more attention than other tests and a particularly useful discussion on deciding whether trend surfaces are meaningful are given by Baird et al (1971) and Whitten (1972) the former work being a reply to criticisms by Chayes (1970). As with the other statistical methods the use of significance tests or the repetition of the analysis employing only part of the data, or further independent data, may be of assistance though the final acceptance, or rejection, of a result is generally based on intuitive judgment. Such a check, for example, can be made by explaining the results on the basis of a model which is already known to be geologically authentic. This is preferable to the erection of a specific model to justify the statistics and yet having an improbable geological interpretation.

For all the elements the cubic "overall-fit" trend surfaces, upon which the "iterative-fit" surfaces have been based, are relatively "weak" and in none of the cases account for more than a 30% "fit". In applying the iterative steps the use of the third order polynomial was taken as a compromise. For the present data, lower order surfaces account for only very small percentage "fits" and higher order polynomials, though possibly giving a good "overall-fit" are likely to produce unjustified local detail in poorly sampled areas. Even for the third order polynomial, sampling effects are still apparent for Bodmin Moor, though these arise from clustering, rather than sparsity, of data. In the Wheal Bray locality (Figs 4-12), for example, there is a cluster of specimens taken from a series of mineralised cores surrounded by an area which has been poorly sampled. The "overall-fit" trend surface maps reflect a marked "high" for this area which in turn produces a dominant increasing trend in concentration for the metallic elements, Cu, Pb, Sn, Zn, towards the north in the "iterative-fit" surface. Hosking (1950) has indicated that a zone of mineralisation cuts the S.E. part of the granite, rather than the northern part, and it would have been expected, therefore, that the trend surfaces would have revealed an increase in metal concentrations towards the south. Although such an increase is just perceptible the picture is obscured by the "high" in the north of which the few specimens from Wheal Bray are the cause.

In the majority of cases, however, the iterative stages tend to smooth out the local inconsistencies which can be quite marked in the "overall-fit" surface and the effects of sample clusters and sparse data areas are not so strongly noticeable. It is admitted, however, that there may be some minor inflections, the most visible of which occur in the Na and K trends, that could be ascribed to sampling imperfections.

The statistical restraints in trend surface contouring are not so easily assessed. Chayes (1970, p.1273) has indicated that as trend surface calculations are a form of analysis of variance then they should be subject to the same general analysis of variance test procedures; in other words the F-ratio test of the mean sum of squares of the variance accounted for by a particular polynomial surface and the mean sum of squares of the total variance. Baird et al (1971) have shown, however, that this comparison does not always hold. In the present work no attempt has been made to apply significance tests to the "overall" or "iterative-fit" surfaces but by virtue of the large percentage explanation of the distribution by the "iterative-fit" surface it can, at least, be assumed that it gives a close approximation to an objective contour map of the data.

For Cu the standard deviation of the error of the observed chemical values to the chemical values after ten iterations of the "iterative-fit" computation (see Table 19) is greater than some of the errors associated with locality sampling (see Table 10). As a consequence a certain limitation is placed on the validity of the Cu trend surface. Similarly for U and Th, where the analytical accuracy is known to be poor (see appendix, XRF analysis) the chemical restraints are such that figured trend surface distributions are of interest rather than of academic importance or validity.

The "iterative-fit" trend surface results for the non-metallic elements, with the exception of Na and K, all reflect concentration increases, or decreases, in an approximately concentric configuration within the pluton. In considering the theoretical significances, therefore, of the trend surface analysis the requirements of interpretation in terms of a geological model are met, as concentric chemical zoning in plutonic bodies is a known geological phenomenon.

There is no immediately apparent pattern in the "difference-maps" though it is possible to perceive a very general N.W.-S.E. elongation for some of the "difference-pools" for many of the elements and it is notable that this similar trend occurs not only in the elongation of the concentric "iterative-fit" surfaces but also in the actual exposure of the granite body as a whole.

Table 19 Percentage of total variation, expressed as sums of squares, satisfied by 'overall-fit' linear, quadratic and cubic trend surfaces and by 'iterative-fit' trend surfaces.

	1 %	2 %	3 %	I %	s.d.	s.d.e.
Li	2.0	12.2	25.0	95.3	100.5	13.9
Na	1.3	8.8	13.0	96.2	6939.2	693.0
K	6.4	9.4	11.8	91.4	7411.6	1365.9
Cu	1.7	4.3	6.2	98.7	176.9	29.3
Zn	1.4	6.2	8.8	96.0	26.5	1.9
Rb	5.3	21.7	25.3	92.0	67.8	8.6
Sr	2.9	16.4	18.2	94.3	19.0	2.9
Y	2.4	16.4	18.4	91.9	7.4	1.1
Zr	0.8	7.2	13.0	95.7	36.8	3.8
Sn	0.7	2.4	4.2	96.8	41.6	4.6
Cs	3.3	19.6	27.1	95.9	16.0	1.9
Ba	2.3	6.4	9.0	92.5	67.1	10.9
La	0.6	9.2	18.3	96.4	8.7	1.0
Ce	1.5	13.4	26.5	95.9	16.6	2.0
Nd	1.3	10.0	17.5	95.7	8.2	1.2
Pb	4.3	10.6	10.9	95.7	12.9	1.9
U	1.4	1.8	4.0	94.4	10.3	2.4
Th	0.4	4.2	10.6	94.7	7.5	0.9

1 - Linear 'overall-fit' trend surface.

2 - Quadratic 'overall-fit' trend surface.

3 - Cubic 'overall-fit trend surface.

I - 'Iterative-fit' trend surface (after 10 iterations).

s.d. - standard deviation in 160 samples employed for trend surface analysis.

s.d.e. - standard deviation of error of observed chemical values to calculated values after 10 iterations.

Fig.4 Lithium (left-hand side of facing plate)

'Overall-fit' cubic trend surface (top)

Percentage of total variation, expressed as sum of squares, satisfied by fitted surface - 25.0%. Contour levels at 60ppm.

'Iterative-fit' trend surface (middle)

Percentage of total variation, expressed as sum of squares, satisfied by fitted surface - 95.3%. Contour levels at 60ppm.

Anomalous specimens	Zobs.	Zcalc.	s.d.%
KEB552	377	412	35
A	313	338	26
L104(26)	419	493	74

'Difference map' (bottom)

Contour levels at 100ppm.

Fig.5 Sodium (right-hand side of facing plate)

'Overall-fit' cubic trend surface (top)

Percentage of total variation, expressed as sum of squares, satisfied by fitted surface - 13.0%. Contour levels at 5000ppm.

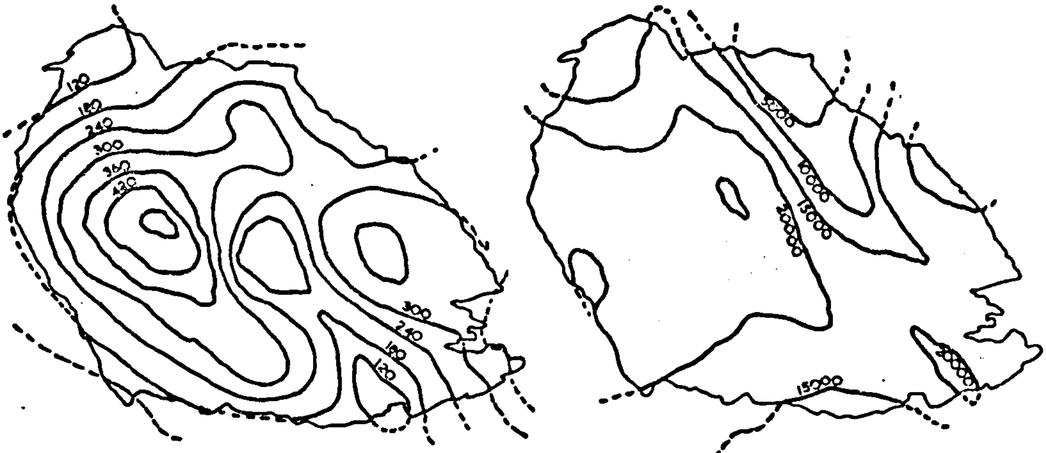
'Iterative-fit' trend surface (middle)

Percentage of total variation, expressed as sum of squares, satisfied by fitted surface - 96.2%. Contour levels at 5000ppm.

Anomalous specimens	Zobs.	Zcalc.	s.d.%
KEB533	21145	23530	34
KEB135	20255	22455	32

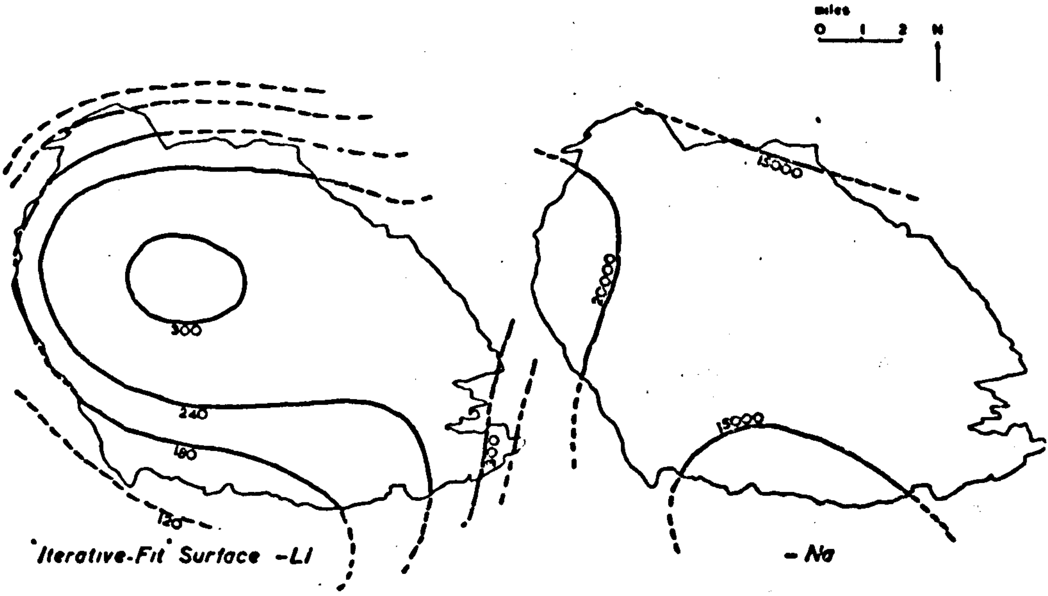
'Difference map' (bottom)

Contour level at 10000ppm.



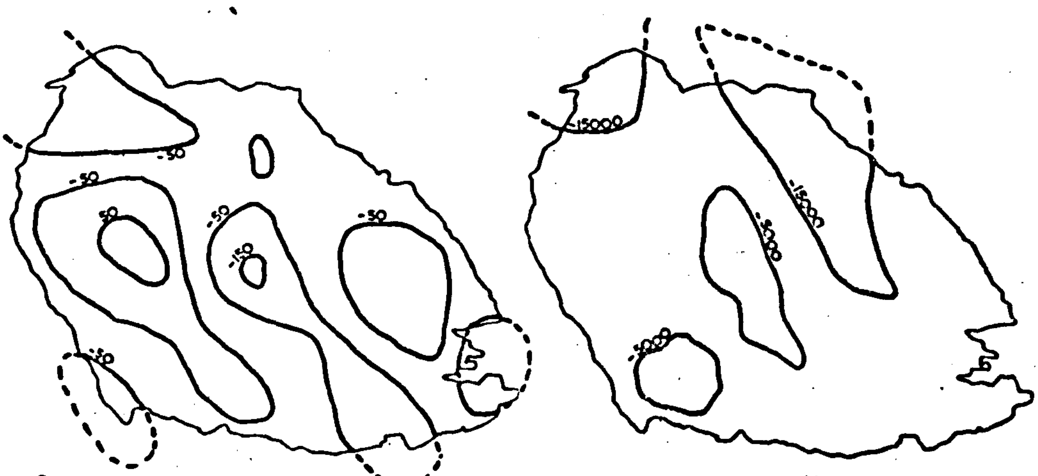
'Overall-Fit' Surface -Li

-Na



'Iterative-Fit' Surface -Li

-Na



Difference Map -Li

-Na

Fig.6 Potassium (left-hand side of facing plate)

'Overall-fit' cubic trend surface (top)

Percentage of total variation, expressed as sum of squares, satisfied by fitted surface - 11.8%. Contour levels at 5000ppm.

'Iterative-fit' trend surface (middle)

Percentage of total variation, expressed as sum of squares, satisfied by fitted surface - 91.4%. Contour levels at 5000ppm.

Anomalous specimens	Zobs.	Zcalc.	s.d.%
KEB28	53936	55962	27
KEB410	60657	65586	66
KEB418	41157	38945	30
KEB532	59745	64845	69

'Difference map' (bottom)

Contour levels at 10000ppm.

Fig.7 Copper (right-hand side of facing plate)

'Overall-fit' cubic trend surface (top)

Percentage of total variation, expressed as sum of squares, satisfied by fitted surface - 6.2%. Contour levels at 40ppm.

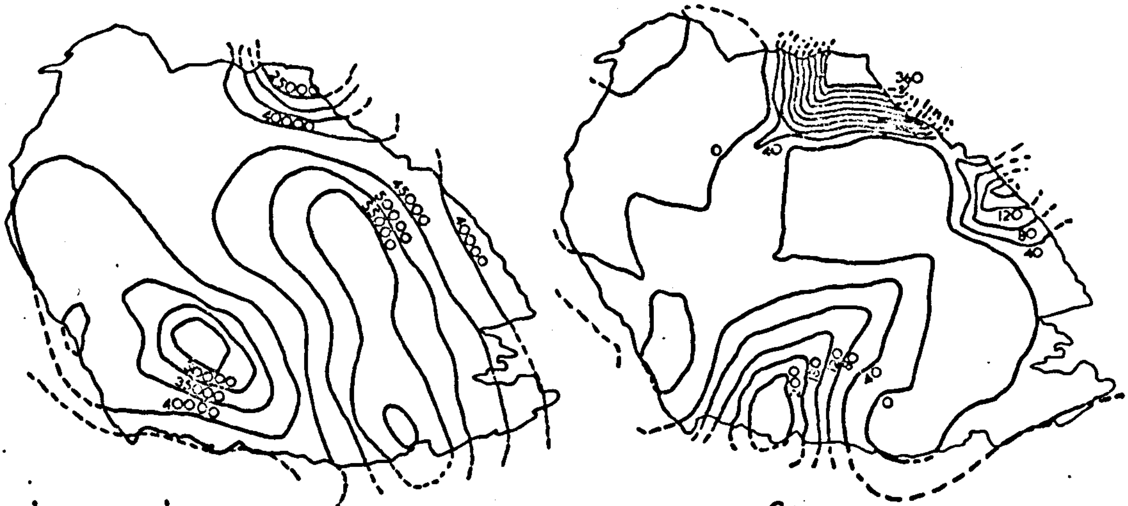
'Iterative-fit' trend surface (middle)

Percentage of total variation, expressed as sum of squares, satisfied by fitted surface - 98.7%. Contour levels at 40ppm.

Anomalous specimens	Zobs.	Zcalc.	s.d.%
KEB533	0.0	-51.2	29
E2(63)	53.6	-60.9	65
W1	55.6	-33.2	50
K2	1.7	-149.0	85

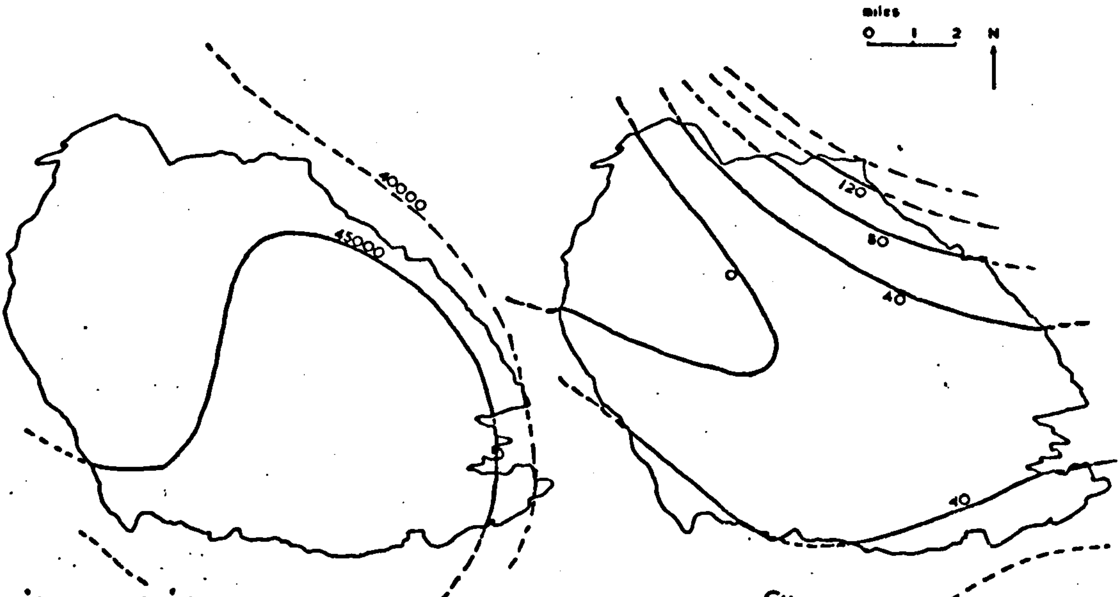
'Difference-map' (bottom)

Contour levels at 1000ppm.



'Overall-Fit' Surface -K

-Cu



'Iterative-Fit' Surface -K

-Cu

Difference Map -K

-Cu

Fig.8 Zinc (left-hand side of facing plate)

'Overall-fit' cubic trend surface (top)

Percentage of total variation, expressed as sum of squares, satisfied by fitted surface - 8.8%. Contour levels at 20ppm.

'Iterative-fit' trend surface (middle)

Percentage of total variation, expressed as sum of squares, satisfied by fitted surface - 96.0%. Contour levels at 20ppm

Anomalous specimen	Zobs.	Zcalc.	s.d.%
EB119	105.6	115.4	37

'Difference map' (bottom)

Contour levels at 10ppm

Fig.9 Rubidium (right-hand side of facing plate)

'Overall-fit' cubic trend surface (top)

Percentage of total variation, expressed as sum of squares, satisfied by fitted surface - 25.3%. Contour levels at 50ppm.

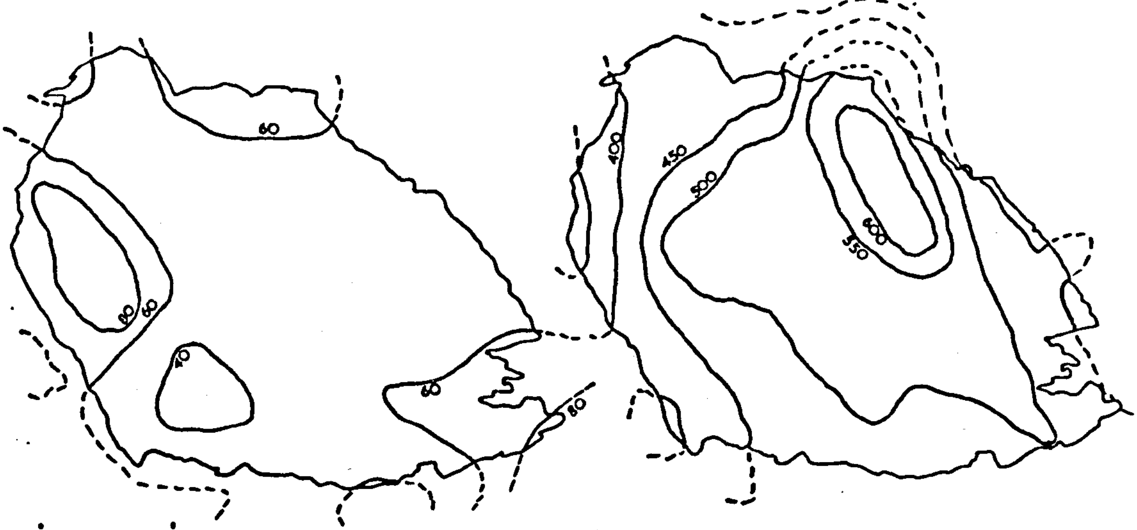
'Iterative-fit' trend surface (middle)

Percentage of total variation, expressed as sum of squares, satisfied by fitted surface - 92.0%. Contour levels at 50ppm

Anomalous specimens	Zobs.	Zcalc.	s.d.%
KEB410	761	780	28
KEB421	352	316	53
KEB427	424	404	30
E1(56)	91	66	37

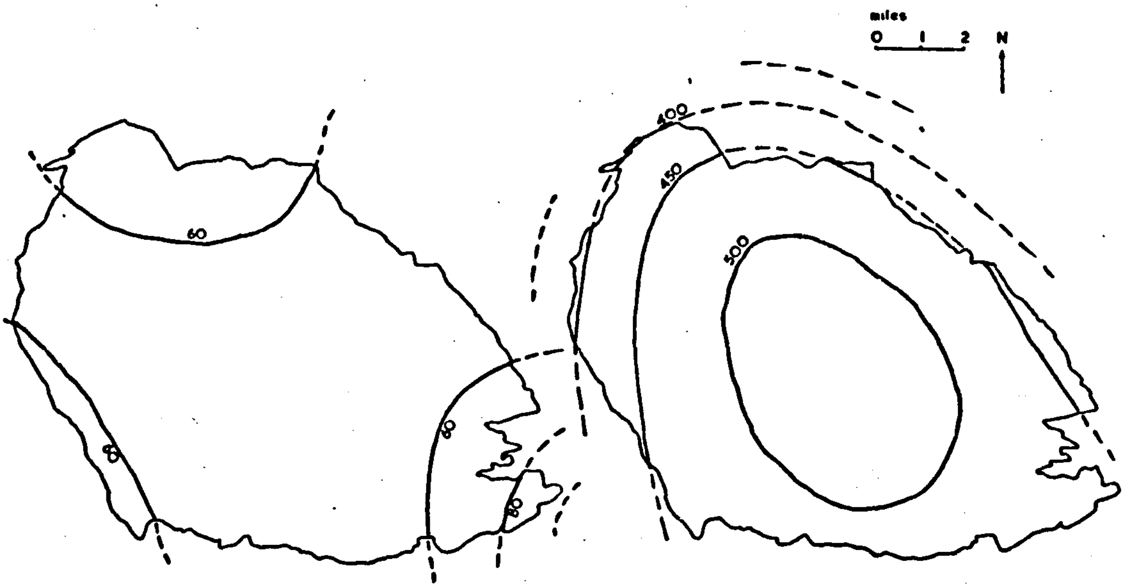
'Difference map' (bottom)

Contour levels at 100ppm.



'Overall-Fit' Surface -Zn

- Rb



'Iterative-Fit' Surface -Zn

-Rb

Difference Map Zn

Rb

Fig.10 **Strontium** (left-hand side of facing plate)

'Overall-fit' cubic trend surface (top)

Percentage of total variation, expressed as sum of squares, satisfied by fitted surface - 18.2%. Contour levels at 10ppm.

'Iterative-fit' trend surface (middle)

Percentage of total variation, expressed as sum of squares, satisfied by fitted surface - 94.3%. Contour levels at 10ppm.

Anomalous specimens	Zobs.	Zcalc.	s.d.%
KEB11	112	118	31
KEB502	88	95	36
KEB533	90	99	45
KEB143	101	108	38
N(97)	60	53	35

'Difference map' (bottom)

Contour levels at 20ppm

Fig.11 **Yttrium** (right-hand side of facing plate)

'Overall-fit' cubic trend surface (top)

Percentage of total variation, expressed as sum of squares, satisfied by fitted surface - 18.4%. Contour levels at 10ppm

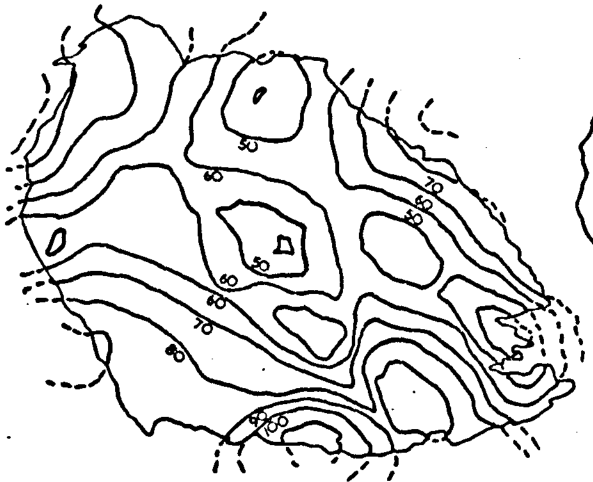
'Iterative-fit' trend surface (middle)

Percentage of total variation, expressed as sum of squares, satisfied by fitted surface - 91.9%. Contour levels at 10ppm

Anomalous specimens	Zobs.	Zcalc.	s.d.%
KEB410	80.0	82.3	31.
KEB414	48.0	49.9	26
KEB421	31.6	27.4	57
EB119	32.3	28.9	46
E	37.2	34.8	32
E1(56)	7.0	4.4	35
W1	39.8	37.5	31

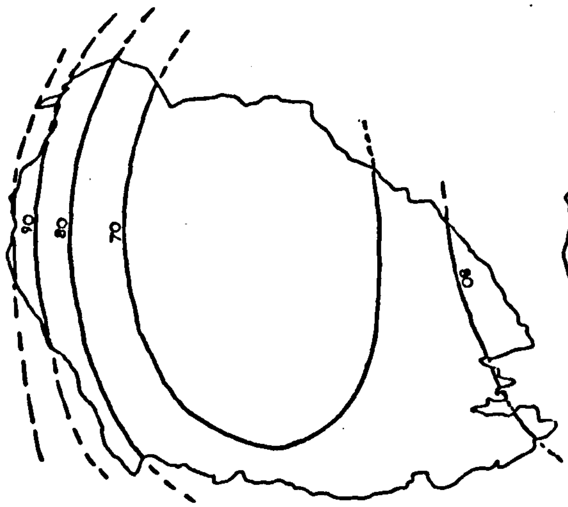
'Difference map' (bottom)

Contour levels at 10ppm

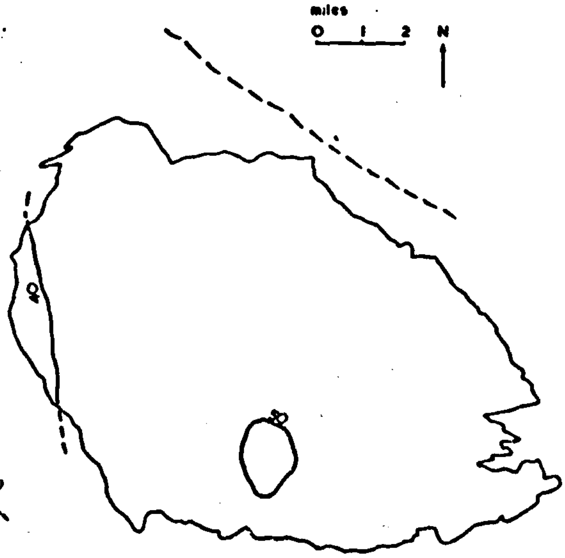


'Overall-Fit' Surface -Sr

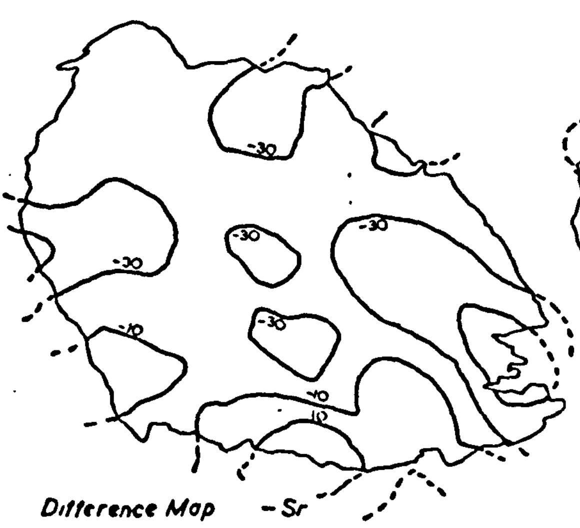
-Y



'Iterative-Fit' Surface -Sr



-Y



Difference Map -Sr

-Y

Fig.12 Zirconium (left-hand side of facing plate)

'Overall-fit' cubic trend surface (top)

Percentage of total variations, expressed as sum of squares, satisfied by fitted surface - 13.0%. Contour levels at 40ppm.

'Iterative-fit' trend surface (middle)

Percentage of total variation, expressed as sum of squares, satisfied by fitted surface - 95.7%. Contour levels at 40ppm.

Anomalous specimens	Zobs.	Zcalc.	s.d.%
KEB17	149	160	30
E1(56)	0	11	29

'Difference map' (bottom)

Contour levels at 20ppm

Fig. 13 Tin (right-hand side of facing plate)

'Overall-fit' cubic trend surface (top)

Percentage of total variation, expressed as sum of squares, satisfied by fitted surface - 4.2%. Contour levels at 10ppm.

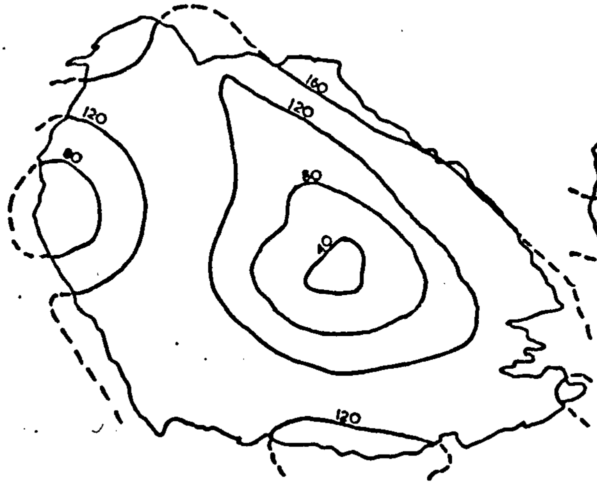
'Iterative-fit' trend surface (middle)

Percentage of total variation, expressed as sum of squares, satisfied by fitted surface - 96.8%. Contour levels at 10ppm.

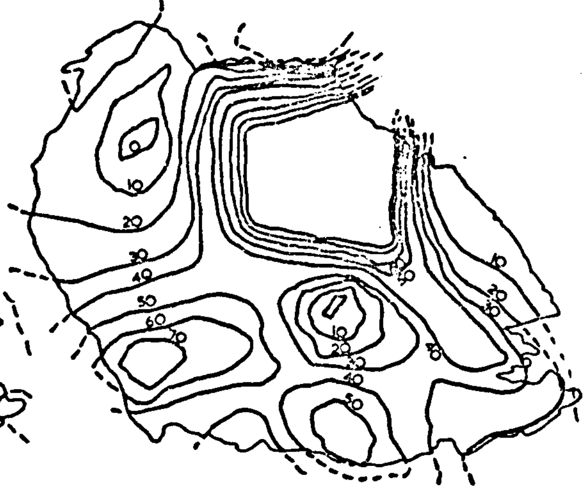
Anomalous specimens	Zobs.	Zcalc.	s.d.%
KEB429	9.9	-10.03	48
KEB160	17.9	6.27	27
KEB162	22.0	4.9	41

'Difference map' (bottom)

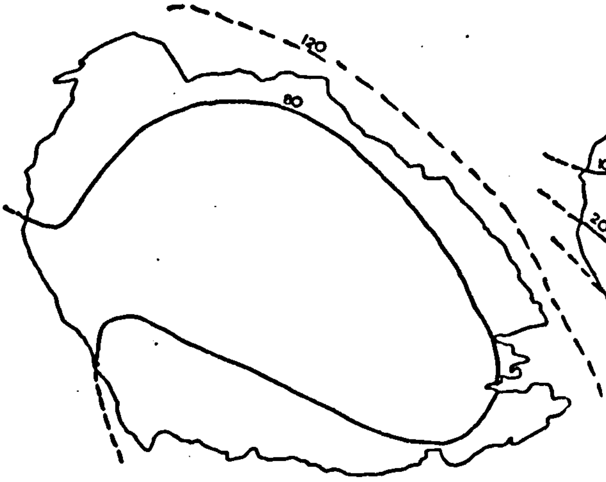
Contour level at 100ppm



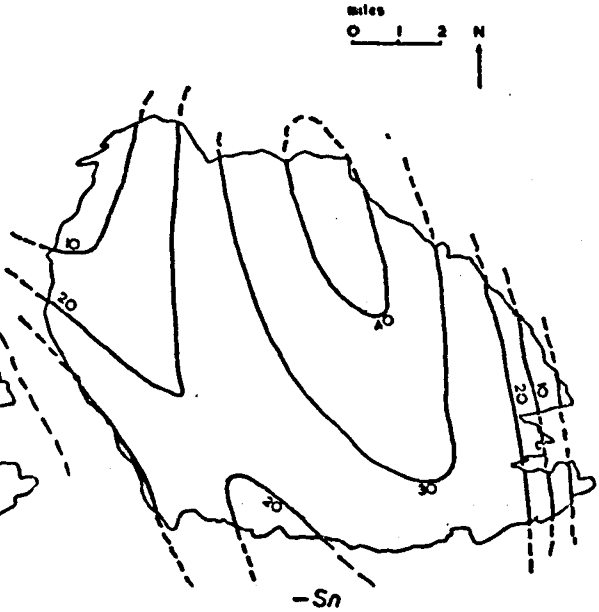
'Overall-Fit' Surface -Zr



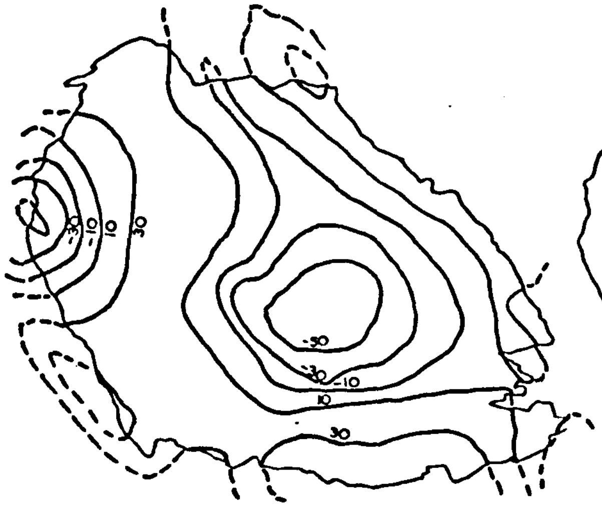
-Sn



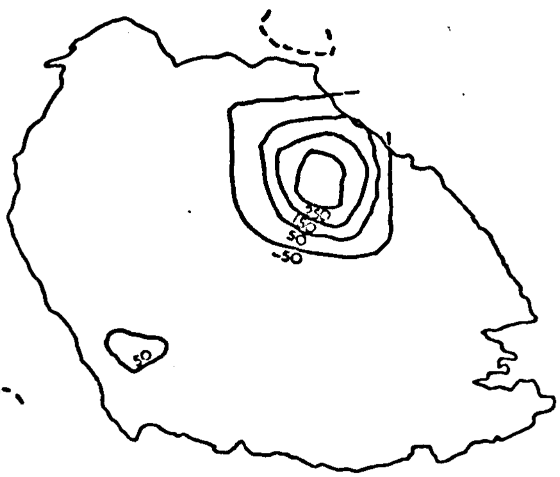
'Iterative-Fit' Surface -Zr



-Sn



Difference Map -Zr



-Sn

Fig. 14 Caesium (left-hand side of facing plate)

'Overall-fit' cubic trend surface (top)

Percentage of total variation, expressed as sum of squares, satisfied by fitted surface - 27.1%. Contour levels at 10ppm.

'Iterative-fit' trend surface (middle)

Percentage of total variation, expressed as sum of squares, satisfied by fitted surface - 95.9%. Contour levels at 10ppm.

Anomalous specimens	Zobs.	Zcalc.	s.d.%
KEB501	17.7	11.1	41
LL	31.9	26.2	36

'Difference map' (bottom)

Contour levels at 10ppm

Fig. 15 Barium (right-hand side of facing plate)

'Overall-fit' cubic trend surface (top)

Percentage of total variation, expressed as sum of squares, satisfied by fitted surface - 9.0%. Contour levels at 50ppm.

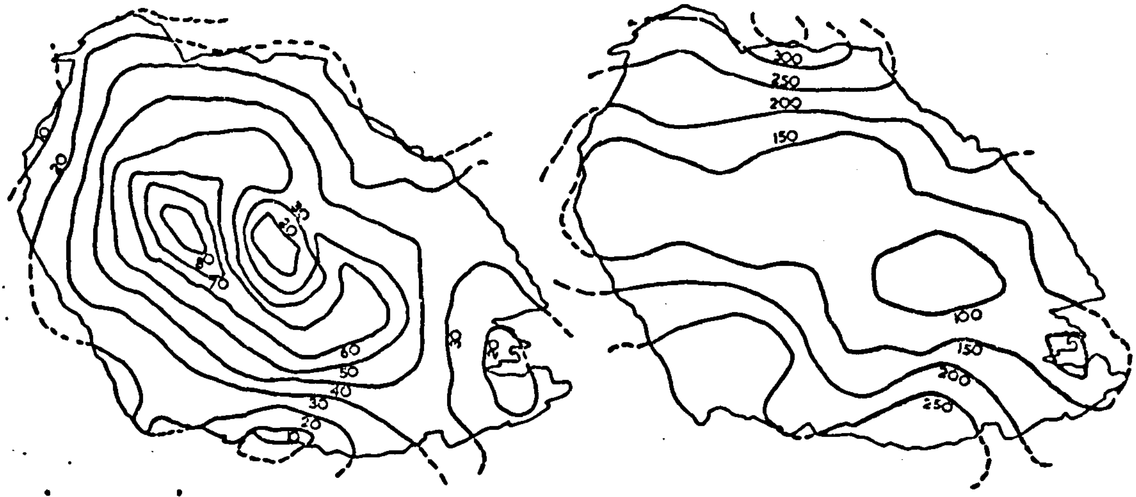
'Iterative-fit' trend surface (middle)

Percentage of total variation, expressed as sum of squares, satisfied by fitted surface - 92.5%. Contour levels at 50ppm

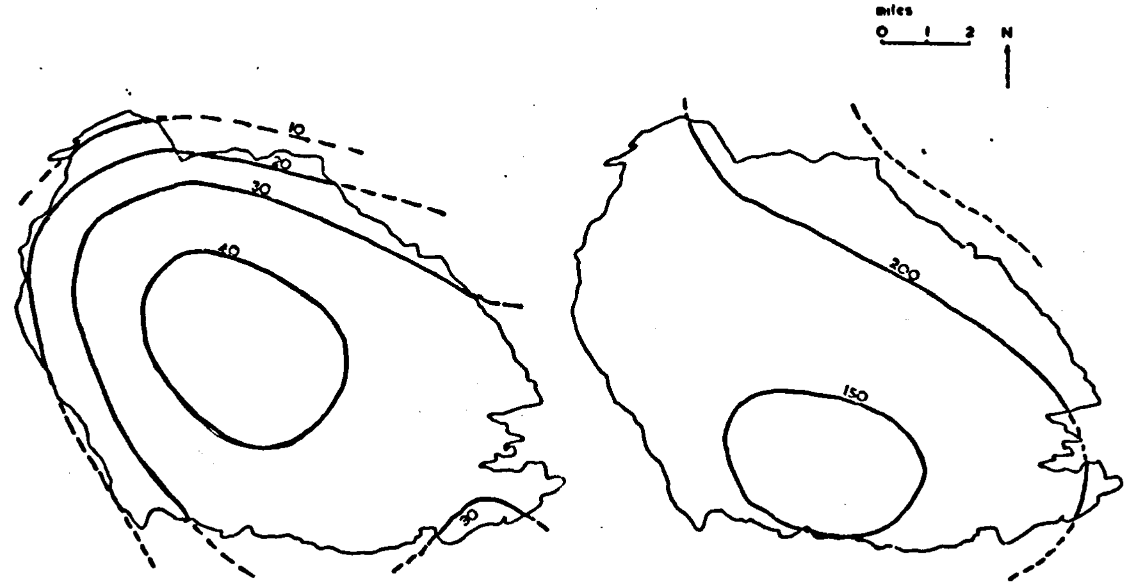
Anomalous specimens	Zobs.	Zcalc.	s.d.%
KEB25	70	52	27
KEB29	267	295	41
KEB502	216	239	34
KEB506	282	317	53
KEB541	107	88	28
KEB135	191	210	29

'Difference map' (bottom)

Contour levels at 100ppm



'Overall-Fit' Surface –Cs –Ba



'Iterative-Fit' Surface –Cs –Ba

Difference Map –Cs –Ba

Fig. 16 Lanthanum (left-hand side of facing plate)

'Overall-fit' cubic trend surface (top)

Percentage of total variation, expressed as sum of squares, satisfied by fitted surface - 18.3%. Contour levels at 5ppm.

'Iterative-fit' trend surface (middle)

Percentage of total variation, expressed as sum of squares, satisfied by fitted surface - 96.4%. Contour levels at 5ppm.

Anomalous specimens	Zobs.	Zcalc.	s.d.%
KEB542	22.2	19.0	37
EB119	31.4	28.2	37

'Difference map' (bottom)

Contour levels at 10ppm.

Fig. 17 Cerium (right-hand side of facing plate)

'Overall-fit' cubic trend surface (top)

Percentage of total variation, expressed as sum of squares, satisfied by fitted surface - 26.5%. Contour levels at 10ppm.

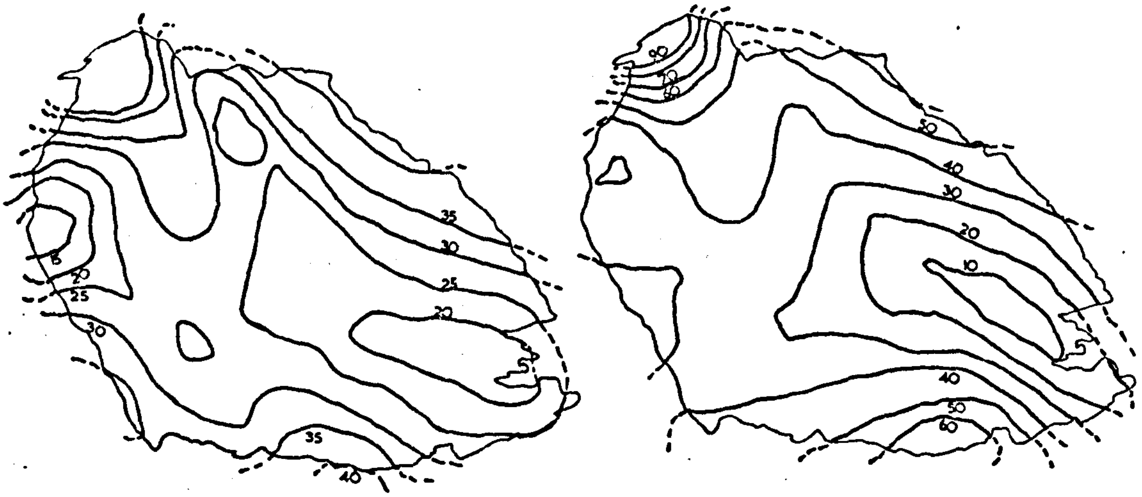
'Iterative-fit' trend surface (middle)

Percentage of total variation, expressed as sum of squares, satisfied by fitted surface - 95.9%. Contour levels at 10ppm.

Anomalous specimens	Zobs.	Zcalc.	s.d.%
KEB421	15.1	10.0	31
KEB542	22.8	15.3	45
EB119	40.2	34.5	34
E	31.2	26.6	28
N(97)	20.5	15.3	31

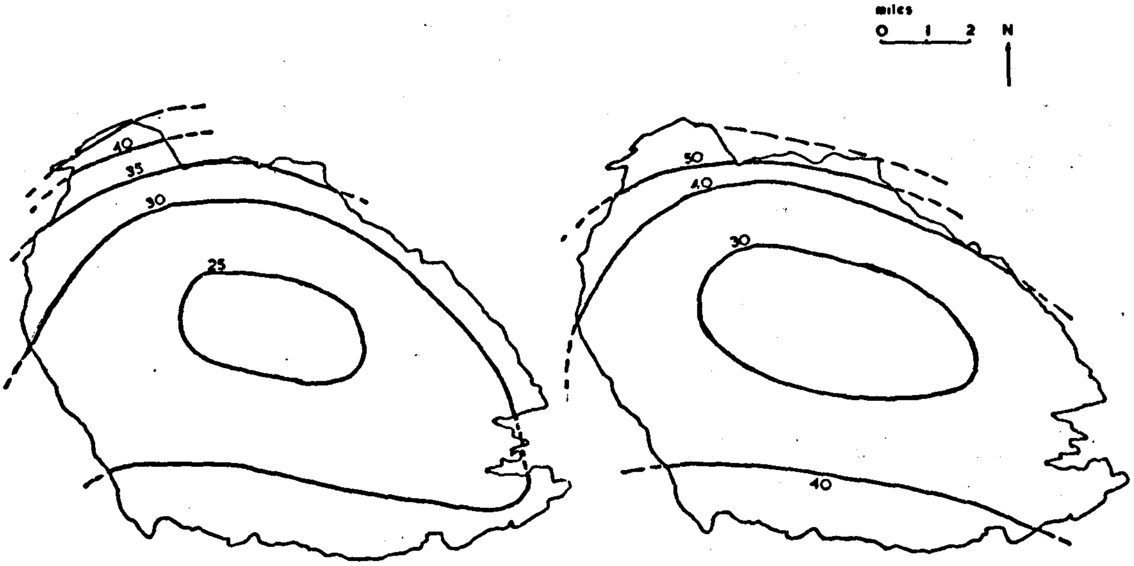
'Difference map' (bottom)

Contour levels at 20ppm.



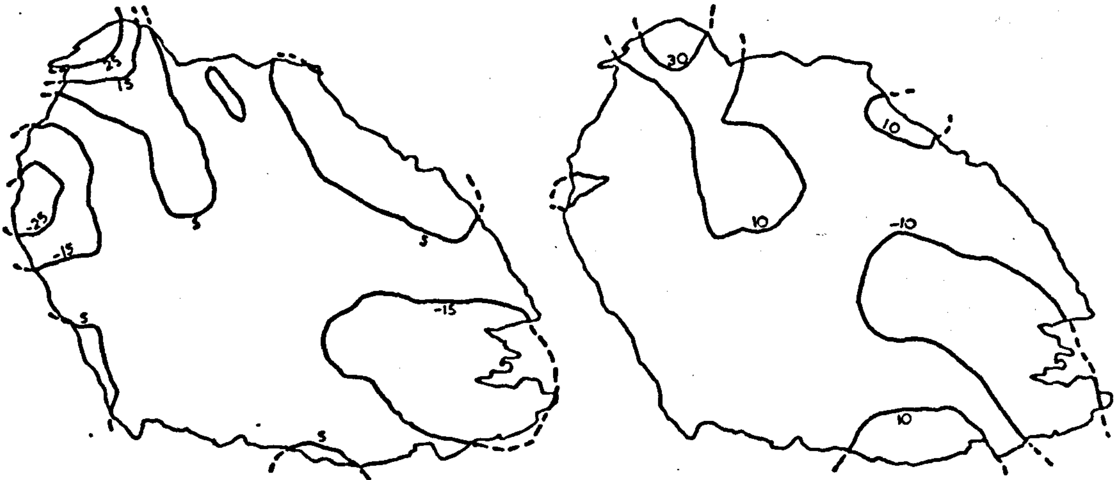
'Overall-Fit' Surface -La

-Ce



'Iterative-Fit' Surface -La

-Ce



Difference Map -La

-Ce

Fig. 18 Neodymium (left-hand side of facing plate)

'Overall-fit' cubic trend surface (top)

Percentage of total variation, expressed as sum of squares, satisfied by fitted surface - 17.5%. Contour levels at 5ppm.

'Iterative-fit' trend surface (middle)

Percenteage of total variation, expressed as sum of squares, satisfied by fitted surface - 95.7%. Contour levels at 5ppm.

Anomalous specimens	Zobs.	Zcalc.	s.d%
KEB428	30.7	28.2	30.1
EB119	36.1	33.0	38
KEB542	28.3	25.1	39
KEB116	33.4	31.1	28
E	27.4	23.6	46.1

'Difference map' (bottom)

Contour levels at 10ppm.

Fig. 19 Lead (right-hand side of facing plate)

'Overall-fit' cubic trend surface (top)

Percentage of total variation, expressed as sum of squares, satisfied by fitted surface - 10.9%. Contour levels at 5ppm.

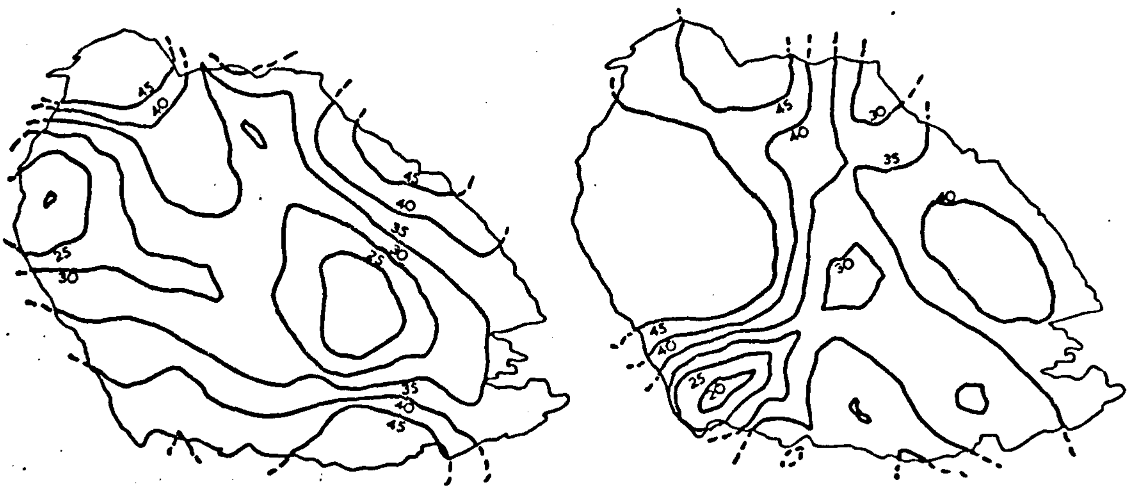
'Iterative-fit' trend surface (middle)

Percentage of total variation, expressed as sum of squares, satisfied by fitted surface - 95.7%. Contour levels at 5ppm.

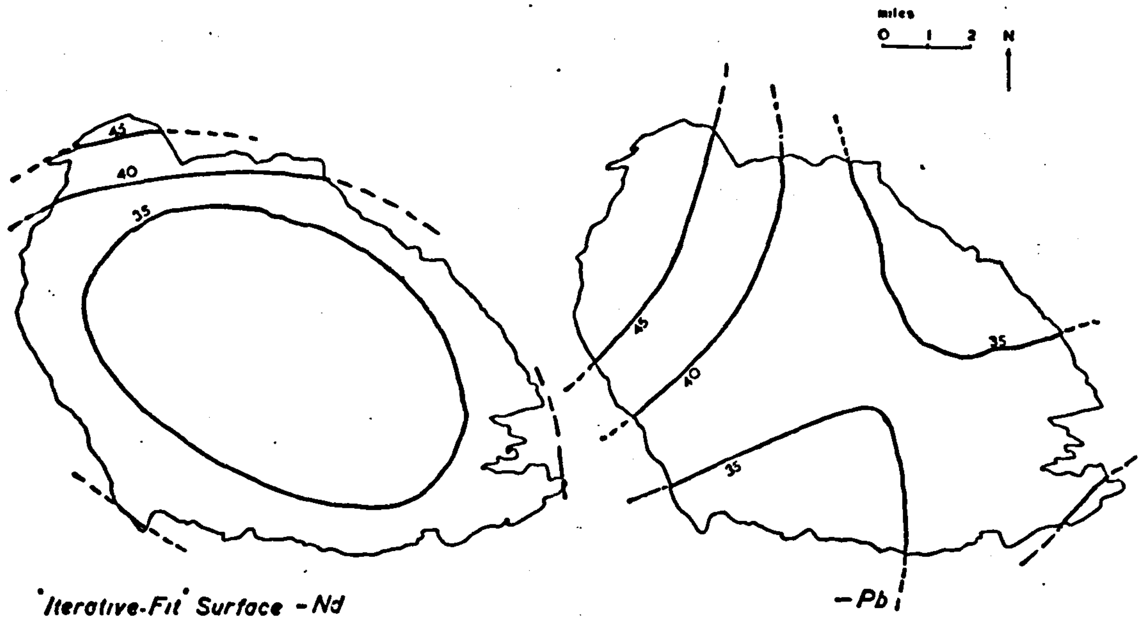
Anomalous specimens	Zobs.	Zcalc.	s.d.%
EB119	62.7	67.0	33
KEB503	32.4	29.0	26
KEB131	41.0	35.4	43
KEB149	33.0	27.0	47
E1(56)	54.0	60.1	47

'Difference map' (bottom)

Contour levels at 10ppm.



'Overall-Fit' Surface -Nd   -Pb



'Iterative-Fit' Surface -Nd   -Pb

Difference Map -Nd   -Pb

Fig. 20 Uranium (left-hand side of facing plate)

'Overall-fit' cubic trend surface (top)

Percentage of total variation, expressed as sum of squares, satisfied by fitted surface - 4.0%. Contour levels at 3ppm.

'Iterative-fit' trend surface (middle)

Percentage of total variation, expressed as sum of squares, satisfied by fitted surface - 94.4%. Contour levels at 3ppm

Anomalous specimens	Zobs.	Zcalc.	s.d.%
KEB30	5.2	-0.5	56
KEB31	19.7	22.6	28
KEB43	1.5	-1.7	32
KEB416	4.8	-1.5	62
KEB419	7.9	3.7	41
KEB423	5.2	-1.0	60
KEB540	6.7	3.5	31
KEB545	5.9	1.1	47
KEB552	6.1	1.7	43
HARR	1.2	-9.2	102

'Difference map' (bottom)

Contour levels at 20ppm

Fig.21 Thorium (right-hand side of facing plate)

'Overall-fit' cubic trend surface (top)

Percentage of total variation, expressed as a sum of squares, satisfied by fitted surface - 10.6%. Contour levels at 5ppm.

'Iterative-fit' trend surface (middle)

Percentage of total variation, expressed as a sum of squares, satisfied by fitted surface - 94.7%. Contour levels at 5ppm.

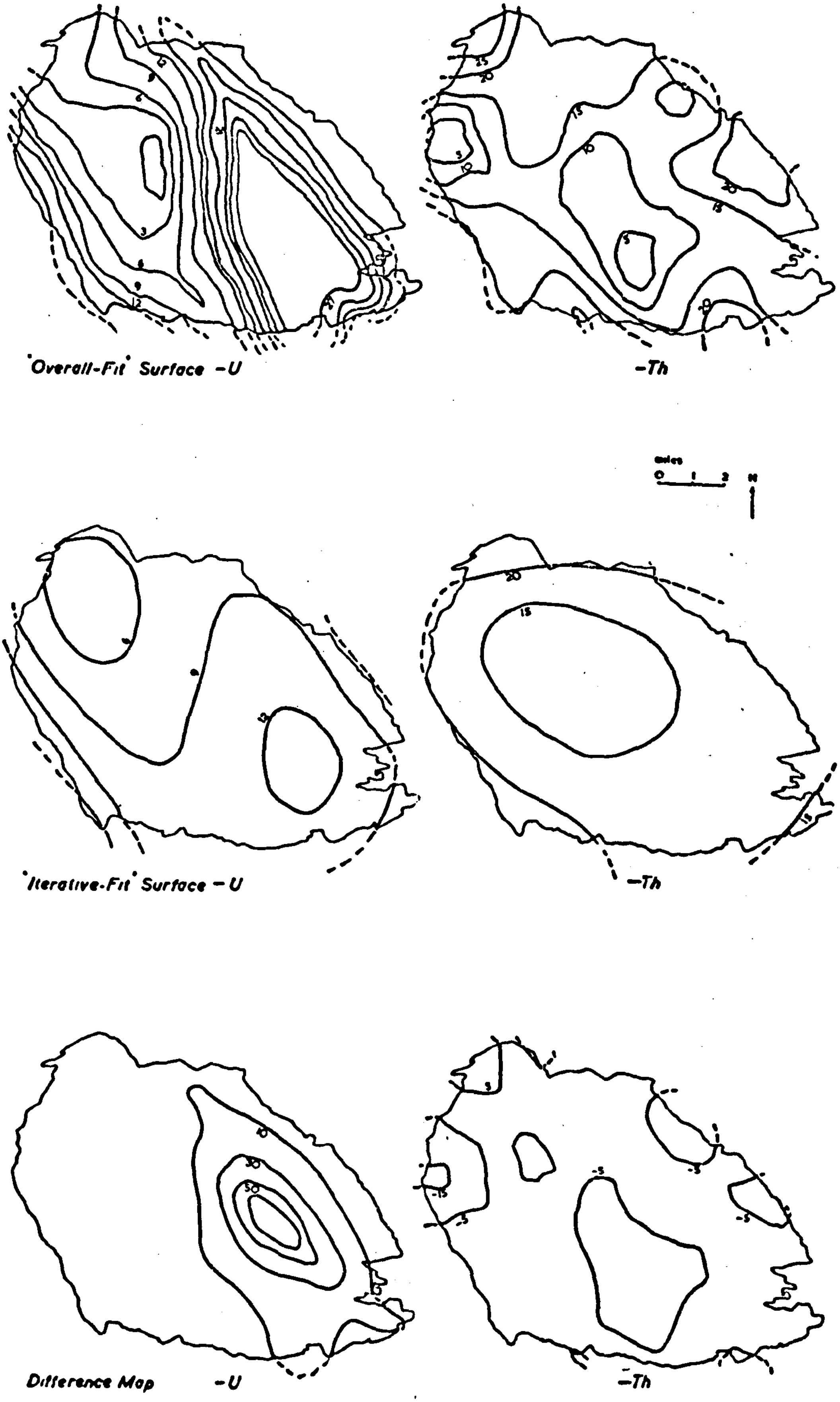
Anomalous specimens	Zobs.	Zcalc.	s.d.%
E	9.4	7.2	30
N(97)	6.7	4.2	34

'Difference map' (bottom)

Contour levels at 10ppm

Z = concentration in ppm, obs. = observed, calc = calculated

s.d. = standard deviation. See text for explanation of anomalous specimens.



'Overall-Fit' Surface -U

-Th

'Iterative-Fit' Surface -U

-Th

Difference Map -U

-Th

G) Some conclusions from the trace element tests of variation

A series of conclusions can be drawn from the various statistical tests of the analysed trace elements from the Bodmin Moor granite and associated rocks. For ease of expression these can be tabulated as follows:-

a) The majority of elements follow a normal, rather than lognormal, distribution.

b) For all the samples the greatest amount of variation (29.1%) can be attributed to concentration changes in La, Ce, Nd and Zr with smaller contributions from Rb, Y and Cs (17.6%) and Li, K and Ba (10.3%).

c) There appears to be no strong compatible relationship between physical and chemical properties. The closest affinity between the two sets of properties is derived by a cluster analysis grouping. From this grouping three assemblages can be recognised and characterised as,

Group 1	Physical Characters	Fine-grained and medium type granites, aplites and kaolinised coarse-grained granites.
	Chemical Characters	Relatively low concentrations of La (mean 18ppm), Ce (mean 15ppm), Nd (mean 25ppm), Zr (mean 62ppm) and Sr (mean 47ppm).
Group 2	Physical Characters	Elvans and mineralised coarse-grained granites.
	Chemical Characters	Relatively low concentrations of Cs (mean 22ppm), Li (126ppm) and relatively high concentrations of Zr (mean 153ppm).

Group 3	Physical Characters	Coarse-grained granite.
	Chemical Characters	Tending to have concentrations intermediate to Groups 1 and 2. For example Zr (mean 125ppm). Concentrations also show exaggerated high or low values compared to "typical" coarse-grained granites (e.g. low calcium granite average of Turekian & Wedephol, 1961).

d) The overlap of results of locality sampling and group deviations reveal inadequacies in considering certain elements in terms of variation within the three cluster groups. However, if the elements exhibiting the greatest amount of variation (those elements included in b) above, but excluding Rb, Y and K) in all the samples are considered in terms of the three cluster analysis groups then the same sequence of increase or decrease can be recognised, that is Group 1 - Group 3 - Group 2 (see Table 16).

e) Multiple regression techniques indicate that within the sampling standard deviation limits the concentration of any element, characteristic of a cluster group, can be assessed on the basis of the other elements in the cluster group. This rule does not apply to Li and Cs in Group 2.

f) Apart from the metallic elements, Na, K and U the geographical distribution trends for the physically defined coarse-grained granites reflect an approximately concentric zoning for the exposed portion of the pluton. Li, Rb, Y and Cs concentrations decrease from the centre towards the perimeter of the pluton whereas Sr, Zr, Ba, La, Ce, Nd, and Th concentrations increase towards the perimeter.

g) It is possible to perceive a very general N.W.-S.E. trend in a number of the trend surface "difference-maps".

Further expansion on some of these conclusions is considered in the subsequent chapters but instead of employing petrographic groupings for the section headings, as with the major element chemistry, it is more convenient to make interpretations under trace element section headings.

3) The behaviour of some elements in the Bodmin Moor granite

A) Lithium

The Li ion, being smaller in atomic size than the other alkali elements, is unable to occupy similar lattice positions. Instead it enters into six-fold co-ordination sites and is commonly regarded as substituting for Mg. Li is, therefore, predicted as being likely to occur in high concentrations in ferromagnesian minerals during fractionation.

Butler (1953), referring to the Bosahan (Carnmenellis) adamellite, and Hall (1971), referring to the Cligga Head granite, both in S.W. England, show that biotite (Hall uses the term protolithionite rather than biotite) accepts Li preferentially to muscovite. Exley (1959), used the term lithionite (=zinnwaldite) to describe a dark brown to colourless lithium bearing mica, and concluded that the tendency for enrichment of Li in the St. Austell granite differentiation series is also attributable to an increase in dark mica. While insufficient modal analyses have been completed to demonstrate the fact conclusively, there can be little doubt that a similar interpretation for the mineral distribution of Li is also applicable to the Bodmin Moor granite for though Li also occurs in tourmalines Power (1968) does not consider that concentrations show any systematic variation that could be related to a fractionation trend in the acid igneous rock types from S. W. England.

Heier & Billings (1969) express the crustal abundance of Li as being between 10 and 20 ppm and Taylor (1965) considers that the most common rock types probably have concentrations lying within a factor of two or three of the average. Turekian & Wedephol (1961) quote a mean of 40 ppm for low calcium granites in which case the Li values for the Bodmin Moor granite (mean 220ppm) must be regarded as indicating extreme enrichment. From Table 20, a compiled list of some trace element values recorded by other authors for the S. W. England granites it is evident that relatively high Li values are common to all the plutons, though the actual concentrations show considerable variation and offer little hope for regional comparison.

For the Bodmin Moor granite the trend surface analysis (Fig.4) indicates a decrease in concentration of Li towards the perimeter of the pluton and if variability is attributed to a magmatic differentiation series then the central portion of the granite can be interpreted as the later fraction. Exley (1959) distinguishes a similar sequence for the St. Austell granite, though the sequence is broken by the Li depleted 'fluorite-granite' which Exley (1959) regards as the last differentiate. Although there is an apparent differentiation trend for other elements between cluster analysis Groups 1 and 3 within the Bodmin Moor granite, the concentrations of the fine-grained granites, aplites and kaolinised coarse-grained granites show no marked increase in Li compared with the coarse-grained granites. In contrast, however, the elvans and mineralised coarse-grained granites of Group

2 reflect a notable fall in concentration (see Table 16). For the St. Austell granite Exley (1959) concluded that the Li in the late stages of the "magma" development must have been depleted by some process and a similar interpretation is appropriate for the Bodmin Moor granite, although the actual decrease in Li concentrations are found in the post-magmatic elvans and mineralised granites rather than in the "granite magma". It is also of interest to note that Hall (1971), describing the Cligga Head granite, found that the highest Li contents occurred in the protolithionite of the unaltered granite, although the mineral is not sufficiently abundant to carry more than 1/2 to 2/3 of the concentrations of Li found in the greisened granites and greisens.

For marine shale Heier & Billings (1969) quote a range of Li contents of 4-400 ppm and on the basis of the very high values associated with the S. W. England plutons the feasability of a derivation from such a highly concentrated source could possibly be implied, especially as the granites are known to be contaminated by shale (Brammall & Harwood, 1932; etc.). Bowler (1959), however, has interpreted the anomalously high concentrations of trace alkalis in the aureole rocks of the S. W. England granites as being metasomatic in origin and it seems unlikely, therefore, that an assimilation of the surrounding country rocks could account for the high Li content of the granites. Mainly on the basis of structural evidence Stone (1971) has concluded that the exposed parts of the S. W. England granites are probably close to the original roof and a more logical conclusion for the unusual Li values could possibly be that a fractionation process, within the differentiation of the granite, has led to an enrichment of the uppermost part of the granite batholith. For a comparable ore bearing Li rich granite in the Krusnehory Mts. of Czechoslovakia, Štemprok & Šulcek (1969) reached a similar conclusion, though they suggested that the Li enrichment of the apical portions of the granites was metasomatic and related to the source of alkalis rather than to differentiation within the granite. Experimentally, Wyllie & Tuttle (1964) have shown that LiO_2 lowers the melting temperature of granite and low temperatures of solidification may be in accordance with the high

Table 20 Trace element analyses of Bodmin Moor and other S.W.England granites quoted in other works.

All values in ppm
Blanks indicate that no analysis figures are available
Tr. - trace
Bracketed values refer to the means of analyses from more than one pluton.
Underlined values refer to analyses from Bodmin Moor.

See quoted authors for methods of analyses and further details.

Mean composition for'low-calcium'granites (worldwide), for comparative purposes (after Turekian & Wedephol, 1961, Table 2)

Li	40	Ba	840
Cu	10	La	55
Zn	39	Ce	92
Rb	170	Nd	37
Sr	100	Pb	19
Y	40	U	3
Zr	175	Th	17
Sn	3	F	850
Cs	4	Cl	200

Ahmad (1966)

Cu concentrations

	analyses	range	mean	st.dev.
Land's End & Carnmenellis				
Coarse-grained granite	19	21-108	76	16
Fine-grained granite	4	53-91	71	17
Aplite	7	11-91	62	26
Total			73	18
St.Austell, Bodmin Moor & Dartmoor				
Coarse-grained granite	25	5-30	17	8
Fine-grained granite	9	15-33	24	5
Aplite	4	25-29	27	2
Pegmatite	5	21-47	30	13
Felsite	5	16-47	27	12
Total			21	9

Blaxland (1971, Table 2, p.317)
Sample No. GB10 (Grid Ref. SX/186-102753, - De Lank Quarry)

Zn in biotite	713

Bowler (1959, Table 1, facing p.5)
Sample No. B.399 (probably from De Lank Quarries, described as West Bodmin Moor) and X, an average of 6 'main-body' granites from S.W.England.

Element	B399	X
Li	805	(595)
Rb	450	(435)
Cs	42	(43)
F	2500	(3500)

Bradshaw (1967, Figs. 4, 5, 8, 10, 11, 12, 14, & 16)

Means of 3 samples from Bodmin Moor, bracketed values are means of 55 samples from S.W.England

Element	Feldspar		Biotite		Muscovite
Cu	20	(25)	42	(23)	(30)
Zn	11	(14)	500	(350)	(130)
Rb	850	(900)	1025	(1020)	(2000)
Sr	275	(200)	3	(5)	(175)
Zr	<15		15	(31)	(110)
Sn	25	(29)	38	(44)	
Pb	200	(154)	27	(31)	(70)

Butler (1953, Table 2, p.160)

	Bodmin Moor	Carnmenellis (Bosahan adamellite)				
	Caradon Hill	w.rock	ortho	biot	musc	tour
Li	130	400	80	1800	320	80
Rb	150	400	400	3500	800	<5
Sr	80	80	45	220	<10	<10
Zr	30	150	<10	150	<10	55
Sn	<15	45	<15	15	30	20
Cs	<50	50	<50	1350	<50	<50
Ba	40	110	225	120	<10	<10
La	<40	<40	<40	150	<40	40?
Pb	15	40	35	15	<15	<15

Exley (1959, Table 1, p.202)
Main varieties of the St.Austell granite

	Biotite-musc. granite	Early lith. granite	Late lith. granite	Fluorite granite
Li	20	32	121	29
Rb	1120	813	1850	1213
Sr	130	48	73	44
Zr	94	50	96	11
Ba	370	83	74	43

Exley (1966, Table 2, p.366)
Mean of 3 'granite' samples from Haig Fras (analyses 1, 2 & 3) and a 'fine leucogranite' from Stannon Clay Pit, Bodmin Moor (analysis 7)

	Haig Fras	Stannon
Li	40	65
Cu	8	5
Rb	356	366
Sr	103	138
Zr	34	Tr
Ba	207	285

Fuge & Power (1969, Table 2, p.890)
Mean of 90'unaltered granite' specimens from S.W.England

F	(1395)
Cl	(507)

Hall (1971, Table II, p.213)
Mean of two analyses of 'granite' from Cligga Head.

Li	485
Cu	107
Zn	102
Rb	695
Sr	175
Zr	65
Sn	40
Ba	150
Ce	95
Pb	35

Harding & Hawkes (1971, Table 2, p.6)
1)'Porphyritic (big-feldspar) granite', Luxulyan Quarry, St.Austell granite (analysis of a composite sample) 2)'Porphyritic (big-feldspar) granite', Blackingstone Quarry, Dartmoor granite.

	1	2
Li	300	260
Cu	<10	100
Zr	100	130
Sr		50
Zr	100	130
Ba	640	170
F	2400	1600

Sabine & Snelling (1969, Table 1, p.48)
'Granite', Pollard Rock 70ft below M.L.W.S, Seven Stones granite.

Li	190
Cu	<10
Sr	400
Zr	<20
Sn	10
Ba	<10
F	700

Wilson (1972, Tables 16 & 17, p.132 & 133)
1)'Coarse-grained granite', Gt.Britain's Rock, Scilly Isles. 2)'Medium-grained granite', Porthloo, Scilly Isles. 3) Mean of 7 samples from the Boscaswell 'granite', Geevor Mine, Land's End (analyses nos. 951-55, 959-60) 4)'Fine-grained granite', Boscaswell Mine, Land's End

	1	2	3	4
Li	1000	1000	370	320
Cu	3	5	6	7
Zn	46	42	45	35
Rb	490	427	480	760
Sr	116	68	95	22
Y	10	10	30	20
Zr	120	16	185	40
Sn	6	9	19	17
Ba	320	105	230	15
La	<100	<100	<100	<100
Pb	30	35	15	20

level positions of the S. W. England granites and their high Li concentrations.

B) Sodium and potassium

The behaviour of Na and K in magmatic melts is fairly well known and there is little value in expanding upon it in great detail. In general there is a trend towards enrichment in K during differentiation, this being reflected by increases in the K_2O/Na_2O ratio. This conduct can be attributed to the behaviour of the main Na and K-bearing minerals in igneous rocks, viz. the feldspars, with the K-feldspars crystallising out during the later stages of differentiation. It might be assumed, therefore, that modal analyses would give an assessment of Na and K relations, though work that has so far been completed on the Bodmin Moor granite in terms of orthoclase/plagioclase ratios is not conclusive (see p. 22).

The average abundances for all the analysed specimens from Bodmin Moor, compared with the figures quoted by Turekian & Wedephol (1961) for low-calcium granites, indicate a depletion in Na and an enrichment in K

	Turekian & Wedephol (1961)	Bodmin Moor
Na	25800	16717
K	42000	45745

The trend surface data for Na (Fig. 4) are not easily interpreted in terms of a simple geological model in that there appears to be an increase in concentration towards the western part of the Bodmin Moor pluton. This agrees with the results of the Kruskal-Wallis statistical test (see p. 17) which indicated a significant variation in Na_2O concentrations between sampling localities.

The "iterative-fit" surface for K (Fig. 5) indicates an increase in concentration in the southern part of the Bodmin Moor pluton with the 45000 ppm "contour" following an almost identical path to that illustrated by Edmondson (1970, Fig. 4) for the division between the 'no microcline' (in the south) and the 'with microcline' (in the north) coarse-grained granites. Edmondson (1970, Table 2) shows that the alkali feldspar compositions in the south are K-rich compared to those in the north, therefore, the overall K chemistry closely follows that of the alkali feldspars, as might be expected. Edmondson (1970) suggested that the variation in the alkali feldspar structural states and compositions of the Bodmin Moor pluton were related to a 'post-magmatic, metasomatic' process involving K-rich fluids and, therefore, the relatively high overall K concentrations in the southern part of the granite must also be related to this process.

Edmondson (1970) considers that the fine-grained granite has also been affected by the metasomatic process and evidence of alkali feldspar megacrysts across aplite-granite margins (Stone & Austin, 1961, Exley & Stone, 1964) implies that the final K distribution occurred after the aplite and fine-grained granites had been injected. The metasomatic process can, therefore, be interpreted as post-dating cluster analysis Groups 1 and 3 and by virtue of the high K values associated with cluster Group 2 it might be suggested that the process was related to that of elvan injection and mineralisation. This is also borne out by the fact that the high K values, in the Bodmin Moor pluton, occur in the southern part of the pluton, thus being related to both Hosking's (1950) Cu-Zn-Sn-Pb mineralisation belt and Bott et al's (1958) axis of gravity anomalies. The significance of this relationship will be discussed further in the section covering the metallic elements.

It might be expected that the elements which closely follow K in their geochemistry might also exhibit the same distribution patterns but as can be seen in the trend surface patterns of such elements as Rb and Cs there is no similarity, neither is there any enrichment of these elements in cluster Group 2 (see Table 16). Thus, the metasomatic process must have, in the main, derived its relatively high K content from some source other than that of normal magma differentiation. Contamination and assimilation are invoked in virtually every account dealing with the S. W. England granites, with Brammall & Harwood (1932) probably being the first instigators giving chemical evidence. The fact that contamination has occurred cannot be contested as there is sufficient field evidence, in the presence of xenoliths and rafts, and textural evidence, in the presence of typical pelitic hornfels minerals such as andalusite and cordierite occurring as accessories in the granite, to confirm that contamination has taken place. Can, however, assimilation of country rock produce an extensive chemical enrichment in terms of a post-injection metasomatic fluid? In dealing with the metalliferous elements it will be postulated that high concentrations of these elements were probably "provided by the re-melting of granite or mobilization of screens of country rock" (after Dangerfield & Hawkes, 1969) but the volume of K in the metasomatic process, though it is impossible to attempt to quote figures, must be envisaged on a considerably larger scale than that of mineralisation. In other words it would seem that the role of assimilation is unlikely to be the main factor in K enrichment.

Exley & Stone (1964) in reviewing some field, textural and chemical evidence on the role of magma and magma differentiation in the S. W. England granites also concluded "differentiation appears to be consequent upon contamination ..... whilst the effects of local potash metasomatism have been superimposed upon the results of both differentiation and contamination". They continue by suggesting that 'metasomatic differentiation' could be the answer to the K enrichment and quote the work of Orville (1963) on the rapid transfer of alkali ions between feldspar and vapour containing large amounts of alkalis, mainly alkali chlorides, as a possible mechanism. Hawkes (in Edmonds et al, 1968) also accepts that there was a late preferential concentration of K in the Dartmoor granite but prefers to envisage the mechanism for such a concentration to be related to an aqueous phase of magmatic crystallisation. Hawkes (op. cit.) quotes the experimental models of Tuttle & Bowen (1958) and Luth, Jahns & Tuttle (1964) as evidence for this theory. Wyllie & Tuttle (1964) on the experimental evidence of silicate systems containing two volatile components found that the combination of H_2O and HCl appeared to destroy the feldspars, there being a strong affinity for Na ions by the Cl ions. The presence of H_2O and HF, on the other hand, caused a lowering of the temperature with the dominant effect of the HF appearing to be that of a flux; dissolving in the liquid and lowering the temperature, though it seems likely that in high concentrations some chemical reactions must occur. In view of these results it may be more appropriate to combine the views of Exley & Stone (1964) and Hawkes (in Edmonds et al, 1968) and suggest that the "metasomatic differentiation" could be related to an aqueous K-halide rich late stage "fluid".

Favourable to such a theory are the relatively high F and Cl concentrations of the Bodmin Moor (see Table 11) and the S. W. England granites (Fuge & Power, 1969) and the fact that in the final stages of emplacement the granite had possibly become saturated by the absorption of meteoric waters from the surrounding country rocks. The model would also fit in with Edmondson's (1970) theory that variations in the alkali feldspar structural states and megacryst development were produced by the transformation of the original magmatic feldspars in the presence of a 'catalytic material'. However, the model cannot offer an explanation for the distribution of Na and there is also a difficulty in introducing alumina if the model is employed to explain the alkali feldspar megacryst development. Similarly there is a problem of a source for the K-rich halides, for while "metasomatic differentiation" may be a suitable title for their development it still does not explain their origin and obviously much further research is necessary before the whole alkali history can be satisfactorily unravelled.

In establishing that K, at least, does not appear to follow the same differentiation trend exhibited by the majority of the other elements, the validity of ratios, based on either Na or K, to show that the Bodmin Moor granite is "well differentiated" become suspect. In other words, the use of the ratios may be to relate two separate events and interpret them as one, that of magma differentiation. As a result of possible ambiguities ratios are not employed in this work and their suitability in connection with the magmatic histories of the other S. W. England granites is also open to question.

C) Copper, Zinc, Tin & Lead

It is generally accepted that the chemistry of the four metallic elements, Cu, Zn, Sn and Pb, is such that their relatively strong covalent bonding nature with oxygen, compared with the major mineral forming elements, results in the enrichment of the metals in late stage melts. There is, however, a tendency for the metallic elements to form sulphide minerals, rather than to be incorporated into silicate lattices (Sn also forms a $(SnO_4)^{4-}$ complex which gives rise to cassiterite), and relatively high element concentrations are not necessarily indicative of differentiation.

Compared with the abundances quoted by Turekian & Wedephol (1961) for a low-calcium granite the Bodmin Moor average values are enriched in all four metals although the inclusion of mineralised specimens probably accounts for part of this increase.

	Turekian & Wedephol (1961)	Bodmin Moor
Cu	10ppm	30ppm
Zn	39ppm	55ppm
Sn	3ppm	26ppm
Pb	19ppm	36ppm

Some values for the other S. W. England granites are quoted in Table 20 and though there is a general enrichment in comparison to Turekian & Wedephol's (1961) averages there is considerable variation between the S. W. England plutons. Ahmad (1966), for example, has interpreted Cu distributions in the Land's End and Carnmenellis granites (mean 73ppm) as generally higher than those of St. Austell, Bodmin Moor and Dartmoor (mean 21ppm). Such a conclusion is not substantiated, however, by the relatively low values quoted by Wilson (1972) for the Land's End granite (see Table 20).

Little significance can be read into the trend surface patterns for Cu, Zn, Sn or Pb for the Bodmin Moor granite (Figs. 5, 6, 8 and 11), mainly as a result of the anomalies produced by the Wheal Bray specimens (see p. 65). Apart from Sn, it is possible, however, to perceive a concentration increase towards the perimeter of the pluton and although this may be purely foruitous it is of interest to note that Hosking (1967) also recognises a similar trend for Cu and Pb in the Carnmenellis granite. In the cluster analysis grouping the mineralised granites are identified with the elvans in Group 2, with each of the four metallic elements classed as good discriminators (see Table 15).

This chemical relationship between the mineralised granites and the elvan samples from Bodmin Moor is of particular interest for it is generally accepted that both post-date the pluton; certainly both exhibit a cross-cutting relationship to the granite. Dangerfield & Hawkes (1969) consider that there is some justification for believing that a relatively open fracture system was a prerequisite for both elvan intrusion and development of the metalliferous lodes in S. W. England. They regard the development of the fracture system as being explained by stress release resulting from the rapid erosion of the land surface. Further evidence for the relationship between elvans and dykes is also implied by Dangerfield & Hawkes (1969) on the basis of similar age dates and a figure approximating to 225my is quoted. There are, however, indications that uranium mineralisation, at least, was repetitive with Darnley et al (1965) quoting dates of 290, 225 and 50-60my.

Dangerfield & Hawkes (1969) suggest that the source for water and the metalliferous substances that gave rise to the lodes and elvans could "have been provided by the re-melting of granite or mobilization of screens of country rock within the Armorican botholith and with both connate and meteoric water possibly playing a part in mineralisation in the early stages". Such a model would explain the somewhat unusual chemistry of the elvans and mineralised granite specimens from Bodmin Moor, particularly the relatively high Ba and rare earth element values and relatively low trace alkali concentrations, none of which fit adequately into a differentiation series model. The possibility of some late stage magmatic material being involved cannot, however, be entirely ruled out.

Henley (1972) has also employed Dangerfield & Hawkes's (1969) model for the intrusion of S. W. England elvans by explaining that when a fracture "extending downward, encountered a reservoir of a fluid-plus-crystals mixture the swift pressure release would result in a self-accelerating fluidization". Henley (1972) also envisages the intrusion as being a near surface process, though the scale of "near" is not implied. Such an idea of a self-accelerating fluidization seems more appropriate than one based on an initial water-borne mechanism, though there can be little doubt that meteoric waters were involved in the later phases of mineralisation.

There are, it is admitted, possible objections to the model proposed by Dangerfield and Hawkes (1969). These could include queries about the heat source for the late aspects of mobilisation and the mechanism by which the initial fractures were developed. If a conclusive and unambiguous heat source for the batholith as a whole could be invoked then it seems probable that a heat source for the later stages of mobilization could be allied to it, possibly as a waning phase of activity. However, as such a heat source for the batholith has not been explicitly defined, though many have been postulated, there is little point in attempting to deduce later heat sources of relatively minor importance.

Dines (1956) suggests that the trend of elvans within the granite is NE-SW but nearer the margin and in the surrounding country rocks the direction becomes E-W orientated. These trends are also closely followed on Dines's (1956) maps by the mineral lodes, although some do have a more N-S directional form. Exley (1965) indicates that the "Bodmin Moor granite is fractured on a relatively large scale along at least six important 'belts' and probably as many less important ones" and that the majority of these "follow the ENE-WSW trends of the fold-axes and tension-joints usually regarded as being Armorican in central and east

Cornwall and south Devon". This explanation for the fractures along which elvan and mineral lodes could develop seems much more logical than that proposed by Dangerfield & Hawkes (1969) particularly as their weathering and subsequent stress release theory is more likely to be associated with sub-horizontal jointing and tor formation (?) than vertical fissuring. By implying that the mineralisation of the Bodmin Moor granite was controlled by structural effects the relationship between the Cu-Zn-Sn-Pb zone of mineralisation (Hoskings, 1950) and the belt of gravity anomalies recognised by Bott et al (1958) across the S.W. England batholith becomes apparent. The effects of structural control can also be extended to include the influence upon the K enrichment recognised in the preceding chapter as well as that of variation in alkali feldspar structural states (Edmondson, 1970) and the logical conclusion of this is that all the post-injection processes which have affected the Bodmin Moor pluton have been structurally controlled from the south by the influence of the S. W. England batholith as a whole.

D) Rubidium & Caesium

Both Rb and Cs have similar chemical properties to K with which they both show a close coherence. Rb has a similar electronegativity and ionisation potential to K but is slightly larger in size. This difference becomes particularly effective under extreme conditions of differentiation when Rb becomes enriched. Cs is considerably larger than both Rb and K and replacement of K lattice sites is subsequently restricted, even though the Cs-O bond is slightly more ionic than the K-O bond.

Cs also tends, therefore, to become concentrated in late stage melts and ultimately may form a separate mineral phase, pollucite, though there is no evidence of such an occurrence in the Bodmin Moor granite. It is, however, possible that this trend of extreme late stage concentration of Cs could account for the element following a lognormal, rather than normal, frequency distribution (p. 40) in the Bodmin Moor pluton.

Rb and Cs enter biotite and muscovite in preference to the feldspars and Butler (1953) confirms this distribution for the Carnmenellis pluton (Bosahan adamellite) quoting the following figures

	Orthoclase	Muscovite	Biotite
Rb	400ppm	800ppm	3500ppm
Cs	50ppm	50ppm	1350ppm

Although Edmondson (1970) quotes figures as high as 1200ppm for Rb for the K-feldspars from the Bodmin Moor granite there is no reason to doubt that muscovite and biotite concentrations are correspondingly higher and that the same distribution relationship also exists for the Bodmin Moor pluton as for the Carnmenellis pluton.

When compared with the low calcium granite abundances quoted by Turekian and Wedephol (1961), Rb 170ppm (477ppm) and Cs 4ppm (31ppm), the Bodmin Moor values (in brackets) reflect a marked enrichment, as do the published results from other S. W. England plutons (see Table 20).

The trend surfaces for both Rb and Cs for the coarse-grained granite (Figs. 6 & 9) of the Bodmin Moor pluton reflect increasing concentrations towards the centre, thus being similar to the results of the other non-metallic trace elements in showing that the central part of the pluton is the later fraction. Both Cs and Rb, in the cluster-groupings, show increases in concentration from Group 3 to Group 1 (see Table 16), this being expected if the two groups represent a coarse-grained granite to fine-grained granite and aplite differentiation trend. For Cs, Group 2 exhibits a reduced concentration compared to both Groups 1 and 3 and even though there are some problems in considering Rb values because of the overlap of the means within the limits of one standard deviation (see p. 54) there is an apparent reduction in concentration of Group 2 Rb values compared to Group 1. In other words the elvans and mineralised coarse-grained granites of Group 2 appear to be unconnected with the magmatic differentiation associated with Groups 1 and 3.

It is commonly argued (Taylor et al, 1956; Bowler, 1959, Floyd, 1972; etc.) that K/Rb and K/Cs ratios for the S. W. England granites reflect extreme fractionation when compared to the results quoted for other igneous bodies. However, the use of K is not considered satisfactory as an indicator of differentiation for the Bodmin Moor granite, and probably for the other S. W. England granites (see p. 77), and the implications of K/Rb and K/Cs ratios may be misleading and are consequently not employed in this account.

There is the alternative possibility that the high Rb and Cs concentrations could be the result of contamination or assimilation but in view of the facts that the crustal abundances of Rb and Cs are relatively low (Cs in particular is regarded as averaging only 3ppm by Taylor (1965)) and that Bowler (1959) found that there was an increase in Rb and Cs concentrations in the aureole rocks of the S. W. England plutons towards the granite contacts, it seems unlikely that assimilations could have produced the high granite concentrations.

E) Strontium

The Sr ion, being intermediate in the size between K and Ca, has a complex geochemistry. As the S. W. England granites are deficient in Ca, however, Sr can be considered in terms of its relationship with K, thus simplifying the behaviour pattern. With K the capture principle operates and Sr tends to enter early fractions, though this can be complicated by the covalent character of the Sr-O bond working in the opposite direction.

Taylor (1965) points out that Sr does not enter micas to any extent, not because of valency difficulties, but probably because of its smaller size and preference for eight or ten-fold co-ordination sites, rather than twelve. Sr will, therefore, prefer K sites in alkali feldspars to those in the micas, although this is not brought out in Butler's (1953) analyses from Carnmenellis (Bosahan adamellite) in which the biotite content (222ppm) is much higher than that of orthoclase (45ppm). Bradshaw (1967), on the other hand, gives a range of values up to 10ppm for Sr in Cornish granite biotites and figures of over 100ppm for the feldspars. Apatite is frequently associated with biotite in the Cornubian granites and Sr can be captured in the Ca positions in the apatite lattice. It is possible, therefore, that the apparently anomalous figures quoted by Butler for Sr in biotite were due to the presence of apatite impurities in his separated mica fraction.

The average concentration of Sr for the Bodmin Moor pluton is 72ppm and when this is compared with the average figure of 1,000ppm quoted by Turekian & Wedephol (1961) for calcium-depleted granites the implication that the Bodmin Moor pluton is a late stage magmatic differentiate is readily apparent. Some Sr values for other S. W. England granites are reproduced in Table 20 and these show a similar magnitude to those from Bodmin Moor.

As with the other elements which reflect the differentiation of the coarse-grained granite there is a concentric zoning of the Bodmin Moor pluton and in the case of Sr the higher concentrations are towards the perimeter, again indicating that fractionation has evolved towards the later, central part of the pluton (see Fig. 7). A similar trend is also apparent between cluster Group 3 and Group 1 (see Table 16) and once again Group 2 values do not appear to be related to the sequence.

F) Yttrium, Lanthanum, Cerium, Neodymium and Zirconium

Although Y is generally considered to exhibit a similar chemical behaviour to La, Ce and Nd, part of the lanthanide series of elements, such a character is not immediately apparent from the Bodmin Moor results. Zr, however, does bear some affinities to the lanthanides of the granite and whilst its treatment is normally covered separately in geochemical texts it is convenient, here, to treat the element with Y and the lanthanides. It is common practice, in dealing with the lanthanides, to divide the abundance of each element by the abundance in chondrites, or to express the concentrations as a percentage value of one of the end members of the lanthanide series in an attempt to standardise values and enhance variations. Such amendments, however, are not required for the Bodmin Moor results and all values are quoted in ppm as determined.

The Y ion is closest in size to the Ca ion, among the major cations, and though it may be expected that trivalent Y would be captured in early formed Ca positions, by virtue of both its size and valency, it tends to concentrate in accessory minerals such as apatite and monzanite. The reason for this behaviour can be attributed to the Y-O bond having a much more covalent nature than the Ca-O bond so that the effect of the bond type is greater than that of the size or valency. A similar explanation also holds for the behaviour of the lanthanide elements with the covalent R-O bond, again resulting in a poor affinity for capture in Ca sites. With the possible exception of Fe^{2+} there is no common major element cation comparable in size to Zr and this element normally forms a separate mineral phase, zircon, which like the accessory minerals harbouring Y and the lanthanides, tends to become concentrated in late stage melts.

There are relatively few analyses of the distribution abundances of Y, La, Ce, Nd and Zr in the individual co-existing rock forming minerals. Herrmann (1969) summarises the available data for Y and the lanthanides and shows that biotites from granites have higher concentrations of these elements than co-existing feldspars and quartz. This is borne out by the results of Towell et al (1965) for the Ribidoux Mountain (U.S.A.) leucogranite and by Gavrilova & Turanskaya (1958) for a Ukrainian granite. This latter work, however, found that 60% of the distribution of Y and the lanthanides was supplied by accessory monzanite and of the remaining 40%, apatite was the major contributor. There is no evidence of monzanite in the Bodmin Moor granite though modal data show values of up to 0.4% apatite (Table 4 and Edmondson, 1970, Table 1) for the coarse-grained granite and CIPW norms give apatite values of 0.5-0.6% (Table 3). It seems probable, therefore, that the major proportion of Y and the lanthanides is concentrated in apatite in the Bodmin Moor granite. Zircon is not recorded in the modal data of Edmondson (op. cit.) as greater than 0.1%, though figures as high as 0.8% are recorded by Jones (1963) for the Scilly Isles granite. For the St. Austell granite Exley (1959) notes the presence of zircon crystals inside pleochroic haloes within lithionite mica and Hawkes (in Edmonds et al, 1968) also reports the presence of apatite and zircons included in biotites from Dartmoor.

Turekian & Wedephol (1961) quote the following figures for the abundance of the lanthanides in low-calcium granites, Y - 40ppm (45), La - 55ppm (29), Ce - 92ppm (36), Nd - 37ppm (35) and Zr - 175ppm (116) (the figures in brackets are the average values for Bodmin Moor, Table 10). Other than Ce, which is approximately 1/3 the concentration, the lanthanides for Bodmin Moor are comparable to those quoted by Towell et al (1965) but are 1/2 to 1/3 lower than those quoted by Gavrilova & Turanskaya (1958). Y, however, is markedly higher for Bodmin Moor than the results quoted by either of the preceding authors. Some of the few available results published for other S. W. England granites are given in Table 20.

For the lanthanides and Zr the trend surface patterns (Figs. 8, 10 and 11) for the coarse-grained granite of Bodmin Moor all exhibit a very similar pattern with increases in concentration towards the perimeter of the pluton. For Y (Fig. 7) it is possible to perceive a similar concentric zoning but in the reverse direction. The concentrations of Zr and the lanthanides in the cluster analysis groups (see Table 16) show a decrease from Group 1 to Group 3, with Group 2 averages lower than either Group 1 or Group 3. If the chemistry of La, Ce, Nd and Zr is accepted as reflecting a differentiation series then the trend surface zoning of the Bodmin Moor pluton implies that the central portion of the granite is the earlier fraction. In other words, the variation in the lanthanides contradicts the results of the other non-metallic trace elements. It is of interest to note, however, that Exley's (1959) results for Zr in the 'fluorite-granite' of the St. Austell pluton also show a very marked depletion when compared with the concentrations of the earlier granite differentiates. Taylor (1965) has suggested that if a magma is dry a pegmatite phase may not separate and Zr and the lanthanides may similarly fail to separate out into a residual phase and instead "will remain dispersed through the granite, perhaps in the lattices of the common minerals, or in small pockets or rare minerals scattered sporadically through the granite". It has been noted in an earlier paragraph that apatites and zircons do occur as inclusions, particularly in the micas, in the S. W. England granites and it is suggested, therefore, that these apatites and zircons must have separated out as an early phase during the magma crystallisation and in doing so tied up the available lanthanide elements; thus giving the impression of a reversal in the differentiation trend of the granite. This explanation would also be an acceptable interpretation of the relatively low average values for the rare earths in cluster Group 1, compared to Group 3, and assuming Dangerfield & Hawkes's (1969) model for the origin of the later elvans and mineralised coarse-grained granites, the comparatively high average values associated with Group 2.

The failure of Y to follow the same behaviour pattern as La, and the other elements, is not fully understood although the high standard deviations associated with the cluster-analysis grouping (Table 10) and a weak trend surface pattern could be an indication that the experimental accuracy is insufficient to clarify significant variations in the regional chemistry. The factor analysis processing verifies this conclusion, to some extent, by showing that La, Ce, Nd and Zr are the most significant contributors to 29% of the total chemical variation of the Bodmin Moor pluton and Y is practically insignificant (Table 13). Y is, however, a significant contributor to the second factor analysis component accounting for 18% of the chemical variation of the granite.

G) Barium

The Ba ion is almost identical in size to the K ion and there is a tendency for Ba to behave according to the classical capture principle and enter early formed K minerals. In other words Ba concentrations are likely to be high in K rich rocks although later stage melts may not exhibit this relationship as Ba becomes depleted by substitution for K.

Unlike Rb and Cs, Ba tends to enter K-feldspars more readily than biotite or muscovite, probably because of the difficulty of balancing charges in the micas. Butler's (1953) analyses for Carnmenellis (Bosahan adamellite) confirm this distribution with K-feldspars (225ppm) having almost twice as much Ba as biotite (120ppm). In view of the high modal content of the alkali feldspars in the Bodmin Moor, and S. W. England granites as a whole, it can be assumed that the majority of Ba is harboured in these minerals.

Turekian & Wedephol (1961) quote an abundance of 840ppm for low-calcium granites and though Taylor (1965) quotes a figure of 600ppm for the average granite content this figure is still considerably higher than that for the Bodmin Moor granite (average 183ppm). The Bodmin Moor figure is, however, comparable to other figures quoted for the S. W. England granites (see Table 20) though any variations between plutons are again difficult to assess because of the limited number of available results.

Trend surface data (Fig. 9) for the coarse-grained granite of Bodmin Moor shows a concentration decrease towards the centre of the pluton. As the relatively low average Ba concentrations for the pluton are indicative of a late stage granite differentiate, the decrease in concentration towards the centre of the pluton indicates that the fractionation of the granite must also have proceeded along this trend. The behaviour of Ba in the cluster-analysis grouping is also comparable to the other non-metallic trace elements and shows a decrease in concentration in the differentiation trend from Group 3 to Group 1. In Group 2 the average concentration is considerably higher than the other two groups (see Table 16), thus implying some enrichment in the elvan and mineralisation phase. This enrichment could be derived from the re-melting of earlier granite or screens of country rock, both of which could have relatively high Ba concentrations.

Exley (1959) found a similar differentiation trend for Ba in the St. Austell granite with a decrease in concentration from the biotite-muscovite granite (early) to the fluorite granite (late). Exley (1959), however, points out that Ba follows the same trend as K, except in the late-lithionite granite. On the basis of the present results, such an interpretation is not considered valid for while Ba and K are geochemically related in magmatic differentiation this relationship cannot be deduced in the S. W. England batholith because of camouflage by the later K "metasomatic differentiation".

H) Uranium and Thorium

Rogers & Adams (1967) consider that average U and Th contents for granites are not obtainable owing to the extreme variation from "one granite type to another". They do, however, proceed to quote a range of values with U given as 2-8ppm (9.3ppm) and Th as 10-20ppm (16ppm), Bodmin Moor averages in brackets. These figures reflect increases in the abundances found in intermediate and basic rocks and the implications are that increased concentrations are found in the more petrologically differentiated rock types. As pointed out by Goldschmidt (1954), however, the concentrations of U and Th in some late magmatic series may not necessarily be well pronounced because of the capture in early formed calcium minerals such as apatite. The pleochroic haloes, around minute zircon crystals, in biotite can also be interpreted as due to the presence of the radioactive elements and it might be expected from this evidence that the distribution of U and Th in the Bodmin Moor granite would be comparable to that of Zr and the rare earths.

For Th both the trend surface analysis of the coarse-grained granite and the cluster-analysis grouping are comparable to Zr and the lanthanides and Th is also a major contributor in the factor analysis component containing these elements (see Table 13). It can be assumed, therefore, that even though the analytical evidence is by no means as accurate as for other elements the results do imply differentiation on the basis of a concentration reduction as the early Th bearing minerals have crystallised out. For U the trend surface picture is not as clear, possibly because of inadequacies in analysis and also from complications arising from later uranium mineralisation (Darnley et al, 1965). Evidence for the latter is also brought out by the higher U concentrations, not only in cluster Group 2 (the elvans and mineralised coarse-grained granites), but also in the distribution of the higher values in the southern part of the trend surface plot of the coarse-grained granite.

I) Fluorine and Chlorine

The halogens are highly mobile in character and during the course of magmatic crystallisation probably become enriched in the later fractions, particularly in residual liquids and vapours. F is likely to replace tetrahedral O, probably at the exposed edges and surfaces of silicate minerals whereas Cl may exhibit isomorphous substitution for the OH ion in the octahedral layer of the hydroxyl silicates, because of the similarities in polarization. As the Cl ion is larger than the F ion it is unlikely that the two ions are interchangeable in silicate structures.

Fuge & Power (1969) express the mean value of F, in 90 unaltered specimens from the S. W. England granites, as 1395ppm and of Cl as 507ppm, both these figures being approximately twice the estimated average values for granites (Turekian & Wedephol, 1961, quote averages of F = 850ppm and Cl = 200ppm). In the Bodmin Moor granite, F values (see Table 11) are comparable to those quoted by Fuge & Power (1969) though Cl values are much lower and closer to the average figure quoted by Turekian & Wedephol (1961). To suggest that there are any regional variations in the halogen concentrations of the S. W. England granites may, however, be fortuitous as the number of determinations is limited and variations may, in part, be controlled by non-magmatic processes (see p. 36).

It has already been suggested (p. 76) that the F and Cl concentrations in the S. W. England granites could be attributed to a late stage aqueous and K-halide rich "fluid". This interpretation is also held by Fuge & Power (1969) and they imply that the actions of the late stage K-rich fluid may have been like that of a reservoir, serving to hold F and Cl in relatively high concentrations. Floyd (1966, 1967) has interpreted the petrography and chemistry of the aureole rocks of the Land's End granite as indicating that the injection of the granite produced a 'front' of migrating water which resulted in conversion of basic intrusions into amphibolite hornfelses. Floyd (op. cit.) has also implied that F was closely associated with this water throughout the phases of contact metamorphism and that this mobile "fluid" also acted as a cation transportation agent. Whether, in fact, it is the K-rich "fluid" which has acted as a reservoir for Cl and F, as implied by Fuge & Power (1969), or whether it is the aqueous Cl and F rich "fluid" that has acted as the transportation agent for K is debatable and while the present work would favour the latter explanation it seems possible that K and the halogens acted in mutual enhancement.

Although Floyd (1966, 1967) suggests that the contact metamorphism of the Land's End aureole rocks was instigated by a migrating "fluid" associated with the magma injection recent experimental and theoretical evidence (see p. 96) favours the emplacement of relatively "dry" granite magmas and Floyd (personal communication) now concedes that the timing of the 'mobile fluid front' may be post magmatic. Such a time relationship of the magma and the K-halide rich "fluid" would be comparable to that invoked in this work.

PART IV

A) Some views on the development of the S. W. England batholith

In this section it is essentially the development of the Bodmin Moor pluton which is being considered, although the chemical, petrological and geophysical evidence suggests that all the S. W. England plutons are related and may, therefore, have a similar history. It is emphasised, however, that time and spatial predictions may not hold throughout the region; indeed it is debatable whether a chronological ordering of events, even for the Bodmin Moor pluton, can be proposed, as controlling influences were probably inter-related in a much more complex manner than revealed by present research techniques.

B) The origin of the magma

Tuttle & Bowen (1958) concluded that in orogenic environments melting begins at depths of 20 to 25km and though the evidence for this suggestion was based on experiments which were conducted with an excess of water more recent estimates (Brown & Fyfe, 1970) of temperatures in the crust make it apparent that granite liquids are unlikely to be produced at a depth much shallower than 20-30km.

Robertson & Wyllie (1971), again on experimental evidence, have found that the effects of heating an igneous rock of intermediate composition, or its metamorphic equivalent, begin with a fusion of quartz and two feldspars and a solution of vapour to produce a water-saturated liquid of granitic composition. For an assemblage of silicate minerals, with or without hydrous minerals, and with a vapour phase there is formation of more liquid at higher temperatures, accompanied by a progressive depletion of water. Within a relatively wide temperature range, 700 - 900°C this water-undersaturated granitic liquid can co-exist with quartz, feldspars and more refactory minerals until at a temperature of around 1100°C there is a complete melting.

Recent models (Ringwood & Green, 1966) have indicated that the lower levels of the earth's crust are probably of intermediate composition and although magma generation within the upper crust and mantle may be attributed to a complex association of dynamic processes, development in the case of the Cornubian batholith can be adequately explained in the context of the Hercynian orogeny. In other words, it is reasonable to believe that the necessary temperatures (of around 800°C) and compositional conditions prevailed allowing anatexis of the lower crustal levels and hence for the development of a magma for the S. W. England batholith. When the vapour is no longer present, at 700°C and above, Burnham (1967) has indicated that in a water-undersaturated liquid-crystal magma the P_{H_2O} may be considerably less than the overall load pressure and upward migration may proceed, without excessive crystallisation, until the two pressures become comparable. Ramberg (1970) has also demonstrated with centrifuged scale models that partial melting in the crust is almost certainly followed by upward, diapiric movements of magmas or mobile rock masses. Thus, having produced a model for the development of the granitic magma in the lower crust there appears to be little difficulty in proposing a means of injection into the upper crustal levels.

As a result of recent geophysical evidence, Bott <u>et al</u> (1970) have revised their hypothesis that the granite magma of the S. W. England batholith developed by fusion of a true granitic layer in the middle of the crust to one in which it was formed by the selective fusion of the rocks forming the lower part of the crust. They suggest that the granite probably originated from a depth below 10 to 12km, at which level they recognise a gradational density change with the lower crustal material now representing the stoped and residual material which sank, or remained, as the granite was emplaced. Bott et al (1970) also consider the fact that the Moho appears to be well defined and apparently undisturbed along the length of the batholith as further evidence of a crustal origin for the granite magma. Floyd (1972), on the basis of the tectonic environment of the basic and acidic rocks of S. W. England also concludes that all the evidence points to a deep seated crustal origin for the Cornubian granite magma.

C) The magma emplacement

Stone (1971) considers that the structural evidence in S. W. England indicates that although initial injection may have caused deformation of the magma envelope the present surface form of the plutons suggests that emplacement occurred by passive stoping and subsidence of the intruded country rocks in the circular or ring-like shape now expressed by the exposed granite bodies.

This model contrasts with the theory of emplacement envisaged by Bott et al (1958) from geophysical evidence. They suggested that the Dartmoor pluton was intruded in the shape of an inverted 'L'; the vertical limb in the south, corresponding to a large negative gravity anomaly, being the feeder channel, and the horizontal limb extending out to give the present exposed pluton form. Bott et al's (1958) model was also employed by Edmondson (1970) to explain the distribution of the alkali feldspar structural states in the Bodmin Moor pluton.

It is difficult to ascribe the distribution pattern of the non-metallic trace elements of the Bodmin Moor pluton (see Part III) to the injection model proposed by Bott et al (1958) and the method of emplacement advocated by Stone (1971) is favoured; the negative gravity anomaly, mineralisation and alkali feldspars structural state distributions now being explained by structural control following magma injection (see p.81). The extreme fractionation in the chemistry of the Bodmin Moor and S. W. England granites is also more compatible with Stone's (1971) model than with that of Bott et al (1958). Brown & Fyfe (1970) have suggested that the rate of ascent of a granite mass may be quite slow, possibly as low as a few centimetres per year if cooling is dominantly conductive. Thus, if the time of ascent is very slow, say thousands of years, then the fractionation could develop with crystallization and settling out of the more mafic constituents leaving a well differentiated mass that could continue to ascend. Thus the apparent "pulses" of more acidic magma, represented by the medium-type and fine-grained granites, aplites and pegmatites could be the later fractionation products puncturing through what may be the contaminated envelope of the pluton (Exley, 1961). It is certainly difficult to envisage the horizontal magma flow required in Bott et al's (1958) model to be a relatively slowly moving body. It is also difficult to interpret the trace element distribution pattern in terms of a horizontal flow of magma.

The NW - SE elongation which it is possible to perceive in the exposed form of the Bodmin Moor pluton and in some of the "difference-pools" for the trace element distribution patterns (p. 67) is interpreted as being the result of deformation influences during the magma emplacement. The possibility that this distortion could be related to the sub-horizontal movement of magma proposed by Bott et al (1958) has not been overlooked although again, as with the actual trend surface distribution patterns of the elements, it seems improbable that horizontal movements could produce the local "difference-pool" anomalies.

D) Post-magmatic effects

The origin and model of the K-metasomatism, and injection of elvans and mineral lodes for the Bodmin Moor pluton have already been proposed (p. 79) though the actual structural control which influenced the model has not been fully developed.

It seems logical to assume that the emplacement of the major plutons in S. W. England must initially have had a "weakening" effect on the upper crust along the axis of their emplacement. Though structural accounts of S. W. England (e.g. Dearman, 1971) do not confirm that there is any structural pattern in the country rocks that would fit the present proposal this does not necessarily signify that the "weakened axis" did not exist. In fact it is more than probable that the still relatively plastic granite bodies absorbed minor earth movements. This is confirmed by Booth (1966), for in a summary of the distribution of joint trends in the Cornubian granites he indicates that the joint patterns are in agreement with a regional tectonic control produced by "internal stress fields set up in response to Hercynian movements". Thus the earth movements which allowed the upward penetration of solutions, fluid and vapours to proceed can be conceived as being structurally controlled along the axis of the emplacement pattern described by the plutons.

One post-magmatic effect of the S. W. England granites that has not yet been considered in detail is that of kaolinisation. The majority, of what are admittedly but a few kaolinised specimens that have been analysed from the Bodmin Moor pluton, fall into the Group 1 cluster (see Table 14). This association with the fine-grained granites and aplites suggests that kaolinisation was related to the later phases of magma emplacement. Bristow (1969) considers that kaolinisation in S. W. England has been caused by weakly acidic hydrothermal solutions percolating through the granite and then being trapped beneath the killas (country rock) roof. The "funnel" structures of the St. Austell clay deposits fit such a theory but according to Bristow (1969) there are some deposits within the Bodmin Moor pluton which seem to suggest that the kaolinised granite occurs in uniform layers underlying areas of boggy ground. Bristow (1969) thinks that these deposits may have been produced by the downward movement of humic acids derived from the overlying peat, or possibly as a result of deep tropical weathering during the Tertiary period. Exley (personal communication) has pointed out that these clay deposits underlying boggy ground may be the product of erosion and transportation of kaolinised granite from the surrounding higher ground levels in which case the primary origin of these deposits as late magmatic may still be appropriate. Exley (1965) has also shown that many of the clay deposits are related, in belts, to fold axes and tension joints in the Bodmin Moor granite, in which case the distinction between late magmatic and post-magmatic, as used in the present context, requires further explanation. It is, therefore, proposed that "late magmatic" should be used to imply an origin related to the differentiation of the granite whereas "post-magmatic" should be used with respect to processes which are not entirely the product of differentiation.

E) Conclusions

The results of the major and trace element chemistry for the Bodmin Moor pluton imply a "typical" igneous differentiation series with the exposed portion of the pluton representing the end members of this series. Regional chemical variations are interpreted in terms of increasing differentiation towards the pluton centre with local variations produced by the "puncturing" of the magma envelope by later differentiates and country rock assimilation and contamination. Subsequent tectonic activity, controlled by the regional setting of the S. W. England batholith, is considered to have influenced the post-magmatic processes of mineralisation and K-metsomatism.

It is also concluded that Edmondson's (1970) 'division' of the Bodmin Moor pluton is not strictly valid when considered in terms of the emplacement history of the pluton although its use is justified in respect of the post-magmatic development of the pluton.

APPENDIX

1) Sample locations, U,V. co-ordinates and rock type descriptions

Spec.No.	U	V	Location	Rock Type
KEB1	6.76	6.50	Quarry S.E.of Dozmary Pool	FGG
KEB2	6.76	6.49	" " " "	"
KEB3	6.75	6.48	" " " "	"
KEB4	6.73	6.47	" " " "	"
KEB5	6.74	6.46	" " " "	"
KEB6	6.75	6.45	" " " "	"
KEB7	6.76	6.44	" " " "	"
KEB8	11.73	1.94	De Lank Quarry (depth 30m)	CGG
KEB9	11.70	1.97	" " " (" 15m)	CGG
KEB10	11.63	1.98	" " " (" 7m)	CGG
KEB11	11.67	2.00	" " " (" 1.5m)	CGG
KEB12	11.55	1.85	" " " S. of main quarry	CGG
KEB13	11.72	1.87	" " " adjacent to entrance	ELVAN
KEB14	11.81	1.87	Workings N.W. of main De Lank Qry.	CGG
KEB15	11.84	1.88	" " " " " "	CGG
KEB16	11.88	2.05	" " " " " "	CGG
KEB17	11.89	2.07	Hantergantick Quarry (depth 3m)	CGG
KEB18	11.86	2.08	" " (" 30m)	CGG
KEB19	12.94	6.84	Roughtor	CGG
KEB20	12.70	6.87	Roughtor	CGG
KEB21	12.85	6.74	Roughtor	CGG
KEB22	12.80	6.96	Roughtor	CGG
KEB23	12.84	7.17	Little Roughtor	CGG
KEB24	12.89	7.19	" "	CGG
KEB25	12.96	7.36	Showery Tor	CGG
KEB26	9.05	2.73	Small quarry adjacent to the A30,	ACGG
KEB27	9.04	2.74	" " (S.W. of Temple	ELVAN
KEB28	9.02	2.75	" " " " "	ACGG
KEB29	2.84	9.18	Disused 'pit', S.of Cheesewring Qry.	MCGG
KEB30	3.31	8.89	Goldiggings Quarry	XCGG
KEB31	3.27	8.94	" "	XCGG
KEB32	3.35	8.90	" "	CGG
KEB33	3.32	8.95	" "	CGG
KEB34	3.25	8.97	" "	CGG
KEB36	2.99	9.45	Stowe's Hill Tor	CGG

Spec.No.	U	V	Location	Rock Type
KEB37	2.94	9.52	Cheesewring Tor	CGG
KEB38	2.87	9.45	Cheesewring Quarry	CGG
KEB39	2.85	9.39	" "	CGG
KEB40	2.82	9.46	" "	CGG
KEB41	2.78	9.49	" "	CGG
KEB42	2.74	9.47	" "	CGG
KEB43	2.69	9.42	" "	XCGG
BB45	4.85	5.10	Park Clay Pit	CCGG
KEB400	5.66	6.07	Brown Gelly	CGG
KEB401	4.56	4.64	White Barrow (Tumulus) S.of Park C.P.	CGG
KEB402	4.15	4.73	W.Mutton's Down	VCGG
KEB403	4.06	4.71	W.Mutton's Down	CGG
KEB404	5.85	3.56	Letter Moor (not in situ)	CGG
KEB405	6.50	3.70	Mennabroom Farm Tor	ELVAN
KEB406	6.44	3.66	" " "	ACGG
KEB407	6.38	3.67	" " "	CGG
KEB408	6.73	3.04	Carburrow Tor	CGG
KEB409	5.82	2.52	N.Warleggan (not in situ)	CGG
KEB410	7.06	4.15	N.Redhill Downs (not in situ)	CCGG
KEB411	12.81	12.30	Alex Tor	CGG
KEB412	10.17	2.94	Treswigger (not in situ)	CGG
KEB413	10.02	2.24	Metherin Clay Pit	CCGG
KEB414	10.05	2.22	" " "	XCGG
KEB415	12.54	3.62	Quarry S.W. of Casehill	CGG
KEB416	7.32	7.96	Smith's Moor (not in situ)	XCGG
KEB417	7.95	7.35	E.of St.Lukes (in barn foundations)	WCGG
KEB418	5.34	8.36	Hill Tor	CGG
KEB419	4.90	9.00	Newel Tor	ACGG
KEB420	4.88	9.04	" "	AFGG
KEB421	9.39	9.29	Smallcombe Tor	CGG
KEB422	5.08	9.27	Quarry on Economic Forest Estate	ACGG
KEB423	6.49	9.23	W.end of Cheesewring Rly. track	CGG
KEB424	6.10	8.46	As per KEB422 but qry. on W. side	WCGG
KEB425	8.02	8.44	Carneglas Tor	CGG
KEB426	9.36	8.98	S.E.of Elephant Rock	VCGG
KEB427	9.00	9.49	Quarry N.Cannaframe Farm on the A30	CGG

Spec.No.	U	V	Location	Rock Type
KEB428	8.60	10.16	Nr.Poldhu Farm, on forest track	CGG
KEB429	8.67	10.64	S.of Trenilk	CGG
KEB430	13.15	5.88	Stannon, Nr.Whitewalls	WCGG
KEB431	12.94	5.76	Dinnever Hill (not in situ)	CV
EB69	3.97	5.48	S.Northwood Downs	ELVAN
EB76	5.30	10.90	W.end of Hawk's Tor	PEG
EB79	4.63	10.01	Kilmar Tor	ELVAN
EB101	1.86	8.75	Minions	CGG
EB119	15.46	6.70	Little Parkwalls	CGG
EB121	14.49	4.88	Trewint	CGG
EB123	14.54	4.07	W.side of Devil's Jump	CGG
EB164	2.98	4.90	Perlock Woods	ELVAN
EB190	8.33	5.33	Brockabarrow Common	XCGG
EB195	13.89	6.96	Poldue Downs	VCGG
KEB500	10.33	7.11	Catshole Tor	CGG
KEB501	10.34	7.38	N.E.Catshole Tor	CGG
KEB502	11.19	4.55	Quarry N. of Leaze	XCGG
KEB503	11.80	3.44	Old workings, Nr.Bolatherick	CGG
KEB504	12.63	2.07	Row Quarry	XCGG
KEB505	12.61	2.06	" "	XCGG
KEB506	13.28	2.69	Rd.cutting nr.Tuckingmill	XCGG
KEB507	2.77	6.68	Entrance to Siblyback Res. dam	WCGG
KEB508	2.67	6.53	Elvan quarry S. of above specimen	ELVAN
KEB509	2.69	6.51	" " " " "	ACGG
KEB510	2.11	6.27	Old workings nr.Redgate	ACGG
KEB512	1.15	9.80	Quarry N.E. side of Caradon Hill	CGG
KEB513	3.05	10.83	Cheesewring W.of Sharp Tor	CGG
KEB514	3.07	10.80	Notter Tor Quarry entrance	PEG
KEB515	3.56	10.06	Notter Tor Quarry	CGG
KEB516	4.06	10.52	Bearah Tor	CGG
KEB517	4.71	10.50	Kilmar Tor	CGG
KEB519	4.04	10.28	Bearah Tor Quarry	PEG
KEB520	4.01	10.31	" " "	CGG
KEB521	8.47	1.62	Colvannick Tor	CGG
KEB522	8.32	1.67	Elvan Quarry, Colvannick Tor	ELVAN
KEB523	8.05	1.54	Elvan Quarry, St.Bellarmin's Tor	ELVAN

Spec.No.	U	V	Location	Rock Type
KEB524	8.07	1.29	Corner Quoit Quarry	CGG
KEB525	7.03	3.03	Hardhead Downs (mine waste)	CGG
KEB526	7.48	2.52	Elvan Quarry, E.Cardinham Moor	ELVAN
KEB527	7.47	2.56	" " " "	ACGG
KEB528	8.73	2.17	Road cutting, A30 nr.Cardinham	VCGG
KEB529	8.90	3.26	Temple Tor	CGG
KEB530	8.86	3.18	" " Quarry	ACGG
KEB531	8.25	3.21	" " "	ELVAN
KEB532	8.25	3.55	Nr.Merrifield, S.of Temple	ACGG
KEB533	11.39	10.19	Bray Down (not in situ)	CGG
KEB534	11.29	10.63	Old workings, S.of Buttern Hill	ACGG
KEB536	12.89	8.42	High Moor (not in situ)	CGG
KEB537	13.18	8.87	" " , old workings	MCGG
KEB538	8.94	4.25	Hawk's Tor China Clay Pit	PEG
KEB539	8.90	4.21	" " " " "	WCGG
KEB540	8.91	8.37	Road cutting, A30 Hgh.Cannaframe	CGG
KEB541	9.61	10.33	Trewint Downs Tor	XCGG
KEB542	9.58	10.36	" " "	CGG
KEB543	7.87	10.43	Fox Tor	CGG
KEB544	8.00	11.25	Shaft/Quarry (?) Nr.Treburland	CGG
KEB545	5.55	9.88	W.Trewortha Tor	CGG
KEB546	5.42	10.36	E. " "	CGG
KEB547	5.30	10.86	Hawk's Tor	FGG
KEB548	5.31	10.94	" "	CGG
KEB549	6.74	9.50	Carey Tor	CGG
KEB550	6.63	11.00	Ridge, N.W.of Rylands	CGG
KEB551	2.97	7.89	Tregarrick Tor	AP
KEB552	2.94	7.89	" "	CGG
KEB44	1.40	9.06	Quarry, W.side Caradon Hill	CGG
KEB65	2.13	6.34	Old workings, Nr.Higher Redgate	MCGG
KEB108	10.91	10.41	Hill, S.of West Carne (not in situ)	CGG
KEB115	14.58	7.84	North Crofty Dam,site (not in situ)	CGG
KEB116	15.10	7.00	Stream section, nr.Advent	CGG
KEB117	13.38	8.38	Lanlavery Rock	QV
KEB119	15.48	6.73	Little Parkwalls	WCGG
KEB131	13.47	2.92	Lower Hamathay Tor	CGG
KEB132	12.59	2.06	Row Quarry	CGG

Spec.No.	U	V	Location		Rock Type
KEB135	12.25	9.46	S.of Old Park (not in situ)		CGG
KEB138	11.70	7.35	Adjacent to trig point, Brown Willy		CGG
KEB139	11.70	5.81	Garrow Tor		CGG
KEB140	10.40	4.45	Carkees Tor		CGG
KEB141	11.00	6.32	Butter's Tor		CGG
KEB142	11.49	6.79	S.of Brown Willy		CGG
KEB143	11.12	5.26	S.of Garrow Tor (not in situ)		CGG
KEB144	10.88	4.38	Quarry S.of Leaze		CGG
KEB145	10.69	3.43	Carbilly Tor Quarry		CGG
KEB149	10.18	4.90	N.of Hawk's Tor (not in situ)		CGG
KEB151	9.88	4.16	Hawk's Tor		CGG
KEB160	10.00	7.18	Tolborough Downs		CGG
KEB161	11.16	7.83	Tor E.of Brown Willy		CGG
KEB162	10.58	8.05	Codda Tor		CGG
KEB172	1.63	6.97	Old workings, E.of King Doniert's (Stone		ACGG
KEB193	11.63	5.15	Sheep pen, Priest Hill		WCGG
A	3.66	7.05	Siblyback Reservoir	(Depth 42ft)	CGG
C	3.20	6.87	" "	(" 46ft)	CGG
E	2.83	6.90	" "	(" 73ft)	CGG
N(40)	2.90	6.92	" "	(" 40ft)	AP
N(97)	2.90	6.92	" "	(" 97ft)	CGG
P	2.70	6.84	" "	(" 141ft)	CGG
12	2.95	6.98	" "	(" 90ft)	CGG
14A	3.00	7.05	" "	(" 12ft)	CGG
E1(19)	11.25	10.70	Wheal Bray	(19ft8in - 24ft2in)	AP
E1(56)	11.25	10.70	" "	(55ft10in - 58ft5in)	MCGG
E1(65)	11.25	10.70	" "	(65ft - 67ft9in)	MCGG
E2(38)	11.36	10.73	" "	(38ft - 39ft)	MCGG
E2(39)	11.36	10.73	" "	(39ft - 41ft7in)	MCGG
E2(63)	11.36	10.73	" "	(63ft - 70ft)	MCGG
W1	11.29	10.36	" "	(74ft - 77ft)	MCGG
K2	11.32	10.48	" "	(43ft7in - 44ft)	XCGG
C216	5.56	4.34	Colliford		ACGG
C217	5.65	4.56	"		CGG
C218(6)	5.69	4.14	"	(Depth 6ft)	ACGG
C218(45)	5.69	4.41	"	(" 45ft)	ACGG
L104(26)	3.56	6.52	Lamelgate	(" 26ft)	CGG
L104(40)	3.56	6.52	"	(" 40ft)	XCGG
L111	3.45	6.60	"	(" 150ft)	AP
L114	3.50	6.73	"	(" 72ft)	CGG

Spec.No.	U	V	Location	Rock Type
DHA	7.60	3.66	Coppin's Park	CCGG
DME2	7.49	4.69	Dewymeads	XCGG
BSE3	7.54	4.53	Nr. Simon's Stone	CCGG
H3	4.45	5.02	Hulke	CCGG
119	8.51.	6.38	Road cutting, A30 nr. Minzies Downs	CGG
121	8.52	6.41	" " " " "	CGG
123	8.54	6.45	" " " " "	CGG
124	8.55	6.48	" " " " "	MCGG
125	8.58	6.53	" " " " "	CGG
HARR	6.37	7.44	Harrowbridge	WCGG
LL	4.97	6.93	Lower Langdon	VCGG

AFGG - Altered fine-grained granite
FGG - Fine-grained granite
ACGG - Altered coarse-grained granite
MCGG - Mineralised coarse-grained granite
XCGG - Contaminated coarse-grained granite
VCGG - Veined coarse-grained granite
WCGG - Weathered coarse-grained granite
CCGG - Kaolinised coarse-grained granite
PEG - Pegmatite
AP - Aplite
CGG - Coarse-grained granite
QV - Quartz vein
CV - Chlorite veined granite

Major element analysis

i) Sample preparation

All the rocks were crushed in a similar manner to the sample preparation procedure outlined in the appendix chapter on XRF analysis (see parts 1 & 2 of "Sample Preparation"). Not less than 500g of rock was crushed.

ii) Experimental details

Major elements, plus lithium, were analysed by employing the rapid analysis techniques of Riley (1958), with some slight modifications. Digestion of rock powder, preparation of the solutions and the subsequent analyses were carried out in the normal manner using a Unicam SP500 Spectrometer (SiO_2, Al_2O_3, total iron as Fe_2O_3, MnO, TiO_2 and P_2O_5), a Southern Analytic A1750 Atomic Absorption Spectrophotometer (CaO, MgO) and an EEL Flame Photometer (Na_2O, K_2O and Li_2O). K_2O/ml. was corrected for interference by Na^+ and LiO_2/ml. corrected for K^+ interference. Water content was determined by the Penfield tube method. All the rock powders were dried (110°C) before analysis.

iii) Assessment of analytical errors

The errors in whole rock analyses, as in any other analyses, can be considered in terms of precision and accuracy. Both are dependent on innumberable related and unrelated factors, though, for the present case operator error can probably be regarded as the greatest influence in precision and procedural error in accuracy.

Whilst duplication may give some indication of precision the actual amount of time expended in multiple replication is limiting. In the present work two specimens, KEB16 and G2, were duplicated in order to make some assessment of experimental error.

		SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	H_2O
KEB 16	(a)	72.76	0.20	15.67	0.18	1.48	0.05	0.40	0.67	2.75	5.52	0.24	0.96
		72.97	0.19	15.16	0.18	1.48	0.02	0.40	0.57	2.75	5.80	0.24	0.96
s.dev.		0.15	0.01	0.36			0.02		0.07		0.20		
G2	(a)	70.06	0.48	14.77	1.40	1.38	0.03	0.84	1.91	4.34	4.66	0.13	0.31
	(b)	69.49	0.49	15.18	1.40	1.45	0.02	0.80	1.83	4.65	4.53	0.13	0.30
s.dev.		0.41	0.01	0.30		0.05	0.01	0.03	0.06	0.21	0.09		0.01

Duplication does not necessarily give a guarantee of accuracy if carried out by the same analyst, for similar errors may be repeated. These systematic errors, however, can be assessed by comparison of the analyst's results, with those of other workers for an international rock standard. Whilst in practice this is subject to numerous possible objections (for example the standard may initially differ in composition as a result of sampling, preparation, etc. and different analysts may employ different instrumentation and analysis techniques producing biased results for certain elements), the principle still offers a check of the analyst's ability. The mean of the two analyses obtained above for G2 is compared below with the mean of the rock analyses compiled by Flanagan (1969, table 4).

	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	H_2O
G2 (a+b/2)	69.77	0.48	14.97	1.40	1.41	0.02	0.82	1.87	4.49	4.60	0.13	0.30
G2 (Flanagan, 1969)	69.19	0.53	15.34	1.08	1.44	0.03	0.78	1.98	4.15	4.51	0.14	0.55

Na_2O, K_2O and Li_2O were also determined separately for all the collected samples. In Table 1, the major element rock analyses, the quoted Na_2O and K_2O values are the mean of the results obtained from the two, and in the case of KEB 8 and 16, three, analyses. As an assessment of accuracy in Li detection G2 was analysed but of the two results obtained both were about 50% greater in value than the mean quoted by Flanagan (1969) and neither fell within the range of quoted values. The values obtained for the spectrograph determinations of Li were taken as a guide to the range of values to be anticipated and standards for construction of the calibration curve were prepared to cover this range. Although G2 has the highest Li content of the international standards it is still considerably lower than that of the majority of the Bodmin Moor rocks and the error in the values obtained for G2 are undoubtedly due to failings in the calibration curve for relatively low concentrations of Li. Where low values (100 ppm) are quoted, no greater degree of accuracy than obtained for G2 can, therefore, be considered. Duplicate analyses and comparisons with the values obtained for spectrograph analyses are given below.

	G2	KEB1	KEB2	KEB5	KEB8	KEB9	KEB11	KEB12	KEB17
Flame P.	68.75	192	110	180	304,273	289	235	341	250
Spec.		215	136	140	345	300	243	343	238

	KEB19	KEB21	KEB23	KEB25	KEB32	KEB34	KEB37	KEB40
Flame P.	257	237	334	166	180	450	230	268
Spec.	330	324	329	228	232	529	295	264

Spectrograph analysis

i) Instrument details

Spectrograph analysis was carried out on a Hilger large quartz spectrograph, type E742. A Judd-Lewis comparator and a Joyce-Loebel, Mk. 3B, microdensitometer were employed in the line identification and measurement. All the equipment was operated as outlined in the respective instruction manuals and by employing the conditions detailed by Power (1966).

ii) Experiment details

a) Alkali elements (Wavelength range 9000-4520 A.U.)

A series of spikes was prepared (see XRF, experimental details) contain Rb, Li & Cs, for construction of calibration curves. All spikes and samples were prepared to less than -120 mesh B.S. grain size and mechanically mixed for one minute using polystyrene vials and pestles. The spikes were run in triplicate (two spikes per plate) and all the samples were run in duplicate (four samples per plate).

The following analysis lines were used, Na 5688.2 (variable internal standard, Na having been determined by flame photometry), Rb 7800.2, Li 8126, and Cs 8521.

b) 'Blue' run (Wavelength range 5480-3850 A.U.)

Two series of spikes were prepared, one containing Sr, Ba and V, and the other containing Sc, Y and La. A mixture of one part spike/or sample and two parts of graphite-Pd mix were used in the analysis. Other aspects of sample preparation were similar to those employed for the alkali elements.

The following analysis lines were used, Pd 3958.6 (internal standard), Sc 4246, La 4333, Y 4375, V 4379.2, and Ba 4934.

iii) Calculation of results

The methods employed for the construction of the calibration curves and calculation of results were the same as those used by Power (1966).

4) XRF analysis

i) Sample preparation

Specimens were prepared using the following techniques:-

1) The samples were broken into small pieces using a rock splitter.

2) These pieces were passed through a "Sturtevant" jaw crusher and the chips produced ground in a "Tema" ring mill. The grinding time was controlled to give a rock powder that would pass through B.S. 120 mesh nylon bolting cloth. Tests on some sample showed that the majority of powder would also pass through B.S. 240 mesh nylon bolting cloth, although around 5 - 10% of the powder, mainly micas, would not pass through the sieving. Before, and during,

steps 1 and 2 the powder was thoroughly homogenized by quartering and re-mixing.

3) 10 drops of 2% Moviol N 90/98 solution were thoroughly mixed with 6g of the homogenized powder and the mixture placed between tungsten carbide plattens and pressed hydraulically for 5mins at 25 tons.

4) After numbering the edge of the pellet it was held in a wire cradle and placed in an oven operating at 110°C, for a period of about 12 hours.

ii) Instrumental details

XRF analysis was carried out on an automatic Philips PW1212 X-ray fluorescence spectrometer. A description of the equipment and its operational use can be found in the manufacturers' manual.

iii) Experimental details

a) Instrument calibration

Accurately weighed amounts of dried (110°C) spectographically pure chemicals were spiked to granite specimen KEB8 such that additions were five to ten times greater than the estimated range of concentration of the elements in the Bodmin Moor rocks. By taking these top spikes and diluting with further amounts of KEB8 a series of spikes was produced to cover the anticipated range of chemical variation. In an attempt to minimize any change in rock matrix and mass absorption over the range of calibration no more than four elements were added to one series of spikes. Where interference of two or more elements was anticipated, either at peak or background positions, these elements were separated into different spikes. The same top spikes were used for calibration in XRF and spectrograph analyses.

b) General analysis methods

In the approach to the optimum operating conditions of the spectrometer the procedures of Leake et al (1969) were taken as a guide. With certain elements, however, the operating conditions were modified in an attempt to improve the precision of the analyses. The two measuring methods employed, the absolute ratio (fixed counts) and absolute (fixed time) techniques, their application and their significance with regard to instrument counting errors are outlined in the manufacturers' instruction manual and by Jenkins & De Vries (Chap. 5, 1970). All counts were monitored against the same standard, KEB8, except where the counting rate was uneconomical in terms of machine operating time, when the lowest value spike of the element being detected was used.

The operating conditions employed are given in Tables XRF1 & 2. The selection of counting time, or number of counts, was determined with regard to the most economical machine operating time and the minimum relative deviation of peak counts to the peak:background ratio on the ratio standard. Further details are given in the notes dealing with the calibration and detection of individual elements.

b) Computation of results

Calibrations and rock specimen analyses were calculated on a Digital PDP-8 computer from the spectrometer punch tape output. A number of programs written by Sedgley (1970) involving the equation $y = mx$, where y is the element percentage or ppm., x is the count ratio to internal standard ratio and m is the slope, were used throughout. Peak minus background (P - B) or peak minus background:background (P/B - 1) was used to determine the count ratio, the choice being the one that gave the most accurate results for various international rock standards when compared with the analyses of other workers (see Flanagan, 1969). The use of (P/B - 1) is regarded by Andermann & Kemp (1958) as an approximate matrix correction in that the ratio of the intensity of the analysis line to the background remains relatively constant for a given concentration of an element in samples having different mass absorption coefficients. Reynolds (1963, 1967) has also described a sample matrix correction involving the use of the Compton scattered portion of the K_α line from the molybdenum X-ray tube as an internal mass absorption coefficient correction.

d) Assessment of analytical errors

As with the major element analysis the analytical errors that arise in XRF analysis can be considered in terms of accuracy and precision with an additional regard for the lower limits of detection. Precision is a function of the errors arising from the sample, the instrument, the calibration, etc. and although accuracy is obviously intimately related it is also dependent on systematic bias. An overall assessment of analytical precision is discussed by Johnson et al (1967) and it is only intended here to derive approximate deviations for the quoted results.

Assuming homogeneity of the pelleted samples and their similar method of preparation any error produced as a result of the sample may be interpreted as systematic. Instrument error can be considered as the sum of the short and long term drift effects. For a large number of counts (N) the random scatter of X-rays may be regarded as approximating to a normal distribution and in fixed time measurements the standard deviation in peak (N_p) and background

(N_b) counts is

$$\text{st. dev.} = \sqrt{N_p + N_b}$$

and the relative deviation in terms of P-B calculations is

$$\text{rel. dev.} = \frac{\sqrt{N_p + N_b}}{N_p - N_b} \times 100\%$$

(Jenkins & DeVries, 1970)

By employing the ratio technique the long term drift of the instrument is eliminated but some allowance must be considered for the increase in short term drift as a result of introducing a further period of counting on a ratio standard. Jenkins & DeVries (1970) indicate that if the count rate of the standard (N_s) is of the same order as the sample then the relative deviation approximates to

$$\text{rel. dev.} = \sqrt{\frac{2}{N_s}} \times 100\%$$

In terms of relative deviation of peak to background counting statistics quoted above, this value is relatively insignificant for large values of N and can be disregarded.

Calibration and chemical errors may either be systematic, e.g. from interference, or random as in the case of normal experimental error. It has been assumed that the calibration curve fulfils a straight line equation, $y = mx$. In practice the calibration may deviate from a straight line for many reasons. Such inflections in the curve can be reduced in magnitude and neglected if the calibration is restricted to cover only the estimated range of concentration of the rocks being analysed. The uncertainty associated with the calibration curve, plus that in analysing a sample with this calibration, are beyond the scope of this work (see Miller & Kahn (1962), Johnson et al (1967) for more detailed discussion on the statistical errors). Some idea of the magnitude of the error, however, can be determined by regressing the count ratio, 'x', onto 'y' for which the standard error of the estimate is generally expressed as

$$\sigma = \sqrt{\frac{\sum(y_i - \bar{y}_i)}{(n - 2)}}$$

where $\bar{y}$ is the mean and n the number of operations.

To calculate this error for every element would be uneconomical in terms of machine operating time, and as it is only an estimate, derivation was limited to two elements, rubidium and thorium. These two elements reflect the best and worst instrumentation errors respectively. The relative deviation of 24 analyses of rubidium for international rock standard G2 was found to be 1% and for thorium, 14%. The magnitude of the deviation, therefore, is similar to that of the instrument deviation (see Tables XRF1 & 2). As the total relative deviation is a function of both instrument and calibration errors it can, at the worst, be generalised that the error in the quoted XRF results is no greater than twice the instrument error.

e) Lower limits of detection

The statistical definition of a lower limit of detection is considered by many workers to be defined as that concentration which gives a count rate equivalent to a background reading plus twice the standard deviation of the background. The time involved in determining the standard deviation of the background is uneconomical in terms of machine operating time and in practice the limit of detection can be taken as that concentration which gives a count rate equivalent to three times the standard deviation of the background count rate, i.e.

$$3\sigma R_b = 3\sqrt{\frac{R_b}{T_b}} \text{ cps.}$$ (Jenkins & De Vries, 1970)

Thus the lower limit of detection for (P - B) is

$$\text{L.L.D.} = \frac{T_b}{m} 3\sqrt{\frac{R_b}{T_b}} = \frac{3N_b^{\frac{1}{2}}}{m} \text{ ppm} \quad (\text{As } N_b = R_b T_b)$$

and for (P/B - 1) the lower limit of detection is expressed as

$$\text{L.L.D.} = \frac{3\, N_b^{\frac{1}{2}}}{m\, N_b} = \frac{3}{m\, N_b^{\frac{1}{2}}} \text{ p.p.m.}$$

The lower limits of detection for the elements analysed are given in Tables XRF1 & 2.

f) Systematic error corrections (Individual element calibrations)

Chromium tube

1) Caesium

In some of the international rock standards, G2, GSP1 and AGV1, the high barium concentrations produced an overlap of the BaLN peak onto the CsL$_\alpha$ peak. For the concentration range of barium and cerium in the Bodmin Moor rocks, however, no interference from the BaLN or CeLL peaks was apparent and corrections have not been applied. The caesium concentrations determined by XRF analyses are consistently higher than those obtained from spectrograph analyses. No definite conclusions have been reached to account for this variance, though it seems possible that the choice of a relatively weak caesium line (8521 A.U.) for the spectrograph may in part be the cause.

Tungsten tube

1) Tin

In setting the lower 2θ background position particular attention was taken to ensure that there was no interference from the $\mathrm{PbL}\beta_1$ peak

2) Neodymium

There are relatively few records of analyses for neodymium in the international rock standards but a comparison with those of Leake *et al* (1969) suggests that values quoted in Table XRF3 are high. No interference in peak or background positions, however, was detected.

3) Lanthanum

The effect of the $\mathrm{CsL}\beta_1$ peak on lanthanum is negligible for concentrations of less than 100ppm caesium. The effect of higher concentrations is quite marked, however, with an increase of approximately 40% in the lanthanum results for 500ppm caesium.

4) Cerium

There is an interference by the $\mathrm{NdL}\alpha_1$ peak on the $\mathrm{CeL}\beta_1$ peak and a subtraction correction of 1ppm per 7ppm Nd has been applied to the cerium results.

5) Barium

The $\mathrm{BaL}\beta_4$ peak is overlapped by the $\mathrm{CeL}\alpha$ peak and an addition correction of 1ppm per 10ppm cerium has been applied to the barium results. Cerium values were adjusted for neodymium before considering the cerium effect on barium.

Molybdenum tube

1) Uranium

The quoted uranium results are not regarded as bearing any significance.

Many of the determinations gave results below the lower limit of detection and the high relative deviation, limits any possible uranium variation in the granite pluton to experimental error.

2) Thorium

Leake et al (1969) indicate a mutual interference between thorium and lead with the PbL_{β_1} and PbL_{β_6} causing an increase of approximately 2ppm for 100ppm lead in the thorium results. In view of the relatively low lead concentrations no compensation has been made in the quoted thorium results for the Bodmin Moor rocks. As with uranium a large relative deviation in the results restricts the significance of any possible regional variation in thorium.

3) Lead

The values obtained for the international standards (Table XRF3) for lead are consistently high. Leake et al (1969) indicate an interference lowering of approximately 2.5 ppm in the lead values for 100 ppm thorium and whilst an interference from a second order SnK_{α_1} line may also be present no corrections have been applied to the Bodmin Moor rocks.

4) Rubidium and Strontium

The precision in rubidium and strontium values are regarded as the best achieved for any element by XRF analyses. Fairburn & Hurley (1970) found that the most satisfactory agreement between XRF analyses and isotope dilution analyses was obtained by averaging the results obtained from matrix corrections based on the reciprocal of the Compton scatter and on background intensities. The most accurate results in this work for rubidium, in comparison with the analyses of the various rock standards of Fairburn & Hurley (1970), however, came from applying a matrix correction from background only. For strontium the best results came from applying a matrix correction from Compton scatter only.

5) Yttrium

It is necessary to correct for interference by rubidium ($\mathrm{RbK}_{\beta_{1,3}}$) and this was applied in computation of the results by employing a slope calibration correction for the rubidium spikes run in the YK peak position, 'm' for $\mathrm{RbK}_{\beta_{1,3}} = 0.0049$. By comparison with the results of other workers for the international standards (Flanagan, 1969) it would appear that this correction has been underestimated, possibly as a result of overspill of the $\mathrm{RbK}_{\beta_{1,3}}$ peak onto the background.

6) Zirconium

A similar type of correction to zirconium results for the influence of $\mathrm{SrK}_{\beta_{1,3}}$ as applied to yttrium for rubidium was required, 'm' for $\mathrm{SrK}_{\beta_{1,3}} = 8.5248$. Again it would appear that the correction has been underestimated.

7) Zinc

A correction for tube interference from a second order MoK_{α} peak was necessary. From the analysis of 'spectrosil' pure silica this contamination was found to be 13ppm and this figure has been subtracted from the XRF results.

8) Copper

A correction for copper interference from the molybdenum tube amounting to 56ppm was subtracted from results based on the analysis of 'spectrosil' pure silica pellets. No interference was detected from the second order ZrK_{α} peak using the 500ppm zirconium spike. Many of the copper results were below the detection limit of the XRF spectrometer.

Table XRF1 Operating conditions and response for the Mo Tube

	Cu	Zn	Rb	Sr	Y	Zr	Pb	U	Th
Line	K_α	K_α	K_α	K_α	K_α	K_α	L_{β_1}	L_{α_1}	L_{α_1}
Bkgrnd	+0.91	+0.87	-1.66	-1.28	-0.98	-0.45	-0.40	-0.43	-1.66
Bkgrnd			+0.42	+0.49	+0.66	+0.85	+0.26	+0.29	+0.76
Counter	s & f	s & f	s	s	s	s	s	s	s
Time	f.c.	f.c.	40sec	40sec	40sec	40sec	40sec	40sec	40sec
Counts	$1x10^4$	$1x10^4$	f.t.	f.t	f.t.	f.t.	f.t.	f.t.	f.t.
Correct-ions	Cu tube	MoK_α 2nd. order	s.b.	s.b. c.s	s.b. $RbK_{\beta_{1,3}}$	s.b. c.s. $SrK_{\beta_{1,3}}$	s.b.	s.b.	s.b.
P-B(P)or P/B-1 (B)	B	P	B	P	B	P	P	P	P
"m"	0.0127	70.72	0.0185	113.5	0.032	34.78	23.03	31.86	26.42
R.st.	KEB8	KEB8	ZrY_{50}	ZrY_{50}	ZrY_{50}	ZrY_{50}	U_{100}	U_{100}	U_{100}
Av.Cnts. or Time	2x112 secs	2x59 secs	2x 38110	2x 12940	2x 21806	2x 13990	4x 2700	4x 5820	4x 2400
P:B	1.7:1	2:1	17:1	5:1	4:1	1.5:1	1.6:1	1.2:1	1.1:1
Inst.R.D.%	2	1.5	0.3	1.2	1.1	4	3	9	12
L.L.D.ppm	3	3	3	1	1	7	5	5	5

mA - 24, kV - 80, Collimator - fine, Crystal-LiF 220, throughout.

s = scintillation, f = flow, f.c. = fixed counts, f.t. = fixed time, s.b. = sloping background, c.s.=compton scatter, R.st. = Ratio standard, Inst.R.D.% = instrument relative deviation. L.L.D = Lower Limit of Detection.

Av. cnts = P-B on ratio standard.

P:B and instrument rel. dev. measurements based on KEB8 sample, uncorrected for any intereference. See text for further details.

Table XRF2 Operating conditions and response for W and Cr (for Cs only) tubes.

	Sn	Ba	La	Ce	Nd	Cs
Line	K_{α}	L_{β_1}	L_{α_1}	L_{β_1}	L_{β_1}	L_{α}
Bkgrnd	-1.30	-2.75	+2.45	-1.30	+1.11	-0.70
Bkgrnd	+0.69					+0.77
Cllmtr.	fine	crse	crse	crse	crse	fine
Crystal	LiF	LiF	LiF	LiF	LiF	P.E.
	220	220	220	220	220	
Counter	s & f	s & f	f	s & f	f	f
mA	24	24	24	24	24	24
kV	80	80	80	80	80	60
Wndw. LL		160		160		
W		420		420		
Crcts.	s.b.	CeL_{α_1}		NdL_{α_1}		s.b.
P-B(P)or P/B-1	B	P	P	P	P	B
"m"	0.0031	24.39	78.88	41.06	32.63	0.0350
R.st.	Sn_{50}	KEB8	La_{50}	KEB8	La_{50}	KEB8
Av.Cnts.	4x	2x79	3x135	2x120	3x79	2x100
or Time	35500	secs	secs	secs	secs	secs
P:B	1.1:1	3.7:1	1.6:1	1.3:1	1.1:1	2.2:1
Inst.R.D.%	4	1	3	5	6	1
L.L.D.ppm	2	6	2	6	8	1.2

see Table XRF1 and text for further details.

Table XRF3. Trace element concentrations in international standards (employing the operating conditions given in Tables XRF1 & 2)

	Cu	Zn	Rb	Sr	Y	Zr	Sn	Cs	Ba	La	Ce	Nd	Pb	U	Th
G2	6.8	98	170	471	7.4	404	2.6	nd.	1970	110	162	74	43	1.6	30
GA	nd.	69	174	296	21	153	6.8	2.8	897	39	47	40	39	6.8	16
GH	nd.	81	382	6.5	102	173	13	2.5	26	28	42	45	55	20	88
GSP1	39	106	245	230	20	723	6.3	nd	1297	158	315	172	74	2.3	126
W1	127	63	27	375	18	201	3.5			9.4		35			
BR	66	113	40	1400	27	102	nd.			78		89			
BCR1	4.9	91	45	337	35	207	0.8		734	22	36	46			
AGV1	72	80	67	660	17	249	4.8		1281	42	58	50	50	3.9	4.5
T1							35								

All values in ppm   Analyst K.Edmondson

nd. not detected.

blanks indicate that the element was not determined.

Note Some of the quoted values in the above table are lower than the lower limit of detection, as shown in Tables XRF1 & 2, for a particular element. Theoretically these low values should not be included but they are recorded here to give some indication of the concentration magnitude.

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