A Geochemical and Petrographical Study of Pillow Lavas from the Thetford Mines Ophiolite Complex, Quebec

A Geochemical and Petrographical Study of Pillow Lavas from the Thetford Mines Ophiolite Complex, Quebec

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ABSTRACT

The pillow lava samples analyzed from the Thetford Mines ophiolite complex have petrographical and geochemical characteristics similar to those of metamorphosed mid-oceanic basalts. The rocks have undergone submarine weathering and low grade metamorphism typical of the greenschist facies. The chemical analyses support the hypothesis that only part of pillow basalt unit of the ophiolite was altered sufficiently to produce a spilitic basalt.

ACKNOWLEDGEMENTS

I would like to thank Dr. D.M. Shaw for the time, guidance and financial support that he gave me during all stages of this research project. I would like to thank Mr. N. Massey for collecting and contributing the rock samples used in this study and for his help and advice during the development of this thesis. I am greatly thankful for the patience of my advisors and all of those who contributed to the collection and processing of the analytical work. I would also like to thank the Department of Geology at McMaster University for their financial assistance which was used to cover part of the analytical cost.

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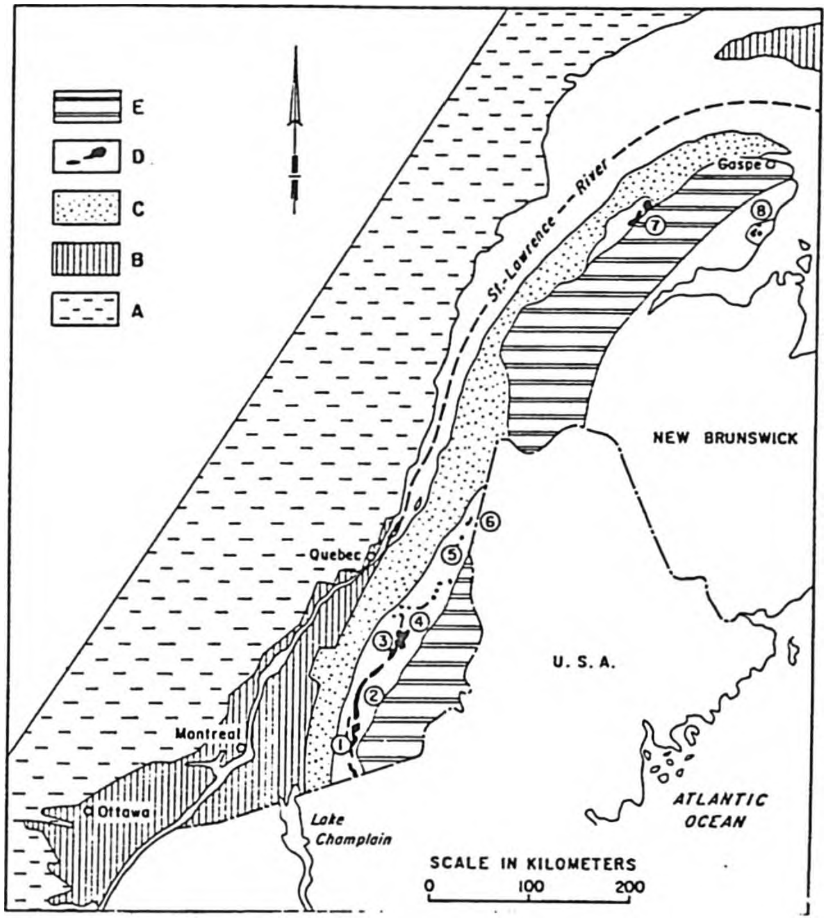
Location and Accessibility

The metamorphosed pillow lavas studied were sampled from a part of the ophiolite complex located approximately 13 kilometers southeast of Thetford Mines Quebec, near the town of St. Daniel. This particular geological locality is generally referred to as the Mont Adstock area. Regional and local maps are found on the following pages (Figure 1). The sample area is accessible by roads leading from St. Daniel and Disrali to Thetford Mines. The specific sample locations are marked on the local geological map (Figure 2).

Figure 1

Map of the Appalachians of S.W. Quebec



Laurent R. (1975) Fig. 1, pp. 444.

A   Precambrian basement
B   Sedimentary cover of the St. Lawrence Platform
C   Outer zone or external flysch trough
D   Inner zone or Notre Dame Trough
E   Siluro-Devonian belt of the Gaspé-Connecticut Valley Synclinorium

1   Orford
2   Asbestos
3   Thetford Mines
4   East Broughtor
5   St. Fabien
6   St. Omer
7   Mont Albert
8   Rivière Port Daniel

Figure: 2

GEOLOGY OF MONT ADSTOC AREA
STOPS: - E-3 , E-4

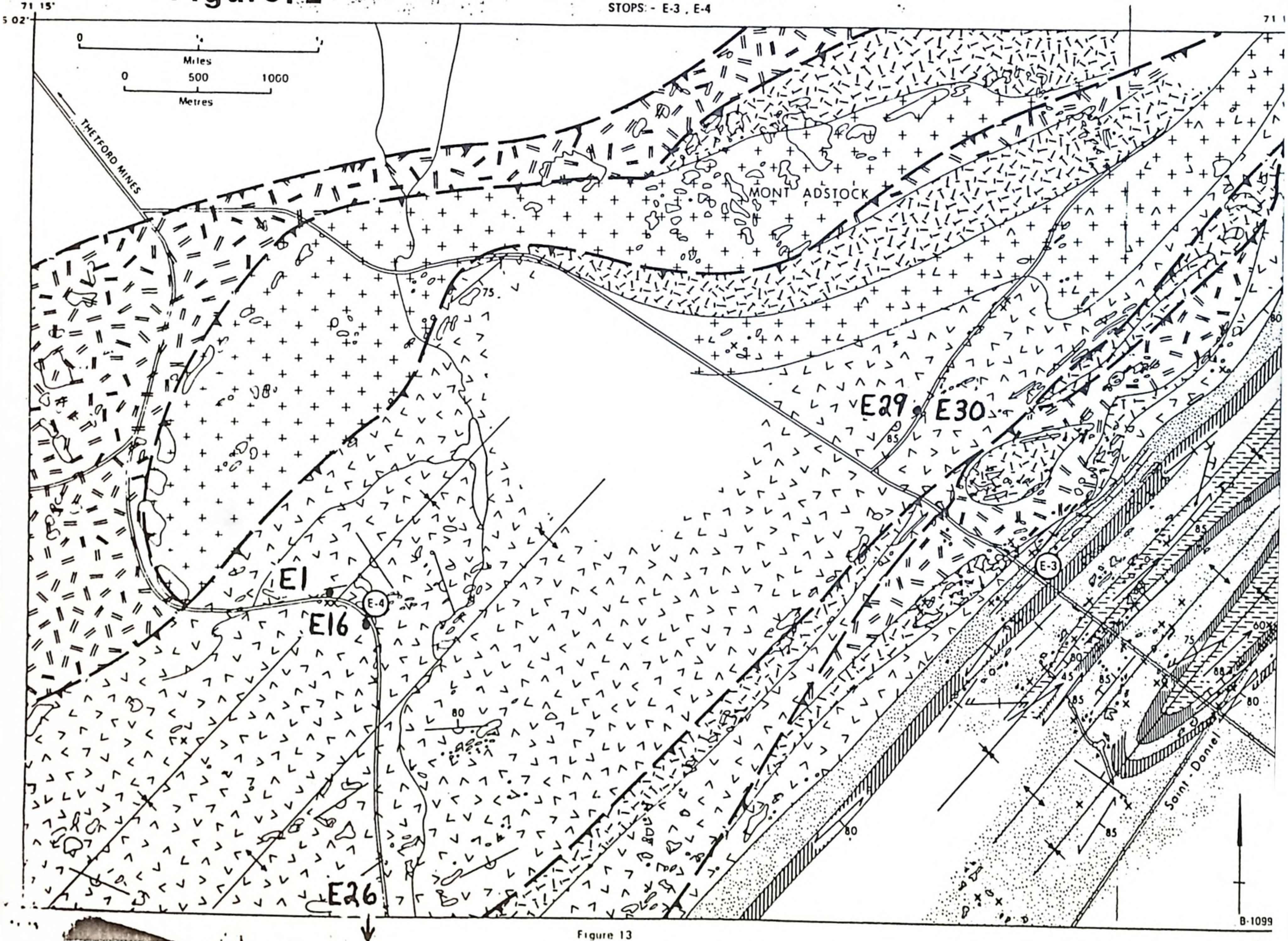


Figure 13

Geology of the Mont Adstock Area

50''
46 02'

LEGEND

ST. DANIEL FORMATION

LOWER ORDOVICIAN(?)

Grey and green slate

Brownish dirty sandstone

Green dirty sandstone and brecciated sandstone

''Shale with blocks'' (''Melange'')

THETFORD-MINES OPHIOLITIC COMPLEX

Pillowed basalt and andesite and associated pyroclastic rocks

Fine to medium grained gabbro and diorite and associated volcanic rocks

Gabbro and diorite

Pyroxenite

Dunite, peridotite and serpentinite

SYMBOLS

a b (a) Outcrop, (b) group of outcrops

Geological contact

Reverse fault

a b Fold axial surface trace (a) anticline, (b) syncline

a b c Strike and dip of bedding (a) inclined, (b) vertical, (c) top known

a b c d Strike and dip of pillows (a) normal, (b) vertical, (c) overturned, (d) undetermined dip

a b Strike and dip of the early schistosity (Phase ''F_1'') (a) inclined, (b) vertical

a b Strike and dip of the late cleavage (a) inclined, (b) vertical

Strike and plunge of fold axis (Phase ''F_1'')

Pierre St. Julien (1972)

Previous Work

A general description of the serpentinized rocks of southeastern Quebec was reported as early as 1913 by Dresser J.A. More detailed reports of the Thetford Mines area were made by Cooke H.C. (1937) and Riordon P.H. (1953, 1954). Recent studies by Karcia (1971) have suggested that the serpentinized sequences represent relatively undifferentiated igneous material. The ophiolite nature of the sequence was proposed by Lamarche (1972) and St. Julien (1972). Stratigraphic sequences were determined and the origin and tectonic emplacement of the ophiolite were suggested by Laurent (1973, 1975). The age of the ophiolite was determined by Ar^{40}/k^{40} analysis performed by Laurent R. and Vallerand P. (1974). Petrological features of pillow lavas were examined from the ophiolite sequence near Mont Adstock by Seguin M.K. and Laurent R. (1975).

Purpose of the Thesis

This thesis deals with the study of the chemical and petrographical variations across transverse cross-sections of five different pillows sampled from a unit within an ophiolite sequence located southeast of Thetford Mines. An attempt to explain the chemical trends existing along the cross-sections of the pillows, will be made by considering the original bulk composition, texture and mineralogy and the redistribution of elements subsequent to marine weathering and metamorphism in the greenschist facies. Secondary metamorphic textures will be explained in terms of the replacement of the original mineralogy; primary textures which persist after metamorphism will also be discussed.

Organization of the Analytical Study

The five pillow lava samples studied contained material ranging from the core to the selvedge, except for one sample (E26), which had no margin preserved. Two slabs cut parallel to the transverse section were removed from the centre of each pillow, one was used for chemical analysis and the other for thin section study. The remaining end(s) of the pillows were used for hand specimen inspection. The slabs were divided up into different regions so that the thin sections, and to some extent the corresponding chemistry, could be analyzed for each of the major internal zones within the pillows. Major element chemical analysis was made by Xray Fluorescence; ferrous iron and total volatiles were determined by wet chemical analysis and loss on ignition respectively. It is important to note that few selvedges are represented in thin section and that the thin section coverage is not continuous, unlike the chemical analysis.

General Geology

The ophiolite sequence of southeastern Quebec forms part of a discontinuous zone of peridotite bodies found within the northern reaches of the Appalachian mountain system. The ophiolites form a belt several kilometers in width, extending for approximately 250 kilometers with a northeasterly trend. On a regional scale, the ophiolites are folded along the synclinorial axis of the Notre Dame trough, a Cambro-Ordovician sequence composed of deep sea sedimentary rocks metamorphosed in the greenschist facies. The Notre Dame trough parallels two other Cambro-Ordovician sedimentary sequences to the north, the External Flysch trough and the St. Lawrence Platform respectively. These two zones represent progressively shallower marine sediments and hence the three belts may represent a portion of the deep sea, continental rise and the continental platform present during the early Paleozoic (Laurent 1973).

The ophiolite bodies occur as complete stratified units and as dismembered lenses within the deep sea sedimentary facies represented by the Notre Dame trough. The ophiolite near Thetford Mines lies between the Cambrian rocks of the Caldwell Group and the early Ordovician melange sequence. The ophiolite shows no continuity with either bounding sequence. The ophiolites are believed to have been part of an oceanic crust formed during the Cambrian and emplaced into late Cambrian basin sediments as a solid mass, during the early Ordovician (Laurent 1975). The ophiolite sequence consists of a thick basal unit of serpentinized harzburgite, with minor dunite and orthopyroxenite grading upwards into pyroxenites, gabbro, diabase, metabasaltic pillow lava, hyaloclastite and cherty argillite.

Petrography

Petrography

A short section describing the general physical features of a pillow is included to serve as background information to the reader.

A brief description of the general texture and of the mineralogy and mineralogical texture will be followed by an interpretation of the petrography in terms of the original mineralogy and texture.

The areas of the different pillow zones from which the thin sections were taken, are shown in figures 3 - 7 incl. (Appendix pp. i).

Petrographic descriptions of the thin sections examined also appear in the appendix. The approximate percentages of minerals recognized in the thin sections are shown on Table I of the appendix. The modal percentages were determined by averaging the eyeball estimates made on at least twelve fields of view (7.0 mm d/a) for each thin section.

Characteristic Features of Pillows

Pillow structures consist of ellipsoidal masses of volcanic flow rock resembling sacks or pillows. Pillows are generally convex upwards along their upper surface and relatively flat along their lower surfaces. They fit closely upon one another "en echelon" forming prominences along the lower surfaces which extend into the areas between the upper and lateral surfaces of underlying pillows. The transverse cross-sections of pillows resemble flattened elliptical shapes with the longest diameter oblique or parallel to the horizontal at the time of their deposition. The longitudinal cross-section is generally assymmetrical and may be more extensive than the transverse cross-sections; the greatest thickness is found at the leading end of the flow and the longest axis is parallel to the flow. Generally, the transverse cross-sections become progressively larger in area in the direction of the flow.

Documented evidence proves that the actual formation of pillows takes place within an aqueous environment by the quenching of fluid lava. The flows progress by a budding process in which magma extrudes from fractures along the newly formed crust, in the direction of the flow.

Generally, pillows are formed from magmas which are basaltic in composition, but andesitic pillows are also known, presumably being formed from fluid, andesitic lavas. Fresh pillows have a glassy outer crust (selvedge), which forms at the time the flow was initially quenched. Internal structures include vesicles which formed due to the presence of gas bubbles, and variolites or globulites which are composed of spherical accumulations of radiating crystals, usually plagioclase. The vesicles are commonly more numerous in the intermediate zone of the pillow while the varioles often become larger and more numerous from the intermediate zone to the core, where they eventually coalesce. Some pillows show radiating fractures or have hollow centres formed by contraction during cooling and changes in magma effluent rates respectively.

A Summary of the Mineralogy and Texture

I Macroscopic Texture

There are three major textural units in each pillow defined by the selvedge, the matrix and the varioles. The selvedge consists of fine-grained, equigranular epidote and clinozoisite with both granular and massive chlorite. The matrix consists of a randomly oriented mass of fine grained, accicular actinolite grams, partially separated by a small amount of interstitial chlorite. The varioles are composed of spherical aggregates of albite with inclusions of actinolite and chlorite grains.

The physical zones of the pillows are divided into the selvedge, the intermediate zone, and the core. The selvedge zone coincides with the selvedge textural unit. The intermediate zone is made up of matrix in the outer parts and matrix with varioles in the inner parts. The core zone contains coalesced varioles. The core is often quite diverse in terms of mineralogy, especially in zones within the near centre of the pillows.

Amygdules are present throughout all of the zones in the pillows, but they are usually concentrated within the matrix of the intermediate zone.

Interpretation of the Mineralogy and Texture

The mineralogy of fresh pillow basalts has been studied extensively and the origin of the texture and mineralogy of the metamorphosed pillows can be extrapolated.

In fresh pillows much of the selvedge and the interior has a high glass content. Aggregates of plagioclase are commonly formed within pillow centres, while euhedral olivine grains can be found throughout the entire pillow. The plagioclase grains occur in spherical crystal sheafs or varioles often intergrown with augite crystals. The intermediate zones of fresh pillows develop a limited degree of crystallinity, in which augite grains form in a glass matrix before the pillow eventually solidifys. Varioles form throughout the pillows but they are usually concentrated in the core and intermediate zones.

The metamorphosed pillows studied here have a mineralogy typical of the greenschist facies or grade of metamorphism. Constituent minerals include chlorite, albite, actinolite, calcite, epidote, clinozoisite $\pm$ quartz. The metamorphosed pillows have similar textures to those found in fresh samples. Chlorite occurs where fresh glass was initially formed, ie. in the selvedge and the matrix of the intermediate zone. Essentially, the glass has been devitrified, hydrolyzed and recrystallized. Actinolite is believed to have replaced augite since the general chemical formulas and spacial relationships of these minerals are similar. Albite varioles in the core could easily have replaced a more calcic rich plagioclase with the removal of calcium + aluminum and the addition of sodium + silica.

The varioles within the metamorphosed pillows are composed of radiating albite crystals with inclusions of actinolite and chlorite. This can be explained by the original mineralogy of the varioles, in which radiating plagioclase grains were interfeathered with fibrous augite grains. Chlorite in the varioles may represent glass fragments which were trapped in the plagioclase-augite aggregates. Needle-like actinolite grains found within the varioles may represent former augite grains which have undergone rather high rates of crystal growth. As one might expect, the greatest degree of crystallinity occurs in the core zone, which was the last zone to cool and solidify. Even though crystalline plagioclase-augite varioles formed, the varioles themselves represent crystal aggregates which underwent high growth rates. Inclusions of chlorite may imply that the quickly formed varioles assimilated small masses of glassy material.

Recently, it has been suggested that variolites formed by the immiscible splitting of a tholeutic magma before it was extruded (Gelinas et al., 1976). The distribution of variolites within pillows could therefore be explained by hydraulic principals, in which case the varioles would collect at an equilibrium zone at the axis of a conduit.

Mineralogical Control of Chemistry

Comparisons between the chemical analysis and mineralogy of the different zones were made for each pillow sample. It is important to note that the chemical analysis of the different zones only approximate the zones covered by the thin sections and that the chemical analysis cannot show progressive changes wighin a given zone as shown by thin sections. See Appendix (pp. i). The minerals listed below were found to control the content of several major oxides within the pillows.

OXIDE	MINERAL
MgO	chlorite $(Mg,Fe^{2+})_5 Al_2Si_3O_{10}(OH)_8$
FeO	actinolite $Ca_2Fe_5^{2+}Si_8O_{22}(OH)_2$ chlorite
Al_2O_3	clinozoisite $Ca_2Al_3(OH)(SiO_4)_3$ epidote $Ca_2(Al,Fe^{3+})_3(OH)(SiO_4)_3$ albite $NaAlSi_3O_8$ chlorite
CaO	calcite $CaCO_3$ epidote clinozoisite actinolite
Na_2O	albite
Fe_2O_3	hematite Fe_2O_3 epidote

Only three pillow samples provided enough material for the major element chemical analysis of the selvedge zone (#E1, E29, E30). Of these, only samples E29 and E1 have thin section coverage for at least part of the selvedge zone (See appendix pp. i). It is obvious that not all of the chemical trends shown on graphs 2,4,6,8, and 10 can be supported by mineralogical control. The chemical trends within the pillow lava samples are carefully discussed noting the limitations of the thin section coverage and the accuracy of the modal analysis. All modal analyses were made by several eyeball estimates of each thin section.

The partial chemical trends within sample E16 are significantly different from the others. The inconsistent migration of several major elements in sample E16 reflects alteration other than by metamorphism. Since there is no thin section coverage for the core and selvedge zone of sample E16, it will not be discussed in this section. The following trends hold true for the intermediate and core zones of sample E26. There is no thin section coverage for E30.

Magnesium: The magnesium content is lowest in the selvedge, it increases to a maximum in the outer section of the intermediate zone and decreases towards the core. Most of the chlorite and hence the magnesium is contained within the matrix, amygdules and chlorite grains within the intermediate zone.

Alumina: Alumina is at a maximum in the selvedge, it decreases markedly in the outer part of the intermediate zone and it may increase slightly within the core. The high alumina content in the selvedge is due to the presence of epidote and clinozoisite. Smaller percentages of alumina occur in the core zone in albite (varioles) and in the intermediate zone in chlorite and albite.

Calcium: There is no clear trend in the distribution of calcite due to its great mobility. Calcium is generally high in the selvedge zone due to the presence of epidote, clinozoisite and calcite. Calcium also occurs in actinolite and numerous calcite amygdules and veins throughout the pillows.

Ferrous Iron: Ferrous iron is least abundant in the selvedge zone and most abundant in the intermediate zone. The ferrous iron content in the core is not significantly different from the intermediate zone. The ferrous iron in the selvedge occurs in chlorite, most of the ferrous iron in the intermediate + core zone occurs in actinolite.

Sodium: Sodium is least abundant in the selvedge and increases in content towards the core zone. Sodium occurs in amygdules in the selvedge and intermediate zones and in albite varioles in the core and intermediate zones.

Ferric Iron: Ferric iron is most prominent in the selvedge zone, decreasing abruptly within the intermediate and core zones. Much of the ferrous iron occurs in epidote and smaller amounts of hematite.

Chemical Classification of the Pillows

Although the sample rocks in this study are not fresh, they are classified in part by the use of the method proposed by Irvine and Baragar (1971). This method has been used successfully to classify similar metavolcanic rocks.

The bulk chemical analysis for each pillow lava sample was calculated using various formulas (Appendix pp.XLI). The volatile component of the samples was subtracted from the total chemical composition and the remaining oxides were normalized to 100% before being used in a norm program. The adjustment for the volatiles allows for a more accurate determination of the norm, since most of the volatile component is water. The analyses were plotted on figures eight through twelve. All of the pillow samples plot in the basalt field and all but one (E16) plots in the tholeiitic field (Fig. 10, 11). Sample E16 plots in the calc alkaline field in figure #10. There are limitations in using the Irvine and Baragar method to classify metavolcanic rocks, especially where K, Na and Ca are the only parameters (Fig. 12). In this case, the samples plot in the K-poor andesite field, since the samples are depleted in Ca and generally enriched in Na relative to fresh volcanic analogs. The K content of the sample rocks are low. The pillow samples plot in the mid oceanic field of the AFM diagram (Fig. 10).

Pearce et al (1975) proposed a method of distinguishing between oceanic and continental basalts using a TiO_2 - K_2O - P_2O_5 plot. Figure 13 represents the plot with the boundary between the oceanic and continental basalts. In order to justify the use of this diagram, rock analyses must be screened using an AFM plot; only those rocks with an alkali content of less than 20% can be used for the proposed diagram, hence pillow E26 is excluded. Pearce et al. suggested that a metamorphosed basalt, falling within the oceanic field of the TiO_2 - K_2O - P_2O_5 diagram is most likely oceanic in origin since significant amounts of potassium are usually absorbed during the metamorphism of basalts.

A Discussion and Interpretation of the Chemical Analyses

Hypotheses for the transformation of modern day mid-oceanic pillow basalts to spilites or low grade metamorphic basalts were suggested by several geologists in the past decade (Melson W.G. et. al. 1968, Hart S.R. 1974). It is logical to use these studies to explain the petrographical and geochemical characteristics of the mafic pillowed flows found in the Thetford Mines ophiolite complex. (Seguin M.K. et. al. 1975).

Most of the recent papers written on the submarine weathering and metamorphism of mid-oceanic pillow basalts agree that changes in the bulk chemical composition are the result of both submarine weathering, and to a greater extent, metamorphism. The major element chemical analyses obtained for this study show variations in the internal chemistry and significant changes in the overall chemical composition of the pillows, relative to their fresh analogs (Melson et. al. 1968). The major element chemical analyses of each pillow lava sample was determined (see appendix) and then compared to an analysis representing fresh mid-oceanic pillow basalt (see table following).

	Fresh Mid-oceanic Basalt (Melson et. al. 1968)	Sample Pillow Lavas (includes the range of each oxide)
SiO_2	49.74	55.55 - 56.99
Al_2O_3	16.52	10.48 - 12.33
Fe_2O_3	2.06	1.61 - 2.15
FeO	7.19	5.15 - 6.87
Total Fe	9.25	7.30 - 8.98
MgO	7.41	8.84 - 13.20
CaO	11.69	6.50 - 7.88
Na_2O	2.70	4.29 - 2.42
K_2O	0.21	0.02 - 0.45
MnO	0.16	0.18 - 0.21
TiO_2	1.53	0.15 - 0.19
P_2O_5	0.06	0.02 - 0.03
H_2O	0.93	* 2.70 - 4.52

* represents percentage of total volatiles, predominantly H_2O.

The sample pillow lavas have a significantly higher percentage of SiO_2, H_2O and MgO and a lower percentage of Al_2O_3, CaO, TiO_2 and total Fe. In addition, the average Na_2O content of the samples analysed is generally higher than in the fresh basalts. These results are consistent with those reported in several papers dealing with studies of similar rocks. (Seguin M.K. et. al. 1975, Cann J.R. 1968, Vallance T.G. 1965).

Even though the internal texture of a fresh pillow lava is variable, the chemical composition is uniform throughout. (Cann J.R. 1968). The internal chemical composition is not homogeneous within metamorphosed pillow lavas because metamorphic alterations vary with the texture.

During metamorphism in an open system, the differential movement of elements cause a change in the overall chemical composition of the rocks relative to a fresh basalt. In this case, the original mineral assembly is transformed into one typical of the Greenschist facies.

Glass, olivine + H_2O	Chlorite + Fe_2O_3
augite	actinolite
calcic plagioclase	albite + epidote + $CaCO_3$

It is this transformation which explains the overall change in the major element content of the rocks. The changes are as follows: (a) H_2O is absorbed by anhydrous basalt and Mg is accumulated during the formation of chlorite at the expense of glass and olivine. (b) Augite is changed into actinolite. (c) Calcic plagioclase loses Ca + Al and gains Si + Na. The results are a net gain in Si, Na, Mg and H_2O and a net loss of Ca, Al, and Fe. Although Al and Mg are relatively inert and Mg and Si tend to be depleted in high temperature (hydrothermal) reactions in sea water, the diffusion of these elements within the basalt follows that prescribed by metamorphism.

The loss of CaO is the result of the high solubility of Ca in sea water and the leaching processes of hydrothermal fluids. (Spooner and Fyfe 1973). The loss of Ca suggests that the partial pressure of CO_2 was relatively high, since the activity of Ca increases with the CO_2 content within the surrounding fluids. The high activity of Ca would in turn precipitate TiO_2 as sphene, hence the TiO_2 content of the pillow samples should not be greatly altered. The TiO_2 content of these pillows is low in comparison to modern mid-oceanic basalts but this is typical for basaltic rocks from the Thetford Mines ophiolite. (Seguin and Laurent 1975).

Si, Mg and Na were added to the volcanic pile from sea water during submarine weathering and metamorphism. It has been suggested that the addition of Na could be facilitated if hydrothermal alteration is significant. (Scott et. al. 1976).

The low potassium content of most of the pillows is probably due to the composition of the original magma rather than because of any removal during metamorphism. In any case, the potassium content tends to increase with the degree of alteration. (Scott et. al. 1976).

A loss in the total percentage of iron can be explained by the active processes of circulating brine solutions and submarine weathering, especially at the pillow margins. The ferrous iron content reflects the result of an initial oxidation, a partial loss of iron and a subsequent reduction in the formation of chlorite and actinolite. The presence of significant amounts of iron in the overlying sedimentary rocks in many ophiolite sequences suggest that the underlying volcanics contribute iron during sedimentation.

A classification of igneous rocks (fresh, weathered, metamorphosed) has been proposed by C.J. Hughs (1973). The classification was designed to distinguish between spilites and other metavolcanic rocks. The classification is formulated on the basis of the total alkalis (wt %) plotted against K_2O/Total Alkalis x 100 (Figure 14). Only one of the pillow analyses in this study fell within the spilite field, the rest plotted outside both the spilite and the fresh igneous rock zones. Most of the pillow lavas have bulk compositions that are low in K_2O and total alkalis, relative to those percentages proposed for the spilite field. The pillow lavas do however have many mineralogical and textural similarities with other spilitic pillow lavas. The K_2O content of the pillows analyzed is low and only 3 of the 5 pillows have a Na_2O content higher than the average for a fresh basalt (2.70%). It may be possible that not all of the basalt in the Thetford Mines ophiolite was exposed to sea water long enough to allow for the additional absorption of K and Na (Hart S.R. 1974, Scott et. al. 1976). It is also possible that the pillow lavas did not suffer a high degree of hydrothermal alteration, in which case the content of Na_2O and possibly K_2O would have been higher. (Scott et. al. 1976, Hart R.S. 1974). The fact that one of the pillow analyses in this study plots in the spilite field of the diagram is good evidence to suggest that only part of the pillow basalt unit within the Thetford Mines ophiolite sequence is spilitized.

The Internal Chemistry of the Pillow Lavas

Few chemical trends were discovered within the pillows analyzed in this study. Most of the pertinent papers written on this topic state that MgO, CaO and total Fe are more abundant towards the selvedge zone, while SiO_2 and Na_2O are more abundant towards the core. With the exception of pillow E16, which appears to have been altered to the greatest extent, the pillow analyses show an increase in SiO_2 and Na_2O towards the core zone. This trend resulted from the formation of Albite at the expense of calcic plagioclase during the metamorphism of the varioles. Unfortunately, only two selvedge analyses are available for the study, both of those pillows show an increase in the CaO percentage towards the selvedge zone. The mineralogical control of the chemistry previously discussed in the thesis explains the chemical trends within each pillow.

Appendix

Schematic Diagram: Pillow E1

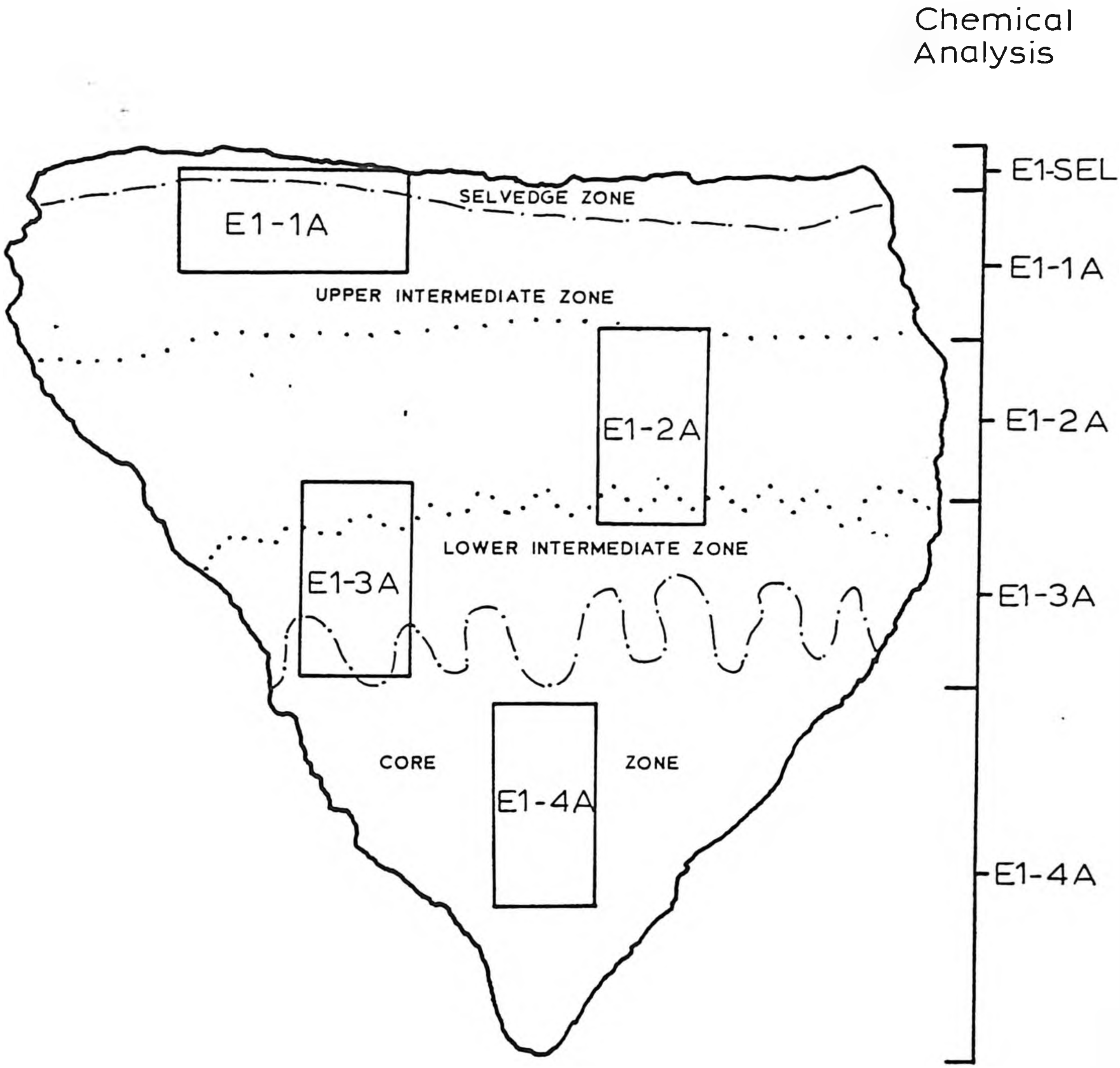


Figure: 3

Schematic Diagram: Pillow E16

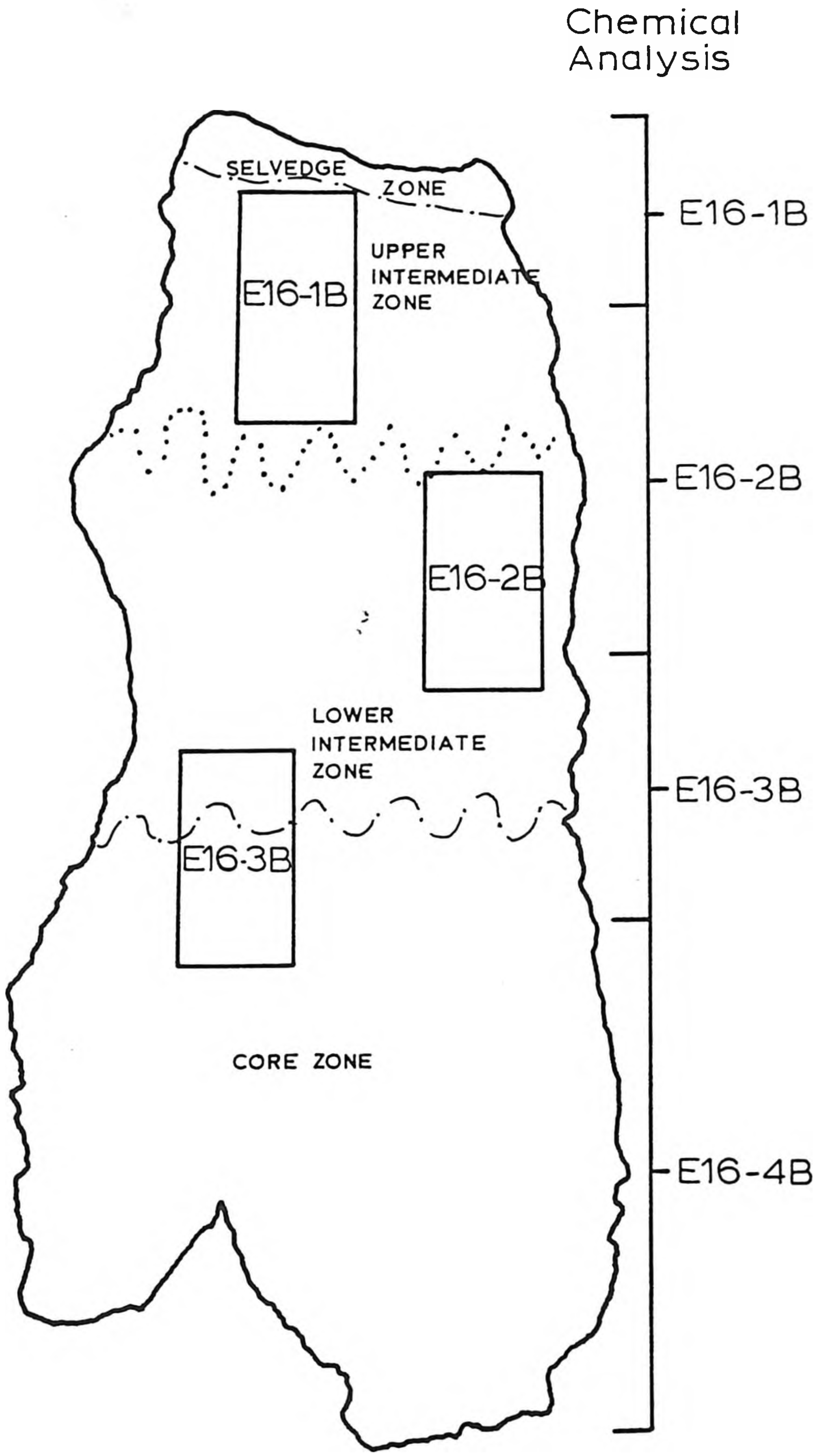


Figure: 4

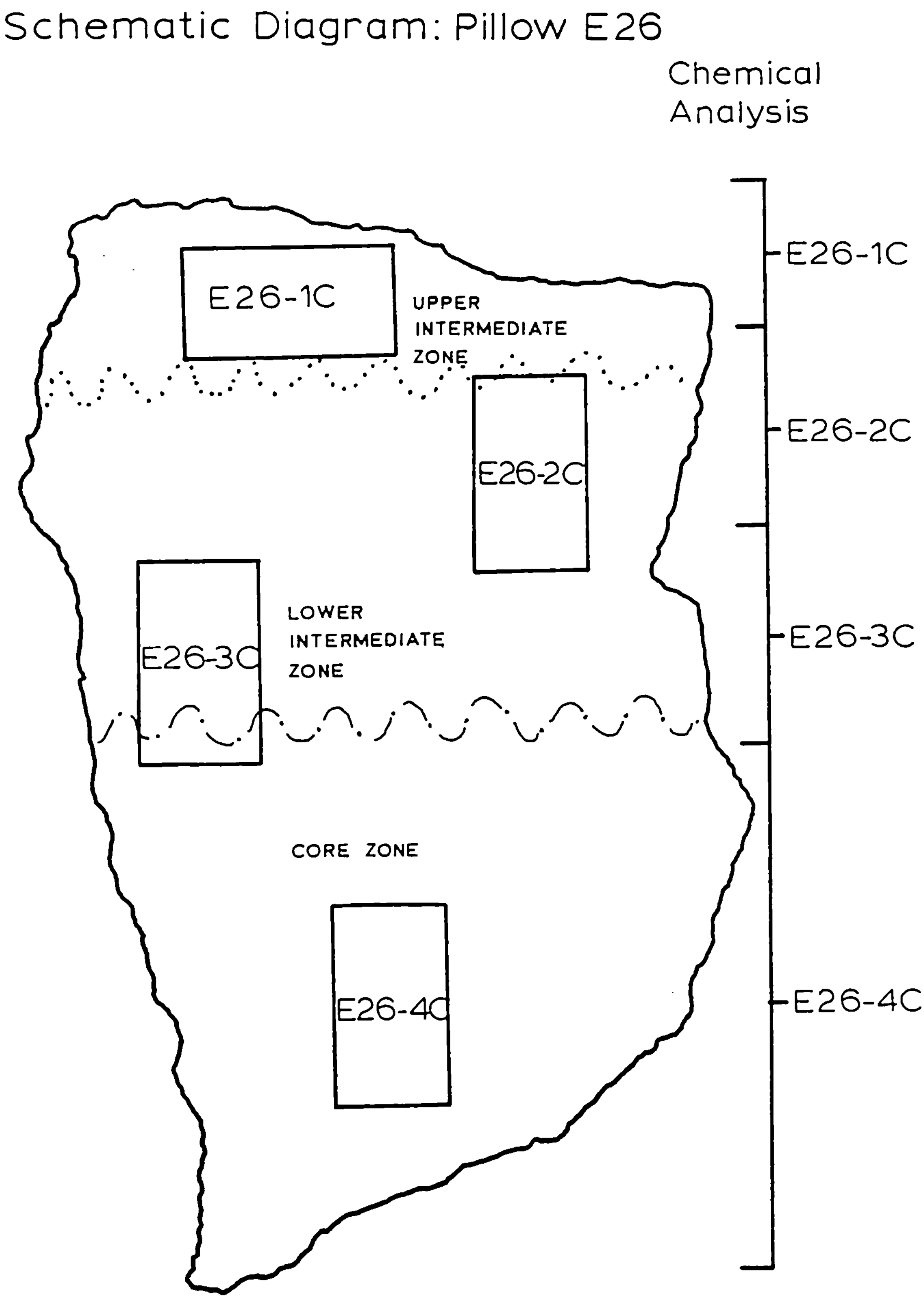

Schematic Diagram: Pillow E26
Chemical
Analysis
E26-1C
UPPER
INTERMEDIATE
ZONE
E26-2C
E26-3C
LOWER
INTERMEDIATE
ZONE
CORE ZONE
E26-4C
E26-1C
E26-2C
E26-3C
E26-4C

Figure:5

Schematic Diagram: Pillow E29

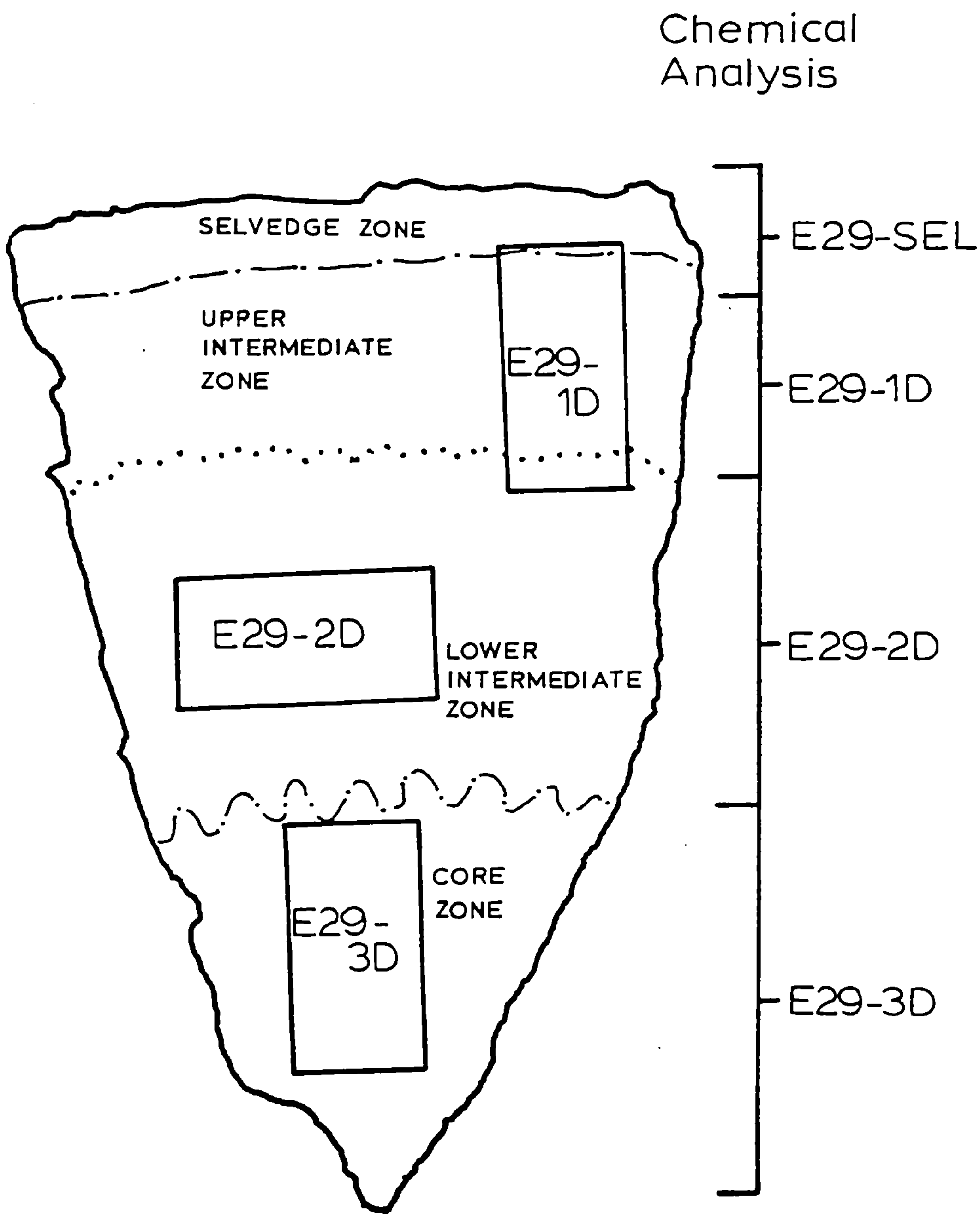


Figure: 6

Schematic Diagram: Pillow E30

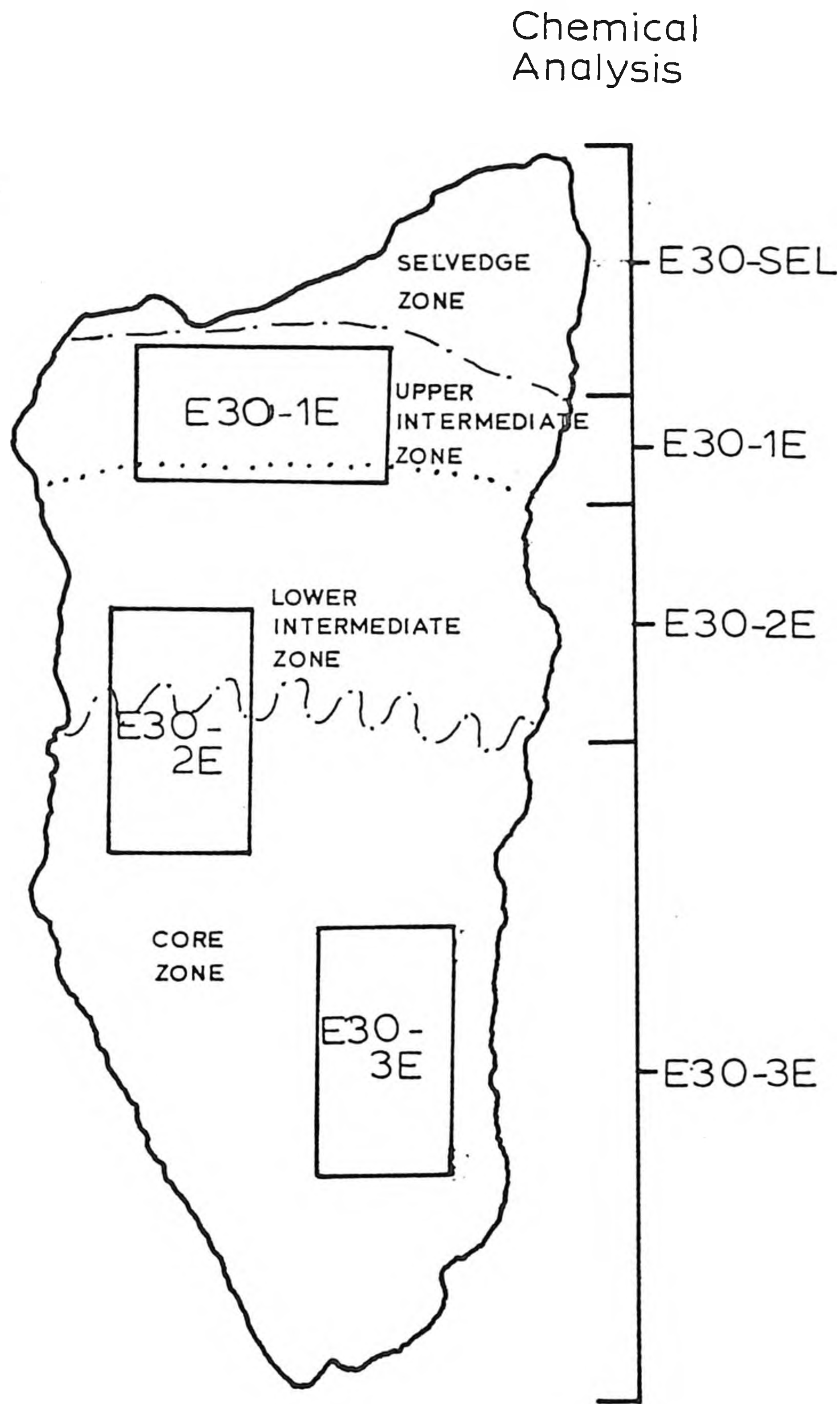


Figure:7

v

Table # 1 Modal Percent (Approximate)

		Actinolite	Chlorite	Albite	Calcite	Quartz	Epidote	Clinozoisite	Opaques	Antigorite
E1	-1A	60	25	5	10	--	tr	5	--	--
	2A	45	25	20	3	4	tr	2	tr	--
	3A	40	15	40	2	3	tr	tr	tr	--

	4A	20	10	55	13	1	tr	--	--	--
E16	-1B	50	20	20	3	2	1	3	--	--
	2B	35	25	29	10	1	tr	tr	--	--
	3B	40	15	30	12	3	--	tr	tr	--
E26	-1C	60	7	17	--	0.5	5	0.5	--	10
	2C	65	5	23	--	0.5	3	tr	tr	3
	3C	20	5	55	7	0.5	12	tr	--	--
	4C	15	3	50	20	--	12	--	tr	--
E29	-1D	60	20	3	5	0.5	--	11	--	--
	2D	50	20	15	12	0.5	0.5	2	--	--
	3D	60	13	20	6	0.5	--	tr	tr	--
E30	-1E	75	12	5	2	3	0.5	2	--	--
	2E	65	17	15	0.5	2	--	--	tr	--
	3E	60	20	13	3	3	0.5	0.5	tr	--

E1-1A

Modal Percent (Approximate)

Actinolite:	60%
Chlorite:	25%
Clinozoisite:	5%
Calcite:	10%
Albite:	5%
Epidote:	tr

Texture: Actinolite is the major mineral component in the thin section. The grains are anhedral to subhedral in form and occur as elongate grains, generally less than 0.4 mm long with a length:width ratio of 7:1. Many of the grains appear frayed at the ends of the crystals. The grains are unoriented except in areas adjacent to amygdules or large mineral grains, where actinolite shows a subtle orientation tangential to the amygdule or grain boundaries. Small needle like actinolite are also present within albite amygdules.

Chlorite appears as anhedral and polygonal shaped grains throughout most of the thin section. The grain size of these minerals does not exceed 1.5 mm dia. Chlorite grains often have albite inclusions. Chlorite also occurs in small amygdules about 0.2 to 0.6 mm dia. The amygdules occasionally contain quartz, calcite or albite. Chlorite occurs interstitial to the actinolite grains in the matrix of the intermediate zone and interstitial to the epidote grains in the selvedge. Chlorite grains of up to 0.8 mm dia also occur in the selvedge.

Albite exists in subrounded amygdules up to 0.8 mm in diameter. The amygdules are present throughout the section comprising 10% of the selvedge zone. The amygdules show a small increase in number and appear to be rimmed by chlorite to a greater degree, towards the bottom of the slide.

Calcite occurs in anhedral granules or amygdules 0.5 mm in diameter. The grains compose ~3% of the selvedge zone and are dispersed throughout the rest of the section. Calcite is often rimmed by chlorite and albite.

Epidote is present throughout the section, but is highly concentrated within the selvedge where it represents 35% of the mineralogy. The grains are anhedral, # and ~ 0.2 mm in diameter. The epidote minerals appear altered.

Clinozoisite occurs with epidote, it comprises 15% of the matrix. The clinozoisite grains are subhedral (tabular) in form and are colourless in thin section.

E1-2A

Modal Percent (Approximate)

Actinolite:	45%
Chlorite:	25%
Albite:	20%
Calcite:	3%
Quartz:	4%
Clinozoisite:	2%
Epidote:	tr
Opaques:	tr

Texture: Actinolite appears to be better defined than the grains in the thin section representing the upper portion of the pillow. Many actinolite grains show crystal imperfections and appear to be hollow or included in both longitudinal and transverse cross-sections. The actinolite appears in the varioles as well as the matrix. In the varioles, the grains are sparse in comparison to those found in the matrix and are randomly oriented. Actinolite grains in the matrix tend to orient themselves tangential to the varioles to a limited extent. The modal percentage of actinolite in the slide decreases downwards within the intermediate zone, as the variole composition increases and the matrix composition decreases. Smaller actinolite grains with very high length:width ratios occur within the varioles.

Chlorite is present in the upper parts of the thin section in the actinolite matrix and in the form of rims around the amygdules. In the lower areas of the slide, chlorite appears in amygdules and as polygonal grains, occasionally boardering varioles. In addition, very small blebs 0.1 mm dia are also dispersed throughout the varioles.

Albite forms subrounded amygdules 1.0 mm in diameter, in the upper parts of the slide only. Most of the albite occurs in varioles, which are roughly spherical in form and are composed of at least 50% albite with equal amounts of chlorite and actinolite. The varioles first appear 1 cm from the upper end of the thin section and increase in size from 0.8 to 2.0 mm in diameter, towards the bottom of the section. The varioles show radial extinction patterns under crossed nicols.

Calcite occurs in irregular grains and amygdules in the upper parts of the section. The amygdules range in size from 0.5 to 1.5 mm in diameter. The calcite grains are sparse within the lower areas of the slide. Calcite also occurs as part of a cavity filling.

Quartz blebs are scarce and exist in the zone in which the varioles first appear. The grains are irregular and have smooth boundaries implying that they may be amygdules. Small grains have been observed within the outer areas of varioles.

Clinozoisite is found in cavity fillings and adjacent to few varioles.

Epidote occurs in veins and in cavities as fine granules.

Traces of hematite were recognized in a cavity filling.

E1-3A

Modal Percent (Approximate)

Actinolite:	40%	Calcite:	2%
Albite:	40%	Opaques:	trace
Chlorite:	15%	Epidote:	trace
Quartz:	3%	Clinozoisite:	trace

Texture: The actinolite grains within the matrix in the upper area of the slide are generally slightly larger than those within the varioles. The actinolite grains within the varioles lack the crystal imperfections shown by many of the actinolite grains in the matrix. The actinolite grains in the matrix are 0.4 mm long.

Albite exists primarily within the varioles, which increase in size to a maximum of 2.5 mm in diameter until they coalesce. Varioles coalesce completely about half way down the slide, marking the boundary between the lower intermediate zone and the core zone. Very few albite amygdules 1.0 mm in diameter occur within the upper parts of the section.

Chlorite exists in the matrix of the upper area of the slide before the varioles coalesce to form the core. A few small grains 1.0 mm in diameter exist at the upper part of the section. Chlorite grains are found within the matrix and within the varioles. Few ovoid amygdules of chlorite are also present. Chlorite also occurs as very small irregular grains within the varioles.

Quartz occurs as small irregular amygdules near the upper areas of the section, within the chlorite and actinolite matrix.

Calcite is present in grains and amygdules generally less than 1.0 mm in diameter. Most of the calcite is concentrated near the bottom of the slide, where the larger grains are located.

Epidote occurs as fine grains and fracture fillings throughout the slide.

Clinozoisite is rare. Very few grains (0.2 mm in diameter) occur within the section.

Opaque minerals are very sparse, few hematite grains were detected in local areas within the slide.

E1-4A

Modal Percentage (Approximate)

Albite:	55%
Actinolite:	20%
Calcite:	13%
Chlorite:	10%
Quartz:	1%
Epidote:	tr

Texture: Most of the albite occurs in the varioles of the core. Albite also occurs in a cavity filling (large amygdule?) and as rare amygdules.

The actinolite grains occur throughout the slide in grains that are 0.4 mm long. Most grains have length:width ratios of 7:1, except for the very fine needle-like grains. Many grains were frayed at the edges and often showed crystal impurities. All actinolite grains are randomly oriented.

Highly irregular calcite grains ranging in size from 0.2 to 1.2 mm in diameter are dispersed throughout the section. Calcite also occurs in cavity fillings.

Chlorite exists as small anhedral grains 0.1 mm in diameter within the vesicles and as patches 0.5 mm across. Chlorite is also found in small, rare amygdules.

Quartz exists in very few small amygdules.

Epidote is sparsely distributed within the section, it generally occurs as small grains 0.2 mm in diameter $\bar{c}$ in veins.

E16-1B

Modal Percentage (Approximate)

Albite:	20%
Actinolite:	50%
Chlorite:	20%
Calcite:	3%
Clinozoisite:	3%
Quartz:	2%
Epidote:	1%

Texture: Albite occurs in rounded and oval amygdules 1.5 mm in diameter throughout most of the section. It also rims chlorite amygdules and fracture fillings. Much of the albite is found near the bottom of the section, appearing as a diffuse mass, similar in some ways to varioles.

The actinolite content is high in the thin section except near the bottom. The grains increase in size from 1.0 mm (dia) in the upper part of the section to 2.0 mm in the lower areas of the slide. The actinolite grains at the bottom of the thin section have higher length:width ratios than the grains in the upper areas. Only the actinolite grains in the lower areas of the section show crystal impurities or imperfections. The actinolite grains are usually oriented tangential to the amygdules and larger grains within the section.

Chlorite appears in dispersed amygdules (0.2 to 1.0 mm dia) and as distinct grains, few of which have relatively straight boarders. Large amygdules are distinguished from chlorite grains by the presence of zones of impurities within the chlorite masses. The chlorite amygdules in the upper portions of the section are often rimmed with albite.

Calcite occurs in irregular grains 0.6 mm in diameter, dispersed throughout the section and as a cavity or vein filling.

Clinozoisite occurs as anhedral and subhedral (tabular) grains 0.4 mm long and are dispersed throughout the slide, more commonly located near the bottom of the section.

Quartz occurs in small amygdules often rimmed with chlorite.

Epidote exists in trace amounts as small, dispersed anhedral grains.

E16-2B

Modal Percent (Approximate)

Albite:	29%
Actinolite:	35%
Chlorite:	25%
Calcite:	10%
Quartz:	1%
Epidote:	trace
Clinozoisite:	trace

Texture: Albite occurs mainly within varioles which first appear at the top of the section. Albite also occurs in few oval amygdules ranging in size from 0.5 to 1.5 mm in diameter. The varioles increase in size from 1.5 to 3.0 mm from the top of the section to the bottom, but do not coalesce.

Actinolite occurs within the matrix and in the varioles. The actinolite grains are generally larger in the matrix and show evidence of crystal imperfections or inclusions. The actinolite grains do not exceed 0.4 mm in length. Actinolite also occurs in a branching form within the varioles and around amygdules near the bottom of the slide. This form of actinolite grain is associated with highly frayed elongate grains.

Chlorite occurs as interstitial material within the actinolite matrix and as irregular and hexagonal grains ranging in size from 0.5 to 2.5 mm in diameter, in the upper portions of the section. Chlorite grains are occasionally found within the outer edges of varioles.

Calcite occurs as irregular grains and in amygdules ranging in size from 0.5 to 1.5 mm in diameter. Most of the calcite is concentrated towards the bottom of the section.

Quartz occurs near the bottom of the section in few varioles 1.2 mm in diameter.

Clinozoisite and Epidote occur as small anhedral grains 0.1 mm in diameter, scattered throughout the section.

E16-3B

Modal Percent (Approximate)

Albite:	30%
Actinolite:	40%
Calcite:	12%
Chlorite:	15%
Quartz:	3%
Clinozoisite:	trace
Opaques:	trace

Texture: Most of the albite occurs as coalesced varioles 0.5 to 2.5 mm in diameter. Few albite amygdules are also present. The radial extinction patterns characteristic to varioles is not easily seen.

Much of the actinolite in this slide was present in the form of frayed and branched grains. The elongate grains present within the thin section are highly frayed. The branching form of actinolite is usually present within or around separate varioles and amygdules.

Calcite is most abundant in the lower parts of the section, occuring as anhedral grains and rounded amygdules. The size of the calcite masses ranged from 0.5 to 3.0 mm in diameter.

Chlorite occurs within the coalesced varioles as small anhedral grains 0.1 mm (dia) and as parts of amygdules with albite.

Few small amygdules of quartz 1.0 mm in diameter exist within the section. Quartz also occurs with chlorite in hexagonal grains up to 1.5 mm long.

Clinozoisite is scarce within the thin section, one subhedral grain 0.7 mm long was the largest grain recognized.

Opaque grains (hematite) are found within the section in trace amounts. Another anhedral opaque mineral was also detected.

E26-1C

Modal Percent (Approximate)

Actinolite:	60%	Epidote:	5.0%
Albite:	17%	Quartz:	0.5%
Antigorite:	10%	Clinozoisite:	0.5%
Chlorite:	7%	Opaques:	trace

Texture: Most of this thin section is composed of actinolite as elongate grains 0.2 mm long. The grains generally have a low length:width ratio of 5:1. There seems to be a slight increase in grain size towards the bottom of the slide. There is no evidence of grain imperfections or inclusions. Actinolite grains within the varioles at the bottom of the section are generally much smaller and have higher length:width ratios than grains in the matrix.

Albite is present near the bottom of the section in the form of small varioles 0.5 mm in diameter.

Antigorite occurs in patches often bounded by polygonal boarders. The grains or patches of grains vary from 0.5 to 3.0 mm in length. The actinolite patches are rimmed with a finely divided dork mineral (leucoxene?) and then by an outer rim of closely spacedepidote. Antigorite occasionally has a chloritic core. Antigorite grains in the areas near the varioles are often invaded by actinolite grains.

Chlorite is present as anhedral grains or amygdules ranging in size from 0.5 to 2.0 mm in diameter. Chlorite also occurs as a minor component present in the interstitial spaces between actinolite grains in the matrix.

Epidote appears throughout most of the thin section as anhedral grains 0.4 mm in diameter and as fracture fillings. Epidote is less concentrated near the bottom of the section.

Clinozoisite is rare, occuring as tabular grains 0.2 mm long, in fracture fillings and dispersed throughout the matrix.

Quartz occurs in small amygdules.

Trace amounts of hematite in the form of subhedral grains were also recognized.

E26-2C

Modal Percent (Approximate)

Actinolite:	65%	Epidote:	3%
Albite:	23%	Quartz:	0.5%
Chlorite:	5%	Opaques:	trace
Antigorite:	3%	Clinozoisite:	trace

Texture: Actinolite occurs as elongate grains 0.3 mm long. No evidence of grain impurities or imperfections are evident. There is a subtle orientation of actinolite grains tangential to the variole boarders.

Albite occurs as "fine grained" varioles ranging in size from 0.5 to 2.0 mm in diameter. The varioles first occur in the upper areas of the slide and increase in size and number towards the bottom of the slide. These varioles are different from all of the others observed in that they have a fine texture (mosaic), and few show radial extinction patterns. Most varioles have extinction patterns which are limited to undulations in a diffuse, fan-like manner. Varioles opposite one another can show either complete radial extinction, or the more diffuse extinction patterns. The varioles may have more than one set of fan-like extinction patterns. The varioles begin to coalesce at the bottom of the slide.

Chlorite forms irregular grains and amygdules ranging in size from 0.5 to 3.0 mm in diameter. Chlorite also occurs in the actinolite matrix, cavity fillings and as small blebs within varioles.

Antigorite grains are present at the top of the section. The mineral often occurs with hexagonal forms. Dark, finely divided granules exist as a rim around the antigorite. Larger antigorite grains are often heavily included by actinolite, especially in the zone in which the varioles appear.

Epidote exists as small anhedral grains (0.1 1.0 mm dia). Euhedral grains are found within cavity fillings.

Clinozoisite is present in trace amounts as small tabular grains dispersed throughout the section.

Quartz is very minor, occurs in one grain 1 mm long.

Traces of hematite are present within the section as well.

E26-3C

Modal Percent (Approximate)

Albite:	55%
Actinolite:	20%
Epidote:	12%
Chlorite:	5%
Calcite:	7%
Quartz:	0.5%
Clinozoisite:	trace

Texture: Albite is present within the variolites, which coalesce completely in the upper part of the section. Radial extinction patterns can be observed within the varioles but they appear to be cloudy.

Actinolite forms grains 0.4 mm long and commonly have length:width ratios of 10:1. Many of the grains have frayed edges.

Calcite forms anhedral grains and rounded amygdules ranging in size from 0.5 to 1.5 mm in diameter. Calcite is concentrated in the lower areas the section (in the core), where it forms highly irregular masses.

Epidote occurs in the middle and lower portions of the slide. The grain size generally increases towards the bottom of the section. The range in grain size is high (0.1 to 0.7 mm dia). The grains are either anhedral or tabular.

Chlorite is found in small irregular patches and as hexagonal grains ranging in size from 0.5 to 1.2 mm in length. Much of the chlorite occurs as small blebs within the variole.

Quartz and clinozoisite are trace constituents, quartz occurs in small rounded grains and clinozoisite forms small tabular crystals.

E26-4C

Modal Percent (Approximate)

Albite:	50%
Calcite:	20%
Actinolite:	15%
Epidote:	12%
Chlorite:	3%
Opaques:	tr

Texture: Albite occurs only within the coalesced varioles in the core.

Calcite forms highly irregular grains (3 mm dia. max.) dispersed throughout the section.

Actinolite is present in highly frayed grains generally 0.3 mm in length. It is rather sparse in the thin section since it occurs only within the varioles.

Epidote occurs as anhedral grains (0.1 - 1.0 mm dia.) and in fracture fillings. It is evenly distributed throughout the section.

Chlorite exists only as small patches within the varioles.

Few hematite grains were seen in the slide as well.

E29-1D

Modal Percent

Actinolite:	60%
Chlorite:	20%
Clinozoisite:	11%
Calcite:	5%
Albite:	3%
Quartz:	0.5%

Texture: The actinolite grains in the thin section are small, generally 1.0 mm long. The length:width ratios of the grains are very low, ranging from 2:1 in the upper areas and increasing to 5:1 in the lower areas of the slide. The actinolite grains in the lower section of the slide appear to contain inclusions or impurities.

Chlorite occurs in grains and amygdules ranging in size from 0.5 to 1.5 mm in diameter. Many of the grains are irregular and elongate in form. Chlorite also exists as interstitial material between the actinolite grains in the matrix.

Clinozoisite grains 0.1 mm in diameter are scattered throughout the section, but are generally more concentrated in the upper areas of the slide. Few larger grains (0.3 mm dia.) are present in the lower areas of the slide. The grains are either anhedral or subhedral (tabular), the larger subhedral grains are usually found with chlorite. Many of the grains appear to be altered.

Calcite occurs in anhedral grains and in subrounded amygdules ranging in size from 0.3 to 2.0 mm in diameter. Calcite is often found in amygdules which are partially composed of albite. Calcite is distributed throughout the thin section rather evenly.

Albite is present within the thin section in amygdules ranging in size from 0.5 to 2.0 mm dia. Albite is also found in the very diffuse varioles which first appear at the bottom of the section.

Quartz is a very minor component of the thin section, it occurs in few small amygdules usually rimmed by chlorite.

E29-2D

Modal Percent

Actinolite:	50%
Chlorite:	20%
Albite:	15%
Calcite:	12%
Clinozoisite:	2%
Quartz:	0.5%
Epidote:	0.5%

Texture: Actinolite appears within the matrix as elongate grains 0.4 mm long. Most grains are frayed and appear to have large inclusions. No change in grain size could be detected throughout the slide. The grains are oriented tangential to the boundaries of varioles, amygdules and large grains.

Chlorite is dispersed throughout the section in the form of anhedral grains 1.5 mm long. Oval shaped varioles 1.0 mm in diameter are also present in the section. Chlorite is also found in the matrix interstitial to actinolite, and as small rounded blebs within the varioles.

Most of the albite occurs within the varioles, which increase in size from 1.0 to 2.0 mm in diameter towards the bottom of the thin section. Extinction patterns within many of the varioles generally follow a fan shaped pattern. Commonly more than one fan shaped extinction pattern can be observed within one variole. Albite is also found in amygdules 1.5 mm in diameter.

Calcite is present in the form of rounded and ovoid amygdules (1.5 mm dia.), as small irregular grains (0.5 mm dia.) and as a vein filling material. Calcite is evenly distributed throughout the slide.

Clinozoisite grains are found throughout the section in the matrix and in the varioles with chlorite grains. The grains are anhedral or tabular in form and are generally 0.7 mm long.

Epidote is a minor component of the thin section, occuring in small anhedral grains throughout the slide.

Quartz occurs in few elliptical amygdules 0.7 mm long.

E29-3D

Modal Percent

Actinolite:	60%
Albite:	20%
Chlorite:	13%
Calcite:	6%
Quartz:	0.5%
Clinozoisite:	trace
Opaques:	trace

Texture: Actinolite forms elongate grains which are frayed at the edges and occasionally have inclusions or impurities. The length:width ratios are low, 3:1. Actinolite appears throughout the whole section and shows no gradational trends in form or size.

Albite is found in the form of coalesced varioles, very few of which have the radial extinction patterns characteristic of most varioles.

Chlorite occurs in irregular, elongate grains ranging in size from 1.0 to 4.0 mm in length.

Calcite is present in the form of irregular grains (0.5 to 1.0 mm dia) and as rounded amygdules (0.5 to 2.0 mm dia.). Most of the calcite is concentrated within the lower areas of the slide.

Quartz occurs within the upper half of the slide in small amounts as small rounded grains or amygdules 0.5 mm in diameter.

Clinozoisite is a very minor component of the thin section, occuring in tabular grains 0.2 mm long.

Traces of subhedral hematite grains were detected in the thin section as well.

E30-1E

Modal Percent

Actinolite:	75%
Chlorite:	12%
Albite:	5%
Quartz:	3%
Calcite:	2%
Clinozoisite:	2%
Epidote:	0.5%

Texture: Actinolite appears within the matrix of the thin section as thick tabular grains. The grains increase in size from 0.2 mm long in the upper areas to 0.3 mm long in the lower areas. The length:width ratios of the actinolite grains also increase towards the bottom of the slide. Grain inclusions are absent in the actinolite minerals of the section.

Chlorite is present throughout the slide in the form of rather small anhedral grains (0.5 mm. dia.) and as amygdule rims.

Albite is found throughout the thin section in rounded amygdules, 1.0 mm in diameter.

Quartz forms small amygdules or grains (0.75 mm dia.)

Calcite is found throughout the section as sub-rounded grains or amygdules 0.5 to 1.0 mm in diameter.

Anhedral and subhedral grains of epidote and clinozoisite are found concentrated in the upper areas of the slide.

E30-2E

Modal Percent

Actinolite:	65%
Chlorite:	17%
Albite:	15%
Quartz:	2%
Calcite:	0.5%
Opaques:	trace

Texture: Actinolite forms elongate grains (0.3 mm long) in the upper half of the section within the matrix. These grains often have large inclusions within them. The actinolite in the lower half of the section occurs in fan like forms.

Chlorite is present throughout the thin section in anhedral grains (2.0 mm long). Few of the grains seem to be fractured and filled with actinolite and albite. Small patches of chlorite (0.2 mm dia) are also distributed throughout the entire section.

Albite occurs in varioles and in amygdules generally 0.5 mm in diameter. The amygdules first appear at the top of the section and increase in size (1.0 to 2.0 mm dia) and number into the centre of the section, where they eventually coalesce. Lesser amounts of albite can be clearly identified in the lower areas of the section, within the core.

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Quartz appears near the bottom of the slide in small rounded grains 1.0 mm in diameter.

Calcite is a minor constituent of the section, and is found dispersed throughout the slide in the form of irregular grains 1.0 mm in diameter.

Traces of opaque minerals were also found, the minerals were small and anhedral in form.

E30-3E

Modal Percent

Actinolite:	60%	Quartz:	3%
Chlorite:	20%	Epidote:	0.5%
Albite:	13%	Clinozoisite:	0.5%
Calcite:	3%	Opaques:	trace

Texture: Actinolite is abundant throughout the section as elongate grains, generally 0.2 mm long. Many of the grains have inclusions or impurities. The mineral also occurs in branching forms, commonly surrounding chlorite and albite grains and cavity fillings.

Chlorite occurs in subangular and elongate grains ranging in size from 1.0 to 2.5 mm long. There is no trend in the grain size within the thin section. Several grains are fractured and are often filled with albite. Small patches of chlorite (0.2 mm dia) also occur within the section.

Albite occurs as small, elongate grains, as fracture fillings and as a diffuse matrix.

Calcite is present in the form of small, anhedral grains (0.5 mm dia) scattered throughout the thin section. Larger grains are found within cavity fillings.

Quartz is occasionally found in grains with chlorite and as cavity fillings.

Clinozoisite and epidote occur in cavity fillings.

Opaque minerals are present in trace amounts as small anhedral grains, associated with epidote in cavity fillings. Hematite is the major opaque mineral.

Bulk Chemistry (Normalized)

	E1	E16	E26	E29	E30
SiO_2	51.55	56.99	55.98	53.32	53.78
Al_2O_3	12.28	10.48	12.33	10.54	11.10
Fe_2O_3	2.11	1.61	2.15	1.95	1.82
FeO	6.87	6.21	5.15	6.33	6.72
MgO	12.09	11.80	8.84	12.77	13.20
CaO	7.05	6.50	7.64	7.88	7.26
Na_2O	3.05	3.28	4.29	2.73	2.42
K_2O	0.02	0.02	0.45	0.02	0.05
TiO_2	0.21	0.19	0.19	0.18	0.20
MnO	0.19	0.17	0.15	0.16	0.17
P_2O_5	0.02	0.02	0.03	0.02	0.02
Volatiles	4.52	2.73	2.70	4.08	3.27
	99.96%	100.00%	99.90%	99.98%	100.01%

Calculation of the Bulk Chemistry

E1 E1-SEL x 0.08 + (E1-1A + E1-2A + E1-3A) x $\frac{0.62}{3}$
+ E1-4A x 0.30

E16 (E16-1B x 3/7 + E16-2B x 3/7 + E16-3B x 1/7) x 0.70
+ E16-4B x 0.30

E26 (E26-1C x 6/15 + E26-2C x 7/15 + E26-3C x 2/15) x 0.60
+ (E26-3C x 1/4 + E26-4C x 3/4) x 0.40

E29 E29-SEL x 0.08 + (E29-1D x 5/13 + E29-2D x 8/13) x 0.62
+ E29-3D x 0.30

E30 E30-SEL x 0.08 + (E30-1E x 1/3 + E30-2E x 2/3) x 0.62
+ E30-3E x 0.30

Assumptions: Selvedge 8% of the total volume of the pillow.
I.Z. 60-70% of the total volume of the pillow.
Core 30-40% of the total volume of the pillow.

Sample Chemistry (Normalized)

	E1-SEL	E1-1A	E1-2A	E1-3A	E1-4A
SiO_2	44.07	49.09	47.04	53.43	57.05
Al_2O_3	19.24	10.43	10.97	13.23	11.95
Fe_2O_3	7.43	1.81	1.75	1.93	1.28
FeO	2.99	8.03	10.17	6.03	5.40
MgO	8.01	14.00	17.15	11.12	9.03
CaO	10.27	9.03	6.43	5.55	6.29
Na_2O	1.91	2.05	1.39	4.29	4.33
K_2O	0.02	0.10	0.02	0.02	0.01
TiO_2	0.26	0.19	0.27	0.18	0.19
MnO	0.16	0.21	0.26	0.17	0.15
P_2O_5	0.04	0.03	0.03	0.00	0.02
Volatiles	5.56	4.97	4.49	4.08	4.27
	99.96%	99.94%	99.97%	100.03%	99.97%

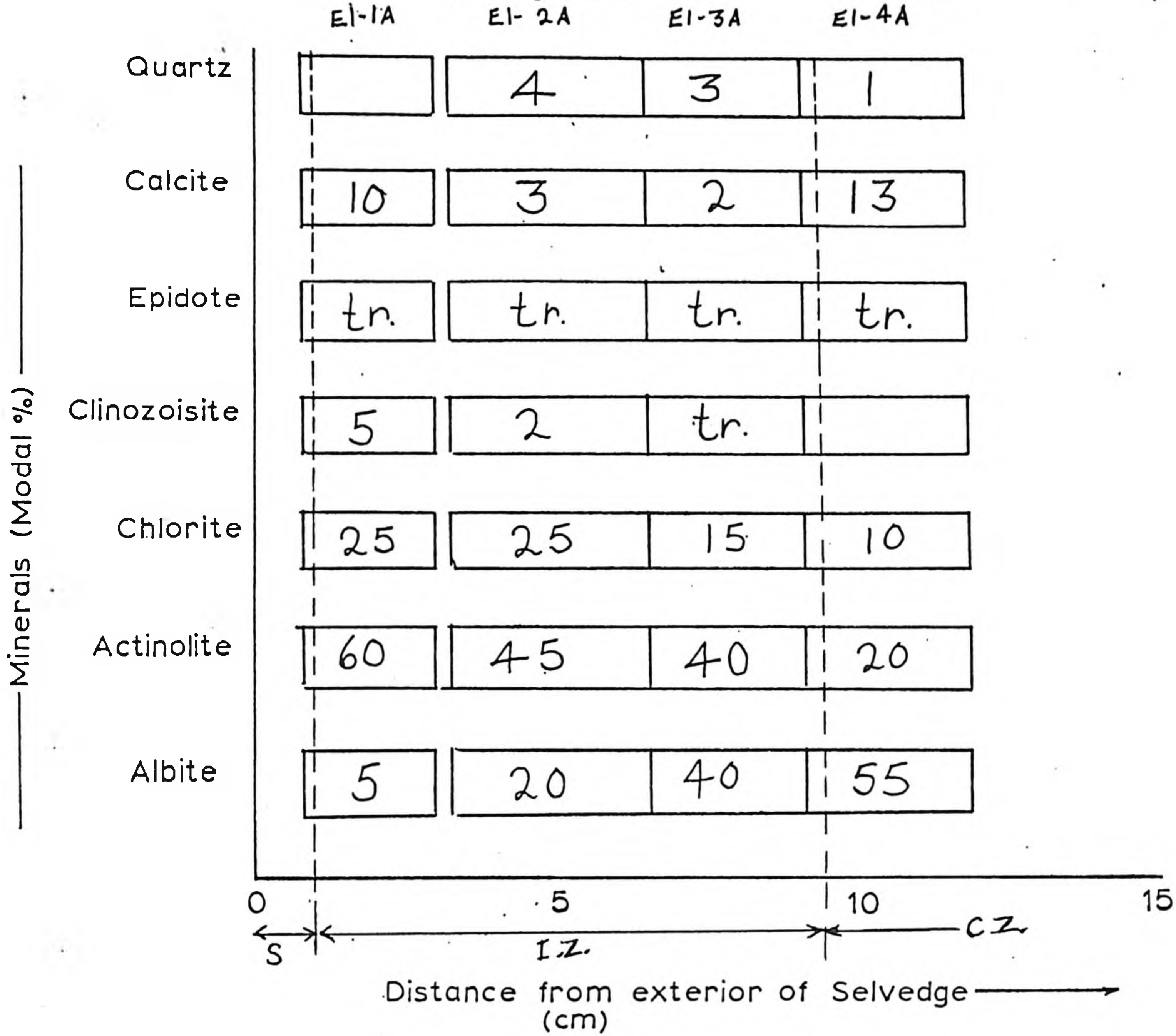
	E16-1B	E16-2B	E16-3B	E16-4B
SiO_2	61.03	60.03	49.62	52.36
Al_2O_3	10.43	10.93	12.02	9.57
Fe_2O_3	0.80	1.33	3.20	2.17
FeO	5.73	5.56	6.77	7.15
MgO	10.04	10.15	13.74	14.55
CaO	5.30	5.55	6.42	8.74
Na_2O	4.11	4.23	2.84	1.66
K_2O	0.01	0.01	0.01	0.02
TiO_2	0.18	0.18	0.21	0.19
MnO	0.15	0.15	0.19	0.20
P_2O_5	0.02	0.02	0.02	0.03
Volatiles	2.19	1.89	4.95	3.37
	99.99%	100.03%	99.99%	100.01%

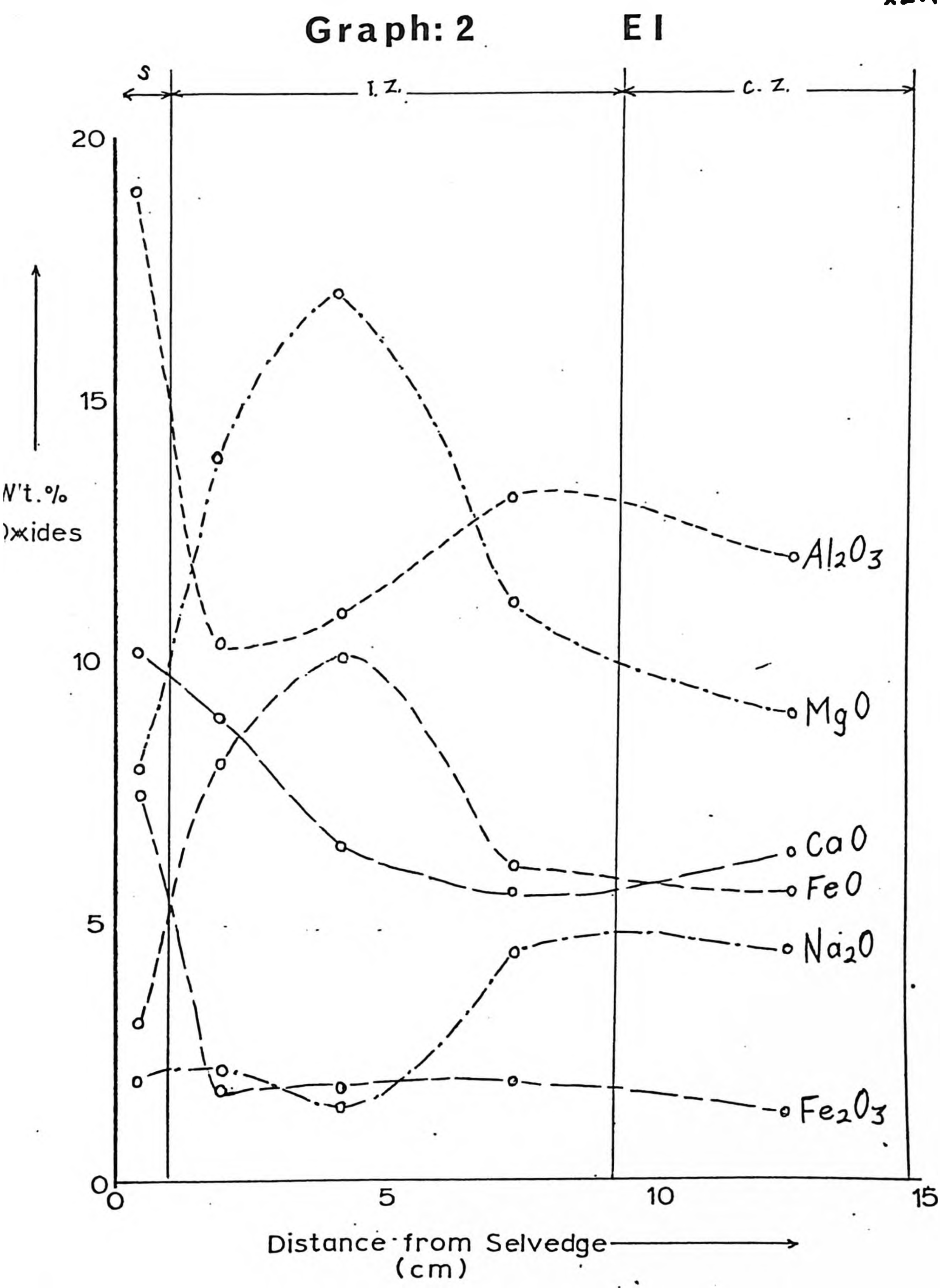
	E26-1C	E26-2C	E26-3C	E26-4C
SiO_2	49.01	60.54	57.82	56.18
Al_2O_3	10.51	10.51	15.00	13.89
Fe_2O_3	3.02	1.81	1.78	2.00
FeO	8.03	4.74	3.71	4.11
MgO	15.41	10.40	4.96	4.45
CaO	9.20	5.30	6.96	9.43
Na_2O	0.35	4.25	6.85	5.95
K_2O	1.64	0.01	0.28	0.02
TiO_2	0.21	0.18	0.17	0.20
MnO	0.22	0.14	0.11	0.12
P_2O_5	0.03	0.01	0.02	0.04
Volatiles	2.38	2.15	2.40	3.65
	100.00%	100.05%	100.06%	100.04%

	E29-SEL	E29-1D	E29-2D	E29-3D
SiO_2	48.69	50.43	51.54	59.10
Al_2O_3	17.02	7.74	10.68	10.85
Fe_2O_3	3.49	2.86	1.51	1.38
FeO	4.86	6.78	7.41	5.00
MgO	9.47	16.13	13.52	10.03
CaO	8.64	9.98	8.01	5.83
Na_2O	2.93	1.47	2.19	4.35
K_2O	0.01	0.02	0.02	0.02
TiO_2	0.24	0.16	0.19	0.18
MnO	0.15	0.21	0.20	0.15
P_2O_5	0.05	0.01	0.02	0.02
Volatiles	4.50	4.26	4.67	3.09
	100.05%	100.05%	99.96%	100.00%

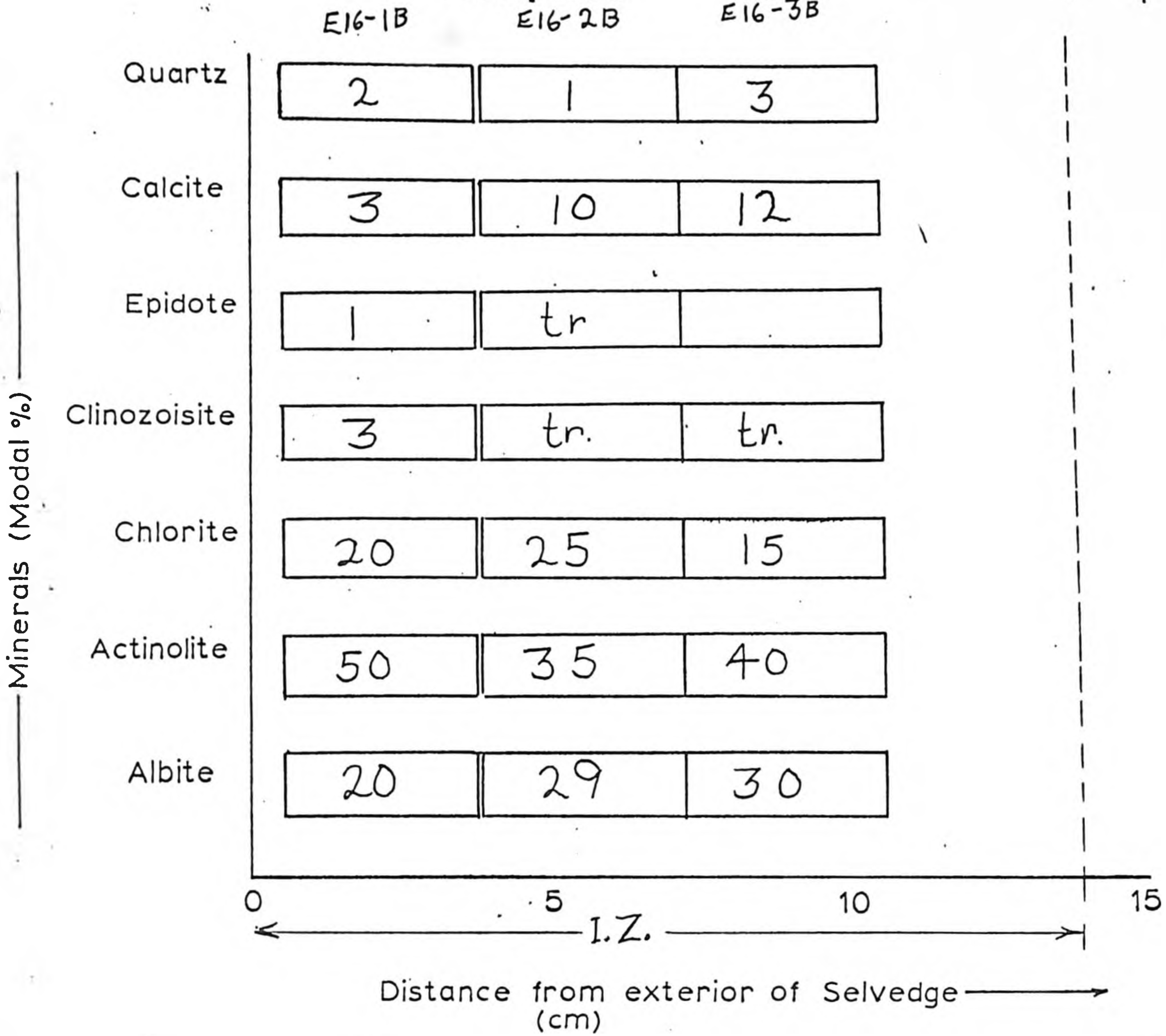
	E30-SEL	E30-1E	E30-2E	E30-3E
SiO_2	47.89	51.95	54.11	56.16
Al_2O_3	18.30	9.23	11.05	10.52
Fe_2O_3	6.61	2.43	1.25	0.92
FeO	1.84	6.90	7.39	6.98
MgO	3.80	15.08	13.77	13.62
CaO	16.14	8.77	5.76	5.91
Na_2O	0.08	1.60	3.13	2.63
K_2O	0.01	0.01	0.02	0.14
TiO_2	0.19	0.17	0.19	0.23
MnO	0.11	0.19	0.18	0.17
P_2O_5	0.05	0.02	0.01	0.01
Volatiles	5.03	3.65	3.17	2.66
	100.05%	100.00%	100.03%	99.95%

Graph: I E1

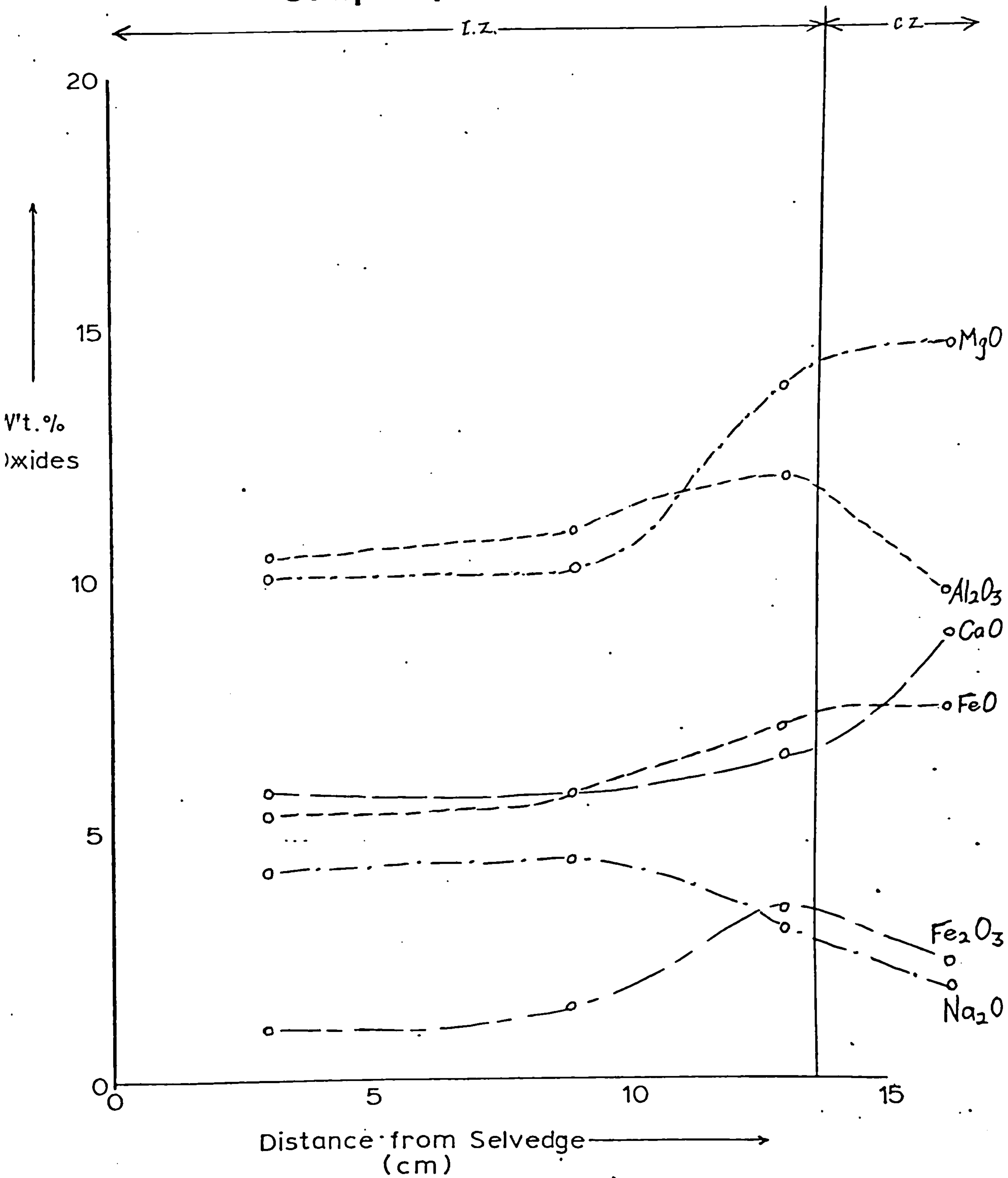

E1-1A
E1- 2A
E1-3A
E1-4A
Quartz
4
3
1
Calcite
10
3
2
13
Epidote
tr.
tr.
tr.
tr.
Clinozoisite
5
2
tr.
Chlorite
25
25
15
10
Actinolite
60
45
40
20
Albite
5
20
40
55
Minerals (Modal %)
0
5
10
15
S
I.Z.
C.Z.
Distance from exterior of Selvedge
(cm)


Graph: 2
E I
S
I. Z.
C. Z.
20
15
10
5
0
W't.%
Oxides
Al_2O_3
MgO
CaO
FeO
Na_2O
Fe_2O_3
0
5
10
15
Distance from Selvedge
(cm)

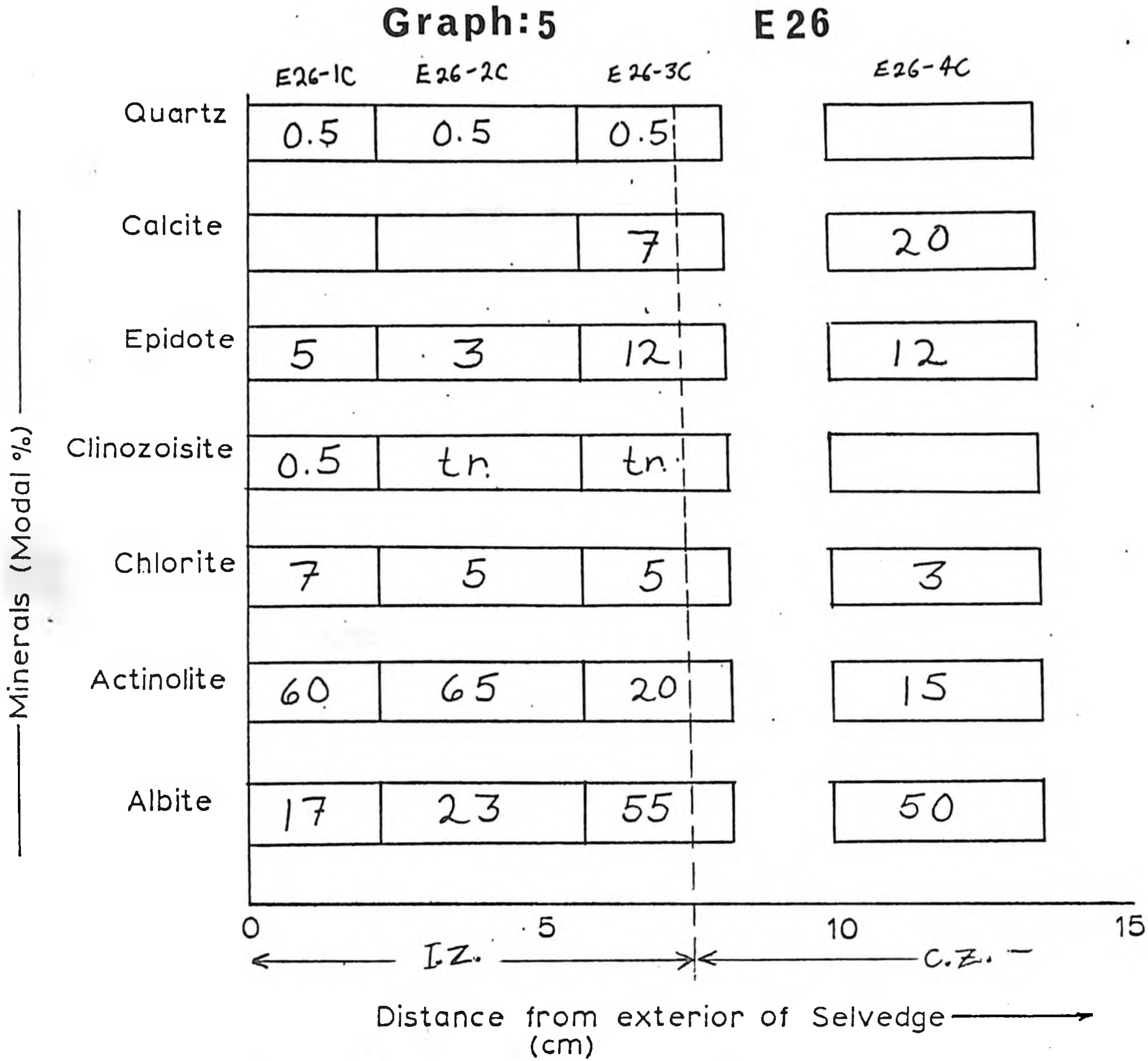
Graph:3 E16


E16-1B
E16-2B
E16-3B
Quartz
2
1
3
Calcite
3
10
12
Epidote
1
tr
Clinozoisite
3
tr.
tr.
Chlorite
20
25
15
Actinolite
50
35
40
Albite
20
29
30
Minerals (Modal %)
0
5
10
15
I.Z.
Distance from exterior of Selvedge
(cm)

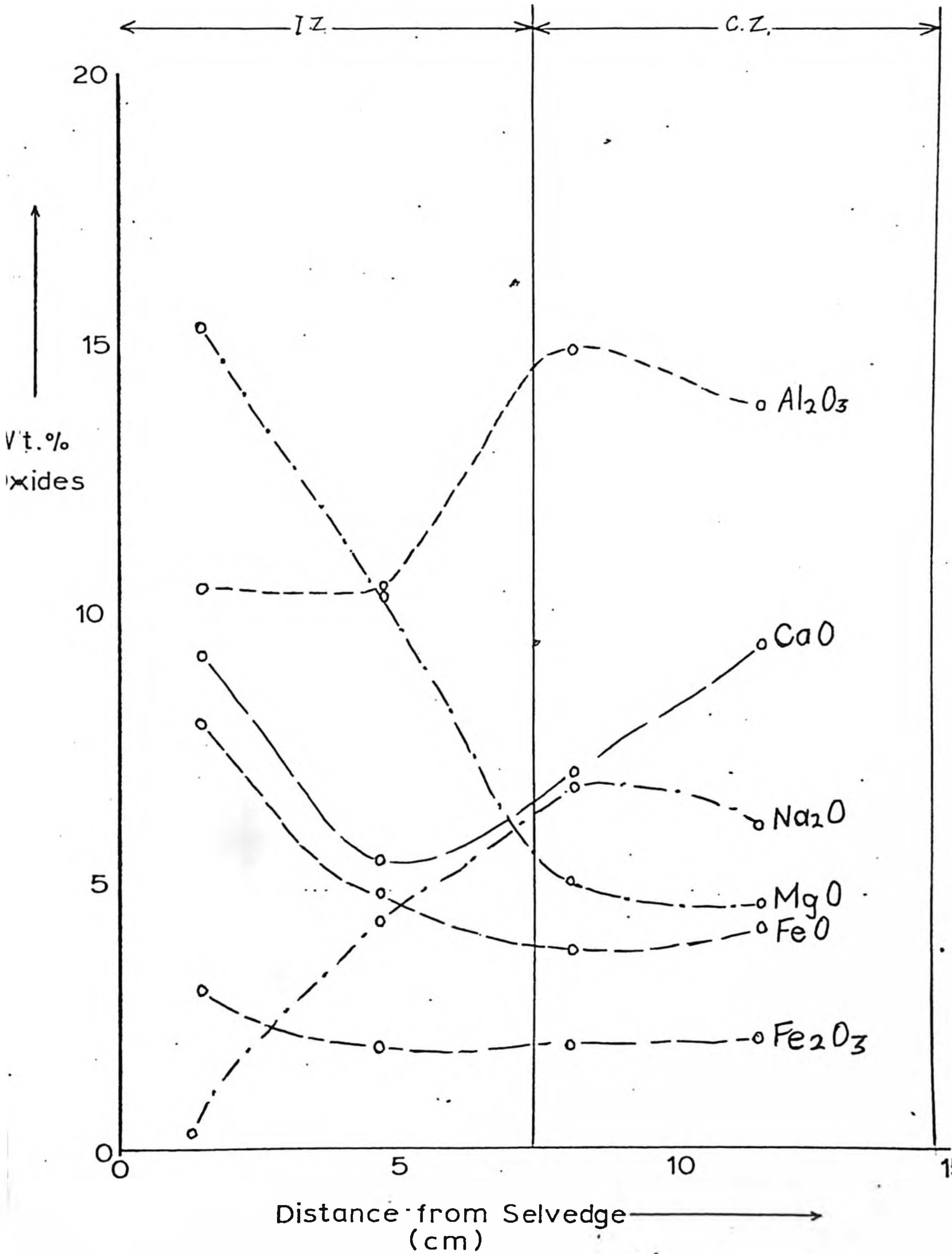
Graph: 4 E 16



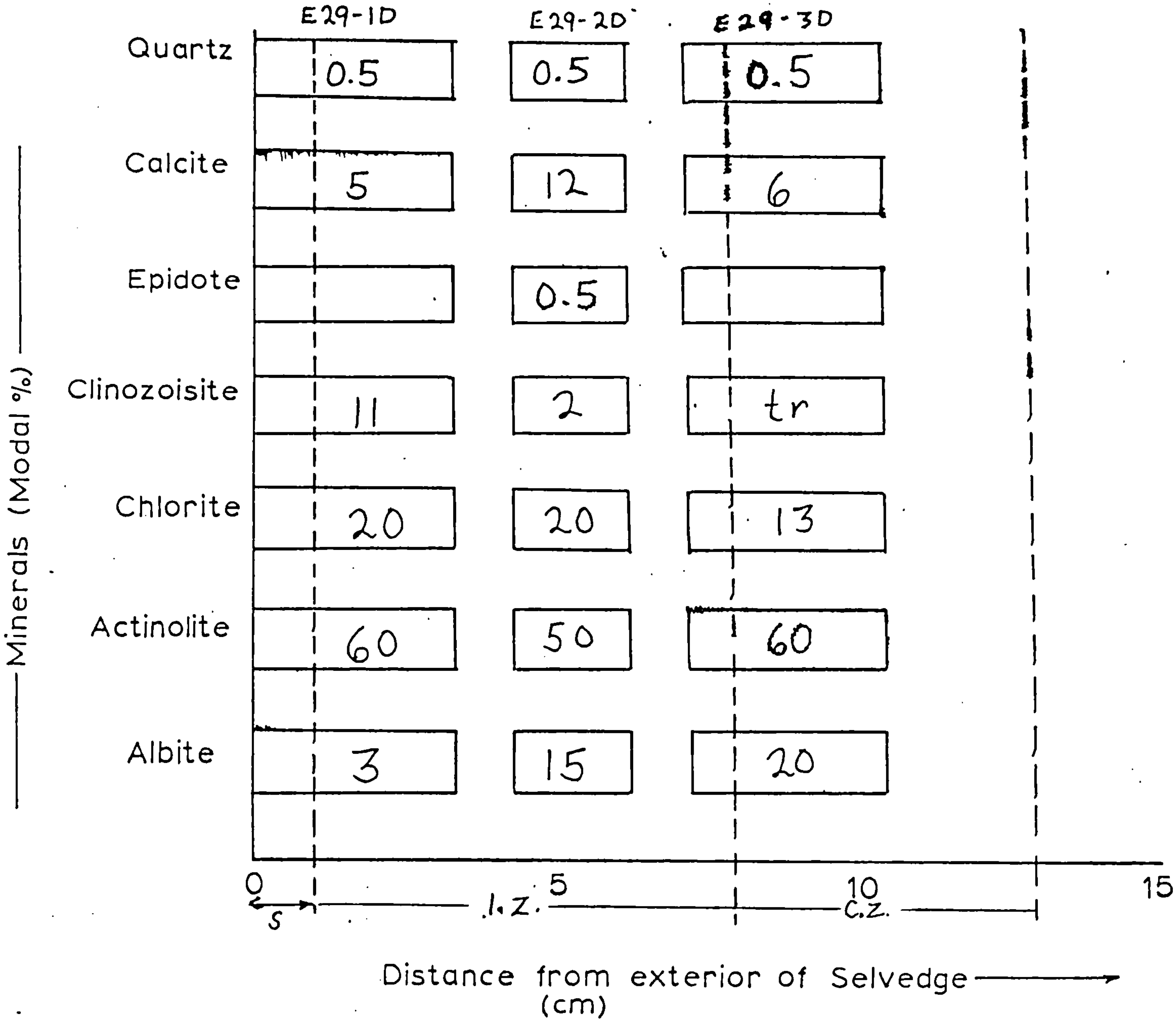
I.Z.
C Z
20
15
10
5
0
V't.%
)xides
MgO
Al_2O_3
CaO
FeO
Fe_2O_3
Na_2O
0
5
10
15
Distance from Selvedge
(cm)


Graph:5
E 26
E26-1C
E26-2C
E26-3C
E26-4C
Quartz
0.5
0.5
0.5
Calcite
7
20
Epidote
5
3
12
12
Clinozoisite
0.5
tr.
tr.
Chlorite
7
5
5
3
Actinolite
60
65
20
15
Albite
17
23
55
50
Minerals (Modal %)
0
5
10
15
I.Z.
C.Z.
Distance from exterior of Selvedge
(cm)

Graph: 6 E26

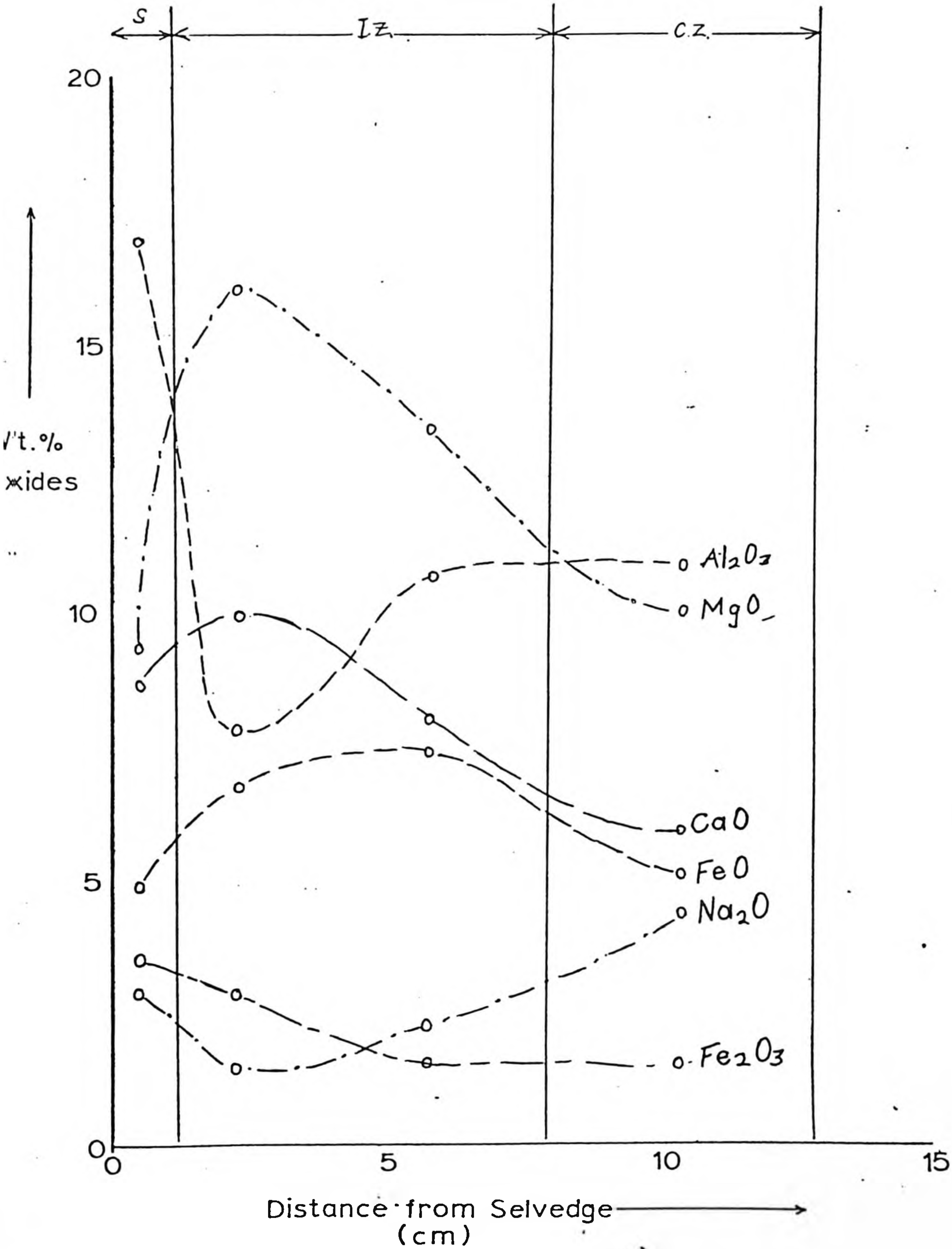

I.Z.
C.Z.
20
15
10
5
0
Wt.%
Oxides
Al2O3
CaO
Na2O
MgO
FeO
Fe2O3
0
5
10
15
Distance from Selvedge
(cm)

Graph: 7 E 29



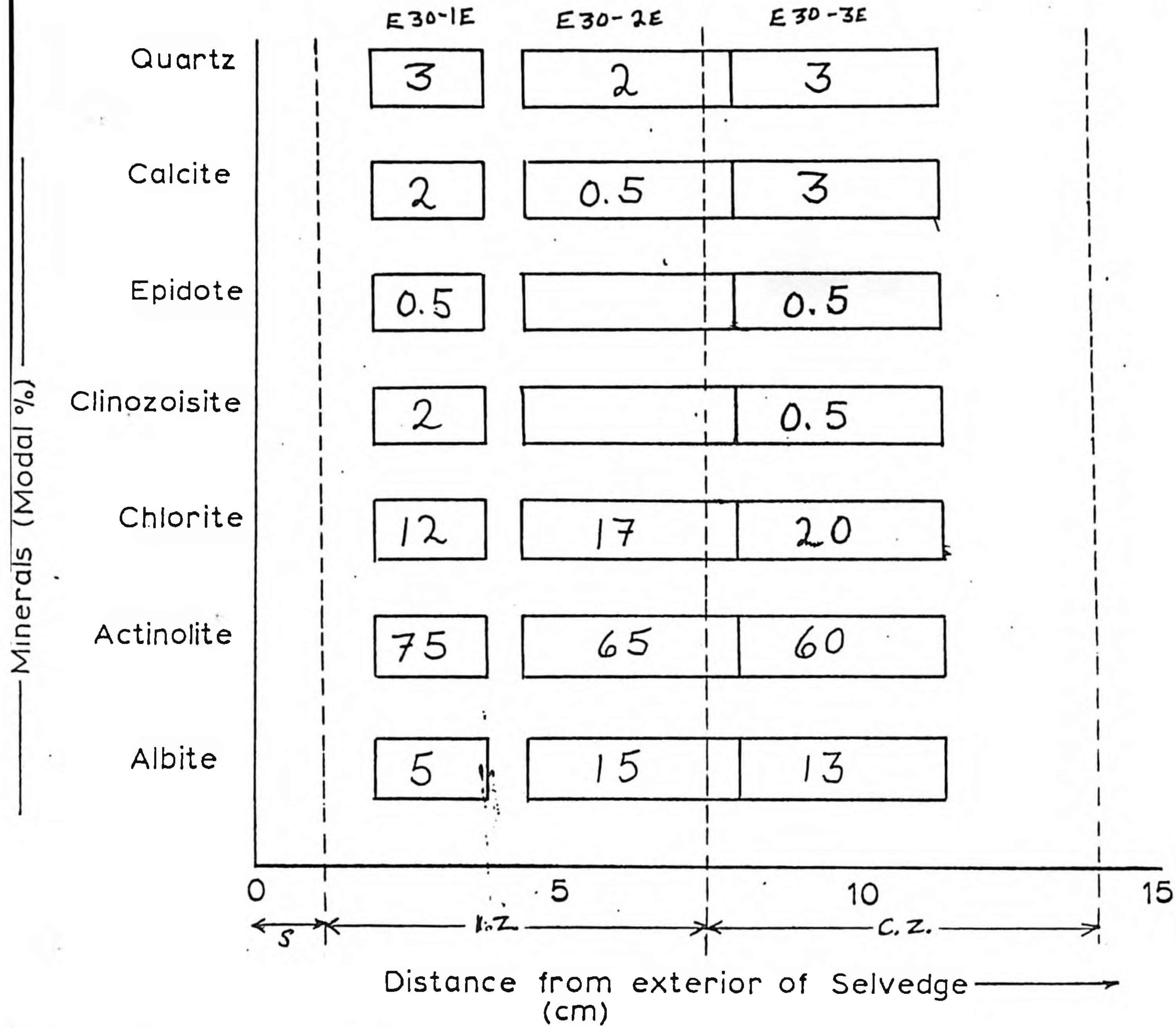
E29-1D
E29-2D
E29-3D
Quartz
0.5
0.5
0.5
Calcite
5
12
6
Epidote
0.5
Clinozoisite
11
2
tr
Chlorite
20
20
13
Actinolite
60
50
60
Albite
3
15
20
Minerals (Modal %)
0
5
10
15
S
I.Z.
C.Z.
Distance from exterior of Selvedge (cm)

Graph: 8 E 29

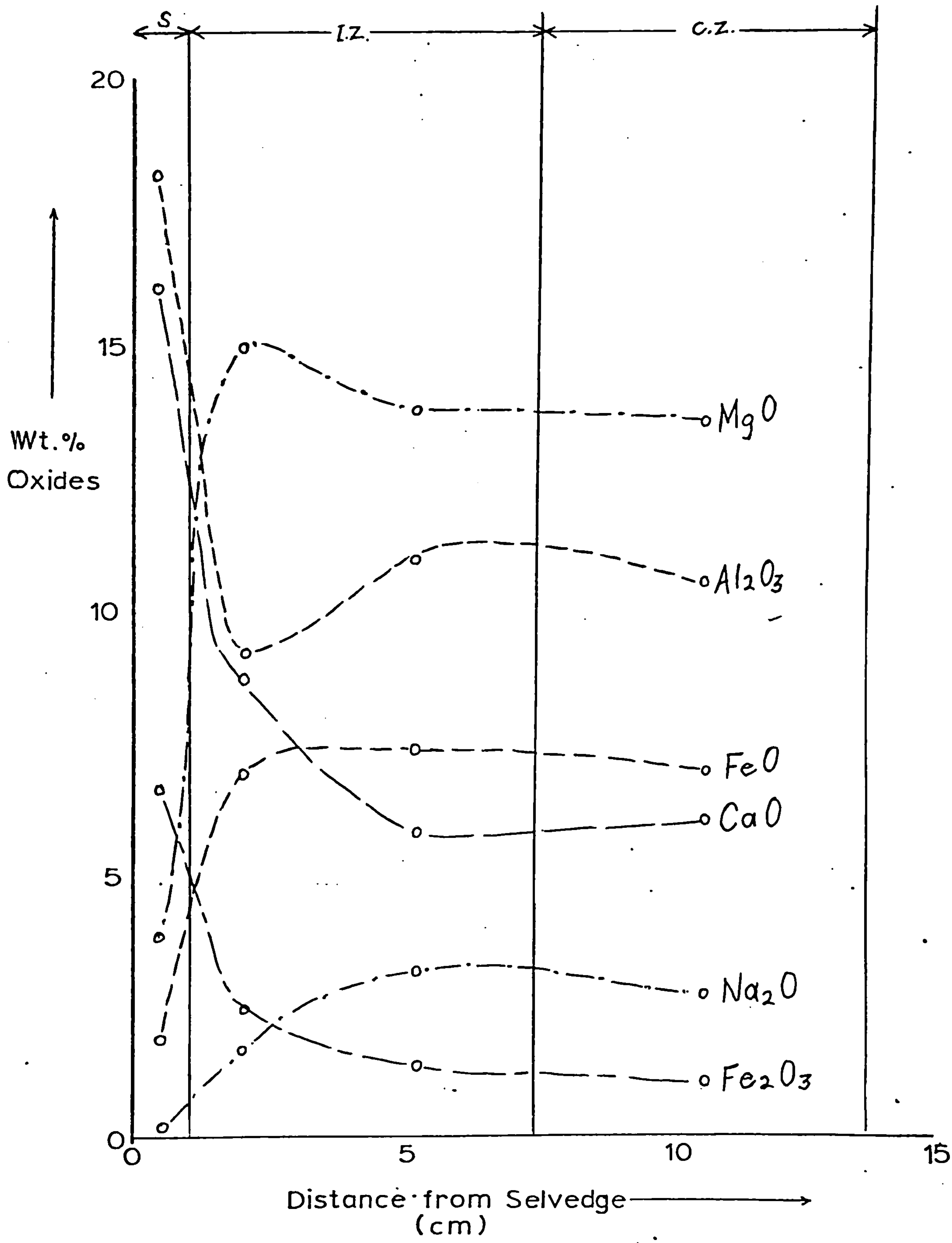


S
I.Z.
C.Z.
20
15
10
5
0
Wt.%
oxides
Al2O3
MgO
CaO
FeO
Na2O
Fe2O3
0
5
10
15
Distance from Selvedge
(cm)

Graph: 9 E30


E30-1E
E30-2E
E30-3E
Quartz
3
2
3
Calcite
2
0.5
3
Epidote
0.5
0.5
Clinozoisite
2
0.5
Chlorite
12
17
20
Actinolite
75
65
60
Albite
5
15
13
Minerals (Modal %)
0
5
10
15
S
I.Z.
C.Z.
Distance from exterior of Selvedge
(cm)

Graph:10 E 30


S
I.Z.
C.Z.
20
15
10
5
0
Wt.%
Oxides
MgO
Al2O3
FeO
CaO
Na2O
Fe2O3
0
5
10
15
Distance from Selvedge
(cm)

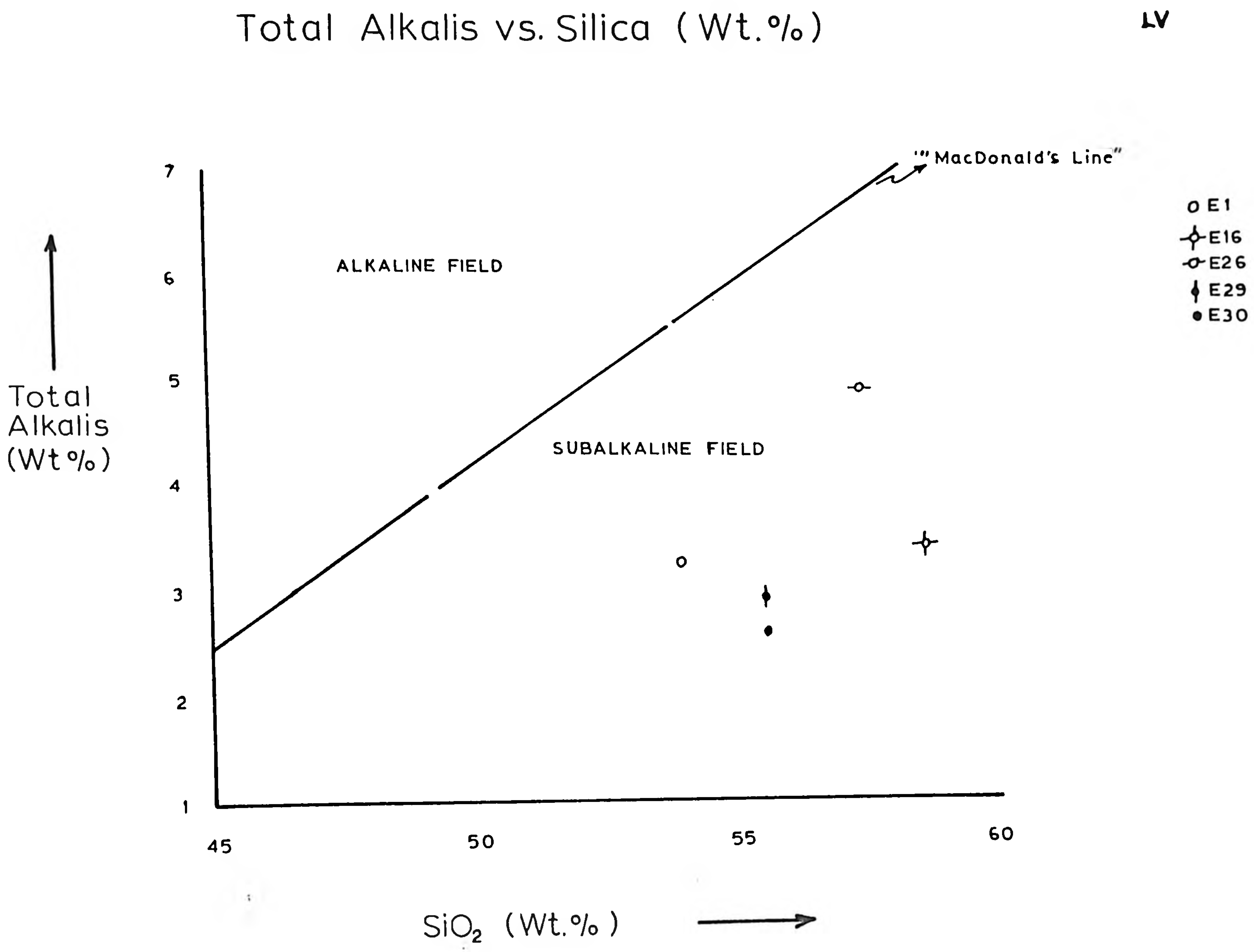
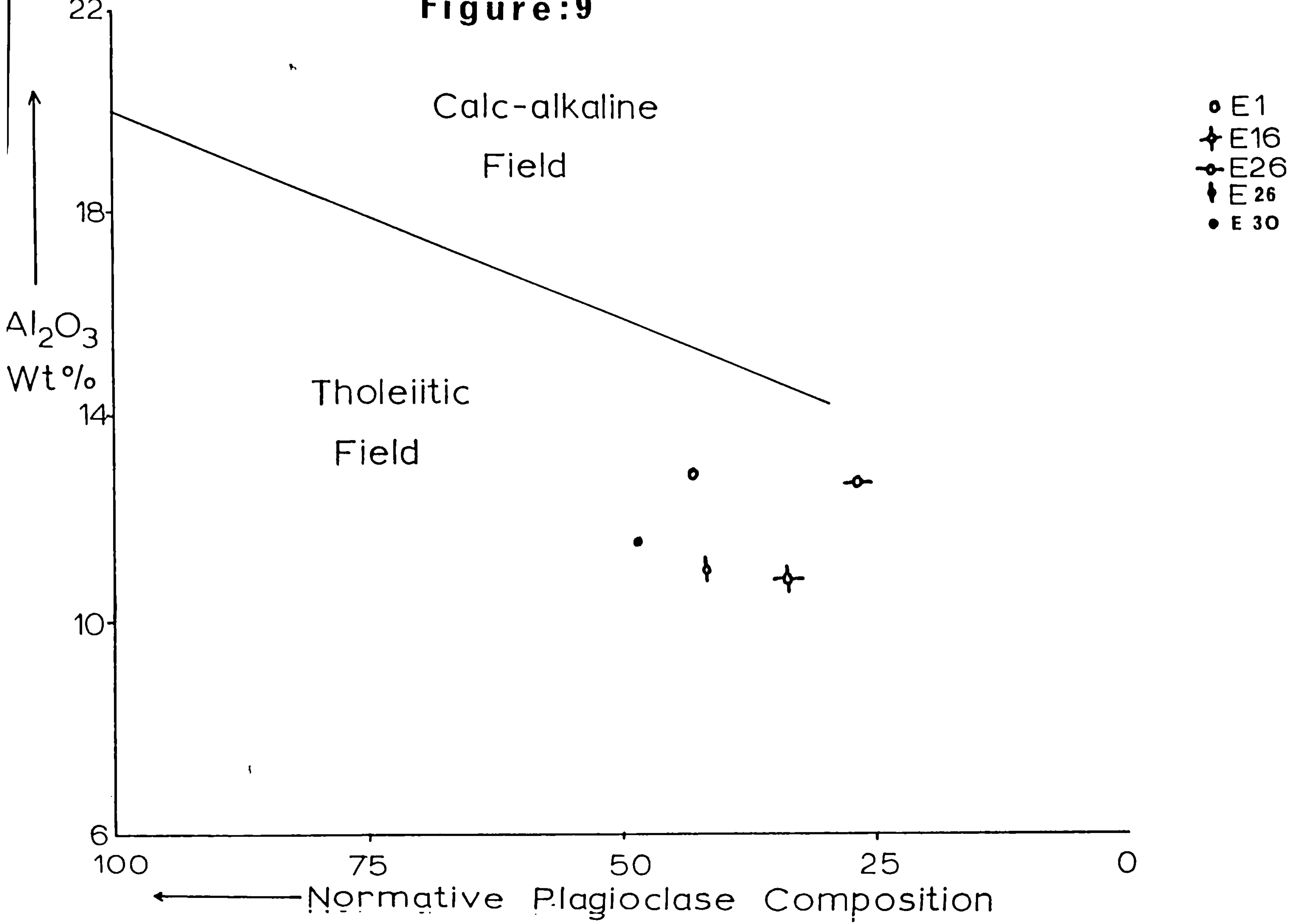

Total Alkalis vs. Silica (Wt.%)
"MacDonald's Line"
ALKALINE FIELD
SUBALKALINE FIELD
Total Alkalis (Wt %)
SiO2 (Wt.%)
7
6
5
4
3
2
1
45
50
55
60
E1
E16
E26
E29
E30

Figure: 8

Figure:9


Calc-alkaline
Field
Tholeiitic
Field
Al_2O_3 Wt%
22
18
14
10
6
100
75
50
25
0
Normative Plagioclase Composition
E1
E16
E26
E 26
E 30

AFM Plot

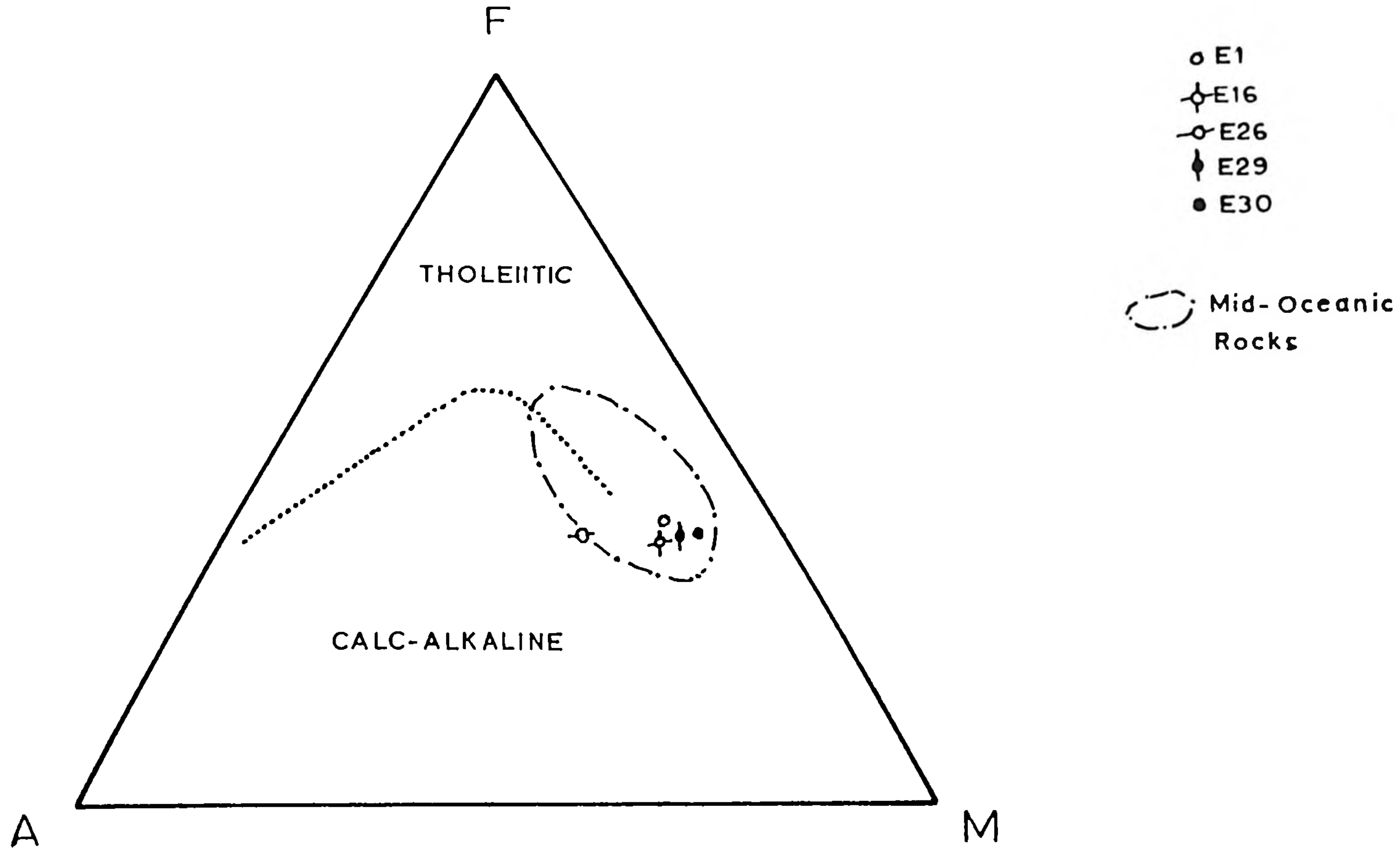
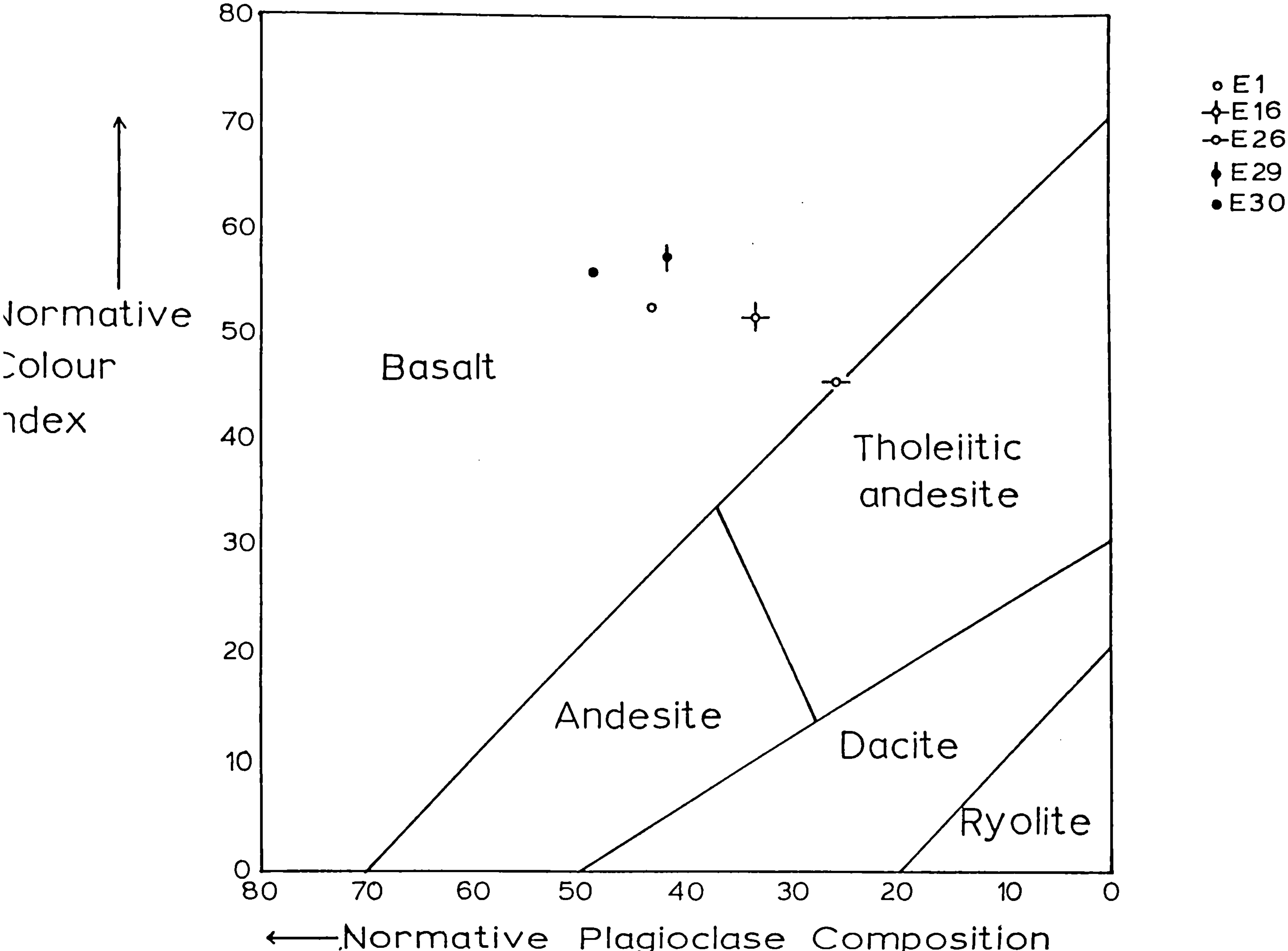


Figure: 10

Figure: 11



80
70
60
50
40
30
20
10
0
80
70
60
50
40
30
20
10
0
Normative
Colour
Index
Normative Plagioclase Composition
Basalt
Tholeiitic
andesite
Andesite
Dacite
Ryolite
E1
E16
E26
E29
E30

An-Ab'-Or Projections of Subalkaline Rocks

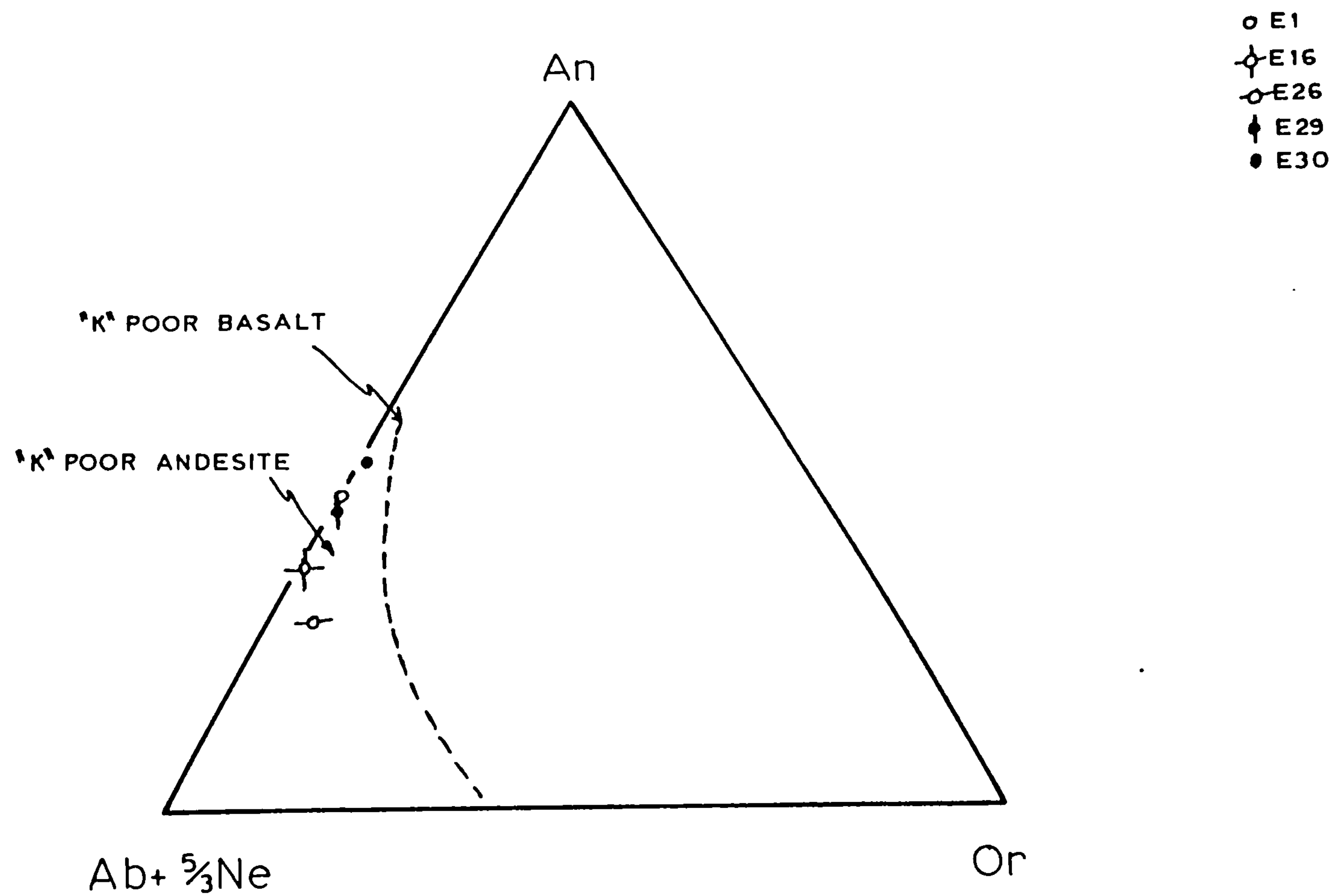


Figure:12

$TiO_2 - K_2O - P_2O_5$ Plot

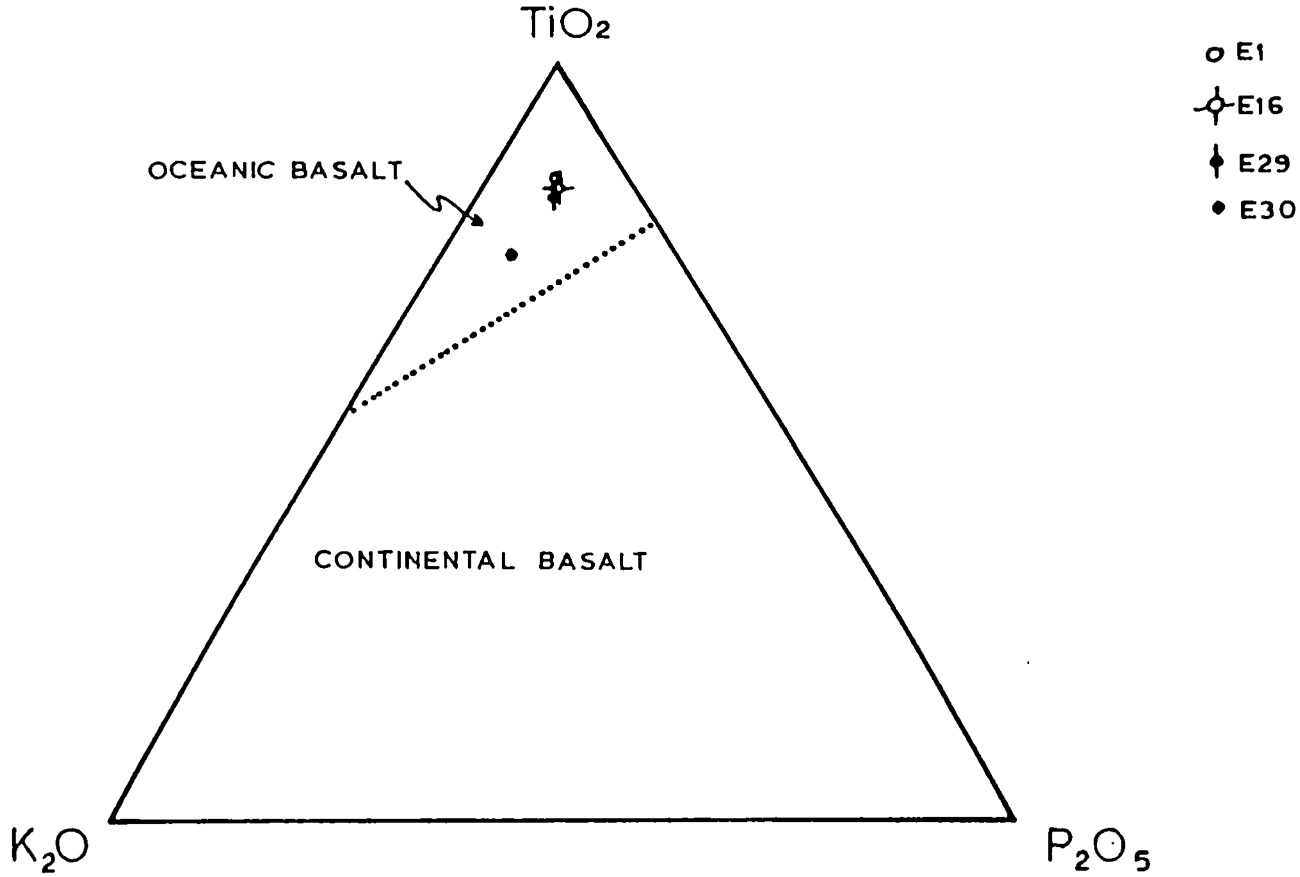
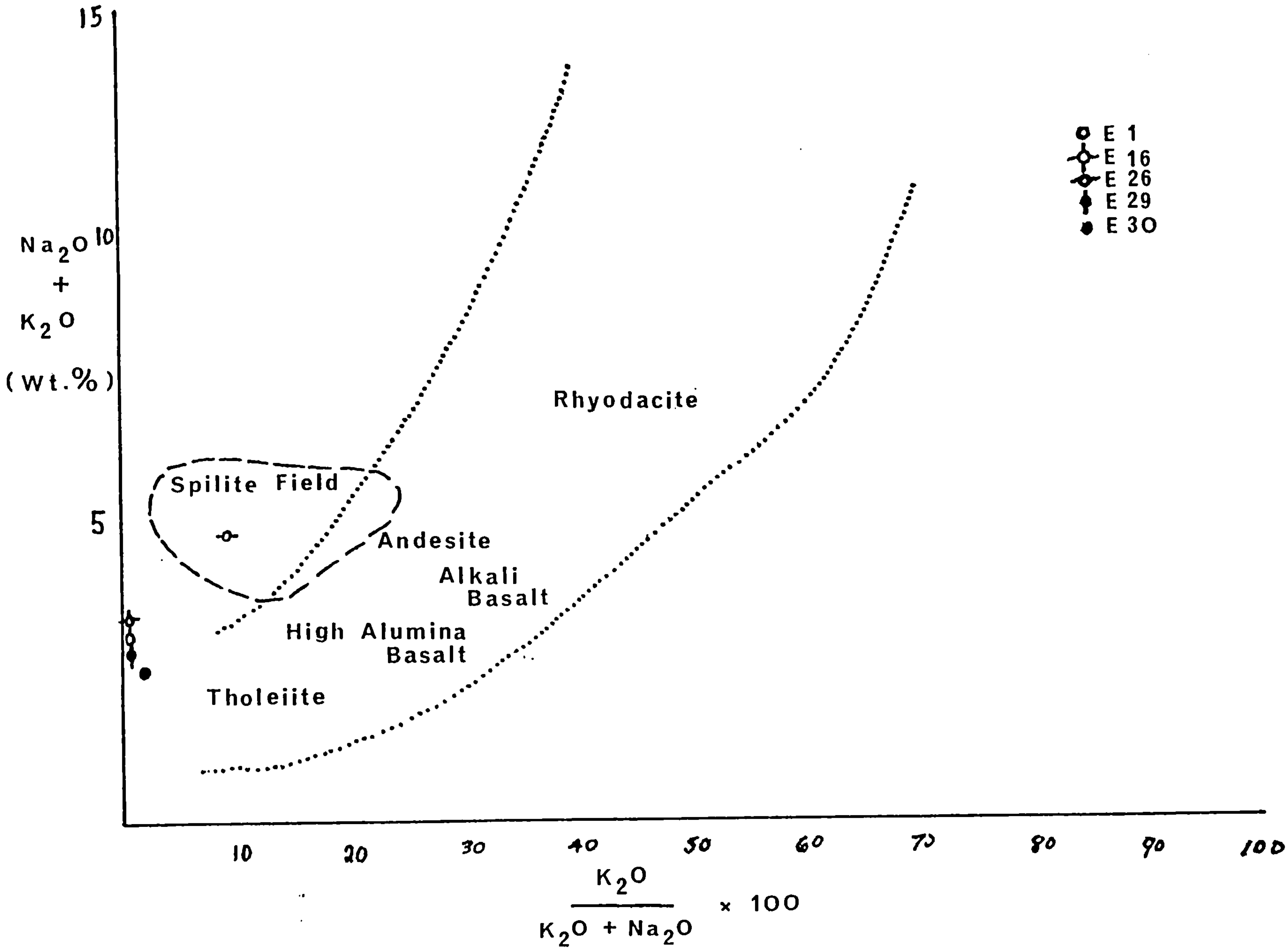


Figure:13

FIGURE: 14

HUGHES DIAGRAM



Analytical Methods (XRF)

Whole rock analyses of the pillows were determined by X-ray Fluorescence. Each sample analyzed was crushed until the fragments were small enough to be milled to 200 mesh by the use of a shatter box. A good representative powder could be obtained from each sample since the pillow slabs were carefully pre-cut and cleaned before being crushed.

A mixture of 2 grams of rock powder and 4 grams of lithium tetraborate was heated in carbon crucibles to 1100 C for 30 minutes. The fused beads obtained were milled to 200 mesh and pressed into flat discs which were covered with a coating of boric acid except for one circular basal section.

The discs were analyzed on an automatic X-ray Fluorescence unit Phillips Model which continually used a standard or drift monitor in order to determine any significant variance produced by the machine during the analysis. Weight percent oxides were obtained from the interpretation of the raw data in the form of counts taken per unit time. The oxides analyzed are as follows: SiO_2, Al_2O_3, Fe_2O_3, MgO, CaO, Na_2O, K_2O, TiO_2, MnO and P_2O_5. The samples were analyzed by comparing the counts per unit time produced for each element, by the samples and those produced by analyzed standards, 21 in all. The ratio of the counts derrived from the standards and those from the samples were determined and the weight percent oxide was then deduced by a computer program. The standard which was most similar to the sample, in terms of the content of all of the elements determined, was chosen to compute the chemistry of the sample. The weight percent oxide determinations were adjusted after the FeO and the total volatile percentages were analyzed.

Analytical Method (Ferrous Iron)

Ferrous iron determinations were made by wet chemical analysis. Approximately 0.4 grams of rock powder was transfered to a platinum crucible and mixed with a solution containing measured amounts of deoxygenated water, sulfuric acid and hydrofluoric acid. The crucible was covered and the mixture was heated over a low heat for approximately 10 minutes, until all of the powder was dissolved. The crucible was then quickly emmersed in a premeasured mixture of deoxygenated water, a boric acid solution and sulfuric acid. Titration of the resultant solution was done with the use of a potassium dichromate solution and the ferrous iron content was deduced.

The procedure was tested with a standard reference and the results obtained were accurate to within 0.05% ferrous iron. Two or three determinations of one sample were made, all of the determination agreed to within 0.04% FeO.

Analytical Methods (Loss of Volatiles)

Rock powders weighing approximately one gram were weighed to four decimal places and transfered into clean, pre-weighed porcelin crucibles. The powders were placed in an oven and heated to 1000 C for one hour. The crucibles were then placed in a dessicator until cooled. The powders and the crucibles were reweighed and the loss of weight by the powder was determined. One empty crucible was also used in the procedure, acting as a blank.

Adjustments in the weight of the heated powders were made for the oxidation of ferrous iron assuming that all of the ferrous iron was oxidized. The correction factor used is as follows: 2 FeO - O Fe_2O_3, FeO x 1.1114 - FeO x. The value x was subtracted from the final weight determination.

II Mineralogy and Microscopic Texture

Actinolite: Actinolite is one of the major constituent minerals of the pillows studied. It is rare or absent within the selvedge zone, where it occasionally occurs as minute grains within albite amygdules. Actinolite is generally found within the matrix of the intermediate zone and to a lesser extent, within the varioles located in the inner portions of the intermediate zone and in the core. It occurs as elongate or accicular grains rarely exceeding 0.4 mm in length with length-width ratios averaging about 7:1. Many very small grains with very high length-width ratios commonly occur within albite amygdules and within varioles along with the larger, more prominent grains. The ends of many grains appear frayed, especially near the boundaries of amygdules and varioles. Feather-like or branching forms of actinolite appear in a few pillows, these forms are usually found within and around amygdules and varioles. The feathery forms of actinolite are associated with highly splintered, elongate grains. Many actinolite grains have crystal imperfections and appear to be hollow or to contain other other material. Judging from the size of the impurity within the longitudinal and transverse cross-sections, the degree of grain imperfection increases with the grain size in zones which show variable grain sizes. The small, needle-like grains within varioles and amygdules lack this imperfection. The variation of the grain size within a pillow is generally low in the matrix. One pillow showed a clear but slight increase in actinolite grain size nearer the core. The length-width ratios of actinolite grains usually increase in the same trend. Actinolite grains within the intermediate zone often show a subtle orientation tangential to the boarders of the varioles and amygdules. Actinolite grains within the varioles are randomly oriented.

Chlorite: Chlorite is found in all of the major zones of the pillows. It comprises about 40% of the selvedge zone, occuring as anhedral and polygonal grains 0.8 mm in diameter and interstitial to the epidote grains. In the intermediate zone, chlorite is found in the form of anhedral or polygonal grains, in amygdules, as interstitial material between the actinolite grains in the matrix and in small patches within varioles. The chlorite grains are found throughout the pillows but are generally concentrated within the selvedge and the actinolite matrix of the intermediate zone. Anhedral and polygonal grains are occasionally found within the varioles as well. There does not seem to be any trend in the grain size distribution. The chlorite amygdules are generally restricted to the matrix of the intermediate zone. Some grains have internal zoning which is evident under crossed-nicols; rims of impurities and of anomalous blue and brown colours can be seen. Chlorite amygdules are commonly rimmed by other minerals, usually albite. One section showed albite-rimmed chlorite amygdules occuring only near the upper part of the intermediate zone, this however was an exception. The amygdules are either spherical or irregular ovals in shape. Both amygdules and grains range in size from 0.5 to 3.0 mm in diameter. Few tabular and hexagonal chlorite grains are present with patches of antigorite in one pillow. Small irregular patches of chlorite 0.1 mm in diameter are found within varioles but they comprise less than 30% of the variole area in thin section.

Albite: Albite is found throughout the pillows, generally being more concentrated in the inner zones. It occurs in amygdules, amygdule or grain rims and as a major component of the varioles. Amygdules of albite are present throughout the pillows but are generally concentrated within the actinolite-chlorite matrix of the intermediate zone. The amygdules are generally 1.0 mm in diameter and may show different grain size trends within pillows. The amygdules increase in size from the outer to the inner part of the matrix in the intermediate zone of a few pillows. Albite amygdules within the core are rare and usually small. Most of the albite occurs in the varioles in the inner part of the intermediate zone and in the core of the pillows. The varioles range in size from 0.5 to 3.0 mm in diameter. Commonly the pillows show a smaller range in variole size. Albite within the varioles show fan-like or radiating extinction patterns, few varioles show more than one set of these patterns.

Calcite: Calcite is present in subrounded amygdules, as highly irregular grains or masses and in veins or fracture fillings. The amygdules are generally restricted to the intermediate zone (matrix) while the grains are present throughout the pillow. Calcite is a minor component of the selvedge, occurring as small irregular grains or in amygdules. The amygdules and grains range in size from 0.5 to 3.0 mm in diameter. The amygdules are often rimmed by chlorite and albite. There does not seem to be any variation in the grain size of the calcite within the pillows. The cores of a few pillows contained large amounts of highly irregular calcite masses. Calcite veins are found within all of the zones of the pillows.

Epidote: Epidote is found in all of the zones of the pillows and is generally a minor constituent. The selvedge zone contains 35% epidote in the form of small anhedral grains 0.2 mm in diameter. Epidote is dispersed throughout the intermediate zone of a few pillows and form anhedral grains 0.3 mm in diameter. Larger anhedral and tabular epidote grains 0.7 mm in diameter occur in the core of one pillow studied. Large euhedral epidote grains are present within a few of the larger cavity fillings: In pillow E26 epidote is present as small grains dispersed in a linear fashion from the centre of the antigorite patches.

Clinozoisite: Clinozoisite is a minor constituent mineral in the pillows studied. It is found within all zones of the pillow and is usually concentrated in the selvedge zone, representing about 15% of the mineralogy. The grain size of the epidote minerals is the same as that for epidote. Large grains are present within cavity fillings and veins. The grains are subhedral to euhedral (tabular) in form.

Quartz: Quartz is a very minor constituent mineral of these pillows. It appears only as amygdules, ranging in size from 0.5 to 1.0 mm long. Few of the amygdules are rounds most are elongate in shape. The quartz amygdules show a mosaic extinction pattern under crossed-nicols.

Antigorite: Antigorite appears in the outer part of the intermediate zone of pillow E26 and occurs in patches, often bounded by polygonal outlines (0.5 to 3.0 mm in length). The mineral has a highly irregular altered appearance and is usually rimmed by a dark, finely divided mineral (leucocene?) and occasionally by an outer rim of epidote grains. Antigorite patches in the inner part of the intermediate zone are invaded by actinolite grains.

Opaques: Traces of opaque minerals were found scattered throughout many of the pillows. The grains are very small, 0.2 mm in diameter and are anhedral or subhedral in form.

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