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THE DISTRIBUTION AND GEOCHEMISTRY OF THE BIG TIMBER DIKE SWARM, CRAZY MOUNTAINS, MONTANA

A dissertation submitted to the

Division of Graduate Studies
of the University of Cincinnati

in partial fulfillment of the
requirements for the degree of

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of the Graduate School of Arts and Sciences

1972

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entitled The Distribution and Geochemistry of the Big Timber Dike Swarm, Crazy Mountains, Montana.

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ABSTRACT

The Crazy Mountains are an elliptical Tertiary uplift in south-central Montana. They consist of two alkali-calcic stocks with associated dikes and sills and a nearby series of alkaline laccoliths, sills and dikes. These bodies intrude and deform Paleocene sediments of the Fort Union formation. The present study, as a part of a continuing effort to understand the igneous geology of the Crazy Mountains, has concentrated on the distribution and chemical variation of the dikes peripheral to the southern and larger Big Timber stock, outside its metamorphic aureole.

Two directions of dike intrusion predominate; N-S and NE-SW. The radial pattern shown on earlier maps of the area is not apparent. The two trends can be related to doming caused by intrusion of the stock (the well developed N-S set) and to tensional fractures resulting from movements on the Nye-Bowler/ Lake Basin megashear couple (the relatively poorly developed NE-SW set). At least some of the dikes post-date the stock and are seen to intrude the stock, metamorphic aureole and the surrounding sediments.

Two series have been defined within the group of analysed dike rocks; one is alkali-calcic and the other mildly alkaline. Although arbituary, the definition emphasizes differences which may have genetic significance. There is some suggestion of a range of primitive magmas in the range. The observed chemical variation of the series is, however, most readily explained by a high-level crystal fractionation/accumulation model involving removal or addition of various proportions of the observed phenocryst phases.

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For his continuing support for my endeavour, I dedicate this dissertation to my late father, Mr. Robert J. Starmer.

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INTRODUCTION

Purpose of Investigation

The present study is concerned with two specific aspects of Crazy Mountains geology: the distribution of dikes around the Big Timber stock and the chemical characterization of these intrusives. It is part of a larger study of the igneous geology of the Crazy Mountains. The distribution of dikes around the Big Timber stock is of interest as it has been used as a "textbook" example of a radial dike swarm (see for example Daly, 1933). The chemical characterization of the dike swarm has been undertaken so that the resulting data may be used in a synthesis of the petrogenesis of the Crazy Mountains igneous rocks, of particular interest because both and alkali-calcic, silica saturated rock series and an alkaline, silica-undersaturated rock series are present in close juxtaposition. The results of this investigation are presented in this report along with consideration on controls of dike emplacement and petrogenesis of the dike rocks.

Previous Work

The Crazy Mountains, located in south central Montana about 80 miles north of Yellowstone National Park, have been the subject of geologic investigation for many years. Simms (1966, PhD. Diss. Univ. of Cincinnati) has presented a detailed review of early geologic and miscellaneous descriptions. The first important descriptions of the range are contained in the U.S. Geological Survey Folios by Iddings and Weed (1894) and Weed (1899). J. E. Wolff (1938) presented the results of more detailed petrologic work. Pirrson (1905) and Larsen (1940) considered the igneous rocks of the range as part of their regional synthesis of the Central Montana Petrographic Province. Recent work has been carried out as a continuing program of study by J. Tappe (1966, PhD. Diss. Univ. of Cincinnati), F.E. Simms (1966, PhD. Diss. Univ. of Cincinnati) and J. Sims (1964, MS Thesis Univ. of Cincinnati; 1967, PhD. Diss. Northwestern Univ.).

General Geology

On the basis of these works, the following generalized picture of the geology of the Crazy Mountains is presented. The range is the result of the intrusion of an igneous complex along the axis of the Crazy Mountains syncline into folded and faulted sedimentary rocks of the Fort Union formation. The sediments (shales and sandstones) are of latest Late Paleocene age (Starmer and Effimoff, in prep.). The igneous rocks are members of the Central Montana Petrographic Province of Pirrson (1905) and Larsen (1940). These rocks range from alkali-calcic to alkaline. The alkali-calcic series make up the bulk of the igneous rocks of the range and are concentrated in two stocks in the center of the range and in dikes (and sills) in and peripheral to the stocks. The alkalic series occurs as small laccoliths, sills and dikes to the north and west of the alkali-calcic intrusives.

The highest peaks of the range occur in the resistant contact aureole of the two stocks which have been deeply sculptured by alpine glaciation. The range is flanked by at least two sets of terraces (Alden, 1932). The older set is equivalent to the Flaville No. 1 terrace and is of late Miocene through Pliocene age. The later set is thought by Alden to be equivalent to the No. 2 terrace set of early Pleistocene age. Pleistocene and recent stream action has incised the terraces and worked headward in most of the larger streams to the outer contact of the contact aureole where beautiful waterfalls are developed.

GEOLOGY OF THE DIKE SWARM

Method of Investigation

Mapping was accomplished in two steps: preliminary definition of points of interest using low-oblique photos followed by final mapping of the dike distribution on aerial photos, photo-indexes, and topographic maps. Because of the lack of good topographic

control and aerial photographs for part of the range, aerial photographic reconnaissance was performed by light plane. Oblique photos were made using a 35 mm camera. These photos were used to define areas of interest throughout the study of the dike swarm.

Final mapping was accomplished on a variety of media. For the southern part of the range, topographic coverage is available and was used in conjunction with Department of Agriculture (ASCS) photo indexes. For the rest of the range the only map coverage consisted of planimetric maps of the U.S. Forest Service. Mapping of these areas was therefore done on high-altitude photos and on ASCS photo indexes. Late in the field work, newly available low altitude photos from U.S. Forest Service coverage were used to supplement the other media. All the information was finally compiled on U.S. Forest Service class C planimetric maps.

Some mention must be made on the possible bias of the mapping technique employed in defining the dike distribution. In the Sunlight Peak area, to the northwest of the Big Timber stock, dense forest cover and extremely rough terrain have caused the coverage to be less than that desired. The terrace cover on the southwest flanks of the range might indicate another point of variance between the distribution of dikes as displayed on the map and that which actually exists. However, in both of these areas, dissection is extensive enough to reveal dikes if they were present in large numbers. To the northeast, the terminal morraine of the Sweet Grass glacier has covered a large area. Here dissection has done little to uncover hidden dikes, and the distribution as mapped in this area must remain in question. In all other sectors of the periphery of the range, the map representation of the dike distribution is probably complete.

Size of the Dikes

Dikes in the Crazy Mountain dike swarm vary in width from a few feet to fifty or more feet in width. The widest dikes observed occur on the southern margin of the range and there, several are as wide as fifty feet. Most dikes are, however, from five to ten feet wide, none narrower than about three feet being observed by the author. Dikes a few inches wide in the Crazy Mountain Basin to the east of the range have, however, been observed by J. Fanshawe (pers. communication, 1970).

The mapped length of a dike does not depend only on the absolute size of the mapped features but also on its shape in the third dimension and on the degree to which it has been exposed by erosion. Since dikes were only mapped as continuous when there was good reason to connect separate outcrops, some long dikes may appear on the map as a series of disconnected segments. If dikes are not intersected by the present day erosion surface, they are obviously not represented at all. With these limitations in mind, some statements may be made as to length of exposed dikes. The longest dikes are seen on the southern flanks of the range. A few such long dikes were mapped on the northeastern flanks of the range. Except for these, most dikes are not longer than a mile and usually all that is observed is a much shorter segment of a few hundred yards or less. Several of the dikes on the northern border of the Big Timber stock are probably much longer than the short segments that have been mapped.

Orientation of the Dikes

In general, the dikes are sub-vertical to vertical. No quantitative data are available on this subject, but deviation from the vertical of more than 5-10 degrees was not observed. Very locally, instances of anamolous dips exist where a dike is inclined considerably for a few tens of feet along its length,

possibly in response to some local inhomogeneity in the country rock. Sims (1967) suggests that dikes are common only in areas where the dip of the sediments is high. In the area studied by the author, however, this relationship to the enclosing sediments was not observed.

External Configuration of the Dikes

Dike contacts are usually quite regular and the two contacts of a dike are normally parallel to sub-parallel. Along the exposure, slight variations of width and/or direction may cause some deviation from the parallel. The contacts are normally smooth or slightly undulating. Instances of small scale, more or less right angle displacement of the dike walls were observed. Such stepping is probably the result of a change of lithology, and hence a change of mechanical behavior, at that stratigraphic horizon. Two examples of small-scale undulations similar to those described by Simms (1966) were observed. These may be important in understanding intrusive mechanisms (I.A. Kilinc pers. communication, 1971) and deserve further study.

In one case a "headed" dike was observed. It was chilled, at least very fine grained, jointed in a platy manner parallel to the contact and the contact zone was more amygdaloidal than the center. Other dikes, just exposed at the surface, even though not exposed in cross section, were considered to be terminated at that level, since they have similar features. These were always flat to slightly bowed surfaces. These blunt terminations are at variance with the idealized "knife edge" termination suggested by Anderson (1951).

The contacts of the dikes in the field show little in the way of chilled (fine grained glossy) margins or of contact metamorphic effects. Chilled margins are rare and have only been observed where one dike was chilled against another. Contact metamorphic

effects are restricted to at the most 6 inches from the margin. The observed effect is a darkening of the sediments close to the contact. Compound dikes often have a pronounced chill margin but no evidence of metamorphism of the earlier dike.

Internal features of the Dikes

Internally, the dikes are generally simple and homogeneous. Conspicuous flow features are absent. Several composite dikes were observed, however. In these, aphyric margins grade to phyric centers or alternatively, the change may be relatively sharp, (similar features are illustrated by Upton and Wadsworth, 1970, fig. 3). The change, gradual or sharp, usually occurs within a foot of the dike margins. That these dikes are composite rather than only chilled is supported by the extreme difference in rock type from center to edge (see analyses 80E - 80C and 40E - 40C where E denotes edge and C denotes center), and gradation of rock type over a relatively large distance (ca. 1 foot for composite dike vs. ca. 2-3 inches for a chilled margin).

Inclusions are an important aspect of many of the dikes studied. These are of two types: those definitely derived from depth and those consisting of locally derived fragments of country rock, sandstone and shale. Among the former, amphibolites, pyroxenites, and quartzites have been observed. These inclusions have undergone more or less reaction with the enclosing dike rocks, some being mere "ghosts". Inclusions of this latter type may be in equilibrium with the host rock since many have similar assemblages to the enclosing dike.

All evidence indicates that the sandstone and shale xenoliths have not traveled far and that little change has occurred in their composition. Rock types are typical of the enclosing Fort Union formation, textures are still sedimentary, contacts are sharp, and, as nearly as can be determined, the mineralogy is little changed from the original. It is possible that some dehydration

reactions have occurred but no close approach is obtained to the assemblage pyroxene, amphibole and plagioclase characteristic of the dike series.

Dike Distribution

The distribution of dikes around the Big Timber stock is of considerable interest. Early mapping (fig. 1) gives the impression of a radial dike swarm, taken by some to be a type example (e.g. Daly, 1933). While the center from which the dikes radiate has indeed been found to be in the Big Timber stock, the dikes are not distributed in a regular manner around the stock (fig. 2). This is important as there seems to be an implication of regularity in the concept of a radial dike swarm, even though the concept is rather vague. This study has defined two preferential directions of intrusion. A north-south direction which is strongly developed and a northeast-southwest direction which is much less well defined, fig. 2. A recent student project (McCandless et al. 1972) produced a rose diagram, reproduced here as figure 3 , of the dikes mapped by the author. Lengths were weighted by dividing each mapped dike into equal length segments. The frequency of segments of a given direction were plotted on a rose diagram using 5^{o} intervals (fig. 3). Here the north-south and northeast-southwest concentrations stand out. The north-south direction is striking. It is strongly developed to the south of the range where some of the longest and widest of the dikes occur, and less well-developed to the north where the Big Elk intrusive and the large latite sills of Lebo Peak interfere with the pattern. The northeast-southwest (NE-SW) trend is much less well developed but seems to continue within the stock (Tappe, 1966, fig. 20). On the map (fig. 2) and the rose diagram (fig. 3) the trend is stronger in the northeast quadrant than in the southwest quadrant. Other directions are, however, much less well represented by dikes.

Other Hypabyssal Intrusives

Sills are common all around the periphery of the range. In some places, concentrations of sills should be mentioned. Along the lower reaches of Sweet Grass Creek, sills are well exposed in the canyon walls. South of Melville, east of the map area, sills are particularly common as they are also in the Kelley Hills to the southeast of the map area. In the South, sills are abundant in the Duck Creek area where the particularly long and continuous dikes are found. Sills are also common on the western border of the range north of Ibex Mountain. The study of the sills has not been pursued but some have been mapped and samples from them included in the chemical analyses.

Several laccoliths are present and deserve mention. Porcupine Butte to the northeast of the map area is a large latite laccolith. Two other large latite bodies were mapped on the east side of the range. Laccoliths were also mapped on the southwest side of the range around Ibex Mountain. Ibex Mountain is a large laccolith of malignite shonkinite and is the southernmost member of the alkalic series which is mostly restricted to the northwest part of the range.

STRUCTURAL AND TECTONIC INTERPRETATION OF THE DIKE SWARM

Introduction

The purpose of this phase of the investigation is to interpret the observed pattern of dikes. It is important to relate the observed pattern to the stock and tectonic setting of the area and to determine the genetic significance of the observed pattern. The map of the dike swarm, fig. 2, serves two purposes. It presents the spatial relations of the dikes and acts as a qualitative rose diagram to show the relative intensity of dike intrusion around the central Big Timber stock.

Somewhat contrary to the findings of the early surveys of

Iddings and Weed (1894) and Weed (1899) as summarized in figure 1, this study indicates that concentrations of dikes occur peripheral to the central Big Timber stock (fig. 2, 3). These directions may be characterized as a strong NS trending set of dikes (N 10-15°W) and a less strongly developed set of dikes trending NE-SW (about N 40°E). The NS set of dikes is composed of the largest and the most continuous dikes, while dikes of the NE-SW set are shorter and smaller. These trends correspond with the trends of the dikes observed by Tappe in the Big Timber stock (1966, fig. 20).

Doming as an Explanation of the Observed Pattern[1]

Dike intrusion is directly related to tensional features in the host rock (Anderson, 1951, p. 22-28) and it is instructive to consider the distribution of tensional features related to elongate domes such as the upper surface of the Big Timber stock. Common to most doubly plunging anticlines is a set of tensional fractures, joints and normal faults, roughly paralleling the long axis of the anticline (DeSitter, 1964, p. 189 ff., Badgley, 1965, p. 163 ff.) with tensional features also weakly developed in other directions. The results of a model experiment by Hans Cloos illustrates this pattern very well (fig. 4, see also Cloos, 1939). Wisser, (1960) has shown this pattern to be predominant for many examples of igneous intrusions from the Western U.S. and Mexico. And Bailey and Smith (1968) have shown this pattern to be common to early phase doming associated with caldera formation.

The stock itself has an upper surface with the shape of an elongate, doubly plunging anticline (Tappe, 1966, plate I and figure 19). That this igneous form continues at depth is supported by the geophysical study of Kelley (1966). The enclosing

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1) This approach has been recently adopted by Tappe (1972) to explain the distribution of his tabular andesites within the stock, equivalent in direction to my NS set of dikes.

sediments are roughly comformable with the stock and indicate intrusion by pushing aside the enclosing sediments (Tappe, 1966, plate I and fig. 19). The form of the upper surface is simply that of an elongate dome. The N-S concentration of dikes in the Crazy Mountains dike swarm is therefore most easily explained by relating it to the assymetric domal shape of the intrusion, dikes being intruded along tension fractures related to the doming, These fractures should be preferentially developed along the N-S trending long axis of the domal feature. The weaker NE-SW set of the dikes may also be related to the same cause as the strong NS set since minor concentrations of tensional fractures are associated with many assymetrical domes (see for example figure 4).

A Possible Tectonic Influence on the Observed Pattern

Since a NE-SW concentration of dikes exists in the area of the present study (fig. 2, 3), and since a similar direction is prominent in the stock (Tappe, 1966, fig. 20 and plate I), it seems worthwhile to consider a possible cause of preferential development of a set of tension fractures with this direction. As major tectonic elements of the region, the Lewis and Clark megashears, fig. 5, and in particular the Nye-Bowler/Lake Basin pair from this system, fig. 6., offer a second uncomplicated cause.

Badgley (1965) suggests that the Nye-Bowler/Lake Basin system of basement rifting provided avenues of stress release for Laramide compression. The regional compression is thought to be resolved into left-lateral strike-slip faulting along pre-existing Precambrian zones of weakness. Whether or not this mechanism is accepted, the two megashears define a block of crust within which the stress field may be simply described as a force couple. The stress-strain relationships of this couple may be presented diagramatically by means of the strain ellipse in

fig. 7. It is readily apparent from this diagram that the direction of greatest stress postulated by Badgely is coincident with the direction of the NE-SW set of dikes in the Crazy Mountains.

This offers an explanation for a concentration of dikes with this direction. It is well known that dikes should be intruded into directions parallel to the direction of greatest principle stress (Anderson, 1951, p. 22-28). The stress-strain relations postulated above suggest that fractures already present in the domal fracture system could at times be preferentially intruded along this direction.

It may also be seen (fig. 7) that the directions of initial shear failure[2] predicted by this model are not coincident with the major NS fault and dike emplacement direction of the complex. In order for the observed NS directions to be the result of such a mechanism, post-failure rotation of the original shear planes on the order of 30-35° CCW would have to be postulated. No evidence of such post rupture rotational strain is present and so this seems an unlikely control of development of the NS set of dikes.

Repeated pulsations of magma intrusion in the stock and repeated movements of the Nye-Bowler/Lake Basin megashear system could be expected to open these tensional features at various times. This could yield periods of preferential intrusion along many directions. The two directions mentioned should, however, be preferentially intruded. Pulses of magmatism should open and fill the NS set of fractures as uplift might be expected from such an event whether it were rejuvenation of an earlier magma body or introduction of a new magma from depth. Stress-strain interaction related to the Nye-Bowler/Lake Basin megashear couple

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2) Taken as 34° based on a selected set of data from Handin (1966), which is felt to reasonably represent possible conditions within and surrounding the stock after consolidation at depth.

might be expected only to tap an existing magma chamber, resulting in intrusion along the NE-SW direction.

The primary mechanisms of control by fractures related to doming is sufficient to explain the observed dike distribution pattern. It explains the observed major concentration of dikes parallel to the domal axis and any subsidiary maxima may be left to chance. The megashear stress-strain mechanism, however, complements the doming mechanism as a secondary process. It offers an explanation of why one particular set of fractures, not predicted to be of special importance by the doming model has been preferentially intruded. Other suggested mechanisms such as chance (L.H. Larsen, pers. communication, 1971) and configuration, of a minor arm of the basin (Tappe, 1972) seem much less plausible to the writer.

PETROGRAPHY AND CHEMICAL VARIATION OF SELECTED DIKES

Introduction

In the following section, petrographic descriptions and chemical analyses are presented for a group of dike rocks which were selected to represent the range of rock types encountered in the field (see page 22for details of the selection procedure). For purposes of discussion, two series of rocks have been defined in what is essentially a spectrum af alkalic and moderately alkalic rock types. By series is meant a group of rocks with similar unique (to the group) chemical characteristics. The two series are defined in terms of chemical rather than mineralogical parameters, reflecting the emphasis of this study, and the similarity, for ahy degree of evolution, of their visible mineralogy. Salient characteristics of the two series are outlined in table 1.

Definition of two series within the Dike Swarm

The first series, containing the majority of the analysed rocks, is defined as being silica saturated to oversaturated (when calculated with all iron as Fe_2O_3, an oxidized norm) and in being moderately potassic (K_2O:Na_2O greater than 1:2 in general). It is alkali-calcic according to the terminology of Peacock (1934) with a Peacock index of 52.4 and is therefore refered to as the AC

series. The second series is characterized by silica undersaturation in the oxidized norm. This series is sodic (K_2O:Na_2O less than 1:2) and has a Peacock index of 48.7 (alkalic). it is refered to as mildly alkalic, however, to distinguish it from the strongly undersaturated, often peralkaline, group of rocks of the northern and western sectors of the range.

There are two reasons to suggest that these two series, although arbitrarily defined, may in fact be equivalent to lineages as defined by Coombs and Wilkinson (1969); and therefore, may have genetic significance. It has been suggested (e.g. by Poldervaart and Parker, 1964, p. 283-284, by Nolan, 1964, p. 155, and by Coombs and Wilkinson, 1969, p. 470-471) that levels of silica undersaturation (or saturation) in basic magmas are maintained (or enhanced) throughout the development of their salic differentiation products. This may be the case for the two Crazy Mountains series presented here, although more data will be needed to confirm this suggestion. It may, however, be significant that almost all members of the MA series occur in the NS set of dikes. Such spatial arrangement lends support to the separateness of the two groups on grounds independent of the arbitrary chemical distinction first used in their definition.

Different ages for the two series would be additional independent evidence. However, only one cross cutting relation has so far been observed for the two series; and, although this indicates a later age for the MA series (7020 cuts 7019), not much emphasis can be put on one occurrence. Lacking concrete time relations, because cross cutting relations are rare in a radial dike swarm, the spatial arguments must serve as evidence that two separate series of rocks may indeed exist.

A Proposed Chemical Classification of the Dike Rocks

In spite of the applicability of Coombs and Wilkinson's (1966) scheme of nomenclature, the author has chosen to retain

with some modification and addition, the terminology of Simms (1966). The terms are, however, defined or redefined in a more precise manner on chemical grounds (table 2). Some of the more alkaline types, particularly the low SiO_2 varieties are not included in the classification (e.g. those with less than 50% SiO_2 and total alkalis greater than 9 %). The classification as proposed, does not apply to coarse grained "plutonic" rocks.

For the more sodic, undersaturated, MA series, the terms 'hawaiite' and 'mugearite' are used for the less envolved members of the series following the usage of Muir & Tilley (1964). It should be noted that Crazy Mountains 'hawaiites' and 'mugearites' do not correspond to type analyses (e.g. Muir & Tilley, 1964, MacDonald, 1968, Coombs & Wilkinson, 1969), particularly in having higher MgO and lower Al_2O_3. Mafic trachyte, trachyte and phonolite correspond to the terminology of Simms (1966).

For the mildly potassic, saturated to oversaturated, AC series, the terminology is slightly different from that of Simms(1966). In particular the terms 'trachybasalt' and 'trachyandesite' are adopted in order to emphasize the higher alkali contents of these rocks when compared to "typical" calcalkaline basaltic andesites and andesites[1]. The trachyandesite usage in particular seems well founded as it is directly comparable to the usage of Nelson & Pierce (1968) for similar rocks from the Absaroka range to the southeast. Quartz-latite is retained from Simms' (1966) usage but rhyodacite is applied where Simms (1966) would use rhyolite[1]. This reflects particularly the relatively low SiO_2 contents (68-70%) of these rocks.

The petrographic observations below are presented as generalizations. They should, however, help the reader to have

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1) see also MacKenzie (1972).

a better understanding of the rocks involved. In the present study phenocryst mineralogy has been given most attention. In the absence of a detailed mineralogical study, the information presented here may be a useful basis upon which to plan further more detailed study.

PETROGRAPHY OF THE ANALYSED ROCKS

Introduction

Brief descriptions of the analysed samples are given in table 2, which summarizes phenocryst mineralogy and gives estimates of volume percentage of phenocryst phases and the maximum size noted. Quantitative determination of mineral optical properties has not been attempted. Groundmass grainsize has been estimated and notes are included where useful information was obtained. Rocks without phenocrysts are termed aphyric, those with maximum phenocryst size less than 2 mm are termed microporphyritic while those which contain phenocrysts with maximum size greater than 2 mm are termed porphyritic. Aphyric rocks with general groundmass grainsize greater than 0.02mm are grouped as coarse aphyric types. In the table, the order of the rock descriptions is the same as that for the chemical analyses.

Petrographic Summary of the AC Series

Within the AC series, the solitary analysed basalt is aphyric and amygduloidal. Ore is abundant in groundmass. The trachybasalts include both aphyric and porphyritic varieties. Clinopyroxene phenocrysts are present in all the porphyritic members of the group, while plagioclase and amphibole phenocrysts are present only in some of the rocks, although not apparently appearing together. Ore and apatite phenocrysts are present in some members of the group. The trachyandesites are more variable and plagioclase is the most common phenocryst

phase. Clinopyroxene is also common. Amphibole phenocrysts are much less common. Ore and apatite are present as phenocrysts in most of the rocks of the group. Olivine phenocrysts or pseudomorphs after them are present in small amounts in four of the trachyandesites. One of the analysed quartz-latites has phenocryst amphibole and ore while both have apatite phenocrysts. The analysed rhyodacite is coarse-aphyric. Groundmass amphibole and/or biotite is present in many of the more evolved rocks and what may be xenocrystal quartz is present in the rhyodacite together with probable xenocrystal sanidine. Calcite patches are seen in some of the rocks and alteration, mostly of chlorite, sericite, ore and some carbonate is common throughout the series.

Petrographic Summary of the MA Series

In the MA series, the predominance of aphyric and coarse-aphyric types is apparent. One analysed hawaiite has clinopyroxene and ore as phenocryst phases. Neither of the two analysed hawaiites has apatite phenocrysts. The mugearites are generally aphyric but the porphyritic members have clinopyroxene as a dominant phase, two also contain plagioclase phenocrysts while two others contain olivine or its alteration products. Apatite and ore are common phenocrysts in the more evolved members of the group. The mafic-trachytes are generally aphyric or microporphyritic. The analysed porphyritic member of the group has small amounts of clinopyroxene and amphibole as phenocrysts. The microporphyritic rock has plagioclase and a trace of clinopyroxene as phenocrysts. None of the mafic-trachytes contain phenocrysts of apatite or ore. Biotite and/or amphibole is common in the groundmass of the series as a whole. Free quartz, anamalous since the rocks are silica undersaturated, is present in three members of the series. This could be due to the presence of biotite, the silica undersaturation of which may balance the excess free silica. Amygdules of calcite or free calcite are seen

in two of the analysed rocks of the MA series. Alteration, variable in intensity, is common. The most common alteration products are chlorite, sericite, calcite, and ore.

Mineralogical Notes on the AC Series

Phenocrysts

Feldspar, as plagioclase phenocrysts, reaches a maximum in size and quantity in the less evolved trachyandesites. The maximum estimated amount of plagioclase is 24% in the most basic trachyandesite but a median value for plagioclase phenocrysts in the porphyritic members of the series is about 10-12%. A maximum length of 8 mm is recorded but the most common size is about 3 mm. Five generalized morphological classes of plagioclase phenocrysts have been defined: 1) complexly zoned crystals, often as synuesis groups (fig. 8); 2) long twinned individual crysts having little or no visible zoning (fig. 9); 3) phenocrysts consisting of overgrowths on anhedral, large relatively simple crysts, fractured and altered along the fractures; and, often heavily altered cores (fig. 10); and 5) simple, relatively small laths, commonly with little zoning (fig. 11). In the rhyodacite, one polycrystalline, probably xenocrystic, sanidine aggregate was found.

Clinopyroxene (diopsidic-augite or augite) is common in the trachybasalts and trachyandesites though never as common, or in such large crystals,as the plagioclase phenocrysts. Maximum volume is about 9%, with a median value of about 5 %, and maximum size is 4 mm with a median value of about 3 mm. Clinopyroxene is sometimes zoned (fig. 12) and may be seen as synuesis groups (fig. 13).

The amphibole is a hornblende of variable nature and is present in phenocrysts in only about 40% of the porphyritic rocks. The maximum size is about 7.5 mm in length with a median size of about 3 mm. The maximum amount present is 12% with a median value of about 6 %.

Olivine only occurs as comparitively fresh small crystals in two trachyandesites. Olivine, or pseudomorphs after olivine, never reaches more than 2% in amount or exceeds 1 mm in diameter. Ore and apatite are much more commonly found, particularly in the trachyandesites but of much smaller size (i.e. about 0.5 mm for ore and 0.3 mm for apatite).

Groundmass

The groundmass of the rocks has not been studied in detail but some observations of interest can be summarized briefly. Plagioclase feldspar occurs throughout the series, often somewhat altered but sometimes quite fresh (fig. 14). Biotite (fig. 15) occurs sporadically throughout the series as more or less well formed red-brown flakes. Amphibole (fig. 16) is even more common, particularly in the later stages of evolution of the series, from the most felsic trachybasalts through the rhyodacite. In the trachybasalts and the trachyandesites, the amphibole is red-brown, in the felsic trachyandesites, the quartz-latites and in the rhyodacite, it is brownish-yellow to olive green. Interstitial quartz is present in rocks of the series as mafic as the most felsic trachytes, is present in many of the members of the trachyandesites, and is common in the quartz-latites and the rhyodacite.

Mineralogical Notes on the MA Series

Phenocrysts

Plagioclase phenocrysts are not common in the MA series, being present in only three rocks. They can reach lengths of 7 mm and can make up as much as 10% of the rock but as a rule are much smaller and much less abundant. Three types were observed: 1) simple laths, 2) anhedral altered individual crysts, and 3) phenocrysts consisting of overgrowths on anhedral cores.

Clinopyroxene (diopsidic-augite or augite) is abundant, one sample containing 16% clinopyroxene phenocrysts although more commonly a value of about 5% is seen. In all cases the diameter of the phenocrysts is less than 5 mm with a value of about 3 mm being most common. Amphibole (a hornblende) is present in significant amounts in only one analysed rock as 5 mm-long crysts. Olivine is present in two analysed rocks, in one as large (4 mm) fresh crystals, and in the other as smaller altered individuals.

Ore and apatite are noticably most abundant in the more evolved mugearites. Ore is present in the hawaiites but absent from the less evolved mugearites and the mafic-trachytes. Apatite is absent from the hawaiites, less evolved mugearites and the mafic-trachytes.

Groundmass

The groundmass of the rocks of the MA series is similar to that of the AC series. Amphibole as the most common mafic silicate does not show systematic changes in pleochroism, in contrast to the groundmass amphibole of the AC series. Plagioclase is present throughout but no alkali feldspar has been recognized. Biotite is common and like the amphibole does not show regular variations in pleochroism. Interstitial quartz is present in several members of the series.

CHEMICAL COMPOSITION

Introduction

The chemical data presented in this section have a twofold purpose: they are intended 1) to characterize the dikes chemically as the basis for further work and comparison with the chemically well characterized rocks of the Big Timber stock, and 2) to allow interpretation of the observed chemical variation in terms of accepted petrologic principles and in the light of the data on

other spatially related rock series.

Selection Procedure

The rocks that were collected during the course of this study were assembled into groups of similar hand specimen appearance. This was accomplished on the basis of texture, phenocryst mineralogy (or lack of phenocrysts) and a rough estimation of color index. Within the groups so defined, the samples were placed in order of this color index. In order to have some sort of a representative sample of the variation of the dike swarm, two to three members of each group were chosen so that they represented a spectrum of variation within the group. Altered samples were excluded from consideration except where all the members of the group were altered. In this case, alteration was considered to be typical of the group. Xenoliths were excluded. This process was aided by slabbing the specimens and taking fresh portions of the slabs without inclusions for analysis. In the end, seven analyses were discarded on analytical grounds (analytical totals were not satisfactory) or on the basis of thin-section observation which indicated extreme alteration effects. Several samples were included that had known time relations.

The selected rocks were analysed by instrumental methods: SiO_2, TiO_2, Al_2O_3, total iron as Fe_2O_3, MnO, MgO, CaO, K_2O, P_2O_5, Rb, Sr, and Ba by X-ray fluorescence and Na_2O by flame emmision spectrophotometry (see apendix for details of the techniques employed). The major element results are given in table 4. Trace element results are presented in table 5. An idea of the precision associated with the determinations may be obtained from the standard deviations presented in table 6. The accuracy of the determinations may be judged from the determination of U.S.G.S. standard GSP-1 (table 6) which was determined in the same manner as the samples.

Graphical Presentation of the Data

The chemical variation of the dike rocks is summarized as a series of variation diagrams. Ideally the elemental variation would be interpreted in terms of liquids which solidified to form the analysed rocks (Bowen, 1928); however, the rocks analysed contain varying amounts of earlier crystallized minerals. The inclusion of these minerals leads to deviation from ideal trend lines and probably produces some of the observed scatter of points. Generalized trends are still observed and can be interpreted in light of known petrogenetic principles.

A second limitation to the interpretation of the analyses is the nature and amount of alteration. A common alteration consists of chloritization and uralitization of mafic phenocrysts. Since chlorite and actinolite-tremolite (?) are common groundmass constituents, replacement of mafics by these minerals probably indicates an attempt to reach equilibrium in the hypabyssal environment rather than addition or subtraction of components for the whole rock. Calcite commonly replaces feldspars and may also be a replacement type of alteration but the patches and amygdule fillings are often single crystals or simple aggregates of a few large crystals and may be the result of late addition of calcium carbonate.

Elemental variation is presented by plotting oxides against a modification of the Kuno Solidification Index (Kuno, 1957) proposed by McBirney and Williams (1969). The two forms of the solidification index are: Kuno's original solidification index (SI);

$$SI = \frac{MgO}{MgO + FeO + Fe_2O_3 + Na_2O + K_2O}$$

, and McBirney and Williams' modification (SI mod);

$$SI\ mod = \frac{MgO}{MgO + \text{total iron as } FeO + Na_2O + K_2O}.$$

In the McBirney and Williams modification as used in this report, iron is summed as FeO minimizing the effects of late stage oxidation and allowing direct comparison of analyses for which only total iron is known with those where FeO and Fe_2O_3 are presented separately.

Additional plots are $Na_2O + K_2O$ against SiO_2, Sugimura's (1960) plot of SiO_2 against agpaitic index, and AFM and Na_2O-K_2O-CaO triangular diagrams. Trace elements are presented as elemental ratio plots with some discussion of the elemental variation.

Oxide Variation Diagrams

SiO_2 and Al_2O_3 are presented in figure 17. The two series show some scatter and are more or less coincident, except for silica which seems a little lower for any degree of differentiation (equivalent SI mod.). Both increase with evolution to lower values of SI mod.

Na_2O and K_2O (fig. 18) rise gradually during evolution of both the AC and MA series. The MA series is notably more soda rich although the difference between the two series is not so noticable for the intermediate members of the two series (SI mod = 35-25). Potash is about the same for the two series for any degree of evolution (equivalent SI mod).

MgO, CaO, and total iron as FeO are presented in figure 19. For both the MA and AC series, MgO falls constantly with evolution. The MgO content of the MA series is very slightly higher in the more mafic members (ca. SI mod = 50 - 40) but the two series are generally coincident below about SI mod = 40. CaO falls constantly with differentiation of the AC series. The MA series has low values of CaO compared to the AC series during evolution to about SI mod = 40 - 35. For SI mod values lower than

about 35, the two series are generally coincident. There is some hint that CaO increases in the MA series down to about SI mod = 30 and then falls. Total iron as FeO falls with evolution of both series. There is no indication of systematic differences between the MA and AC series and both series seem to have a break at about SI mod = 25.

P_2O_5. TiO_2, and MnO are present in figure 20. P_2O_5 rises gradually in both the MA series and the AC series to about SI mod = 35 and then falls gradually, both series being more or less coincident and the trends being described as a diffuse cloud of points, particularly below SI mod = 35. TiO_2 falls during evolution of both series and there is an ill defined break at about SI mod = 20. MnO falls very gradually in the MA and AC series and is strongly depleted only in the AC series rhyodacite (7027).

Two other diagrams show the characteristics of the two series and are useful for comparison purposes. Firstly, the $Na_2O + K_2O$ vs. SiO_2 plot, figure 21, is useful to demonstrate the alkaline nature of the MA series and that, during the late stages of differentiation, the rocks of the AC series, as well as the rocks of the stock become less alkaline, most analyses falling below the empirical line of MacDonals and Katsura (1964) which separates the alkaline rocks from those of other series. On this diagram, the coincidence of the AC series and the stock may also be seen. The difference between the "truely alkalic" series of the northwest and the mildly alkaline series is plainly illustrated, total alkalis being much higher in the alkaline rocks.

Secondly, the Sugimura diagram which plots silica (SiO_2) vs. the agpaitic index (molecular proportions $Na_2O + K_2O/Al_2O_3$), figure 22 is interesting because it appears to separate the AC series and the stock rocks from the MA series and these from the alkaline (prealkaline) series. Sugimura (1960) suggests that this

diagram separates rocks from different Japanese volcanos (and by implication rocks of different rock series) from each other. This would appear to be the case for the Crazy Mountains and would seem to indicate that three (possibly more?) separate chemical rock series are present.

Triangular Diagrams

The two triangular diagrams that are presented in figure 23 serve a dual purpose: they help summarize the variation of the two rock series and to emphasize some differences, and because they summarize the major rock forming elements, they are also used to compare the rocks of the Big Timber stock and the alkalic series of the north and west with the dikes of this study.

On the AFM diagram for the dikes, figure 23, the points show a large scatter but the points for the MA series define a weak trend which shows less iron enrichment than the AC series and the stock. Neither the AC nor the MA series trend shows the late alkali enrichment of the stock aplites. The alkalic trend of the northwest shows even less iron enrichment than either of these trends, but does show late stage alkali enrichment.

On the Na_2O-K_2O-CaO diagram, figure 23, the Na_2O rich character of the MA series is well defined. The AC trend does not show this excess of soda to as great an extent. The trend for the AC series is roughly similar to that of the stock. The alkaline series is also relatively Na_2O rich but does not show strong soda enrichment even in the late stages of its development.

Trace Elements

Trace elements are presented as diagrams of ratios against the major element with which the trace element is most often associated (of the form major element / trace element vs. major

element). The reported Rb values may be systematically low as a result of strontium background interference. Attempts to correct for the high strontium background using the method suggested by Norrish and Chappell (1967, p. 187-189) produced no results different from the original by more than 1-2 ppm. The trends shown are therefore thought to be valid, because the high Sr contents of the rocks (varying between 700 and 1100 if two values are ignored) are relatively constant.

The K/Rb vs. K trend shows normal values (fig. 24) of 200 - 500 (cf. Erlank, 1968, Lessing et al. 1963, Gunn, 1965) for the less evolved members of the two series (less than about 1.5% K), a sharp increase and then gradual decrease. Rubidium values (table 5) show no pronounced differences among the MA series, the AC series, and the few members of the stock suite for which Rb values were obtained. The K/Ba plot (fig 25) is very diffuse, possibly showing a weak tendency toward increasing K/Ba with evolution (increasing K) and with the MA series rocks plotting generally on the low side of the cloud of points. Barium is somewhat higher in the MA series (table 5). Ca/Sr falls (fig 26) with evolution (falling Ca) and there is a slight tendency for the MA series to be located on the low side of the trend. Strontium is generally a little higher for the MA series than for the AC series, (table 5).

PETROGENESIS

Introduction

In assessing the possible causes of variation in the rock types observed in the dike swarm, possible mechanisms may be suggested and evaluated to the extent permited by the available data. In so doing, it is possible to evaluate what further data will be needed to come up with a more final evaluation of possible mechanisms. The possible mechanisms may be broadly classified as

as being of two types: 1) deep processes involving magma generation and modification of this magma during transfer to higher levels, and 2) high-level porcesses involving modification of this magma in relatively near surface magma chambers after transfer from the deep source. During the discussion, the distinction between closed system (no material transfer to or from the country rock) and open system (varying degrees of material transfer to or from the coutry rock) conditions of the magma must be kept in mind when considering the different possible processes.

Magma generation by partial or complete melting of the mantle or lower crust may be expected to give rise to a great variety of primitive magmas (using the term primitive in the sense of O'Hara, 1965) depending on the depth of magma generation (pressure), the local thermal conditions at the time of magma generation (temperature), and the nature of the source material (composition): e.g. O'Hara (1968), Green and Ringwood (1967). The conditions of rise of the primitive magma may also be considered as deep processes controling the composition and condition of the magma which is finally supplied to the high-level environment and then modified by high-level processes before final intrusion or solidification in the magma chamber. The system may be open or more or less closed allowing operation of mechanisms ranging from zone refining (e.g. Harris, 1957) to varying lesser degrees of liquid/wall-rock equilibration. In the closed system case (although not restricted to that case) crystal fractionation is probably dependent on crystal/liquid equilibria under polybaric/polythermal conditions (e.g. Jamieson, 1970).

Crystal fractionation, considered by many to be the most important mechanism of magma evolution at high levels is in essence very simple. The actual operation of this mechanism can,

however, be complicated by many factors. Changes in total pressure, temperature, and partial pressure of water for example can cause significant changes in the assemblage of minerals being removed from the magma (e.g. O'Hara, 1968, Brown and Schairer, 1971, Osborne, 1962, Holloway and Burnham, 1972). Changes from quiescent to turbulent conditions of differentiation may homogenize a zoned magma chamber or return previously fractionated phases to the melt (e.g. Wright and Fiske, 1971). These already fractionated phases could be incorporated in the magma as cognate xenocrysts (or xenoliths), or, partially to completely resorbed, effectively producing a new parental magma. New primitive magma could be added to the system at any time (Wright and Fiske, 1971). Addition of wall-rock material and/or wall-rock equilibration at high level may also change the composition of the magma. The effects of all of these possibilities may be overprinted to varying degrees by post-emplacement deuteric alteration and/or introduction of country rock fluids.

High-Level Processes

Despite the multitude of alternatives and their possible clouding effect, a crystal-fractionation hypothesis must be considered as a mechanism of major importance in the evolution of the Crazy Mountains magma(s) at high level. This is suggested by the abundance of porphyritic rocks (underestimated in table 3 because of the selection of aphyric rocks whenever possible for analysis), the observed phenocryst assemblage, and the chemical data presented above.

Fractionation and/or accumulation of varying proportions of the observed phenocryst suite (i.e. plagioclase, clinopyroxene, amphibole, an ore mineral, apatite and minor olivine) could well be responsible for the observed chemical variation. These minerals taken collectively are rich in CaO, MgO, FeO, and P_2O_5 and poor in

SiO_2, Al_2O_3, Na_2O, and K_2O. The removal of various proportions of these constituents can clearly explain the variation of oxide concentrations described above (i.e. falling CaO, MgO, FeO and P_2O_5, and rising SiO_2, Al_2O_3, Na_2O, and K_2O). A specific illustration of this is provided by P_2O_5, variation of which must be almost entirely due to the separation of apatite. Basic members of the series contain no phenocryst apatite and are relatively P_2O_5 poor. A gradual (and not extremely marked rise in P_2O_5 is seen in more evolved mafic rocks and after apatite becomes a phenocryst phase (in less evolved salic rocks) the P_2O_5 content falls off gradually. While the case is theoretically simple because only one fractionating phase is involved, it is probably complicated by trapping of apatite by other phenocryst phases. In a study of the thin sections it was noted that the phenocryst apatite in the more evolved rocks is most commonly found included in other phenocrysts. The inclusion of apatite in other phases means that apatite accumulation/fractioation is partially controlled by the behavior of other phases. This effect masks to some extent the ideal trend.

Trace element data also support the importance of crystallization fractionation in the evolution of the Crazy Mountains dike rocks. Ca/Sr ratios fall regularly with evolution of the series while Sr remains more or less the same. This indicates that Sr is being systematically excluded from the fractionated phases. This is reasonable since published distribution factors (e.g. Berlin and Henderson, 1968, 1969, Brooks, 1968, and Philpotts and Schnetzler, 1970) indicate that only plagioclase will fractionate Sr. The fractionation of clinopyroxene and amphibole could well obscure the effect of plagioclase (Berlin and Henderson, 1968, and Brooks, 1968). Potassium/Rubidium ratios also suggest the importance of crystal fractionation, particularly of amphibole and/or plagioclase

(Hart and Aldrich, 1967, Murthy and Griffin, 1970) in explaining the observed concentration of Rb relative to K. Other crystallizing phases would have little effect on the ratios as they accept neither potassium nor rubidium in significant amounts. Potassium/barium ratio behavior for the rocks may be explained on similar grounds (Philpotts & Schnetzler, 1970).

Two other points can be discussed briefly. The possible role of amphibole in genesis of the dike rocks deserves special mention, not only as a phase which if removed helps explain the geochemical variation of the series by crystal fractionation (particularly the AC series with its relatively strong silica enrichment trend, e.g. Brown and Schairer, 1971) but as one which is resorbed could be responsible for the generation of MA series magmas from AC series magmas (e.g. Bowen, 1928, Yoder and Tilley, 1962). Because of the importance of amphibole as a phenocryst phase in many of the described and analysed rocks (table2), and the common presence of amphibole rich xenoliths and extremely large amphibole crystals, some of which may be cognate, amphiboles take on special significance and deserve special attention in future studies of these rocks.

Another problem that deserves attention is the question of the nature of alteration of the dikes. The author has observed textural and mineralogical variation between groundmasses of dikes of similar chemical composition intruded into different environments (e.g. the presence of more hydrous phases such as biotite and chlorite in rocks intruded into sediments contrasted with less hydrous phases such as amphibole in rocks intruded into the stock or other dikes). Valuable information on the conditions of dike intrusion and the nature of dike alteration processes, particularly regarding addition or loss of material, might be expected to emerge from a study concentrating on single

dikes which are sufficiently extensive to cut the stock, metamorphic aureole and sediments, or by piecing together the necessary information from single dikes which cut two of the three environments.

Possible Primitive Magma(s)

Two of the analyses from this study (70105 and 7084, see table4) deserve discussion as primitive magma candidates. They are basic, aphyric, and difficult to relate to each other by reasonable high-level processes, suggesting that they could represent two liquids corresponding to two different primitive magmas. There is for example no mechanism available for doubling the alkali content (or alternatively having it depending on which magma is assumed to be parental) which produces acceptable simultaneous variation in the other elements. In order to explain the observed two-fold increase in alkalis, 50% of the 70105 liquid must crystallize to an alkali free assemblage, and the residual liquid be removed to give a derivative magma. There is no concievable suit of minerals which will do this and also increase the MgO and FeO content. In fact, it has not been possible to find any mineral or combination of minerals, actually found as phenocrysts, which will fulfill the necessary requirements, In addition, the tie lines connecting these two compositions on most variation diagrams deviate markedly from the general fractionation trends which have been discussed above.

A range of primitive magmas might be expected to be present in the Crazy Mountains because of the extremely diverse nature of the basic rocks that have been discovered to date. Among these rocks there may be other candidates for primitive magmas but it is fruitless to discuss the subject further because of the scarcity of descriptive data.

When more data on the basic members of the Crazy Mountains

suit are available, two conditions must be met in order to test the hypotheses of multiple primitive magmas. One is that the mafic rocks that are thought to be primitive must not be obviously related to each other by reasonable high-level processes. The second is that the rocks should not be suspected of being of cumulate origin, a particularly important consideration for the plutonic rocks of the Big Timber stock.

In summary, it may be noted that most of the rocks described and analyzed in this study can be interrelated by well established processes of crystal fractionation and that at least some of the variation within and possibly between the MA and AC series may be the result of fractionation and/or resorption of significant amounts of amphibole. Mineral analyses, particularly of the amphibole(s), are needed to support these suggestions. On the basis of the few analyses of basic rocks that are available, it is possible to suggest that a range of primitive magmas is present. Two rocks from this study have been shown to be parental candidates but the fact that they are only two in number illustrates the problem involved. More data are needed on basic aphyric rocks. The unravelling of the fine structure of the high-level processes responsible for the diversity of rock types that have been observed necessitates more whole-rock analyses, careful petrographic work on the analysed rocks, and mineral analyses. After the detailed nature of the high-level processes has been determined, the status of the various series and the possibility of multiple parental magmas may be evaluated.

SUMMARY

Data have been presented in the foregoing discuasion concerning the distribution of dikes around the Big Timber stock outside it's metamorphic aureole. In addition, data are presented for

a selected group of these rocks which gives some indication of their chemical and petrographic variation. Based on these data, the intrusive history of the Crazy Mountains igneous complex appears much more intricate than previously thought.

In particular, dikes are not found to be evenly distributed around the periphery of the range, some sectors being more densly populated by dikes than others. Rather than two series of igneous rocks, there seem to be at least three series present (alkali-calcic, mildly alkaline, and peralkaline). These three series have distinctive chemical characteristics and occur in spatial domains (alkali-calcic rocks in the stock and all around the stock, mildly alkaline rocks concentrated in the NS set of dikes and the peralkaline rocks restricted to the north and west of the range). The rocks within the individual series can be related to each other by crystal fractionation of observed phenocryst phases at high level as a major evolutionary process. The causes of observed differences between the series is less clear. Some indication of a range of parental magmas is available but amphibole resorption, particularly as an explanation of the differences between the MA and AC series, may also be suggested.

Most of the proposals made in this report are far from being proven. Without more whole rock analyses, particularly those with known time and space relations, modal data on the analysed rocks and mineral analyses, particularly of amphibole and clinopyroxene from the analysed rocks, little more than speculation is possible. The present study points up these needs and suggests the importance of the mafic rocks of the suite in determining the nature of the original magma(s) and the importance of the evolved rocks in demonstrating evolutionary trends. It is hoped that the data presented in this report will prove useful to future investigators and that the suggestions made, based on these data, will stimulate further study of Crazy Mountains igneous geology.

Apendix A: Sample Preparation and Analytical Procedures

General

The sample is broken with a hammer into 2 inch pieces. These pieces are checked for iron contamination. The pieces are fed into a small jaw crusher with steel plates and crushed to less than 3/8 inch. Approximately 200 ml of sample is split out with a Jones splitter. This material is then ground for 10 minutes in a Speck Shatter Box. The container of the shatter box is of tungsten carbide. To this point then, the major contamination is only from iron, mostly from the jaw crusher. This source of contamination has been circumvented by slabing the sample and putting pieces of the slab directly into the Shatter Box. Tungsten or cobalt, from the shatter box container, is a very minor contaminant because of the low wear resulting from the grinding action of the shatter box and the extreme hardness of the tungsten carbide container. The resulting product from the shatter box grinding is less than 200 mesh. The small grain size is imperative for the X-ray flourescence procedure as accurracy and reproducibility are a function of grain size. The small grain size also improves the results of the fusion technique.

From this less than 200 mesh portion, 4.5 grams of sample, and 0.5 gram phenylformaldehyde are weighed out and put in a 7 dram vial (Brockway Snap Cap) with a small lucite bead. The resulting mixture is a 10% dilution of the original sample, and the phenylformaldehyde serves as a light element plastic binder for the sample powder. The sample is homogenized for 5 minutes in a modified Spex Industries Shakermill. The shaking process homogenizes the sample and binder and the sample is then ready for pressing.

The sample is put in the 1-1/4 inch die which was supplied with the 25 ton press. The sample die is evacuated with a small vacuum pump to remove intrained air and pressed for 10 minutes at 25 tons per quare inch, to yield a coherrent high density pellet. Sample pressing time is kept equal (10 min) and pressing pressure is kept equal (25 tons per square inch) in order to keep the density of the resulting pellets equal. Equal sample density is another factor in improving reproducibility. The dies which are the upper and lower contact surfaces, are polished often to a mirror smooth surface using quarter micron diamond powder on a silk lap. This assures a smooth uniform surface to improve reproducibility, particularly for the light elements where surface effects are important. At this time the sample pellet is fairly coherrent, but it is cured for 10 min. at 110° centigrade to set the phenylformaldehyde binder producing a very strong sample. This sample may be handeled many times without fear of breakage.

Fusion and Solution for Na_2O Analyses

A lithium metaborate fusion is employed in the analysis of Na_2O. One tenth (0.1) gram of sample is mixed with five tenths (0.5) gram of reagent grade anhydrons $LiBO_2$ (G. Fredrick Smith Chemical Co., No. 304). This mixture is rolled on smooth paper to homogenize the sample and flux. The homogenized mixture is carefully placed in a small graphite crucible (Ultra Carbon Corp. No. 815074) and fused in a muffle furnace at 950° C for 10 minutes. The fusion is swirled in the crusible to collect small beads and dumped in 50 ml. of cold 4% Nitric Acid. The nitric acid is in polypropylene beakers in which a small stirring bar has been placed. The beaker is on a magnetic stir plate and is stirring. As soon as the fusion is dumped, a top is placed on the beaker. Stirring is continued for 15 minutes by which time solution is complete. The resulting stock solution is stored in

soda lime bottles with plastic stoppers. This stock solution is useful for flame photometric determination of Na_2O as was done in this study and for atomic absorption determination of other elements (Medlin, Suhr and Bodkins, 1969).

X-ray Fluorescence Analysis

The x-ray fluorescence analysis was performed on pressed pellets and follows the proceedures described by Leake et al. (1969). After determining operating conditions, Table A-1, calibration curves were constructed by counting pellets prepared from standard rocks. A ratioing technique was employed to reduce the effects of instrumental drift. The resulting curve for peak-background (sample)/peak-background (standard) vs. accepted concentration was used to determine concentration in the unknown. The actual data reduction was performed on a Wang 500 desk top computer using a program developed for this purpose (Starmer and Lattman, 1971). This program accepts the following information, counting times, constants for the best fit calibration curve equation and unlimited sets of raw data. The coeficients of the best fit line for the calibration were determined using BMD-02R of the Biomedical Programs package in use on the University Computer Services IBM 360/65 (Dixon (ed.), 1967). Rubidium and Strontium were determined by the method of Hahn-Weinheimer (1965) and Fairbairn (1966). This method uses the factor 1/B as an estimate of the mass absorption coeficient of the sample. The unknown is compared directly to one standard and concentration determined from the equation:

$$X^{sa} = \frac{(cps)^{sa}}{(cps)^{std}} \times \frac{(1/b)^{sa}}{(1/b)^{std}} \times X^{std}$$

where:

X = concentration, sa = sample, std = standard,
cps = peak cout rate - background cout rate,
1/b = 1.0 / background cout rate.

Flame Photometric Determination of Na_2O

Soda was determined by flame photometry using accepted techniques. A 1:20 dilution was found to be adequate. A working curve was constructed using standard rock solutions and emission of the unknowns was compared to the curve. A Bekman DU-2 was used for the determinations and the emission line used was 589 nm with an H_2-O_2 total consumption burner.

Table 1. Relevant characteristics of the Proposed Series

AC series

saturated to mildly oversaturated (3)

K_2O:Na_2O generally greater than 1:2

magnesian

femic members CaO rich compared to the MA series (range 11-5%)

subdivisions	basis (DI^1)
basalt	less than 30
trachybasalt	30-45
trachyandesite	45-65
quartzlatite	65-75
rhyodacite	greater than 75[a]

a) rhyolites seem likely to have a lower DI limit of 85-90 but none are known at this time

MA series

mildly undersaturated (2)

K_2O:Na_2O generally less than 1:2

relatively magnesian

femic members CaO poor relative to the AC series (range 4-7.5%)

subdivisions	basis (DI^1)
hawaiite	30-45
mugearite	45-65
mafic trachyte	65-75
trachyte[b]	greater than 75

b) "trachytes" with greater than 10% ne are phonolites

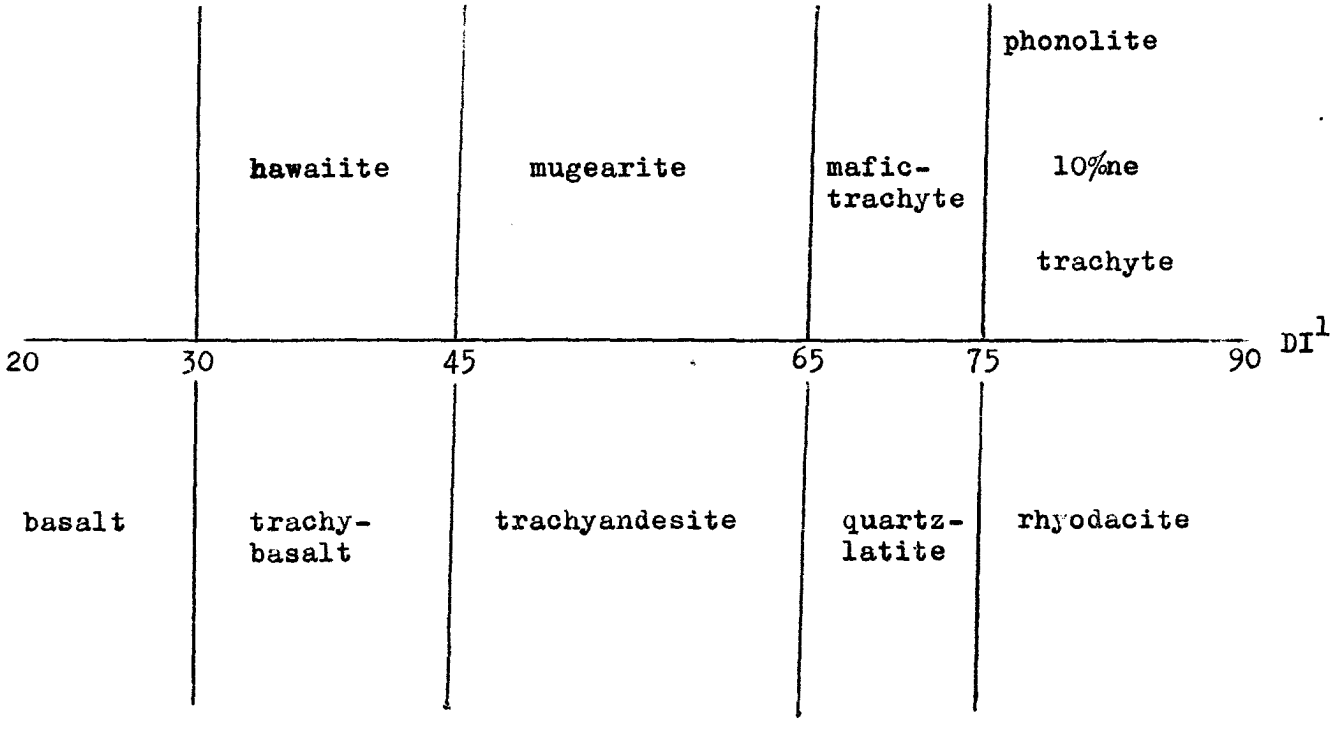
(1) DI is th differentiation index of Thornton and Tuttle (1960) and equals the sum of normative q, ab, or, ne, and lc.

(2) Nepheline normative with all iron as Fe_2O_3

(3) Hypersthene normative with all iron as Fe_2O_3

Table 2. Chemical Classification Scheme

Rocks are classified by determining the degree of silica saturation with all iron as Fe_2O_3 and then named on the basis of the DI[1] value.



1) DI is the differentiation index of Thornton & Tuttle (1960) and equals the sum of normative q, ab, or, ne and lc.

Table 3. Descriptions of the analysed rocks. Explanation of the symbols is given on the last page of the table.

Smpl.No	Chemical Name	Texture	Phenocryst Mineralogy						groundmass grain size (mm)
			Plag.	Cpx	Ol	Amph	Ore	Apatite	
70105	basalt	a	-	-	-	-	-	-	0.2
69D16	trachybasalt	p	-	7(3.5)	-	7(4.0)	+	+	0.10
70112	trachybasalt	p	5(3.5)	4(2.5)	-	-	+	-	0.20
7082	trachybasalt	mp	7(1.5)	6	2	-	-	-	0.20
70132	trachybasalt	mp	-	3(2.0)	-	2(1.5)	-	-	0.30
69S32	trachybasalt	ca	-	-	-	-	-	+	0.40
69S33	trachybasalt	a	tr	-	-	-	-	+	0.20
69S9	trachyandesite	p	24(3.0)	6(3.0)	tr	-	+	+	0.05
70121	trachyandesite	p	13(3.0)	-	1(0.5)	5(5.0)	±	-	0.02
707	trachyandesite	p	16(3.0)	5(4.0)	2(1.0)	-	+(0.5)	-	0.10
7037	trachyandesite	mp	5(1.0)	-	-	-	+	+	0.20
7097	trachyandesite	p	-	9(3.5)	-	-	+	+	0.40
7014	trachyandesite	p	tr(3.0)	4(2.0)	-	-	+	+	0.30
70118	trachyandesite	mp	tr	tr	-	tr	+	+	0.30
70125	trachyandesite	p	12(8.0)	5 (2.5)	2(1.0)	-	+(0.5)	+	0.20
70114	trachyandesite	p	10(5.0)	7(2.5)	2	-	+(0.5)	+	0.08
70123F	trachyandesite	p	12(4.0)	5(3.0)	-	-	+(0.5)	+	0.02
7040E	trachyandesite	mp	2(1.0)	7(2.0)	-	-	-	-	0.20
70123M	trachyandesite	mp	-	1(1.0)	-	5(1.5)	+	+	0.20
7096	trachyandesite	p	5(4.0)	2(6.0)	-	-	+	+	0.20
69S25	trachyandesite	p	tr(3.0)	?tr	-	tr(7.5)	tr	+	0.20

Table 3 cont.

Sample no.	remarks
70105	abundant ore, amygduals with chlorite and calcite
69D16	some free calcite
70112	phenocryst plagioclase with altered cores, glomeroporphiritic texture, red-brown groundmass biotite
7082	cpx and olivine phenocrysts altered small zoned plag. phenocrysts, red-brown groundmass biotite
70132	-
69S32	phenocryst plagioclase laths, very minor interstitial quartz, red-brown amphibole in groundmass
69S33	simple plag. laths altered, minor interstitial quartz, red-brown groundmass amph.
69S9	olivine phenocrysts altered, plag. large fresh glomeroporphiritic (some anhedral cores), green and red-brown groundmass amphibole
70121	questionable altered amphibole, large enhedral plag. laths, red-brown groundmass amphibole
707	simple plag. laths, red-brown biotite in groundmass
7037	small simple plagioclase, green groundmass amphibole
7097	plag. phenocrysts very altered, very minor interstitial quartz
7014	simple plag. phenocrysts, red-brown groundmass amphibole
70118	large phenocryst plag. laths, red-brown groundmass amphibole
70125	altered olivine phenocrysts, complexly zoned glomerophyric plag., red-brown groundmass amphibole, interstitial quartz common
70114	altered olivine phenocrysts, some plag. with anhedral cores, red-brown biotite in groundmass, interstitial quartz
70123F	large complexly zoned plag, green amphibole in groundmass, interstitial quartz
7040E	simple phenocrysts of plag., red-brown groundmass amphibole
70123M	red-brown groundmass amphibole, minor interstitial quartz
7096	red-brown/brown-yellow amphibole and red-brown biotite in groundmass, minor interstitial quartz
69S25	large plag. laths altered along fractures, red-brown biotite in groundmass

Table 3. cont.

Smpl.No	Chemical Name	Texture	Phenocryst Mineralogy						groundmass grain size(mm)
			Plag.	Cpx	Ol	Amph	Ore	Apatite	
7040C	trachyandesite	p/mp	4(2.5)	-	-	10(2.0)	+	+	0.20
70136	trachyandesite	ca/p	?2	-	-	-	-	+	0.40
70124	trachyandesite	p	9(4.0)	3	-	4(2.0)	+	+	0.10
7019	quartzlatite	p	-	-	-	12(4.5)	+	+	0.10
703	quartzlatite	a	tr	-	-	-	-	+	0.20
7027	rhyodacite	ca	tr	-	-	-	-	+	0.30
7084	hawaiite	ca	-	-	-	-	tr	-	0.30
7067	hawaiite	p	-	5(5.0)	-	-	+	-	0.20
7080E	mugearite	a	-	-	-	-	-	-	0.20
69S46	mugearite	ca	-	tr(0.1)	-	-	-	-	0.50
7080C	mugearite	ca	-	-	-	-	-	-	0.40
69D40	mugearite	ca	-	-	-	-	-	-	0.40
7059	mugearite	a	-	-	?	-	-	-	0.10
69S48	mugearite	p/mp	-	16(3.0)	2 alt (2.0)	-	+	+	0.20
69S42	mugearite	p	10	2	-	-	+	+	0.20
7020	mugearite	p	6(7.0)	5(3.0)	2(4.0)	-	+	+	0.02
7078	mugearite	ca	-	-	-	-	-	-	0.60
70144	mugearite	ca	-	-	-	tr	tr	+	0.60
70104	mafic trachyte	a	-	-	-	-	-	-	0.20
7088	mafic trachyte	ca	-	-	-	-	-	-	0.30
70138	mafic trachyte	p	-	tr(2.5)	-	3(5.0)	-	-	0.20
69S36	mafic trachyte	mp	5(0.9)	tr	-	-	-	-	0.20

Table 3 cont.

sample No.	remarks
7040C	relatively simple plag. phenocrysts, brown-yellow amphibole + quartz in groundm.
7013G	large plag. laths, brown-yellow biotite and amphibole in groundmass
7012A	altered CPX phenocrysts, simple plag. laths, minor quartz in groundmass
7019	green "microtites" of amphibole in groundmass, interstitial ploycrystaline quartz
703	green amphibole in groundmass, plycrystaline interstitial quartz
7027	green amphibole in groundmass, masses of polycrystaline quartz,"xenocryst" of polycrystaline sanadine with altered grainboundaries
7084	-
7067	anhedral altered plag. phenocrysts, possibly 2% altered amphibole, red-brown biotite in groundmass
7080E	amygduloidal calcite abundant
69S46	red-brown groundmass amphibole
7080C	-
69D40	abundant groundmass biotite, minor interstitial quartz
7059	green groundmass amphibole, quartz present
69S48	altered olivine phenocrysts, glomeroporphs of cpx with continuous mantles, brown-green-yellow groundmass amphibole
69S42	altered plagioclase and cpx phenocrysts, altered feldspar phenocrysts, green groundmass biotite
7020	phenocryst plag. with altered anhedral cores and some fresh with complex zones red-brown groundmass amphibole "microtites"
7078	red-brown groundmass amphibole
70144	brown-yellow groundmass amphibole
70104	green groundmass biotite
7088	abundant green-brown groundmass biotite, quartz present
7013B	red-brown amphibole and biotite in groundmass
69S36	simple plag. phenocryst, red-brown groundmass biotite, strong carbonate alteration

Table 3 cont.

Explanation of the symbols used in the table.

Names are given based on the chemical classification table 2.

Texture is denoted by a, aphyric, ca, coarse-aphyric, p, porphyritic, and mp, microporphyritic (see text for definition of terms).

Phenocrysts are represented by two numbers indicating estimated volume percent and maximum dimension in mm (in parenthesis), tr indicates present in amounts considerably less than 1%, --- indicates not observed and for ore and apatite present (+) or not observed (-) with estimated maximum dimension of the observed ore where noted in parenthesis is used.

Groundmass grainsize is given in mm.

Notes are included under remarks where information of interest was not suitable for tabulation.

Table 4. Major element chemical analyses, CIPW norms and selected geochemical parameters.

Sample No.	70105	69D16	70112	7082	70132	69S32	69S33	69S9	70121	707	7037	7097	7014
SiO_2	46.93	49.84	51.44	51.59	52.56	52.85	53.93	51.99	52.37	52.43	52.72	52.76	53.77
TiO_2	1.91	1.22	1.72	1.17	1.34	1.09	1.04	1.44	1.37	1.38	1.44	1.43	1.40
Al_2O_3	13.67	13.44	12.98	13.24	14.29	12.85	14.55	14.37	14.11	14.35	15.99	13.92	14.49
Fe_2O_3	10.07	10.88	11.00	9.52	10.20	9.89	8.99	9.52	11.24	11.32	9.52	10.99	12.35
MnO	0.12	0.20	0.16	0.11	0.14	0.12	0.12	0.14	0.08	0.11	0.11	0.12	0.14
MgO	10.92	8.09	7.29	11.48	9.15	9.20	8.55	6.59	4.94	6.58	4.59	6.50	5.18
CaO	11.09	8.84	8.27	7.62	6.81	7.82	4.83	8.22	7.94	6.89	5.77	6.76	5.76
Na_2O	2.30	3.60	2.78	2.86	4.00	3.22	3.36	3.27	3.63	3.66	4.51	3.92	4.15
K_2O	0.97	1.42	1.81	1.80	0.75	2.49	3.53	1.70	1.77	1.86	2.22	2.55	2.60
P_2O_5	0.25	0.70	0.38	0.27	0.38	0.36	0.32	0.43	0.40	0.43	0.26	0.37	0.42
BaO	0.20	0.27	0.17	0.13	0.13	0.20	0.31	0.16	0.16	0.31	0.32	0.18	0.77
SrO	0.11	0.13	0.10	0.11	0.12	0.13	0.05	0.11	0.09	0.09	0.09	0.18	0.09
Total	98.54	98.63	98.10	99.90	99.87	100.17	99.58	97.94	98.01	99.23	97.54	99.68	100.43

Table No. 4 cont.

Sample No.	70105	69D16	70112	7082	70132	69S32	69S33	69S9	70121	707	7037	7097	7014
Q	0.00	0.00	5.22	0.00	1.83	0.00	0.19	4.09	5.39	3.61	1.52	0.83	3.49
Or	5.73	8.39	10.70	10.64	4.43	14.72	20.86	10.05	10.46	10.99	13.12	15.07	15.37
Ab	19.46	30.46	23.52	24.20	33.85	27.25	28.43	27.67	30.72	30.97	38.16	33.17	35.12
An	24.11	16.32	17.59	17.97	13.82	13.26	14.19	19.51	16.98	17.23	16.83	12.86	13.23
Ne	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ol	7.77	1.86	0.00	1.94	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hy	7.52	10.14	12.31	20.42	19.56	15.43	19.40	11.14	6.56	12.86	9.14	10.92	9.87
Di	18.50	15.87	12.60	11.65	6.96	16.03	4.08	11.37	12.38	7.99	4.94	11.36	6.54
DI	25.19	38.85	39.44	34.84	40.11	41.96	49.48	41.81	46.56	45.57	52.80	49.07	53.98
SI mod	46.96	35.32	33.47	45.88	39.64	38.71	36.34	32.74	24.15	29.52	23.08	28.43	22.48

Table 4 cont.

Sample No.	70118	70125	70114	70123F	7040E	70123M	7096	69S25	7040C	70136	124
SiO_2	53.92	54.72	54.81	55.08	55.73	55.95	56.36	56.42	56.72	57.79	59.07
TiO_2	1.71	1.38	1.61	1.30	1.31	1.34	1.57	1.09	1.56	0.99	0.92
Al_2O_3	14.96	14.83	16.24	16.44	13.13	15.70	15.16	16.80	16.15	16.57	15.90
Fe_2O_3	10.49	10.70	9.64	10.64	10.43	9.14	10.64	7.04	10.21	10.26	8.12
MnO	0.12	0.11	0.14	0.14	0.10	0.14	0.11	0.17	0.10	0.14	0.16
MgO	5.36	5.09	5.24	5.24	6.62	4.11	4.77	5.16	3.36	3.75	3.71
CaO	5.27	5.81	5.72	6.21	6.26	5.42	5.75	5.36	5.23	5.58	4.88
Na_2O	4.79	4.51	4.10	3.56	3.92	4.68	4.35	4.87	4.46	4.14	4.14
K_2O	2.36	2.39	2.96	2.67	3.13	2.93	2.58	2.96	2.78	3.12	3.40
P_2O_5	0.32	0.37	0.35	0.35	0.29	0.32	0.35	0.46	0.34	0.37	0.31
BaO	0.16	0.17	0.19	0.18	0.15	0.16	0.16	0.32	0.18	0.24	0.26
SrO	0.11	0.11	0.11	0.13	0.09	0.10	0.18	0.13	0.08	0.11	0.13
Total	99.57	100.18	101.11	101.94	101.16	99.99	101.98	100.78	101.17	103.06	101.00

Table 4 cont.

Sample No.	70118	70125	70114	70123F	7040E	70123M	7096	69S25	7040C	70136	124
Q	1.04	3.08	2.34	5.50	2.73	3.06	5.16	0.48	6.46	6.80	8.28
Or	13.95	14.12	17.49	15.78	18.50	17.32	15.25	17.49	16.43	18.44	20.09
Ab	40.53	38.16	34.96	30.12	33.17	39.60	36.81	41.21	37.74	35.03	35.03
An	12.35	13.16	17.17	20.99	8.99	13.18	4.22	15.24	15.84	17.42	14.76
Ne	o.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ol	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hy	10.88	9.26	11.41	11.52	10.52	7.32	9.07	10.62	7.14	7.28	7.19
Di	5.31	7.37	3.53	3.31	12.87	6.29	6.06	4.81	2.66	4.44	4.43
DI	55.52	55.36	54.52	51.40	54.40	59.98	57.22	59.18	60.63	60.27	63.41
SI mod	24.42	23.54	24.98	24.90	28.71	20.61	22.42	26.70	16.98	18.52	19.99

Table 4 cont.

Sample No.	7019	703	7027	7084	7067	7080E	69S46	7080C	69D40	7059	69S48
SiO_2	60.34	64.33	68.00	45.94	41.79	47.50	48.68	50.23	50.35	50.45	50.54
TiO_2	0.81	0.62	0.55	2.17	1.79	1.50	1.85	1.48	1.96	1.66	1.09
Al_2O_3	14.42	15.65	15.15	13.49	14.03	15.45	12.22	15.20	15.85	14.31	13.67
Fe_2O_3	8.59	5.54	3.32	12.53	14.07	10.55	10.66	11.31	9.93	11.03	8.59
MnO	0.12	0.11	0.03	0.13	0.16	0.12	0.14	0.17	0.13	0.15	0.13
MgO	3.32	1.42	1.43	12.56	9.03	8.29	14.21	7.31	7.34	8.93	8.73
CaO	5.06	3.82	2.78	5.59	6.22	7.46	5.88	5.46	5.56	6.92	7.14
Na_2O	4.36	4.58	5.11	4.94	3.83	5.16	4.37	5.47	4.51	3.52	4.82
K_2O	3.25	3.23	3.07	1.22	1.70	2.74	2.05	2.00	1.63	2.63	2.68
P_2O_5	0.28	0.22	0.11	0.36	0.35	0.33	0.35	0.33	0.32	0.41	0.37
BaO	0.31	0.27	0.27	0.65	0.27	0.66	0.28	0.19	0.45	0.20	0.32
SrO	0.12	0.11	0.12	0.16	0.14	0.15	0.15	0.17	0.12	0.16	0.23
Total	100.97	99.90	99.94	99.71	100.38	99.91	100.84	99.32	98.15	100.37	98.31

Table 4 cont.

Sample No.	7019	703	7020	7084	7067	7080E	69S46	7080C	69D40	7059	69S48
Q	10.18	16.53	19.38	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Or	19.21	19.09	18.14	7.20	10.05	16.19	12.12	11.82	9.63	15.54	15.84
Ab	36.89	38.76	43.24	32.07	32.41	20.46	30.20	40.24	38.16	29.79	29.61
An	10.18	12.61	9.34	11.03	16.07	10.90	7.67	11.02	18.19	15.48	7.75
Ne	0.00	0.00	0.00	5.27	0.00	12.57	3.67	3.27	0.00	0.00	6.05
Ol	0.00	0.00	0.00	19.61	7.70	9.20	21.19	10.16	6.43	8.80	9.37
Hy	4.07	2.10	2.57	0.00	8.69	0.00	0.00	0.00	8.32	5.43	0.00
Di	9.05	3.10	2.15	6.95	6.06	16.21	11.09	7.98	1.67	9.19	18.05
DI	66.28	74.38	80.76	44.55	42.46	49.22	45.99	55.34	47.80	45.33	51.50
SImod	17.79	9.99	11.35	41.81	33.17	32.28	47.02	29.29	32.74	35.71	36.43

Table 4 cont.

Sample No.	69S42	7020	7078	70114	70104	7088	70138	69S36
SiO_2	51.54	52.50	53.29	53.84	52.95	56.28	56.34	56.93
TiO_2	1.58	1.20	1.70	1.15	1.47	1.17	1.41	0.96
Al_2O_3	14.87	16.04	17.11	16.93	15.49	17.04	15.30	15.35
Fe_2O_3	8.24	9.81	10.13	9.09	10.15	8.05	8.25	6.55
MnO	0.11	0.12	0.13	0.13	0.14	0.13	0.10	0.10
MgO	6.20	4.85	4.13	4.27	5.47	2.73	4.85	3.84
CaO	5.93	6.31	4.93	4.50	3.71	3.67	3.31	4.64
Na_2O	5.21	5.38	5.15	5.23	6.47	6.33	6.48	6.07
K_2O	3.31	3.31	2.33	2.59	2.15	2.62	2.78	2.70
P_2O_5	0.31	0.47	0.33	0.37	0.33	0.36	0.48	0.24
BaO	0.40	0.26	0.15	0.24	0.21	0.22	0.22	0.43
SrO	0.08	0.18	0.27	0.14	0.28	0.15	0.12	0.09
Total	97.78	100.43	99.62	98.48	98.82	98.75	99.64	97.90

Table 4 cont.

Sample No.	69S42	7020	7078	70114	70104	7088	70138	69S36
Q	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Or	19.56	19.56	13.77	15.31	12.71	15.48	16.43	15.96
Ab	34.49	35.91	43.58	44.26	50.62	53.56	54.83	51.36
An	7.41	9.84	16.69	15.07	6.88	10.35	4.45	6.66
Ne	5.20	5.21	0.00	0.00	2.23	0.00	0.00	0.00
Ol	6.81	4.50	0.99	1.39	8.04	1.11	7.18	1.71
Hy	0.00	0.00	8.36	7.86	0.00	4.21	0.00	2.47
Di	12.35	12.20	1.10	1.69	4.64	2.16	3.95	10.02
DI	59.25	60.68	57.35	59.56	65.56	69.05	71.26	67.32
SI mod	28.01	21.68	19.93	21.06	23.55	14.43	22.52	20.75

Table 5. Trace elements (Rb, Sr, Ba in ppm, K and Ca in weight percent).

AC series

Sample No.	K	Ca	Rb	Sr	Ba	K/Rb	Ca/Sr	K/Ba
70105	0.81	7.93	---[1]	932	1765	---	85	5
69D16	1.18	6.32	---	1089	2449	---	58	5
70112	1.50	5.91	26	885	1480	578	67	10
7082	1.49	5.44	31	894	1184	482	61	13
70132	0.62	4.87	---	1048	1180	---	46	5
69S32	2.07	5.59	27	1110	1794	765	50	12
69S33	2.93	3.45	64	434	2762	458	80	11
69S9	1.41	5.88	35	957	1474	403	61	10
70121	1.47	5.68	---	740	1391	---	77	11
707	1.54	4.92	20	759	1166	772	65	13
7037	1.84	4.13	20	724	2893	921	57	6
7097	2.12	4.83	50	827	1588	423	58	13
7014	2.16	4.05	41	769	1528	526	53	14
70118	1.96	3.77	27	913	1478	725	41	13
70125	1.98	4.15	32	877	1549	620	47	13
70114	2.46	4.09	75	968	1720	328	42	14
70123F	2.22	4.44	29	1071	1586	764	41	14
7040E	2.60	4.48	31	794	1386	838	56	19
70123M	2.43	3.88	43	882	1419	566	44	17
7096	2.14	4.11	32	1504	1469	669	27	15
69S25	2.46	3.83	48	1097	2828	512	35	9
7040	2.31	3.74	---	706	1591	---	53	15
70136	2.59	3.90	69	926	2187	375	43	12
70124	2.82	3.49	66	1104	2296	428	32	12
7019	2.70	3.62	86	1038	2679	314	35	10
703	2.68	2.73	75	897	2383	357	30	11
7027	2.55	1.99	58	1025	2426	439	19	11

1) --- indicates amount present below limit of detection

Table 5 cont.

MA series

Sample No.	K	Ca	Rb	Sr	Ba	K/Rb	Ca/Sr	K/Ba	
7084	1.01	4.00	---	1374	5846	---	29	2	
7067	1.41	4.45	---	1200	2401	---	37	6	
7080E	2.27	5.33	30	1291	5955	758	41	4	
69S46	1.70	4.20	34	1251	2502	500	34	7	
7080C	1.66	3.90	---	1405	1661	---	28	10	
69D40	1.36	3.98	72	1043	4017	188	38	3	
7059	2.18	4.95	---	1393	1754	---	36	12	
69S48	2.22	5.11	25	1959	2844	890	26	8	
69S42	2.75	4.24	43	683	3547	639	62	8	
7020	2.75	4.51	52	1559	2292	528	29	12	
7078	1.93	3.52	---	2250	1354	---	16	14	
70144	2.15	3.22	28	1221	2115	768	26	10	
70104	1.78	2.65	---	2345	1878	---	11	10	
7088	2.17	2.62	33	1269	2004	659	21	11	
70138	2.31	2.37	30	992	1992	769	24	12	
69S36	2.24	3.32	39	777	3860	575	43	6	
Rocks from Stock Area (see Tappe 1966 for smpl. descriptions)									
A263	0.99	7.40	27	546	938	366	136	11	
A253	1.12	6.65	36	800	664	311	83	17	
A083	1.27	5.64	39	812	1106	325	69	11	
A203	2.00	5.13	39	1113	1647	513	46	12	IP
A114	2.26	5.16	28	853	2360	806	60	10	IP
C083	2.31	4.20	57	802	1477	405	52	16	andesite
A024	2.61	2.51	45	865	1917	579	29	14	terminal phase
C113	2.64	3.32	79	827	1630	334	40	16	andesite
B402	2.82	1.45	62	986	2798	455	15	10	aplite
A034	2.89	2.52	51	853	1942	566	30	15	terminal phase
C103	3.20	2.71	77	702	1879	416	38	17	andesite
B462	3.42	1.50	104	635	1599	329	24	21	aplite

Table 6.

Precission based on indicated reproducibility for three samples and accuracy based on determination of GSP-1 in the same manner as the unknowns.

	GSP-1 this study	GSP-1 average[1]	pooled standard deviation for 3 samples[2]	% relative deviation[5]
SiO_2	67.51	67.28	0.43(21)[3]	0.79
TiO_2	0.70	0.70	0.01(18)	1.20
Al_2O_3	15.60	15.11	0.16(21)	1.19
Fe_2O_3total	5.58	4.33	0.05(12)	0.75
MnO	0.04	0.05	0.08(18)	3.92
MgO	1.27	0.96	0.35(18)	8.89
CaO	2.21	2.03	0.08(18)	1.49
Na_2O	2.77	2.88	0.25(8)[4]	8.68[4]
K_2O	6.04	5.49	0.09(18)	2.85
P_2O_5	0.23	0.29	0.05(18)	9.29
Ba[6]	1455	1360	116 (24)	8.00
Rb	240	247	10 (17)	16.70
Sr[6]	235	247	55 (17)	6.51

1) Flanagan, 1969

2) pooled variance = $S_p^2 = \dfrac{(n_1-1)\,S_1^2 + (n_2-1)\,S_2^2 + (n_3-1)\,S_3^2}{N-3}$

for three samples: n_i = number of determinations for sample i, i=1,3

S_i^2 = variance for sample i, i=1,3

N = total number of observations

pooled standard deviation = sp = S_p^2

3) total number of determinations

4) based on 8 determinations of GSP-1

5) average value of observed relative deviations

Table 6 cont.

6) several determinations were found to be in good agreement with direct reading optical spectrographic determinations by N. H. Suhr, Penn. State (F.L. Koucky, written communication, 1971).

Table AI.

XRF analysis operating conditions for the General Electric XRD-6, Univ. of Cincinnati, August 1971.

Element	Peak[1]	Backgr.[2]	Tube	KV	ma	Gain	El[3]	Eu[3]	Xtal.	slits	Counter Tube
Mg	Ka	-1.08	Cr	40	30	16+4.5f	2.0	7.0	ADP	0.005	FPC[5]
Al	Ka	-2.10	Cr	40	30	12+4.5f	1.0	6.0	PET[4]	0.005	FPC
Si	Ka	+1.37	Cr	40	30	12+4.5f	2.0	7.0	PET	0.005	FPC
P	Ka	+3.58	Cr	50	40	12+4.5f	1.6	6.0	PET	0.020	FPC
K	Ka	+3.96	Cr	40	20	12+4.5f	3.0	9.0	PET	0.005	FPC
Ca	Ka	+3.18	Cr	40	20	12+4.5f	4.0	10.0	PET	0.005	FPC
Ti	Ka	-2.03	Cr	40	30	12+4.5f	8.0	14.0	PET	0.005	FPC
Mn	Ka	-2.45	W	50	30	12	2.0	9.0	LiF_{220}	0.020	FPC[2]
Fe	Ka	+6.20	W	40	20	12	7.0	14.0	LiF_{220}	0.005	FPC[2]
Rb	Ka	+1.00 -1.00	W	55	20	12+4.5f	1.0	7.0	LiF_{220}	0.005	SCINT.
Sr	Ka	+1.00 -1.00	W	55	20	12+4.5f	1.0	8.0	LiF_{220}	0.005	SCINT.
Ba	Lß	+2.00	W	60	20	12+4.5f	5.5	14.5	LiF_{220}	0.005	FPC

1) Empiracly found at half peak height

2) May also be counted with Xe-proportional Counter

3) May be different because of new line voltage than stated and should be redetermined

4) Might be effectively replaced by KAP

5) FPC - flow proportional counter, SC - scintallation counter

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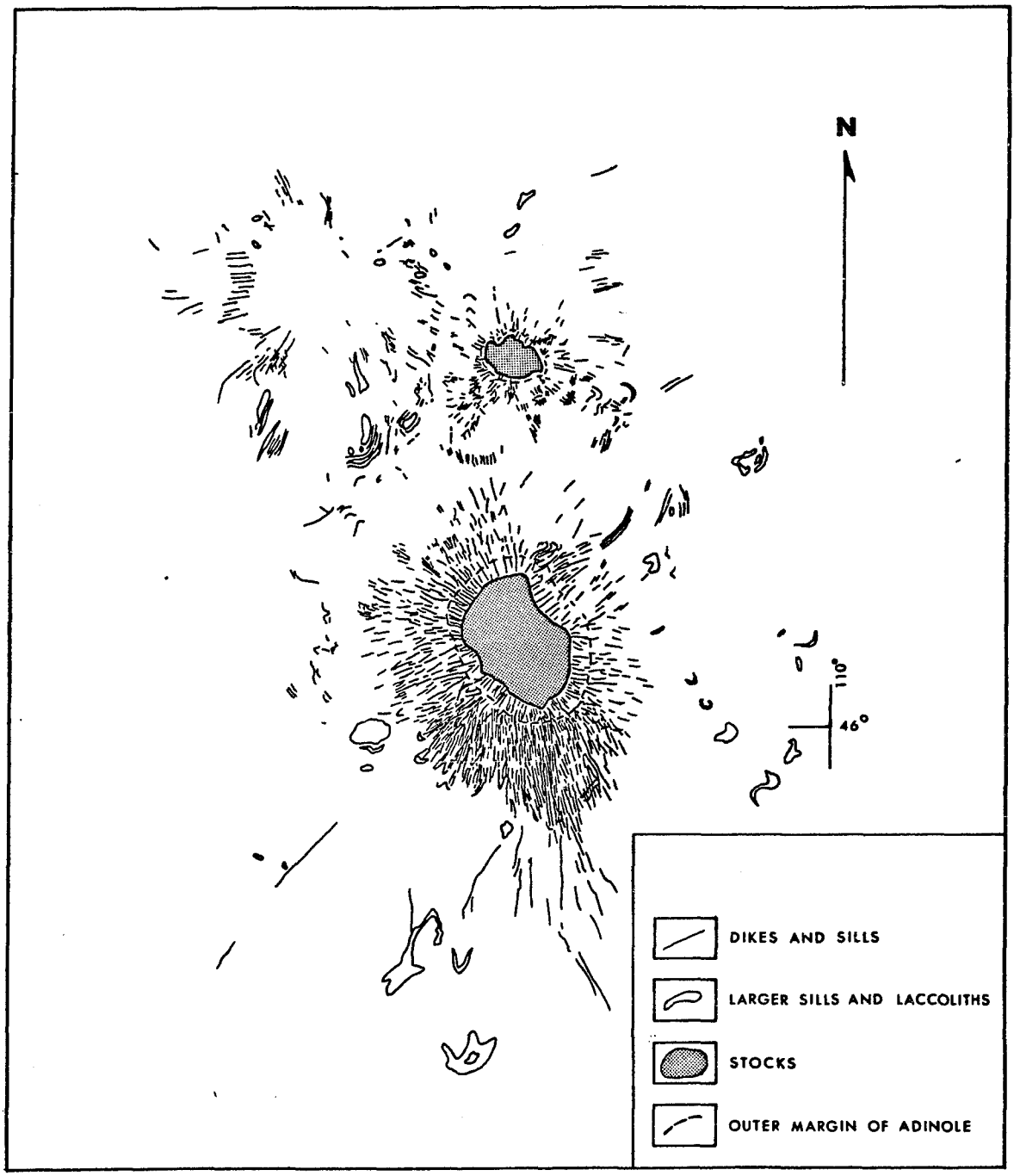


Figure 1. Map of the Crazy Mountains dike swarm compiled from U. S. Geological Survey Atlas Folios 1 & 56 (Iddings and Weed, 1894, and Weed (1899).

Figure 2. Map of the Crazy Mountains dike swarm. In pocket.

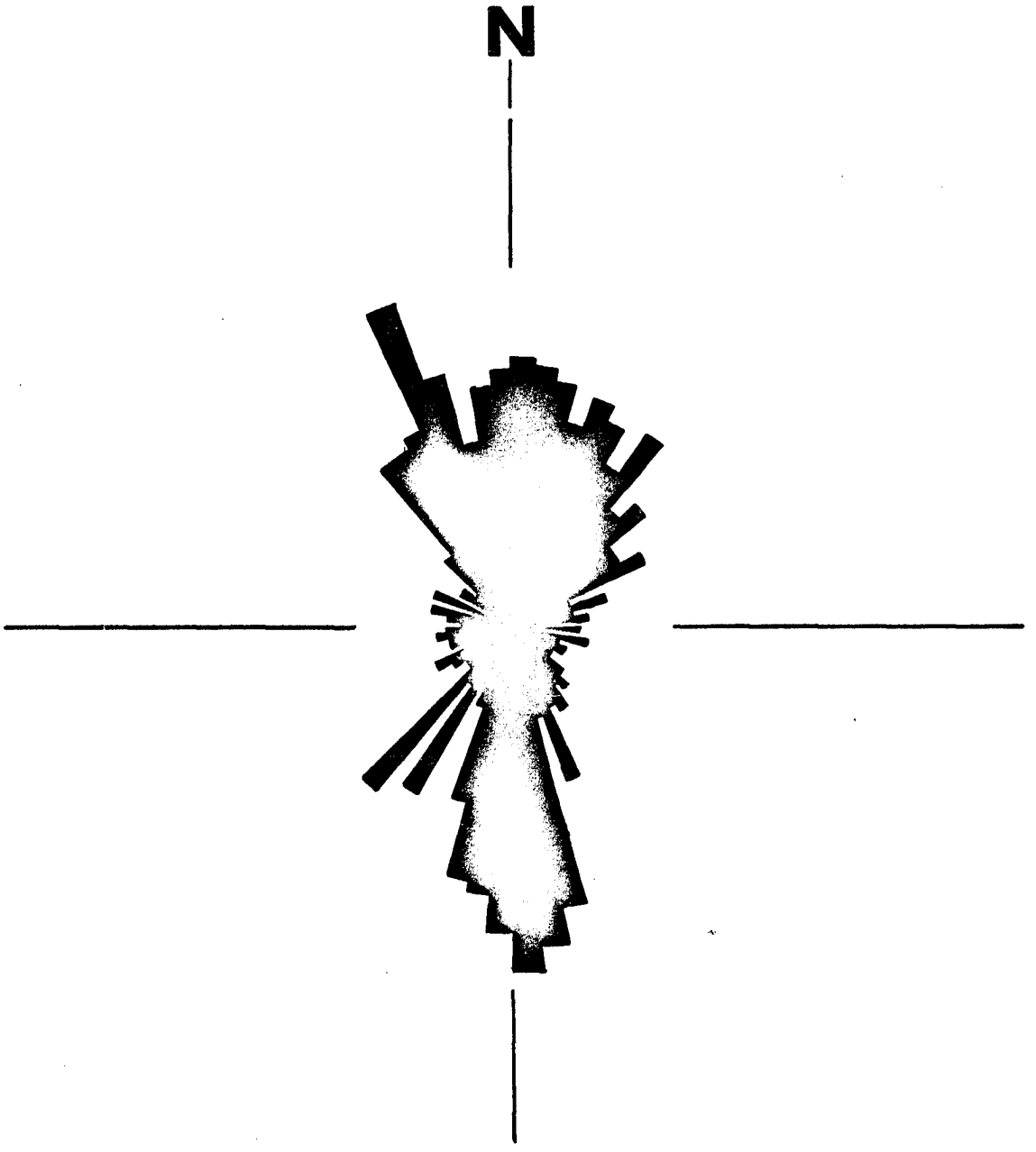
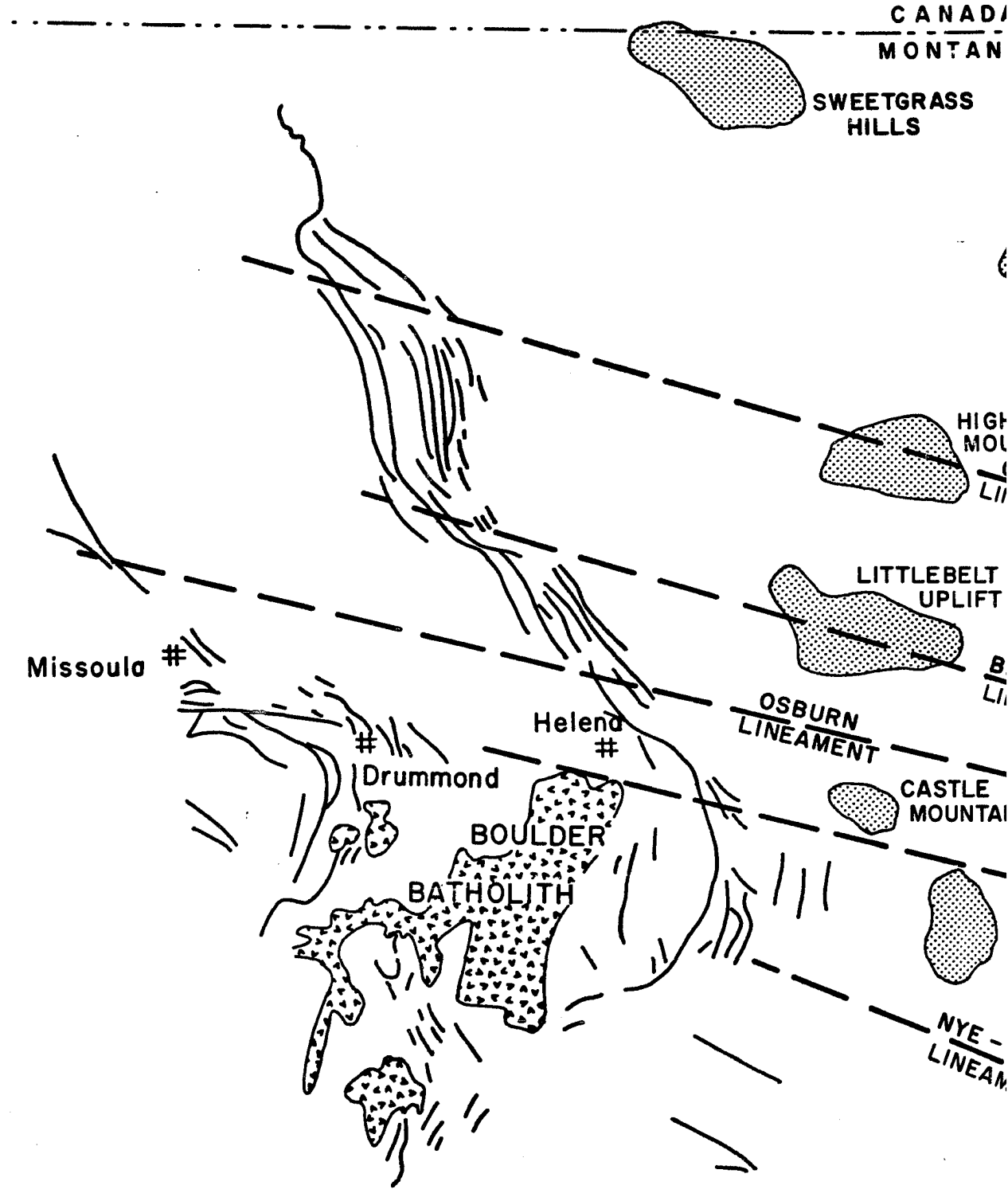


Figure 3. Rose diagram of observed dike directions. Dikes are given direction depending on the sector of the range in which they occur and are weighted according to length. After McCandless et al. (1972).

Figure 4. Plaster cast of clay cake experiment by Hans Cloos, demonstrating the fractures produced by doming over an elongate form. Model no. HC133 in the collection of the University of Cincinnati. Short end of model is 7-7/8".



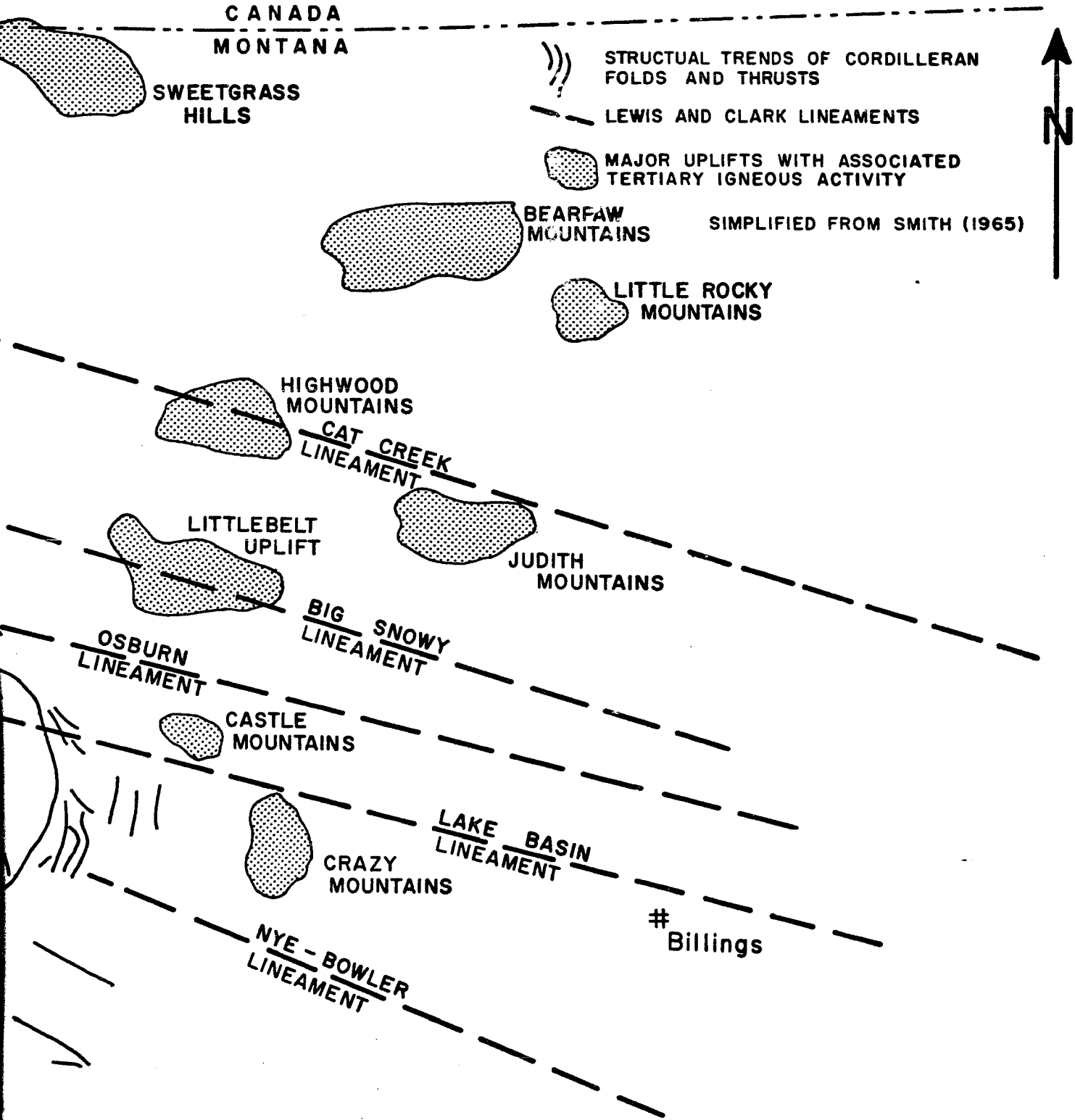


Figure 5. Lewis and Clark megashears after Smith (1965).

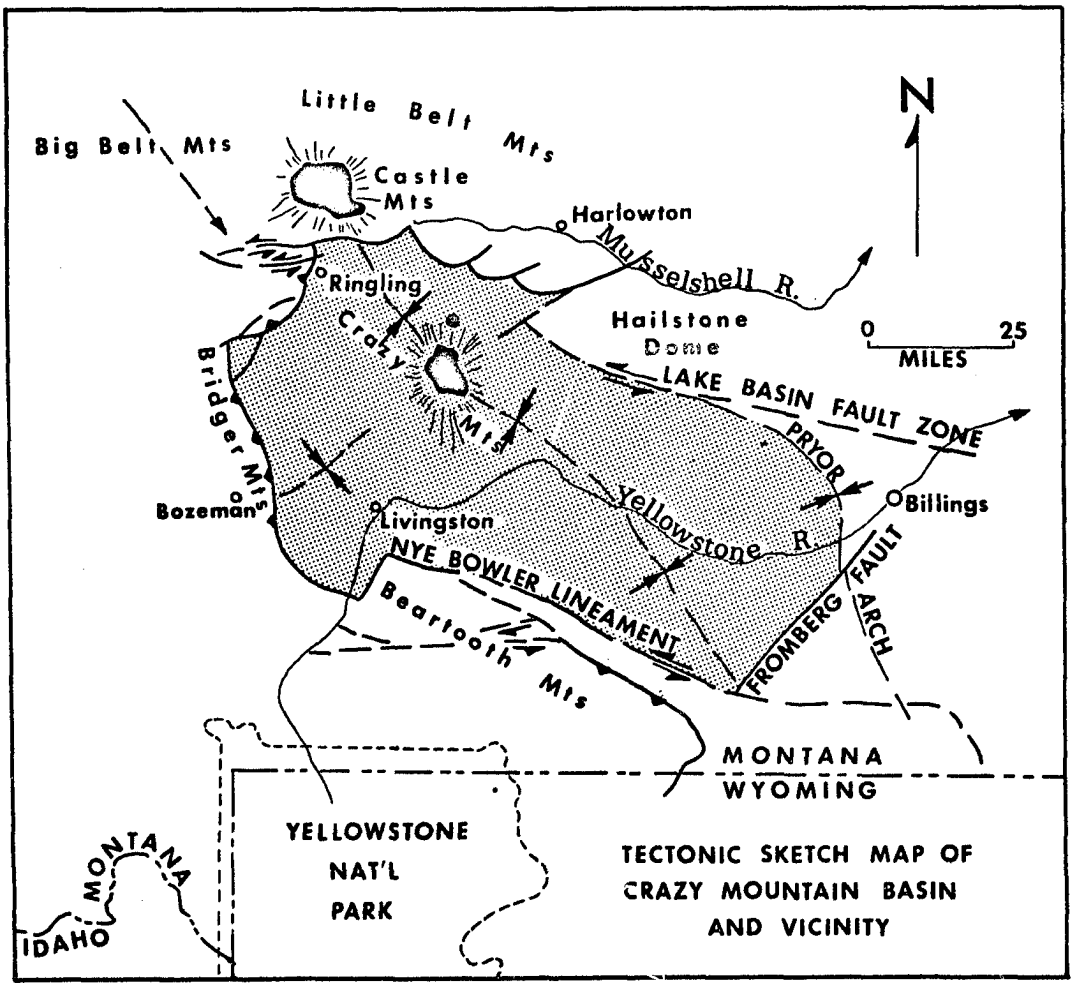


Figure 6. Nye-Bowler/Lake Basin megashear pair from the Lewis and Clark megashears. Their relationship to the Crazy Mountain basin and the Crazy Mountains intrusives is clear. Diagram after Thom (1957).

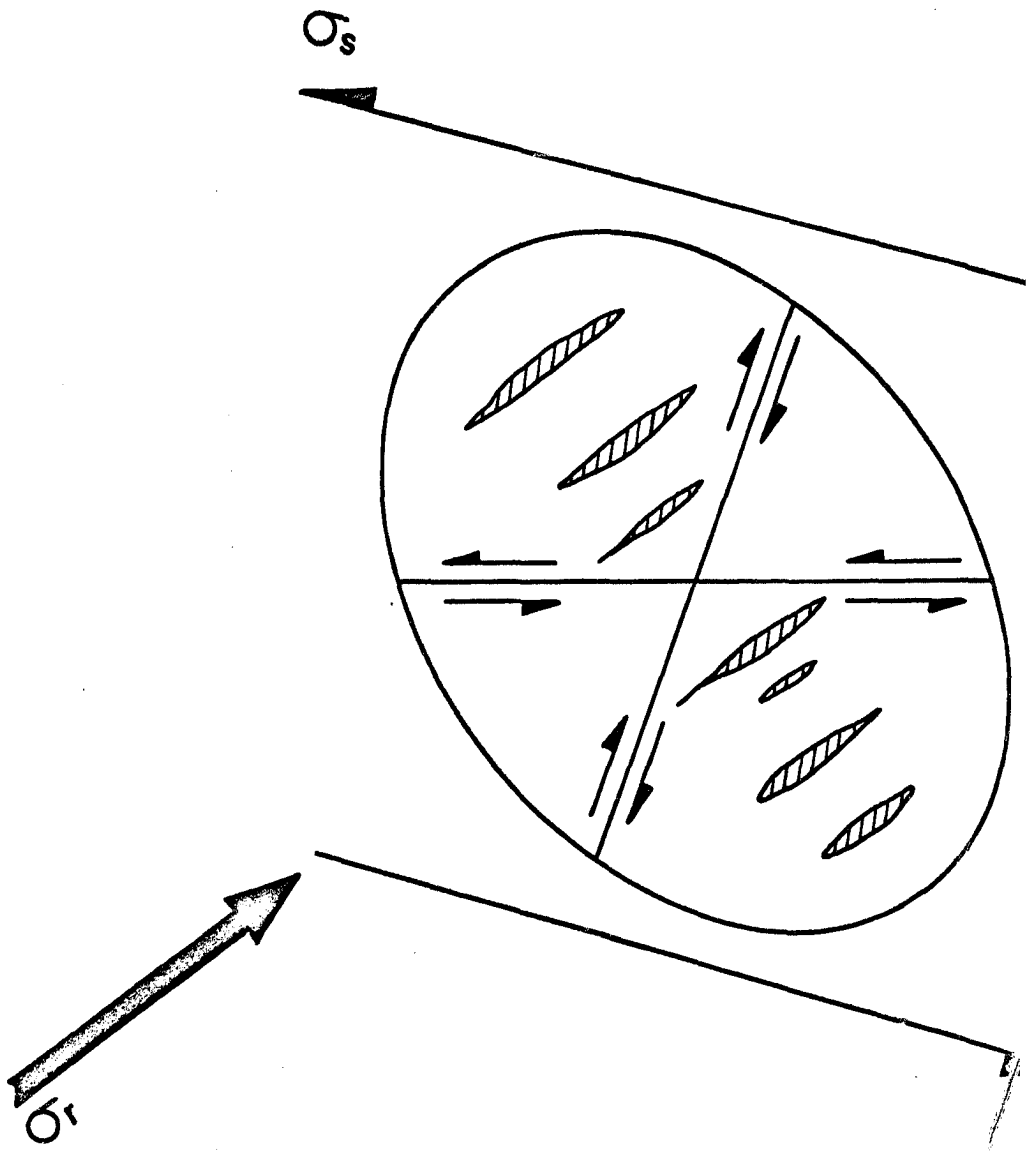
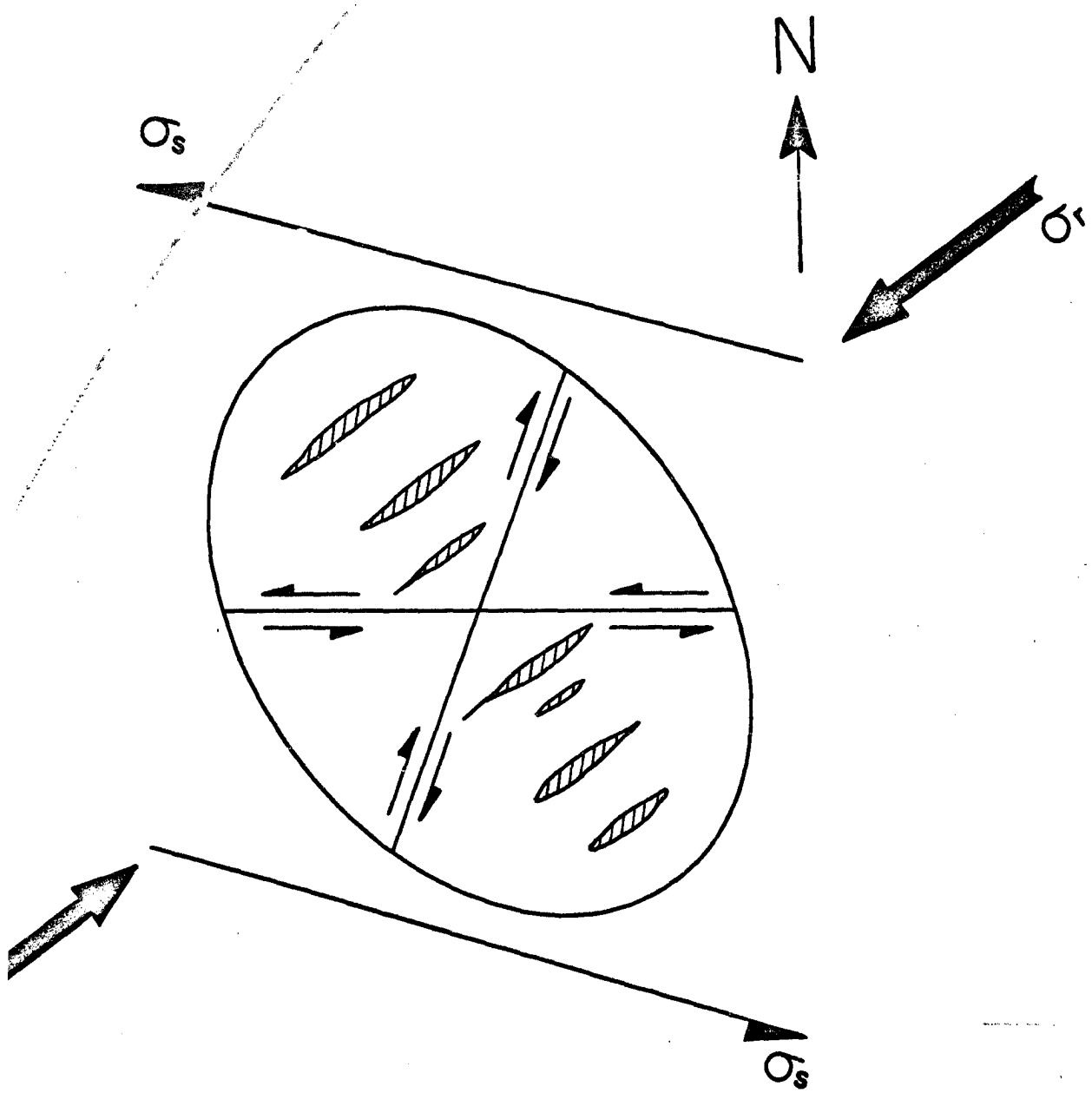


Figure 7. The strain ellipse representing the implied stress-s relationships described in the text. Hachured "c ash illustrate the preferred direction of dike intru sion these conditions. The shear stress couple (σ_s) resu the resolution of the regional compression of stress on the megashear pair.



The strain ellipse representing the implied stress-strain relationships described in the text. Hachured "gash fractures" illustrate the preferred direction of dike intrusion under these conditions. The shear stress couple (σ_s) results from the resolution of the regional compression of stress (σ_r) on the megashear pair.

Figure 8. Synuesis group of zoned plagioclase. Sample No. 69S9, 44 x, crossed polars.

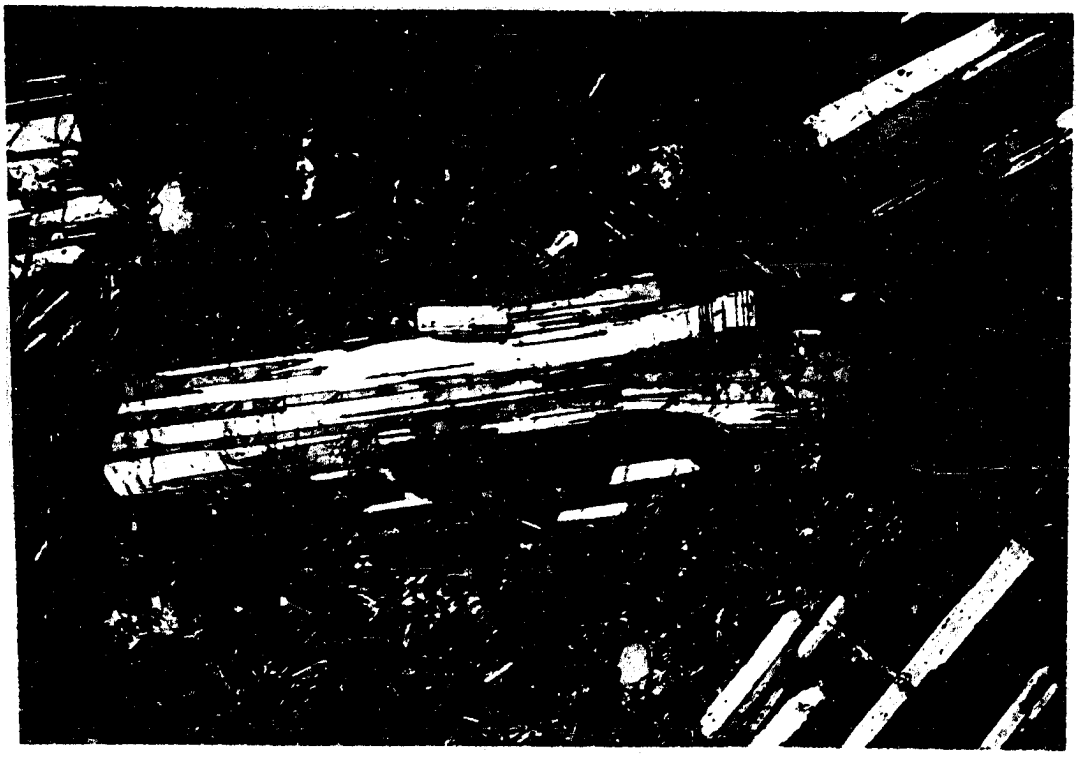


Figure 9. Simple plagioclase phenocryst. Sample No. 70121, 44 x, crossed polars.

Figure 10. Plagioclase phenocryst consisting of a well crystallized overgrowth on an altered anhedral core. Sample no. 70112, 44 x, crossed polars.

Figure 11. Small simple plagioclase phenocrysts with simple twinning and little or no zoning. Sample No. 69S32, 44 x, crossed polars.

Figure 12. Zoned (and twinned) clinopyroxene phenocryst. Zoning is emphasized by fine exsolution lamellae. Sample no. 7097, 44 x, crossed polars

Figure 13. Synuesis group of small clinopyroxene phenocrysts. Twinning of the clinopyroxene is pronounced and the synuesis group includes anhedral ore phenocrysts (black). Sample no. 707, 44 x, crossed polars.

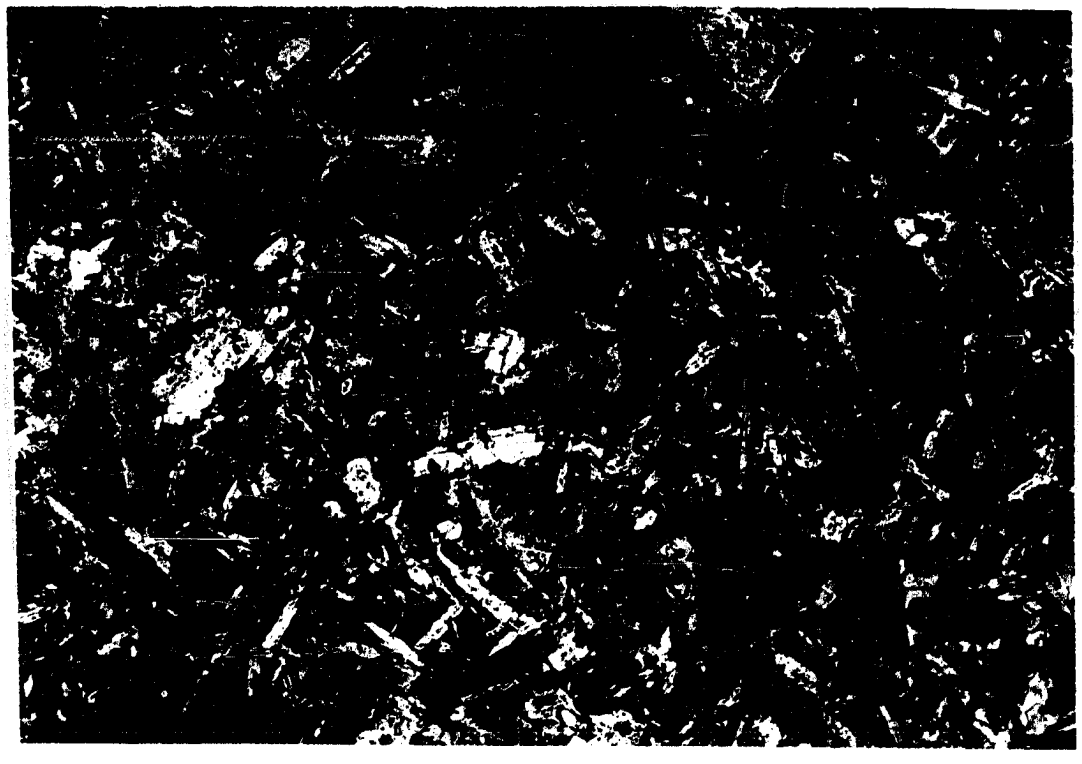


Figure 14. Groundmass plagioclase, simple and more or less altered, normally having well developed crystal outlines. Sample no. 70118, 44 x, crossed polars.

Figure 15. Groundmass biotite (the larger crystal is close to being a microphenocryst). Sample no. 69S33, 108 x, crossed polars.

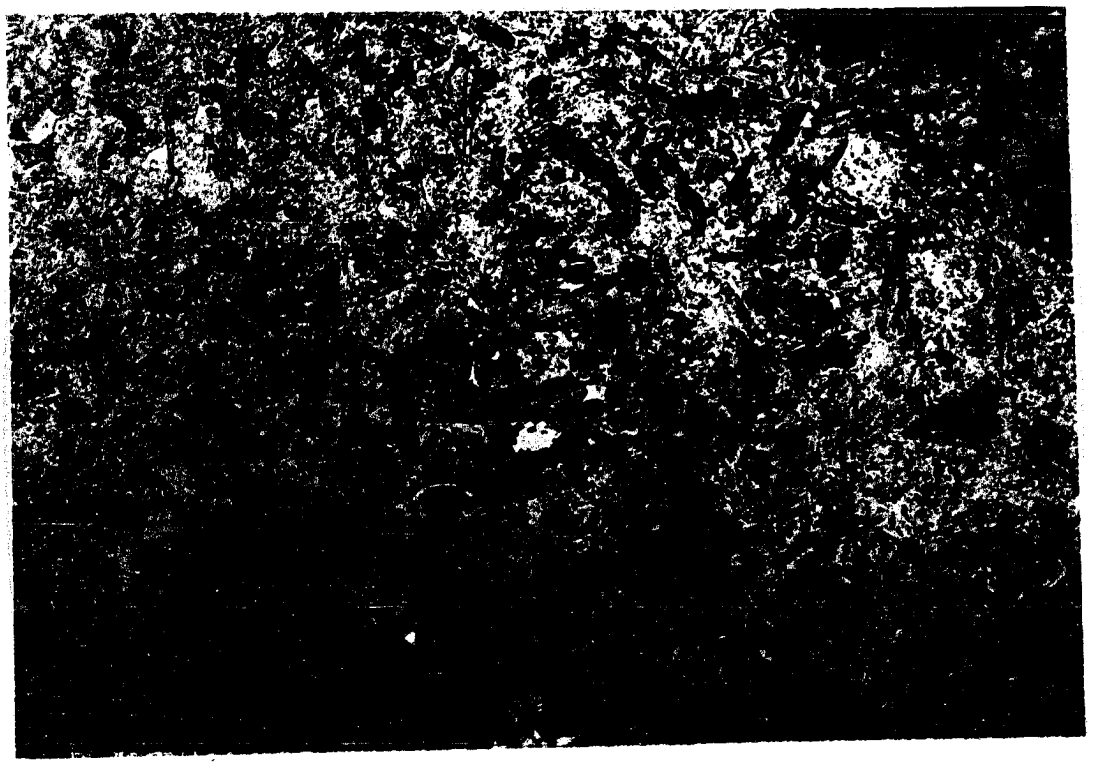
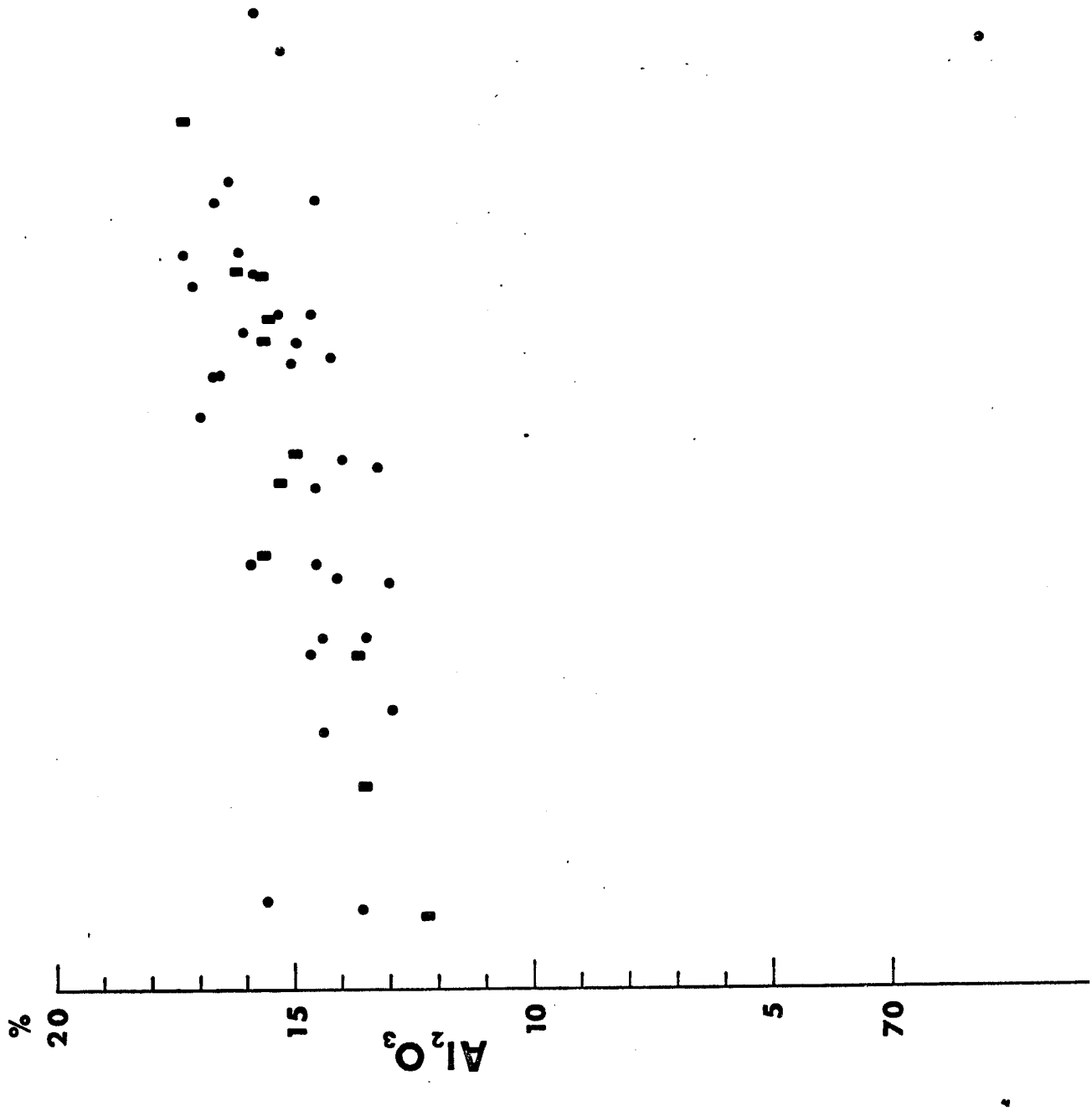


Figure 16. Groundmass amphibole, some ore phenocrysts (black). Sample no. 70118, 44 x, lower polar only.



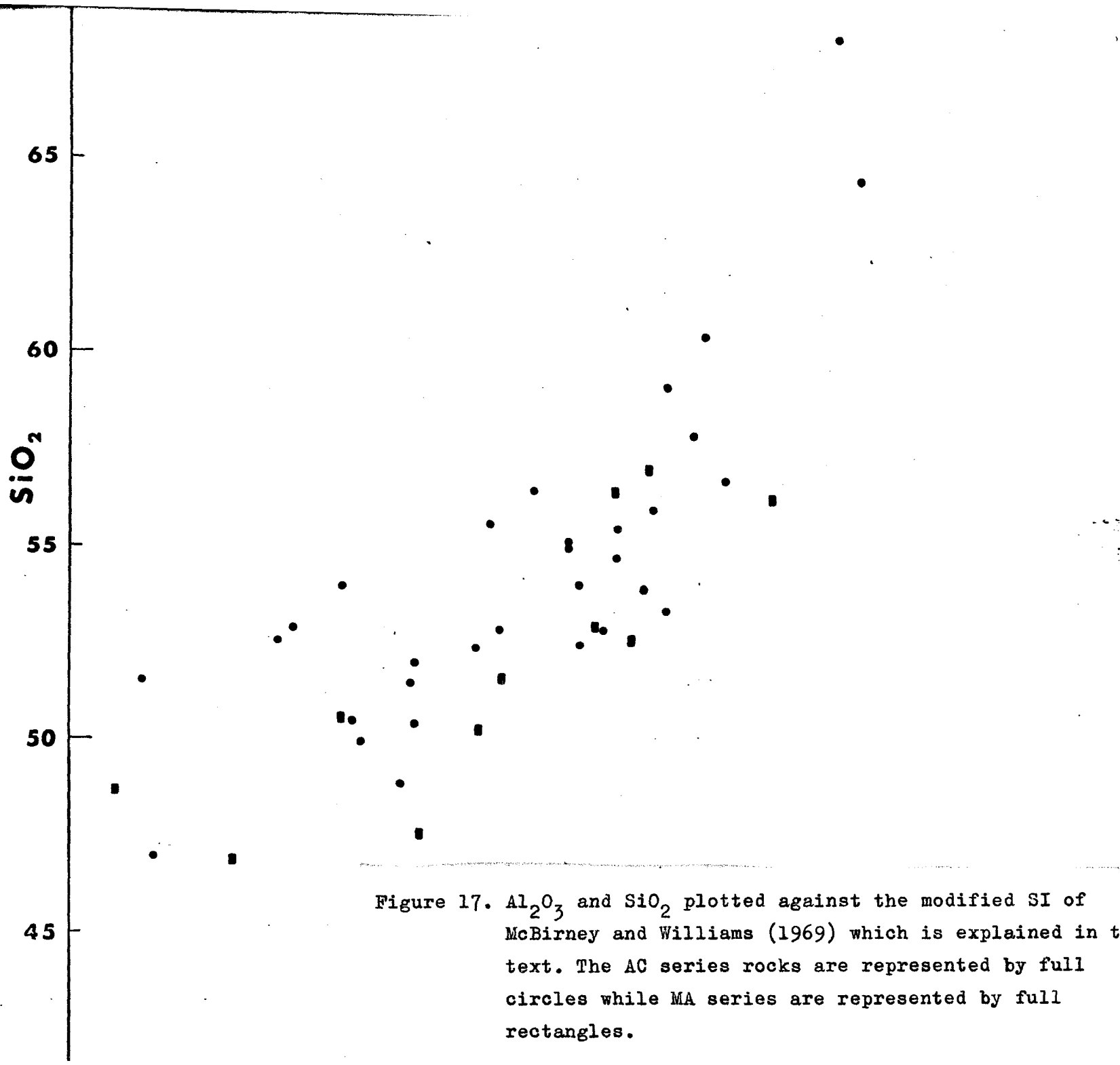


Figure 17. Al_2O_3 and SiO_2 plotted against the modified SI of McBirney and Williams (1969) which is explained in the text. The AC series rocks are represented by full circles while MA series are represented by full rectangles.

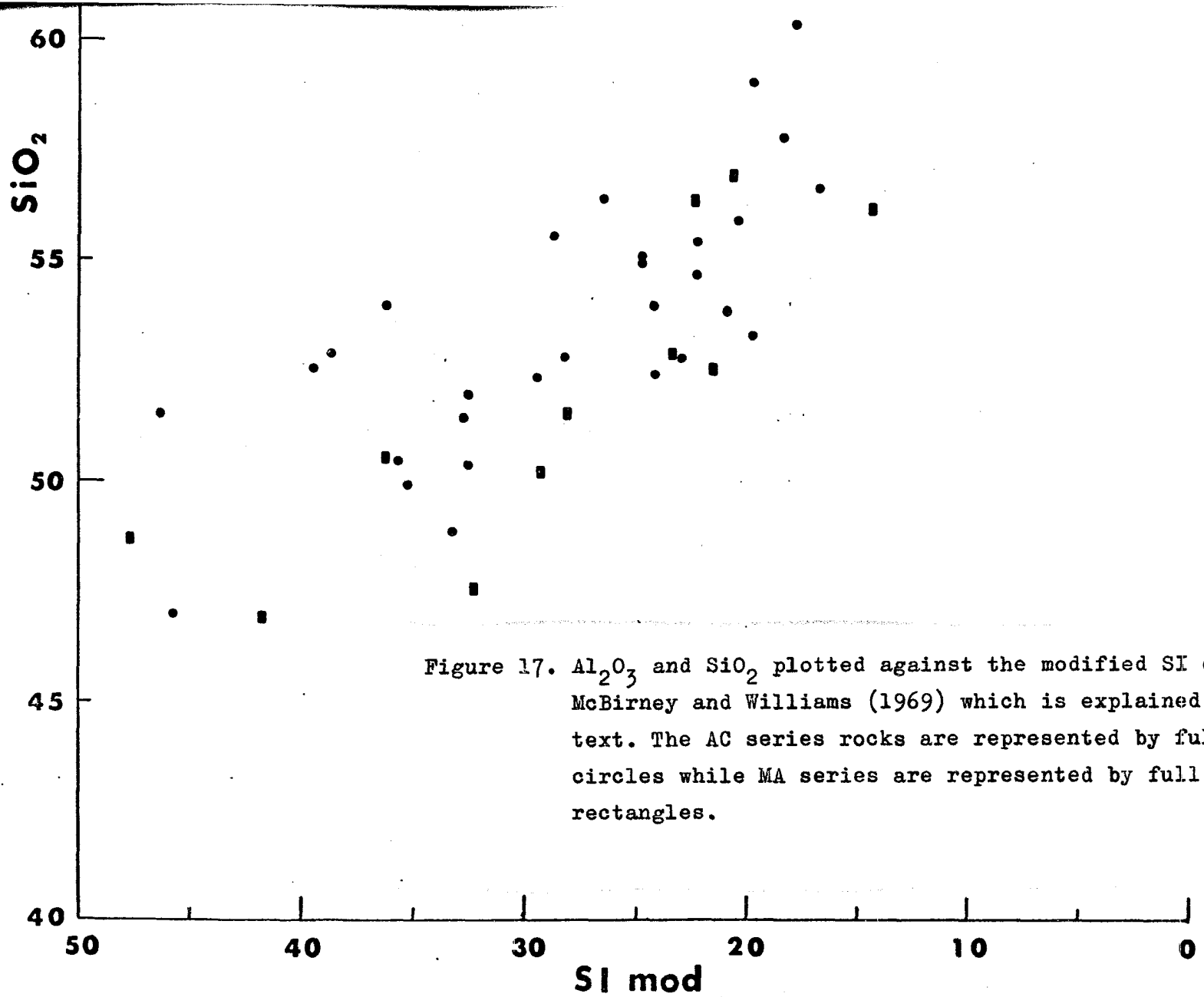


Figure 17. Al_2O_3 and SiO_2 plotted against the modified SI of McBirney and Williams (1969) which is explained in the text. The AC series rocks are represented by full circles while MA series are represented by full rectangles.

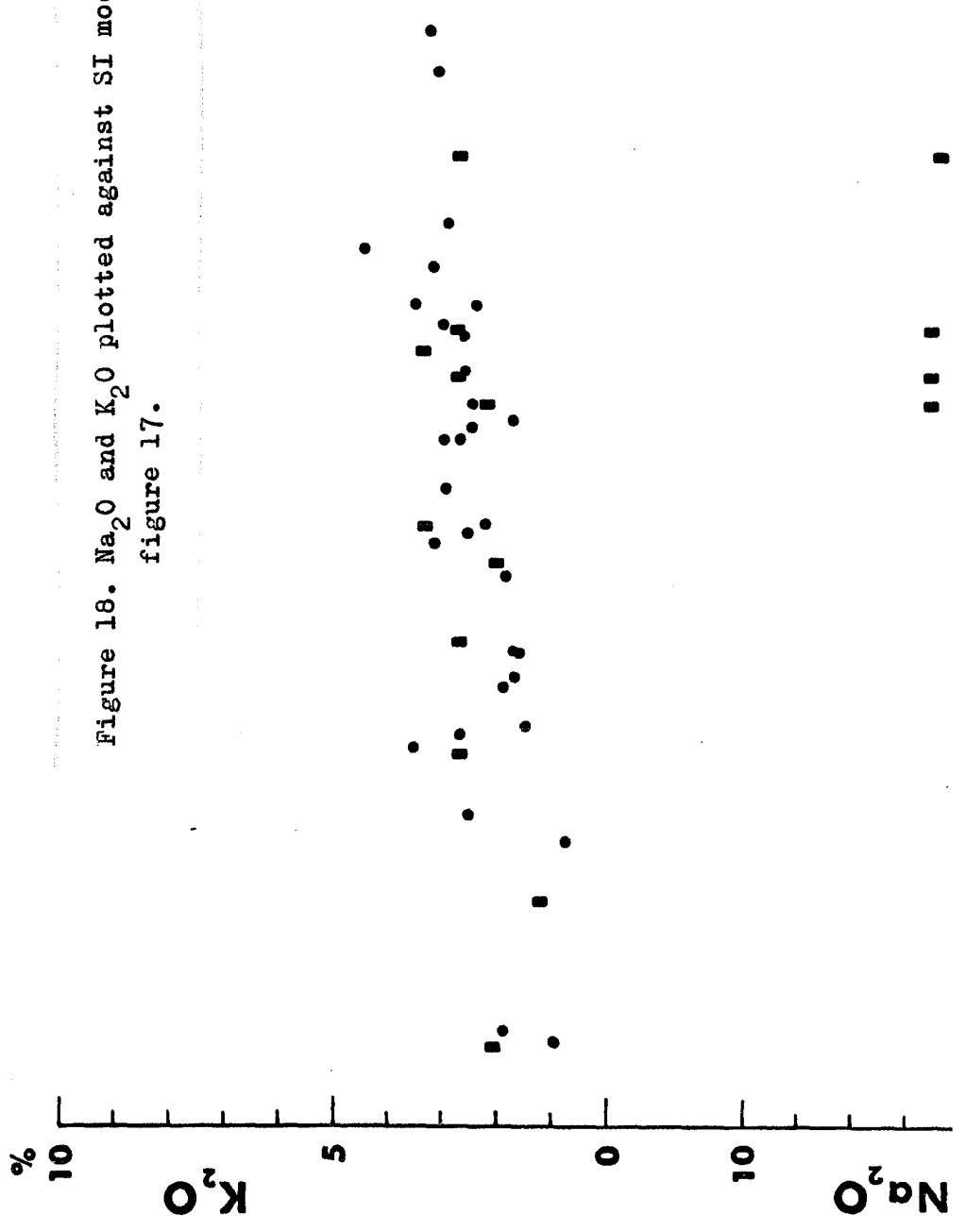


Figure 18. Na_2O and K_2O plotted against SI mod. Symbols as in figure 17.

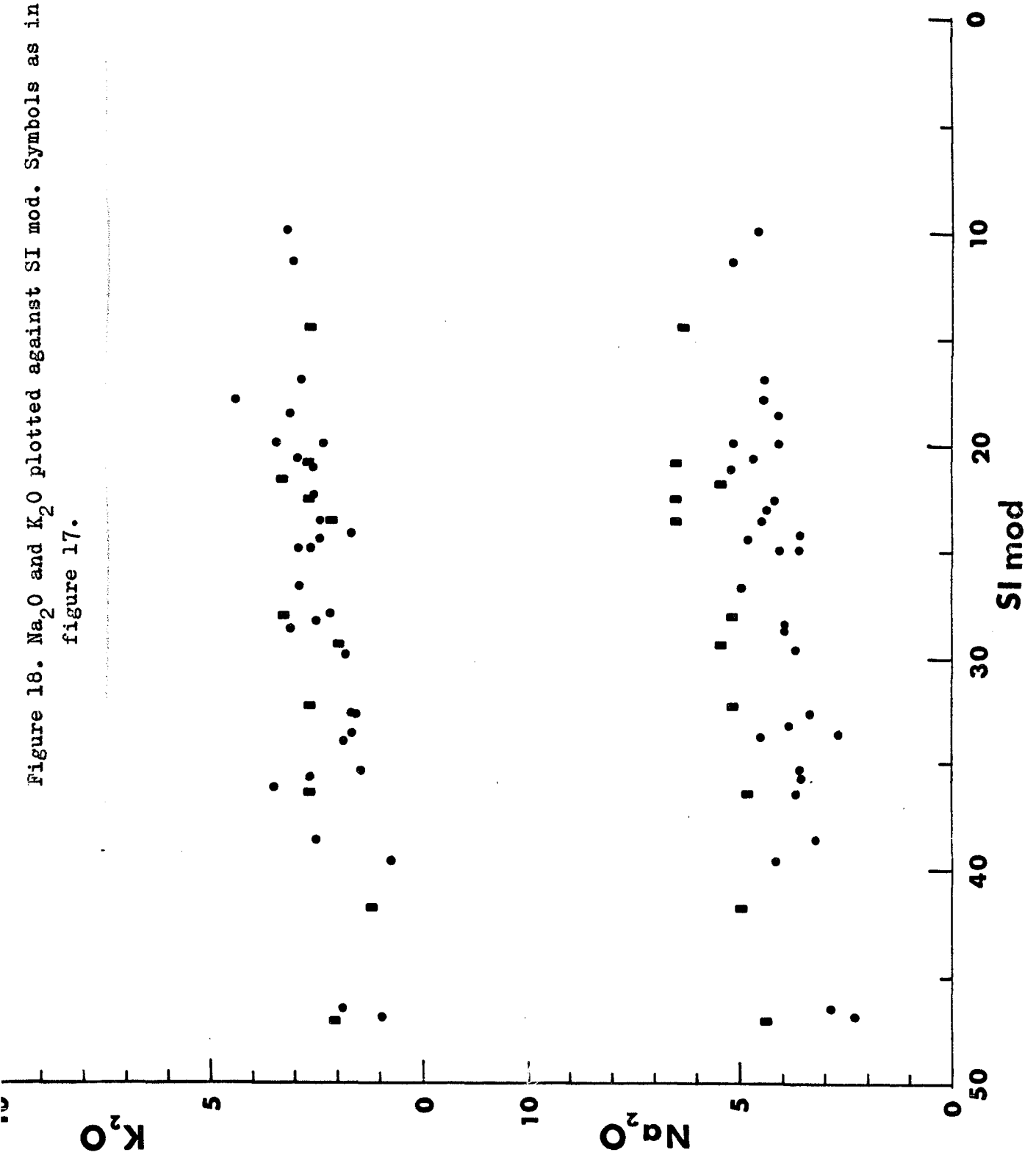


Figure 18. Na_2O and K_2O plotted against SI mod. Symbols as in figure 17.

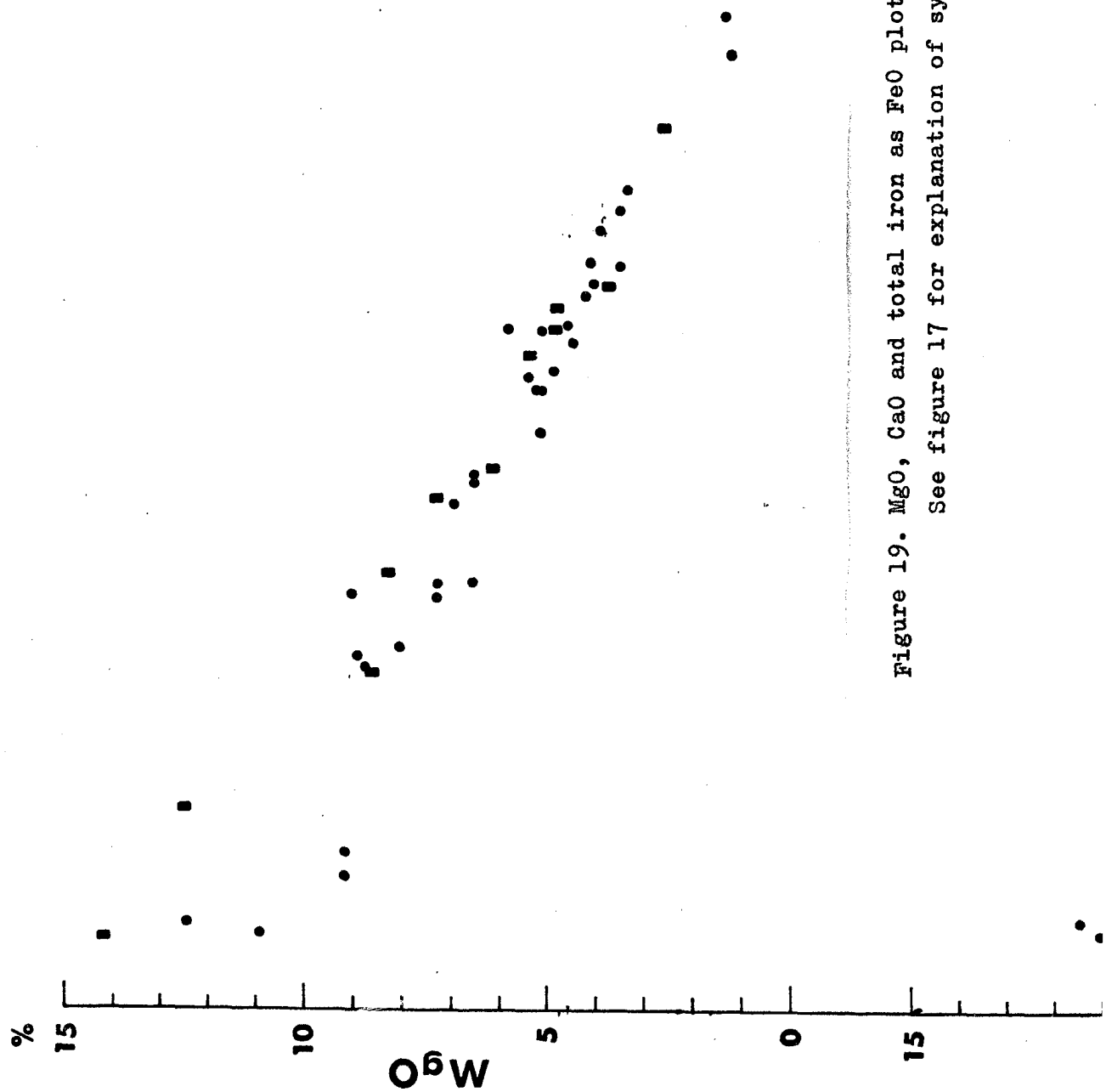


Figure 19. MgO, CaO and total iron as FeO plotted against SI mod.
See figure 17 for explanation of symbols.

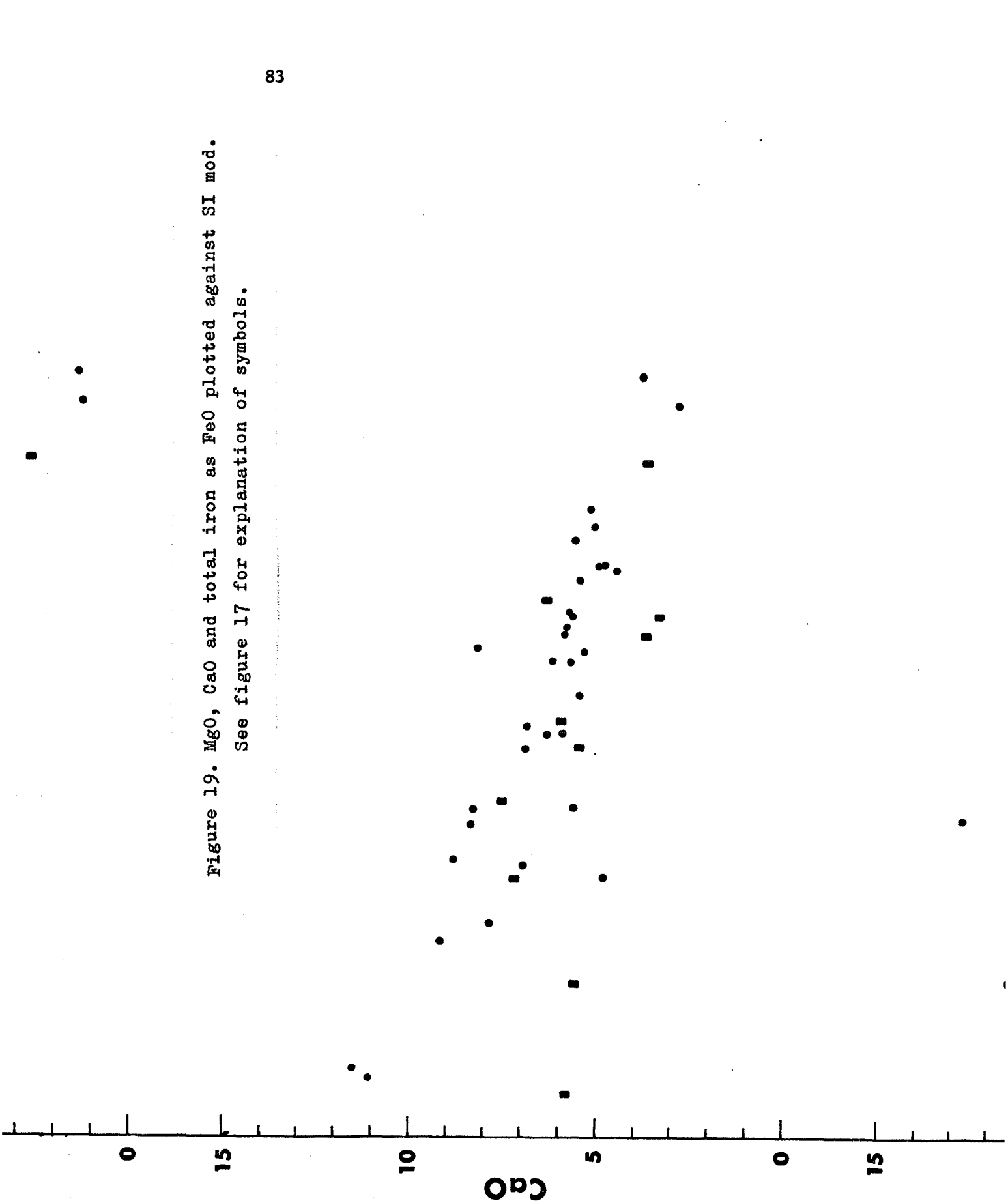
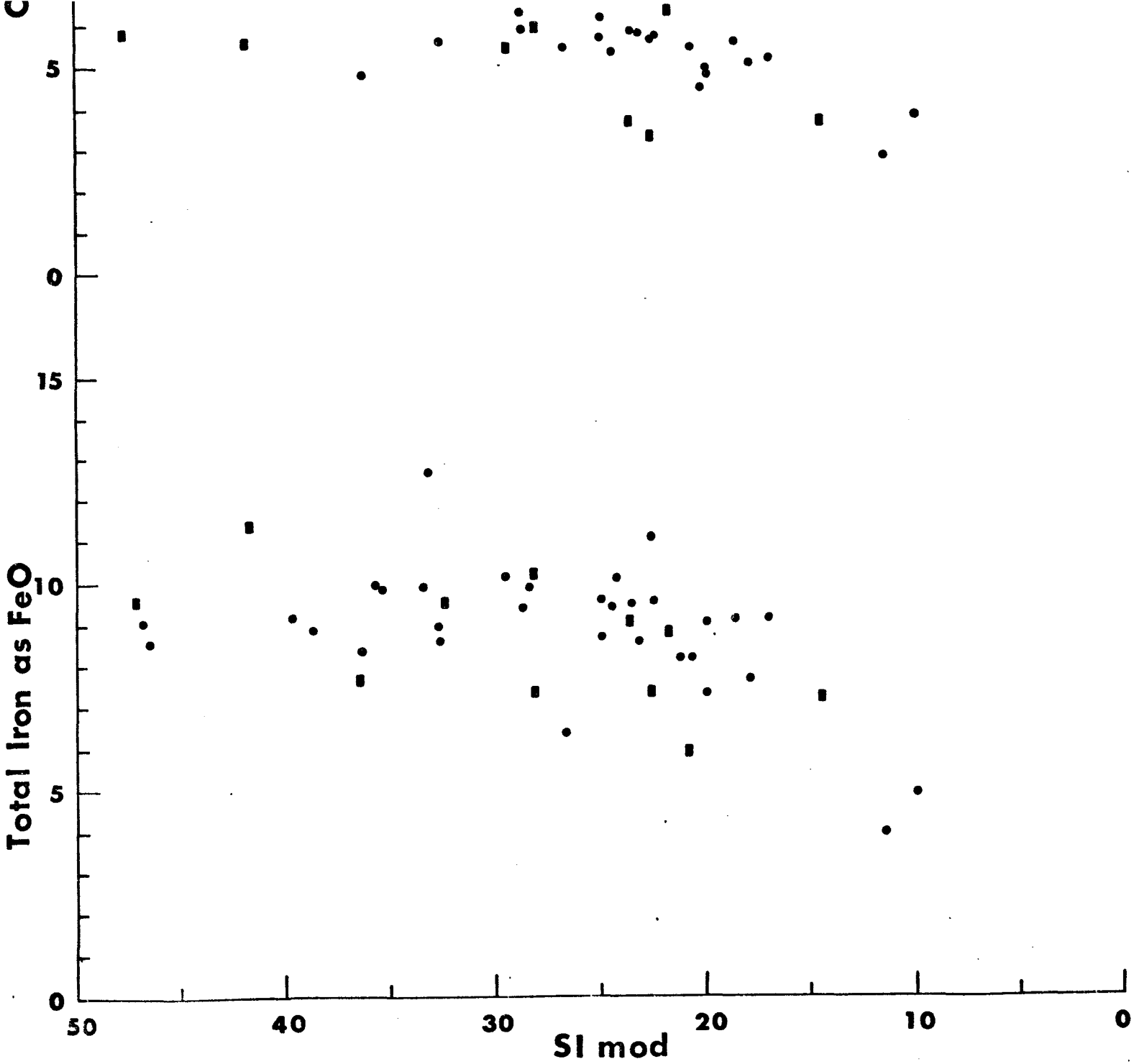


Figure 19. MgO, CaO and total iron as FeO plotted against SI mod.
See figure 17 for explanation of symbols.



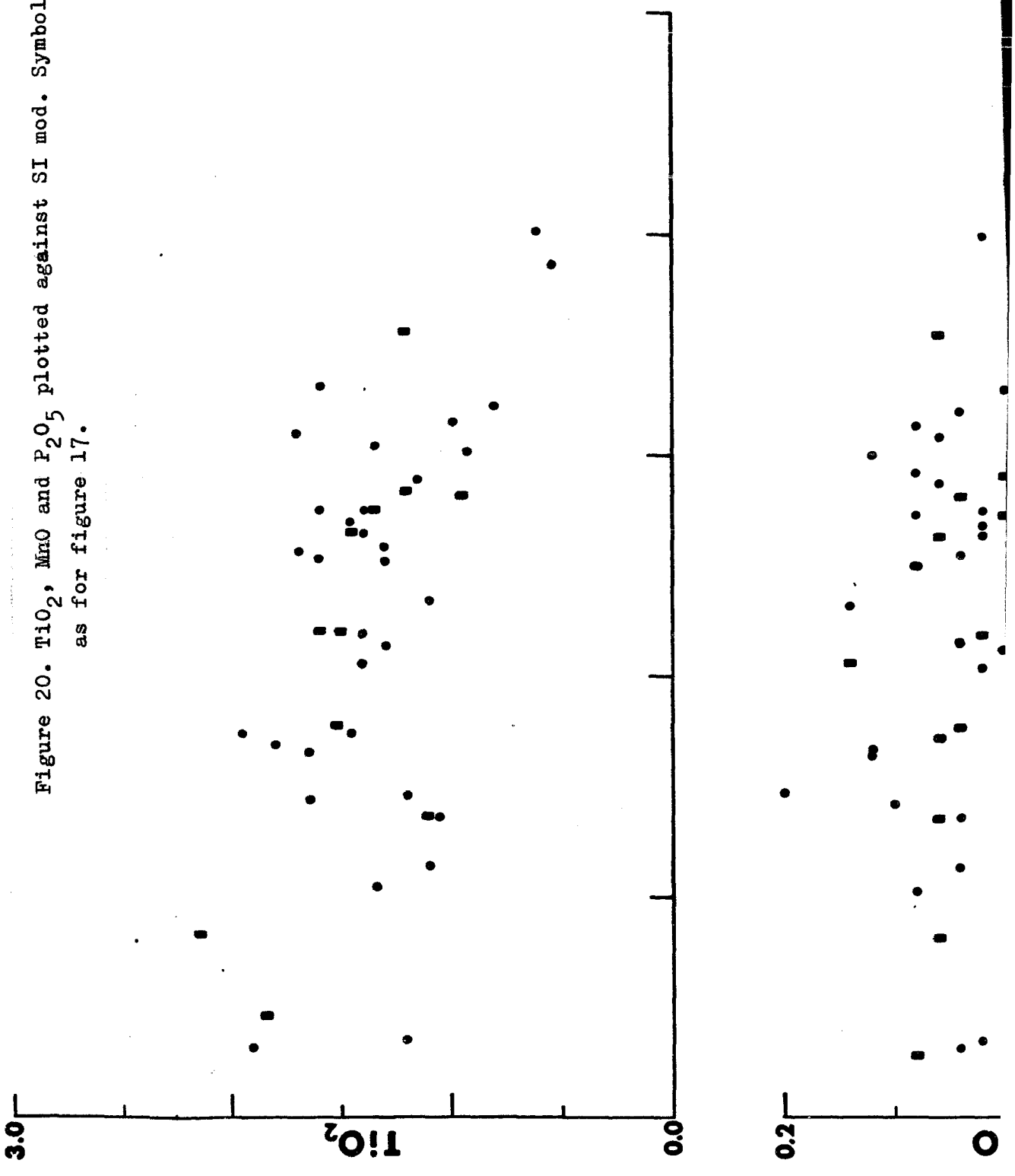
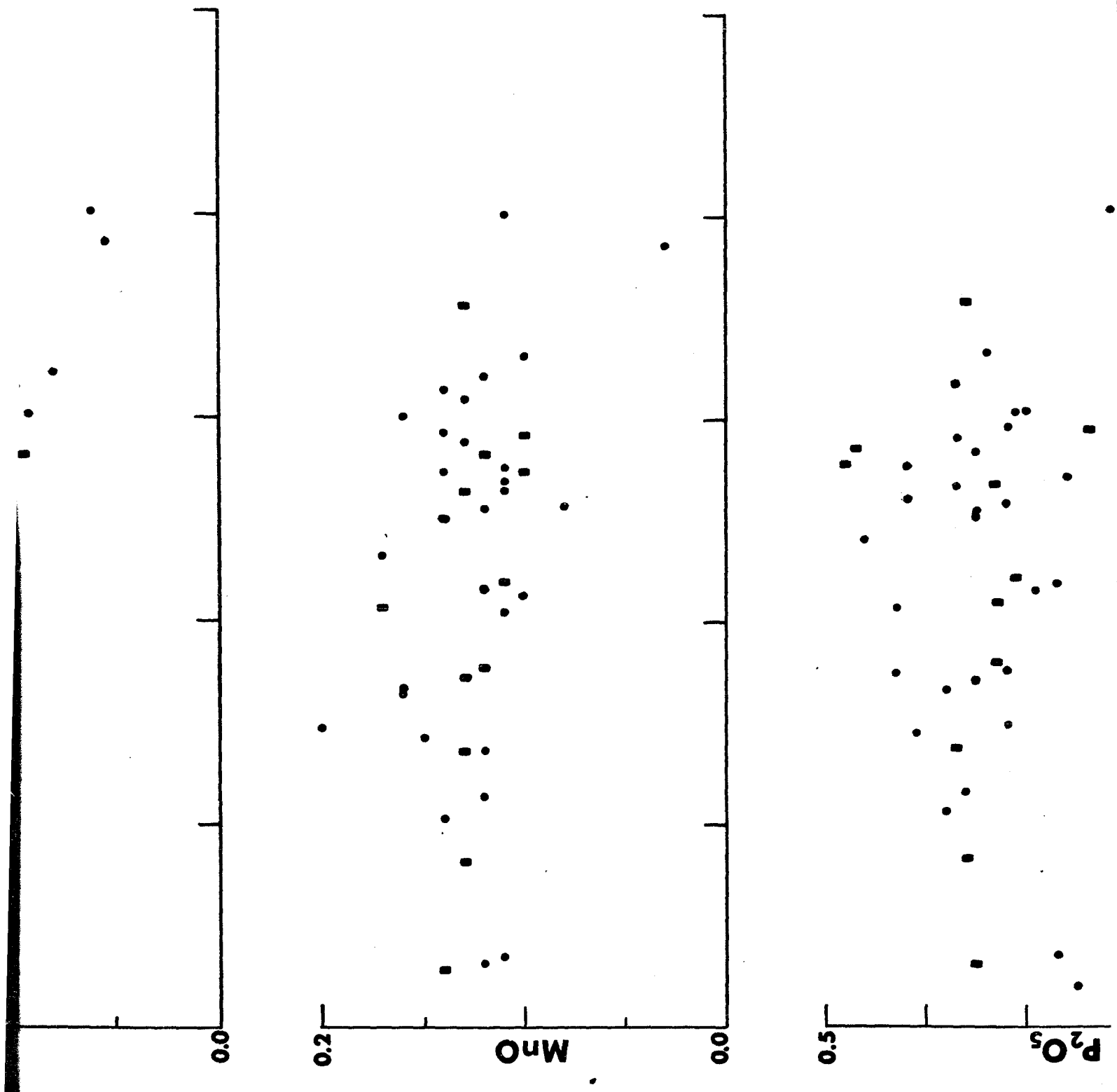
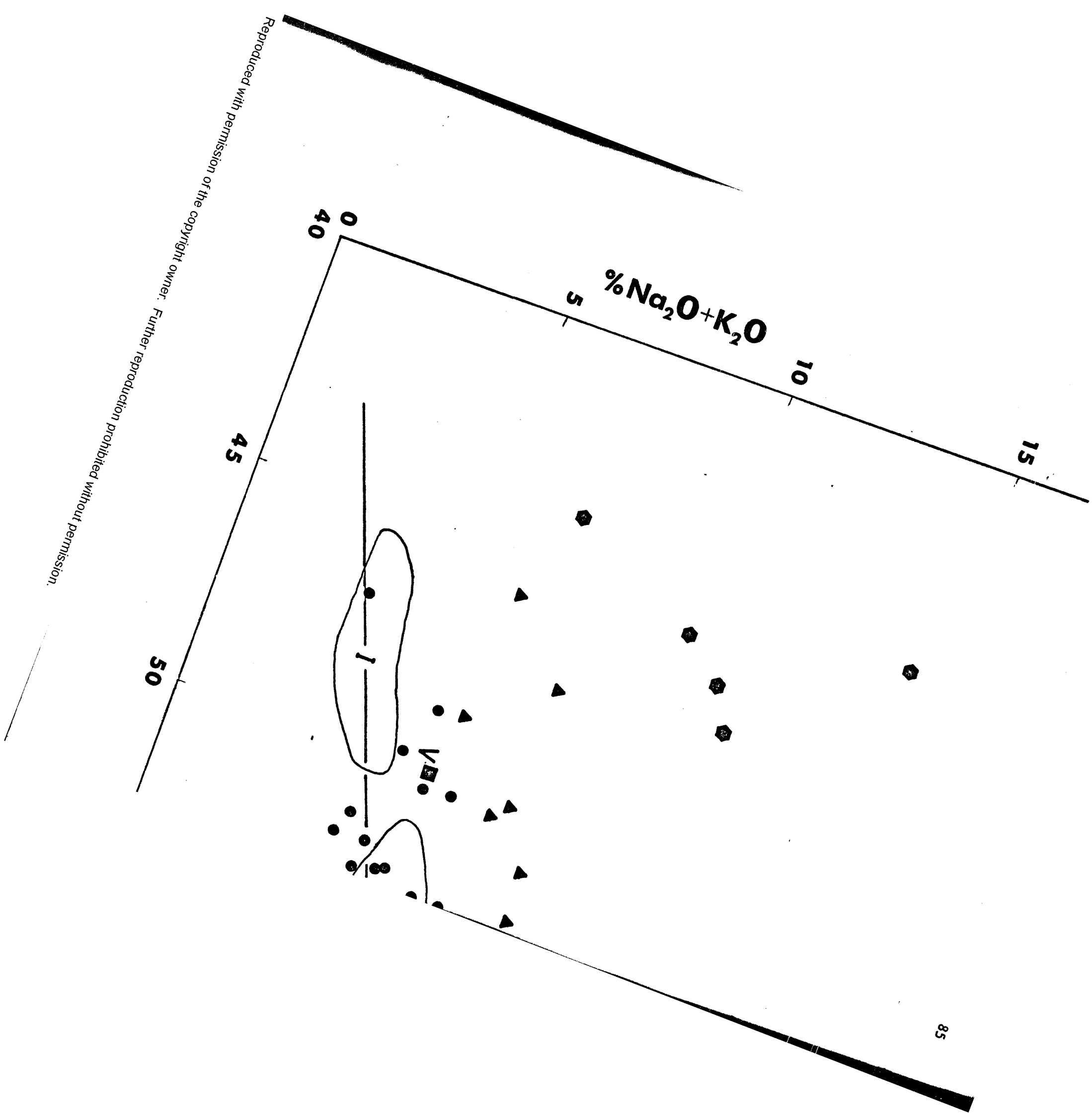
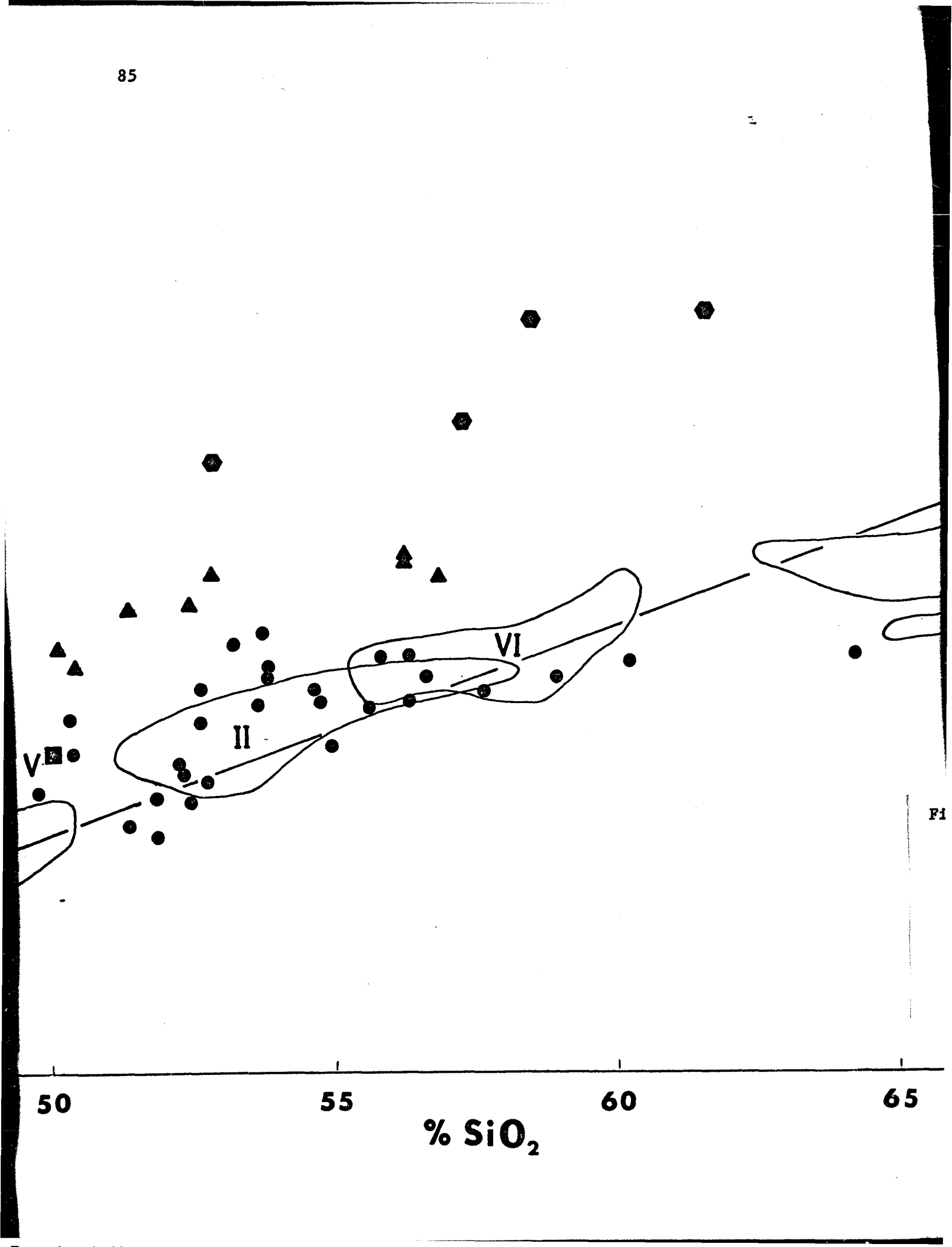


Figure 20. TiO_2, MnO and P_2O_5 plotted against SI mod. Symbols as for figure 17.







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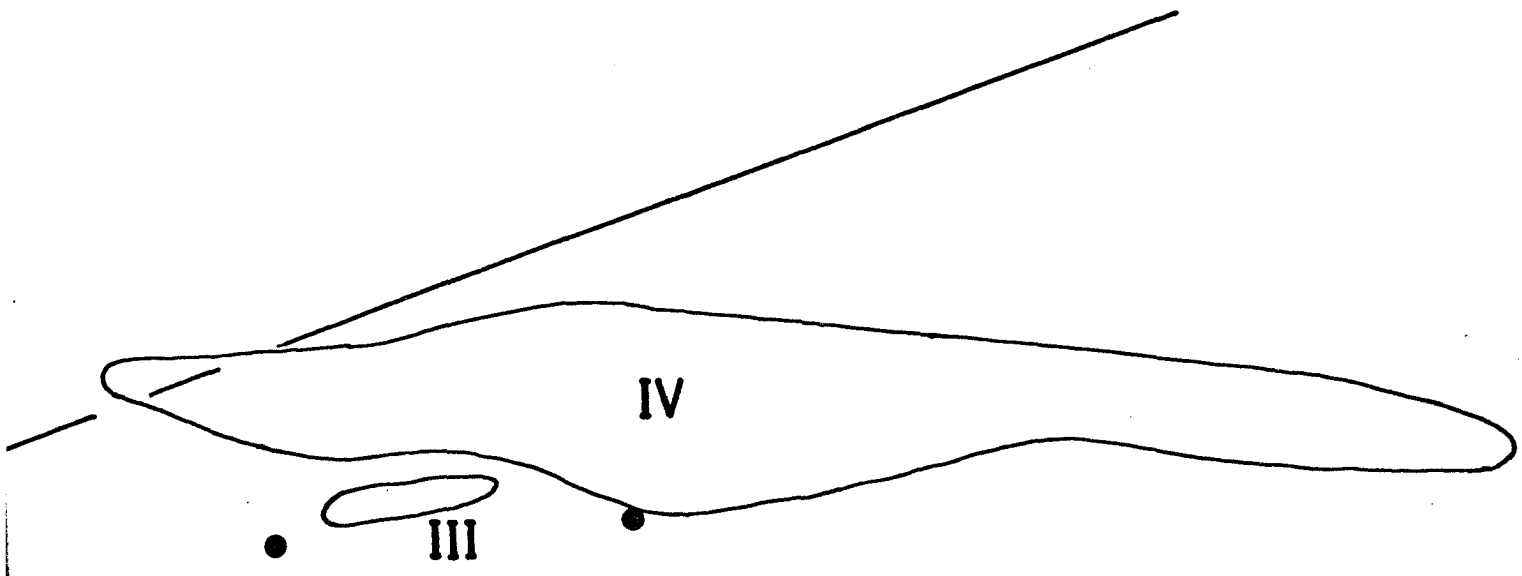


Figure 21. Total alkalis ($Na_2O + K_2O$) plotted against SiO_2. The AC series is represented by full circles, the MA series by full triangles, the alkaline rocks from the north and west by full hexagons. The rocks from the stock are represented by fields: I, basic border phase, II, intermediate phase, III, terminal phase, IV, aplite dike phase, V, basaltic dike phase, VI andesite dike phase, after the terminology of Tappe (1966). The line is the empirical line of MacDonald and Katsura (1964) which separates alkaline from other rocks.

65 70 75

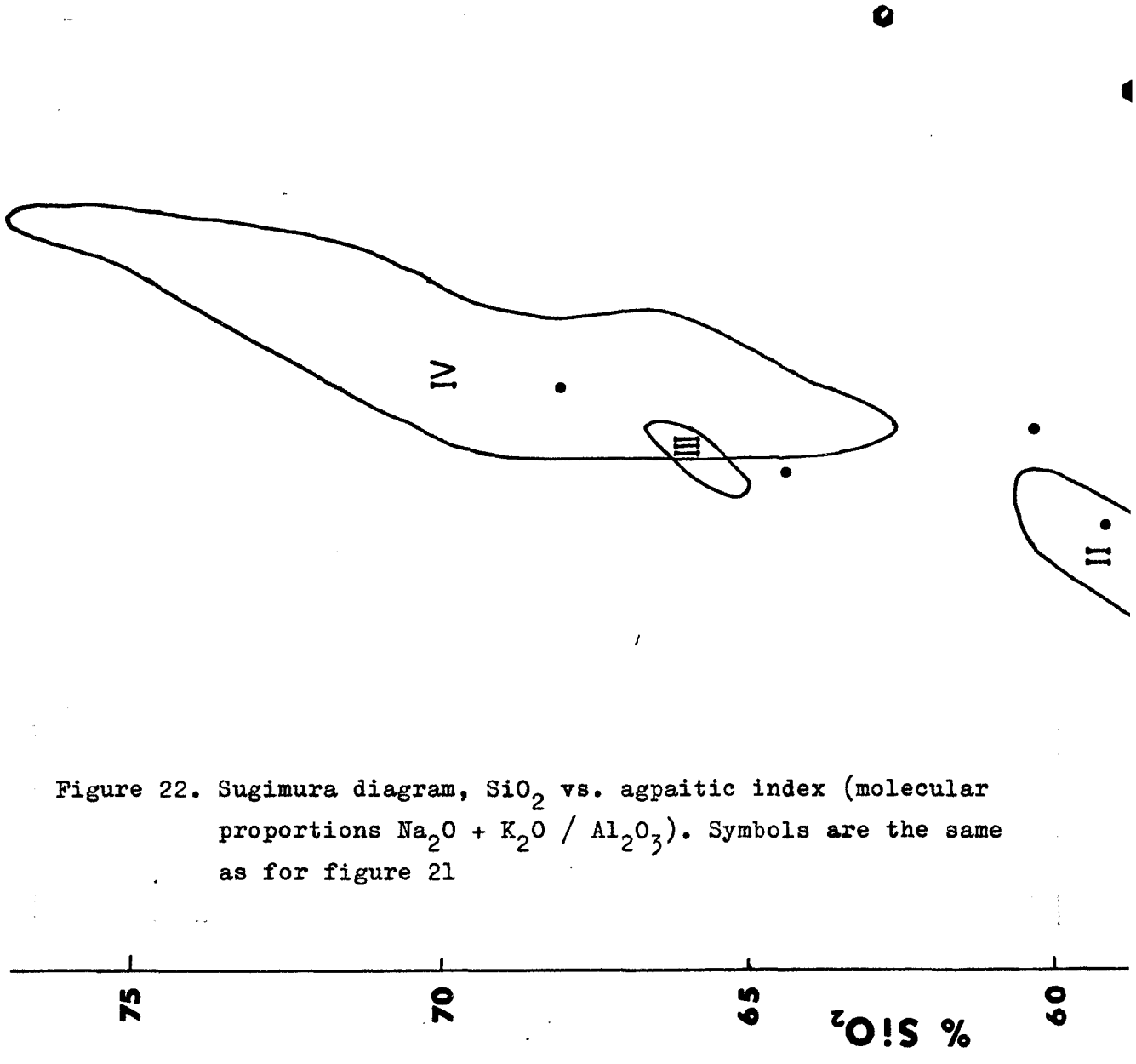
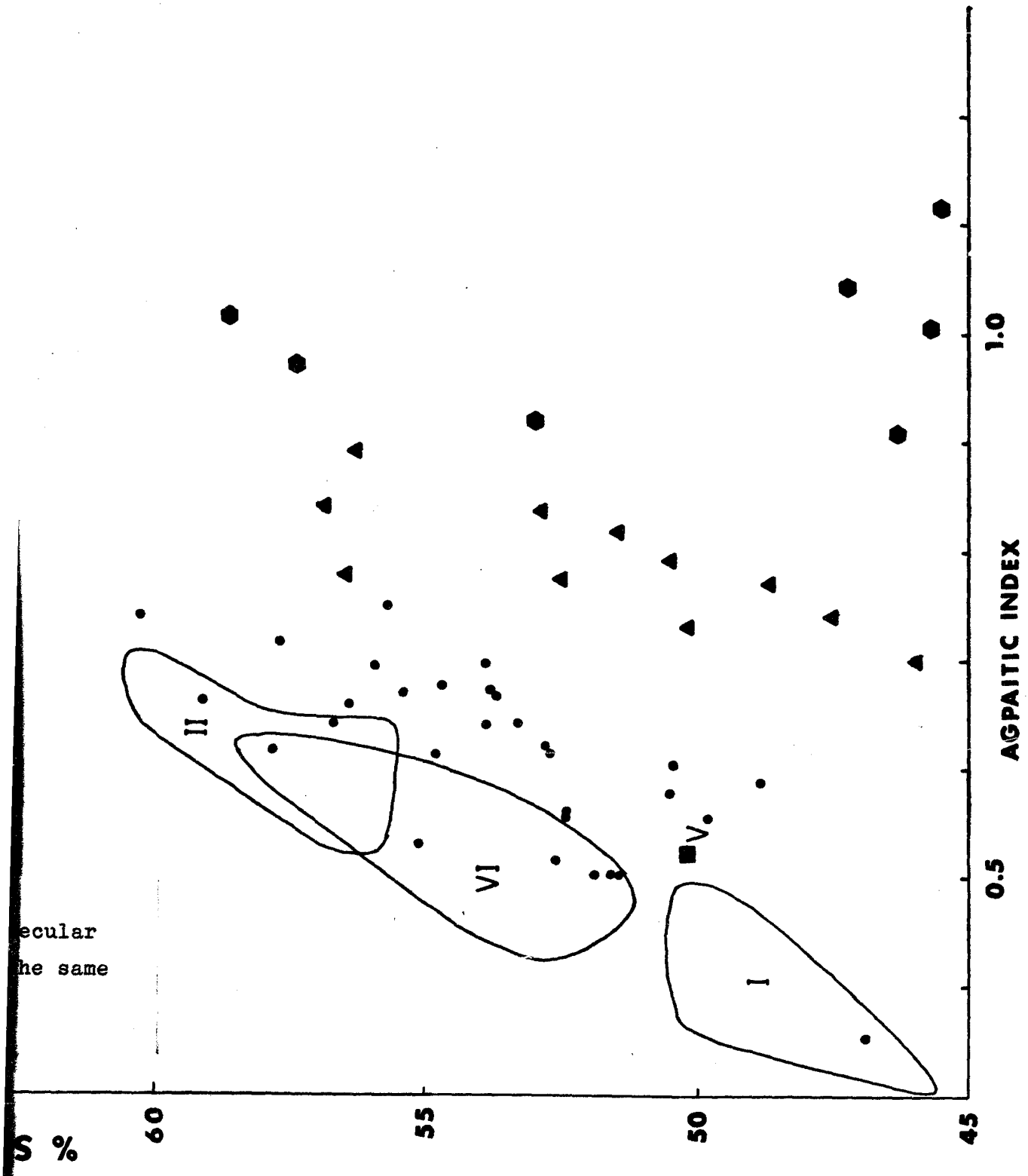


Figure 22. Sugimura diagram, SiO_2 vs. agpaitic index (molecular proportions $Na_2O + K_2O$ / Al_2O_3). Symbols are the same as for figure 21



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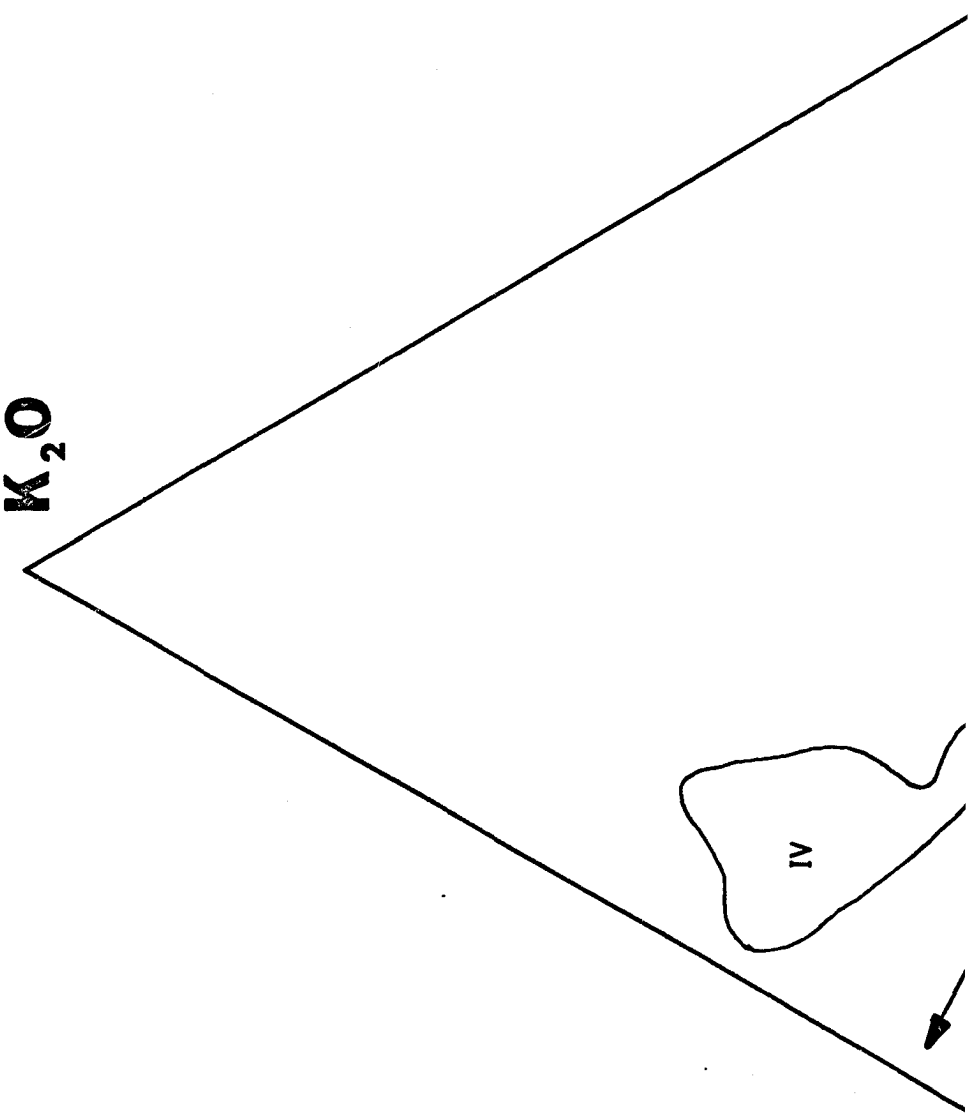

Figure 23. Triangular diagrams: AFM and Na_2O-K_2O-CaO. Symbols as in Figure 17 with the addition of the stock rock fields of Figure 21 and generalized trends for the alkaline rocks of the north and west of the range.

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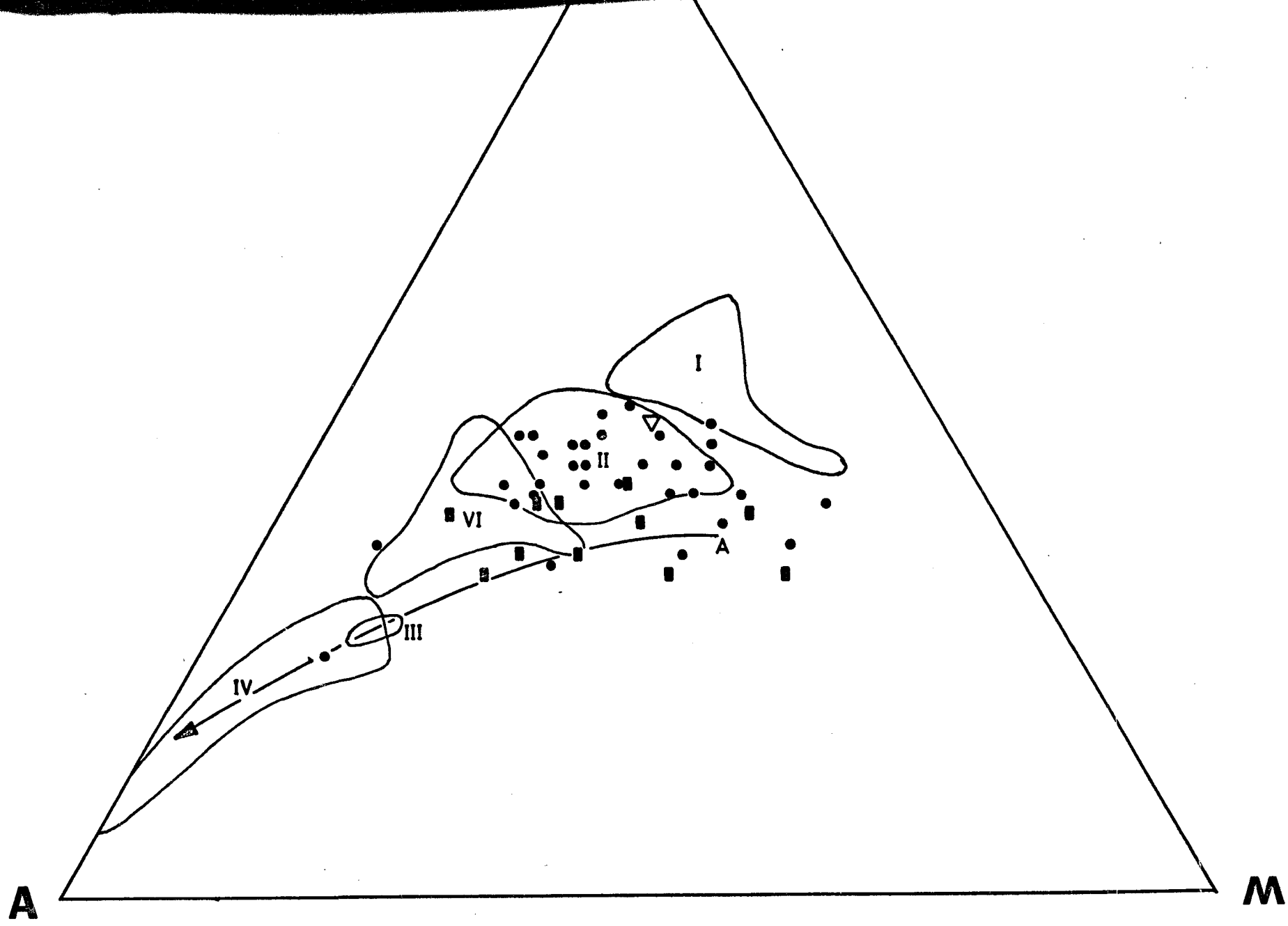
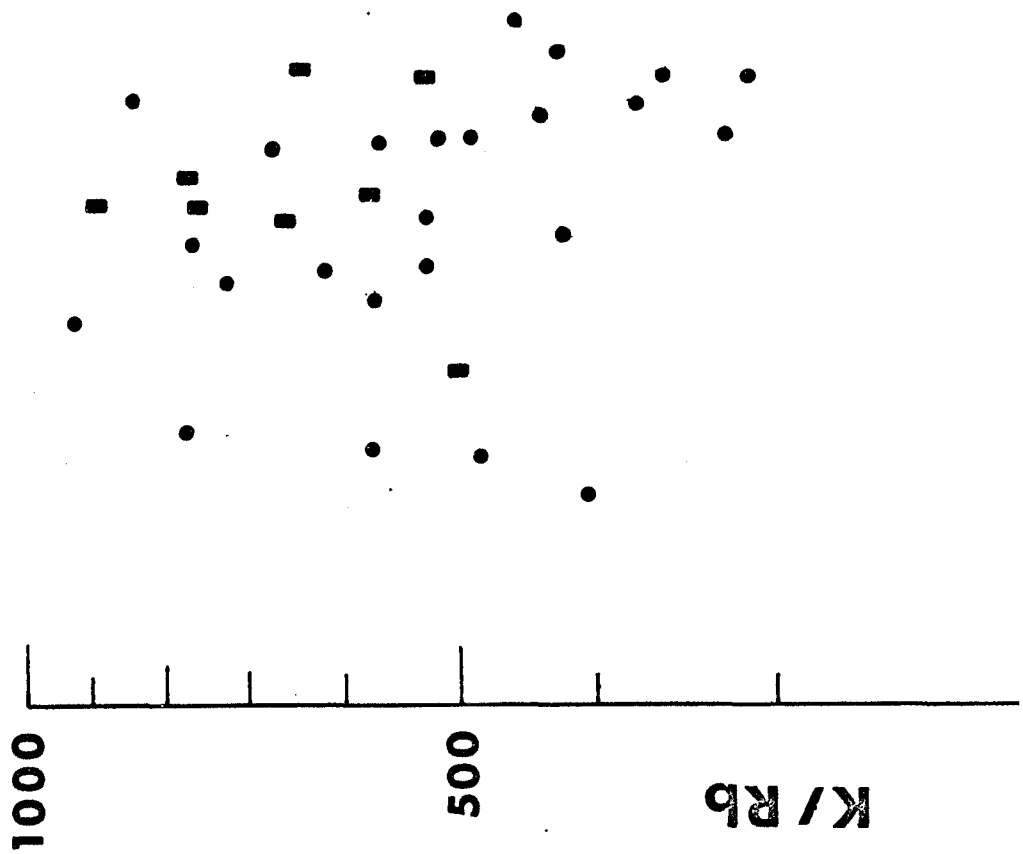
kaline





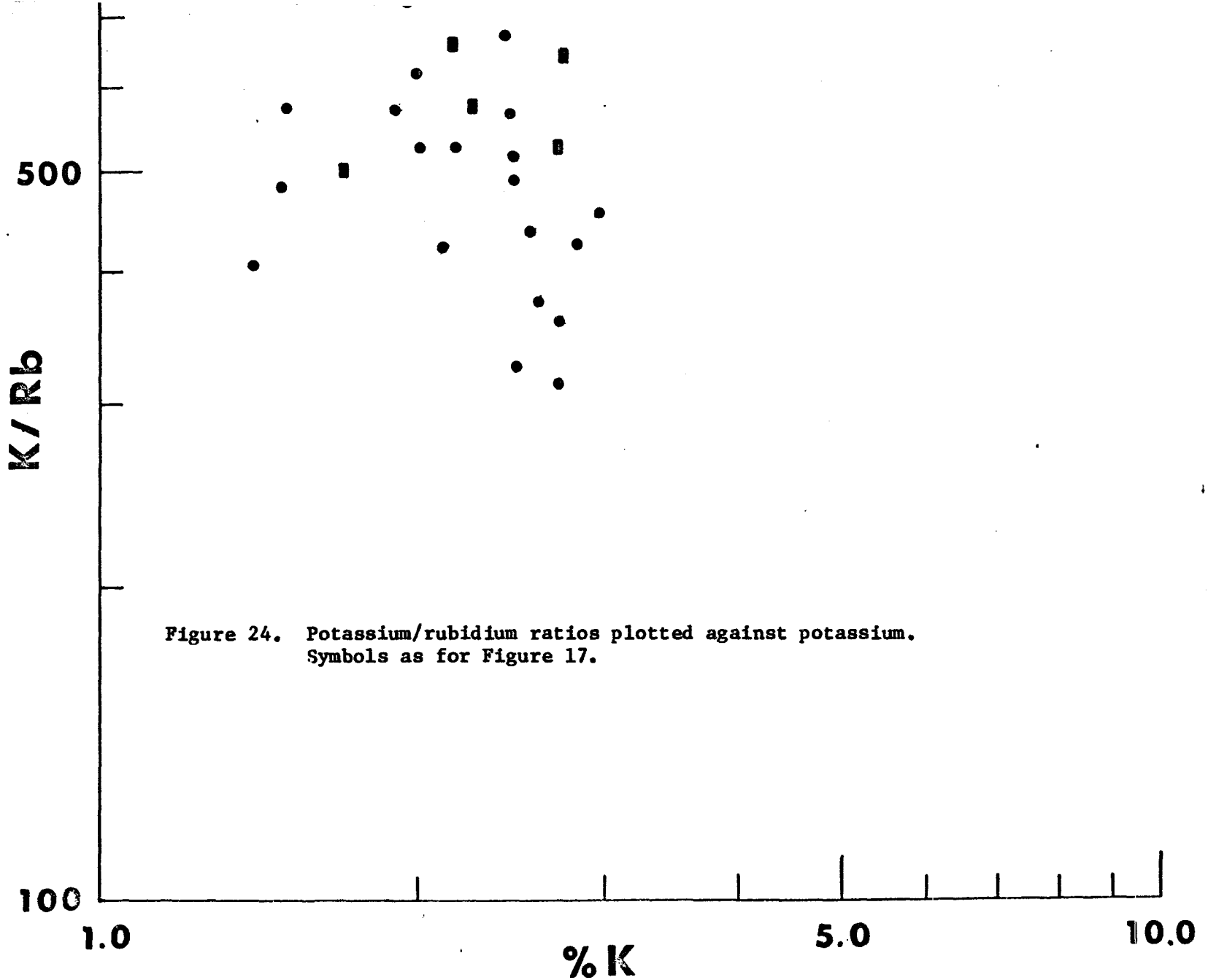
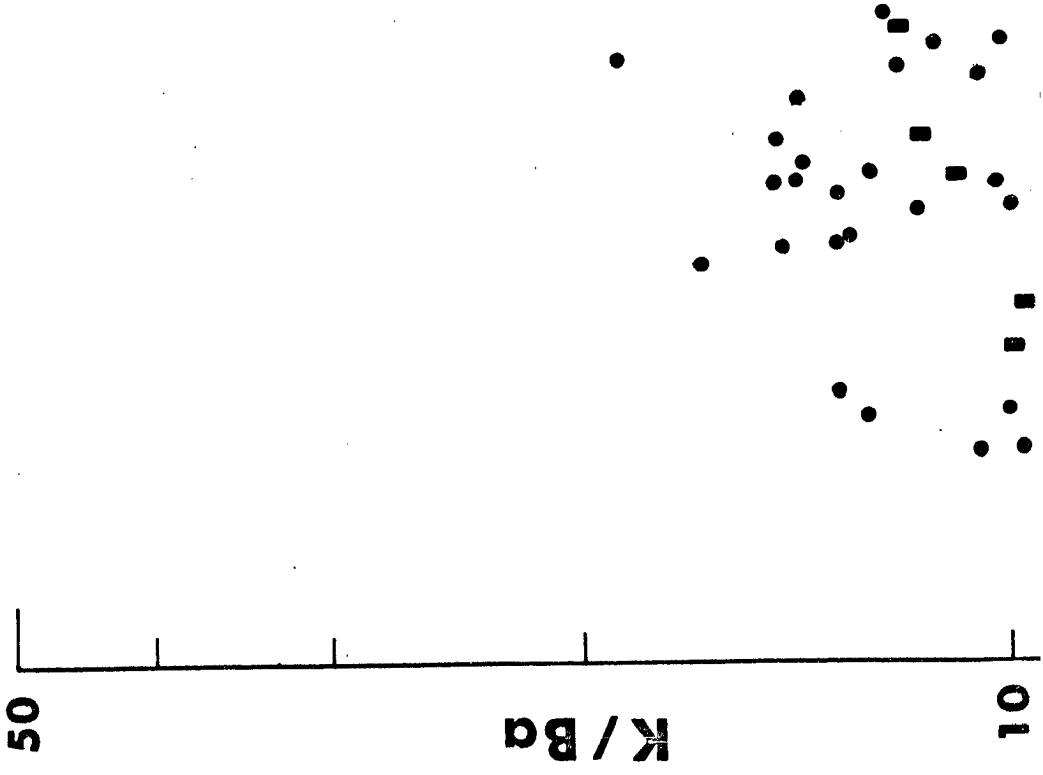


Figure 24. Potassium/rubidium ratios plotted against potassium. Symbols as for Figure 17.



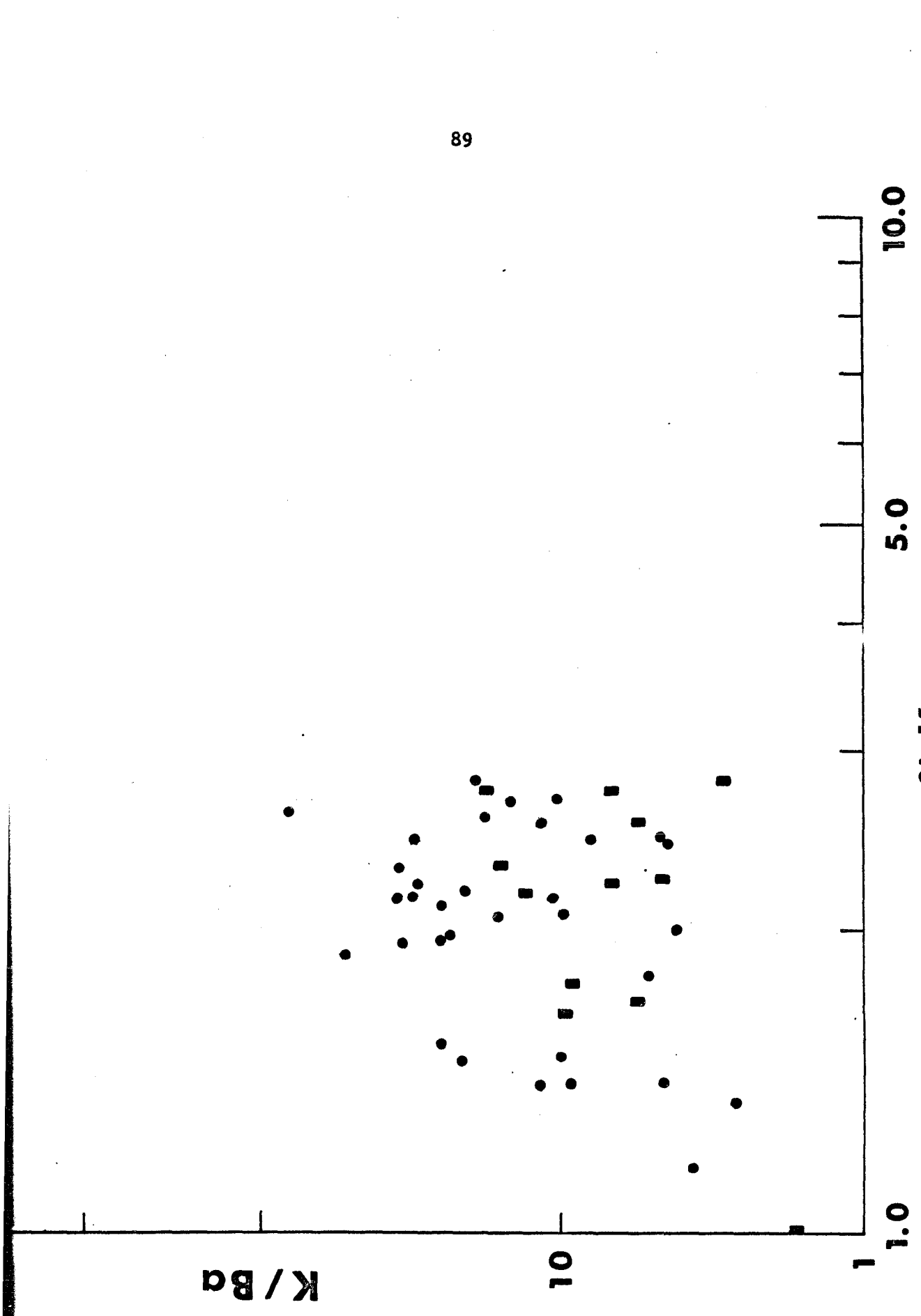
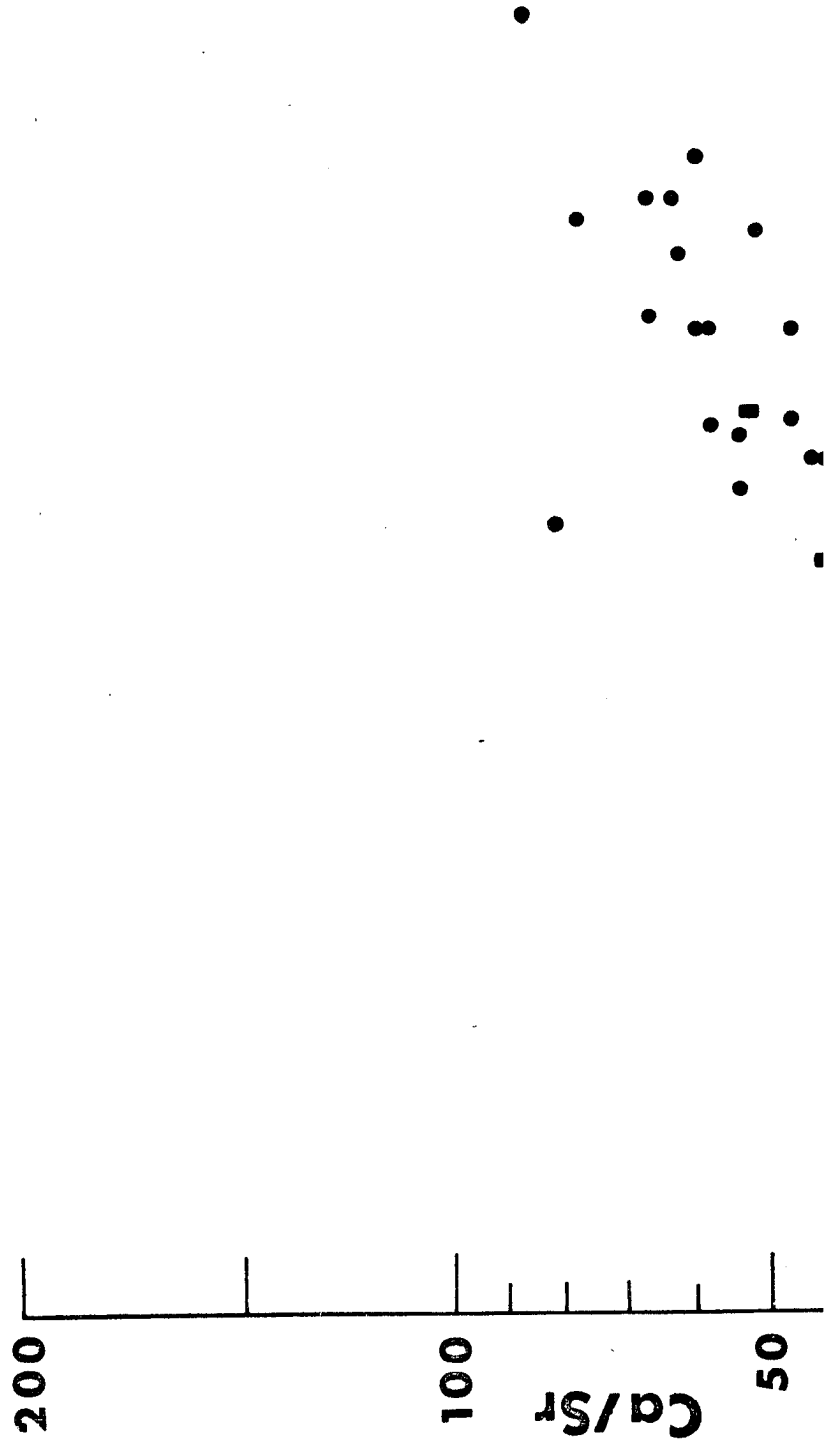


Figure 25. Potassium/barium ratios plotted against potassium. Symbols as for Figure 17.



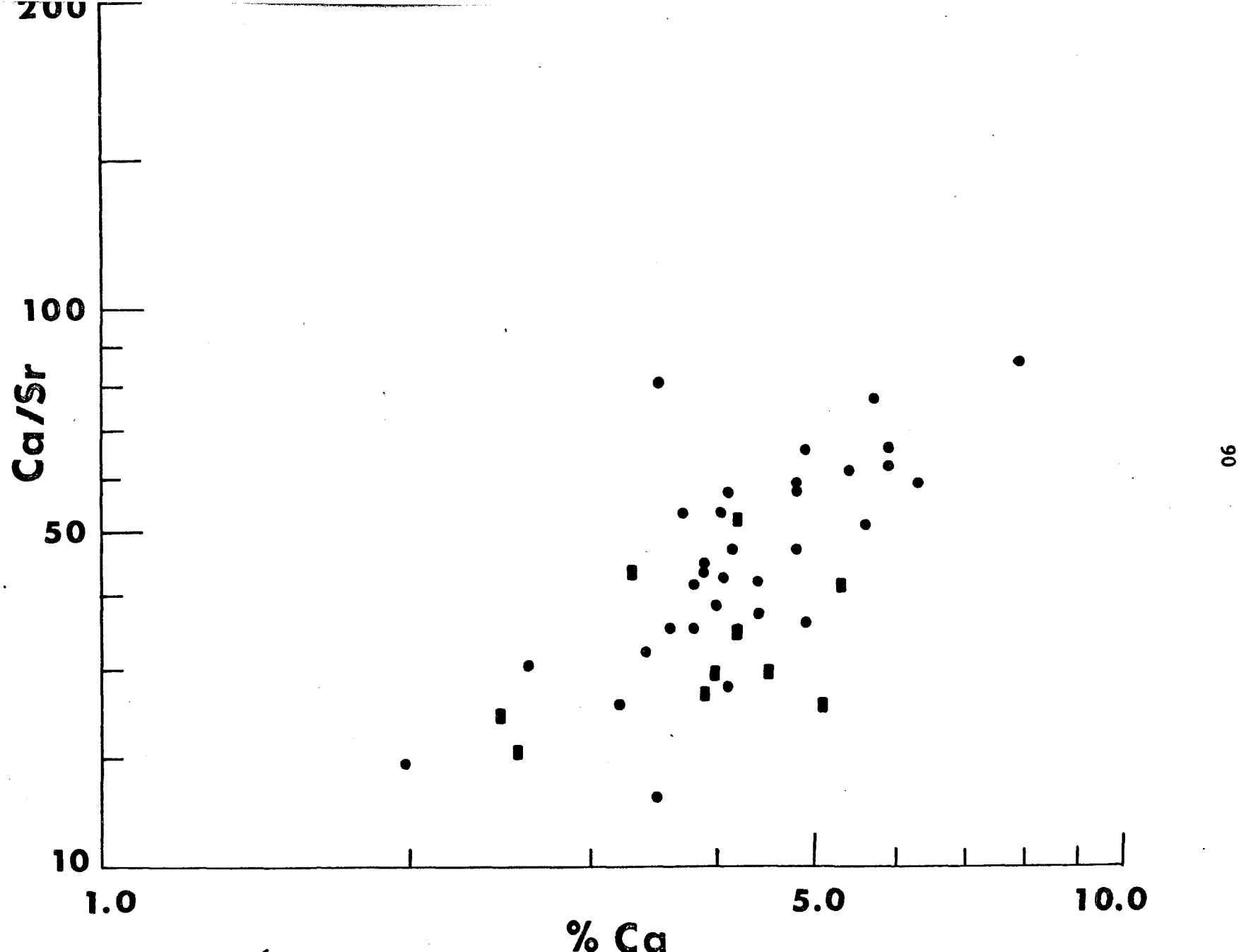
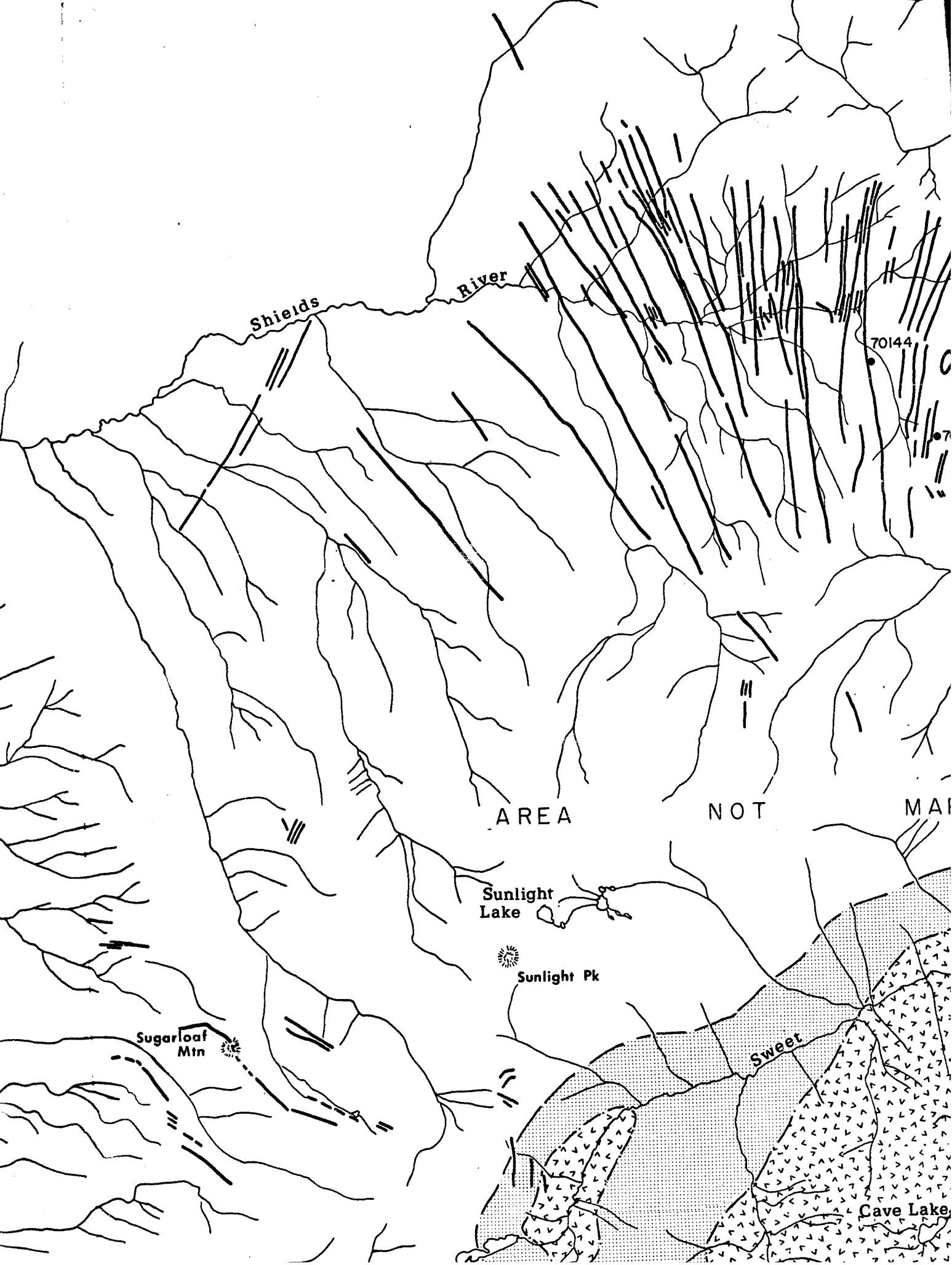
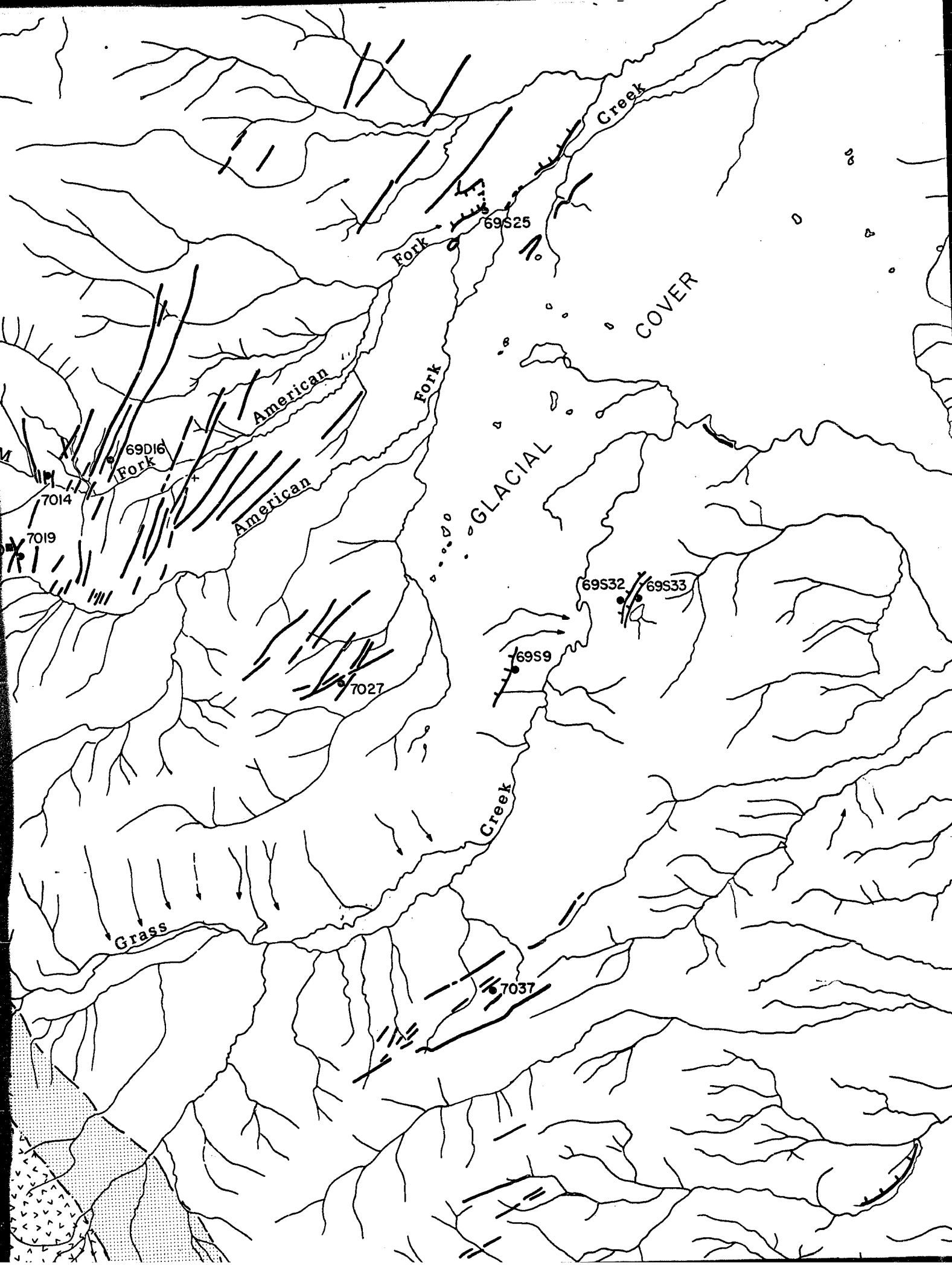
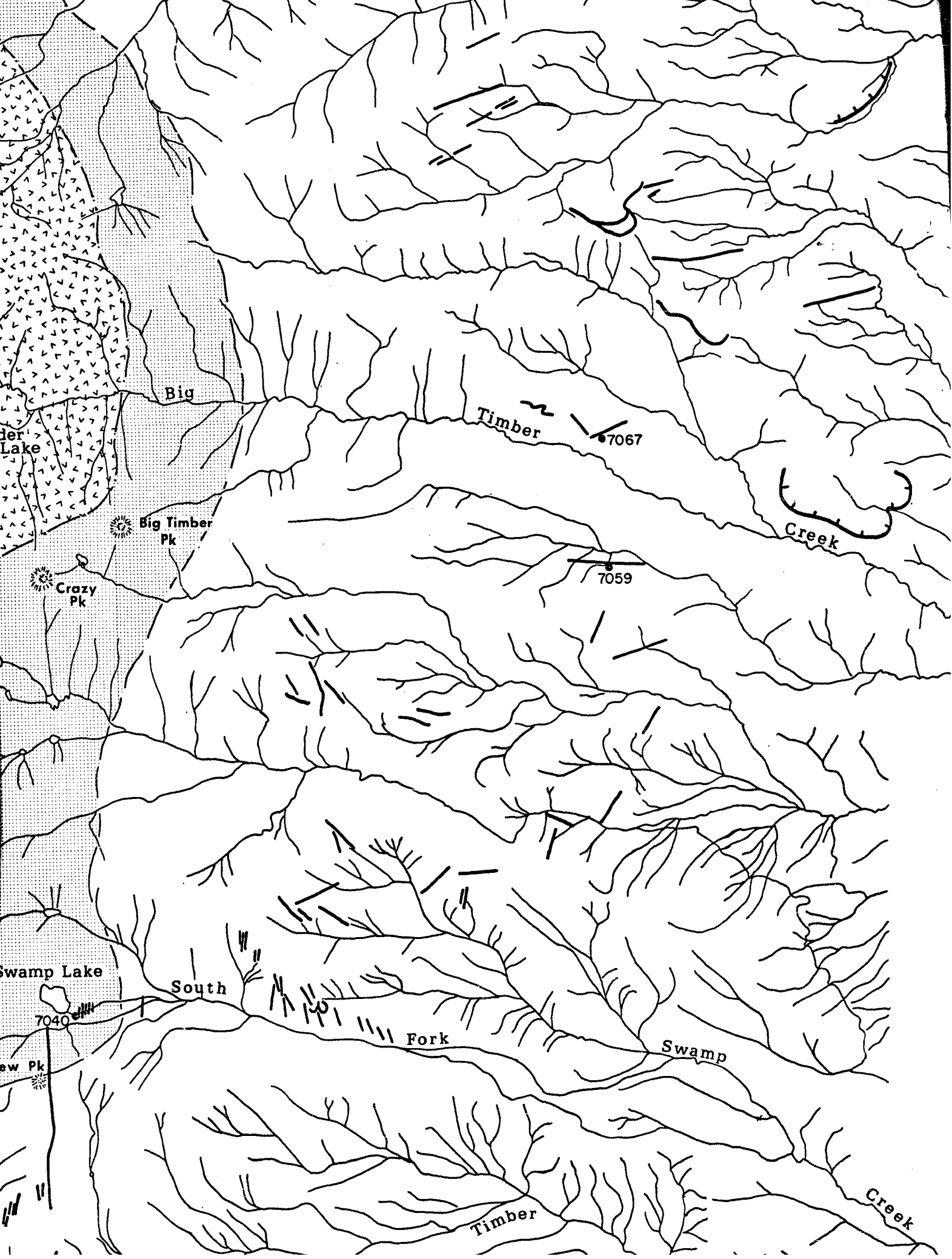
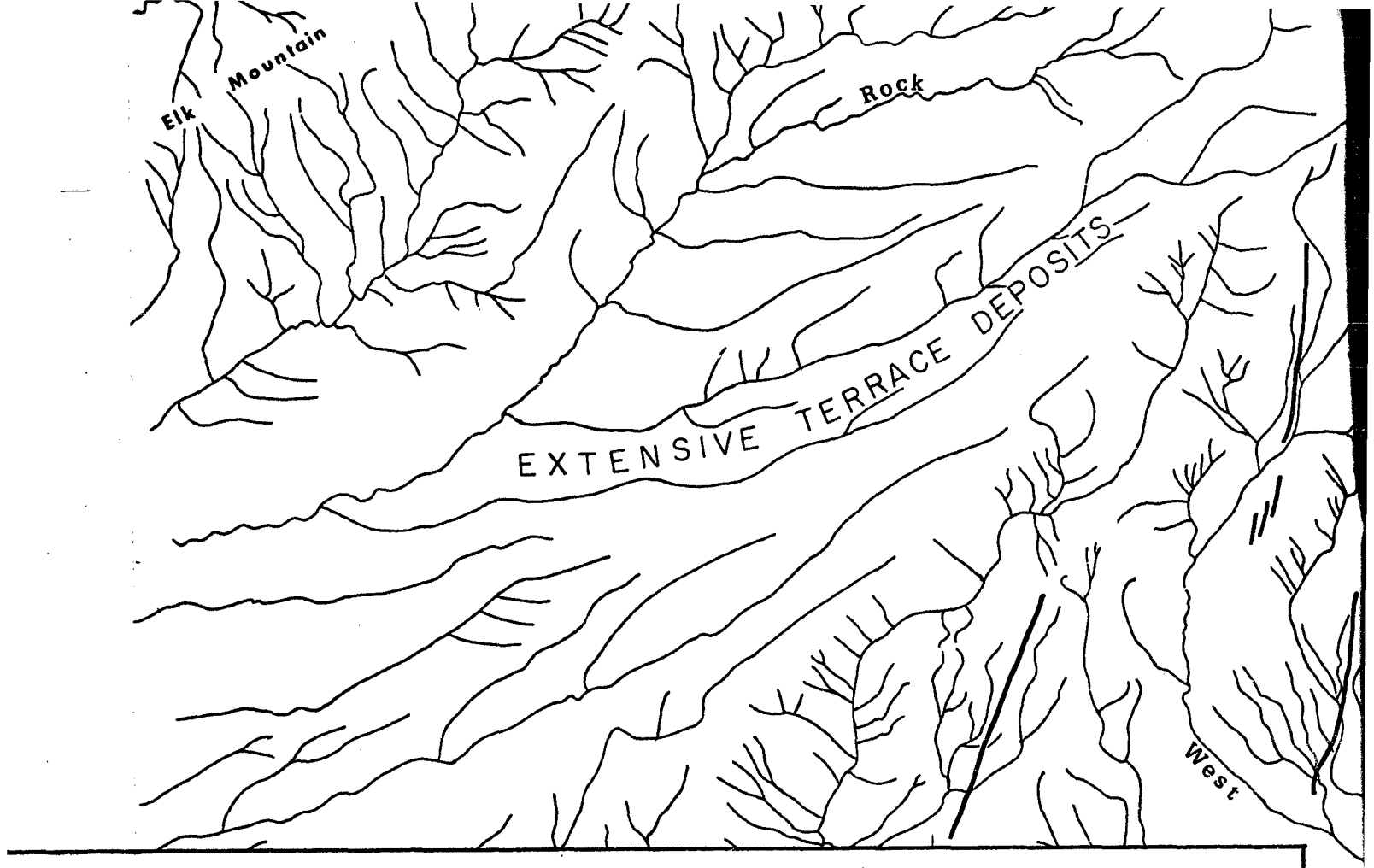


Figure 26. Calcium/strontium ratios plotted against calcium. Symbols explained in Figure 17.









GEOLOGY OF PART OF THE CRAZY MOUNTAINS, MONTANA

EXPLANATION

- DIKES, Sills hachured in direction of dip
- ADINOLE
- BIG TIMBER STOCK
- FORT UNION AND YOUNGER SEDIMENTS
- STREAMS
- LAKES
- Alkali-Calcic Dike or Sill
- Mildly Alkaline Dike or Sill
- MOUNTAIN PEAKS

N

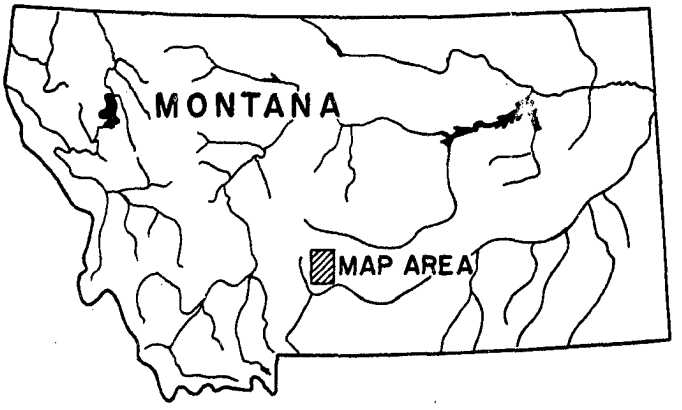
MAG. NORTH

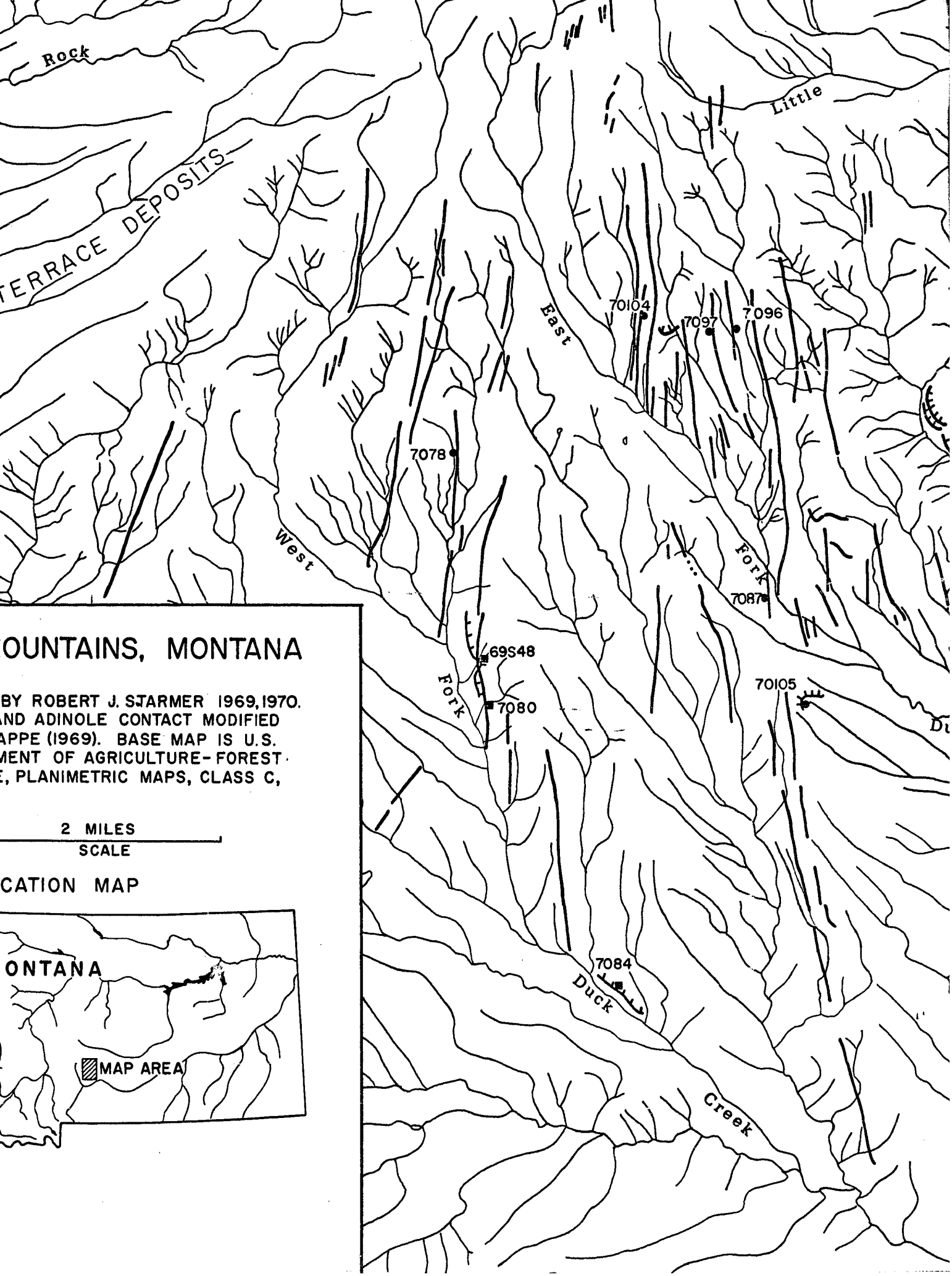
18°

GEOLOGY BY ROBERT J. STARMER 1969, 1970. STOCK AND ADINOLE CONTACT MODIFIED FROM TAPPE (1969). BASE MAP IS U.S. DEPARTMENT OF AGRICULTURE-FOREST SERVICE, PLANIMETRIC MAPS, CLASS C, 1970.

2 MILES
SCALE

LOCATION MAP





OUNTAINS, MONTANA

BY ROBERT J. STARMER 1969, 1970.
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MENT OF AGRICULTURE-FOREST
E, PLANIMETRIC MAPS, CLASS C,

2 MILES
SCALE

CATION MAP