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PETROLOGY OF THE GRANITIC ROCKS
IN THE VICINITY OF REPUBLIC TROUGH
IN THE UPPER PENINSULA OF MICHIGAN

By

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ABSTRACT

PETROLOGY OF THE GRANITIC ROCKS IN THE VICINITY OF REPUBLIC TROUGH IN THE UPPER PENINSULA OF MICHIGAN

BY

Syed Mohammad Zainuddin

Republic Trough is a narrow, tightly folded syncline of Animikie metasediments, located towards the western part of Marquette County in the upper peninsula of Michigan. Granitic rocks are exposed in the area surrounding the trough. The number of granitic intrusions and their age relations have been a subject of controversy for many years.

The present study was conducted to determine the number of genetically different types of granite based on field observations and petrographic variation. The field relation and textural variation indicate the occurrence of three types of granitic rocks of significant areal extent: an even-grained granite gneiss, foliated porphyritic granite with small phenocrysts, and the coarse porphyritic granite. (The foliated porphyritic granite and coarse porphyritic granite have not been differentiated by earlier workers.)

The modal composition of the three granites can not be used to resolve them into genetically different types since the variation within one type is greater than the difference between two types. The trace elements composition is also not significantly different. K/Rb ratios in the K-feldspars of the three granite types are generally similar and range within the published values for granites. However, the Na/K ratios in the K-feldspars of the two porphyritic granites show a bi-modal distribution and are significantly higher for the coarse porphyritic

granite. Statistical analyses of the plagioclase twin types clearly demonstrate that the samples of the foliated porphyritic granite and the coarse porphyritic granite belong to significantly different populations.

The granite gneiss is texturally and mineralogically very heterogeneous, probably reflecting varying conditions of the genesis of the rock type. Xenoliths of the granite gneiss have been found in the other two granites which indicate that the granite gneiss is the oldest of the three granitic rocks. The intrusive relation of the gneiss into the pelitic schist suggest a magmatic origin of the gneiss.

Unlike the other granites in the area, the foliated porphyritic granite is mineralogically homogeneous. The modes plotted on the Qtz-Or-Ab ternary phase diagram are restricted to the low temperature trough. This indicates a slow cooling of the rock maintaining chemical equilibrium. The highly ordered structural state of the K-feldspar and the distribution coefficient of albite between coexisting feldspars also support this view.

The macro measurements and petrofabric analysis of the foliated porphyritic granite indicate that a strong NW-SE foliation, parallel to the axial plane of Republic Syncline, was superimposed on an earlier N25W-S25E foliation. The structural relation indicates a pre-Animikie age of the rock type.

A younger granite, referred to as coarse porphyritic granite, was emplaced along the anticlinal axis between the Republic Syncline and Marquette Syncline. The granite shows great mineralogical variation ranging from granite to trondhjemite in composition. General lack of NW-SE foliation, as observed in the field and revealed by petrofabric analysis, suggests a post-Animikie age of the coarse porphyritic granite.

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INTRODUCTION

Purpose of Study

The granitic rocks around the Republic Trough in Marquette County, Michigan called "Basement Complex" by Van Hise (1911) and "Republic Granite" by Lamey (1933), have been a subject of discussion since 1850. The controversy among the different workers is related to the actual number of granitic intrusions in the area and their relative age. There is, however, a general agreement that at least two types of granites are exposed in the area. The relationship of the granites with the Animikie metasediments and the relative areal extent of the granites is still a matter of controversy. Most of the discussions by the previous workers in the area are attempts to explain the age relation of the granites and the Animikian rocks based largely on field relations; the petrology of the granites has not been described clearly.

The purpose of the present study was to determine the number and range of granite types in the area and to determine the extent that petrographic variations coupled with field observations could resolve the granitic rocks into a combination of genetically different types.

Geography

The Republic Trough is a narrow syncline of Animikian rocks located towards the western part of Marquette County in the Upper Peninsula of Michigan (Figure 1).

The area mapped surrounds the trough and covers about sixty square

INDEX MAP

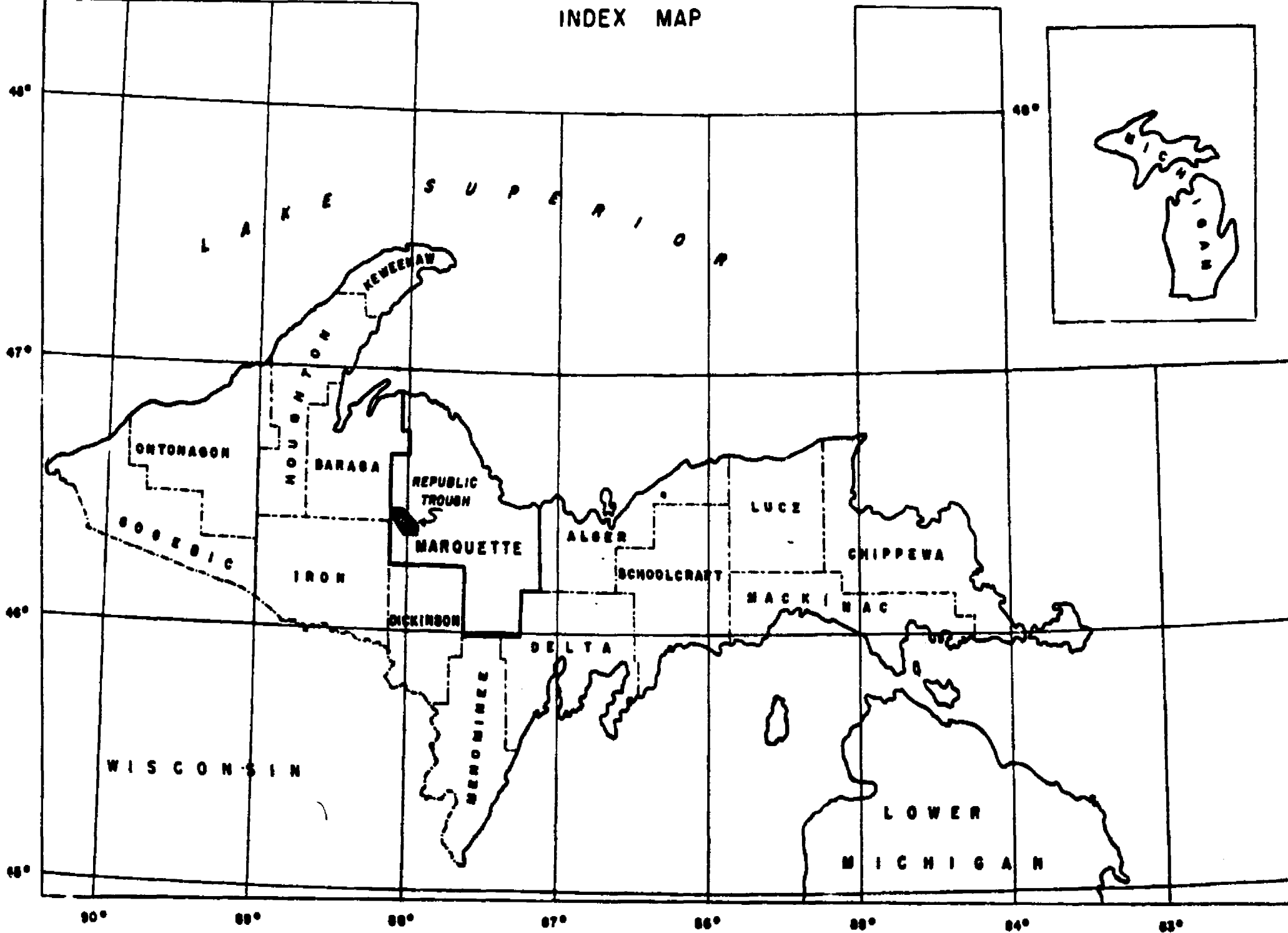


Figure 1. Index Map Showing Location of the Republic Trough Area.

miles encompassed within latitudes $46^{\circ}20'$ and $46^{\circ}28'$ north; longitudes $87^{\circ}53'$ and $88^{\circ}06'$ west. It includes Townships 46 and 47 north; Range 29 and 30 west. The area is dissected by the Michigamme River flowing southeast along the axis of the trough.

The town of Republic, towards the southeast of the trough, is located on State Highway M 95 and is also accessible by a few county roads. The southern part of the area is traversed by few paved roads accessible by automobile; the northern part has only a few logging roads and is completely inaccessible by automobile.

The outcrops of rocks are very few and sporadic, covering less than five per cent of the area, but road cuts have exposed the rock at many places. New State Highway M 95 runs north-south along the whole length of the area, and the cuts along the road provide the best exposures for study and expose fresh unweathered rocks for sampling. Most of the remainder is covered by sand plains; swamps cover the shallow depressions. Exposures of rocks are seen on the summits and flanks of small isolated knobs separated by wide cover of glacial deposit.

Geological Setting

The area known as the Southern Complex (Dickey, 1936) is dominantly composed of granite, outside the Republic Trough. Reconnaissance survey revealed the presence of three texturally distinct types of granites of significant areal extent, an even-grained granite gneiss, foliated porphyritic granite with small phenocrysts and coarse porphyritic granite lacking any visible foliation. The foliated porphyritic granite and coarse porphyritic granite have not been differentiated by previous workers in the area and have commonly been referred to as "Republic Granite" since first named by Lamey (1933).

The number of granitic intrusions in the area and their age relations with the Animikie metasediment have been a matter of controversy since 1850. Van Hise and Leith (1911) reviewed the problem and work up to 1909 and concluded that there are two intrusions of granite in the area: one pre-Animikie (pre-Huronian), and the other post-Animikian. The relative areal extent of pre-Animikie and post-Animikie granites have also been a controversial problem. Lamey (1937) believes that most of the granites of the Southern Complex are post-Animikie, whereas Dickey (1936) contends that much of the Southern Complex consists of pre-Animikie granites. Foster and Whitney (1851), the earliest workers in the area, suggested that the granite of the Southern Complex is intrusive into the Animikian.

Lamey (1937) has compiled an excellent review and evaluation of the many writings and work on the problem of the granitic rocks of the Southern Complex. In a series of articles, he has concluded that the entire area of the Southern Complex with minor exceptions is intruded by granites of post-Animikie age. Lamey has reported the intrusion of granite into quartzite, presumably of Animikie age, south of National Mine in Ishpeming. His idea is further supported by the metamorphism of Animikie sediment which he attributes to the contact effect of post-Animikie granite (Lamey, 1934).

Metamorphism of Animikie sediment has been cited as evidence for the post-Animikie age of porphyritic granite by some other workers (Swanson, 1929; Zinn, 1930; Snelgrove, Seaman and Ayres, 1944). Swanson (1929) and Zinn (1930) have also recognized the occurrence of an older heterogeneous gneiss in the area upon which Animikie was laid down.

Swanson (1929) also reported the intrusion of granite into Animikie

sediment seen in a drill hole in Section 20, T47N, R28W, and has correlated this granite with the Republic granite. The basis of his correlation is, however, not mentioned.

Dickey (1936) has dated the porphyritic granite as pre-Animikie in age and cited the following evidences in support of his view:

- (a) Lack of intrusion of porphyritic granite in Animikie (Huronian) rock.
- (b) Deformation and shearing of granite after solidification.
- (c) Basal Animikian conglomerate containing boulders of porphyritic granite.

The conglomerate was exposed at the southeastern end of the Republic Trough in the northeast quarter of Section 18, T46N, R29W. According to Dickey, boulders of porphyritic granite up to five feet in diameter are included in the conglomerate; the foliations in the boulders are at varying angles to the general foliation of porphyritic granite. The conglomerate was first described by Smyth (1893) who also reported the presence of boulders of granite in the conglomerate.

Lamey did not find any evidence of granite boulders in the conglomerate and disputes the finding of Dickey in a later paper (Lamey, 1937). According to Lamey, the conglomerate is chiefly quartzitic. The total absence of porphyritic granite in Animikie conglomerate has also been reported by Marsden, Tyler et al (1940).

The outcrop has since been covered by waste material from the Republic Mine and could not be examined during the course of this study.

Dickey (1938) has recognized a post-Animikie granite in Republic area which he called "Killarney Granite." He reports that this granite is sporadic in occurrence and that it is exposed in disconnected small areas. He has attributed its origin to the partial fusion of porphyritic

granite during the Killarney orogeny. The periods of granitic intrusion in the Southern Complex and their age relation with other Precambrian rocks of the area, as recognized by Dickey, are shown in Table 1.

Table 1. Age Relations of the Rocks of Southern Complex (after Dickey, 1938)

Era		Period	Formation
Paleozoic		Cambrian	
Precambrian	Algonkian	Keweenawan	Lipalian Interval----- Killarney granite

		Huronian	Upper ----- Middle ----- Lower
	Archean		Eparchean Interval----- Granite-porphyry
		Laurentian	Granite of the Archean injection gneiss
		-----	-----
		Keewatin	Schists

James (1958) proposed the classification of the Precambrian rocks of Northern Michigan into Lower, Middle, and Upper Precambrian. This three-fold nomenclature has been adopted by the U. S. Geological Survey.

James also proposed the term Animikie for the metasediments previously called Huronian. Table 2 shows the succession of the Precambrian rocks in Northern Michigan, adapted to the Marquette Synclorium.

Table 2. Sequence of Precambrian Rocks in Northern Michigan
(from Gair and Thaden, 1968)

Upper Precambrian	Keweenaw Series	Diabase dikes	
Middle Precambrian	Animikie Series		Peridotite age uncertain Pegmatite
			Mafic intrusive rocks of uncertain age
		Menominee Group	Siamo Slate Ajibik Quartzite
Lower Precambrian			Unconformity or Disconformity
		Chocolay Group	Wewe Slate Kona Dolomite Mesnard Quartzite Enchantment Lake Formation
			Unconformity
			Metamorphosed mafic intrusive rocks of uncertain age- may be partly or entirely of Animikie age intrusive contact
			Compeau Creek Gneiss and related dikes intrusive contact
			Metamorphosed mafic intrusive rock intrusive contact
			Mona Schist including Lighthouse Point Member

Field Mapping

Field work for this investigation was carried out during the summers of 1966 and 1967 and continued for part of the summer in 1968. An area of about 60 square miles covering parts of Republic SW, Republic, Witch Lake NE, and Witch Lake 7.5 minute quadrangles, was studied. U. S. Geological Survey topographic maps on 1 inch to 2000 feet scale were used as base maps.

Wherever available, county roads and logging roads were used for traverses; other traverses were taken along section lines. Outcrops were plotted by pace and compass method of survey, using a Brunton Compass. The area is densely forested, which prevents the easy location of available exposures. This handicap was partly overcome by the use of aerial photographs in locating positions of outcrops.

Deviation of compass reading was noted near the Animikie rocks due to the presence of iron formation; deviations as much as 80° were recorded in some localities. The compass reading in areas of magnetic disturbance was corrected using the sun chart compass correction method of Fraser (1963). Sun compass was also used for some readings, but was not very practical because of the long time required for each reading.

Based on textural variation and field relations, three distinct types of granites were recognized: granite gneiss, foliated porphyritic granite with small phenocrysts, and a coarse porphyritic granite.

GENERAL LITHOLOGY OF THE GRANITIC ROCKS

Granite Gneiss

The rock is massive, fine to medium grained, and is composed primarily of microcline perthite, quartz, and plagioclase in varying proportions. The granite gneiss is very heterogeneous in composition, ranging from a quartzose granite (location: north of Michigamme River along M 95) through granodioritic (location: (a) northern part of Section 29, T47N, R29W; (b) S W $\frac{1}{4}$ of Section 25, T47N, R29W) to true massive granite.

Textural variation in the rock is also very prominent. The parallel aligned biotite flakes at places form banding and attain a true gneissic texture. At a few locations, lit-par-lit injection of granitic liquid into pelitic and semi-pelitic Lower Precambrian rocks has resulted in the formation of injection gneiss which consists of coarsely crystalline quartzo-feldspathic bands alternating with biotite quartz bands.

Near the trough, outcrops of granite gneiss generally flank Animikie metasediments; and also mantle the coarse porphyritic granite in the northern sector of the area. Near Republic, the granite gneiss occurs in juxtaposition with foliated porphyritic granite; at places they are much intermingled.

The rock possesses a NW-SE foliation which was superimposed on a N25W-S25E foliation, parallel to the axis of the syncline, probably developed by Animikie folding.

Foliated Porphyritic Granite (with small phenocrysts)

The rock is generally grey in color showing a well-developed planar foliation marked by parallel alignment of biotite flakes. Subhedral to anhedral phenocrysts of microcline and plagioclase, sometime form a fairly prominent linear structure in the foliation. The phenocrysts are usually one to two cm in length, and display an augen appearance in a few localities.

The trend of the early foliation in general is N25W-S25E with a very steep to vertical dip. The granite was probably folded with the Animikie rocks and in the process acquired a NW-SE orientation. The foliation is generally concordant with the Animikie metasediments near the contact, but at a location south of Republic Mine (NE $\frac{1}{4}$ of Section 18, T46N, R29W), the discordant relation of the granite with the meta-sediments is clear. The field relation of the rocks at this location indicates that the N25W-S25E foliation in the granite developed before the folding of the Animikie rocks, was folded later with them.

Unlike the other two types of granite in the area, the rock is generally homogeneous in composition.

Coarse Porphyritic Granite (with big phenocrysts)

The rock lacks any planar foliation but shows a strong linear orientation marked by parallel to subparallel arrangements of euhedral to subhedral phenocrysts of microcline. The large (3 to 4 cm long) phenocrysts of microcline are set in a coarse matrix of quartz, plagioclase, and biotite, with accessories.

The feldspar phenocrysts in the rock are arranged linearly in a N65W-S65E direction, probably caused by flow. The trend of lineation in the rock has a very discordant relation with the foliation of the

foliated porphyritic granite in the central part of the outcrop, but gradually attains parallelism near the contact with the foliated porphyritic granite. The phenomenon is well illustrated by the change in lineation trend from sample location 57 (Section 32, T47N, R29W), proceeding southwest to sample locations 58, 59, 60, and 185 near the contact (see Figure 2). The lineation changes gradually from N62W-S62E to N25W-S25E at location 185. This suggests that the development of lineation is due to flow and that the change in the trend as the contact is approached is a result of interference by the wall rock (Balk, 1937).

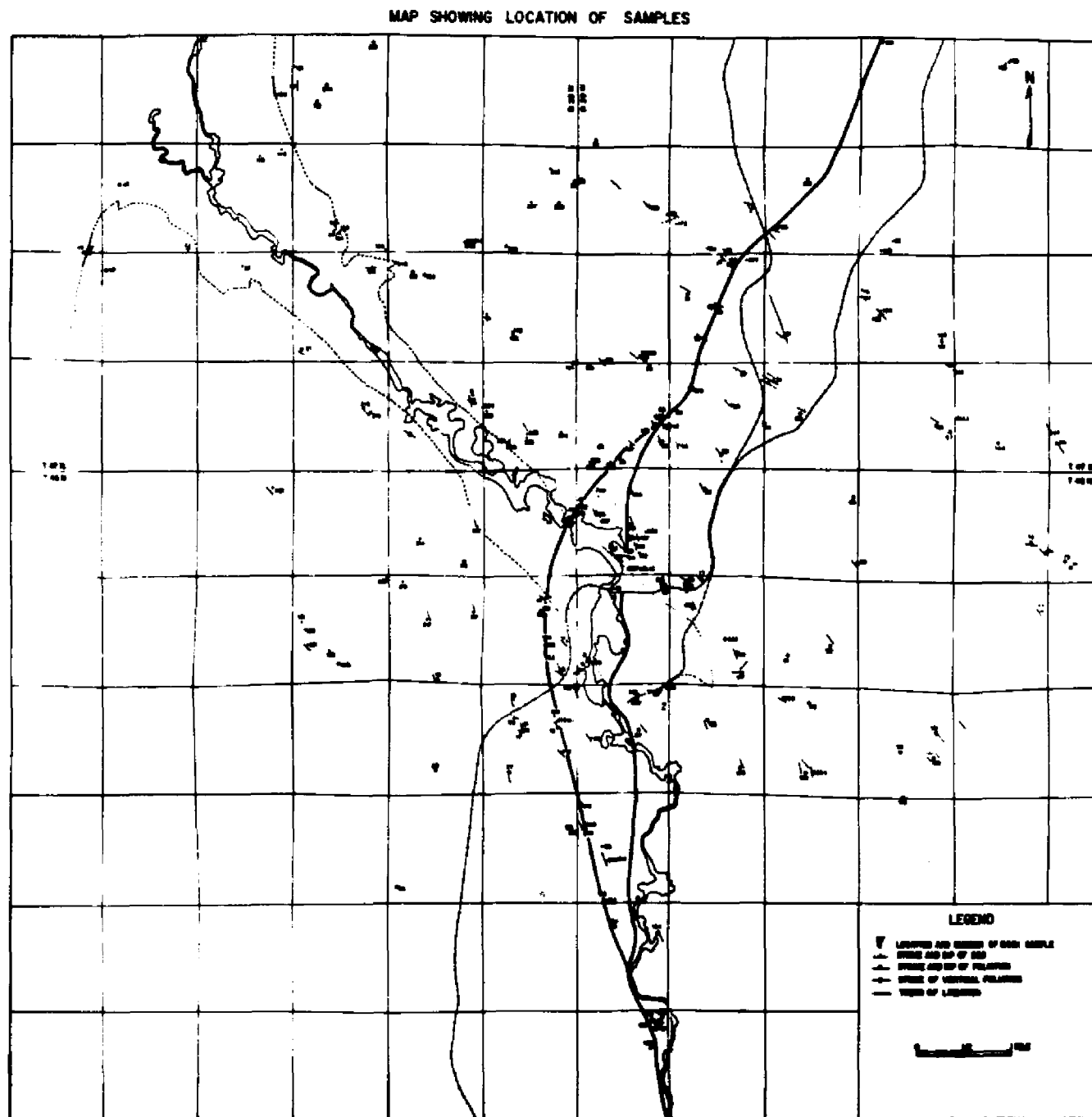


Figure 2. Map Showing Sample Locations

GENERALIZED SCHEMATIC MAP OF REPUBLIC TROUGH AREA

The structure of the Republic Trough area is very complex. There are clear evidences of many phases of deformation, each phase having partially deformed the structure developed by earlier phases. The various phases of deformation have complicated the field relations of the different granitic rocks. Field observation to resolve the relationship of the granites was greatly handicapped by the lack of sufficient rock exposures in the area.

The granite gneiss is exposed mainly around the Animikian rocks along the trough. The contact relations of the two rocks could not be observed at any place; commonly an erosional valley separates the granite gneiss and Animikie metasediments. The intrusive relation of the granite gneiss into hornblende-quartz-schist is very clear at a few locations south of the Michigamme River. The gneiss is also seen to be generally mantling the coarse porphyritic granite, but field relations are difficult to determine since the outcrops are very small and isolated.

Xenoliths of granite gneiss, varying in size from a fraction of a meter to a few meters, are found in coarse porphyritic granite as well as foliated porphyritic granite. The presence of xenoliths clearly indicates that the granite gneiss is the oldest of the three granitic rocks in the area.

The field relations of foliated porphyritic granite and coarse

porphyritic granite are not very clear. The outcrops of the two rock types are everywhere separated by glacial deposits; the transition between the two types is sharp.

There are, however, a few small sporadic outcrops of well-foliated coarse porphyritic granite at the following locations:

- (a) Eastern part of Section 13, T46N, R30W
- (b) Southern part of Section 36, T47N, R30W
- (c) Northwestern $\frac{1}{2}$ of Section 19, T46N, R29W

The rock is well-foliated and has been mapped as foliated porphyritic granite. It may also be related to coarse porphyritic granite and have acquired the foliation as the result of flow during intrusion. The margin of coarse porphyritic granite at places has developed planar foliation presumably due to the flow along the contact.

Figure 3 shows the general bedrock geology of the area. Pegmatite and amphibolite have not been shown on the map because of their small outcrops.

Petrofabric analysis of 13 rock samples (5 each of coarse porphyritic granite and foliated porphyritic granite and 3 of granite gneiss) was carried out to determine the age relation of the rocks by the number of phases of deformation and their effect on the rock. The samples were collected from scattered outcrops to get a representation of the whole area. Two oriented sections were cut from each rock--one parallel to the horizontal plane and the other from a vertical plane. Orientation of C-axis (the principal axis) of quartz was recorded for 200 quartz grains in each section. The plot of the vertical section was rotated along the N-S axis to bring it to a horizontal plane. C-axis emergence on lower hemisphere was plotted on a "Schmidt equal area net." A

GEOLOGIC MAP OF REPUBLIC AREA, MARQUETTE COUNTY, MICHIGAN

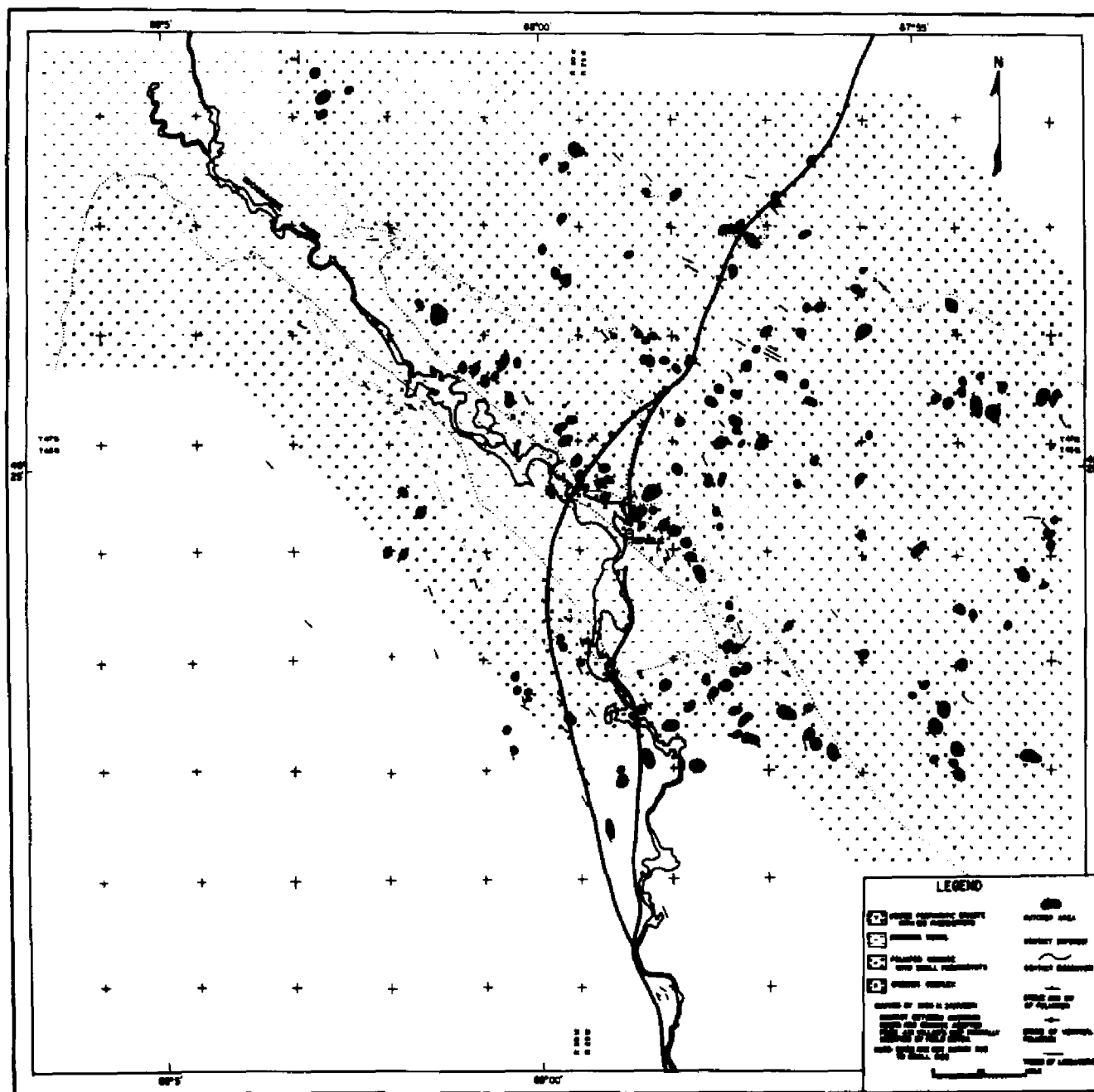


Figure 3. Geologic Map of Republic Area, Marquette County, Michigan

composite plot of the two sections in each rock was contoured at a one percent interval. Plot of two sections at right angles to each other is likely to eliminate bias in the selection of the plane of observation.

The petrofabric analysis of the rocks revealed that the granite gneiss and the foliated porphyritic granite have a strong orientation in NW-SE direction, which is concordant with the axis of the Republic Trough. It is likely that the development of this orientation is synchronous with the folding of the Animikie metasediments and is superimposed on the earlier formed planar foliation striking N25W-S25E.

The age of emplacement of coarse porphyritic granite is not very clear. Lack of planar foliation and a general absence of NW-SE orientation in petrofabric analysis (only two of the five rocks examined have any significant concentration in NW-SE direction) suggest a post-Animikie age of the coarse porphyritic granite. The rock appears to have been emplaced as a sheet with a general strike of N60W-S60E and occupies the anticlinal axial position between the Republic Syncline and Marquette Syncline. It intruded along the axial plane of the anticline after or during the waning phase of Animikie folding.

The metamorphism of the Animikie rocks may be related to the intrusion of the coarse porphyritic granite. It is also likely that only the roof of the coarse porphyritic granite pluton is exposed in the area and the rock extends more widely at depth. The presence of xenoliths in the rock and the extensive metamorphism of the Animikie metasediments supports this idea.

Weak orientation in E-W and NE-SW direction is revealed by a few samples of all the three types of granite in the area. These orientations

developed after the emplacement of coarse porphyritic granite and may be associated with the numerous pegmatite and amphibolite intrusions in the area.

Taylor (1967) studied the structure of the Lower Precambrian rocks in the Champion-Republic area. He recognized four phases of deformation by the measurements of minor structures.

PETROLOGY OF THE GRANITES

A) Modal Analysis of the Granites

Determination of the minerals and their relative proportions in the three types of granitic rocks was carried out to study the mineralogy of the granites and examine the difference between the various types. The point count method of Chayes (1956) was employed for determining the relative proportions of minerals in thin sections. About 1200 to 1400 points were counted in each section of coarse porphyritic granite; whereas 1000 to 1200 points were counted in the other lithologies, the number being determined by the coarseness of the rock.

The three types of granites are similar in mineral composition; variation within a type is sometimes greater than the difference between the types. The average modes of the three granites are presented in Table 3, and these are plotted on the K-feldspar-plagioclase-quartz ternary diagrams (Figures 4, 5, and 6).

The plots for the granite gneiss (Fig. 4) are concentrated mainly in the central part of the diagram, which corresponds to the low temperature trough on the quartz-orthoclase-albite ~~phase~~ diagram of James and Hamilton (1969).

Few samples completely devoid of K-feldspar were collected from granite gneiss-coarse porphyritic granite contact zone, except for one which is from an outcrop north of Republic where the granite gneiss is intermingled with the foliated porphyritic granite. The depletion

Table 3. Mineral Composition of the Three Types of Granitic Rocks

Mineral	Average Mode of Granite Gneiss (18 samples)			Foliated Porphyritic Granite (18 samples)			Coarse Porphyritic Granite (18 samples)		
	Mean	Range	Standard Deviation	Mean	Range	Standard Deviation	Mean	Range	Standard Deviation
Microcline	20.5	0.0 - 33.7	10.7	30.0	15.4 - 39.4	6.0	25.0	0.0 - 54.1	15.2
Quartz	30.1	7.0 - 39.1	8.6	31.3	22.9 - 41.6	5.0	35.6	13.9 - 55.4	10.3
Plagioclase	35.4	21.1 - 74.3	14.0	25.4	11.6 - 37.6	6.8	27.8	15.0 - 54.2	13.0
Biotite	5.3	0.0 - 13.8		4.2	1.4 - 7.7		3.6	0.3 - 8.6	
Muscovite	5.3	0.0 - 15.1		6.2	2.0 - 16.0		5.6	3.1 - 10.1	
Chlorite	1.7	Tr. - 3.9		1.4	0.3 - 6.7		1.2	Tr. - 3.2	
Myrmekite	1.0	0.0 - 2.9		0.7	0.0 - 2.7		1.0	0.0 - 2.6	
Zircon	Tr.			Tr.			Tr.		
Epidote	Tr.	0.0 - 1.8		Tr.	0.0 - 1.8		Tr.		
Apatite	Tr.			Tr.			Tr.		
Calcite	Tr.			Tr.			Tr.		
Opaque	Tr.			Tr.			Tr.		

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*Allanite, garnet and hornblende were identified in few rocks.

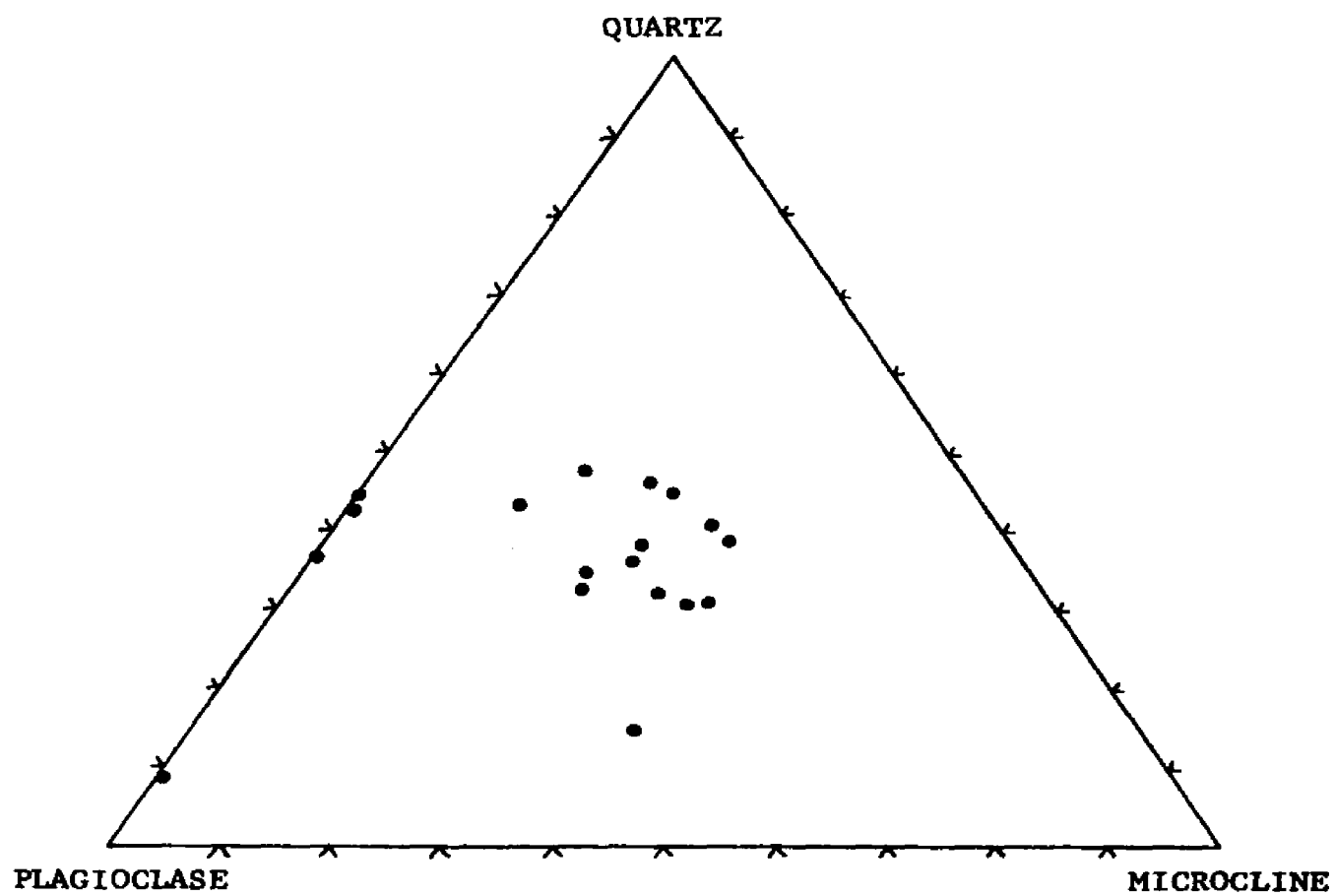


Fig. 4 Ternary diagram of quartz-plagioclase-microcline modal values for granite gneiss

of K-feldspar in the rock may have been caused by the replacement of microcline by albite. Evidence of such replacements is seen in a few rocks (Figure 7).

The average modal composition of the granite gneiss is 20.5% K-feldspar, 30.1% quartz, 35.4% plagioclase (An_{6-18}), 5.3% biotite, 5.3% muscovite, 1.7% chlorite, 1.0% myrmekite and traces of zircon, epidote, apatite, calcite, and ferruginous opaques. Allanite, garnet, and hornblende are rare accessories (Table 3).

All the values for the foliated porphyritic granite fall within a strikingly restricted area near the low temperature trough (Figure 5). This indicates that the rock cooled slowly, maintaining perfect equilibrium throughout the cooling.

Unlike the other granites in the area, the foliated porphyritic granite is fairly uniform in composition. The average modal compositions of the granites, given in Table 3, indicate that in comparison with the coarse porphyritic granite, the foliated porphyritic granite is richer in K-feldspar but poorer in quartz and plagioclase. Zircon, epidote, clinozoisite, and apatite are rare and occur only as inclusions in the plagioclase, probably formed later by the alteration of the plagioclase.

Plots of the coarse porphyritic granite (Figure 6) are very dispersed and do not follow any regular pattern with relation to its location in the field. Most of the values are concentrated near the center, slightly away from the plagioclase field. Five samples have less than five per cent K-feldspar and their plots lie on or near the plagioclase-quartz tie line. Most of these rocks are located in the contact zone with granite gneiss. The low K-feldspar rocks are generally rich in plagioclase, whereas the quartz content remains about average.

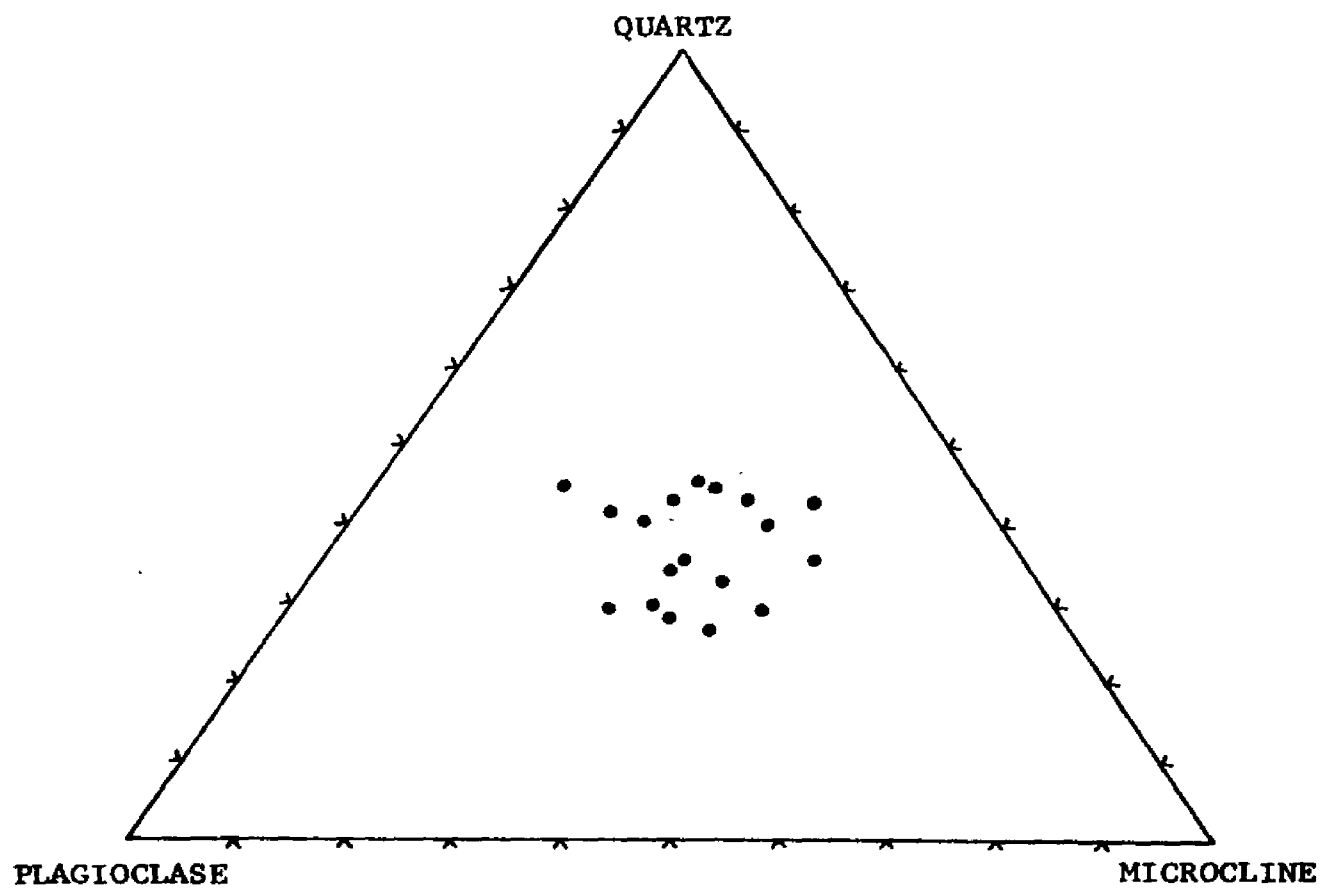


Fig. 5 Ternary diagram of quartz-plagioclase-microcline modal values for foliated porphyritic granite

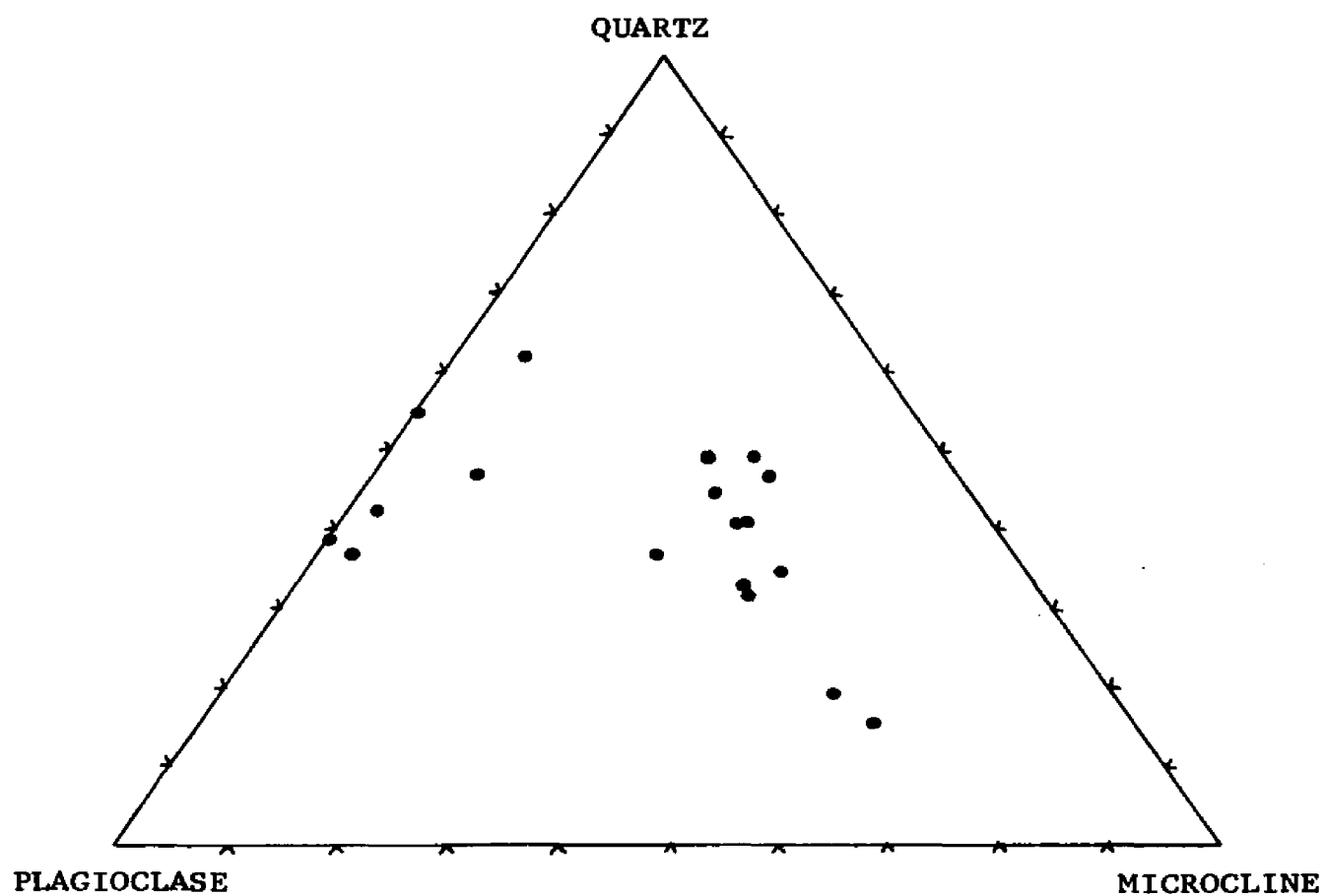


Fig. 6 Ternary diagram of quartz-plagioclase-microcline modal values for coarse porphyritic granite

There is no significant correlation with the An-content of the plagioclase and the variation in the plagioclase:microcline ratio.

Na-metasomatism during or after the emplacement of coarse porphyritic granite has probably caused the replacement of microcline by albite.

Fractionation of alkalies between a fluid phase and crystalline feldspar is mainly dependent on temperature; the physical condition of the fluid has very little effect on the alkali ratio (Orville, 1963). According to Orville, the colder rocks will be enriched in K-feldspar, whereas the warmer rocks will be depleted in K-feldspar. Replacement of K-feldspar by albite in these rocks may be attributed to the thermal gradient established near the contact by the emplacement of hot granite magma into the cold country rock. Evidences of such replacements are seen in samples of coarse porphyritic granite (Figure 8).

The modal composition of coarse porphyritic granite is very variable; the average mode (Table 3) indicates that in comparison to foliated porphyritic granite the rock is poorer in K-feldspar and richer in average plagioclase content. Epidote, apatite, and calcite are much more common accessories. The total muscovite formed by the alteration of feldspar is significantly more.

B) General Texture of the Granitic Rocks

Granite Gneiss

The granite gneiss is extremely heterogeneous both in the mineralogy and texture. It varies from even grained massive granitic texture to banded gneissic texture; a few samples have metasedimentary appearance.

The granite gneiss is the oldest of the granitic rocks in the area which can be inferred by its occurrence as xenoliths in the other



Figure 7. Microcline (M) - plagioclase (P) intergrowth.
Crossed polars.

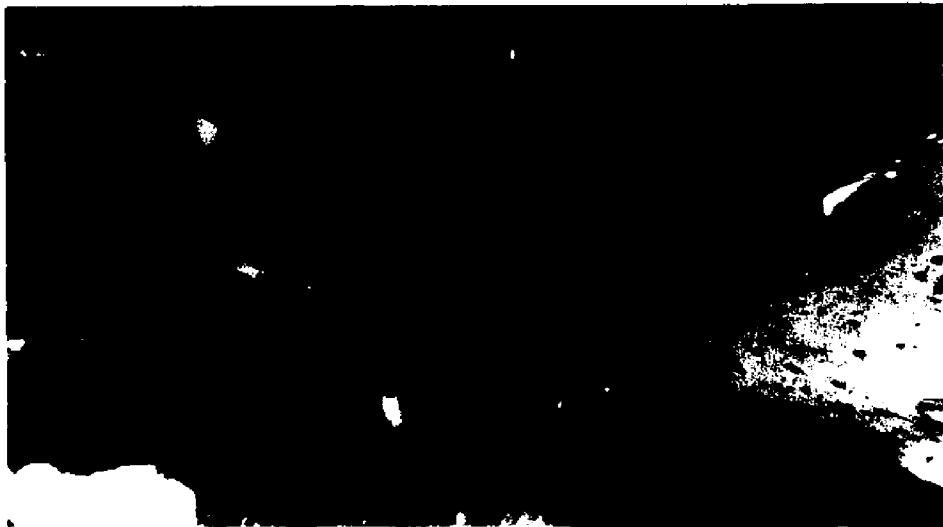


Figure 8. Antiperthitic plagioclase. Plagioclase (P)
replacing microcline (M). Crossed polars.

two types of granites. Evidence of metamorphism on the rock is indicated by recrystallization texture which is clearly exhibited by the mosaic type arrangement of small subhedral plagioclase crystals (Figures 9 and 10). However, presence of zoning and Carlsbad twinning of plagioclase in a few samples suggest that total recrystallization has not occurred. Suwa (1965) observed that the Carlsbad twinning in plagioclase gradually disappears with progressive recrystallization.

Antiperthitic intergrowth of microcline and plagioclase is very commonly observed in the granite gneiss. In a few rock samples, the antiperthites may have originated by the exsolution of K-feldspar which was probably facilitated by the strain due to shearing stress on the rock (Sen, 1969). Antiperthites of replacement origin have also been recognized in some rocks (Figure 7). Vogel, Smith, and Goodspeed (1968) have reported the development of antiperthite due to nucleation of K-feldspar on low energy surfaces in the charnockitic rocks of New Jersey. Formation of antiperthite in a few samples of granite gneiss may be attributed to the growth of microcline on low energy surfaces within earlier formed plagioclase. The boundary of quartz crystal, enclosed within plagioclase, acted as a favorable site for the nucleation of later formed microcline (see Figure 11). These rock samples have a very high content of plagioclase and their modes plot in the plagioclase field on the quartz-orthoclase-albite ternary phase diagram of James and Hamilton (1969), which suggests that the plagioclase crystallized early. The interstitial growth of microcline between plagioclase crystals also indicate later crystallization of microcline in these rocks.

The microcline in most of the granite gneiss samples is not very perthitic. Vein perthite, observed in a few rocks (Figure 12), is



Figure 9. Recrystallization exhibited by mosaic arrangement of subhedral crystals of plagioclase. Crossed polars.



Figure 10. Plagioclase crystals showing mosaic texture. Crossed polars.



Figure 11. Antiperthitic plagioclase. Microcline (M) mantling quartz (Qtz). Crossed polars.



Figure 12. Vein perthite - microcline (M) and plagioclase (P). Crossed polars.

believed to be of exsolution origin (Deer, Howe, and Zussman, 1963).

Rims of albite mantling the higher An-plagioclase, commonly seen in the other two granites, are generally lacking in granite gneiss. Lack of such rims may be attributed to the metamorphism of the rock.

Foliated Porphyritic Granite

The rock type has a porphyritic texture with phenocrysts of microcline and plagioclase set in an even-grained coarse matrix of quartz, plagioclase, K-feldspar, and biotite. The phenocrysts form a prominent linear structure in the strong foliation defined by planar orientation of muscovite and biotite flakes. Bending and displacement of twin lamellae of plagioclase (Figures 28 and 29) indicate deformation of the rock after solidification. Granulation of the phenocrysts frequently observed in the rock provides further evidence of deformation.

Aggregates of quartz exhibiting a mosaic texture are interpreted as having been formed by recrystallization (Figure 13). However, occurrence of albitic rims surrounding plagioclase suggests that the recrystallization is not complete. Carlsbad twinning and zoning observed in the plagioclase in a few rocks are indicative of original igneous features that have escaped later recrystallization (Suwa, 1965).

The texture of the foliated porphyritic granite indicates that the plagioclase crystallized both earlier and later than microcline. The earlier formed euhedral to subhedral crystals of plagioclase are enclosed within microcline and have a highly sericitized core of more calcic plagioclase surrounded by clear albitic rims. Later formed plagioclases, interstitial between microcline and quartz, are low in An-content.

The clear albitic rims mantling a more calcic core are



Figure 13. Quartz (Q) crystals exhibiting recrystallization texture. Crossed polars.



Figure 14. Rim of albite (A) mantling plagioclase (P) on plagioclase - microcline (M) interface. Crossed polars.

interpreted to have formed by the exsolution of albite from the microcline and migration to a favorable site. Plagioclase grain boundary in contact with microcline appears to be the most favorable site as the albitic rims are usually restricted to microcline-plagioclase contact (Figures 14 and 15 clearly demonstrate this fact). The rim is well developed on the microcline-plagioclase boundary but is completely lacking on plagioclase-plagioclase interface in Figure 14. The absence of the rim on the plagioclase-quartz contact is evident in Figure 15. The restricted occurrence of the albite rim on plagioclase-microcline interface suggests that the rim has developed by the reaction between microcline and plagioclase. The albite is likely to have exsolved from microcline and was nucleated on the plagioclase boundary. Albite exsolved from microcline is seen to be migrating towards plagioclase and is nucleating on the grain boundary (Figure 16). In some rocks, exsolved albite from microcline is intergrown as belbs into plagioclase as seen in Figure 17. The sharp contact of the rims with microcline indicates a reaction in the solid state after the crystallization of the magma. In a few cases, particularly where the albite rims occur on plagioclase-quartz interface, the rims may have been formed by the exsolution of albite from the plagioclase and migration to the grain boundary.

Vermicular intergrowth of quartz in plagioclase is fairly common and is considered to be exsolution myrmekite because of its frequent association with microcline (Hubbard, 1967). In one sample, clear belbs of quartz extend across a twin plane in plagioclase without any distortion (see Figure 18) which suggests that the myrmekitization took place after the development of twinning in the plagioclase and is probably a late stage phenomena.



Figure 15. Clear albite rim (outlined in ink) restricted to microcline (M) - plagioclase (P) contact. No rim on microcline - quartz (Q) and plagioclase - quartz interface. Crossed polars.



Figure 16. Nucleation of albite exsolved from microcline (M) on plagioclase (P) boundary. Crossed polars.



Figure 17. Albite (clear blebs) exsolved from microcline (M) is intergrown with plagioclase (P). Crossed polars.



Figure 18. Rods of quartz in twinned plagioclase. The rods extend across the twin plane without any distortion. Crossed polars.

Microcline in the foliated porphyritic granite is generally not very perthitic (average 5.5 mole % exsolved albite as compared to 12.3% Ab in coarse porphyritic granite). Antiperthite is, however, very common in the rock.

Coarse Porphyritic Granite

Unlike the foliated porphyritic granite, the coarse porphyritic granite is not much deformed and lacks any well developed foliation. The modal composition of the rock is very variable, but texturally the rock is fairly homogeneous. Large phenocrysts of microcline are set in a matrix of plagioclase, quartz, microcline, muscovite, and biotite. The parallel alignment of the phenocrysts form a prominent lineation in the rock.

The plagioclase crystals in some rocks are zoned and generally have highly corroded cores which are heavily charged with epidote, clinozoisite, calcite, and sericite. The dirty cores are surrounded by clear less calcic rims (Figure 19), which are optically continuous with the cores. Where twinning is present, the lamellae cross from the core to the rim without deflection (Figure 20).

The K-feldspar content of the rock is very variable ranging from 0.0 to 54.1%. Replacement and resorption of microcline by plagioclase is indicated in a few rocks (Figure 21). The intergrowth of microcline and plagioclase, under crossed nicols, exhibits a common extinction throughout. Such optical continuity probably reflects a growth control imparted by the pre-existing microcline. The texture of some rocks also indicates the replacement of microcline, probably due to Na-metasomatism after the solidification of the rock.

Albitic rim mantling the plagioclase is very common in the rock



Figure 19. Zoning in plagioclase. The more calcic core is altered. Crossed polars.



Figure 20. Zoned plagioclase (P). The lamellae cross from core to rim without deflection. Crossed polars.

occurring generally on the plagioclase-microcline interface. The plagioclase in the trondhjemitic variety with little or no microcline significantly lacks any albitic rim. The frequency of albitic rim and the amount of myrmekite is directly related to the microcline content of the rock. Generally, the plagioclase at the contact of microcline either has a clear rim of albite or has inclusions of blebs of quartz forming myrmekite. Lack of albitic rim on the microcline-myrmekite interface may be attributed to the assimilation of albite with the plagioclase in the myrmekite during the exsolution process. In some cases, the albite exsolved from microcline is intergrown as blebs into plagioclase (Figure 17). Myrmekite is very common in the coarse porphyrite granite which may indicate a high crystallization temperature of the rock (Hubbard 1967). The close association of myrmekite with microcline (Figure 22) suggests an exsolution origin of myrmekite (Hubbard, 1966 and 1967). Hubbard (1967) indicated that a significant proportion of the anorthite molecule may be included in alkali feldspar as solid solution at high crystallization temperature. Wyart and Sabatier (1965) have demonstrated that the alkali feldspar can take up to 30% of $\text{Ca}_{\frac{1}{2}}\text{AlSi}_3\text{O}_8$ into solid solution at 600°C. Calcium is accepted in alkali feldspar in the form of "Schwankte's (1909) high silica anorthite molecule."

This anorthite molecule is accommodated in normal lattice sites in alkali feldspar. For each Ca^{++} cation accepted in the monovalent lattice framework, a vacancy defect in the corresponding site will be generated. The ability of the lattice to retain vacancies is strongly dependent on the temperature. Therefore, acceptance of significant amounts of calcium in the ternary alkali feldspar suggests high

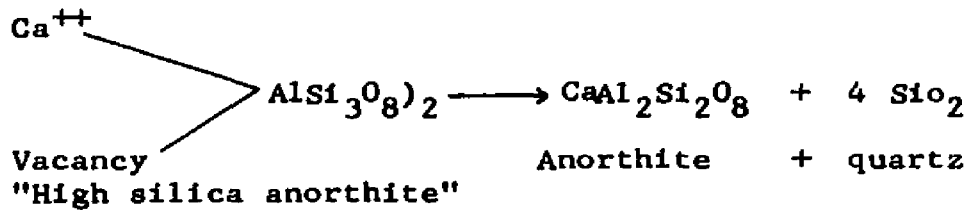


Figure 21. Replacement and resorption of microcline (M) by plagioclase (P). Crossed polars.



Figure 22. Myrmekite on microcline (M) - plagioclase (P) interface. Crossed polars.

crystallization temperature. With cooling, growth of anorthite and quartz takes place as the vacancies are annihilated.



The precipitating albite from the ternary feldspar would combine with anorthite to form plagioclase. The new plagioclase finds an ideal growth site along the periphery of pre-existing plagioclase and forms as an overgrowth which advances into K-feldspar (Figure 22).

In case of low crystallizing temperature, there will be low concentration of anorthite in the original ternary feldspar which will result in the absence of quartz from the plagioclase aggregate.

The coarse porphyritic granite magma cooled very slowly presumably under deep-seated conditions which resulted in the growth of large crystals that form the phenocrysts in the rock. The finer texture of the groundmass may be attributed to an increase in the rate of cooling, probably due to the intrusion of magma to a shallower depth. In this process, the early formed phenocrysts developed a parallelism due to flow. Formation of muscovite and sericite at the expense of feldspar and alteration of epidote to chlorite is commonly observed in the rock indicating a retrograde effect, probably caused by the concentration of volatiles during the later stage of rock formation. The source of the volatiles for the retrograde change in the rock may be the later intrusion of pegmatite in the area, but the widespread occurrence of the feature does not favor the idea of an external source.

C) Composition of the Coexisting Feldspars in the Granites

The feldspar composition is a qualitative indication of the thermal history of the rock and may be used to compare the granites in the area. During the crystallization of the rock, albite is distributed between potassium feldspar and calcium feldspar. The distribution coefficient (the ratio of albite in alkali feldspar to albite in plagioclase) is a function of the temperature of crystallization (Barth, 1962). However, the temperature recorded represents a chemical equilibrium at a certain temperature in the process of the formation of the rock and may be lower than the highest temperature the rock had attained.

An Content of Plagioclase

The composition of the plagioclase of 60 samples, 20 each of the three types of granites, was determined by the Rittmann method (Emmons, 1943). Ten to twelve grains were studied in each of 60 samples. The dispersion method (Tsuboi, 1923) and the use of a revised dispersion chart based on the α' 001 curve (Morse, 1968) were employed to check some of the results of the Rittmann method. The results of the two methods were remarkably similar.

The average composition of the plagioclase in the three types of granitic rocks is fairly similar; generally the plagioclase is poor in calcium. The plagioclase in the granite gneiss contains an average of 11.5% An (range An_{6-18} , Standard Deviation = 2.4). The average plagioclase composition of the foliated porphyritic granite is $An_{11.8}$ ranging from An_5 to An_{18} (S.D. = 1.9); whereas the coarse porphyritic granite ranges from An_{5-18} (S.D. = 3.2), the average of 20 samples being 11.1% An. There is no systematic variation in the An- content of the plagioclase with relation to the occurrence of the rock in the area.

Ab Content of the K-Feldspar

The composition of potassium feldspar was determined by ($\bar{2}01$) X-ray method of Orville (1958, 1967). KBrO_3 was used as an internal standard to prepare the smear mount for X-ray diffraction runs. Thirty samples, ten each of the three rock types, were analyzed. The result of the analysis is given in Table 4.

The $\bar{2}01$ peak of K-feldspar is a measure of the mole percent albite in solid-solutions in the K-feldspar. The bulk composition of K-feldspar (i.e., the total amount of albite in solid solution and exsolved) was determined by dry homogenization of the feldspar at 1050°C . for 48 hours (after Orville, 1967). The difference in the analysis of homogenized sample (total Ab in K-feldspar) and the unheated sample (Ab in solid solution) determined the amount of exsolved albite in the K-feldspar. The amount of Ab in solution in the crystal structure of K-feldspar after homogenization represents the amount that the lattice could hold at the fixation temperature.

Mole percent Ab in solid solution in K-feldspar is plotted against total Ab content of K-feldspar for foliated porphyritic granite and coarse porphyritic granite in Figure 23. K-feldspars in the coarse porphyritic granite have much higher Ab content than K-feldspars of foliated porphyritic granite. The amount of Ab in solid solution, however, is generally similar.

Table 4. Average Composition of K-feldspars (10 samples of each type of granite).

Rock Type	Mole percent Ab in solid solution		Mole percent exsolved Ab		Mole percent total Ab	
	Mean	Range	Mean	Range	Mean	Range
Granite gneiss	3.4	0.0 - 4.8	7.9	1.2 - 22.0	11.3	7.3 - 26.8
Foliated porphyritic granite	4.2	2.1 - 6.3	5.5	2.5 - 8.8	9.7	7.3 - 13.1
Coarse porphyritic granite	3.9	2.1 - 5.8	12.3	6.8 - 29.5	16.2	10.0 - 32.2

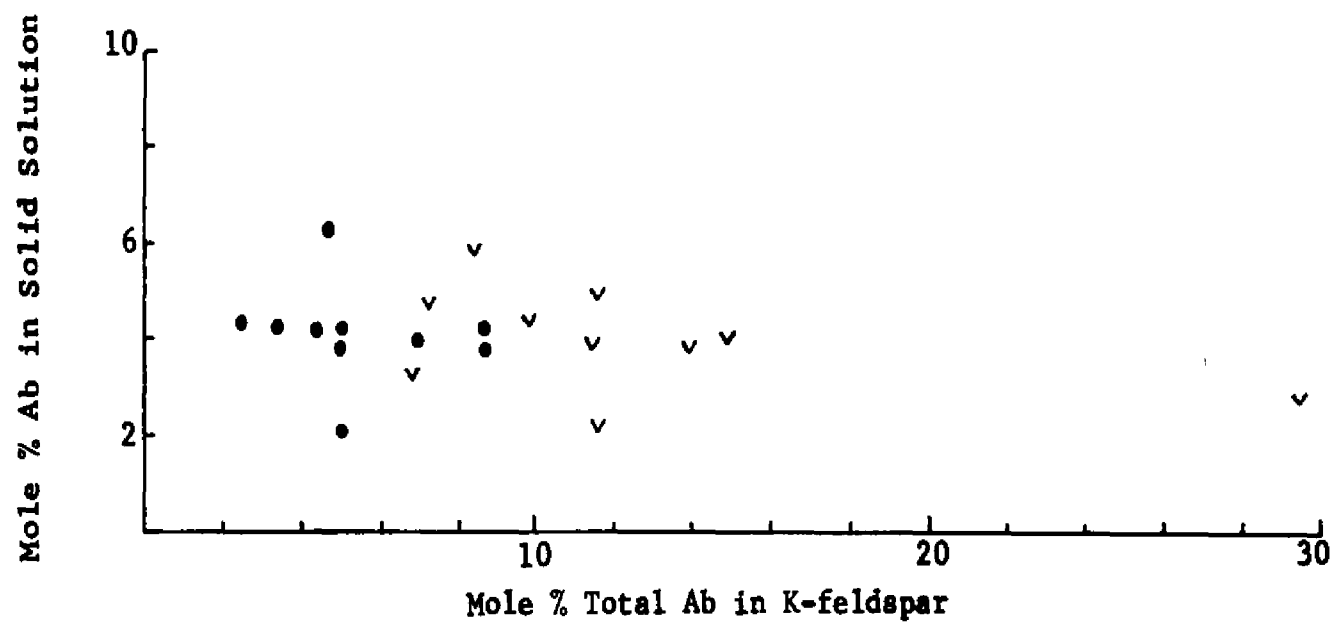


Figure 23 Mole percent albite in solid solution plotted against mole percent total albite in K-feldspar. Foliated porphyritic granite (●) and coarse porphyritic granite (v) are indicated.

Six samples of the coarse porphyritic granite, collected at 10 feet apart from a single outcrop, were analyzed to check the variation within the rock type in a small area. The K-feldspar composition, determined by the ($\bar{2}01$) method, were remarkably similar (Table 5).

Table 5. K-feldspar Composition of Six Samples of Coarse Porphyritic Granite from the Same Outcrop.

Mole percent Ab in solid solution	Mole percent total Ab in K-feldspar
4.8	16.2
3.2	18.8
3.8	18.8
4.8	18.8
3.2	19.3
3.8	18.8
Mean = 3.9	Mean = 18.4
Standard Deviation = 0.6	Standard Deviation = 1.1

The dependence of distribution coefficient of Ab between coexisting feldspars on temperature has been suggested by many workers (Barth, 1951 and 1962; Orville, 1962; Perchuk and Ryabchikov, 1968). Virgo (1969) studied the partitioning of sodium between coexisting feldspars from some metamorphic rocks and found an overlap in the data from rocks of different metamorphic facies. He concluded that the compositions of coexisting feldspars do not give any indication of their temperature of crystallization. However, in the present study, temperature determined by feldspar composition corresponds with the temperature indicated by trace element distribution. This suggests a correlation of coexisting feldspar composition with temperature.

The curves in Figure 24 represent the isotherm of Ab distribution between coexisting plagioclase and K-feldspar in equilibrium at 1000 Kg/cm² (after Perchuk and Ryabchikov, 1968). The plots of six samples of each type of granite indicate that the approximate temperature of crystallization of the granite gneiss ranges from 430°C to 560°C; the foliated porphyritic granite ranges from 440°C to 480°C; whereas the coarse porphyritic granite varies from 460°C to 580°C.

Recrystallization of the rock may affect the distribution coefficient of Ab, and the temperature indicated may actually represent the recrystallization temperature rather than the fixation temperature during magmatic cooling. However, lower metamorphic environment in most of the area suggests the temperature of the feldspars represent fixation at the end of magmatic cooling and not the metamorphic thermal condition.

The narrow range of crystallization temperature of foliated porphyritic granite probably indicates that the rock cooled very slowly, maintaining chemical equilibrium during the process.

The significantly higher Ab content of K-feldspar in coarse porphyritic granite (than in the other two types of granite) indicates a higher temperature of crystallization of the rock. High temperature favors the solubility of sodium in K-feldspar (Heier, 1962). Most of the albite in the K-feldspar is, however, exsolved and this is interpreted to have been facilitated by the concentration of volatile constituents during the late stage of crystallization. Indication of volatile concentration is provided by the formation of secondary muscovite at the expense of feldspar which is commonly observed in the rock. The alteration of the plagioclase probably released calcium to form calcite, apatite, and epidote which occur interstitially within the plagioclase in

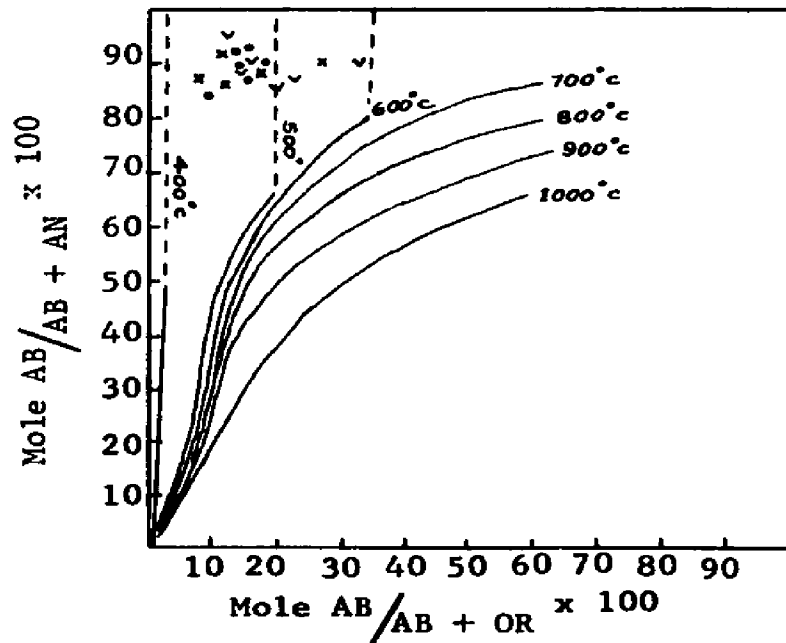


Figure 24 Geothermometer based on the distribution of albite between K - feldspar and plagioclase in granite gneiss (x), foliated porphyritic granite (•) and coarse porphyritic granite (v). (after Perchuk and Ryabchikov, 1968).

the rock.

D) Structural State of K-Feldspar

The structural state of K-feldspar was determined to compare the thermal histories of the three types of granite. The distribution of Al and Si in the tetrahedral sites of feldspars is controlled by the rate of cooling of the rock; duration of time that the feldspar was held near the temperature of transformation may have great effect on the Al:Si arrangement (Wright, 1967). The nature and extent of the ordering of Al and Si ions in the feldspars determine the structural state of the mineral. In all low feldspars, there is an idealized, ordered arrangement; whereas a high energy environment causes random arrangement of the Al and Si ions and the structure is considered disordered (McGaw, 1959).

A method to determine structural state and composition of alkali feldspar by using cell dimensions has been described by Orville (1967); Wright and Stewart (1968). Measurement of 2θ values for the three reflections, ($\bar{2}01$), (060), and ($\bar{2}04$) can be used to determine unit cell parameters a, b, and c respectively (Wright, 1968). Orville (1967) has reported that the variation in 'a' is only slightly dependent on Al:Si ordering. However, 'a' varies greatly with composition.

The alkali feldspars have been termed "anomalous" by Wright and Stewart (1968) if the 2θ value for ($\bar{2}01$) estimated from (060) and ($\bar{2}04$) plot differs from the 2θ value measured directly for ($\bar{2}01$) by $0.1^\circ 2\theta$. The structural state of the "anomalous" feldspar can, however, be determined by ($\bar{2}01$) method (Wright, 1968).

2θ values for (060) plotted against ($\bar{2}04$) for the three types of granite (12 samples each) are shown in Figures 25, 26, and 27. It is evident from the figures that the K-feldspars in the three granites are

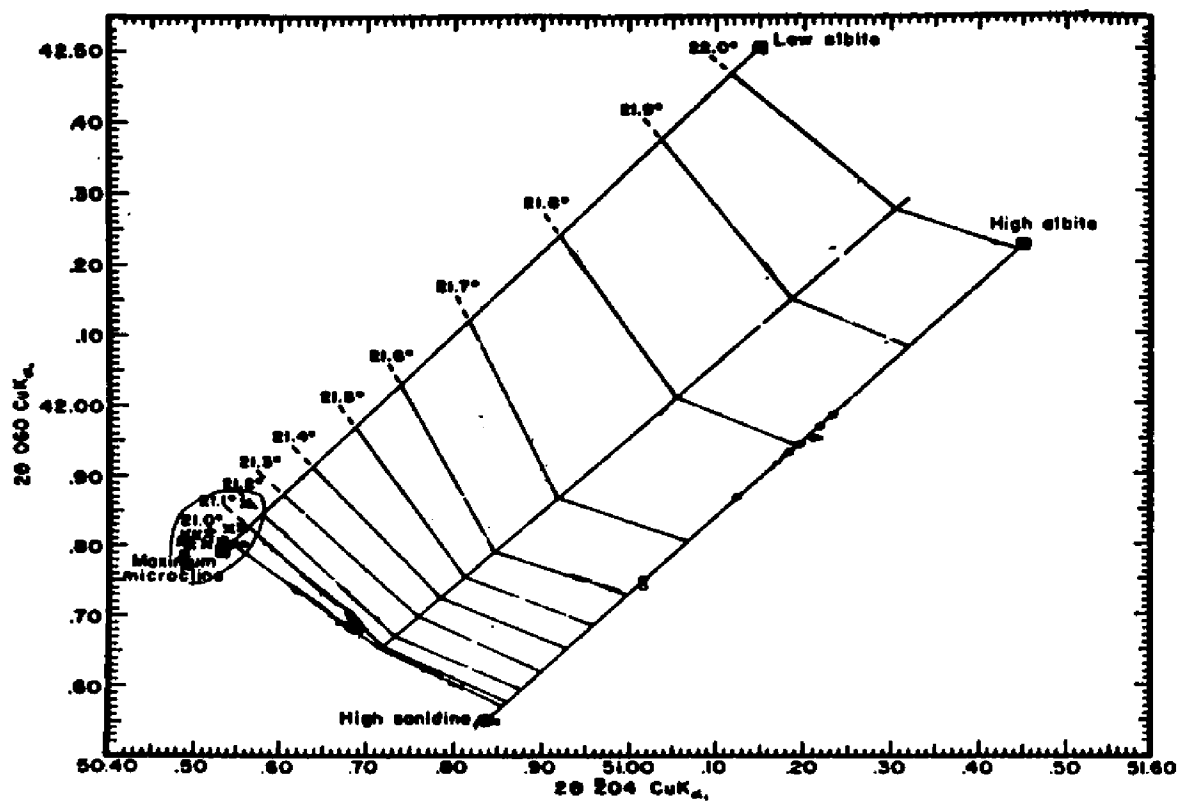


Figure 25 Plots of $2\theta\ (060)$ against $2\theta\ (\bar{2}04)\ \text{CuK}\alpha$ for K - feldspars in granite gneiss (x), (after Wright, 1968).

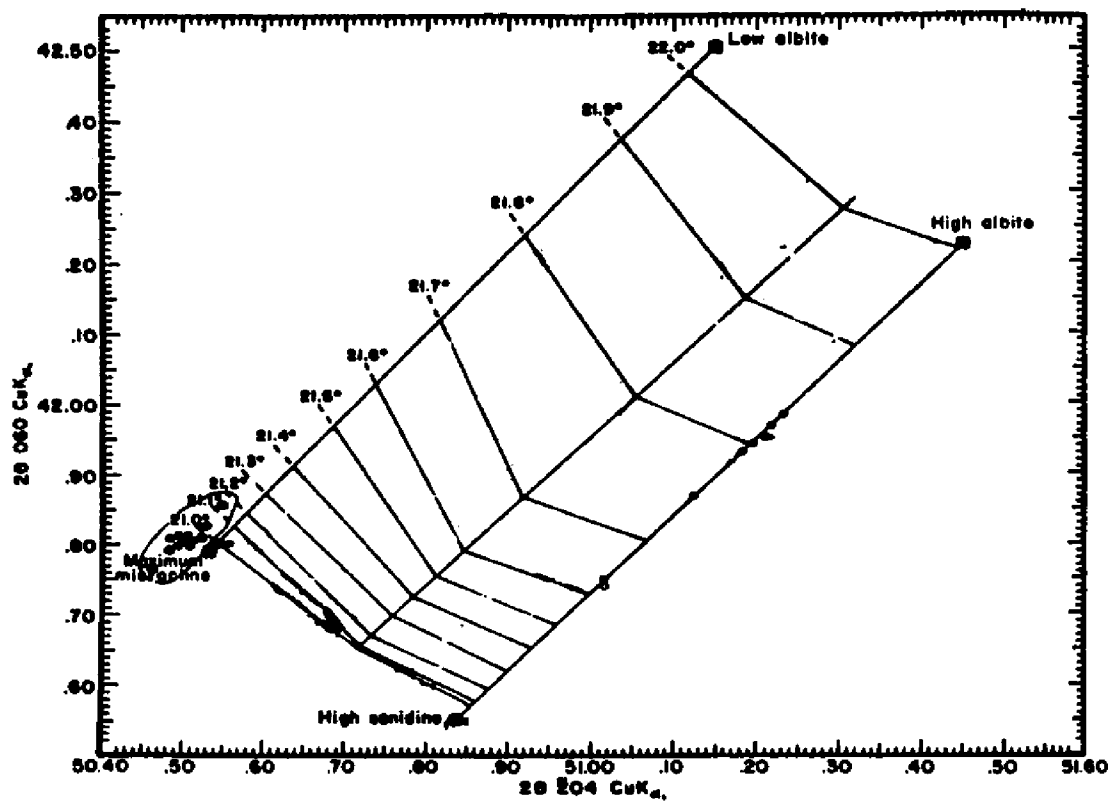


Figure 26 Plots of 2θ (060) against 2θ ($\bar{2}04$) $\text{CuK}\alpha$ for K - feldspars in foliated porphyritic granite, shown by dots ($\cdot$), (after Wright, 1968).

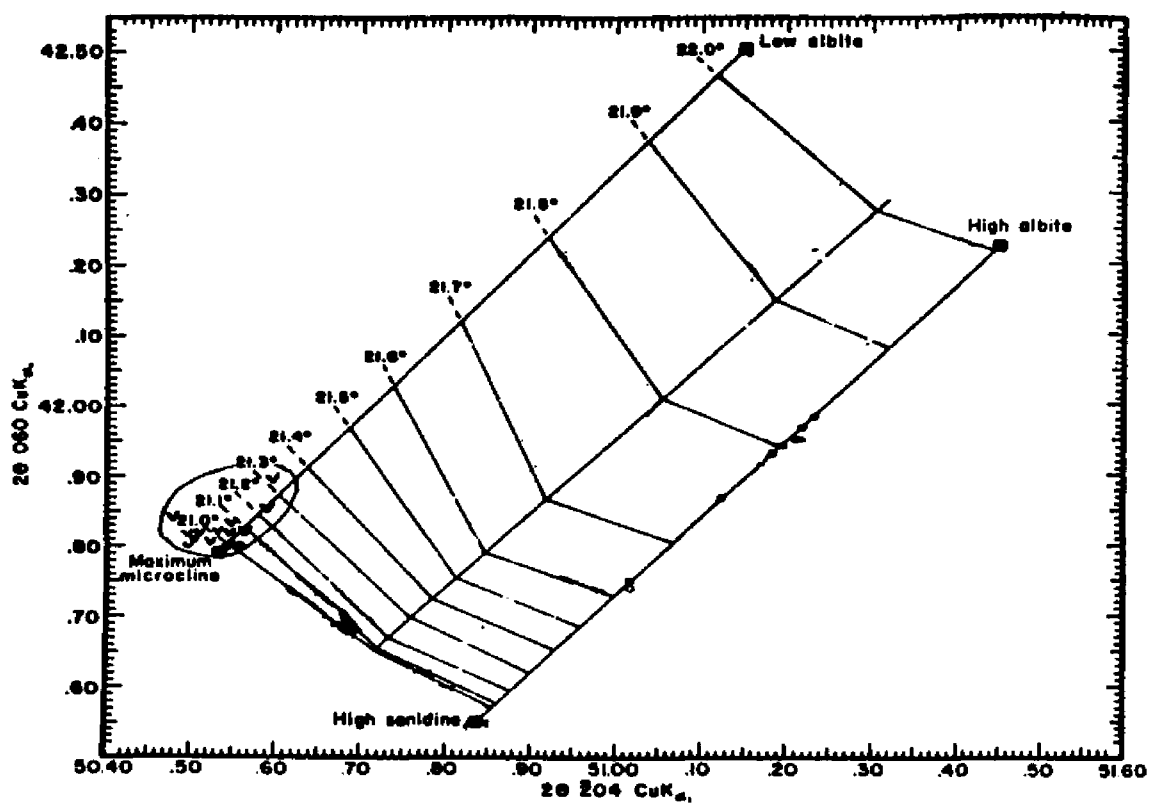


Figure 27 Plots of 2θ (060) against 2θ ($\bar{2}04$) $\text{CuK}\alpha$ for K - feldspars in coarse porphyritic granite, shown by (v), (after Wright, 1968).

highly ordered and may be termed as "maximum Microcline" (after Wright 1968).

Another method of the determination of the structural state of K-feldspar is a measure of triclinicity (Δ) using the difference in spacing of the diffraction peaks of (131) and ($1\bar{3}1$), as suggested by Goldsmith and Laves (1954). The triclinicity (Δ) is calculated as follows:

$$\Delta = 12.5 \, d(131) - d(1\bar{3}1)$$

The values observed by this method for the three types of granite, are shown in Table 6.

Table 6. Triclinicity of K-feldspars in the Three Granite Types (4 samples of each).

Rock Type	Range of Δ -value
Granite gneiss	0.89 - 0.95
Foliated porphyritic granite	0.95 - 0.96
Coarse porphyritic granite	0.90 - 0.93

The triclinicity index corresponds very well to the structural state determination using (060) and (204) reflections. The highly ordered structural state of K-feldspars of all the three types of granites suggests a very slow rate of cooling of the rocks.

MacKenzie and Smith (1961) determined the temperature of inversion from monoclinic to triclinic symmetry of K-feldspar as 525°C. Tomisaka (1962) produced a monoclinic K-feldspar at a temperature as low as 400°C under a water pressure of 350 bars. Steiger and Hart (1967) have

concluded that the transition temperature is around 400°C. Wright (1967) in his study of the K-feldspar in pegmatites in the contact aureole of the Eldora Stock, Colorado agrees with the findings of Steiger and Hart and concludes that the upper stability limit of "maximum microcline" is $375 \pm 50^\circ\text{C}$.

The structural state of K-feldspar is related to a number of factors other than temperature. MacKenzie and Smith (1961) have suggested that the pressure and volatile content may have sufficient effect on the temperature of inversion. Many other parameters such as total hydrostatic pressure and composition of the original material may influence the orthoclase-microcline transition (Steiger and Hart, 1967). Little is known about the effect of total pressure or partial pressure of water on the phase transformation in the K-feldspar. Experiments performed by Tomisaka (1962) indicate that the partial water pressure or total pressure has very little effect on the inversion temperature. MacKenzie and Smith (1961) and Wright (1967) have suggested a great dependence of the inversion temperature upon the Na-content of K-feldspar. The orthoclase-microcline conversion temperature increases with the amount of sodium dissolved in K-feldspar (Wright, 1967). The quantitative data on this are, however, not available.

The highly ordered K-feldspar in the coarse porphyritic granite may represent a higher temperature of transformation due to the high Ab content of K-feldspar in the rock type (average = 16.2 mole % Ab). The amount of albite in the K-feldspars of foliated porphyritic granite is generally low (average = 9.7 mole %). It may be inferred that the phase transformation of K-feldspar in the foliated porphyritic granite occurred at about 400°C (Wright, 1967).

E) Plagioclase Twinning

Type and nature of twinning in plagioclase may be a good indicator of the history of formation of the rock. Plagioclase crystallized from a melt shows more varied pattern of twinning than plagioclase of metamorphic origin (Tobi, 1962). A qualitative and quantitative analysis of the plagioclase twinning in the three types of granite was carried out to study and compare the nature and extent of deformation of the rocks, also to differentiate the granites based on statistical analysis of twinning.

Smith (1962, p. 255) considers the twinning to have formed by a specific type of disturbance of crystal structure either during or after the growth and that it may have many different causes. Gorai (1951) in his study of plagioclase twins has concluded that there is a characteristic difference in the type of plagioclase twin in magmatic and metamorphic rock. He has classified the plagioclase twin types into two groups. A-twins, found in igneous as well as metamorphic rocks include the simple and polysynthetic twins and their modification. Secondary glide twins formed due to deformation by forces external to rock after the growth of the crystal are also grouped in A-twins. The C-twins included Carlsbad, albite-Carlsbad and penetration twins which are developed in the crystals during growth. Appreciable amounts of C-twins are characteristic of undeformed igneous rocks. This amount is, however, dependent on the An content of plagioclase; calcic plagioclase has more C-twins than sodic plagioclase.

Vance (1961) has concluded that the polysynthetic twinning in plagioclase may represent both primary growth twin and secondary glide twin. Morphology of the twin can be used as the criteria to differentiate

the two. Bending and termination of lamellae as long tapering points are indicative of secondary twinning. However, several workers such as Baier (1930), Kohler and Raaz (1947), Emmons and Mann (1953), and Vogel (personal communication) consider all polysynthetic twinning in plagioclase as secondary.

Deformation twins are common in granite gneiss and foliated porphyritic granite (Figure 28 shows glide lamellae in granite gneiss). Fracturing and displacement of glide lamellae by a later phase of deformation is observed in some samples of foliated porphyritic granite (Figure 29).

Twinning in plagioclase may be lost by recrystallization and intense or continued deformation (Barth, 1969). With increased deformation, the twin lamellae may coalesce and assume an untwinned appearance (Vance, 1961, p. 1110). Kohler (1948) and Turner (1951) have observed that plagioclases in metamorphic rocks are untwinned or only slightly twinned.

Frequencies of A and C-twin types and untwinned plagioclase were determined in 20 sections of each rock type using Gorai's (1951) method. About 100 - 200 grains were examined in each section; some large grains may have been counted more than once. It was observed that the small crystals of plagioclase in the groundmass are relatively untwinned compared to the big crystals. Apparently glide lamellae are developed in big crystals due to stress; whereas the finer crystals take up the strain by rotation. Gorai (1951) has demonstrated that the frequency of secondary twinning in plagioclase varies directly with the grain size and composition. The plagioclase composition of the three rock types is fairly uniform. The effect of the grain size factor was minimized by



Figure 28. Glide twinning in plagioclase. The lamellae thin in unison. Crossed polars.



Figure 29. Displacement of twin lamellae in plagioclase by a later phase of deformation. Crossed polars.

counting only the grains more than 0.4 mm in diameter. The average frequency of the twin types in the three granites is shown in Table 7.

Table 7. Average Frequencies of Plagioclase Twin Types in the Three Types of Granite (20 samples each).

	% A-twin	% C-twin	% Untwinned
Granite gneiss	51.2	2.7	46.1
Foliated porphyritic granite	42.4	3.0	54.6
Coarse porphyritic granite	55.7	5.9	38.4

Higher proportion of untwinned plagioclase is recorded in the foliated porphyritic granite; whereas the coarse porphyritic granite has a much higher ratio of twinned plagioclase (Table 7). The granite gneiss, which is considered the oldest granite in the area and has probably undergone maximum deformation, should have a higher proportion of untwinned plagioclase. The slightly higher frequency of twinned plagioclase in the rock type may be attributed to the fine grained equigranular texture of the rock.

Two samples of the same rock type having undergone similar deformation are likely to have the same proportion of twinned plagioclases. The frequency, however, may vary with the intensity of the deformation. A ratio of twinned versus untwinned plagioclase may indicate the degree of deformation of the rock. The frequencies of twinned plagioclases in the rock were plotted against untwinned plagioclases for foliated porphyritic granite and coarse porphyritic granite (Figure 30). The figure indicates that the twinned versus untwinned plagioclase ratio is generally

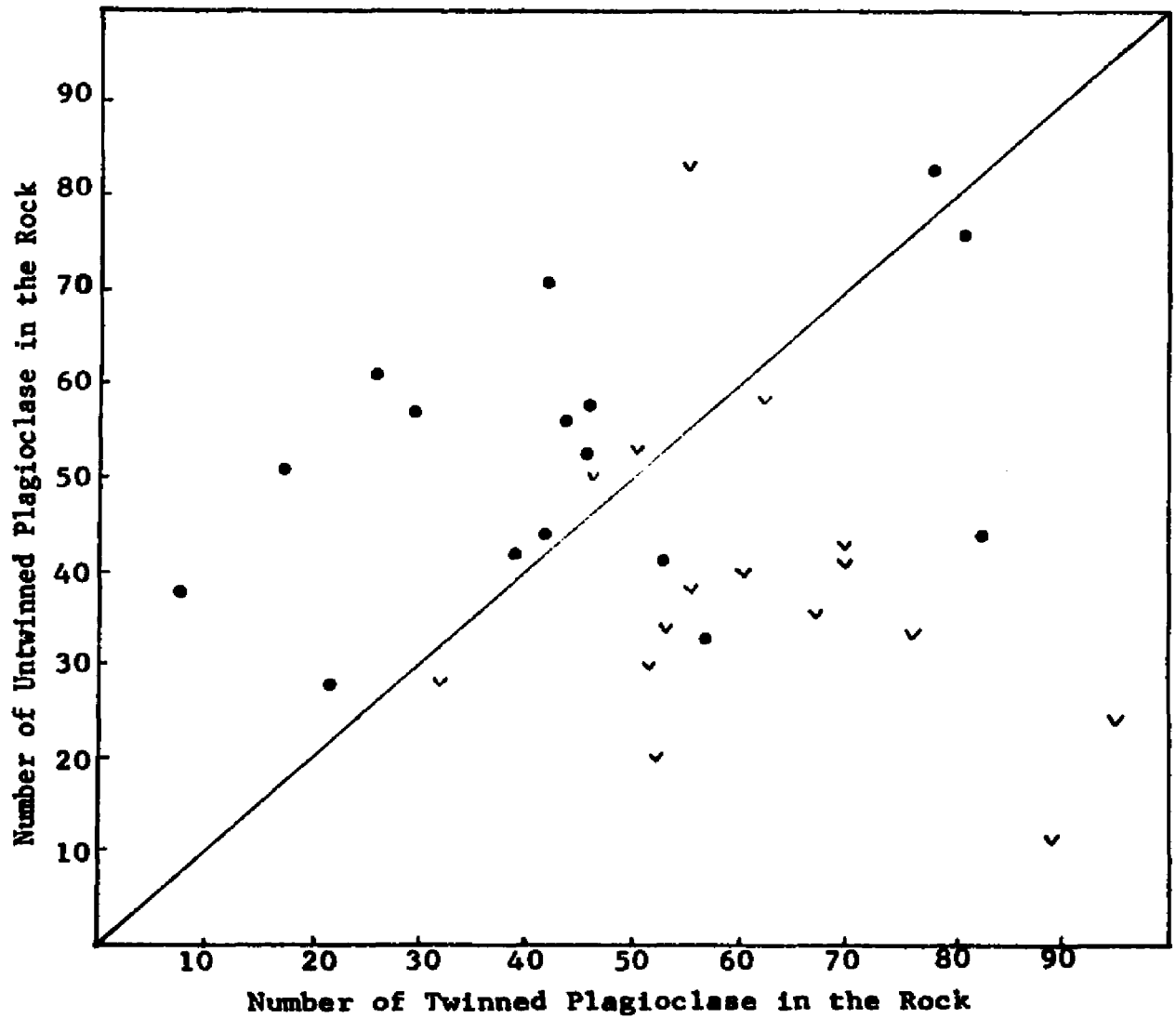


Figure 30 Plots of twinned (A + C) against untwinned plagioclase frequencies in foliated porphyritic granite (•) and coarse porphyritic granite (∇).

less than 1.0 in most of the foliated porphyritic granite which suggests that the rock type was subjected to more intense deformation.

The field relation of the coarse porphyritic granite and foliated porphyritic granite is not conclusive. Previous workers in the area have mapped both of the granites as the same. Statistical analysis of the plagioclase twinning of the two rock types was done to test whether samples of the two rock types are similar.

Statistical Treatment

A Chi-square test of the twinned and untwinned plagioclase frequencies (Table 8) in coarse porphyritic granite and foliated porphyritic granite was applied to determine whether they are from the same population (see Griffiths, 1967, p. 353).

Table 8. Frequencies of Twinned and Untwinned Plagioclases in Coarse Porphyritic Granite and Foliated Porphyritic Granite

Rock type	Twinned	Untwinned
Coarse porphyritic granite	1111	683
Foliated porphyritic granite	743	808

$$\chi^2 = 66.2$$

Degree of freedom = 1

P < 0.001

The Chi-square value is significant beyond the 0.001 confidence level. Hence, the chance that such a sample will be drawn at random from a similar population is less than 1 in 1000.

Chi-square value using the A, C, and U type plagioclases in the

two rock types also suggests a very significant difference in the two.

Table 9 represents the test.

Table 9. Comparison of the A, C, and U Plagioclase Twin Frequencies in Samples of Coarse Porphyritic Granite and Foliated Porphyritic Granite.

	A	C	U	Total
Coarse porphyritic granite	892	94	614	1600
Foliated porphyritic granite	<u>679</u>	<u>47</u>	<u>874</u>	<u>1600</u>
Total	1571	141	1488	3200
Expected value	785.5	70.5	744.0	
O - E (coarse porphyritic)	+106.5	+23.5	-130.0	
O - E (Foliated porphyritic)	-106.5	-23.5	+130.0	
$\frac{(O-E)^2}{E}$ (coarse porphyritic)	14.4	7.8	22.7	
$\frac{(O-E)^2}{E}$ (Foliated porphyritic)	<u>14.4</u>	<u>7.8</u>	<u>22.7</u>	
Total	28.8	25.6	45.4 = 89.8	

$$\chi^2 = 89.8$$

Degree of freedom = 2

$P < 0.001$

Student's "t" was also calculated in order to compare the means of twinned plagioclase frequencies in the two types of granite. The result of the test is shown in Table 10.

The null hypothesis (H_0) to be tested is that samples of coarse porphyritic granite and foliated porphyritic granite are drawn from the same population.

Table 10. Comparison of the Means of Plagioclase Twin Counts in Coarse Porphyritic Granite and Foliated Porphyritic Granite using t-test.

Rock Type	Mean Percent Twinned Plagioclase	Variance
Foliated porphyritic granite	45.4	$s_1^2 = 196.5$
Coarse porphyritic	61.6	$s_2^2 = 142.7$
$n_1 = n_2 = 16$		
$t = \frac{\bar{X}_1 - \bar{X}_2}{\sqrt{s_1^2 + s_2^2 / n - 1}}$		
$= 3.4$		
Degree of freedom = 2 (n-1) = 30		
$P < 0.002$		

The "t" value is highly significant. Thus, the null hypothesis is rejected. The chance that the two means are from the samples of the same type of rock is less than 2 in 1000.

F) Distribution of Trace Elements in K-Feldspar

The distribution of certain trace elements in the rock can be used to interpret the stage of fractional crystallization and the petrogenesis of the rock.

Ion size and charge were considered as the main factor which controls the ionic substitution in a crystal lattice (Goldschmidt, 1937). However, exceptions to this rule suggest the influence of some other factor also. Fyfe (1951) and Ringwood (1955) implied that the ability

of an ion to substitute in a crystal lattice depends on its electronegativity. Heier (1962) considers ionic character of the element, crystal structure, and physicochemical condition as main factors that govern the incorporation of minor elements in minerals. Table 11 lists the ionic properties of some of the elements which can occupy alkali position in feldspar lattice.

Table 11. Ionic Properties of the Elements that can substitute for Alkalies in the Feldspar Lattice.

	K	Na	Ca	Rb	Ba	Sr
Electrostatic charge	1	1	2	1	2	2
Ionic radius (Ahrens, 1953)	1.33	0.97	0.99	1.47	1.34	1.18
Ionization potential (Ahrens, 1953)	4.34	5.14	11.9	4.2	10.0	11.03
Electronegativity	0.8	0.9	1.0	0.8	0.9	1.0

A bonding energy function combining radius, charge, and electronegativity was devised by Nockholds (1966). The bonding energy of X-O bonds (a hypothetical 'molecule') is given by

$$\text{Bonding energy}_{\text{X-O}} = \frac{11.8(S_m + 5.5)}{R} - 5.6 + \frac{26.5\Delta^2}{R}$$

where S_m is the stability ratio of the 'molecule' X-O , Δ is the electronegativity difference between the metal, X, and oxygen, and R is the bond length. The bonding energy X-O is an approximation of bonding energies of common metals bonded to oxygen for bond lengths found in six-fold coordination. Bonding energy values should be used as relative

values only, as absolute bonding energies will vary with the coordination and probably with different environments having the same coordination. The relative total bonding energies (RTBE) are the values that should be used to interpret cation distribution. Nockolds offered two rules to explain the substitution:

- a) When two cations of the same valency are capable of substitution in a crystal lattice, the one having the greater relative total bonding energy will be incorporated preferentially.
- b) When two cations of different valency involving coupled substitution are capable of substitution in a crystal lattice, that substitution will take place preferentially whose sum of relative total bonding energies is the greater. (Nockolds, 1966, p. 272)

The possible substitution for K in K-feldspar is listed in

Table 12.

Table 12. Substitution Possibilities for K in K-feldspar (after Nockolds, 1966)

Cation	RTBE	Bond Length	Cation	Coupled RTBE	Bond Length
K ⁺	90	2.77	K ⁺	K Si 470	2.77
Rb ⁺	85	2.90	Ba ⁺⁺	Ba Al 480	2.76
Tl ⁺	74	2.62	Sr ⁺⁺	Sr Al 490	2.56
Na ⁺	100	2.40	Ca ⁺⁺	Ca Al 500	2.40

Sr⁺⁺ and Ba⁺⁺ have greater RTBE than K⁺, hence they should enter the crystal lattice more easily than K. Sr should be able to enter earlier than Ba but the bond length of K-O (2.77) is similar to Ba-O (2.76); whereas the bond length Sr-O is much less. Hence, Ba is

incorporated more easily in K-feldspar.

With increasing fractionation of the rock, the sequence of incorporation of elements in "K-position" in K-feldspar is: Na, Rb, Tl, and Cs in order for univalent atom; for coupled substitution the order is Ba, Sr, Ca, and Pb.

Ba forms a strong ionic bond with oxygen which causes it to be captured by K-minerals and is relatively enriched in early formed K-feldspar. Rb is admitted into K-feldspar at a later stage of crystallization; as such, the K/Rb ratio decreases with differentiation (Taylor and Heier, 1960). Taylor and Heier (1960) found the Ba/Rb ratios to be the most sensitive indicator of fractionation process in feldspars. Many workers have used the K/Rb ratio of the rock to interpret order of intrusion in a sequence of genetically related rocks. (Tauson and Stravrov, 1957; Butler et al., 1962; Taylor, 1965; Reynolds et al., 1967). The K/Rb ratio in the early stages of fractionation does not show much variation; only in extreme cases is any marked variation observed (Taylor and Heier, 1962). In some cases, the K/Rb ratio may lead to a false interpretation. Zlobin and Lebedev (1960) determined the K/Rb ratio of the two genetically related plutons, Lovozero alkaline rock and Khibina rocks, and found it to be different by as much as 1.5 times.

Ba and Rb contents of K-feldspar in the three types of granitic rocks were determined by X-ray fluorescence. Six samples of each rock type were analyzed. The results are presented in Table 13. The amount of K in K-feldspar was calculated after making corrections for the Ab content of the K-feldspar.

The average K/Rb ratio in the three types of rock is similar; the values are within the published range of values for other granitic

Table 13. Arithmetic Means and Ranges of Concentrations of K, Rb, and Ba in K-feldspars in the Three Types of Granite (6 samples of each)

Rock Type	Percent K	Rb ppm	K/Rb ratio	Ba ppm	Ba/Rb ratio
Granite gneiss	Mean - 11.96 Range - (10.45-13.38)	408 (350-485)	300	1294 (833 - 1917)	3.1 (2.1 - 3.9)
Foliated porphyritic granite	Mean - 12.78 Range - (12.3-13.14)	420 (365-470)	306	1462 (1111 - 1872)	3.6 (2.4 - 5.1)
Coarse porphyritic granite	Mean - 11.67 Range - (9.7-12.2)	432 (350-565)	277	1178 (734 - 1532)	2.8 (1.9 - 4.4)

rocks (Heier and Taylor, 1959; Aldrich et al., 1965; Condie et al., 1970). Plots of ppm Rb against mole percent K in K-feldspar in Figure 31 indicate that the foliated porphyritic granite and coarse porphyritic granite samples fall in separate restricted zones. The plots for granite gneiss are scattered unsystematically which may reflect varying conditions of the rock formation, and this may be supported by the wide range of Ba content of K-feldspar in the rock type (see Table 13).

The slightly higher average Rb content in K-feldspar of coarse porphyritic granite and a lower average Ba content indicates that the coarse porphyritic granite is a more differentiated rock than the foliated porphyritic granite and granite gneiss. The Ba:Rb ratio of the coarse porphyritic granite is considerably lower than the ratio in the foliated porphyritic granite. However, the range of Rb content of the coarse porphyritic granite is very great, probably representing a great range of temperature of formation. This supports the suggestion mentioned earlier that the coarse porphyritic granite magma cooled very slowly generally maintaining the chemical equilibrium. However, at a few locations, particularly in the marginal zone, the equilibrium may not have been maintained; this may indicate higher temperature. The field relations are, however, inconclusive because of the lack of sufficient outcrops.

Plots of ppm Rb against ppm Ba in K-feldspar (Figure 32) show no systematic variation.

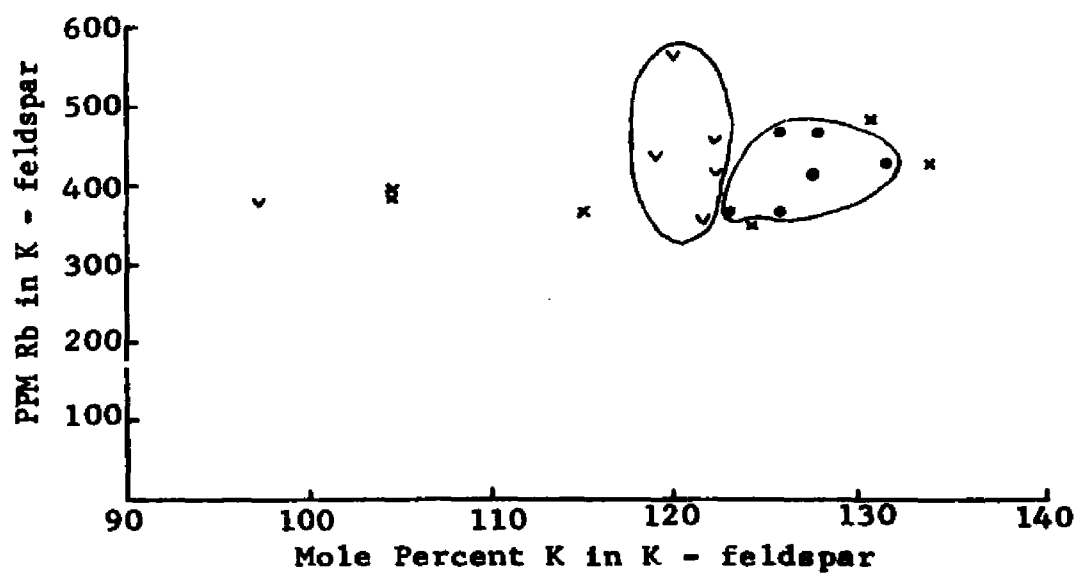


Figure 31 Percent K vs ppm Rb in granite gneiss (×), foliated porphyritic granite (●) and coarse porphyritic granite (∇).

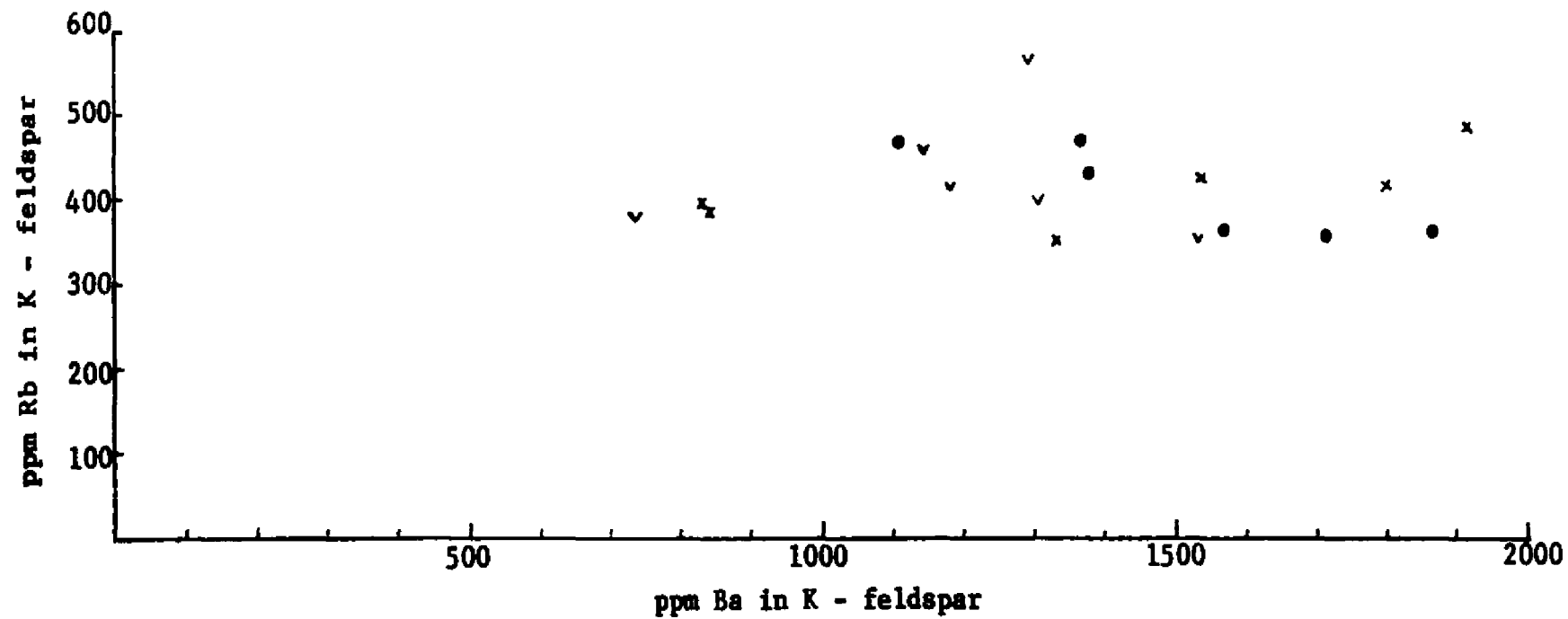


Figure 32 ppm Rb plotted against ppm Ba in K - feldspar. Granite gneiss is shown by cross (x), foliated porphyritic granite by dots (•) and coarse porphyritic granite by (v).

SUMMARY AND CONCLUSION

The classification of the granitic rocks in the area based on textural variation and field relations is corroborated by the laboratory investigations. It may be inferred that texturally and genetically at least three types of granite occur in the area: granite gneiss, foliated porphyritic granite, and coarse porphyritic granite.

Based on field relations, the granite gneiss is considered as the oldest granite in the area. The age relation of the rock type is evident by the presence of xenoliths of the gneiss in the other two types of granite. The gneiss exhibits great textural and mineralogical variation and may include more than one genetic type. The area mapped as granite gneiss (see Figure 3) may include some granitized metasediments, which could not be differentiated because of inconclusive field relations due to small and isolated outcrops.

The study of the trace elements distribution in the K-feldspar indicates a great variation in Ba content and K:Rb ratio in the rock (see Table 13 and Figure 31) which may be interpreted as representing varying conditions of rock formation. The occurrence of growth twinning in plagioclase and the intrusive relation of the rock into older schist observed at a few locations indicate that at least part of the granite gneiss crystallized from a melt. Such intrusions at some place have resulted in the development of injection gneiss.

Subsequent deformation of the granite gneiss is indicated by the bending of glide lamellae in plagioclase. Evidence of at least two phases

of deformation of the rock type is revealed by the petrofabric analysis. Such deformations may have modified the petrology of the rock. Mosaic texture observed in a few rocks indicate recrystallization. However, the presence of chlorite and low An-plagioclase in the rock and the general absence of garnet and other high grade metamorphic minerals suggest low metamorphic environment. The highly ordered K-feldspar indicates very slow cooling of the rock.

The rest of the area is occupied by the porphyritic granite which has not been differentiated by the previous workers in the area. The strong foliation in porphyritic granite observed near Republic is significantly lacking in the outcrops north of Republic. Instead, the rock acquires a crude lineation marked by large feldspar phenocrysts. The distinct difference in the texture was used as a criterion to map the rock separately as foliated porphyritic granite (containing small phenocrysts) and a non-foliated porphyritic granite (containing large phenocrysts). The contact between the two rock types was not observed at any place. However, the transition between the two is generally sharp or narrowly gradational. Statistical analysis of plagioclase twinning corroborates the field observations to resolve the porphyritic granite into two genetically different types of granite (see Tables 9 and 10). This is further supported by the major- and trace-element distribution in K-feldspars of the two granite types (see Figures 23 and 31).

The foliated porphyritic granite is both texturally and mineralogically homogeneous and it probably represents a uniform condition of rock formation. Occurrences of xenoliths in the rock outcrops indicate a magmatic origin of the rock which is also supported by the presence of Carlsbad twinning in the plagioclase. The structural state of the

K-feldspar indicates that the foliated porphyritic granite magma cooled very slowly. Later metamorphism of the rock is exhibited by the recrystallization texture. However, lack of any high grade metamorphic mineral indicates a low temperature metamorphic condition.

The age of emplacement of the rock type which has been a matter of discussion for many years is not very clear by the field relations. The foliation of the rock generally has a concordant relation with the strike of the Animikie rocks in the contact zone. However, at one location near the Republic mine, a discordant relation within a short distance was observed. The foliation of the granite abuts against the foliation of the Animikie metasediments. The contact of the two rock types is, however, not exposed. The field relation at this location indicates that the foliation in the rock developed before the Animikie folding and was later folded with the Animikie rocks. The fracture and displacement of glide lamellae in plagioclase suggests at least two phases of deformation of the rock. The strong N25W-S25E foliation probably represents the first phase of deformation which was later superimposed by NW-SE foliation, parallel to the axis of Republic Syncline and was probably acquired during the Animikie folding. The structural relation of the rock and the evidence of at least two phases of deformation suggest a pre-Animikie age of the rock. The absence of the granitic material in the Animikie rocks inside the trough (a few reported occurrences are from areas outside the trough) in spite of the nearness of outcrop is not very likely unless the granite is older. Occurrence of boulders of porphyritic granite in basal conglomerate of Animikie age reported by some workers, also supports this inference.

Occurrence of intrusive granitic rock in Animikie metasediments, as reported by Lamey (1934) and Swanson (1929) indicates the presence of a post-Animikie granite in the areas. The metamorphism of the Animikie sediment has been attributed to the contact effect of this granite. Lack of the NW-SE foliation in the rock, parallel to the axis of Republic Syncline, suggest a post-Animikie age of the coarse porphyritic granite intrusion and this is supported by the absence of evidence of shearing and deformation of the granite. The rock is probably equivalent of Killarney granite.

The granite is exposed in the axial position between the Republic Trough and Marquette Syncline and was likely intruded as a sheet. The linear arrangement of feldspar phenocrysts probably represents a "flow structure" as indicated by the change in the trend of lineation when the contact is approached.

The occurrence of xenoliths and the presence of flow structure in the rock indicate an igneous origin of the coarse porphyritic granite. Abundance of growth twinning in plagioclase also supports the magmatic origin.

In comparison to the foliated porphyritic granite, the coarse porphyritic granite contains more myrmekite; the K-feldspar in the rock is also high in Ab content. This may indicate a higher crystallization temperature of the rock. The granite cooled very slowly as indicated by the structural state of the K-feldspars. During the later stage of crystallization the concentration of the volatile constituents caused the exsolution of albite and the alteration of feldspar to form secondary muscovite.

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A P P E N D I C E S

APPENDIX A

LOCATIONS OF XENOLITHS FOUND IN FOLIATED PORPHYRITIC GRANITE AND COARSE PORPHYRITIC GRANITE

Xenoliths of granite gneiss in the foliated porphyritic granite are observed at the following locations:

- (a) Northeast $\frac{1}{4}$ of Section 31, T46N, R29W
- (b) Southwest $\frac{1}{4}$ of Section 19, T46N, R29W
- (c) Northeast $\frac{1}{4}$ of Section 13, T46N, R30W
- (d) Southwest $\frac{1}{4}$ of Section 36, T47N, R30W

The contact of the two rock types is not very sharp, but there is no visible indication of any reaction between the two rocks. The gradational contact near Republic suggests partial remobilization of granite gneiss.

The granite gneiss occurs as xenoliths in the coarse porphyritic granite at the following locations. The margin of the xenoliths is fairly sharp.

- (a) Southeast $\frac{1}{4}$ of Section 30, T47N, R29W
- (b) Southeast $\frac{1}{4}$ of Section 23, T47N, R30W
- (c) Central part of Section 24, T47N, R30W
- (d) Northeast $\frac{1}{4}$ of Section 29, T47N, R29W

APPENDIX B

METHOD OF SEPARATION OF K-FELDSPAR FROM THE ROCK

A portion of the rock sample was crushed to obtain (-) 100 to (+) 160 mesh size particles. The sample was washed to remove all dust acquired during grinding. K-feldspar was separated from plagioclase, quartz, and other minerals using a "heavy liquid." The liquid was prepared by mixing tetrachloroethelane with bromoform in proportions such that the density of the liquid was about 2.60. The density was checked by putting pieces of pure quartz, microcline, and albite in the liquid and ascertaining that only the microcline floated; whereas the quartz and albite sank to the bottom. The separation was checked under the microscope, and the process was repeated until at least about 99% pure separation of K-feldspar was obtained.

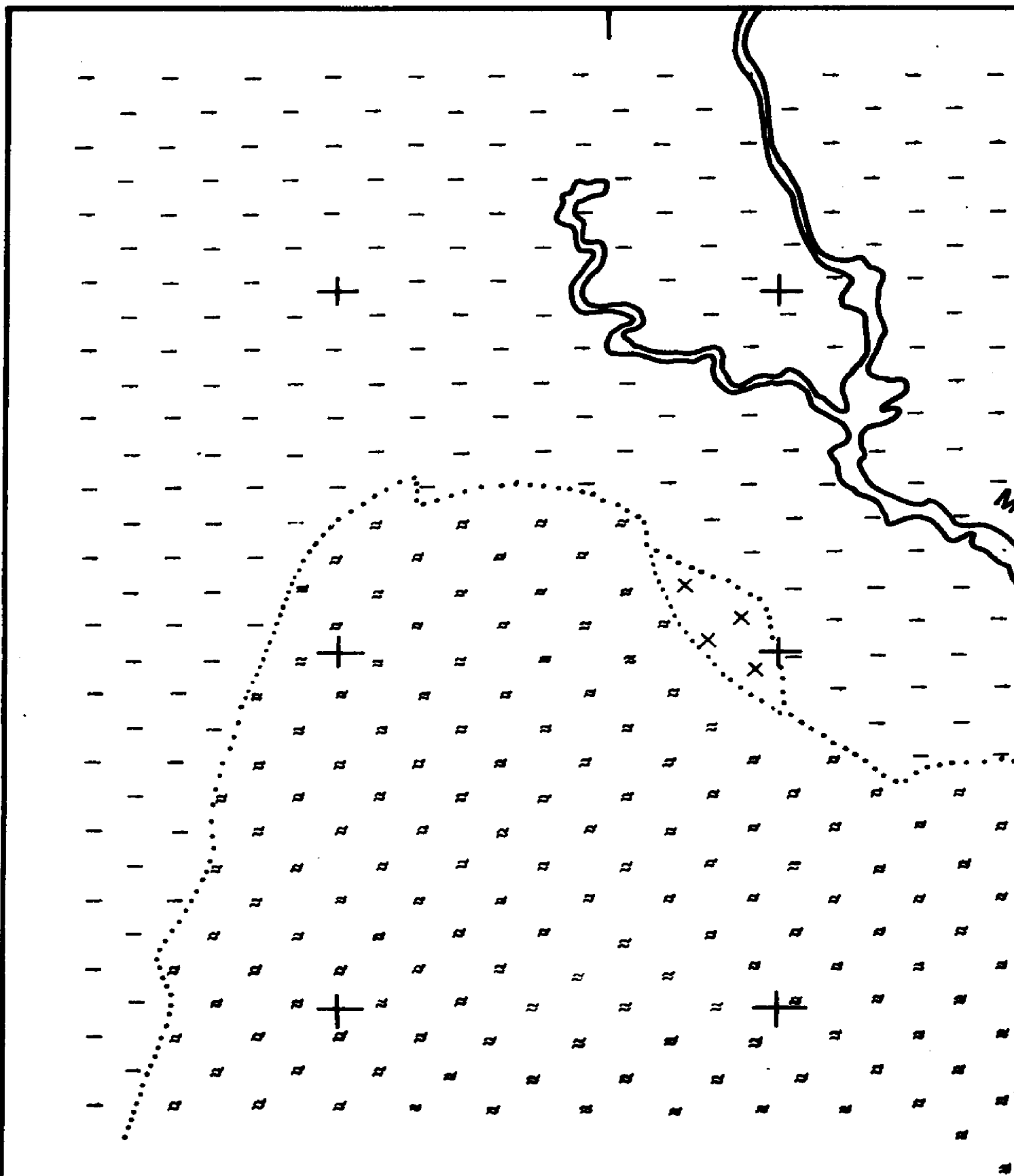
APPENDIX C

X-RAY METHOD FOR DETERMINATION OF STRUCTURAL STATE OF K-FELDSPAR

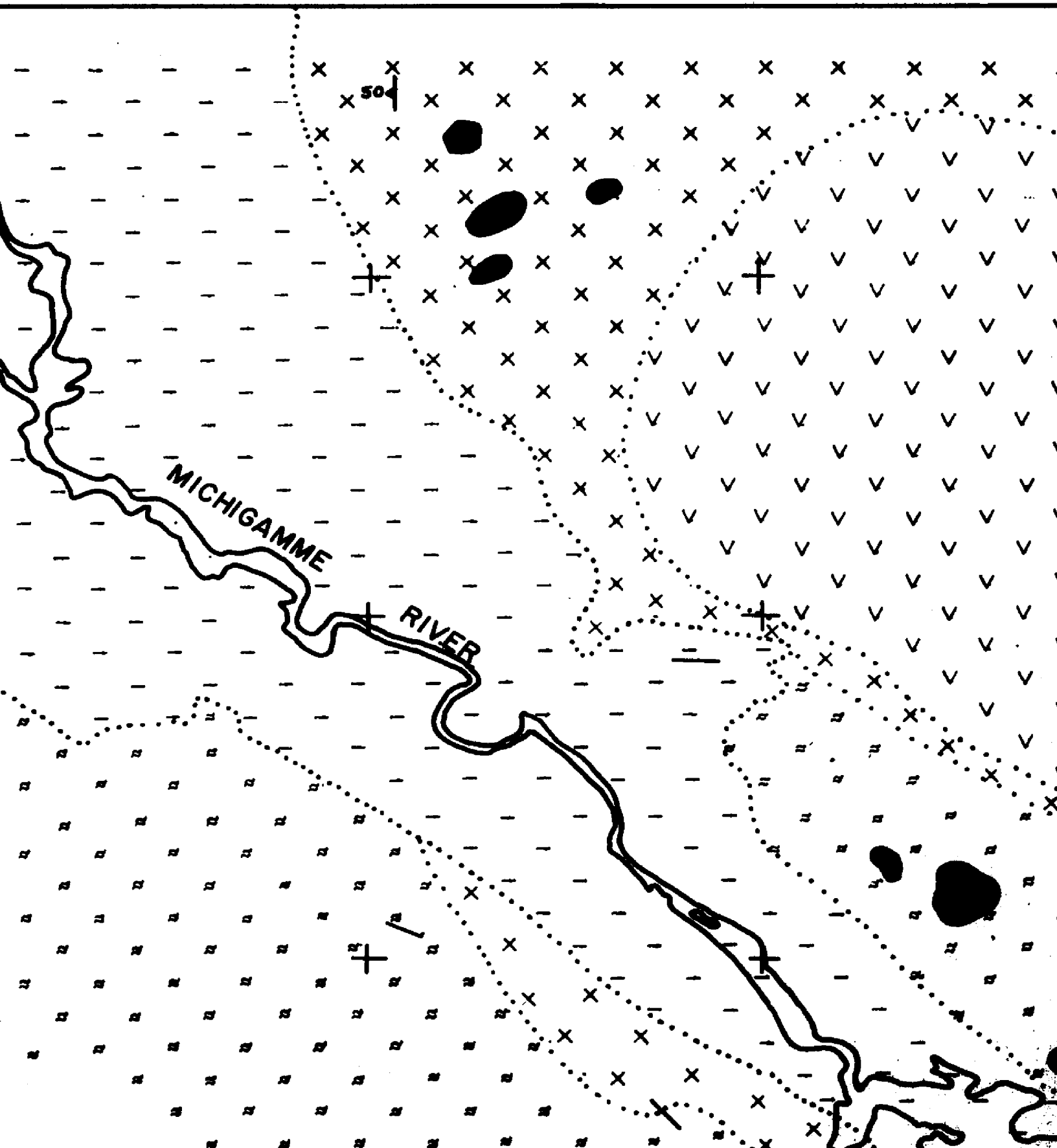
Smear mounts were made of finely ground K-feldspar mixed with CaF_2 as an internal standard ($2\theta_{\text{Cu}}(220) = 47.01$). The mounts were run on an X-ray diffractometer at a goniometer speed of 0.4° per minute. The chart speed was set so that $1^\circ 2\theta = 1$ inch. Peak positions were measured at the estimated center line of approximately top 1/10 of each peak (Orville, 1967). Duplicate diffraction was run from higher to lower 2θ (opposite of the first run) and an average of the two 2θ values was recorded. If the difference in the two values exceeded 0.04° , a third run was taken. Measurements of 2θ values for the three reflections, $(\bar{2}01)$, (060) , and $(\bar{2}04)$ were recorded.

GEOLOGIC M

88°5'

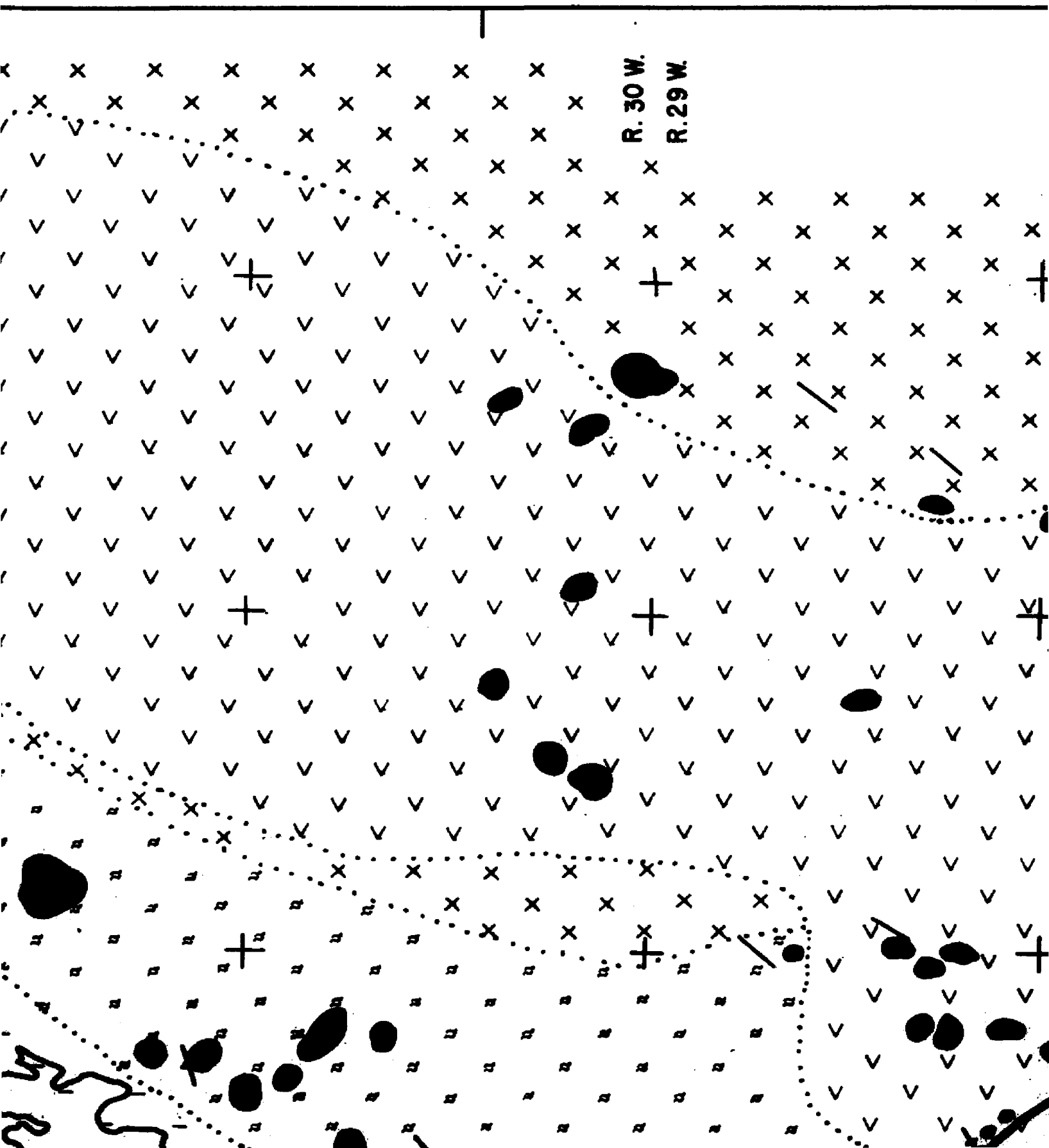


LOGIC MAP OF REPUBLIC ARE

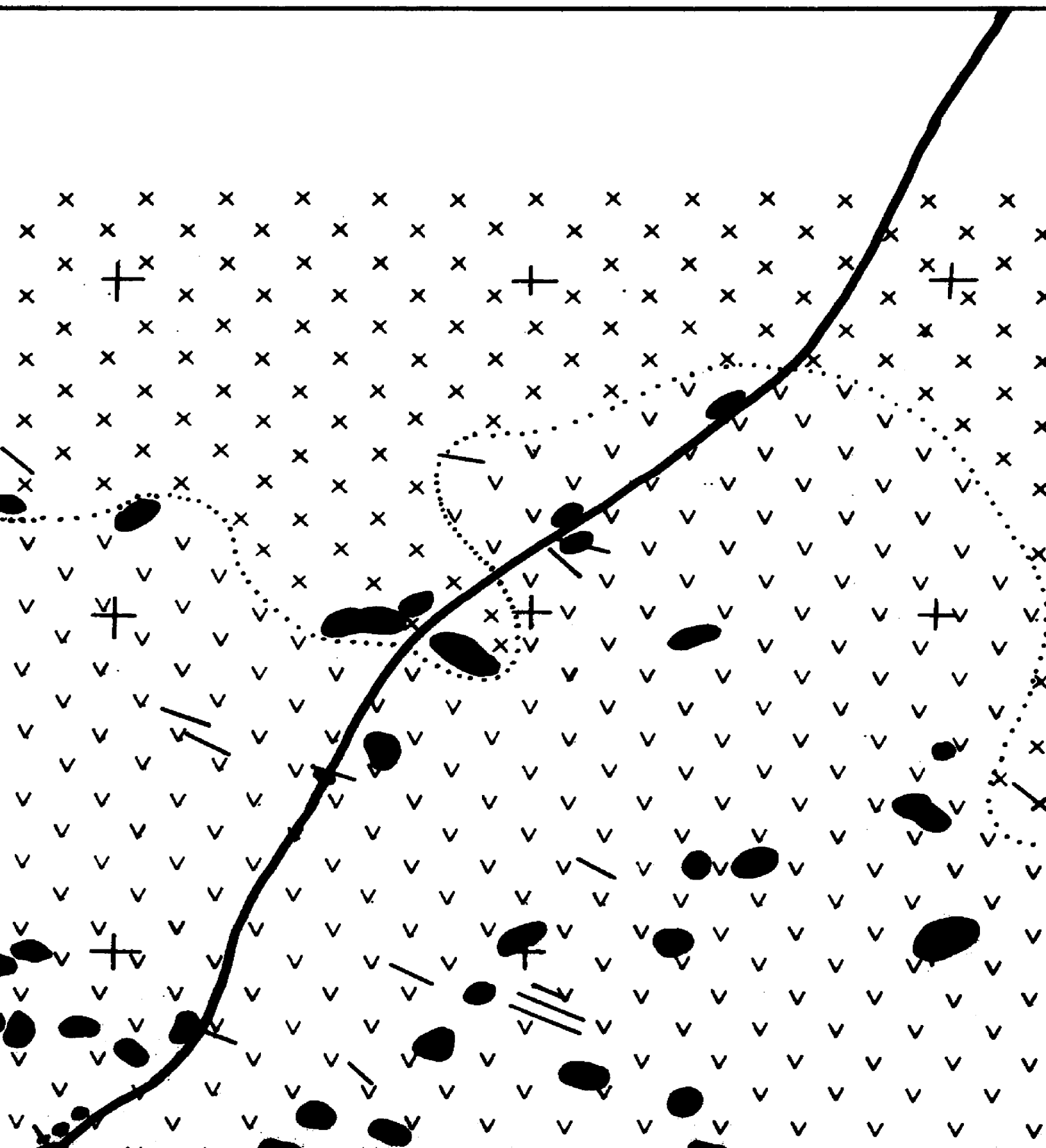


AREA, MARQUETTE COUN

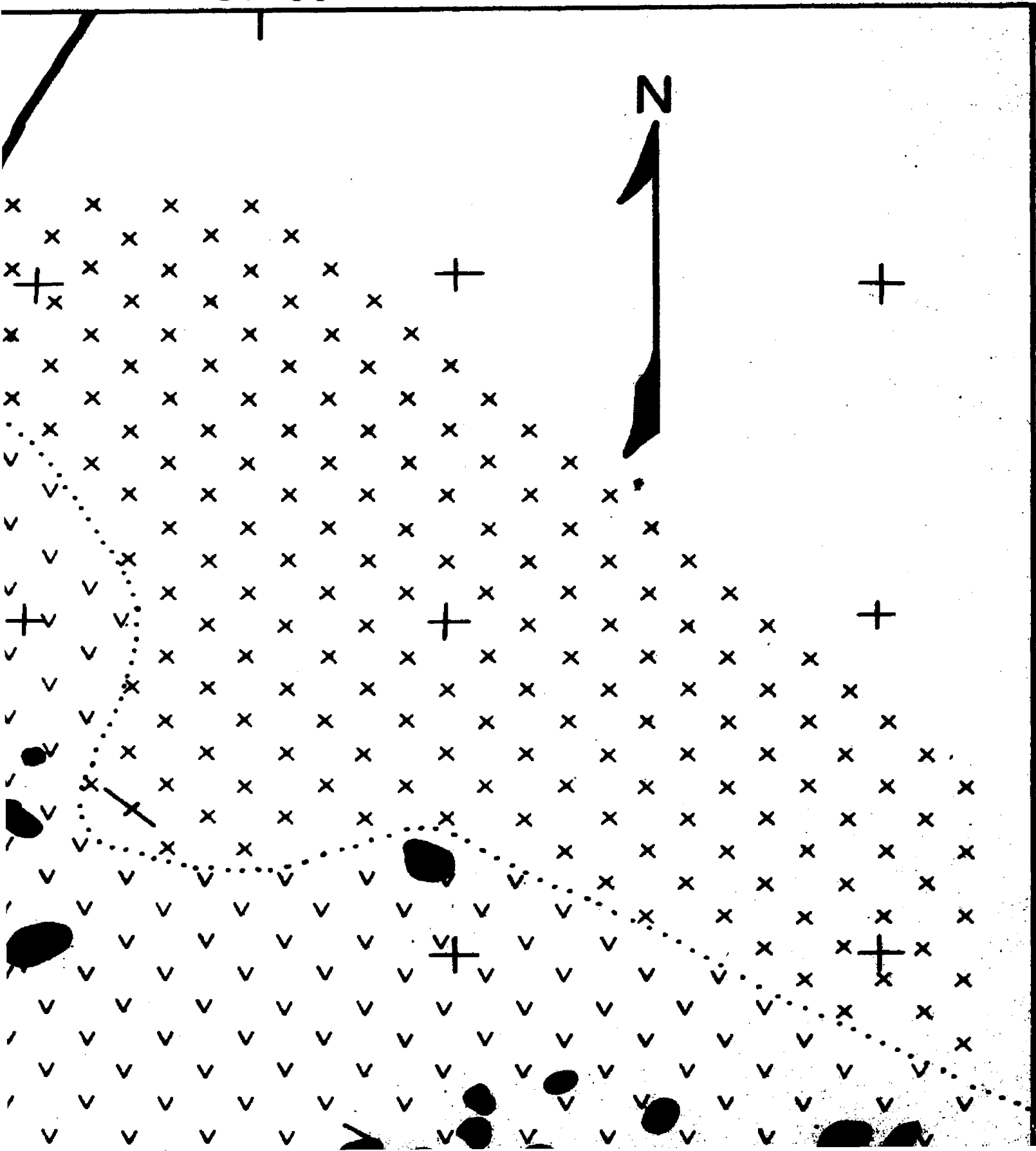
88°00'



UNTY, MICHIGAN



87°55'



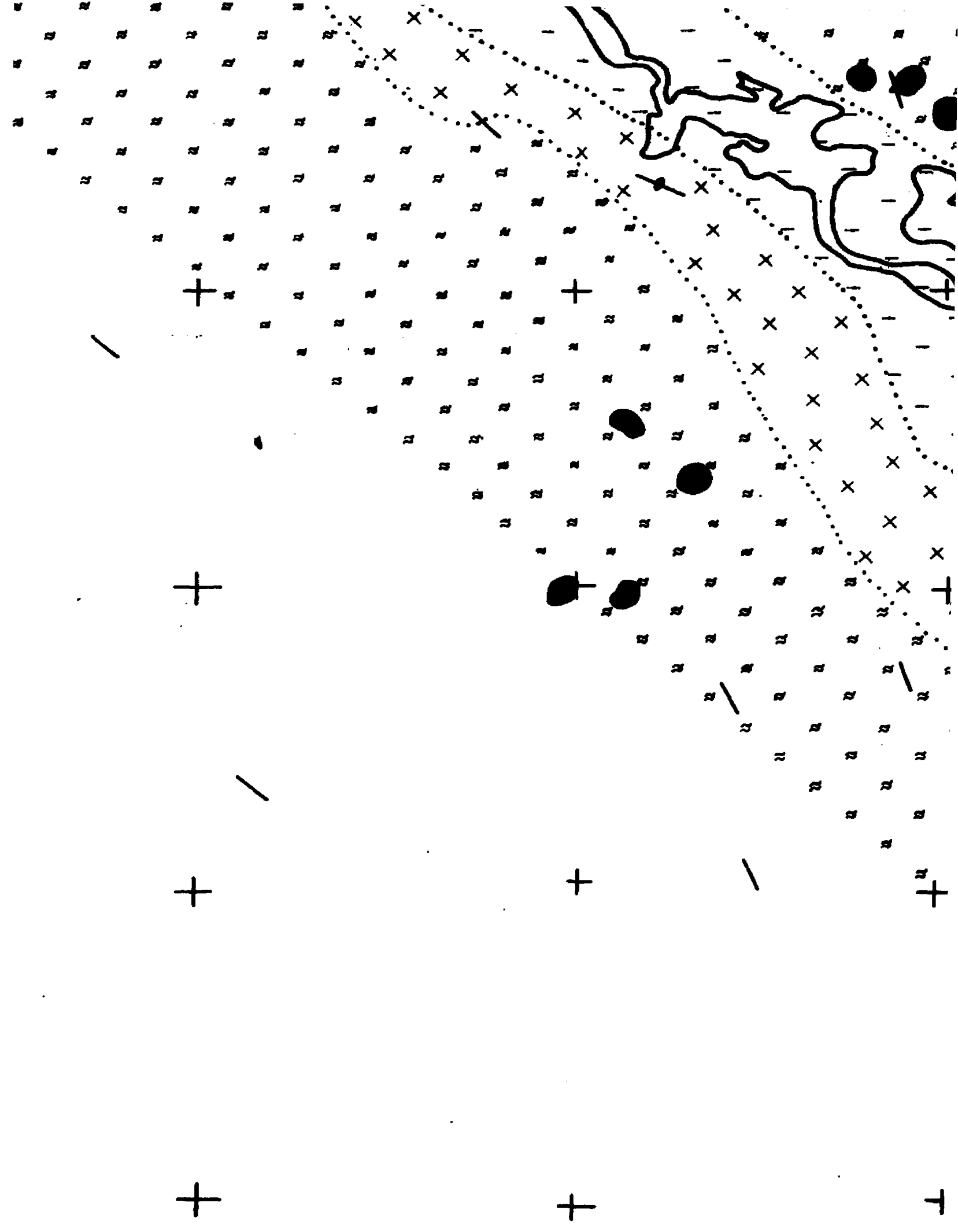
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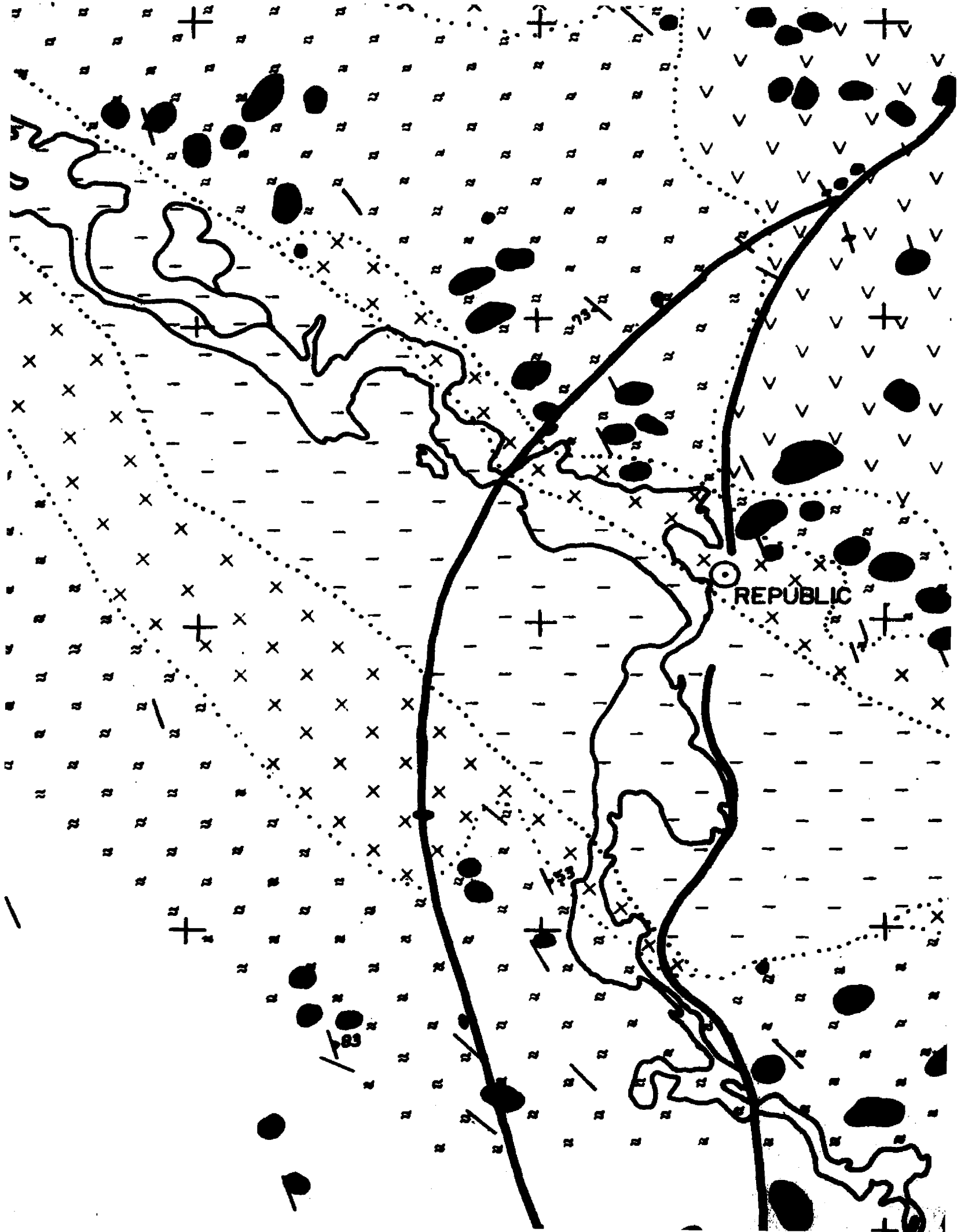
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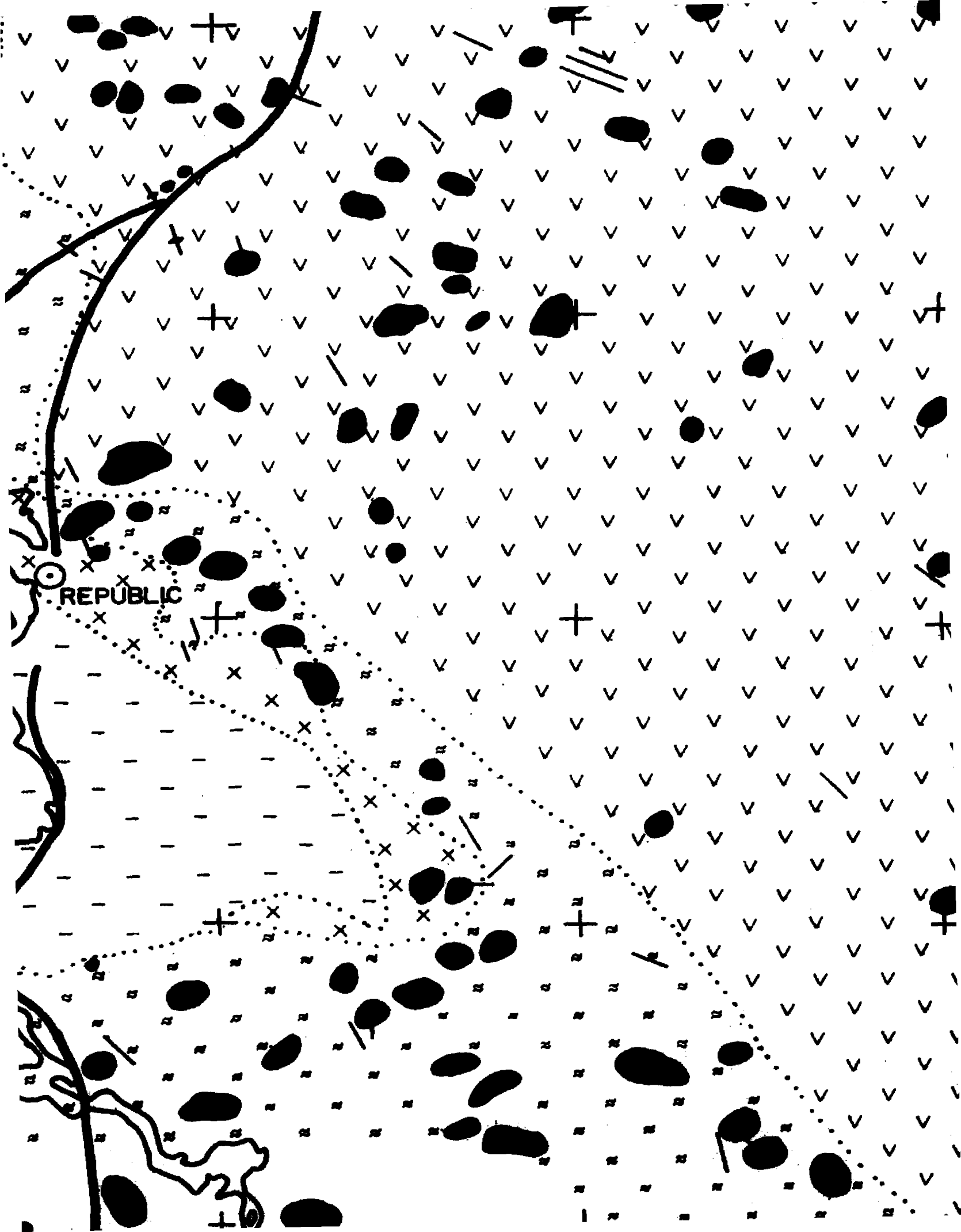
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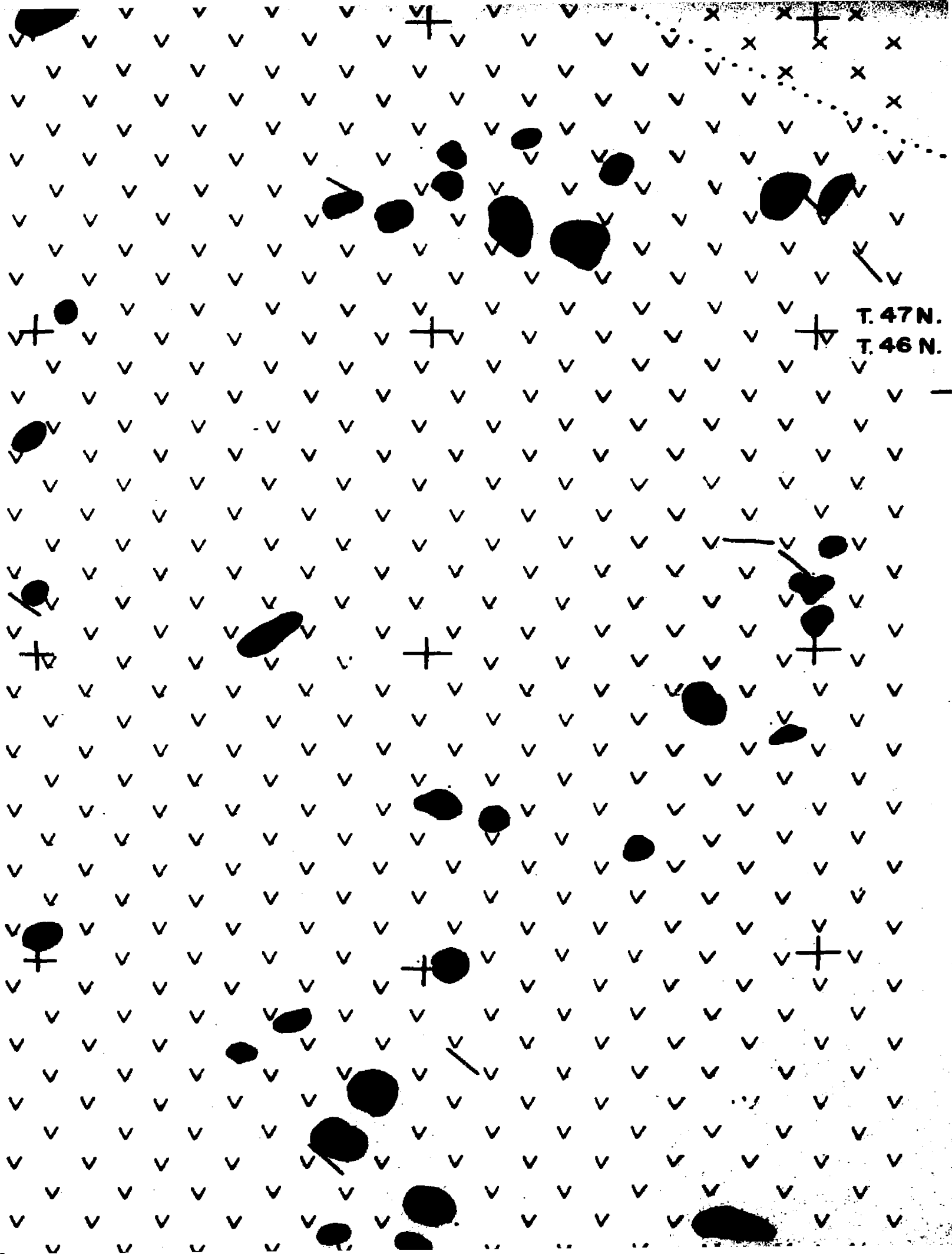
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88° 5'

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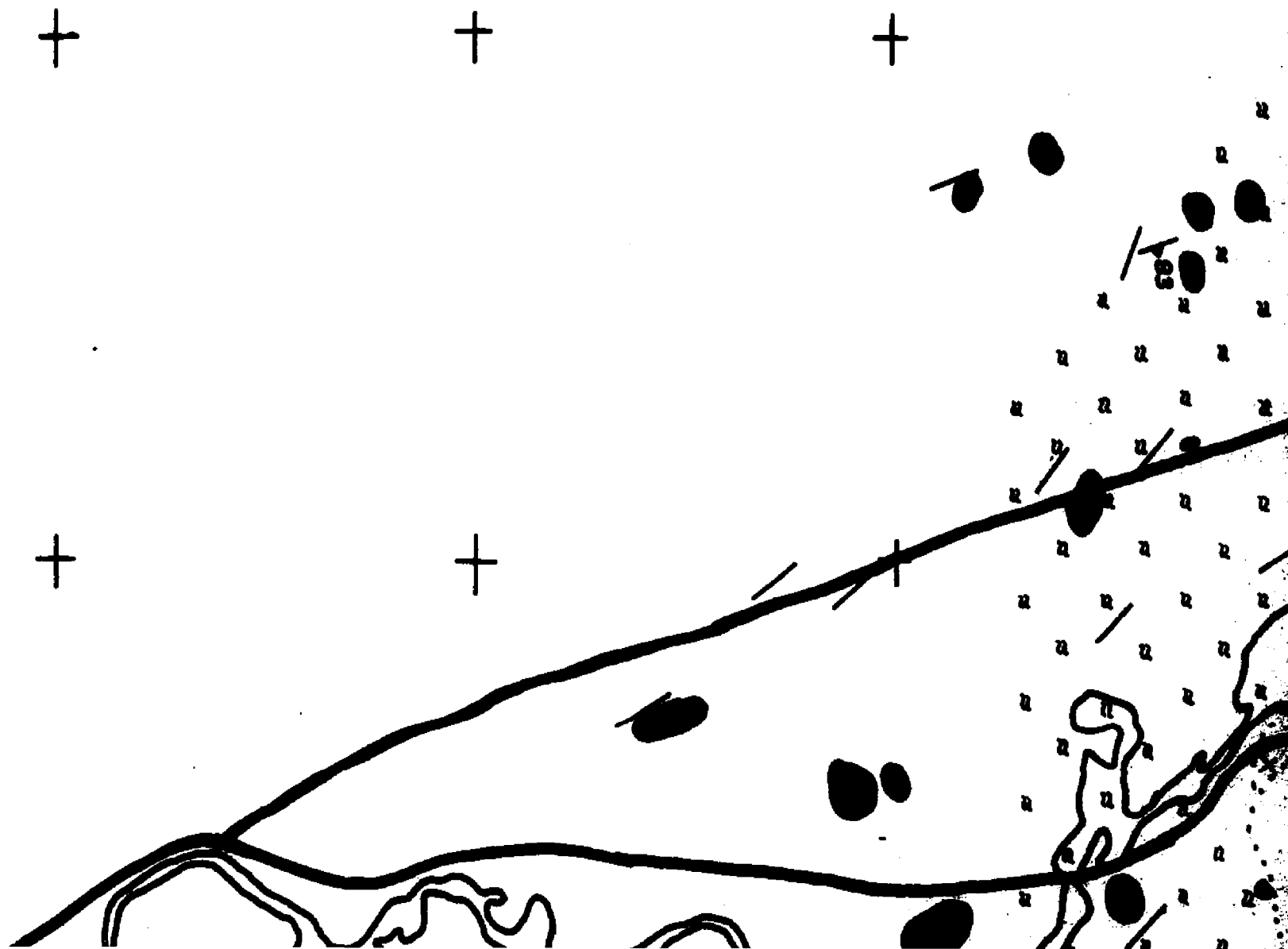
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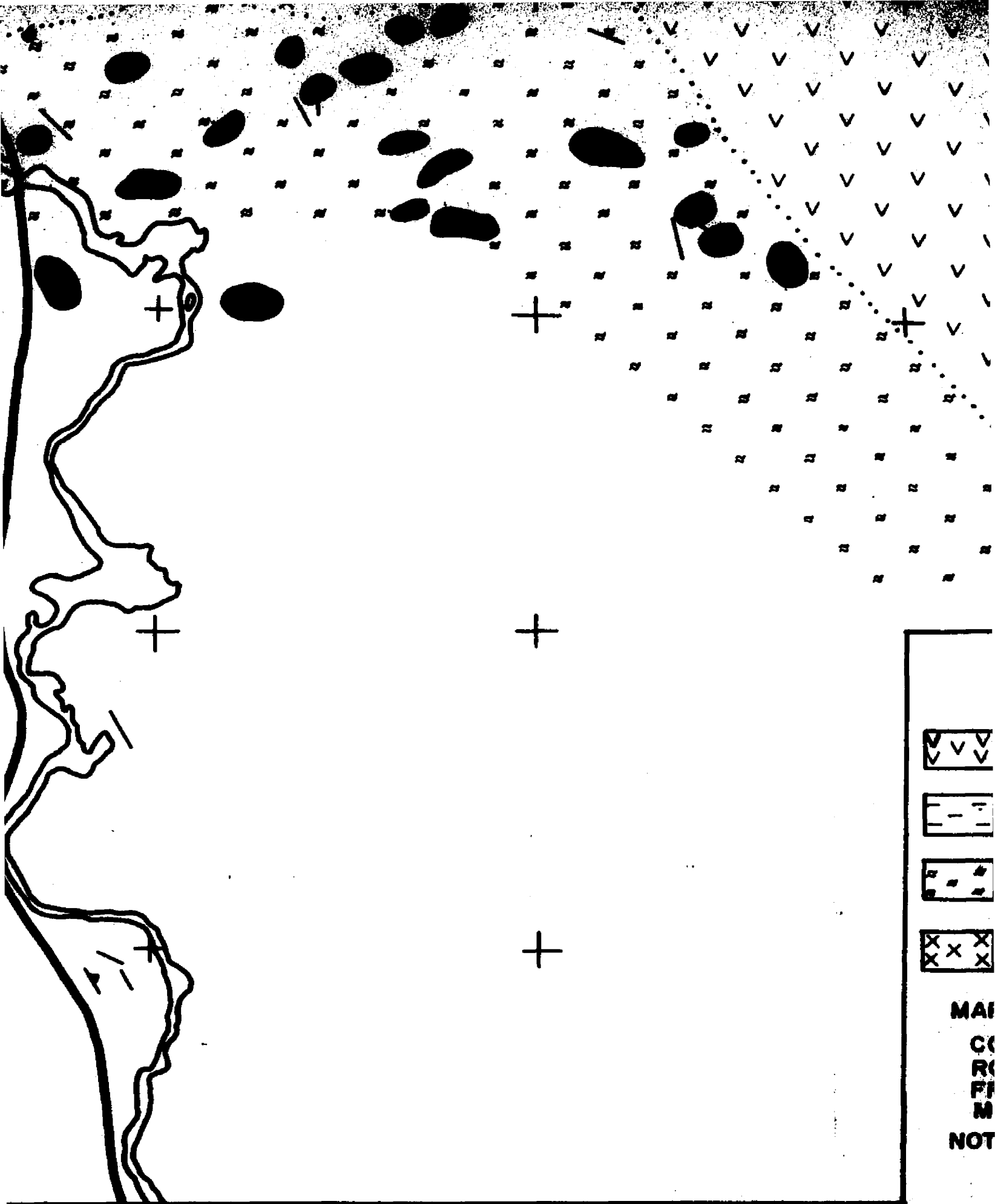
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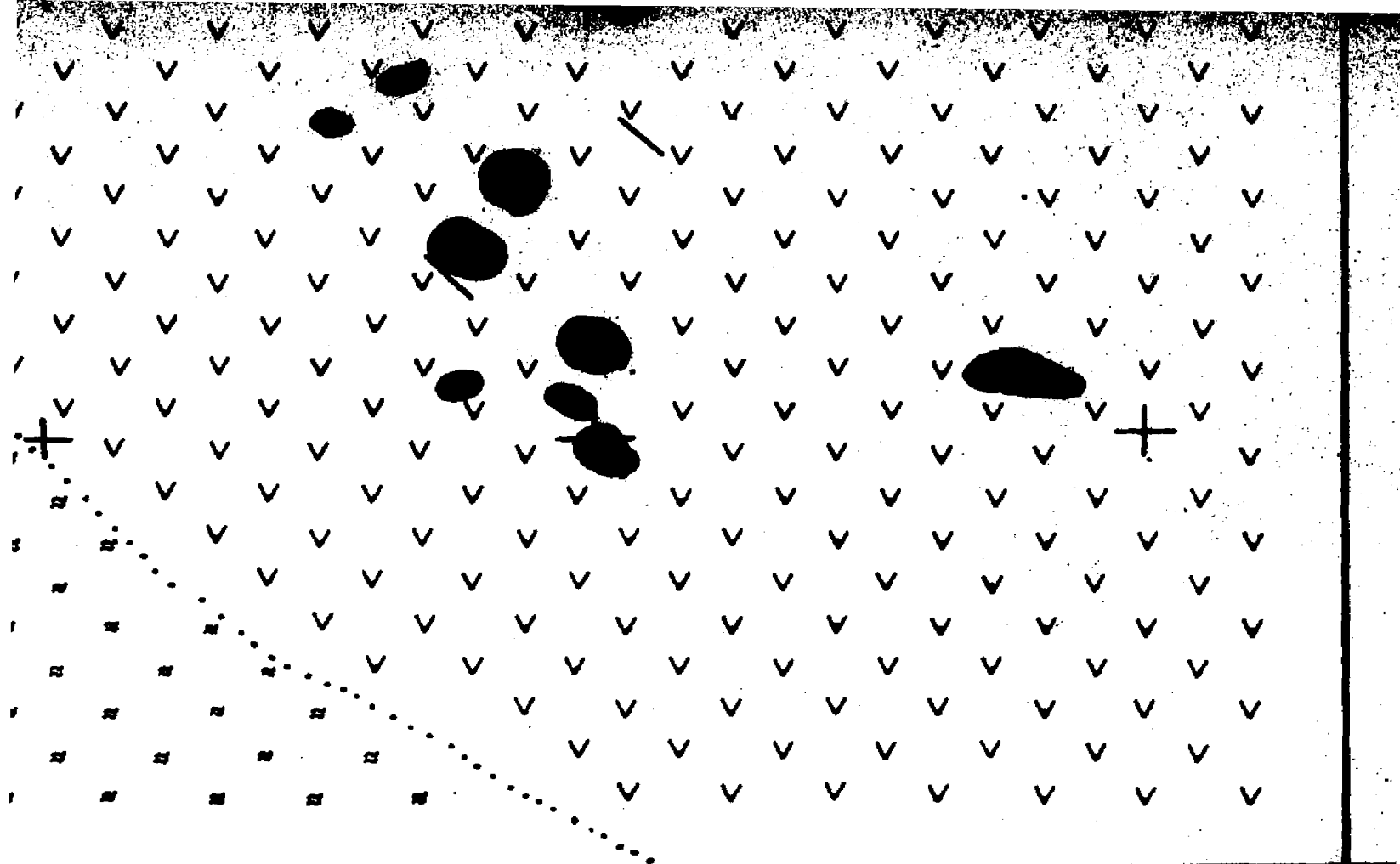
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R.30 W.
R.29 W.







LEGEND



COARSE PORPHYRITIC GRANITE
WITH BIG PHENOCRYSTS



ANIMIKIAN ROCKS



FOLIATED GRANITE
WITH SMALL PHENOCRYSTS



GNEISSIC COMPLEX

MAPPED BY SYED M. ZAINUDDIN

CONTACT BETWEEN ANIMIKIAN
ROCKS AND GRANITE ADOPTED
FROM J.W. VILLAR'S MAP PARTIALLY
MODIFIED BY FIELD NOTES.

NOTE: DIKES ARE NOT SHOWN DUE
TO SMALL SIZE.

OUTCROP AREA

CONTACT (INFERED)

CONTACT (OBSERVED)

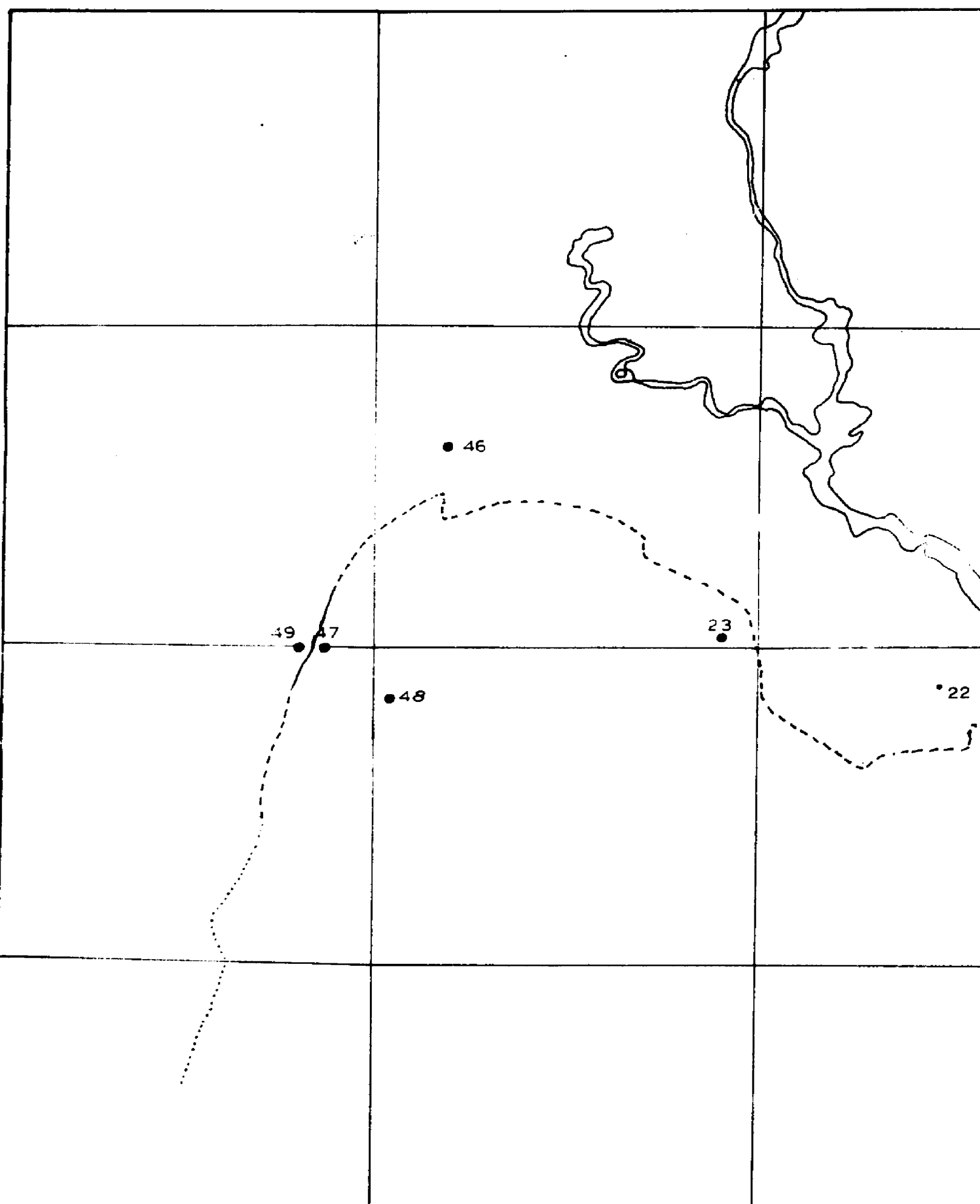
STRIKE AND DIP
OF FOLIATION

STRIKE OF VERTICAL
FOLIATION

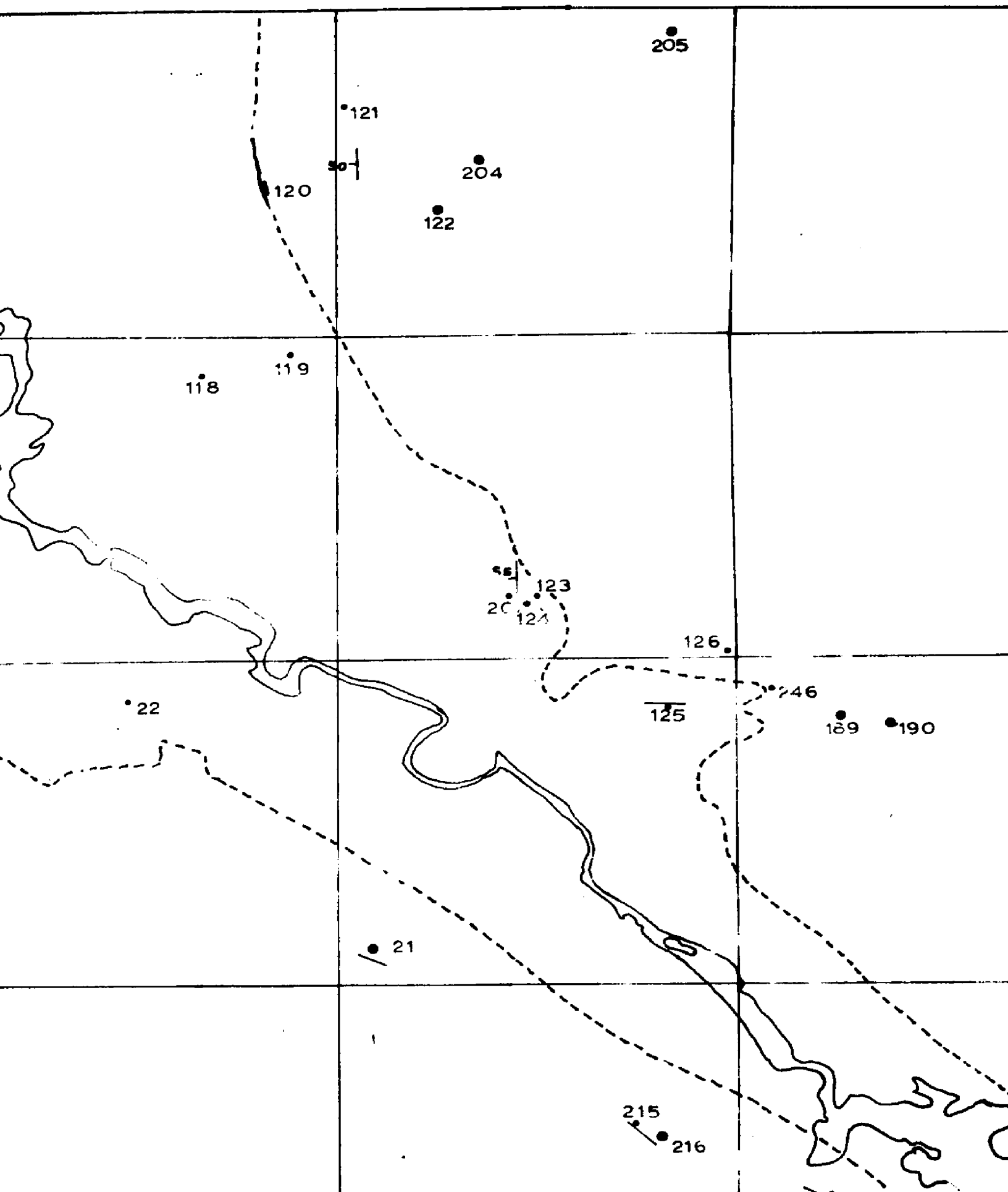
TREND OF LINEATION
1 MILE

0 1/2 MILE

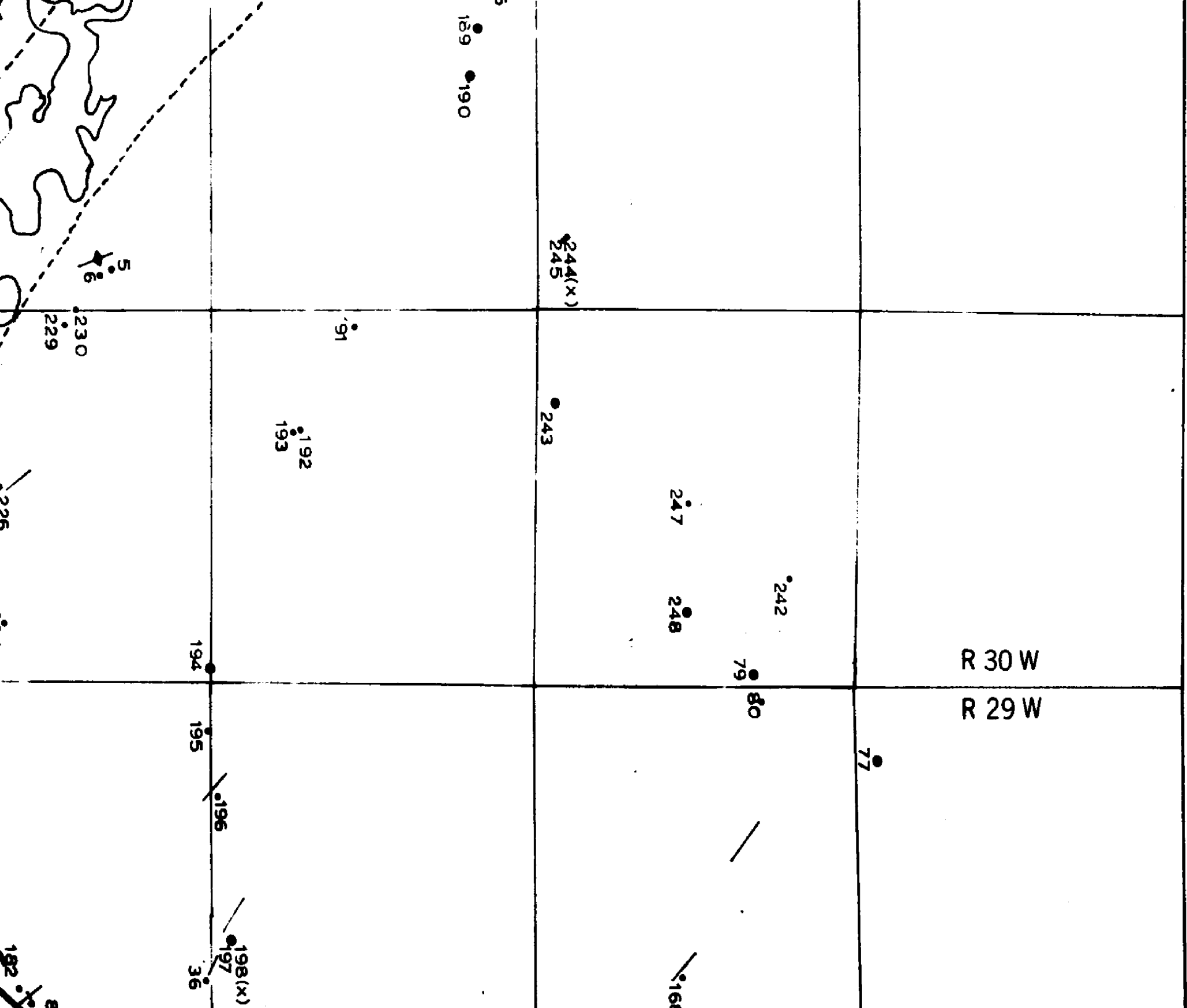
SCALE 1:24000



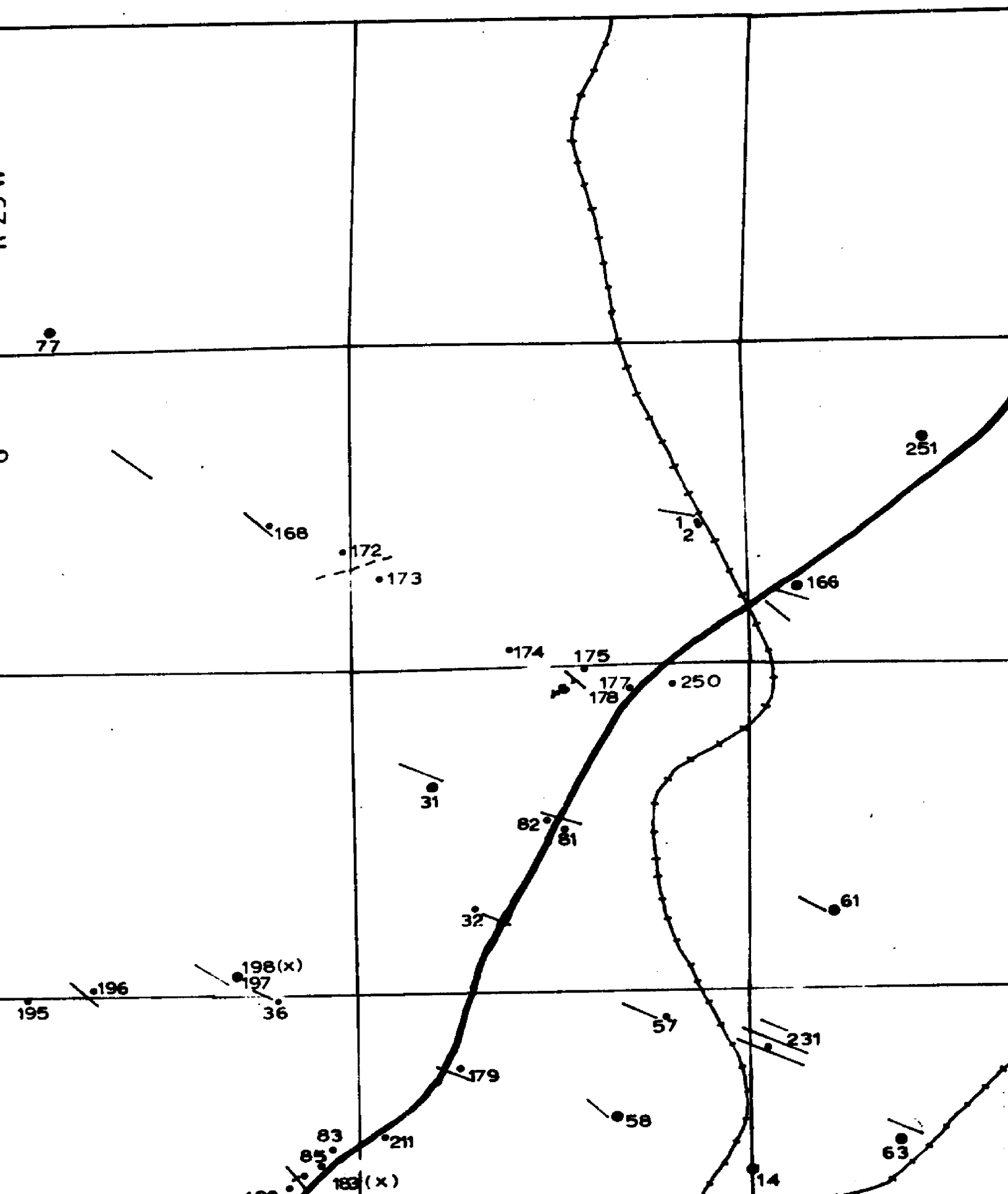
MAP . SHO

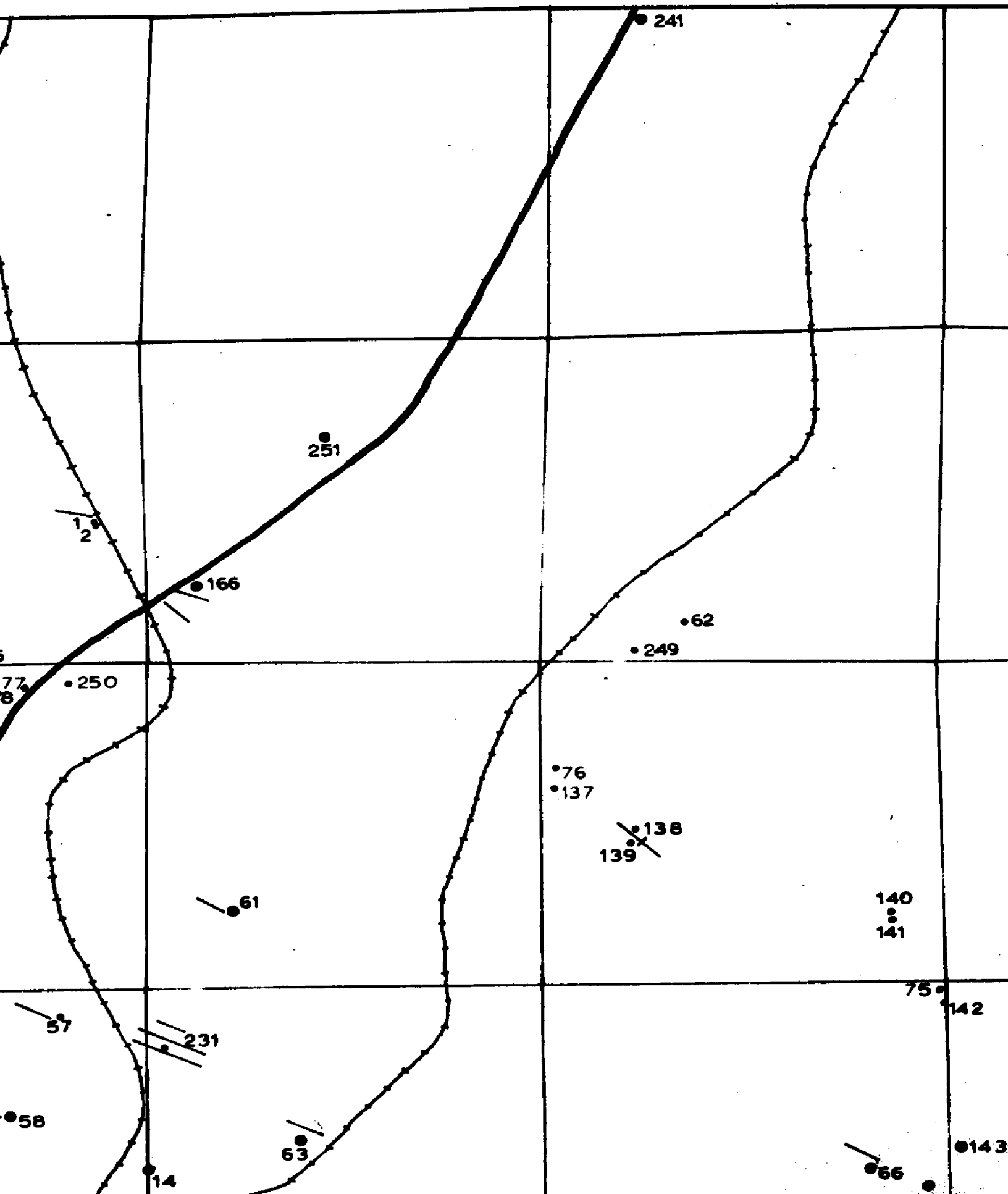


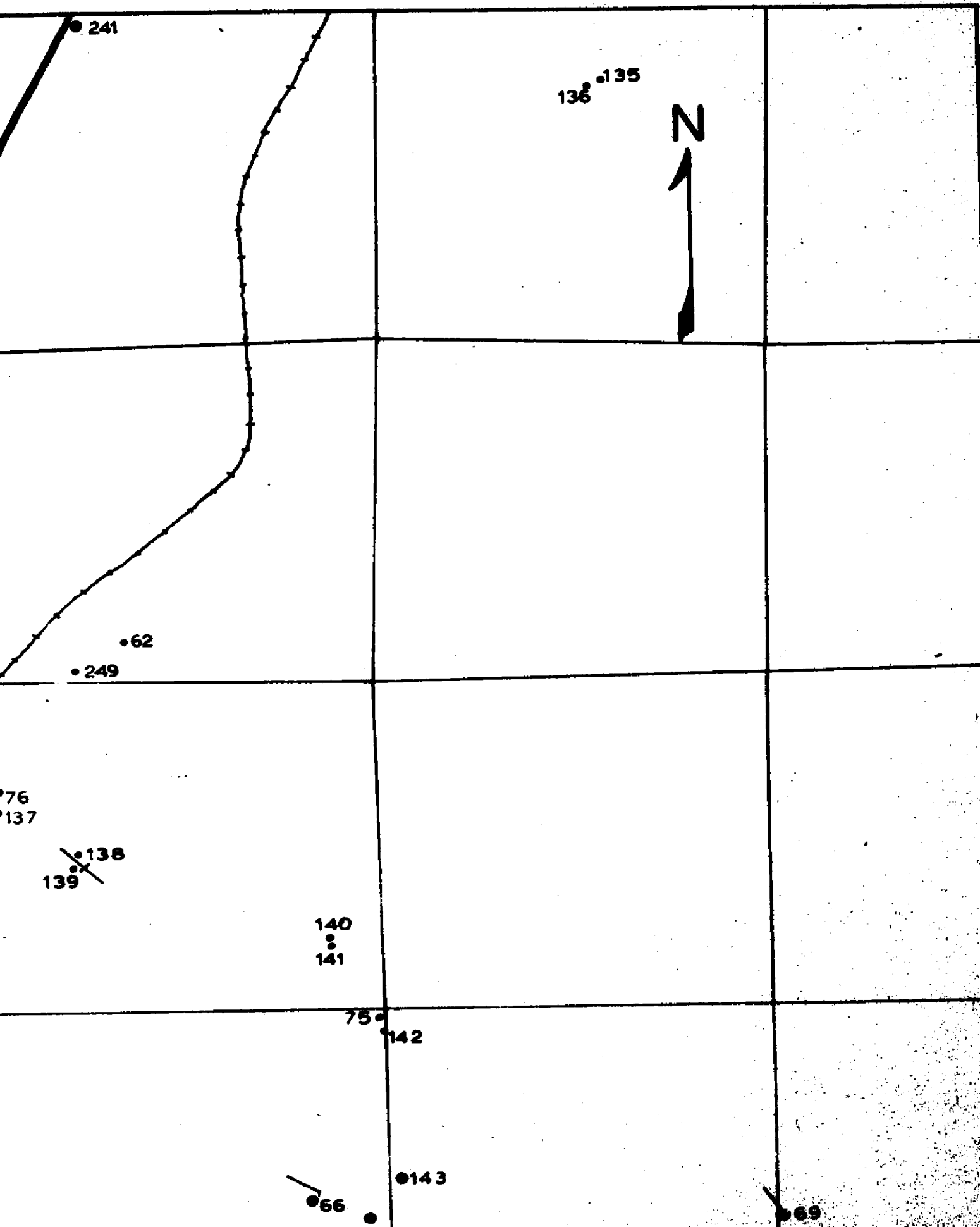
MAP SHOWING LOCATION OF SAMPLE



OF SAMPLES

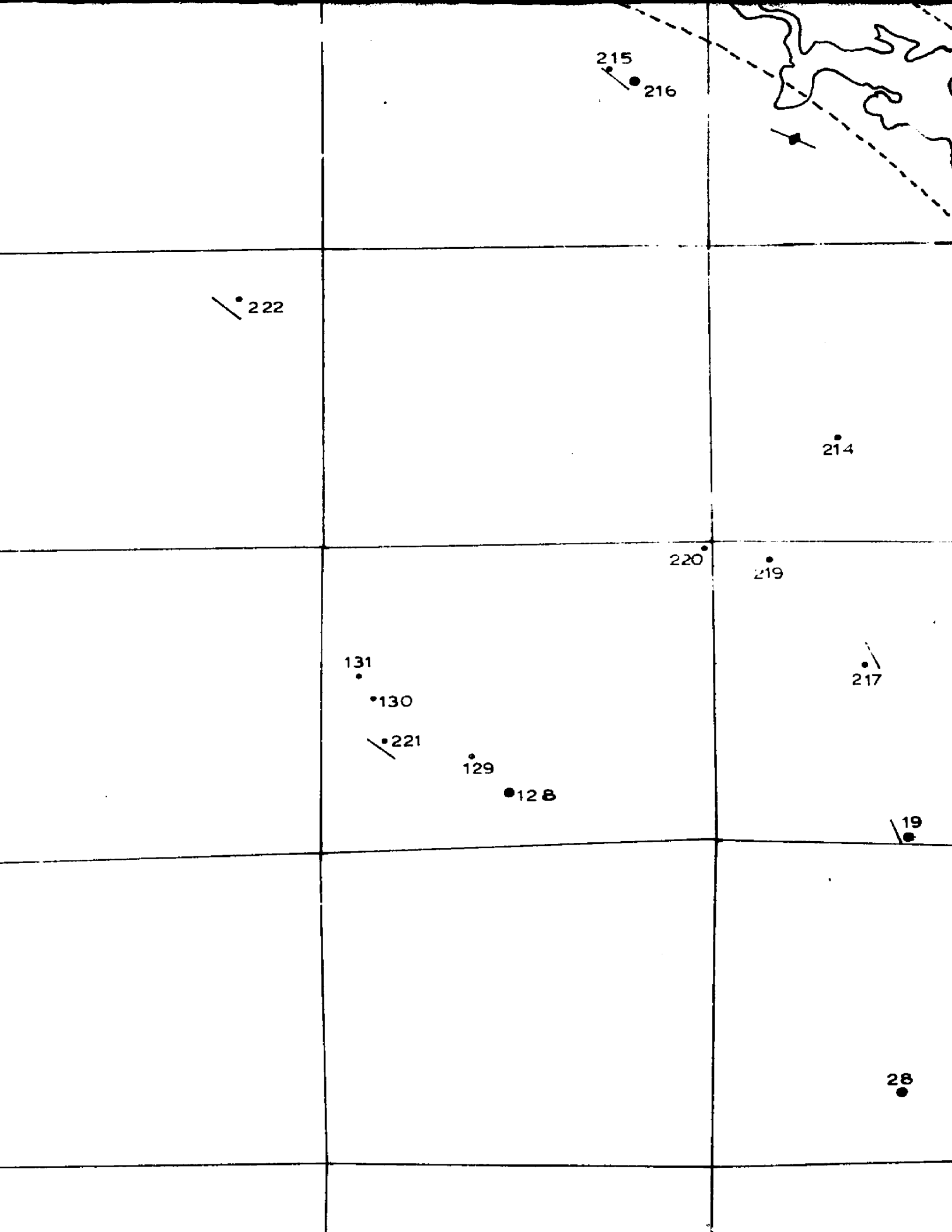


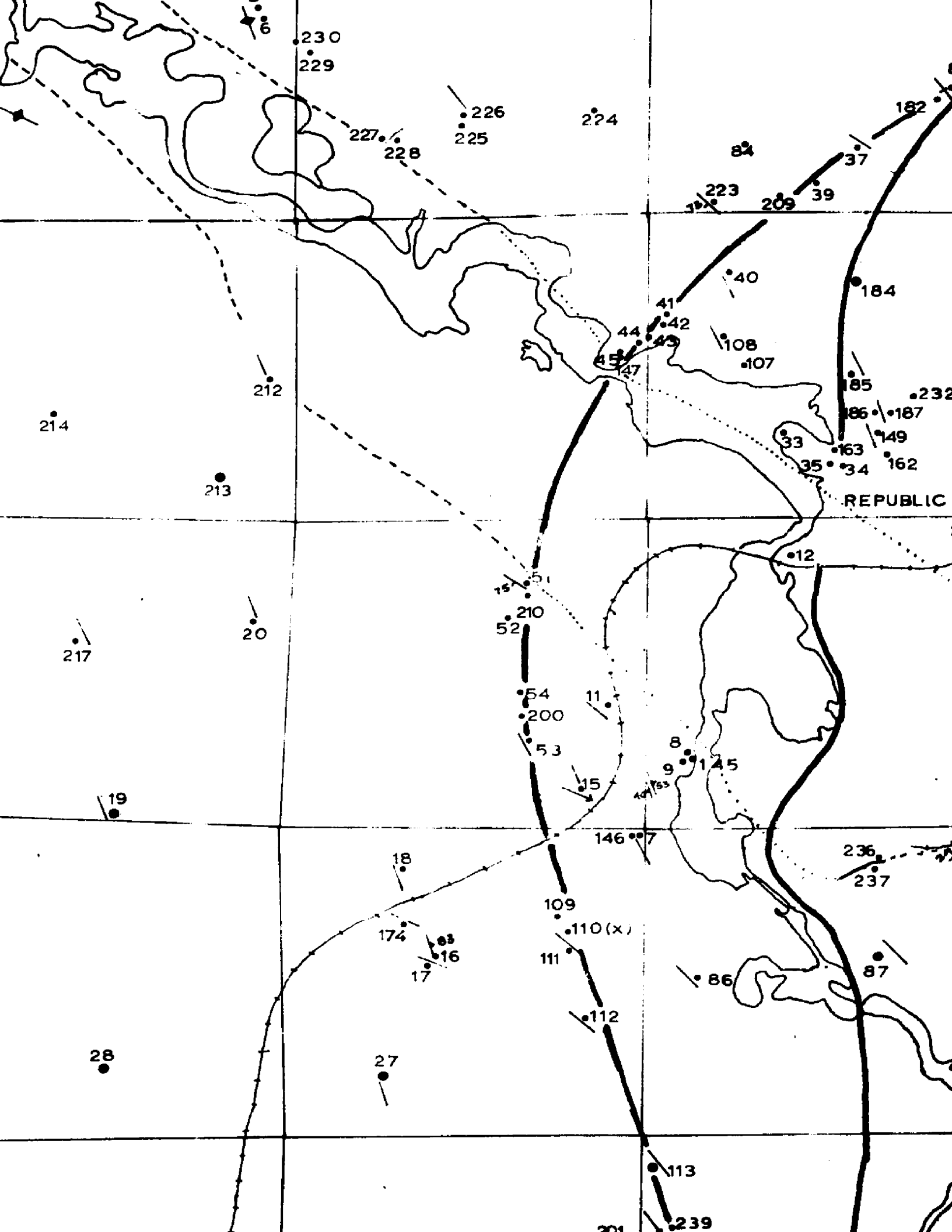


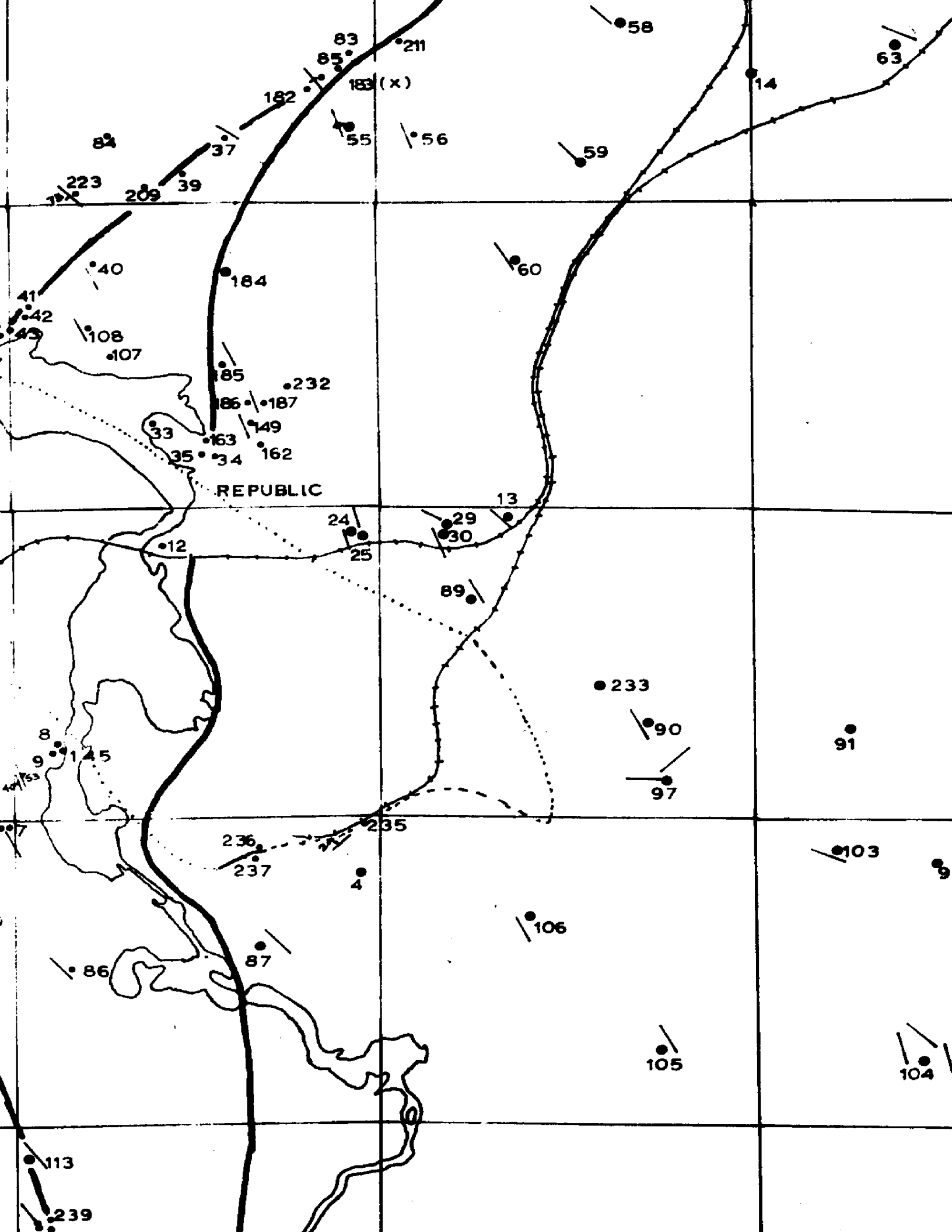


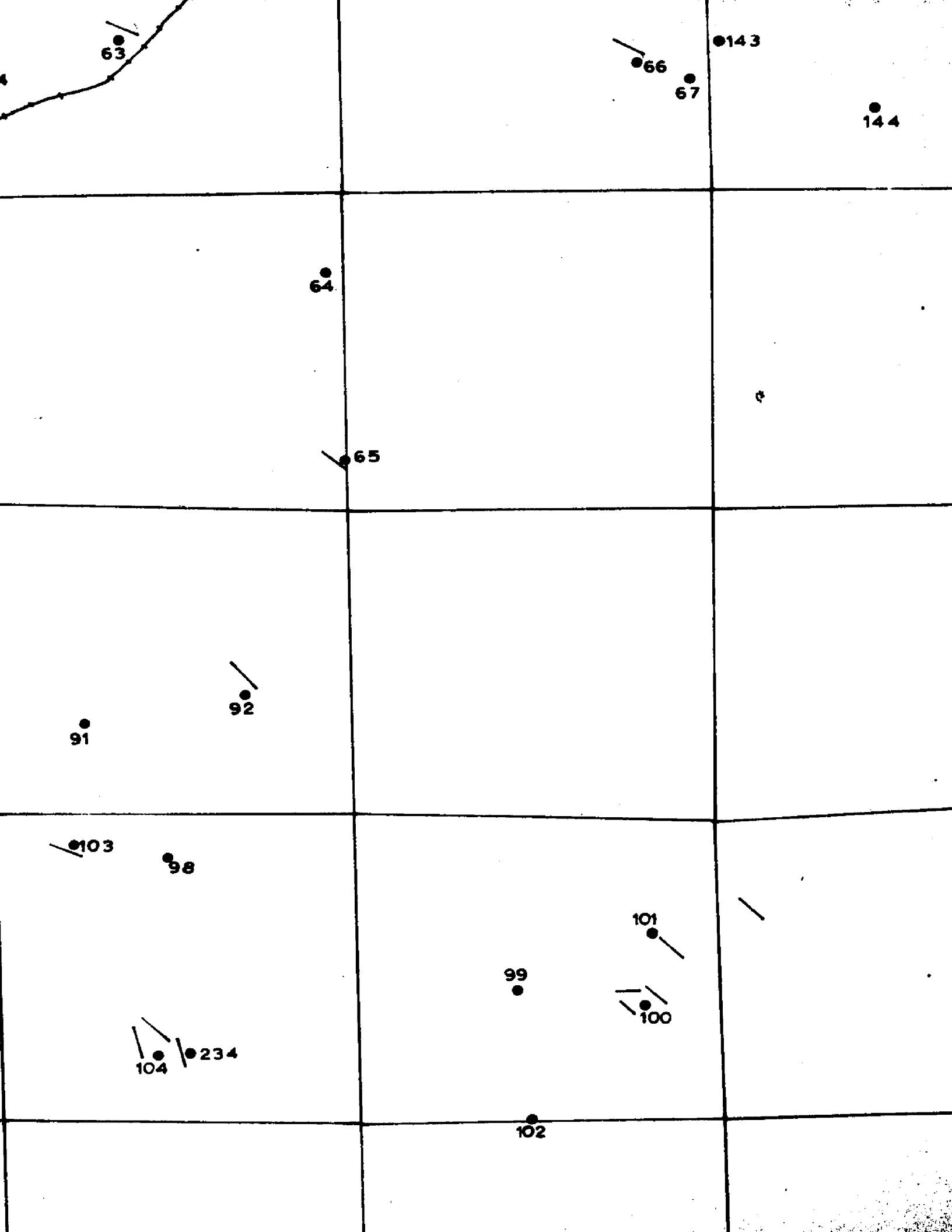
T. 47 N.

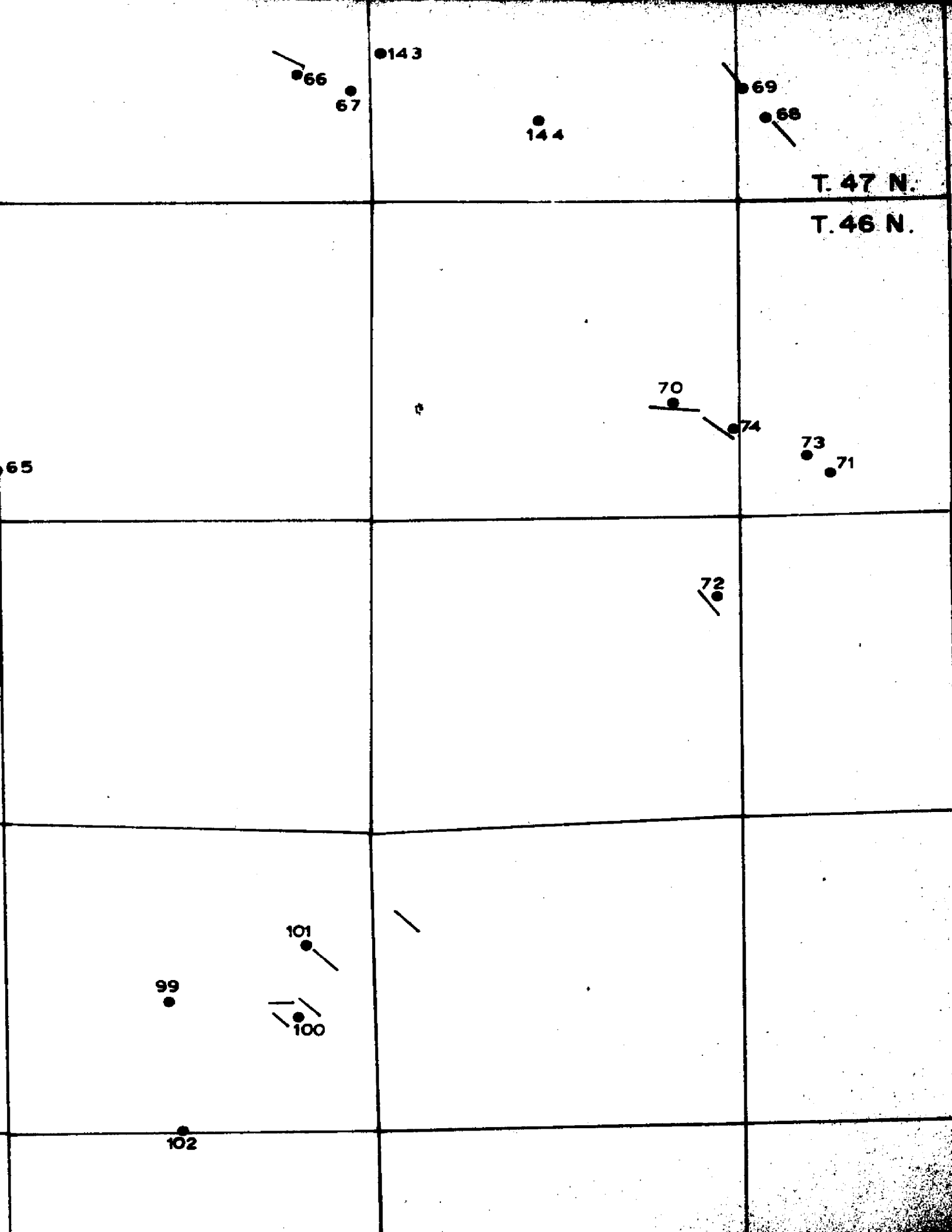
T. 46 N.

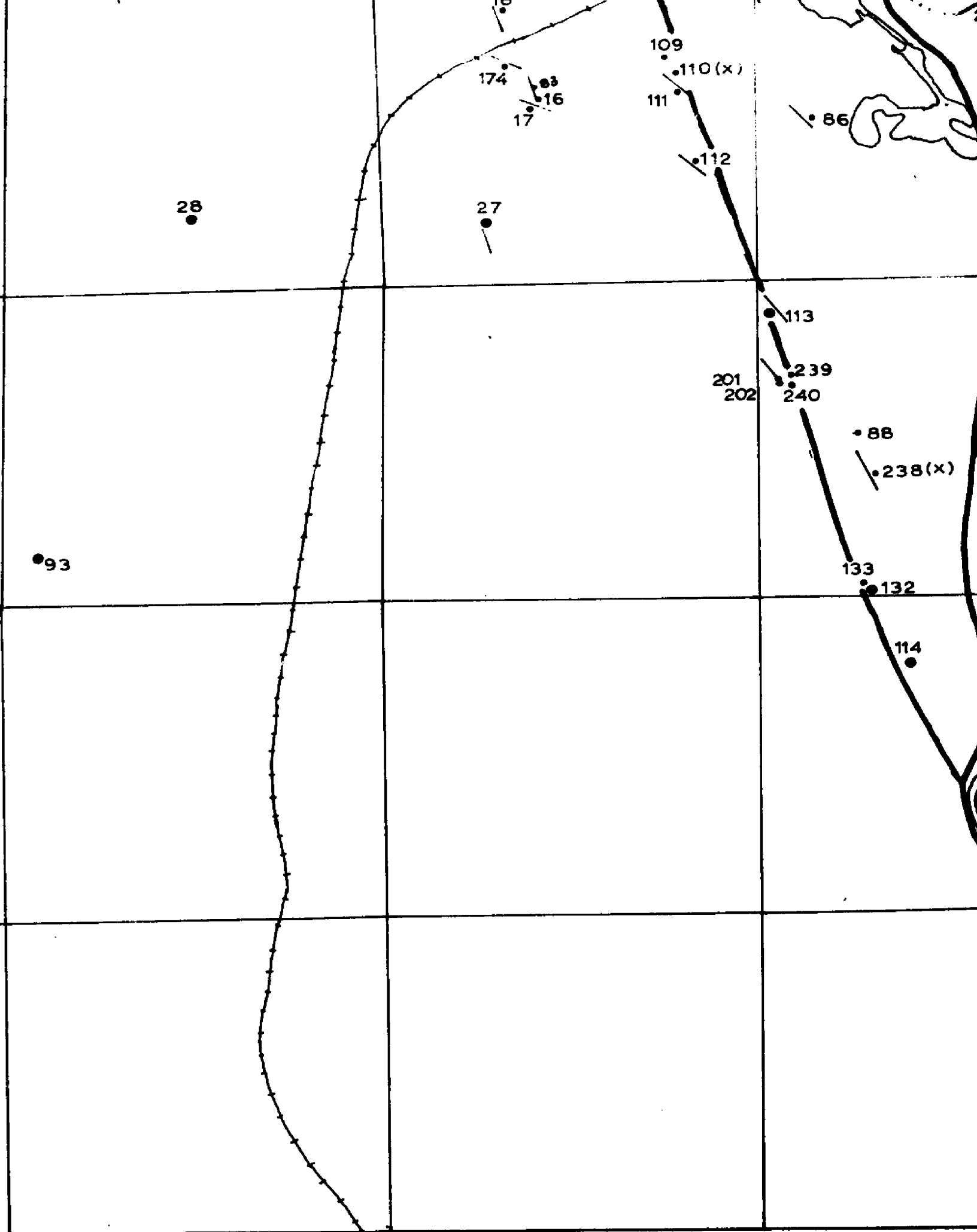


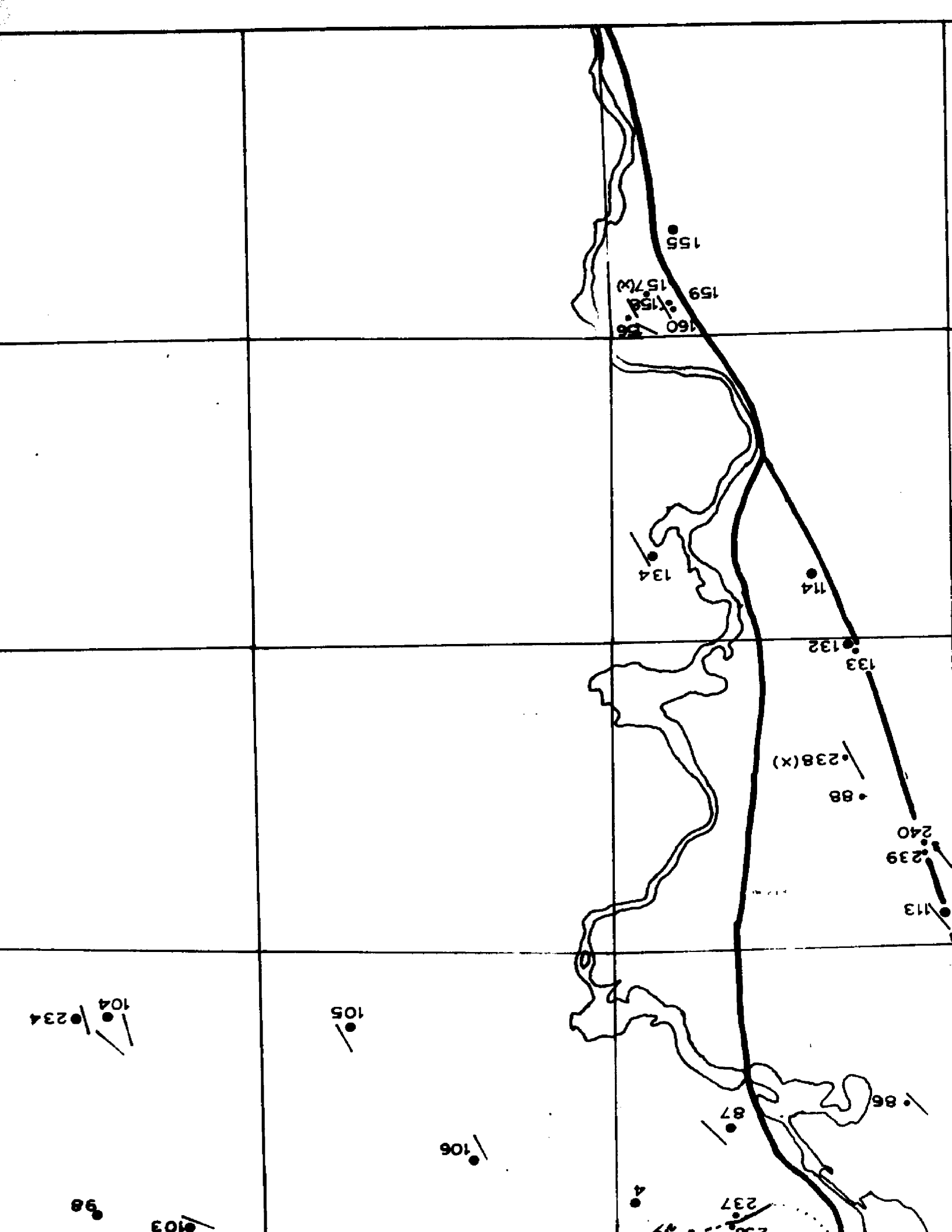


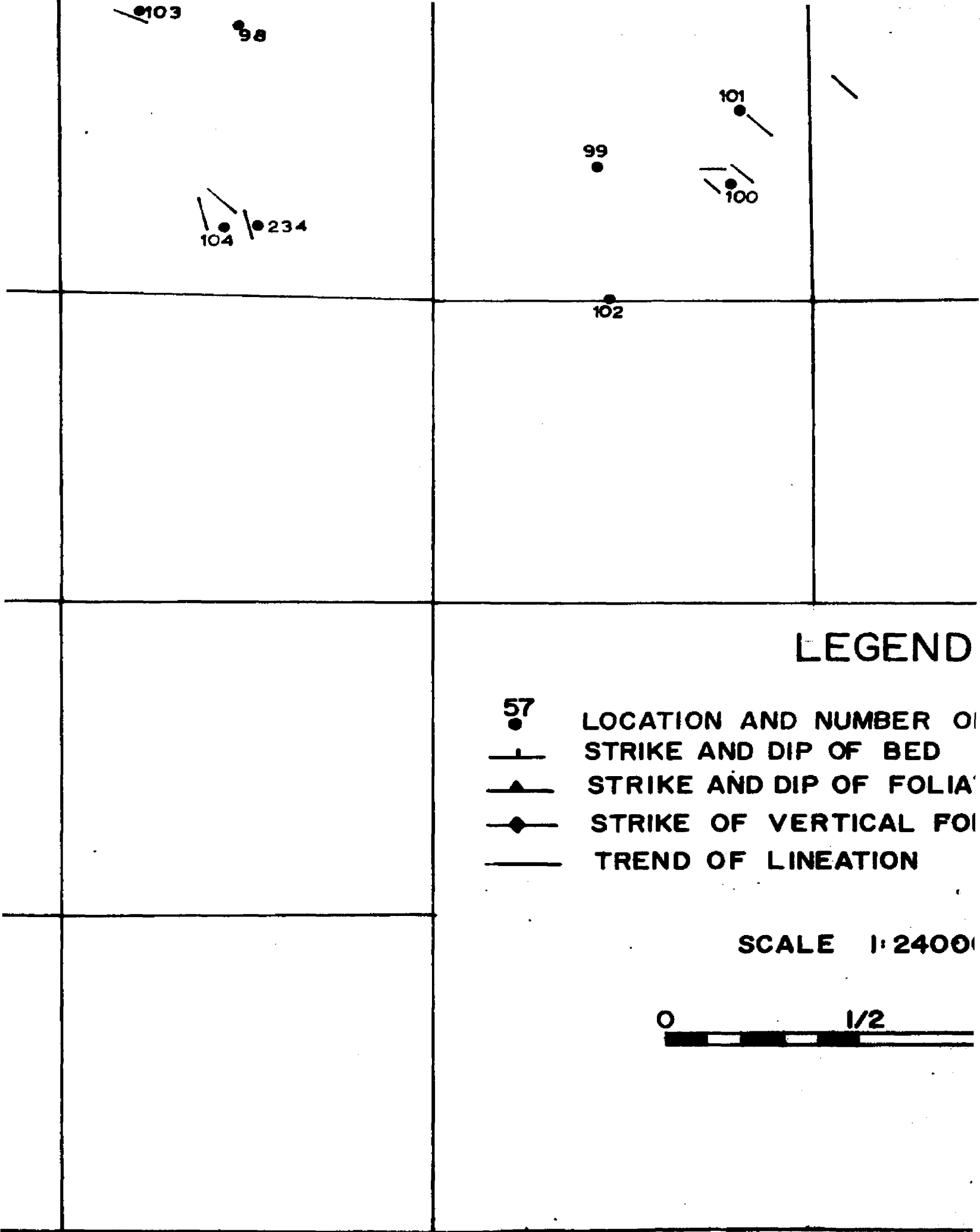










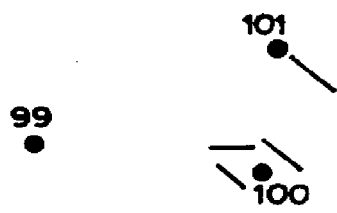


LEGEND

- 57 ● LOCATION AND NUMBER OF
- ┐ STRIKE AND DIP OF BED
- ▲ STRIKE AND DIP OF FOLIA
- ◆ STRIKE OF VERTICAL FOI
- TREND OF LINEATION

SCALE 1:24000





LEGEND

- 57 ● LOCATION AND NUMBER OF ROCK SAMPLE
- ┘ STRIKE AND DIP OF BED
- ▲ STRIKE AND DIP OF FOLIATION
- ◆ STRIKE OF VERTICAL FOLIATION
- TREND OF LINEATION

SCALE 1:24000

