STRUCTURAL GEOLOGY OF THE

LONG LAKE AREA MANITOBA

A Thesis

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by

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ABSTRACT

At Long Lake Manitoba the Rice Lake greenstones have had a complex structural and metamorphic history. A period of isoclinal folding (D_1) and greenschist facies metamorphism were the earliest events. They were followed by open cross folding (D_2) accompanied by dynamic metamorphism and retrogression of biotite to chlorite. A period of minor kink folding (D_3) was the last event.

The development of folds during D_1 is not well understood. During D_2, folds were produced by passive slip parallel to a well developed axial plane foliation (S_2) which strikes west and transects the axial surfaces of the early folds. The apparent direction of tectonic transport during D_2 was parallel to mineral lineations (L_2) and slickensides (L_2') which pitch steeply to the east or west in the plane of S_2. Volcanic fragments elongated in these directions and flattened in the plane of S_2 are interpreted as possible evidence for near-vertical elongation and north-south shortening of the rock mass during D_2.

The last period of deformation (D_3) resulted in a conjugate set of kink folds and a series of small concentric folds in the foliation (S_2). These folds were probably produced by flexural slip on S_2 parallel to a set of horizontal slickensides (L_3).

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CHAPTER I

INTRODUCTION

This study represents a geometric and kinematic analysis of the diastrophic structures of the metamorphosed Archean sedimentary and volcanic rocks in the Long Lake area of Manitoba. The geometric analysis is based on field mapping and on the interpretation of the orientation data from various types of s-surfaces and various types of lineations. The kinematic analysis is based on the character of the surfaces of deformation and the lineations, on the microscopic fabric of the rocks and on the shape and orientation of deformed fragments.

Location

The map-area is located about 15 miles southeast of Bissett, Manitoba and covers about 4 square miles of Township 22, Ranges 15 and 16, at the east end of Long Lake (Fig. 1).

Acknowledgments

The writer wishes to thank Professor W. C. Brisbin for supervising his work. He is indebted to Dr. W. Weber and Dr. D. McRichie of the Manitoba Mines Branch for their valuable assistance in the field and to Dr. A. Turek for introducing him to computer techniques in structural

geology. Mr. F. H. A. Campbell was very helpful in discussing the stratigraphy with the writer.

Course of Investigation

Six weeks of field work was done in the fall of 1967 and three weeks in the fall of 1968 under the auspicies of the Manitoba Mines Branch. Laboratory work was done during the winter months of 1967 and 1968 at the University of Manitoba and at the Mines Branch. Mapping was carried out to the scale of 16 inches to 1 mile on enlargements of air photos Nos. A 18881-218 and -220. No correction for distortion was made on the final maps. Structural data was recorded in the field on a computer oriented field data sheet (Haugh et al., 1967) and contoured stereograms were prepared using the computer. Oriented specimens of all rock types were collected throughout the map area and important structural features were photographed or sketched. In the laboratory a number of specimens were cut perpendicular and parallel to prominent s-surfaces and lineations. Thirty-two oriented thin sections were prepared and examined.

General Geology

The Long Lake map-area is located on the southern flank of the Rice Lake greenstone belt in the Superior structural province of the Canadian Shield. The belt is composed of the Rice Lake Group of metamorphosed Archean sedimentary and volcanic rocks, which extend northwest from the Ontario-Manitoba boundary to Manigotogan on Lake Winnipeg (Fig. 1). The Greenstones are flanked by granitic rocks on the northeast and by the English River granites and gneisses on the southwest (Dwibedi, 1966). The Rice Lake Group has been intruded by numerous dykes and sills of basic and intermediate plutonic rocks. A quartz diorite batholith is located one half mile north of Long Lake (Paulus, 1968).

In the Long Lake area all rock units belong to the Rice Lake Group. They consist of meta-sedimentary rocks and metamorphosed volcanic rocks (both clastics and flows) which have been intruded by dykes and sills of quartz diorite, quartz-feldspar porphyry, gabbro and diabase. The eastern part of Long Lake is in the centre of the map-area and all rock units trend west, parallel to the elongate shape of the lake (Map 1). Along the north shore of the lake there is a narrow belt of arkosic greywacke interbedded with chert and iron formation and basic volcanic flows, and intruded by numerous dykes and sills. A unit of intermediate to acid volcanic breccias and tuffs strikes through the lake and is best exposed on the east shore and on a number of islands. Interbedded greywacke, shale, chert and iron formation outcrop on a string of islands and peninsulas along the south shore of the lake. The area south of the lake consists of

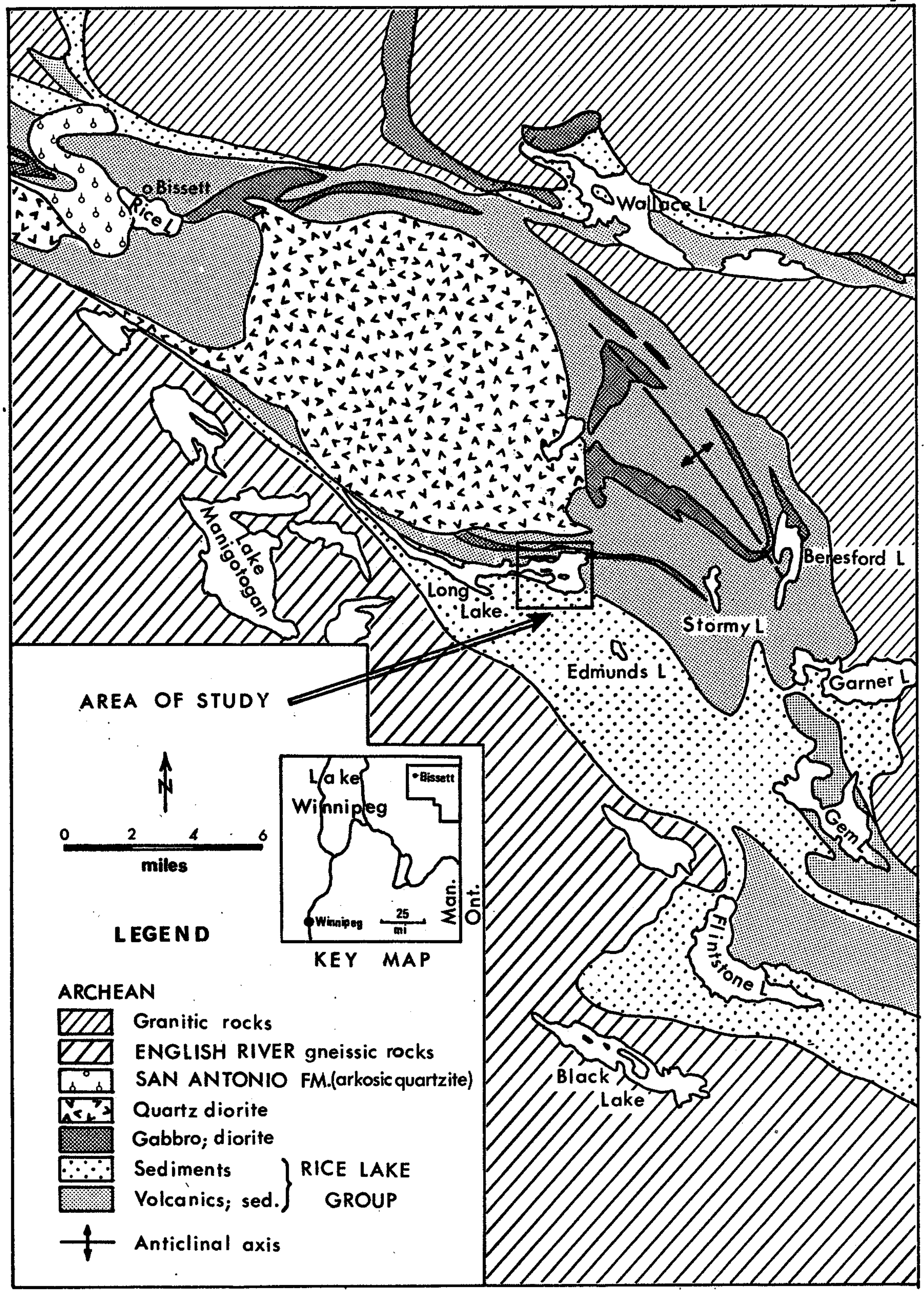

Figure 1. Location map and general geology, (after Turek, 1968).

quartzose greywacke. Only a few narrow dykes occur in the central and southern parts of the map-area.

The Beresford Lake area which includes the Long Lake area was mapped in 1938 by C. H. Stockwell (G. S. C. Map 809 A). In the marginal notes Stockwell indicated that sedimentary rocks rest conformably on acid to intermediate volcanic rocks and that tops are generally to the south. However he did not separate arkosic greywackes from pyroclastic rocks north of Long Lake. South of the lake he recognized that

> grain variations indicate that (sedimentary) rocks have been folded into a succession of closely compressed isoclinal folds

and that the present area of study lies on the southwest flank of a large anticlinal structure.

All rock types have been subject to regional metamorphism of the greenschist facies, and many have suffered considerable dynamic metamorphism. Quartzo-feldspathic rocks have preserved most of their primary structure but basic and pelitic rocks have been converted to chlorite and sericite schist. In shear zones a few bands of mylonitic schist have been developed.

The map-area is characterized by strong westerly linear trends expressed by the elongate shape of the lake, narrow bays and islands and westerly trending ridges and depressions adjacent to the lake. These features can be readily related to a west-striking, steeply dipping foliation. This foliation is ubiquitous throughout the Long Lake area. It is defined by a strong rock cleavage caused by the tabular alignment of platy minerals. Several types of linear structures are developed on the foliation surfaces and the foliation is occasionally kink folded.

Contacts between formations, beds and igneous bodies strike west to northwest and generally have steep dips. In the southern part of the map-area bedding contains numerous major and minor folds. A large number of veins occur throughout the area. These veins generally trend parallel to the regional foliation but a few veins are folded throughout the entire area.

CHAPTER II

STRATIGRAPHY

The formational names used in this thesis have not been published previously. They are presented here to facilitate the description of the structures of the rocks in the Long Lake area. All units belong to the Rice Lake Group (Stockwell, 1945) and all appear to be conformable.

In the map-area rocks can be divided into three formations. A west-trending unit of arkosic greywacke which underlies the area north of Long Lake has been named the Stormy Lake Formation after a small lake east of the map-area. This unit faces south and overlies a unit of basic volcanic rocks. The succession of pyroclastic and epiclastic volcanic rocks also trends west and overlies the Stormy Lake Formation. It outcrops on the east shore of Long Lake and on some of the islands. This unit has been called the Long Lake Formation. The overlying greywacke unit south of the lake has been named the Edmunds Lake Formation after a small lake southeast of the map-area. The geographic location of the lakes is given in Figure 1, and the distribution of the formations is depicted on Map 1.

Stormy Lake Formation (Map Unit 1)

The oldest rocks in the map-area are the arkosic

TABLE I

FORMATIONS

Group	Formation	Map Unit	Lithology
Rice Lake	Edmunds Lake	3c	arkosic sandstone, pebble conglomerate
		3b	quartzose greywacke
		3a	arkosic greywacke, shale, chert, iron formation
	Long Lake	2d	volcanic breccia and tuff breccia of intermediate to acidic composition, minor sandstone
		2c	crystal tuff of intermediate composition
		2b	volcanic breccia and tuff breccia of intermediate composition, minor shale and sandstone
		2a	volcanic breccia of intermediate to basic composition, minor sandstone
	Edmunds Lake	1d	andesite or basalt
		1c	volcanic pisolite
		1b	iron formation
		1a	arkosic greywacke, chert, arkose
Intrusive Rocks		5	quartz-feldspar porphyry, quartz diorite
		4	gabbro, diabase, diorite

greywackes interbedded with chert, iron formation, volcanic pisolite and basic volcanic flows which are exposed on the low-lying outcrops north of Long Lake. Most of the high outcrops in this vicinity consist of meta-gabbro or quartz-feldspar porphyry sheets which have been intruded into the Stormy Lake Formation.

The Stormy Lake Formation is characterized by the following lithologies:

Arkosic greywacke interbedded with chert and arkose (map unit 1a);

Banded magnetite rich iron formation (1b);

Volcanic pisolite (1c);

Massive and pillowed andesite or basalt (1d).

The greywacke (1a) is grey-green to dark green on weathered surfaces and the interbedded chert is light grey. In a number of the coarser beds the grain size grades from coarse at the bottom to fine at the top. The arkose is massive and is difficult to distinguish from the quartz-diorite sills. The iron formation (1b) is black and serves as marker beds. There are at least three units of iron formation, each of which consists of one or two 12 inch beds. There is a single unit of volcanic pisolite (1c) which is up to 20 feet thick. It is a tuffaceous sedimentary rock which is composed of small ovoid bodies ranging from 2 to 10 mm in diameter. Two or three basic volcanic flows (1d) are intercalated with the sedimentary rocks. The maximum thickness of a single flow is 75 feet. The dark green colour of these rocks suggests that they are andesites or basalts. They are usually highly schistose.

Long Lake Formation (Map Unit 2)

The Long Lake Formation consists of layered and massive clastic volcanic rocks. The formation is exceptionally well exposed in the map area; the east end of Long Lake was chosen as type section. These rocks form large high outcrops on the east shore of the lake, north and south of the Narrows, and on many of the islands. The formation is light green on weathered surfaces. It consists of predominantly pyroclastic rocks which can be divided into volcanic breccia, tuff breccia and sand-size crystal tuff. There are subordinate amounts of epiclastic rocks which consist of tuffaceous sandstone and shale. Mappable units of the Long Lake Formation comprise the following lithologies:

Volcanic breccia with intermediate to basic fragments (map unit 2a);

Volcanic breccia (Fig. 2) and tuff breccia (Fig. 3) with intermediate fragments (map unit 2b);

Crystal tuff (map unit 2c);

Volcanic breccia and tuff breccia with intermediate and acidic fragments (Figs. 4 and 5, map unit 2d).

Basic fragments are confined to the basal zone of

Figure 2. Deformed volcanic breccia of intermediate composition, map unit 2c, Long Lake Formation.

Figure 3. Deformed tuff breccia of intermediate composition, map unit 2c, Long Lake Formation. Fragments are outlined with marker pen.

Figure 4. Deformed tuff breccia with intermediate and acidic fragments, map unit 2d, Long Lake Formation. Note two directions of fracture cleavage.

Figure 5. Deformed tuff breccia with intermediate and acidic fragments, map unit 2d, Long Lake Formation. Note foliation parallel to long dimension of fragments.

the formation and to several beds north of the Narrows. Breccias with intermediate fragments (2b) and the crystal tuff (2c) are interlayered. However, the crystal tuff is confined to the east shore of the lake and to several islands and is absent at the Narrows. Acidic fragments occur only near the top of the formation. Thin lenses of tuffaceous sandstone and shale occur sporadically throughout the Long Lake Formation.

Edmunds Lake Formation (Map Unit 3)

Conformably overlying the Long Lake Formation is the Edmunds Lake Formation which consists of quartzose greywacke in the centre of the unit and of greywacke, shale, chert and iron formation at the base of the unit. This formation outcrops south of Long Lake and on several islands but is especially well exposed in an area south of the lake which has been burned over by a forest fire. The colour of weathered surfaces varies from buff for the sandy layers to dark grey for the shaly layers.

The part of the Edmunds Lake Formation which is exposed in the map-area is characterized by the following lithologies:

Interbedded arkosic greywacke and shale with isolated lenses of chert and iron formation (map unit 3a);

Quartzose greywacke with isolated beds of shale and sandstone (map unit 3b);

Massive arkosic sandstone and pebble conglomerate (map unit 3c).

Greywacke, shale, chert and iron formation (3a) overlie the Long Lake Formation and the entire assemblage varies in thickness from less than 100 feet in the western part of the map-area to over 300 feet in the eastern part of the area. The lower 50 feet of this unit consist mainly of shale and near the top of the unit greywacke predominates. These rocks are well bedded and many beds grade from sandstone to shale. The composition of clasts in the sandy beds ranges from predominantly feldspar at the base of the unit to predominantly quartz at the top.

Shale and greywacke (3a) grade upwards into quartzose greywacke (3b). These strata are vertically and laterally uniform. However, they contain several beds of coarse arkosic sandstone (3c) about 1000 feet south of Long Lake and there is an isolated occurrence of conglomerate (3c) farther east. The greywacke is well bedded and most beds are graded. Quartz and feldspar clasts comprise 25 to 75 per cent of the rock and quartz-feldspar ratios range from 5:1 to 10:1. The matrix contains sericite, biotite and minor amounts of chlorite, calcite and iron oxides.

Intrusive Rocks

Over 50 per cent of the area north of the lake is underlain by intermediate and basic intrusions whereas south of the lake only a few narrow bodies of diabase have been found.

The basic intrusions are concordant with the bedding and vary in thickness from 1 foot to 500 feet. They are of mainly gabbroic composition. Only the large sill at the north shore of the lake is partly dioritic.

The basic intrusive rocks are cut by younger dykes of quartz-feldspar porphyry and quartz diorite which are generally subparallel to the bedding. Many of them show chilling against the gabbroic bodies and occasionally quartz-diorite dykes have porphyritic margins.

Veins

Several types of veins occur throughout the map-area. The vein material is commonly quartz but a few veins consist of calcite and some quartz veins have accessory calcite and chlorite. In the northern part of the area some larger veins near a white quartz stockwork contain accessory pyrite. Elsewhere, quartz veins are typically smoky black and barren.

CHAPTER III

METAMORPHISM

Thirty-two oriented thin sections were prepared from specimens of the major rock types. Most sections were cut parallel to the mineral lineation and perpendicular to the foliation.

Petrography

The mineral assemblage of the Stormy Lake and the Long Lake Formations is quartz, sodic plagioclase, sericite, chlorite, with accessory calcite, epidote magnetite and leucoxene. The same assemblage with the addition of up to 20 per cent biotite is found in the Edmunds Lake Formation.

Textures indicate that the biotite is not stable. Flakes are generally bent and fragmented. They are strained and their edges are often bleached. Chlorite is pseudomorphic after biotite or party replaces it (Fig. 6). Altered flakes of biotite lie in the plane of the foliation but relict patches of well shaped flakes form an interlocking texture with quartz (Figs. 6, 7). These flakes are darker brown than the fragmented biotite and their margins are not bleached. However, some of them are partly replaced by chlorite.

Sericite always has a pronounced tabular alignment. It is curved around phenocrysts and clastic grains, to form

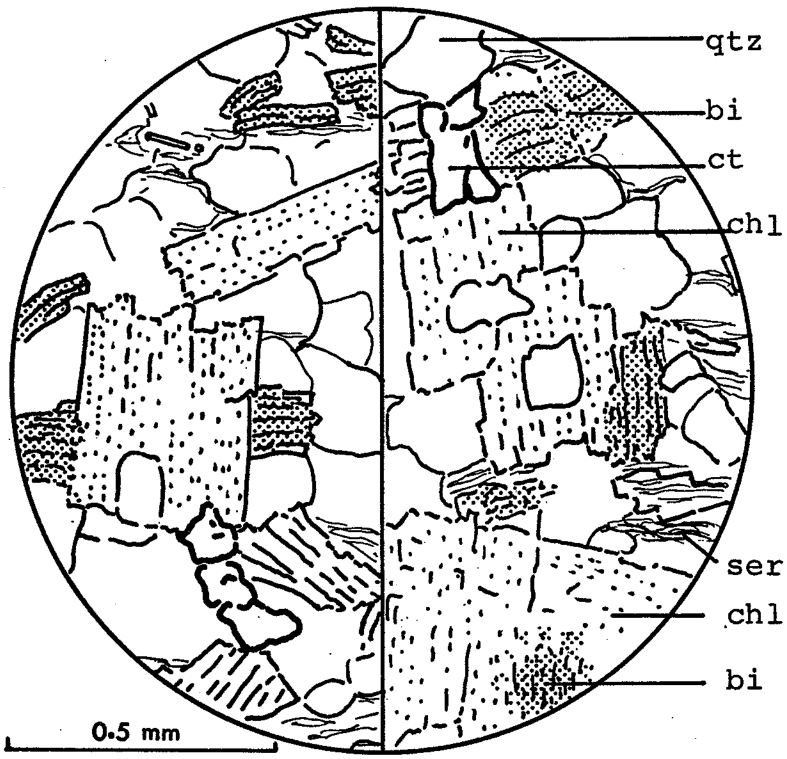

Figure 6. Late metamorphic chlorite and calcite. Biotite is strained and relict patches of biotite occur in chlorite (lower right). Specimen 1221, Edmunds Lake greywacke, cut perpendicular to foliation.

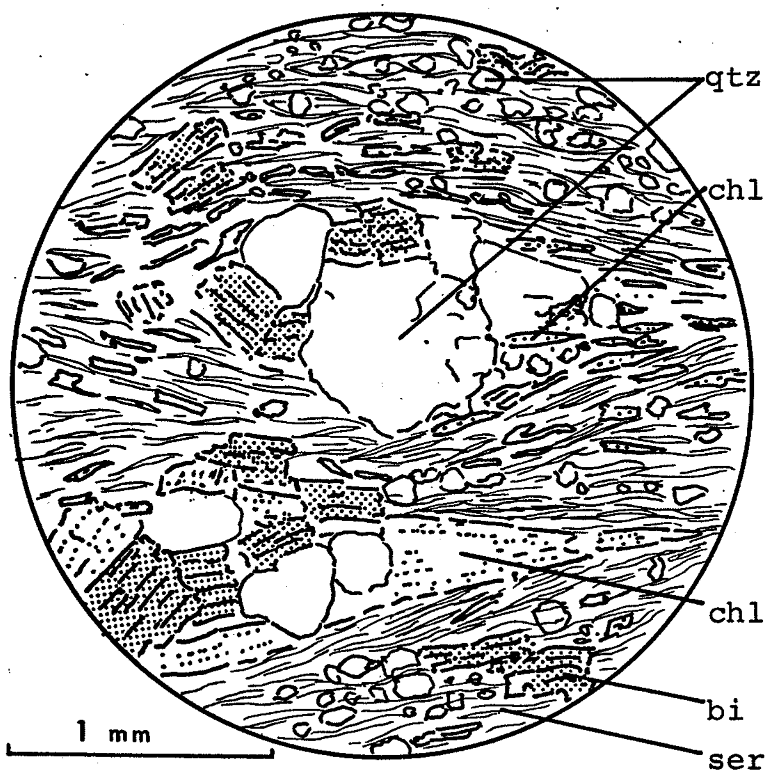

Figure 7. Augen structures; Sericite curves around larger mineral grains and chlorite grows in pressure shadows. Specimen 1153, Edmunds Lake greywacke, cut perpendicular to foliation, and parallel to lineation.

augen structures (Fig. 8). Chlorite has a linear and tabular alignment (Figs. 9, 10). Large well formed blades of chlorite grew in the pressure shadows of competent grains and form part of a mineral lineation (Figs. 9, 11). Other plates which are probably pseudomorphic after biotite have no preferred alignment (Fig. 6). Actinolite occurs in small clusters of needles cutting across the other grain boundaries with a fabric parallel to the chlorite lineation (Fig. 11).

Quartz grains and feldspar phenocrysts appear to be primary minerals and are generally unaltered. Subhedral plagioclcase is occasionally still zoned. In well foliated specimens with cataclastic textures large grains of quartz and feldspar are partly crushed and rounded (Fig. 8). Highly sheared rocks have flaser structures in which flattened spindles of crushed material have a tabular and linear alignment.

Discussion

The mineralogy and textures of these rocks indicate that all units have been subjected to greenschist facies regional metamorphism. However, biotite is restricted to the Edmunds Lake Formation and its textures suggest that it is unstable. Biotite appears to have formed in the quartz-albite-epidote-biotite subfacies. Sericite, chlorite and calcite which form the regional foliation seem to have

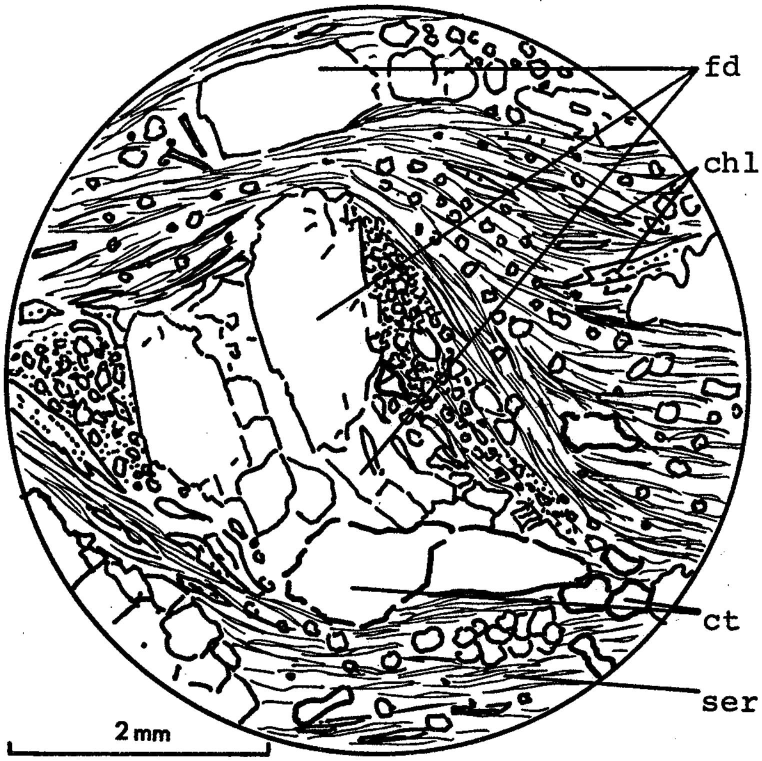

Figure 8. Augen structure. Crushed material and calcite occur in the pressure shadows. Specimen 1395, Long Lake tuff breccia, cut perpendicular to foliation and parallel to lineation.

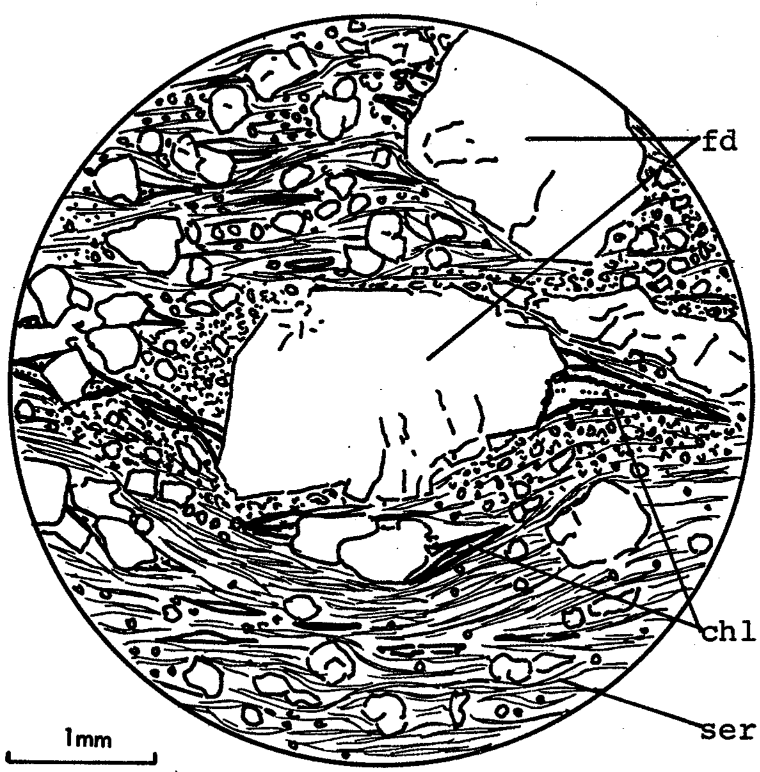

Figure 9. Augen structure. Crushed material and chlorite occurs in the pressure shadows. Specimen 1019, Long Lake tuff breccia, cut perpendicular to the foliation and parallel to the lineation.

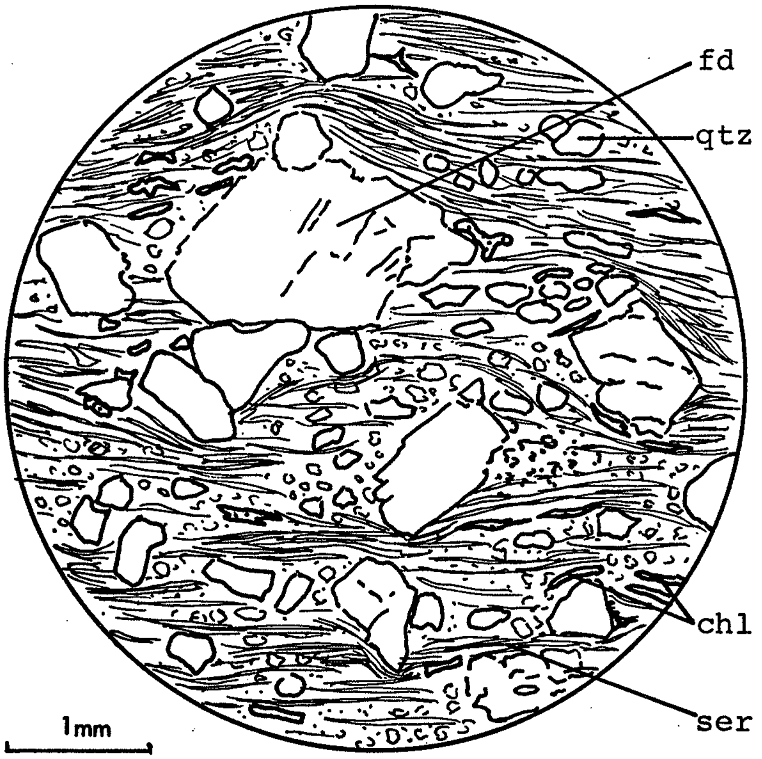

Figure 10. Cataclastic and schistose textures. Specimen 1019 (as Figure 9), cut perpendicular to lineation and foliation.

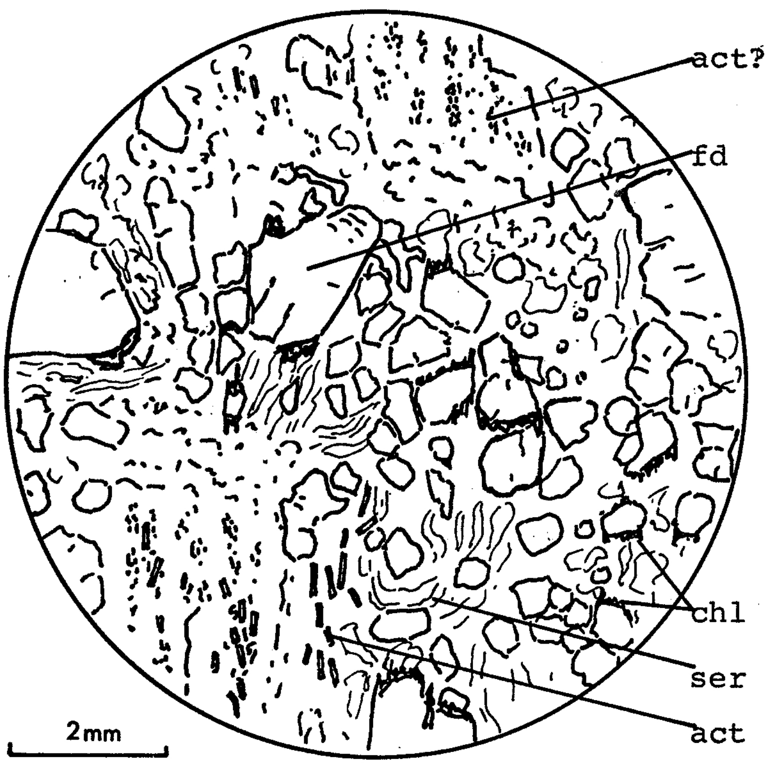

Figure 11. Mineral lineation of acicular actinolite and bladed chlorite. (Lineation is indicated from top to bottom of page.) Sericite curves around mineral grains. Specimen 1019 (as Figure 9), cut parallel to foliation.

developed retrogressively during the cataclasis. Biotite was apparently partly altered to chlorite during the retrogression.

CHAPTER IV

STRUCTURE

This chapter presents a description of the tectonic elements and diastrophic structures in terms of their distribution in the Long Lake area and their characteristics as observed in the field and in thin sections. Evidence for the relative ages of s-surfaces, lineations and folds is presented and is used as a basis for a system of structural nomenclature.

Structural Elements

Bedding

Bedding is preserved in all but the most highly sheared rocks. The Stormy Lake Formation is well bedded to massive. Light coloured cherty layers are usually most conspicuous in the field. In a number of sandy beds grain variations from coarse on the bottom to fine at the top are evident. The Long Lake Formation is generally massive but there are several lenses of sandy and conglomeratic material near its base. Lenses of basic tuff and contacts between flow units and cooling units are considered bedding planes in the main part of this formation. The Edmunds Lake Formation is well bedded and the direction of facing can be determined from graded bedding on most outcrops.

Veins

Veins occur throughout the map-area. They are often parallel to the foliation or to the bedding but some are oriented obliquely to these s-surfaces. The veins vary in width from 1/8 inch to over 12 inches; they pinch and swell and are often discontinuous.

Foliation

There is a well developed penetrative foliation throughout the entire map-area. On outcrops it appears as a tabular mineral alignment or as a set of closely spaced, subparallel fractures that strike west and dip steeply to the north. Occasionally, the foliation occurs as a slip cleavage along which the bedding is displaced (Figs. 16a, 16d, 19). Apparent lateral movement can be dexteral or sinistral.

The foliation is not uniformly developed everywhere. Crystal tuff and tuff breccia in the centre of the Long Lake Formation are usually weakly foliated and basic rocks in the Stormy Lake Formation are often well foliated. Shear zones occur where the foliation is exceptionally well developed. The most prominant shear zone trends east-southeast from the Narrows (Map 2). Another shear zone follows the north shore of the lake, south of a prominent gabbro sill. Highly sheared rocks are highly fissile and always cleave along the foliation. The bedding is parallel to the foliation in these rocks. Weaker shear zones occur along the upper and lower contacts of the Long Lake Formation and along several dykes in the northern part of the map-area. The rocks are moderately fissile in these vicinities.

In thin section the foliation appears as the preferred plane of orientation of sericite and chlorite. Clastic grains and phenocrysts are slightly rounded and they are partly crushed (Fig. 7). In weakly foliated specimens mortar texture is common and in highly sheared rocks flaser structure and zones of crushed material occur (Fig. 8). Sheared basic rocks have an extremely well developed lepidoblastic texture of chlorite with narrow lenses of calcite lying in the plane of the foliation. A specimen taken from one of the shear zones is a mylonitic schist. It is a finely laminated flinty rock in which the platy minerals have a perfect tabular alignment and other minerals are crushed.

Strain-slip Cleavage

A non-penetrative strain-slip cleavage occurs sporadically where the regional foliation is well developed. It dips steeply and has a variable strike. On outcrops it appears as a set of slip surfaces cutting the foliation or as narrow zones sharply flexuring the foliation (Fig. 14). Cleavage planes are from 1/8 inch to 1 inch apart. In one thin section the strain-slip cleavage appears as narrow kink bands in the foliation. Within the kink zones calcite has recrystallized and fills small tension gashes where the foliation has been dilated. Where strain-slip was intense the platy minerals are oriented parallel to the new cleavage.

Fracture Cleavage

A set of short fractures which are from 1/2 inch to several inches apart occur in the competent layers and in the competent fragments in the shear zones. There is no apparent lateral movement on these fractures but they are slightly dilated and are occasionally filled with calcite. This cleavage is often oriented perpendicular to the foliation or at about 45 degrees to it (Figs. 4, 5).

Joints

Joints occur in all rock types but they are best developed in the intermediate volcanic rocks and the intrusive rocks. There appear to be three sets of joints in the map-area. One set, which is spaced from 3 inches to 3 feet, has a steep dip and strikes roughly perpendicular to the foliation. Two, more widely spaced sets of joints dip steeply and strike about 45 degrees to the foliation. Other joints have an apparently random orientation.

Mineral Lineations

Throughout the map-area small patches of chlorite, needles of actinolite and crushed grains of quartz and feldspar have a tabular and linear alignment in the plane of the foliation. Pieces of broken crystals tend to accumulate in the pressure shadows of the larger grains and blades of chlorite and crystalloblastic calcite grow preferentially in the same pressure shadows (Figs. 7 to 11). Flakes of sericite often curve around the large grains and give the rocks a distinct augen structure with a linear fabric.

Fragment Lineations

Volcanic fragments and sedimentary intraclasts are deformed into triaxial ellipsoids throughout most of the map-area. The intermediate axes of these ellipsoids appear to lie in the plane of the foliation and the long axes appear to be subparallel to the mineral lineation which lies in the foliation. An attempt was made to measure the long axes independently where fragments rich in chlorite and calcite have been weathered out and form ellipsoidal holes at the edge of Long Lake. However, the weathering process may have been affected by the foliation such that small angles between the long axes of the fragments and the plane of the foliation are not apparent. Nevertheless, there is a good correspondence between the attitude of the mineral lineations and the pitch of the apparent long axes of the fragments in the foliation. To reduce the reading error and the error introduced by the original shape of the fragments, an average of five or ten attitudes was taken on each outcrop. The fragment lineation is defined by the long axes of ellipsoidal holes and is plotted on Map 2.

The attitude of the plane containing the long and the intermediate axes of the ellipsoidal holes was measured by aligning a clip board with the longest horizontal direction and the plunging long axis. The poles to these planes are the short axes of the ellipsoidal holes.

Slickensides

Slickenside lineations were measured on many well developed foliation surfaces. There are two sets, one of which is parallel to the mineral lineations and another set of finer slickensides which is almost horizontal. The plunging slickensides occur in the entire area; the shallow slickensides are restricted to the strongly foliated rocks.

Folds

Folds in the Foliation

Where the regional foliation is well developed it is folded into a set of steeply plunging kinks and small concentric folds. These structures are most abundant in the shear zone which runs from the Narrows to the mouth of the Manigotogan River. However, a few kinks are found scattered throughout the entire map-area. They are minor structures and generally have a relief of less than 6 inches (Fig. 12). One exceptionally large kink fold with 6 feet relief occurs in the Edmunds Lake greywacke. In the schistose rocks in which kinks are most abundant the relief is usually 1 or 2 inches. Kink bands often die out after a short distance and their right sections[1] often have a concentric style. Their hinges are sharp but some true concentric folds with the same orientation as adjacent kinks have been found (Figs. 13c, 13d). There are a few chevron style folds but most kinks are asymmetrical. Right-hand kink bands (with Z asymmetry) strike northeast and left-hand kink bands (with S asymmetry) strike northwest. Where they occur together conjugate folds are formed (Fig. 13 a-c).

Folds in Veins

Many veins are subparallel to the foliation and are not folded but veins which are oblique to the foliation are frequently folded in all parts of the map-area. These folds are small-scale structures which have a relief ranging from a fraction of one inch to several feet. Each vein defines a parallel fold with little thickening in the hinge area (Fig. 15a). However, several parallel veins that have been deformed together have a nearly similar profile (Fig. 17).

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[1]Sections normal to the hinge lines.

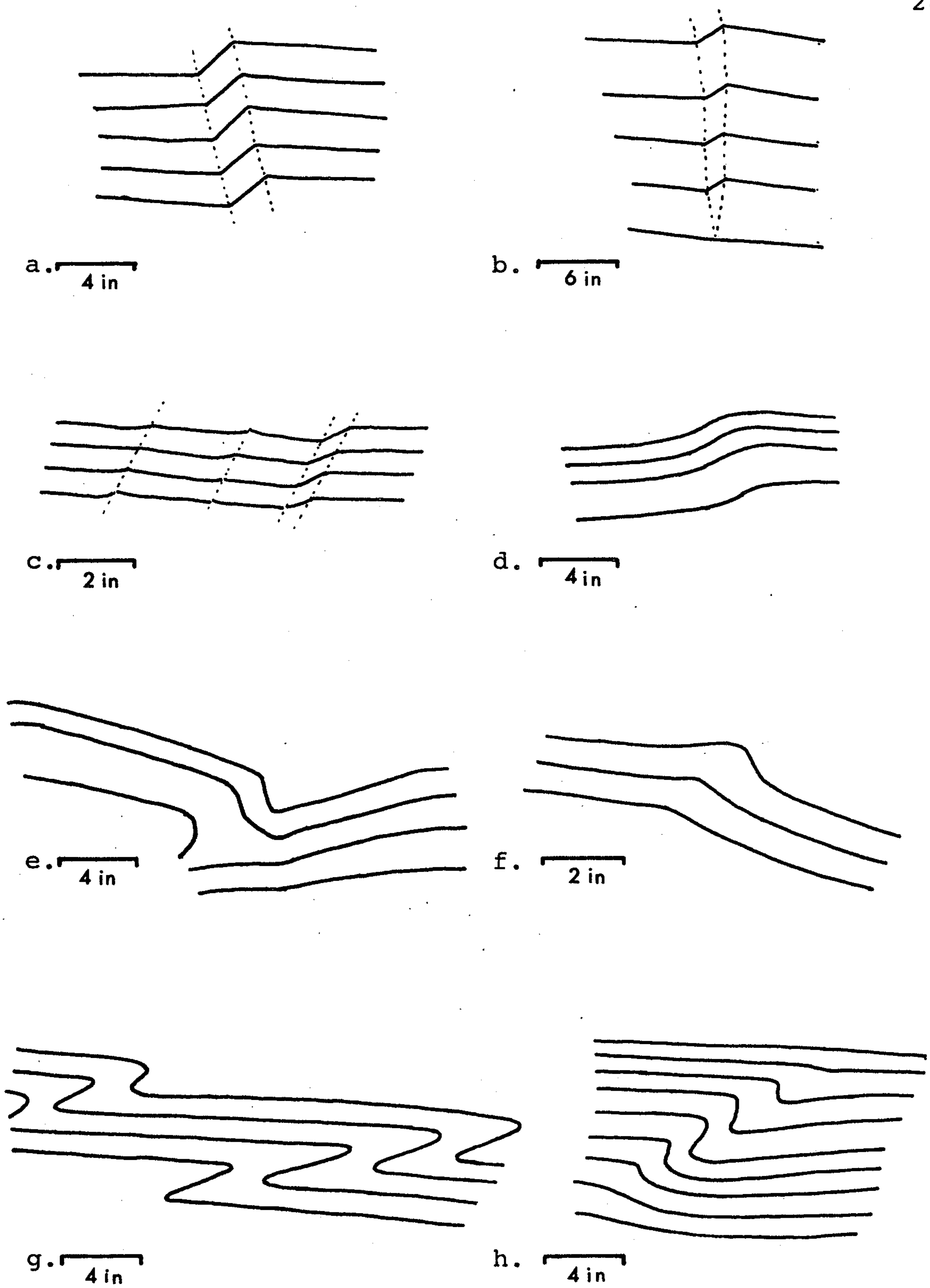
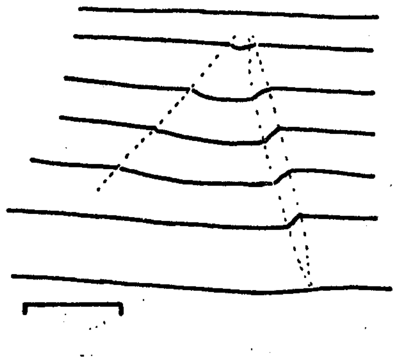
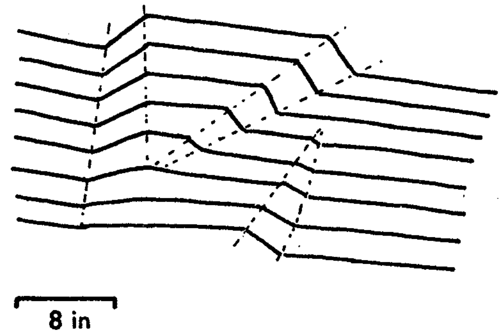


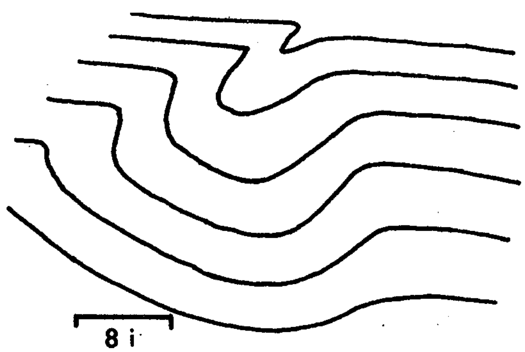
Figure 12. Right sections of kink folds in the foliation.



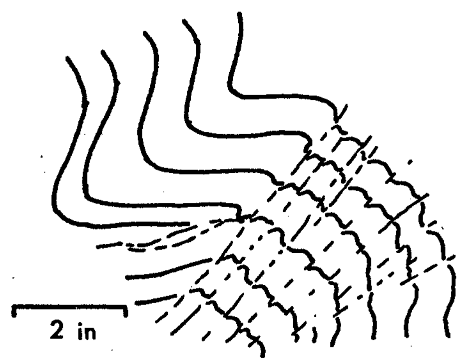
a. Conjugate kink folds.



b. Conjugate kink folds.

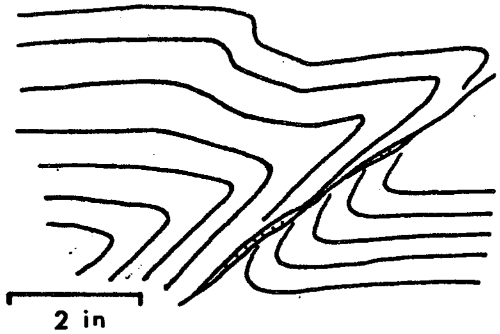


c. Conjugate concentric fold.

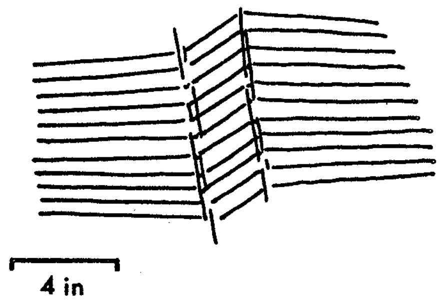


d. Concentric fold with axial plane strain-slip cleavage.

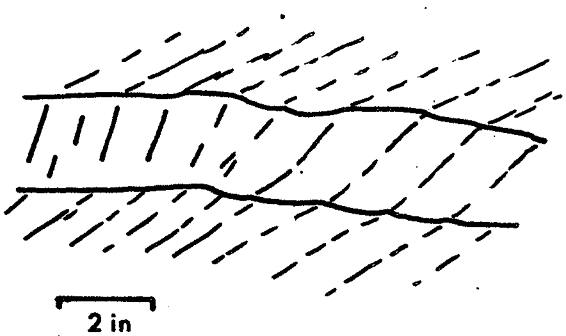
Figure 13. Right sections of third generation structures in the foliation.



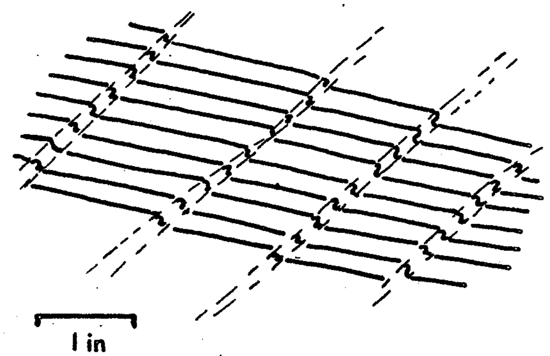
a. Kink fold with axial plane cleavage containing calcite.



b. Kink fold with axial plane cleavage.

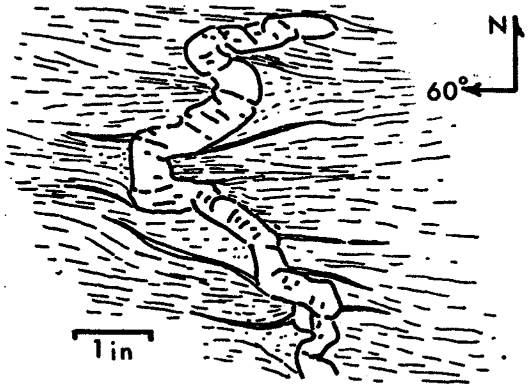


c. Strain-slip cleavage passing into fracture cleavage in a competent fragment.

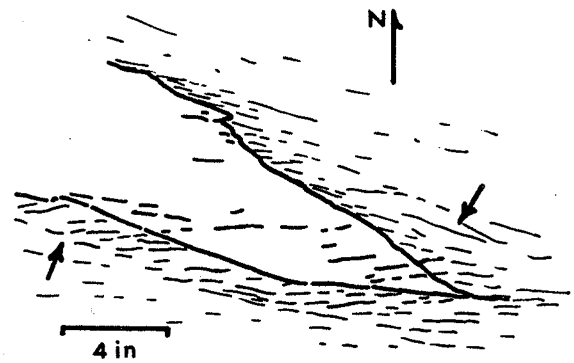


d. Coarse strain-slip cleavage cutting foliation.

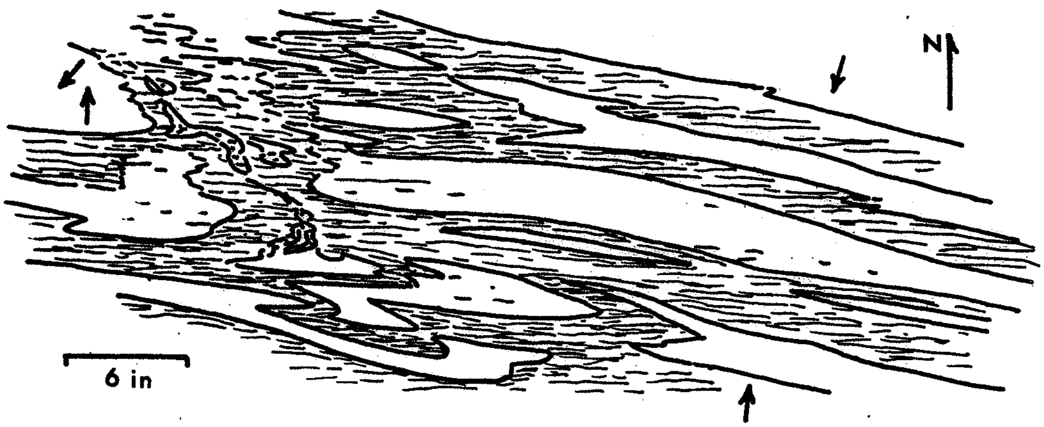
Figure 14. Right sections of third generation structures in the foliation.



a. Quartz vein in greywacke folded during the second period of deformation. Plunge is to the west at 60°. The foliation strikes west, parallel to the axial planes of the folds.



b. Tight first generation fold in quartz rich greywacke (light) and shaly greywacke (dashed). Dashes indicate foliation transecting the axial surface. Tops are indicated by arrows. See also Figure 21.



c. Hook shaped interference structures of first and second generation folds in quartzose greywacke (light) and shaly greywacke (dashed). Dashes indicate foliation parallel to axial planes of the cross folds. Tops are indicated by arrows.

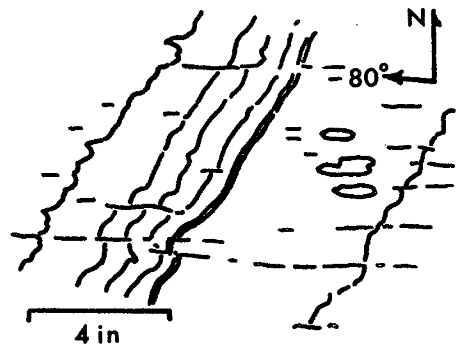
Figure 15. Oblique sections of first and second generation folds in Edmunds Lake greywacke.

The angle of closure and the symmetry of the folds in the veins is highly variable. Their axial planes strike west and dip steeply to the north, parallel to the regional foliation.

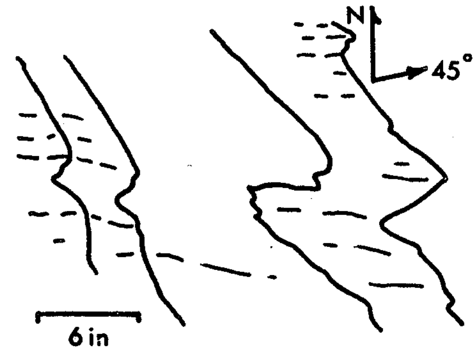
Folds in Bedding

In the Stormy Lake and the Long Lake Formations the bedding is only gently warped but the Edmunds Lake greywacke is isoclinally folded. In the burned-over area the greywacke is disposed in a series of tightly appressed synclines and anticlines which can be mapped where the direction of facing of the graded beds is apparent. The axial surfaces of these folds are 25 to 500 feet apart. Isoclines occur also in the southeast and southwest corners of the map-area (Map 2). The limbs and axial surfaces of these folds are curviplanar and strike west or northwest and dip northeast. The attitudes of opposite limbs differ by only a few degrees.

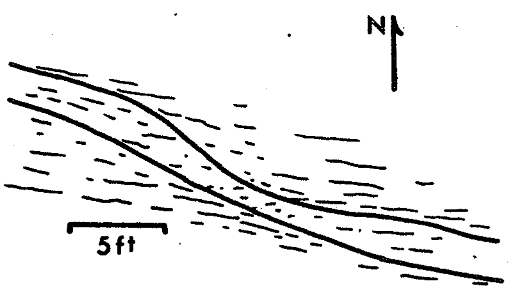
Minor folds in the bedding are also restricted to the Edmunds Lake Formation. These minor folds are nearly similar, their relief is less than 3 feet and they have variable angles of closure. Their axial planes strike west and dip steeply to the north, parallel to the regional foliation. These characteristics are illustrated in Figures 16a, 16b, 18 and 19. They are predominantly Z-shaped structures ie. fold pairs with dextral asymmetry such as in Figure 18. Their plunge varies but it is



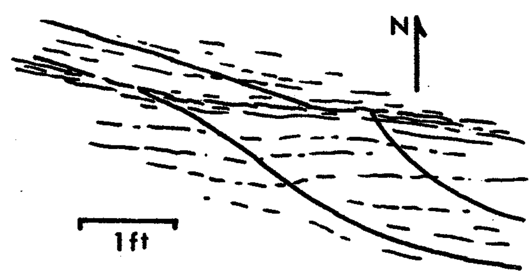
a. Second generation minor fold and discrete displacements in the bedding of greywacke. The axial plane foliation (indicated by dashes) is the slip surface. The horizontal elongation of the intraclasts is parallel to its strike.



b. Typical second generation fold in greywacke. The style is nearly similar and the axial planes are parallel to the foliation (indicated by dashes).



c. Pich structure in greywacke is probably a second generation fold. The foliation is indicated by dashes. The plunge is unknown.



d. Swell structure in greywacke is probably a second generation fold with similar style. The foliation is indicated by dashes. The plunge is unknown.

Figure 16. Oblique sections of second generation folds in Edmunds Lake greywacke.

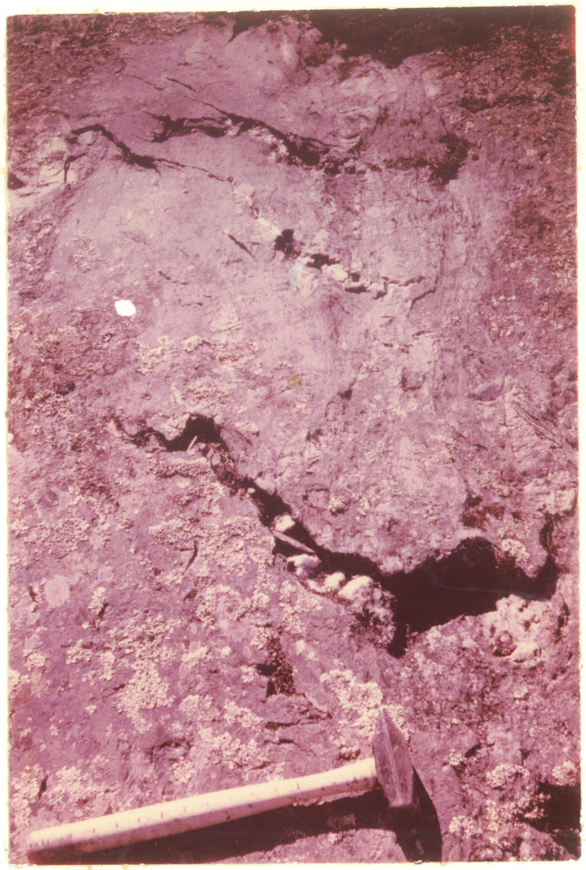


Figure 17. Second generation minor fold in partly eroded quartz veins, Long Lake Formation. Note nearly similar profiles and axial plane foliation (top to bottom of photograph). The plunge is towards the top of the photograph.

Figure 18. Second generation minor folds in bedding (outlined with marker pen), Edmunds Lake Formation. Foliation and elongate fragments (outlined) trend left to right.

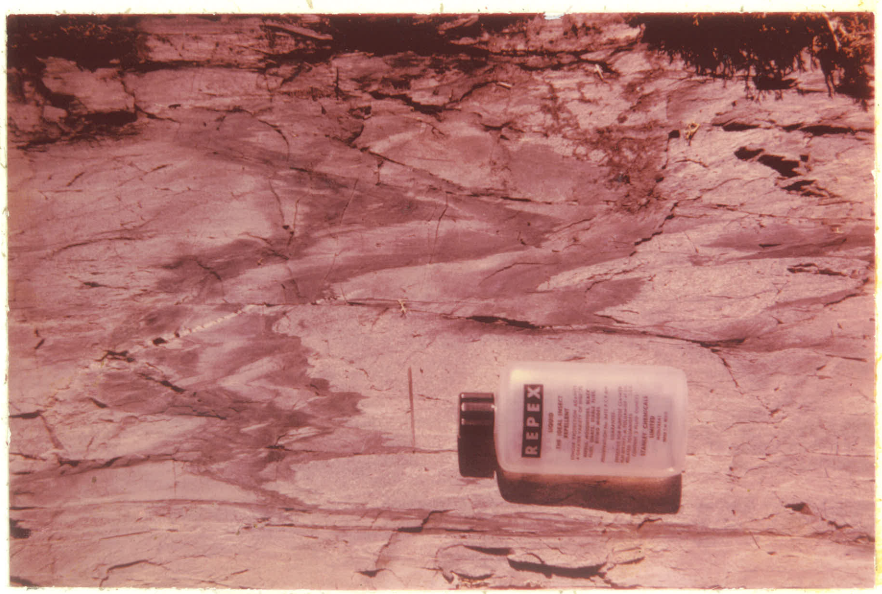


Figure 19. Second generation minor folds in bedding, Edmunds Lake Formation. Note axial plane foliation, displacements along foliation, and feathery outline of bedding.

predominantly at a moderate angle towards the east. Where the bedding is parallel to the foliation no folds occur in the bedding. Where the angle between the foliation and the bedding is small, such as on the north shore of the burned-over area, a type of pinch and swell structure occurs (Figs. 16c and 16d).

South of the Narrows, just east of the power line, small hook-shaped minor structures seem to be part of an interference pattern that was formed by cross folding (Fig. 15c). These structures occur in the hinge area of a very narrow isoclinal fold about 20 feet south of the trough line of a major isocline. Minor similar folds are developed in the bedding on the same outcrop. The hook structures occur where the small similar folds interfere with the narrow isoclinal folds.

Diamond shaped structures in the centre of the burned-over area also suggest cross folding (Fig. 20) as do the axial surfaces of the isoclinal folds which have the shape of a fold pair with Z asymmetry. The traces of the axial surfaces of the cross-folded isoclines are depicted on Map 2 on which their open Z-shape is apparent. The relief of the cross-fold pair is about 750 feet. There is an abundance of small similar folds on the limbs of the structure. Small Z-shaped fold pairs occur on the long limbs and S- and Z-shaped fold pairs occur on the common limb. Where the bedding dips and faces northeast small

Figure 20. Diamond shaped structures, probably formed by interference between first and second generation folds, Edmunds Lake Formation. Plunge is to top of photograph.

Figure 21. Foliation cutting obliquely across early closure (see also Fig. 15b), Edmunds Lake Formation.

synclines and anticlines are developed but where the bedding is overturned and faces southwest small synclinal antiforms and anticlinal synforms are developed.

Relative Age Relationships

The regional foliation is the most prominant s-surface in the Long Lake area. Its development is a convenient time indicator in the evolution of the diastrophic structures in the area. The joints, the kinks and the non-penetrative cleavages postdate its development. One generation of folds was formed during its development and another generation of folds preceded it.

Structures Postdating the Foliation

The joints, the fracture cleavage and the strain-slip cleavage all cut across the foliation. The joints transect all other structural elements and the majority is probably the youngest structural element in the Long Lake area. The non-penetrative cleavages postdate the foliation and the horizontal slickensides are superimposed upon all other lineations.

These late structural elements are geometrically related to the kink folds and to the small concentric folds in the foliation. The strain-slip cleavage is in the axial plane of the concentric folds and it is subparallel to the kink zones (Figs. 13d, 14a, 14b). Both the kink bands and the strain-slip cleavage form a conjugate set. Occasionally the fracture cleavage forms a conjugate set parallel to the strain-slip cleavage (Figs. 4, 5). The horizontal slickensides are often perpendicular to the axes of the kink folds. The fact that the late structural elements and the kinks are almost entirely restricted to the same zone which runs from the Narrows to the mouth of the Manigotogan River suggests that they are interrelated features.

Structures Related to the Foliation

The foliation is geometrically related to the mineral lineations, to the plunging slickensides to the deformed-fragment lineations and to the similar folds in the bedding and in the veins. All these structural features are found throughout the entire map-area and all occur most frequently where the foliation is exceptionally well developed. The mineral lineations and the slickensides are in the foliation surface and they are parallel to the pitch of the apparent long axes of the deformed fragments. The axial planes of the folds are parallel to the foliation and displacements in the layering are along the foliation. In the shear zones the bedding is parallel to the foliation.

Structures Predating the Foliation

The foliation cuts across the axial planes of some of the isoclinal folds in the bedding of the Edmunds Lake Formation. A closure exposed on the south shore of Long

Lake is cut obliquely by the foliation indicating that the tight folds were formed before the foliation was developed (Figs. 15b, 21). In the centre of the burned-over area the axial planes of the small similar folds in the bedding cut across the axial surfaces of the isoclinal folds indicating that the isoclines were formed before the similar folds, related to the foliation, were developed. The similar folds were superimposed upon the isoclines and the isoclines were warped into an open Z shape.

Summary

The relative age relationships of the structural features at Long Lake suggest that there are three generations of folds developed during three separate periods of deformation. During the first period of deformation the Edmunds Lake Formation was tightly folded. During the second period of deformation the Edmunds Lake Formation was cross folded and small similar folds were formed in the veins throughout the entire area. A penetrative axial plane foliation was developed at that time. During the third period of deformation kink folds and small concentric folds were formed in the foliation and several types of non-penetrative cleavages were developed.

The age relationships of the structural features and descriptions of folds are given in Table II.

TABLE II

AGE RELATIONSHIPS OF STRUCTURAL FEATURES

Period of deformation	Generation of folds	Deformed surface	Fold style	Fold closure	Fold symmetry	Surface(s) developed	Lineation(s) developed
D_1	f_1	bedding	unknown	isoclinal	unknown	none or destroyed	none or destroyed
D_2	f_2	bedding veins	similar	variable, mainly open	variable, mainly Z-shaped	foliation	mineral lineations, slickensides, fragment lineations
D_3	f_3	bedding veins foliation	kink concentric chevron conjugate	variable	variable	strain-slip cleavage, fracture cleavage	slickensides

Nomenclature

S-surfaces and lineations are given chronological subscripts according to the age relationships given in this chapter. Bedding is designated by S_o and veins by S_o'. Tectonic elements associated with a specific period of deformation are given the same subscripts as the folds produced during that event as indicated on Tables II and III.

TABLE III

NOMENCLATURE OF STRUCTURAL ELEMENTS

bedding.	S_o	mineral lineations	L_2
veins.	S_o'	plunging slickensides. . .	L_2'
foliation.	S_2	fragment lineation	L_2''
strain-slip cleavage .	S_3	horizontal slickensides. .	L_3
fracture cleavage. . .	S_3'		
joints	S_4		

CHAPTER V

GEOMETRIC ANALYSIS

This chapter presents a geometric analysis of the data collected for all of the structural elements.

The map-area was divided into the three main lithological subareas: Subarea I, the Stormy Lake Formation; Subarea II, the Long Lake Formation; Subarea III, the burned-over area, covering part of the Edmunds Lake Formation. These subareas are outlined on Figure 22. In this chapter they are used to trace the variations of the attitudes of several structural elements and to compare the attitudes on synoptic diagrams. Some structural elements occur only in a single subarea.

Orientation Data

Subarea I

Poles to bedding (S_o) in the Stormy Lake Formation form a single maximum concentration giving a strike of N 80^o E and a dip of 85^o S (Fig. 22a).

The foliation (S_2) strikes west and dips 85^o N. Mineral lineations (L_2) and slickensides (L_2') plunge steeply to the west (Fig. 22b).

Subarea II

Poles to bedding (S_o) in the Long Lake Formation produce a maximum with a strike to the west and a dip of 80° N (Fig. 22c).

The foliation (S_2) strikes west and dips 85° N. Mineral lineations (L_2) plunge to the east; the maximum plunges 65° to N 82° E. Slickensides fall into two concentrations. L_2' slickensides are parallel to L_2; L_3 slickensides plunge at a shallow angle to the east or west (Fig. 22d).

The fragment lineation (L_2'', the long axes of ellipsoidal holes) is subparallel to L_2, and the short axes of the holes (Fig. 22e) are perpendicular to S_2 (Fig. 22d).

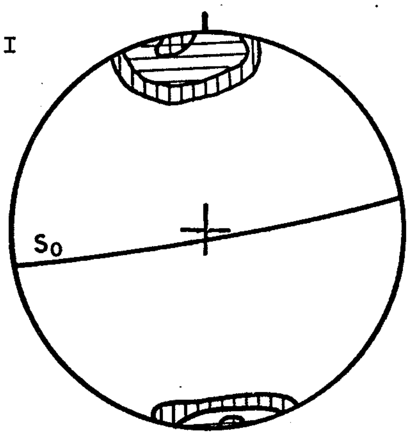
Subarea III

Although poles to S_o are scattered (Fig. 23a), they lie roughly along a partial great circle that has a π axis plunging approximately 50° to N 87° E. In this girdle is a maximum with the bedding striking west and dipping steeply to the north.

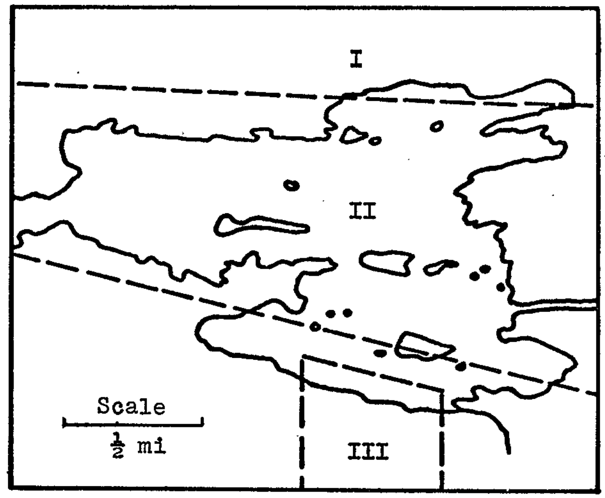
S_2 (Fig. 23d) and the axial planes of similar folds in the bedding (Fig. 23e) also strike west and dip steeply to the north. Minor fold axes generally plunge east at a moderate angle but several plunge more steeply and a few plunge steeply to the west. Nevertheless, the most frequent plunge is about 45° to the east and almost coincides with the π axis of poles to S_o.

Mineral lineations (L_2) and fragment lineations (L_2'') have an average plunge of about 60° to the east. The

I

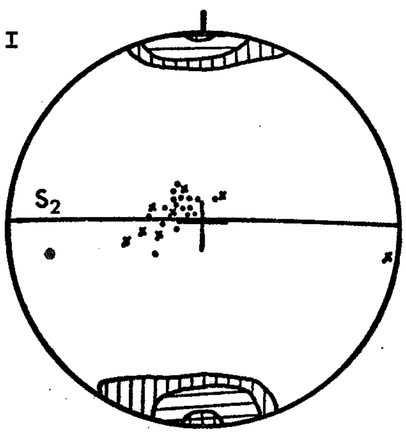


a. BEDDING (S_0), 46 poles



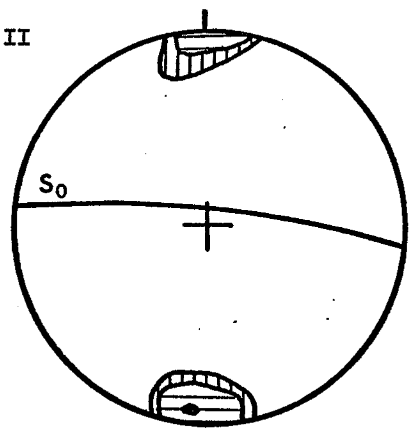
SUBAREAS

I



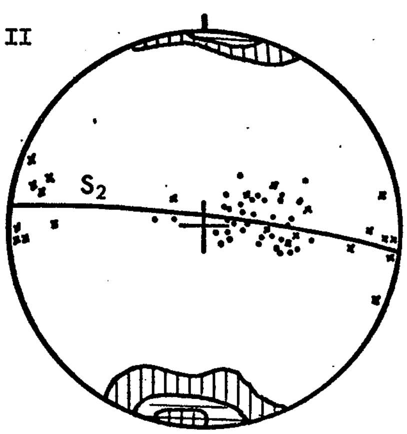
b. FOLIATION (S_2), 94 poles (contoured)
MINERAL LINEATIONS (L_2) (dots)
SLICKENSIDES (L_2' and L_3) (crosses)

II



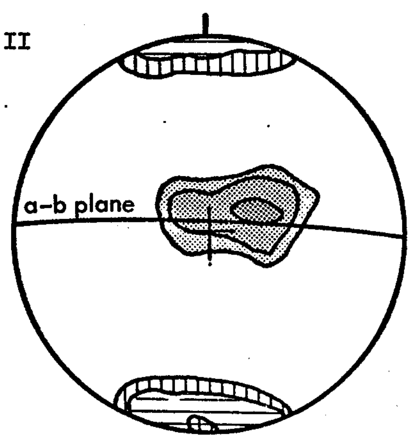
c. BEDDING (S_0), 14 poles

II



d. FOLIATION (S_2), 312 poles (contoured)
MINERAL LINEATIONS (L_2) (dots)
SLICKENSIDES (L_2' and L_3) (crosses)

II



e. DEFORMED FRAGMENTS (L_2'')
Long axes, 35 (dots)
Short axes, 29 (lines)

Figure 22. Lower hemisphere, equal-area stereograms of Subareas I and II. Contours: 1%, 7%, 30%.

slickensides plunge to the east or the southeast. Some of them are parallel to L_2 and others have a shallower plunge (Fig. 23d).

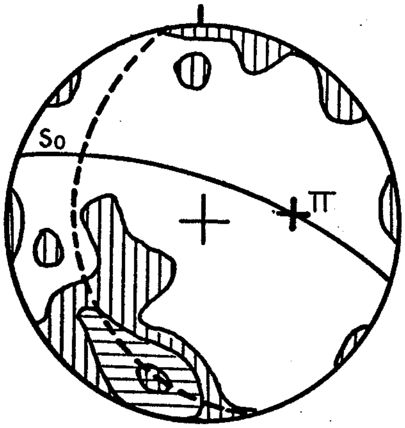
The poles to the beds (S_o) facing northeast are plotted on Figure 23b and the poles to the southwest facing beds (S_o) are plotted on Figure 23c. These beds are from the upright and the overturned limbs of the f_1 isoclines respectively. The figures show that the poles fall into nearly identical partial π-girdle distributions in either case, that the f_1 folds are true isoclines, and that both sets of f_1 limbs are cross folded about an easterly plunging axis.

Total Map-area

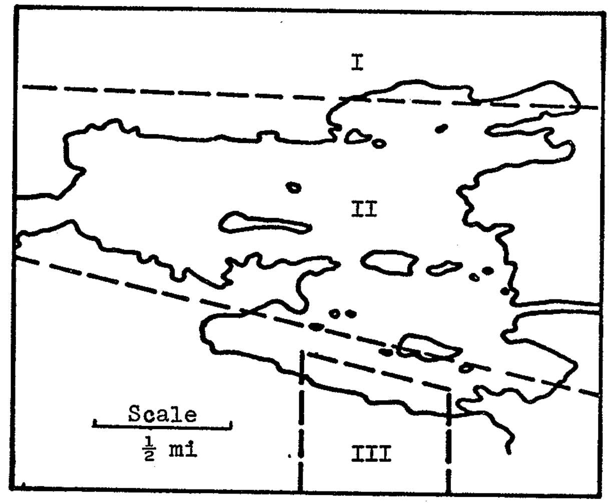
Figure 24a indicates that the variation of the attitude of the foliation (S_2) is small throughout the map-area. The most frequent strike of S_2 is N 84^o W and the dip is 84^o N. The pitch of the mineral lineations (L_2) in the foliation is more variable but there is a maximum at 63^o to the east.

Figures 24b and 24c show that the mean attitude of the veins (S_o') is the same as the attitude of S_2, that the axial planes of the folds in S_o' are parallel to S_2, and that the axis of these folds pitch at various angles in S_2.

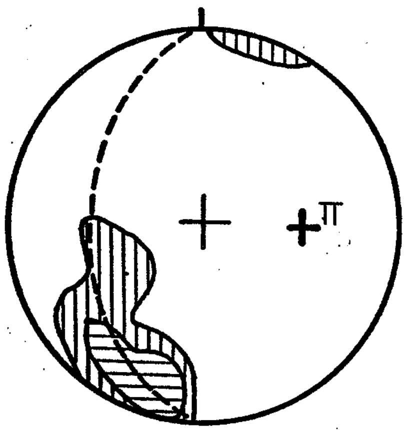
The kinks and concentric folds (shown in Figure 24d)



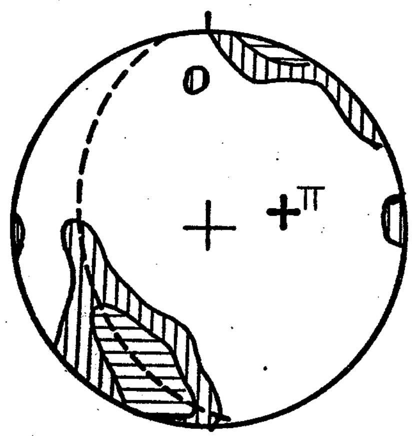
a. BEDDING (S_0), 147 poles (total)



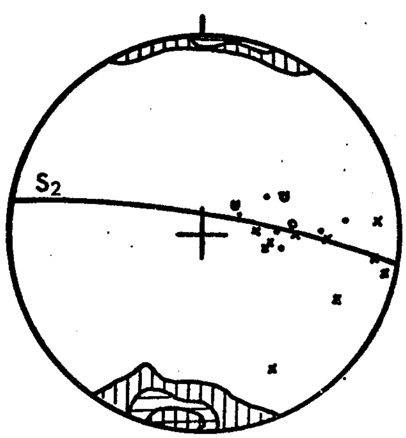
SUBAREAS



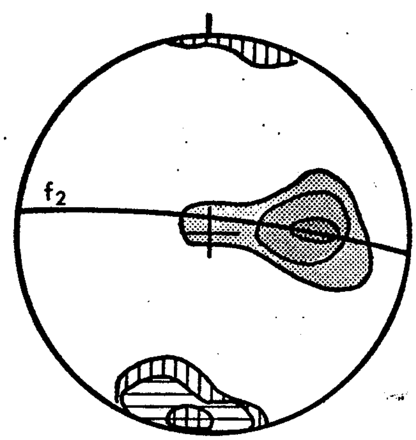
b. BEDDING (S_0) facing northeast 63 poles



c. BEDDING (S_0) facing southwest 64 poles



d. FOLIATION (S_2), 128 poles (contoured)
MINERAL LINEATIONS (L_2), (dots)
SLICKENSIDES (L_2' and L_3), (crosses)
LONG AXES OF DEFORMED FRAGMENTS (L_2"),(°)



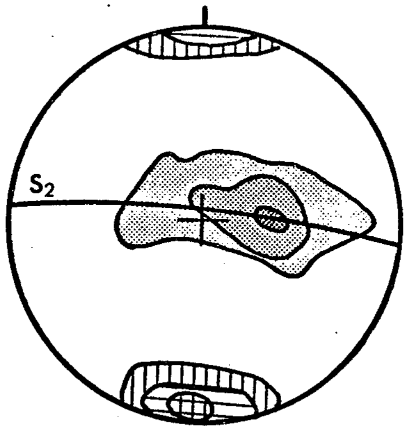
e. MINOR FOLDS IN BEDDING (f_2)
Axial planes, 34 poles (lines)
Axes, 40 (dots)

Figure 23. Lower hemisphere, equal-area stereograms of Subarea III. Contours: 1%, 7%, 30%.

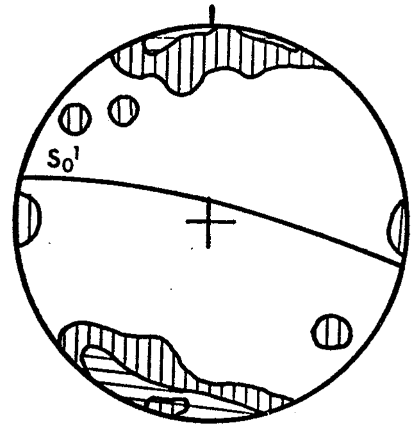
and the strain-slip cleavage (shown in Figure 24e) have developed in two directions forming conjugate sets with nearly the same respective orientations. The attitudes of the axial planes of the folds vary considerably. However, the most frequent strike of the axial planes of right-hand folds is N 74° E and the dip is 80° NW. The axial planes of left-hand folds commonly strike N 14° W and dip 83° SW. Their average dihedral angle is 93°. Right-hand and left-hand kinks occur with approximately the same frequency but most concentric folds are right-hand structures (with Z asymmetry) and their axial planes trend northeast. The two directions of strain-slip cleavage strike N 44° E and N 28° W and 78° NW and 88° SW respectively. The northeast striking cleavage is much better developed and lies in the axial plane of some concentric folds. However, both directions of cleavage are parallel to the kink zones.

Slickensides (shown on Figure 24f) fall into two concentrations. One group (L_2') plunges to the east or steeply to the west, parallel to the mineral lineation (L_2), and another group (L_3) plunges at a very shallow angle to the east or to the west.

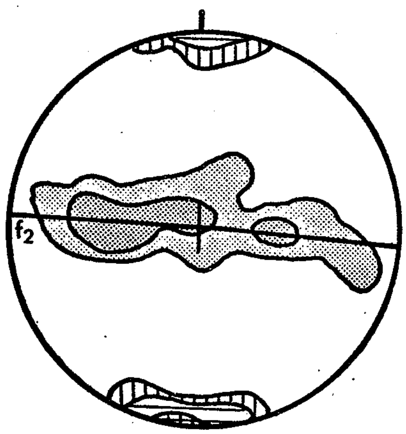
Figures 25a and 25b indicate that the fracture cleavage (S_3') and the joints (S_4) generally have a steep dip but that their strike is variable. There is a slight predominance of S_3' that strike northwest and a possible predominance of S_4 that strike north.



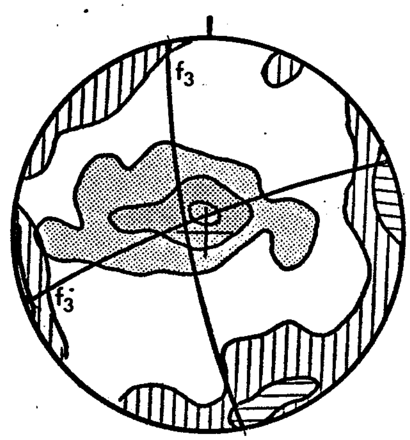
a. FOLIATION (S_2), 506 poles (lines)



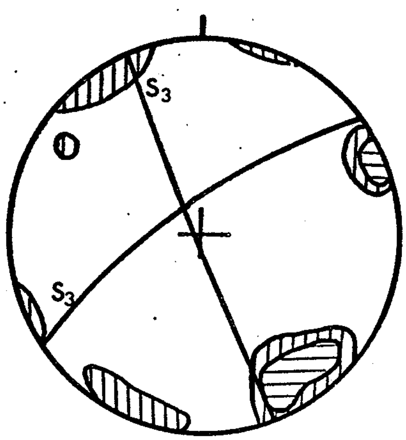
b. VEINS (S_0'), 52 poles



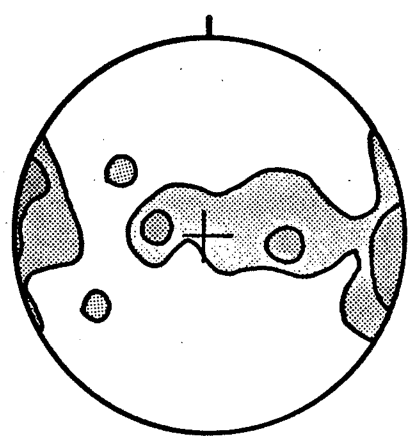
c. MINOR FOLDS IN VEINS
Axial planes, 34 poles (lines)
Axes, 34 (dots)



d. KINK FOLDS IN FOLIATION
Axial planes, 85 poles (lines)
Axes, 85 (dots)



e. STRAIN-SLIP CLEAVAGE (S_3)
21 poles



f. SLICKENSIDES (L_2' and L_3)
60.

Figure 24. Lower hemisphere, equal-area stereograms of the total map-area. Contours: 1%, 7%, 30%.

Synopsis

If the most frequent attitudes of S_o from each subarea are superimposed on a synoptic stereogram (Fig. 25c), they are found to intersect on a β axis that plunges to the east at 50^o. This axis coincides with the average fold axis in Subarea III. Even though no minor folds in S_o were observed in the northern subareas, it appears that throughout the entire map-area, rocks were cylindrically folded about an axis that plunges at 50^o to the east. The pitches of a few axes of minor folds in S_o are scattered in the axial plane, but this may be expected in a cross-folded terrain. Figures 23e and 25c indicate that statistically the bedding in the Long Lake area is folded about a single axis.

Although the veins (S_o') are frequently parallel to S_o there is a significant variation in their attitude. The axial planes of the minor folds in S_o' are always parallel to S_2 but the fold axes pitch at various angles in S_2 and suggest that they lie on the intersection of S_o' and S_2.

The pitch of the mineral lineation (L_2) in the map-area also shows a variation. L_2 forms a broad maximum that plunges to the east at 63^o; however, in Subarea I L_2 plunges west at about 70^o. The average plunge of the fragment lineations (L_2'') and the plunging slickensides (L_2') is also to the east, and on each outcrop it is parallel to L_2. Map 2 reveals that south of the lake, all the lineations formed during D_2 plunge to the east at about 60^o; northwards across the lake they become gradually steeper until they plunge to the west, on the north shore of the lake.

The geometric relationships of the structural elements and the folds formed during D_3 are revealed in Figures 24d to 24f. There are insufficient attitudes of the strain-slip cleavage (S_3) to measure its mean orientation accurately. However, the figures support the field evidence that S_3 and the axial planes of the f_3 folds form conjugate sets with similar orientations. The axes of the f_3 folds tend to be steep. They are statistically perpendicular to the horizontal slickensides.

The fracture cleavage (S_3') and the joints (S_4) do not produce sharp maxima in Figures 25a and 25b. The joints tend to be perpendicular to S_2.

Interpretation

The geometry of the structural features at Long Lake is consistent with the hypothesis that there are three generations of folds resulting from three corresponding periods of deformation.

Folds in the Bedding

Most bedding planes (S_o) are cylindrically folded about axes that plunge to the east. However, in Subarea

III the direction of facing of the beds is not related to this geometry. Upright and overturned beds are parallel to each other and their poles are distributed along nearly identical π circles. This geometry and the field evidence indicate that there was an early period of isoclinal folding (D_1) followed by a period of cross folding (D_2) during which the upright limbs, the overturned limbs and the axial planes of the isoclines were folded about axes which plunge to the east. The isoclinal folds (f_1) are readily identified from graded bedding in the Edmunds Lake Formation. The cross folding is most obvious in the centre of the burned-over area where the large open Z-shaped structure is superimposed upon the isoclines (see Map 2). The orientation data on Figure 23 indicates that the Z-shaped fold pair plunges to the east at about 50^o. Its long limbs are subparallel to the foliation (S_2) and produce a maximum concentration of poles to S_o near the maximum of poles to S_2. The common limb produces the partial π girdle distribution of poles. The small angle of closure of this fold restricts the poles almost entirely to the southwest quadrant of the stereonet.

The orientation data on Figure 23 also indicates that the small similar folds (f_2) are coaxial with the large Z fold-pair and suggests that the small folds are parasitic folds on the larger structure. If this is so the axial planes of the Z fold-pair probably strike west and dip steeply to the north and the folds must have formed during D_2. This is not immediately apparent in the field because of the small angle of closure of the structure.

It was shown in chapter III that the minor similar folds (f_2) in the bedding interfere with the isoclinal folds (f_1) and that their axial planes and axial plane foliation (S_2) cut obliquely across the isoclines. Figure 23 indicates that the present geometry of S_o is an interference pattern of f_1 and f_2 folds. The synoptic diagram (Fig. 25c) suggests that the entire map-area is cylindrically folded. Consequently the bedding must have been parallel in all subareas at the onset of the D_2 deformation as it would have been if the f_1 folds had been isoclinal.

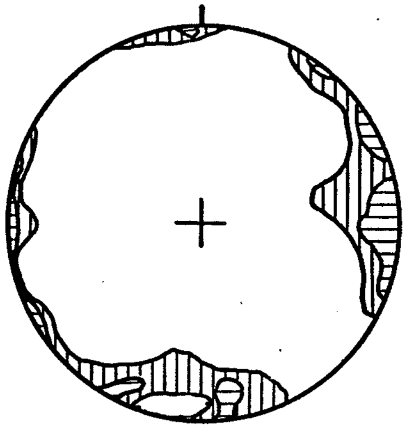
Folds in Veins

Similar folds (f_2) in the bedding (S_o) are restricted to the Edmunds Lake Formation. However, f_2 folds in the veins (S_o') occur throughout the map-area and indicate that the D_2 deformation was pervasive. S_o' is the only folded surface in Subareas I and II probably because S_o is almost parallel to S_2 and may have been deformed without producing visible folds.

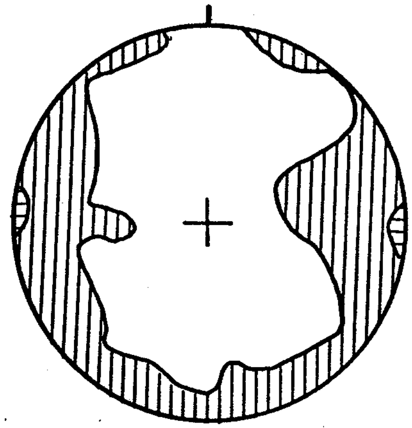
Folds in Foliation

S_2 is folded only in restricted zones where it is exceptionally well developed and only on a minor scale. Kinks and other f_3 folds are never mappable and do not affect the geometry of the major units.

Figure 25d indicates that variations in the attitude of S_2 are small.

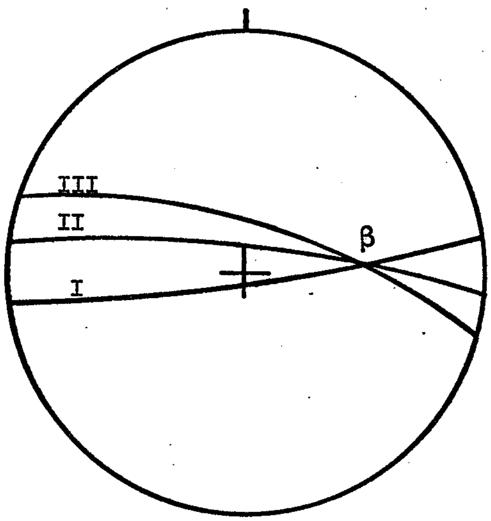


a. FRACTURE CLEAVAGE (S_3')
26 poles



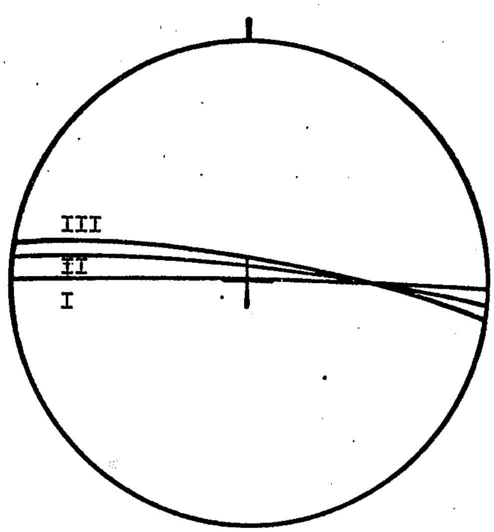
b. JOINTS, 264 poles(S_4)

(a, b) Total map-area, Contours 1%, 7%.



c. MOST FREQUENT ATTITUDE
OF BEDDING (S_0)
Subareas I, II and III

(c, d) Synoptic diagrams, total map-area.



d. MOST FREQUENT ATTITUDE
OF FOLIATION (S_2)
Subareas I, II and III

Figure 25. Lower hemisphere, equal-area stereograms.

CHAPTER VI

KINEMATIC ANALYSIS

First Generation Folds

The first generation folds (f_1) are readily identified in the Edmunds Lake Formation. In the map-area they have been deformed during a later period of folding (D_2). This cross folding has produced geometric complications and may have destroyed some of the fabric resulting from the first period of deformation. Consequently the plunge of the f_1 folds cannot be identified nor can the movements which produced these folds. The available data leads only to the conclusions that the folds are isoclinal.

Second Generation Folds

Folding Mechanism

Considerable evidence is present to suggest that the second generation fold mechanism was passive slip. This mechanism was described by Donath and Parker (1964) as macroscopically visible slip crossing the boundaries of layers which exercise little or no control over their own deformation. This evidence is summarized in the following statements:

1. The profiles of the folds closely resemble a similar form.

2. There is a penetrative foliation, the mean orientation of which is parallel to the axial surface of the folds and along which discrete displacements of the layering can be observed under the microscope and with the unaided eye.

3. Slickensides (L_2') occur on S_2 and crushed elongated mineral grains and bladed minerals are aligned parallel to L_2' indicating that S_2 is a slip surface.

4. Many of the foliated rocks have a cataclastic texture in which there are indications that crushed mineral matter has been transported into the pressure shadows of the larger grains producing augen structures which are aligned with L_2'.

5. The axes of the f_2 folds have the same orientation as the intersection between S_2 and the layering (S_o and S_o').

6. The fold axes are obliquely inclined to the slickensides produced during the folding. (In flexural slip folding they are generally perpendicular to the slickensides.)

Kinematic Directions

The identification of passive slip on S_2 suggests that S_2 is the kinematic a-b plane of the movements which produced folds during the second period of deformation. In passive folding the direction of tectonic transport must be inclined to the fold axes but need not be perpendicular to them. This condition is met by the plunging lineations (L_2 and L_2') which are obliquely inclined to the π axis. The following evidence indicates that L_2 (and L_2') are parallel to the apparent direction of tectonic transport in the plane of S_2 or possibly to the true direction of tectonic transport (kinematic a).

1. The slickensides (L_2') define the direction of the movement which took place on the foliation (S_2).

2. Crushed elongated mineral grains and augen structures in the cataclastic rocks are aligned with L_2'.

3. Deformed fragments were elongated parallel to L_2' or at a small angle to L_2'.

Third Generation Folds

Folding Mechanism

There is evidence to suggest that during the third period of deformation the mechanism of folding was flexural slip. This mechanism was described by Donath and Parker (1964) as slip restricted by layer boundaries which exercise an active control over their own deformation. In the Long Lake area kink folds and small concentric folds in the foliation (S_2) were formed by means of flexural slip as suggested by the following evidence:

1. The axial planes tend to bisect the interlimb angles of the kink folds, a condition which can exist only

where the layer thickness is constant.

2. In true kinks the radius of curvature is almost zero. However, in the f_3 concentric folds with rounded hinge areas the radius of curvature often decreases toward the centre of the fold.

3. The L_3 slickensides lie in the plane of S_2 and are generally perpendicular to the axes of the f_3 folds.

Kinematic Directions

Consistent with the flexural slip mechanism of folding only the kinematic b direction and the a-c plane can be defined for the third period of deformation. The b direction is parallel to the statistical fold axis which is vertical in the map-area. Consequently, the a-c plane is horizontal. The azimuth of kinematic a on different parts of the folds depends on the attitude of the limbs. The a direction is given by the horizontal slickensides (L_3). These can be measured on the long limbs of the kinks. Apparently, during the third period of deformation movement was horizontal and in an east-west direction on the long limbs of the kink folds. Local developments of L_3 where kinks are absent suggest that there may have been horizontal slip movements on S_2 even where S_2 is not folded.

Deformed Fragments

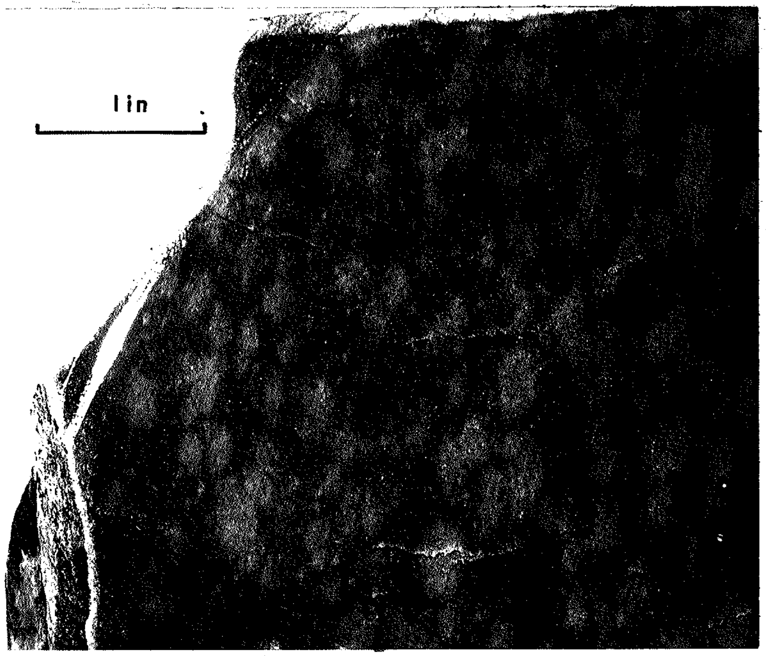
Orientation Data

The attitude of deformed fragments can be determined most easily from oriented hand specimens which have been cut in the following three orthogonal planes:

1. parallel to S_2,
2. perpendicular to S_2 and L_2,
3. perpendicular to S_2 and parallel to L_2.

Three specimens containing small volcanic fragments and one specimen of volcanic pisolite were sectioned. Specimen 1564 is a volcanic pisolite (map unit 1c) from the Stormy Lake Formation; specimen 1608 was taken from the volcanic breccia with intermediate and basic fragments (2a) at the bottom of the Long Lake Formation; specimen 1021 is from the dacitic breccia (2b) in the middle of the Long Lake Formation, and specimen 1267 contains intermediate and acidic fragments (2d) from the top of the formation.

Fragments and pisoliths have nearly elliptical sections on all surfaces of the specimens thus indicating that they are triaxial ellipsoids (Fig. 26). Their orthogonal dimensional axes, (the long, the intermediate and the short axes) are designated by a, b and c respectively. The a axes are parallel to L_2 (and L_2') and lie in the plane of S_2. The b axes are perpendicular to the a axes and lie in the plane of S_2. The c axes are perpendicular to S_2. This observation agrees with a study of the deformed pebbles in the San Antonio Formation near



a. Volcanic pisolite, cut parallel to the foliation. Note elongation of pisoliths from top to bottom of photograph.

b. Volcanic pisolite cut perpendicular to foliation and parallel to mineral lineation. Note high elongation ratios in this cut. The right edge of the specimen is parallel to the foliation.

Figure 26. Volcanic pisolite, specimen 1564 (map unit 1c), Stormy Lake Formation.

Bissett done by Bell (1968) and it agrees with the orientation data gathered from the ellipsoidal holes presented in Chapter IV (Fig. 22e). Exceptions to this relationship occur in some rhyodacite fragments which are in a matrix of dacitic tuff. The foliation is curved around such fragments or it is refracted as it passes through them. The foliation is generally better developed in basic fragments than in the surrounding matrix of intermediate composition. In Specimen 1564 of volcanic pisolite the attitude and stage of development of the foliation are not affected by the pisoliths. In this specimen the deformed pisoliths always have a tabular and a linear alignments parallel to S_2 and L_2 respectively (Fig. 26).

Dimension Ratios

Dimension ratios of deformed fragments were studied on horizontal exposures in the field and on three orthogonal planes cut in the oriented hand specimens. True dimension ratios could be calculated from the data from hand specimens because the dimensional axes of the fragments lie in the plane of sectioning. Only apparent dimension ratios (elongation ratios) could be calculated from the field data because horizontal exposures are oblique sections. However, the elongation ratios from the field data approximate the b:c ratios calculated from the hand specimens because the plunge of the fragment lineations is steep.

Dimension ratios of ten fragments were calculated and averaged on each surface cut from the four specimens. As a check of accuracy, average a:b ratios were calculated from average a:c / b:c ratios. The results are show in Table IV.

Although there is a considerable variation in ratios, if the a:b ratios are calculated from the other ratios, there is a significant error only in specimen 1608 which is a thin slab and very small fragments had to be measured on surfaces perpendicular to the foliation. The most accurate data is from specimen 1564, the volcanic pisolite.

The mean dimension ratios from all sectioned specimens expressed as a:b:c is 8:4:1.

In the course of the mapping at Long Lake the elongation of fragments exposed on horizontal surfaces was determined at each field station where fragments occurred. The elongation was calculated by averaging the ratios of the horizontal lengths to the horizontal widths of five to ten fragments. The results are plotted on Map 2 on which areas with high and low elongations of fragments are outlined for the Long Lake Formation. Very little data could be obtained from the other units. The elongation ranges from 2:1 to 16:1. There are belts and lenses of rocks with highly elongate fragments and lenses with relatively weakly elongate fragments. Both types of zones trend parallel to the foliation (S_2). Along the north shore of

TABLE IV

DIMENSION RATIOS

Specimen 1021			Specimen 1267			Specimen 1608			Specimen 1564		
a:c	b:c	a:b	a:c	b:c	a:c	a:c	b:c	a:b	a:c	b:c	a:b
13.7	4.6	1.5	12.0	2.0	2.1	6.3	2.6	0.5	5.6	5.0	1.8
6.5	4.4	1.5	6.5	3.0	2.4	7.1	5.0	1.6	4.8	4.0	1.9
17.0	5.0	1.6	10.0	3.2	3.3	7.0	6.6	1.2	4.6	2.8	1.5
6.0	4.3	1.6	7.0	2.0	2.2	11.0	5.3	0.8	5.0	2.5	2.5
9.0	4.1	3.0	7.3	4.0	2.1	5.0	3.7	1.0	9.3	2.8	2.2
14.0	4.0	1.7	12.0	3.8	2.5	3.5	2.5	2.0	4.0	4.0	1.8
10.0	5.8	1.7	8.2	4.0	2.2	3.3	4.0	1.0	4.5	4.0	2.0
10.0	2.3	2.2	6.0	3.3	4.4	6.2	3.6	1.5	6.9	2.4	1.3
10.0	6.0	2.2	9.0	2.7	3.3	11.0	2.5	1.1	6.0	3.5	1.6
8.8	4.0	2.3	12.0	3.6	2.4	6.0	5.3	1.4	7.0	4.0	1.4
Average:											
10.0	4.9	2.1	9.0	3.2	2.7	6.6	4.1	1.2	5.8	3.2	1.8
a:c/b:c		2.0			2.8			1.6			1.8

Long Lake the elongation ranges from 4:1 to 6:1 and along the south shore it ranges from 4:1 to 16:1. A large body of crystal tuff and tuff breccia in the centre of the Lake contains only weakly elongate fragments with ratios ranging from 2:1 to 4:1. The zones with strong elongation are curved around this body.

Discussion

There is an excellent positive correlation between the development of the foliation, the dynamic metamorphism and the distortion of the fragments which suggests that the elongate shape of the fragments is a result of deformation. Where no foliation can be seen the fragments are almost equidimentional and appear to be undeformed (Fig. 27a). Where S_2 and L_2 are well developed and augen structure can be seen under the microscope, elongation ratios between 3:1 and 5:1 are common (Fig. 27b). When ratios are greater than 6:1 rocks become very fissile and slickensides appear on S_2. In thin section, flaser structure is common and chlorite and sericite have good tabular alignment. Moreover, the long axes of the fragments are parallel to the tectonic lineations, L_2 and L_2' throughout the map-area. Consequently, the elongation of the fragments is interpreted to be a tectonic feature and much of the fragment deformation must have taken place during D_2. Nevertheless, the total strain at Long Lake is

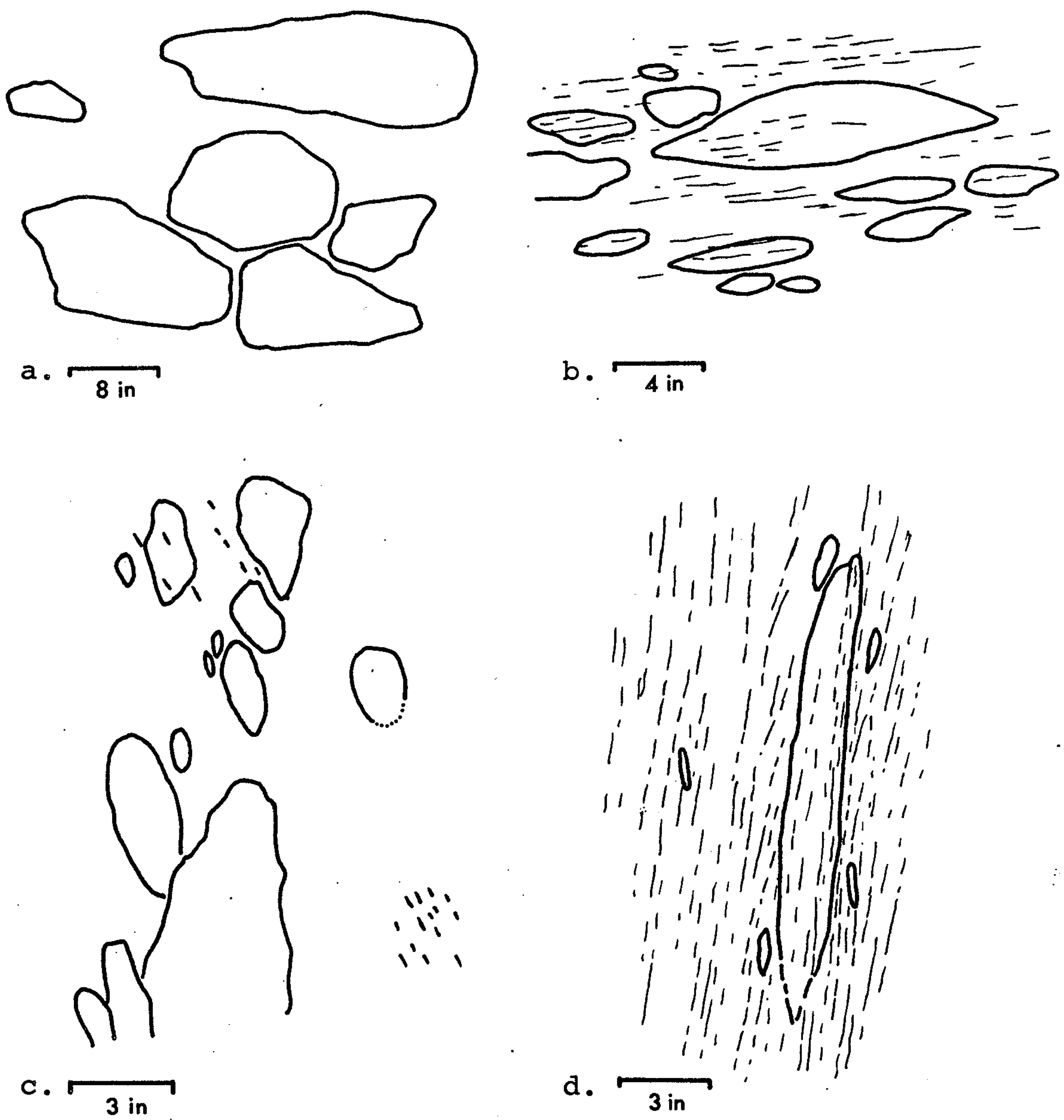


Figure 27. a. Weakly elongate fragments in unfoliated tuff breccia as observed on a horizontal surface.

b., c., d. Elongate fragments in foliated tuff breccia.

b. in horizontal section.

c. in vertical section, parallel to the foliation, with mineral lineation also indicated.

d. in vertical section, perpendicular to the foliation.

the sum of the D_1 and D_2 strain components. Unfortunately, wherever fragments are common in the map-area, S_2 is parallel to the bedding (S_o) which is also the axial plane of the f_1 isoclines. There is one exception, in the burned-over area where S_2 is nearly orthogonal to S_o but the deformed sedimentary intraclasts are elongate parallel to S_2 and support the conclusion that the major component of stretching is a result of the D_2 deformation (Fig. 16a).

The apparently undistorted fragments in the weakly foliated rocks in the centre of the map-area suggest that the original shape of some fragments was nearly spherical (Fig. 27a). However, many fragments may have been tabular before deformation or they may have been stretched in a plastic state during the deposition of the tuff (Schminke and Swanson, 1967). Nevertheless, where the unit of volcanic pisolite (1c) outcrops between Beresford Lake and Stormy Lake, on the crest of the large double plunging anticline (Fig. 1), pisoliths are spherical or weakly elongate in weakly foliated rocks. Consequently, the original shape of the pisoliths in the strongly foliated rocks at Long Lake was probably spherical before deformation and their present shape is interpreted as a tectonic feature. Even though volcanic fragments and sedimentary intraclasts may not have been originally spherical, their present shape and orientation is largely the result of the D_2 deformation.

Distribution and Types of Strain

First Period of Deformation

During the D_1 deformation the bedding was isoclinally folded but the nature and the distribution of the strain is obscured by the later deformations.

Second Period of Deformation

The relative displacements and the similar folds in the layering (S_o and S_o') as well as the linear structures on the foliation (S_2) are powerful evidence that a large component of the D_2 strain was nonaffine slip on S_2 parallel to L_2. The microtextures described in Chapters III and IV indicate that the slip took place by cataclasis, recrystallization and relative movements between mineral grains. Resistant grains and competent fragments were partly crushed and may have been rotated.

Competent fragments were probably less distorted than their surrounding matrix. However, many fragments and especially the pisoliths appear to have been deformed passively. Consequently, their shape and orientation is interpreted to be related to the amount and the type of strain suffered by the host rock.

The fact that the pisoliths and most of the examined fragements have a tabular and linear alignment in the plane of S_2 suggests that a significant component of the D_2 strain was extension parallel to L_2 and shortening perpendicular to S_2. Crushed mineral matter deposited in the pressure shadows of the resistant grains and chlorite and calcite growing in the same sites probably resulted from this strain.

Ample evidence has been presented indicating that during D_2 the layering was folded by passive slip. This strain mechanism may represent a second significant component of the D_2 strain contributing to the distortion of the fragments.

The long axis of fragments deformed by passive slip must be inclined to the slip surface. In the Long Lake area all examined fragments were found to be elongated in the plane of the foliation. Therefore fragments were not deformed simply by passive slip. The available data can be interpreted as evidence for nonaffine slip on S_2 accompanied by or producing elongation of fragments in the plane of S_2 with shortening perpendicular to S_2. A detailed analysis of such a strain model is complex. Fragments may have responded differently than their surrounding matrix and do not necessarily reflect the strain of the whole rock. However, volcanic fragments having a composition similar to that of the tuff matrix and especially pisoliths suggest that they were deformed passively. Under this condition the whole rock would have been elongated parallel to L_2 and shortened perpendicular to S_2.

If S_2 is considered the kinematic <u>a</u>-<u>b</u> plane during the D_2 deformation then the direction of tectonic transport (a) was parallel to L_2. In the more complex strain model of the whole rock mass a would be inclined to the mean foliation surface.

An analysis of the horizontal elongation ratios of the fragments in the Long Lake Formation suggests that the amount of D_2 strain appears to have been controlled by the distribution of the major lithological units with different rheological properties. Shear zones of rocks with highly elongate fragments and well developed cataclastic textures follow the trend of the contact between the Long Lake Formation and the Edmunds Lake Formation and the trend of the gabbro sills north of the lake. (See Map 2). The large body of crystal tuff interbedded with tuff breccia may have acted as a resistant block and several shear zones are curved around it. This large structure is a large-scale manifestation of the augen structures with cores of resistant minerals observed under the microscope. The same phenomenon can be seen on some outcrops where the foliation is curved around competent fragments.

Third Period of Deformation

It has been established that during D_3 flexural slip took place on S_2 and that a large component of this slip was in a horizontal westerly direction parallel to L_3. The conjugate geometry of kink zones indicates that there was an east-west component of shortening. However, right-hand kinks are better developed than left-hand kinks and concentric folds and strain-slip cleavage are found mainly on the northeast trending axial planes. Apparently there was also a component of external, right-hand rotation.

The development of the joints and the fracture cleavage is partly related to the late brittle deformation (D_3). On individual outcrops they often form a conjugate set which is parallel (or perpendicular) to the kink bands and the strain-slip cleavage. This is well demonstrated in Figure 4. However, they strike more consistently north. An analysis of these brittle fractures involves stress relationships and is beyond the scope of this thesis.

CHAPTER VI

CONCLUSIONS

At Long Lake Manitoba, the Rice Lake Group can be divided into three lithologic units. The arkosic greywackes and volcanic flows of the Stormy Lake Formation occur north of the lake and are conformably overlain by the clastic volcanic rocks of the Long Lake Formation. The quartzoze greywacke of the Edmunds Lake Formation rests conformably on the Long Lake Formation. The Rice Lake Group was invaded by intermediate and basic dykes and sills.

Detailed mapping has revealed that the area had a complex structural history and that the local structures were formed by cross folding. An analysis of styles of folding and orientation of s-surfaces and lineations indicates that there were two major phases and one minor phase of deformation.

During the first period of deformation the Edmunds Lake greywacke was folded into a series of isoclinal folds that presently trend west or northwest and are overturned towards the southwest. These structures may be parasitic folds on the southwest flank of the large double-plunging anticline northwest of Long Lake (Fig. 1). However, no first generation axial planes were identified in the central and northern parts of the map-area.

Basic and intermediate dykes and sills and quartz veins were intruded before the second deformational event.

During the second period of deformation the first generation folds were warped into an open Z-shaped fold pair in the burned-over area south of Long Lake. Minor similar folds were produced in the Edmunds Lake Formation and veins were folded throughout the entire map-area. The axial planes of these folds strike west and dip steeply to the north. The plunge of their fold axes is variable but there is a strong preference for folds in the bedding that plunge at about 50° to the east. Stereograms indicate that all bedding was folded about this axis.

The mechanism of folding during the second period of deformation was passive slip on the regional foliation. Bedding served as passive marker in the Edmunds Lake Formation but it is parallel to the foliation in the Long Lake Formation and, because of its orientation, may have been active there.

There is a set of plunging slickensides and mineral lineations which are in the plane of the foliation and pitch about 60° to the east in the southern part of the map-area and about 70° to the west in the northern part of the area. These lineations are interpreted to be parallel to the direction of tectonic transport of that component of second generation strain which lies in the foliation and which caused passive folding of the bedding.

Elongate fragments have a planar and linear alignment parallel to the foliation and the plunging lineations respectively. This shape and orientation is interpreted to have a tectonic origin indicating that there was another component of second generation strain which is expressed as elongation parallel to the steeply plunging lineations and north-south shortening, perpendicular to the foliation.

The amount of second generation strain was controlled by the distribution of competent and incompetent lithological units. For example, a large body of crystal tuff in the centre of the map-area has undergone less deformation than the adjacent rocks.

During the second period of deformation the rocks at Long Lake have suffered dynamic and retrogressive metamorphism. The earlier metamorphism of the greenschist facies is suggested by unstable biotite in the Edmunds Lake Formation. The retrogression is indicated by sericite, chlorite and calcite which grew parallel to the long axes of the deformed fragments.

In the third period of deformation the regional foliation was kink folded. Small concentric folds, an axial plane strain-slip cleavage and a fracture cleavage developed during the kinking. The mechanism of folding was flexural slip and the direction of tectonic transport was nearly horizontal.

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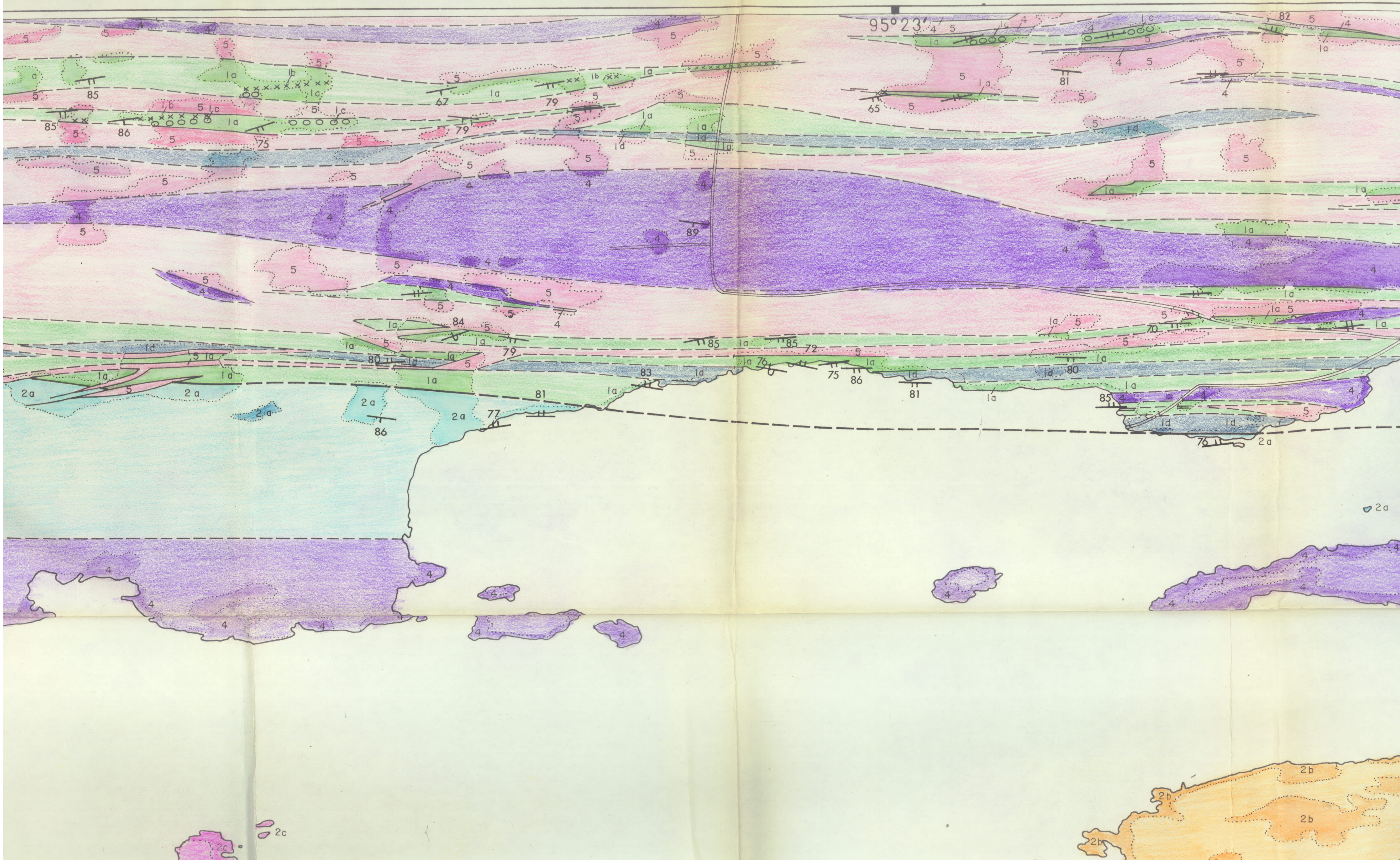
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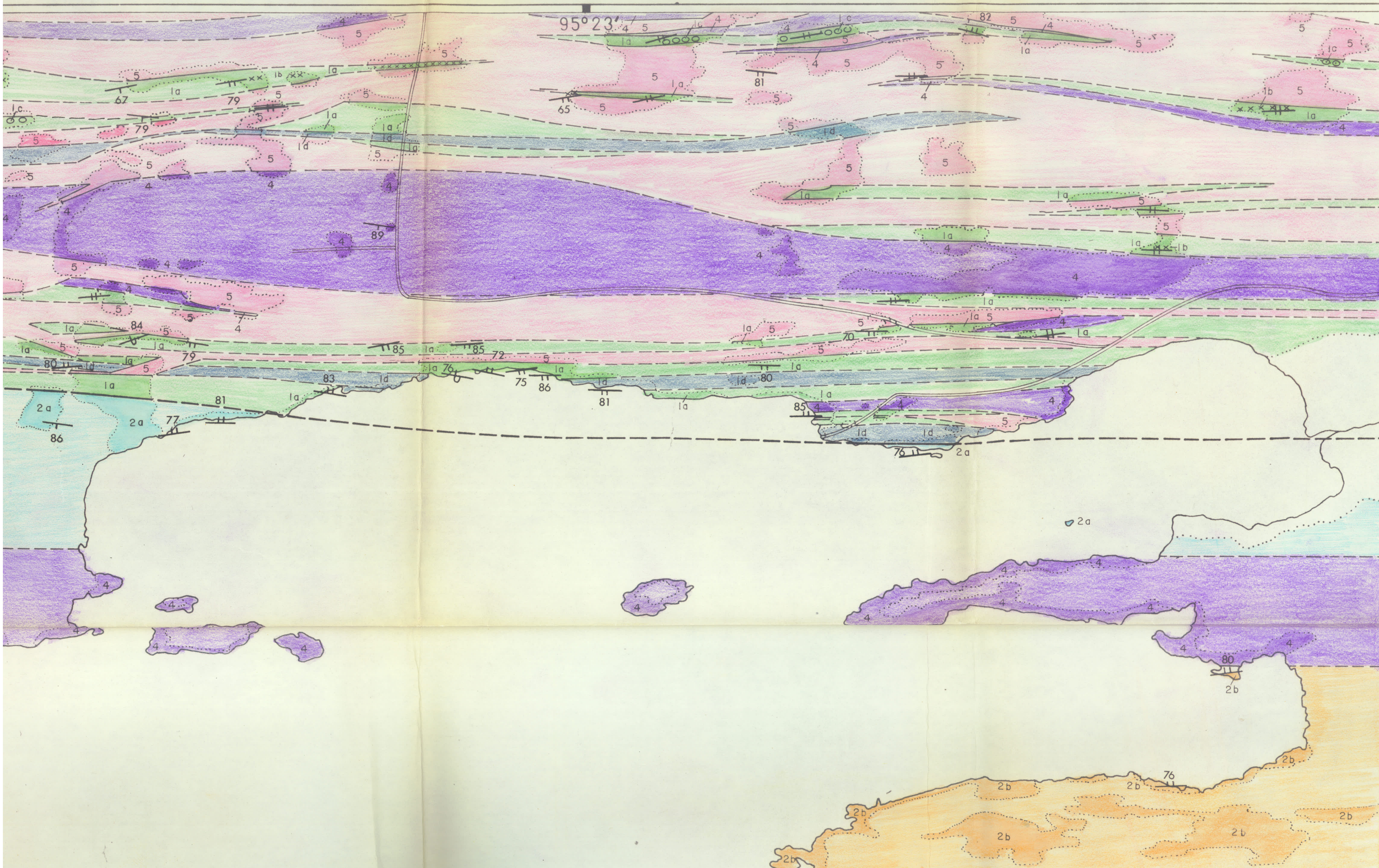
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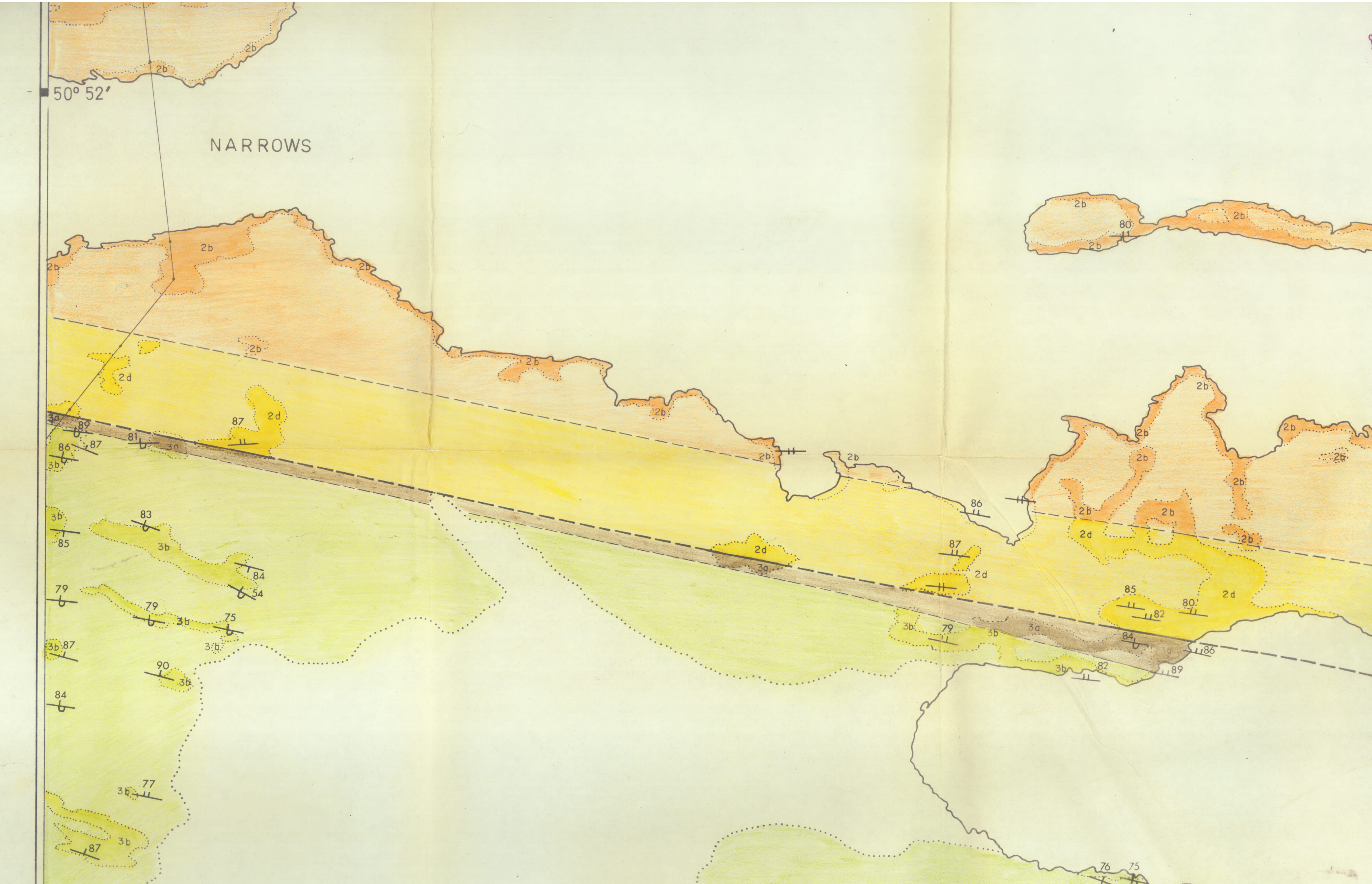
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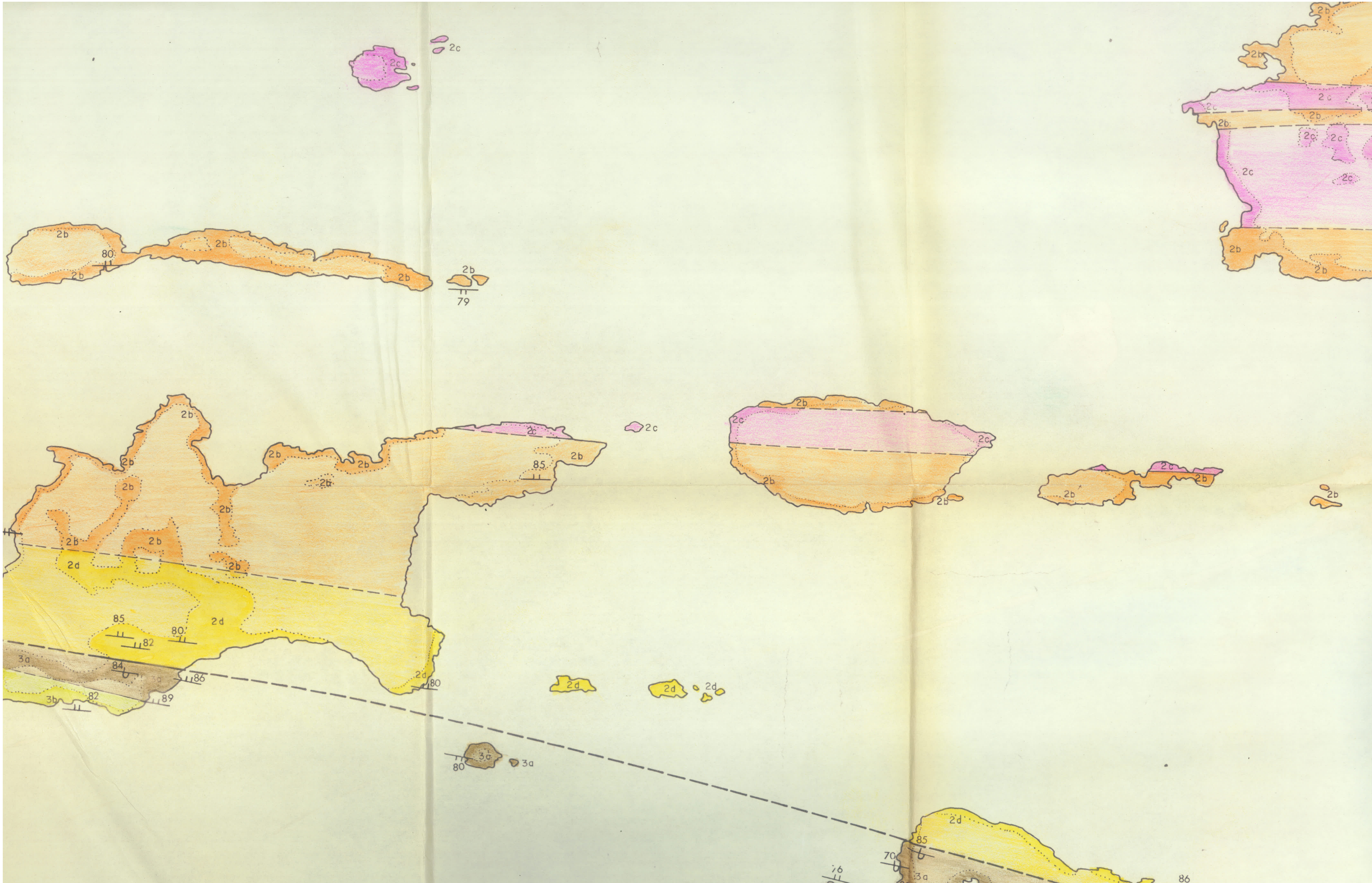

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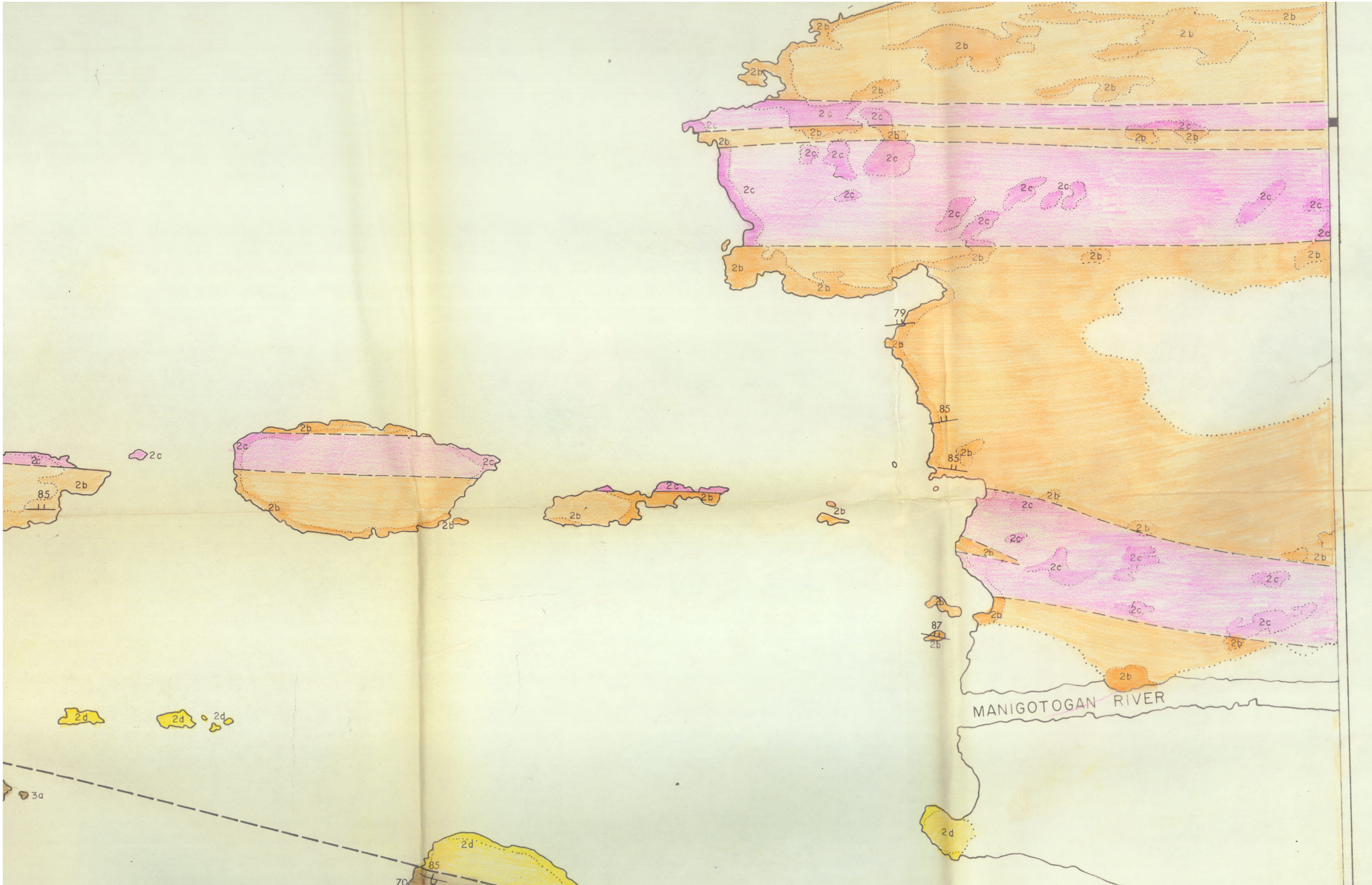
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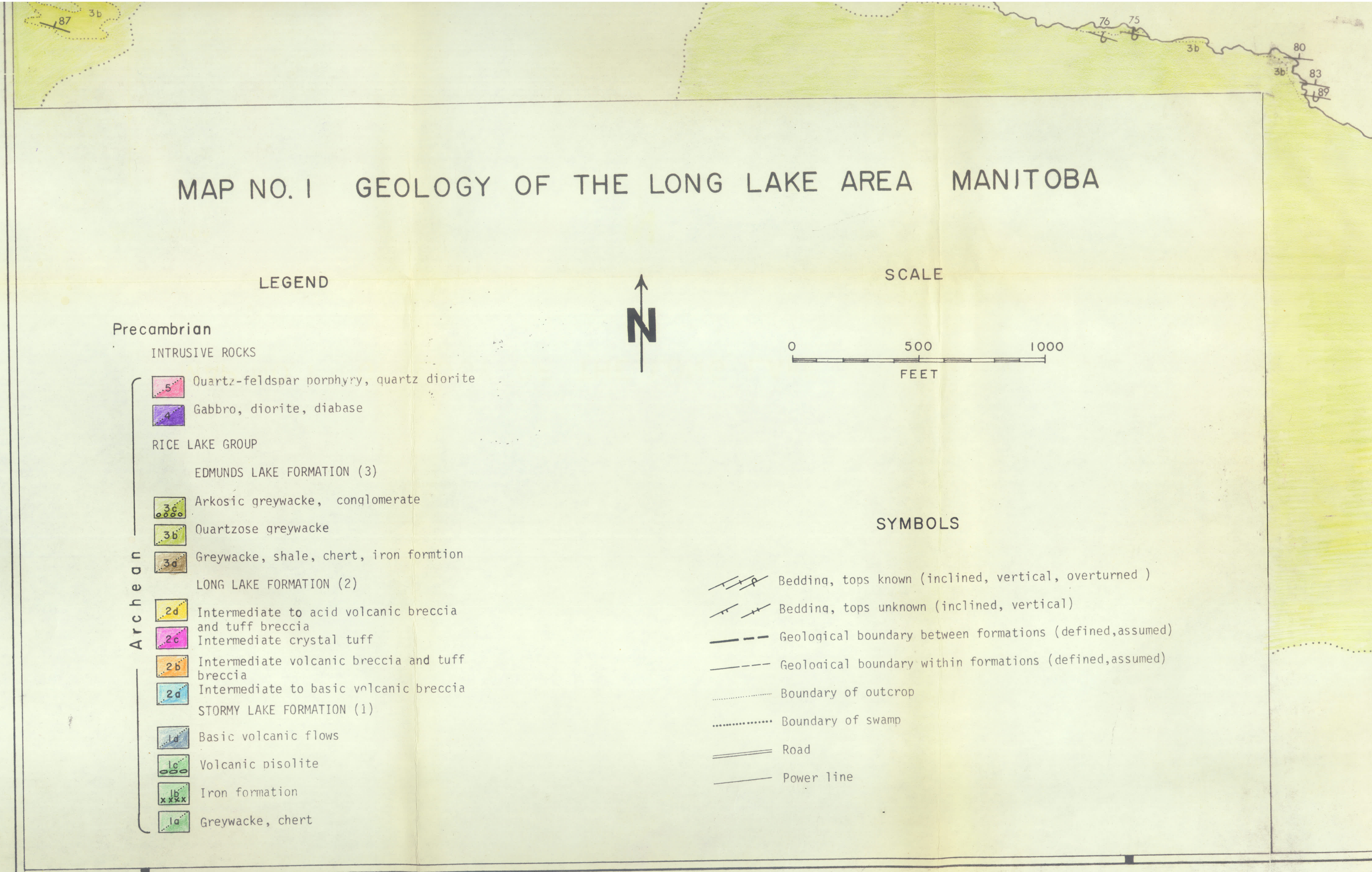
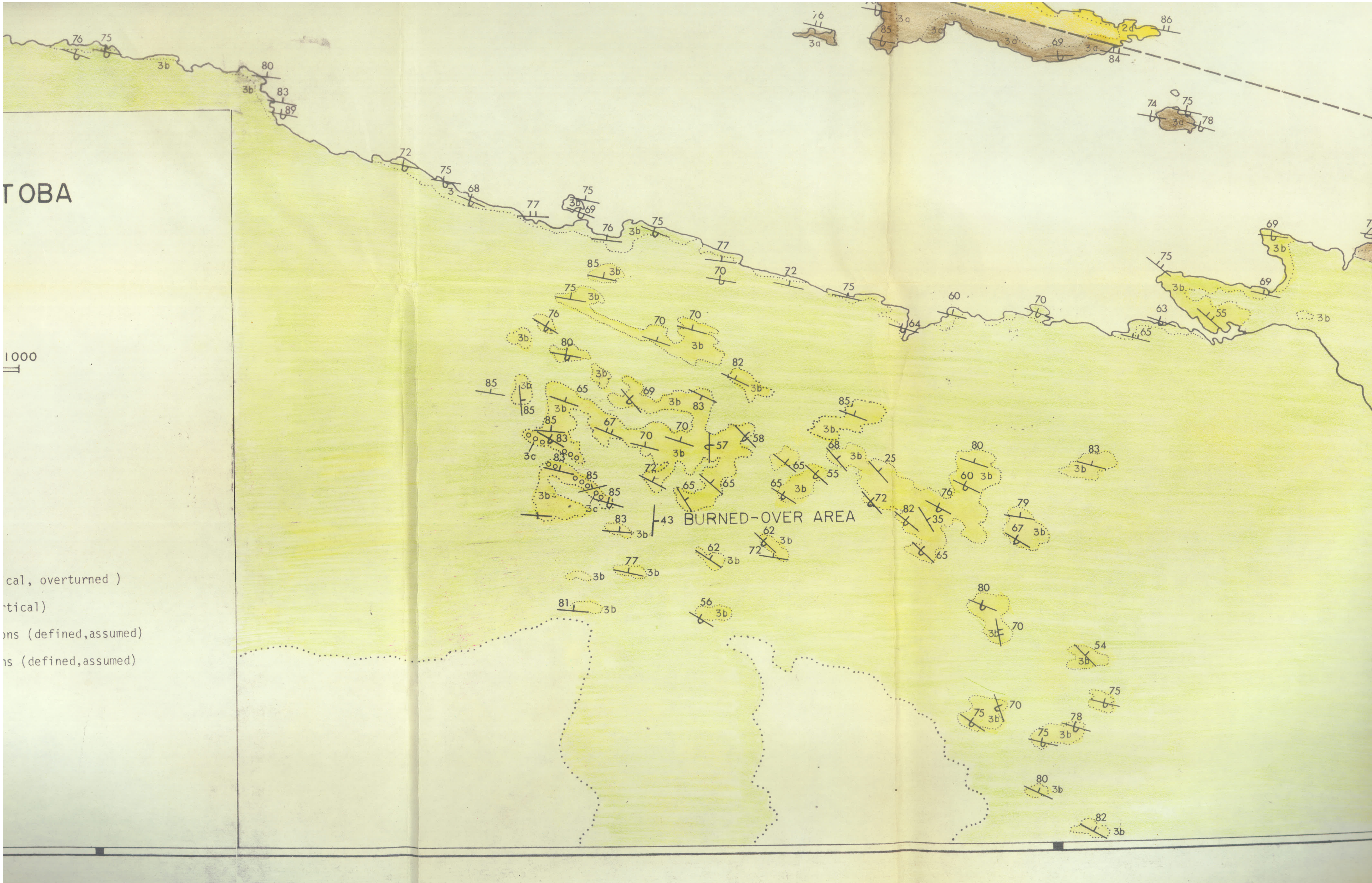
2d
3a
MANIGOTOGAN RIVER


MAP NO. I GEOLOGY OF THE LONG LAKE AREA MANITOBA
LEGEND
Precambrian
Archean
INTRUSIVE ROCKS
5 Quartz-feldspar porphyry, quartz diorite
4 Gabbro, diorite, diabase
RICE LAKE GROUP
EDMUNDS LAKE FORMATION (3)
3c Arkosic greywacke, conglomerate
3b Quartzose greywacke
3a Greywacke, shale, chert, iron formtion
LONG LAKE FORMATION (2)
2d Intermediate to acid volcanic breccia and tuff breccia
2c Intermediate crystal tuff
2b Intermediate volcanic breccia and tuff breccia
2a Intermediate to basic volcanic breccia
STORMY LAKE FORMATION (1)
1d Basic volcanic flows
1c Volcanic pisolite
1b Iron formation
1a Greywacke, chert
N
SCALE
0 500 1000
FEET
SYMBOLS
Bedding, tops known (inclined, vertical, overturned)
Bedding, tops unknown (inclined, vertical)
Geological boundary between formations (defined,assumed)
Geological boundary within formations (defined,assumed)
Boundary of outcrop
Boundary of swamp
Road
Power line
87
3b
76
75
80
83
89



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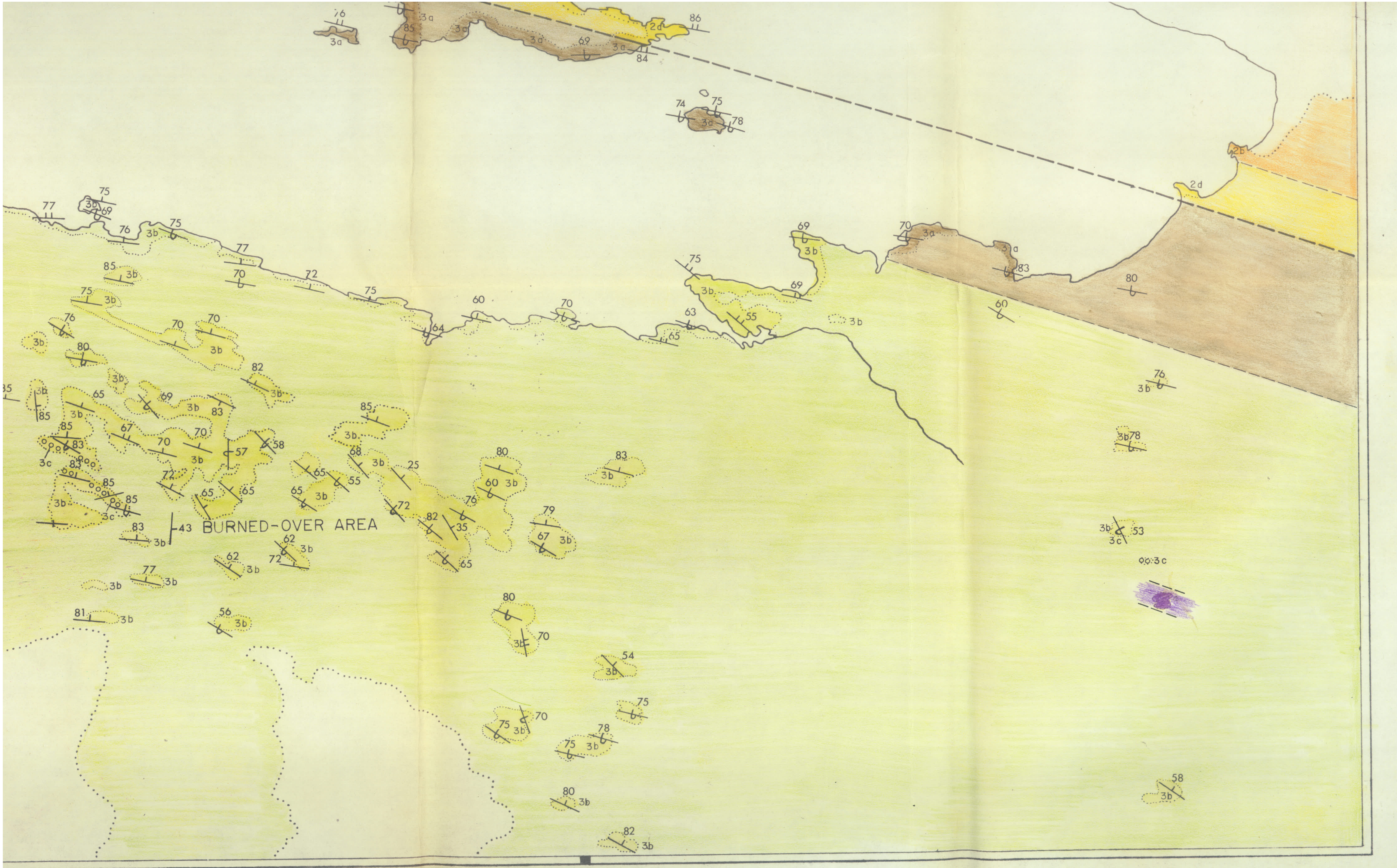
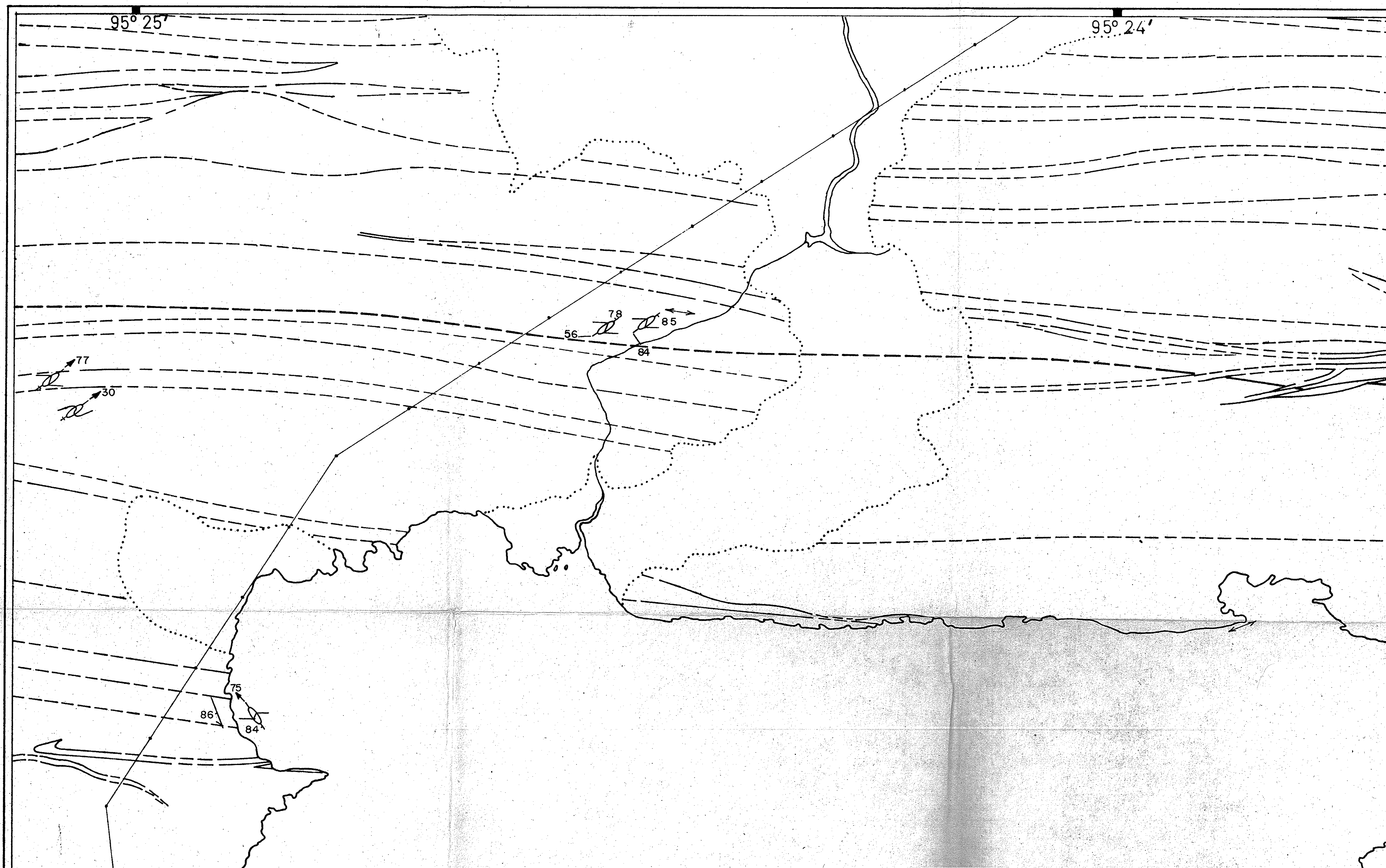
ical, overturned)
rtical)
ons (defined,assumed)
ns (defined,assumed)
BURNED-OVER AREA
3a
3b
3c
2a


BURNED-OVER AREA


95° 25′
95° 24′
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85
56
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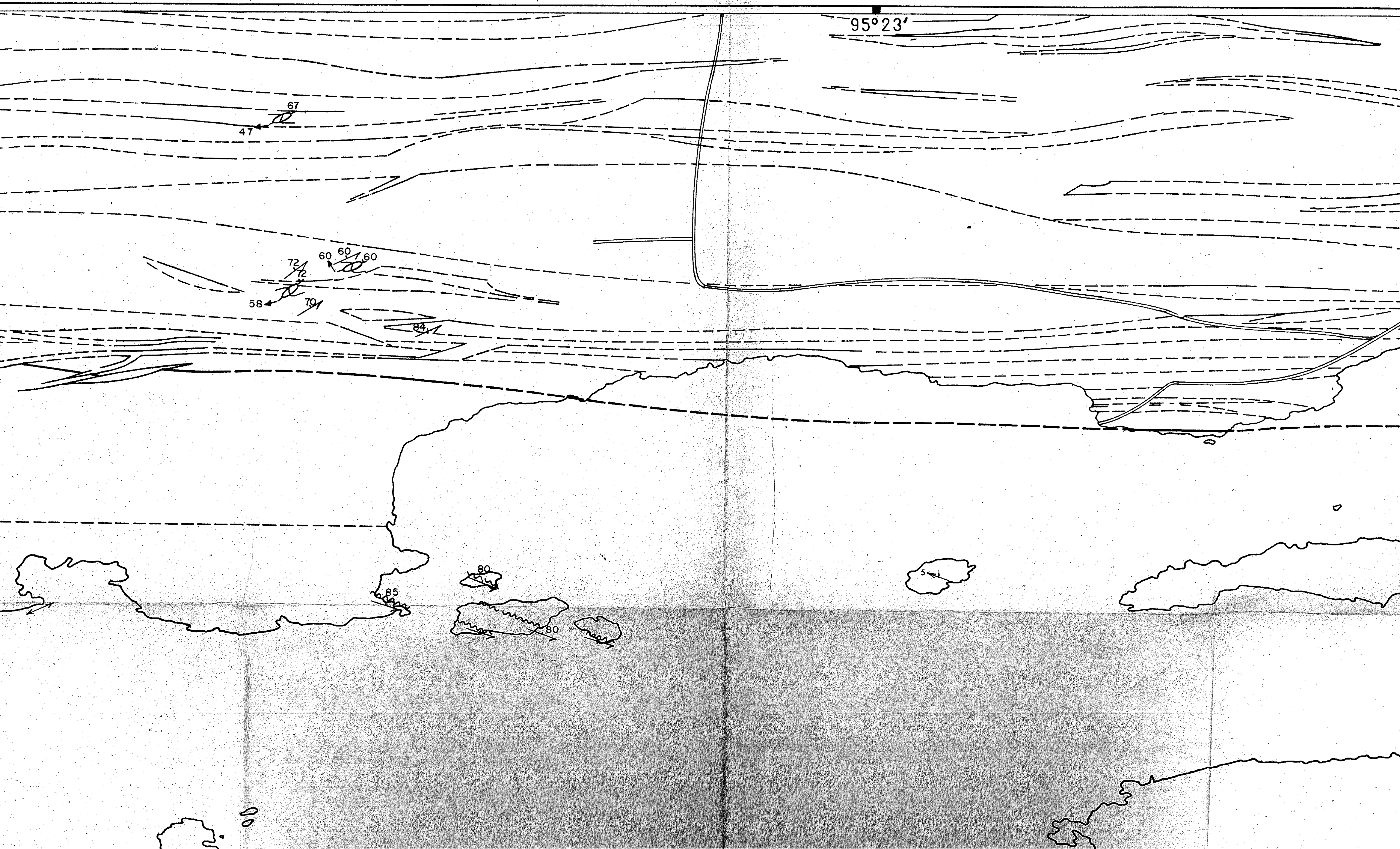
77
30
75
86
84


95°23′
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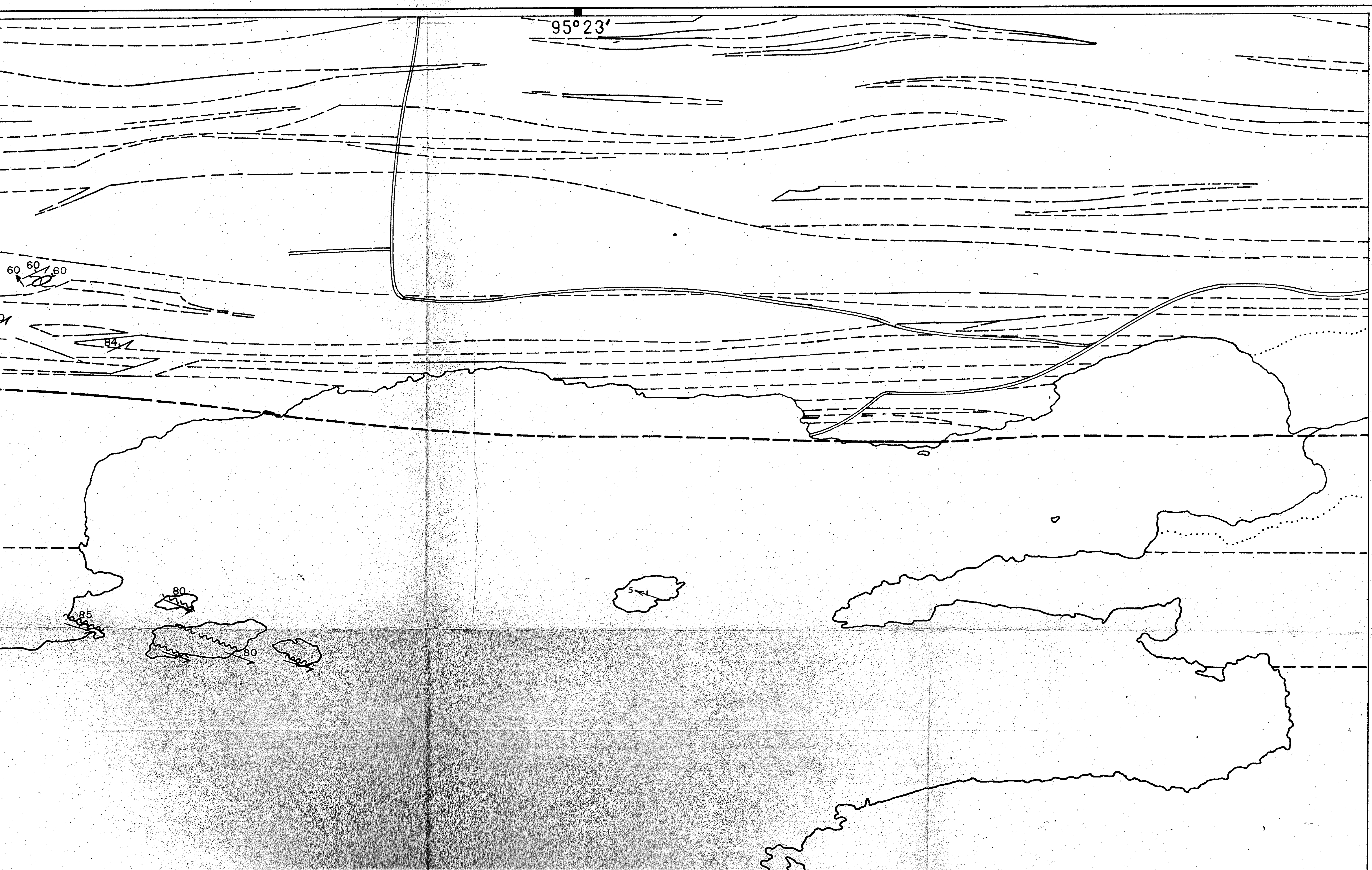
95°23′
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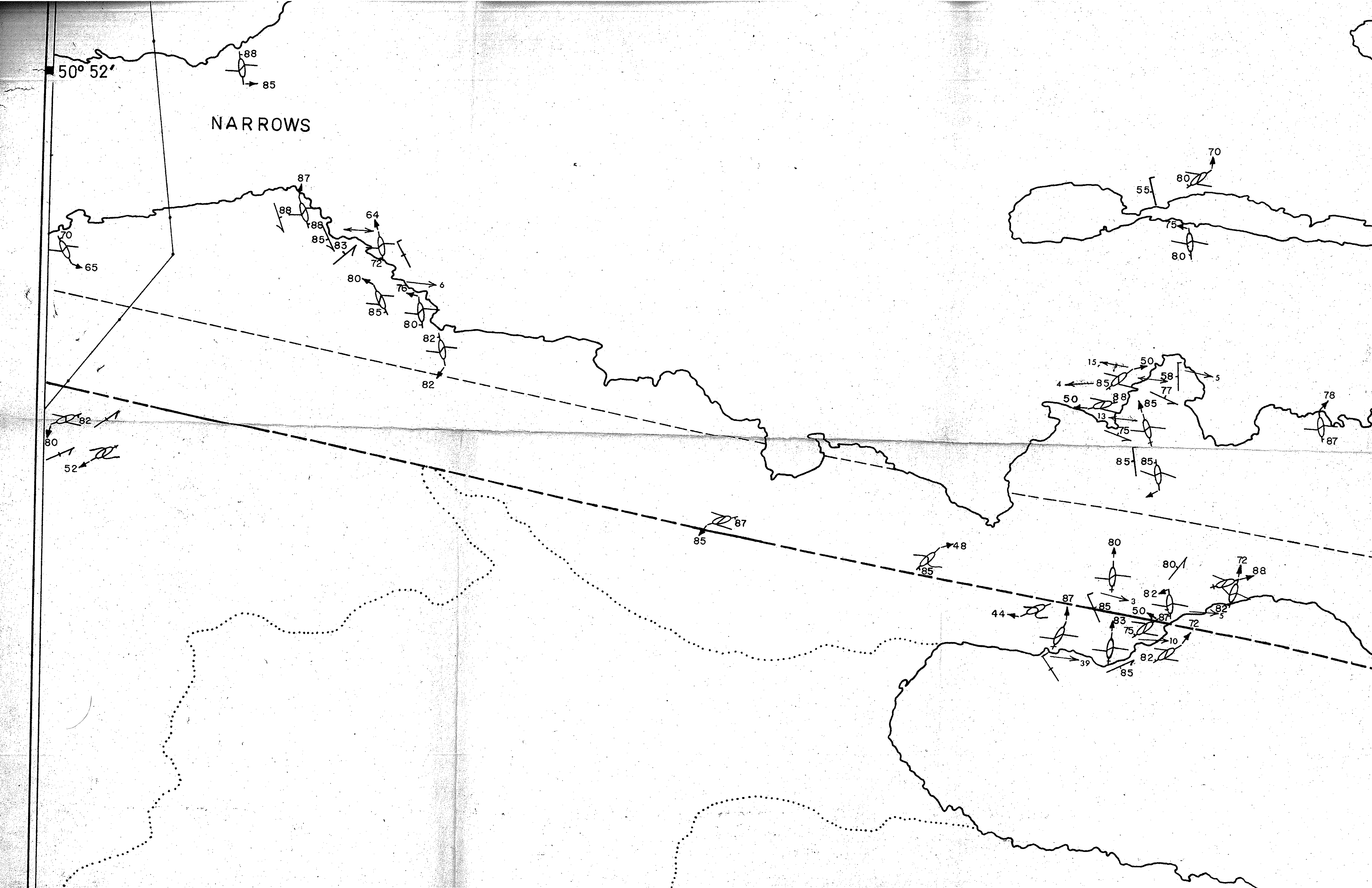
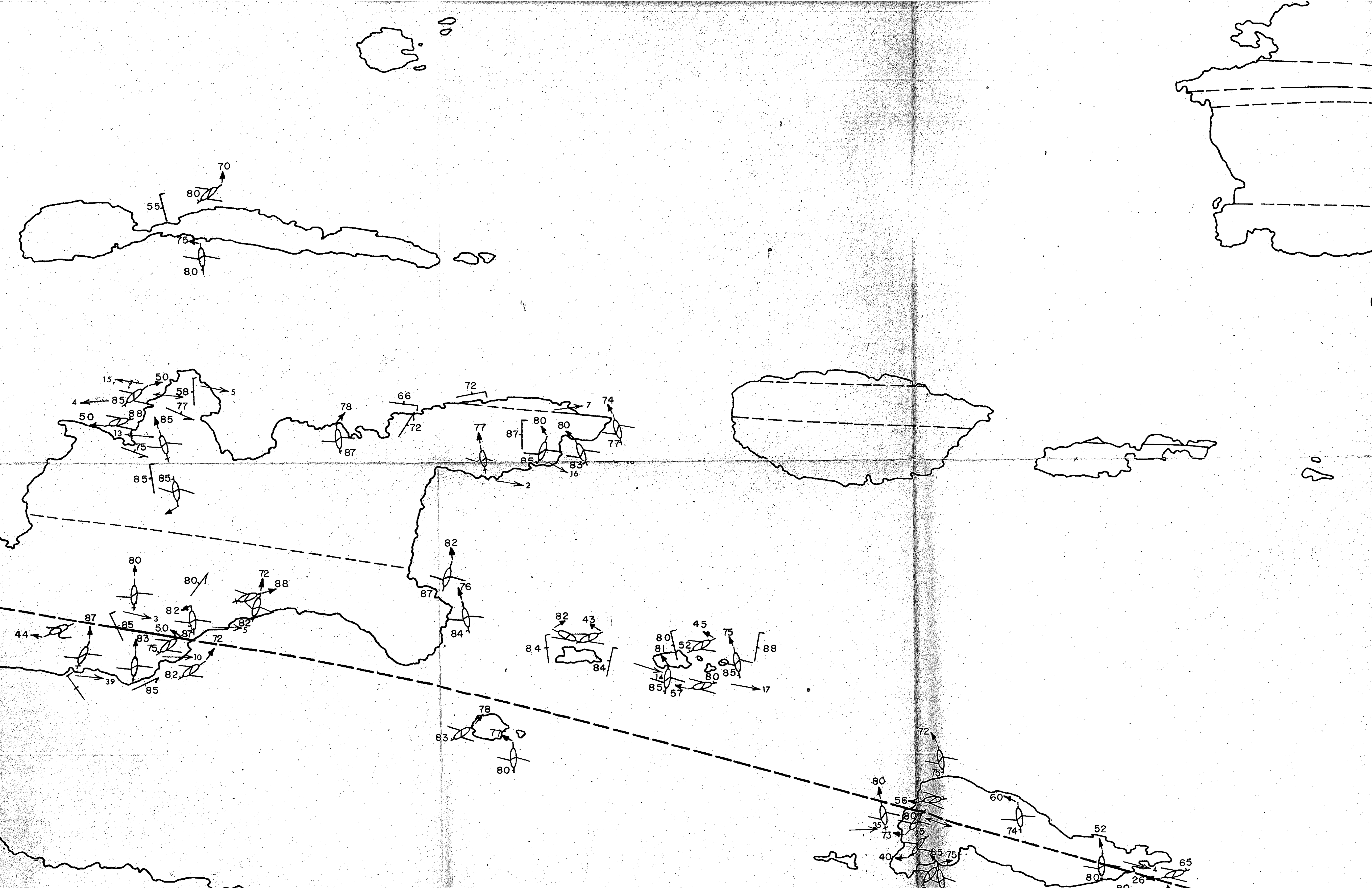

50° 52′
NARROWS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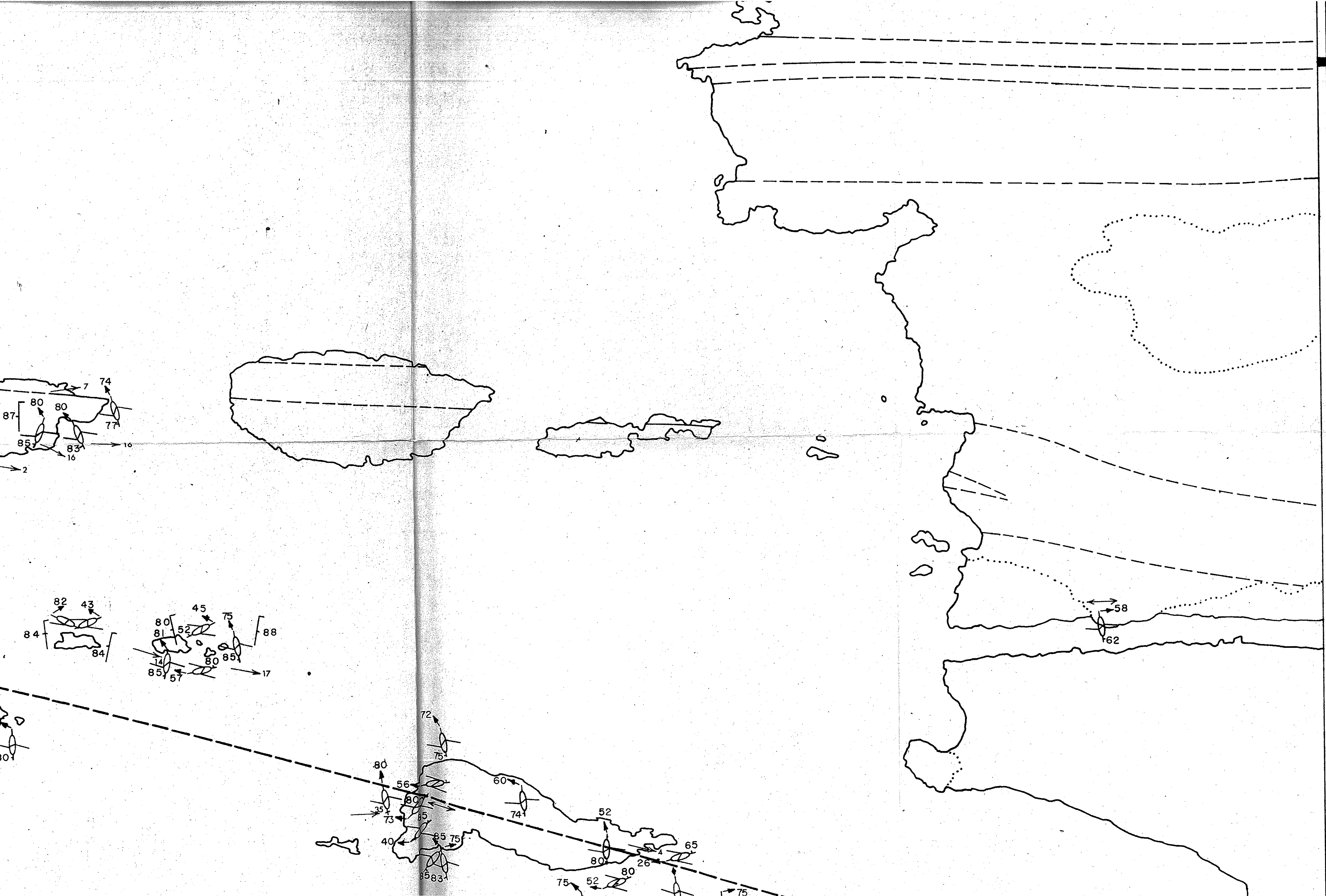

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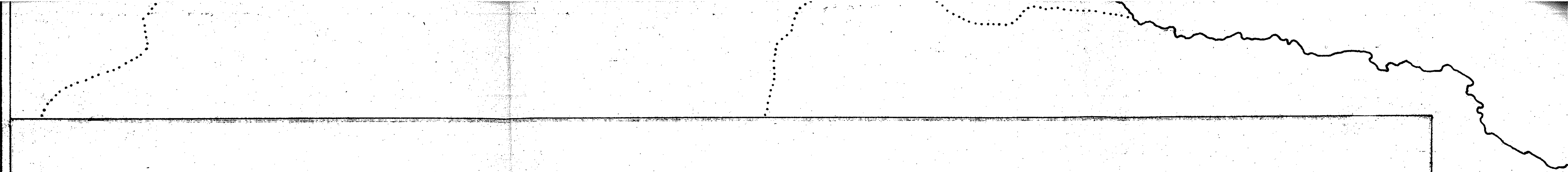


MAP NO. 3 STRUCTURES OF THE THIRD PERIOD OF DEFORMATION IN THE LONG LAKE AREA

N

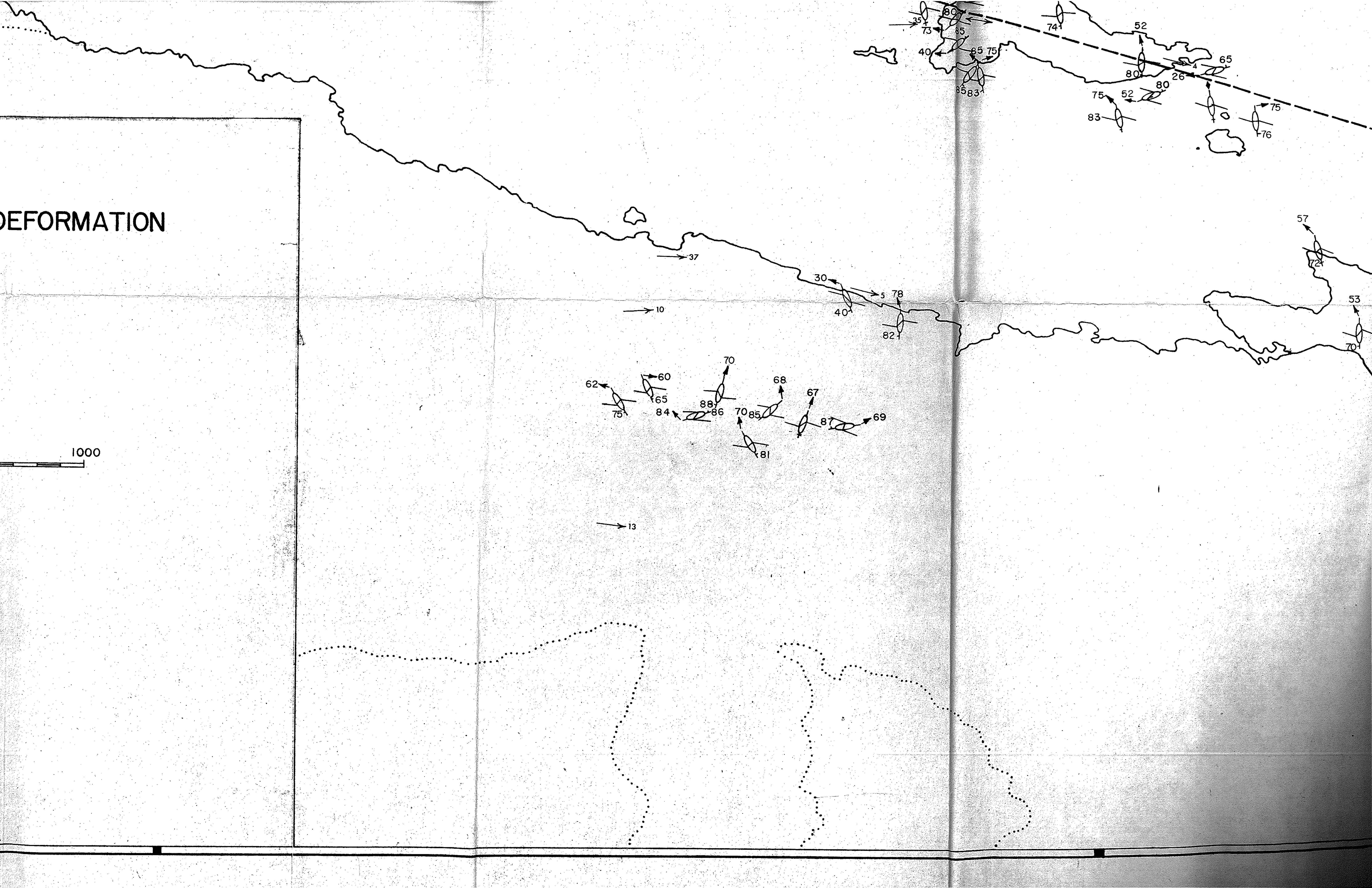
SCALE

0 500 1000

FEET

LEGEND

- Strain-slip cleavage (inclined, vertical)
- Fracture cleavage (inclined, vertical)
- Slickensides (inclined, horizontal)
- Axial planes of minor folds in foliation (inclined, vertical)
- Axes of minor folds in foliation (inclined, vertical)
- Kink fold (sense of folding, strikes of limbs, axial plane)
- Concentric minor folds (sense of folding, strikes of limbs, axial plane)
- Conjugate folds (senses of folding, strikes of limbs, axial plane)
- Geological boundary between formations
- Geological boundary within formations
- Fault
- Boundary of swamp
- Road
- Power line


DEFORMATION
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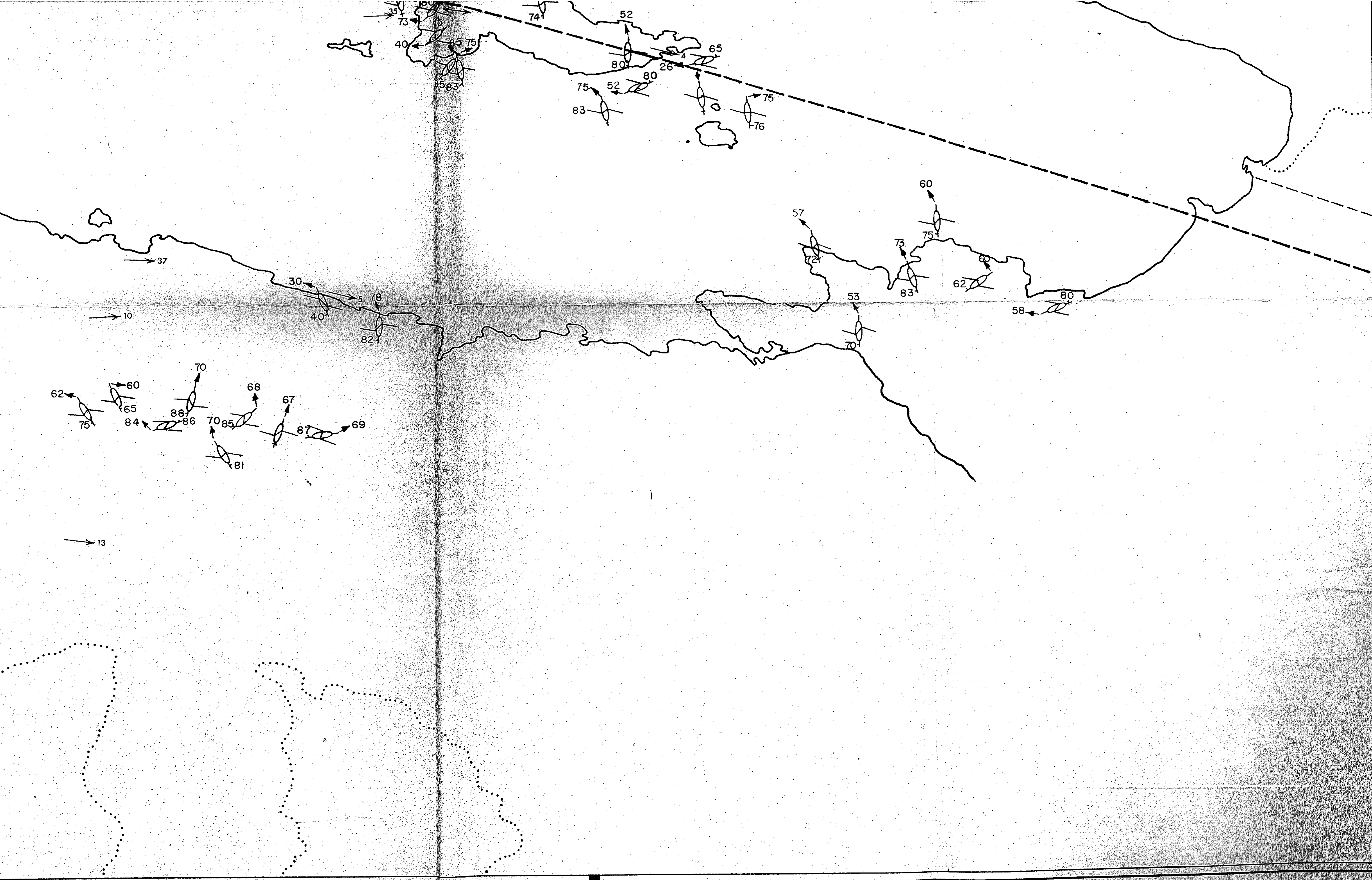

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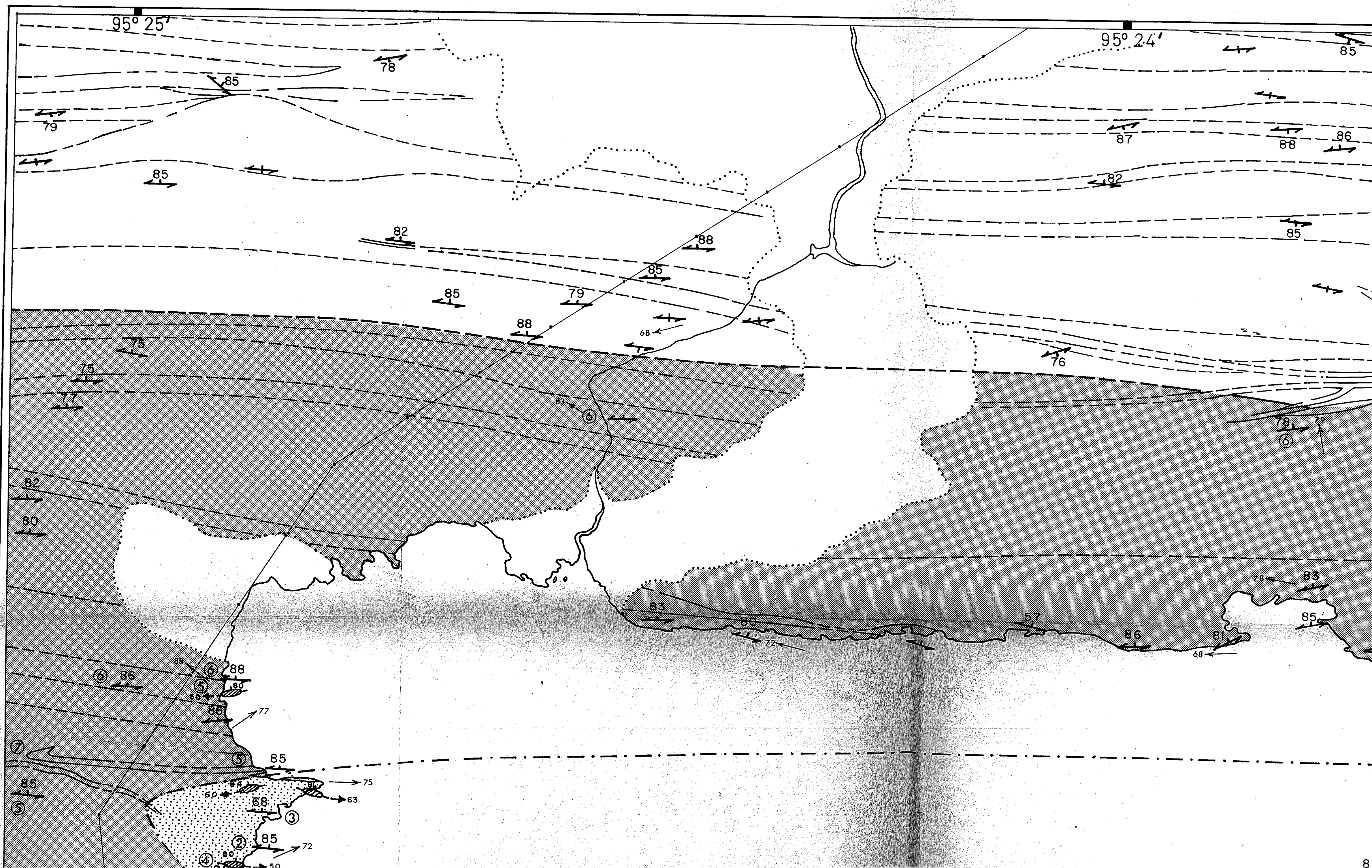
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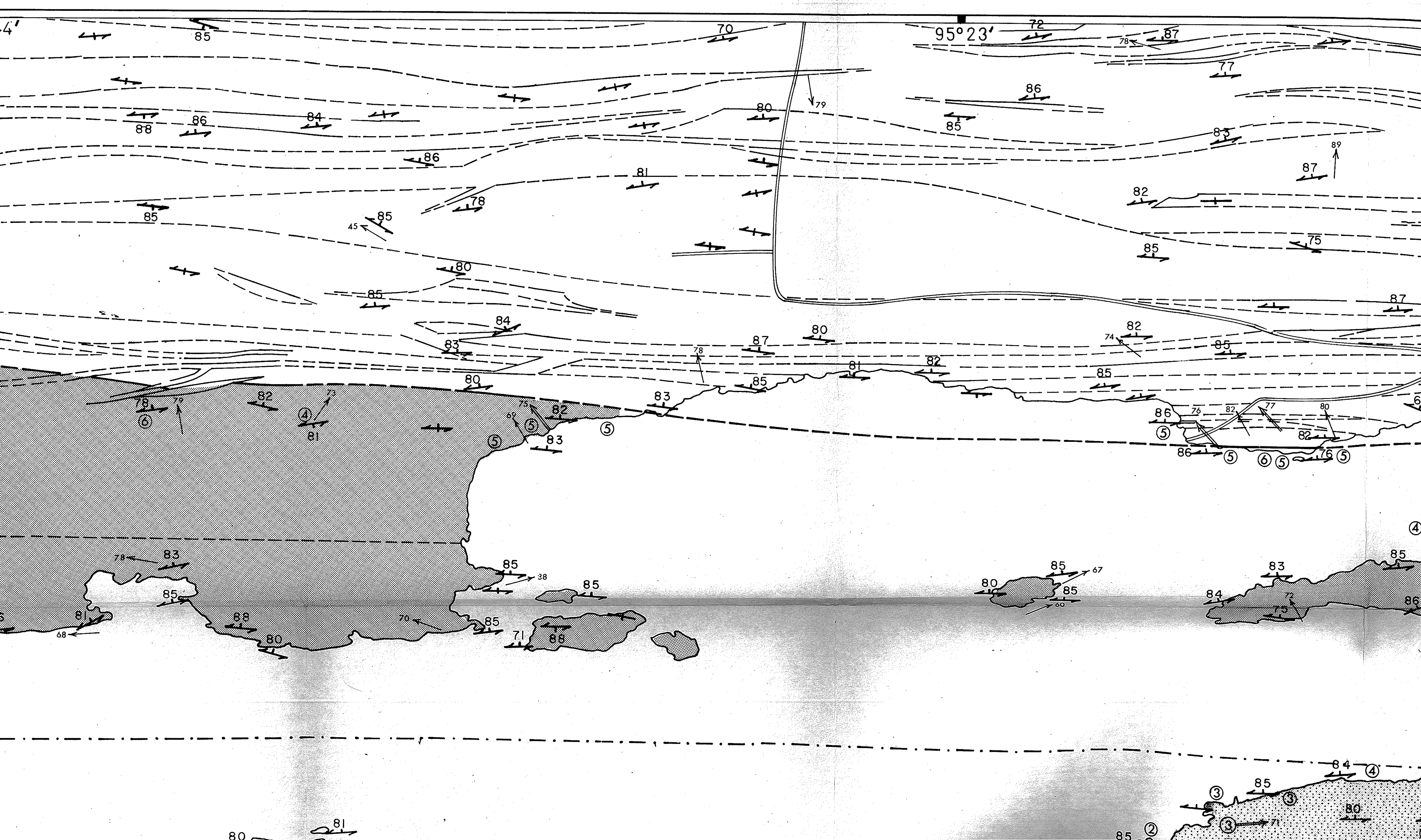
95° 24′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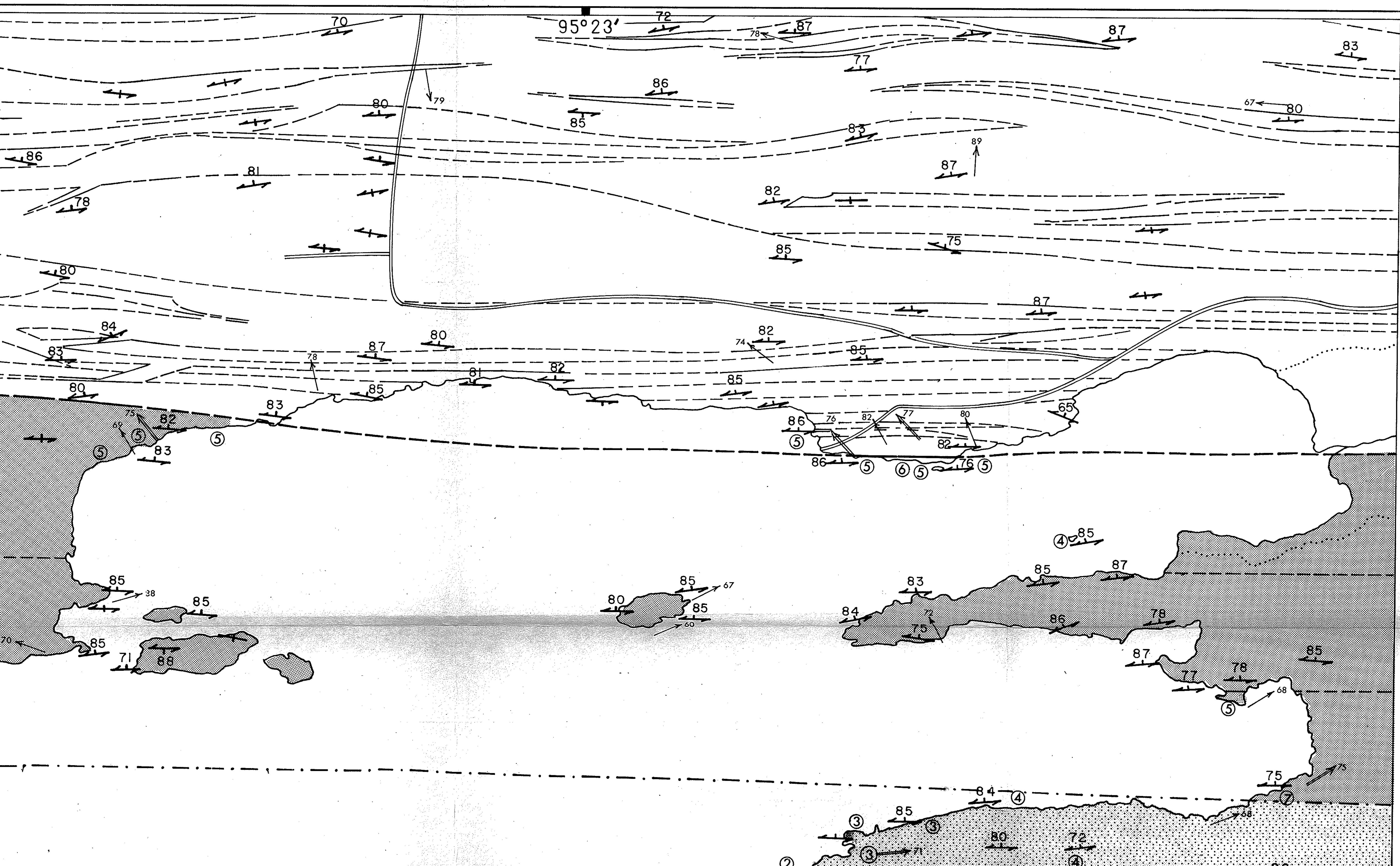
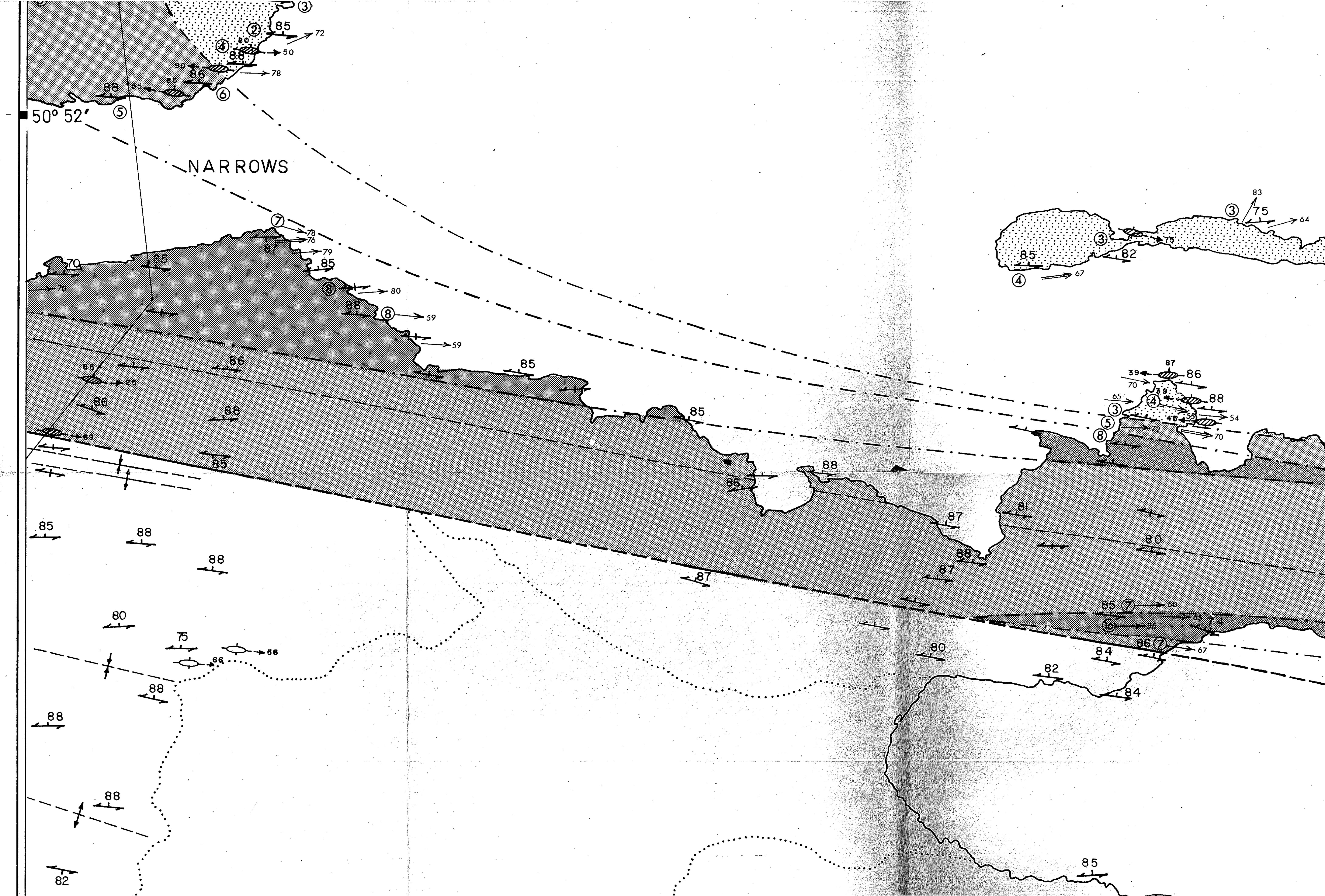
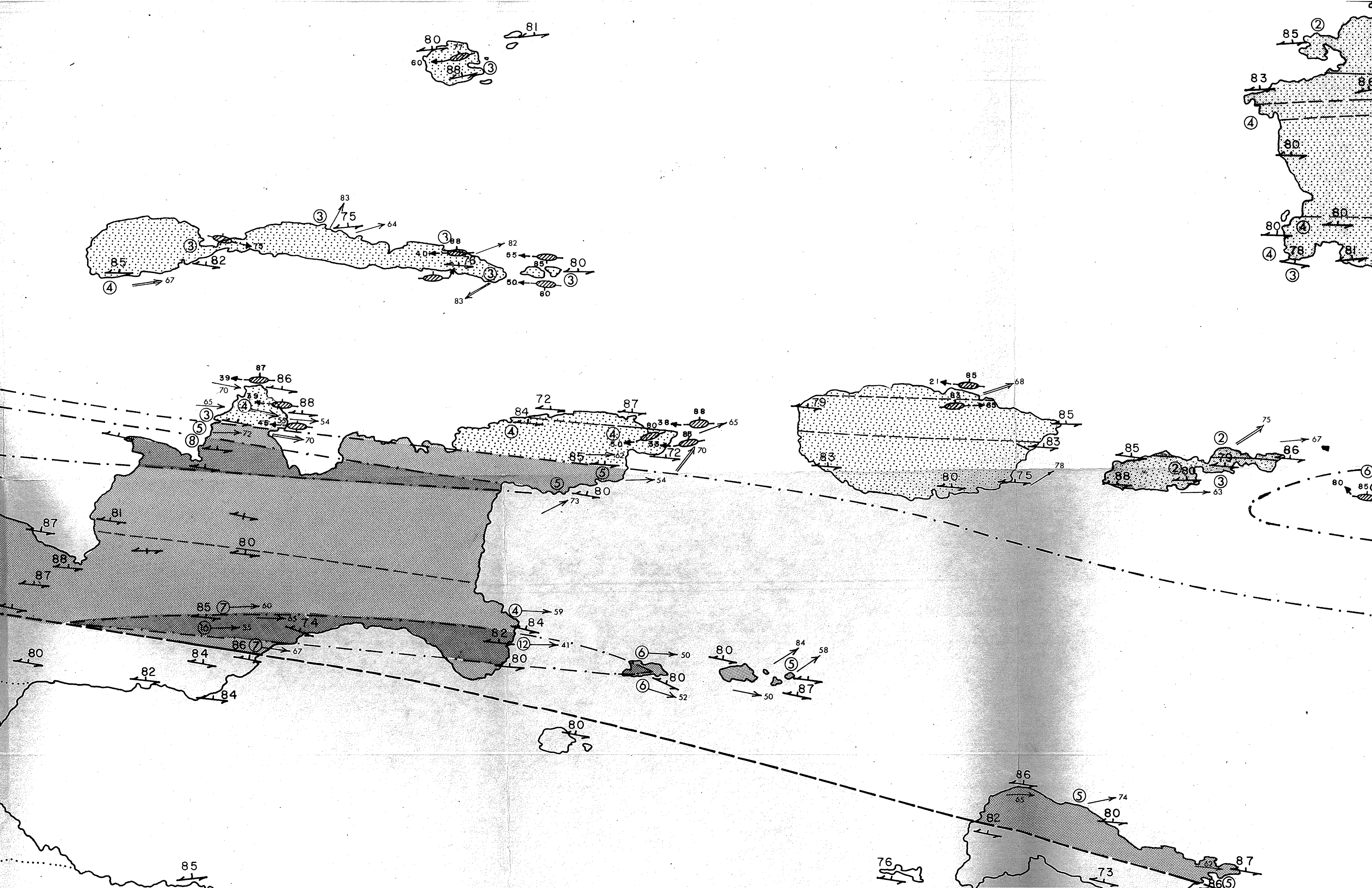

95°23′


50° 52′
NARROWS



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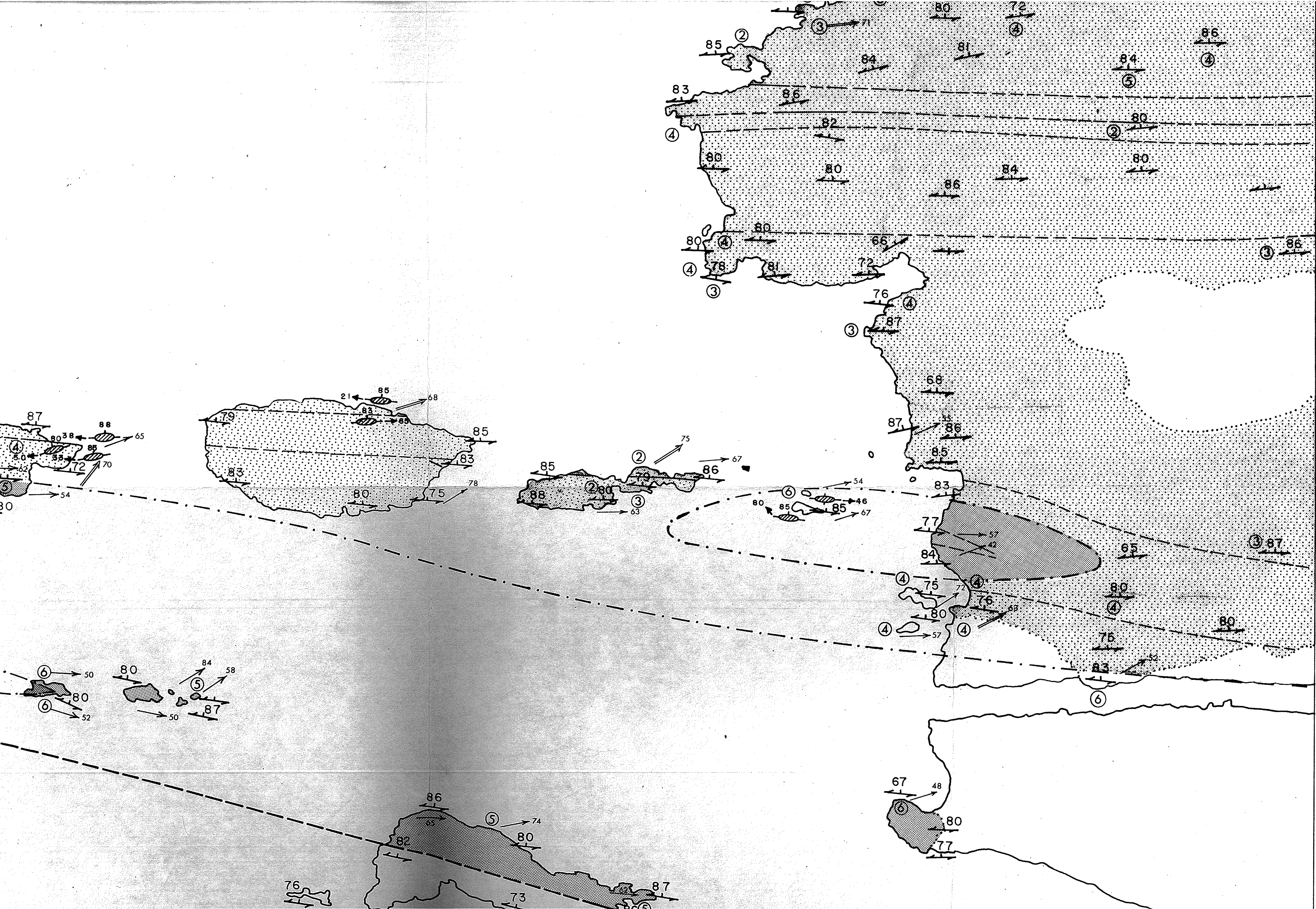
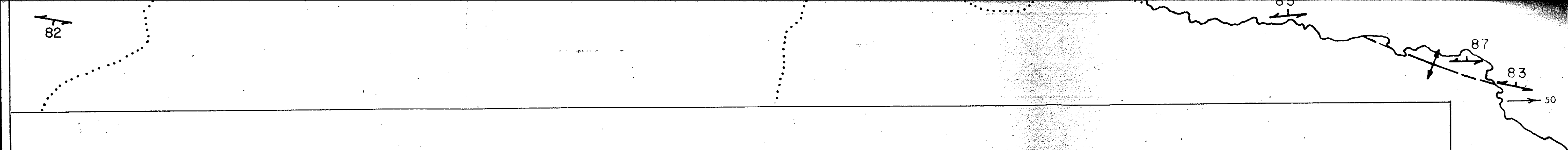




MAP NO. 2 STRUCTURES OF THE FIRST AND SECOND PERIODS OF DEFORMATION IN THE LONG LAKE AREA

SYMBOLS

- Foliation (inclined, vertical)
- Mineral lineations, slickensides
- Fragment lineations
- Axial planes of minor folds in bedding (inclined, vertical)
- Axial planes of minor folds in veins (inclined, vertical)
- Axes of minor folds (inclined, vertical)
- Boundary between areas with different elongation ratios of fragmets
- Axial trace of anticline (defined, assumed)
- Axial trace of syncline (defined, assumed)
- Geological boundary between formations (defined, assumed)
- Geological boundary within formations (defined, assumed)
- Boundary of swamp
- Road
- Power line

N

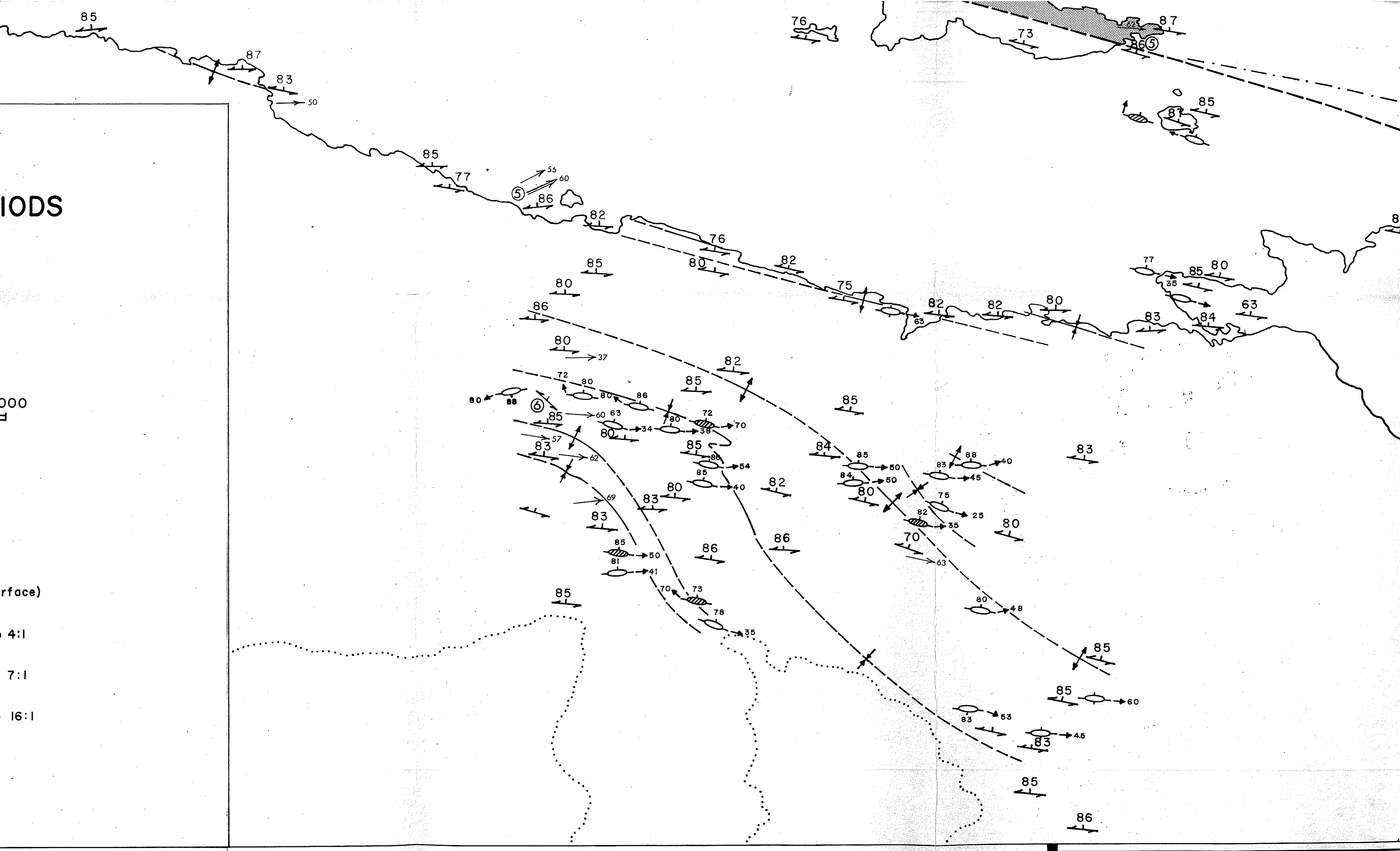
SCALE

0 500 1000

FEET

LEGEND

- ④ Elongation of fragments – (length/width on a horizontal surface)
- Area with elongation from 2:1 to 4:1
- Area with elongation from 4:1 to 7:1
- Area with elongation from 7:1 to 16:1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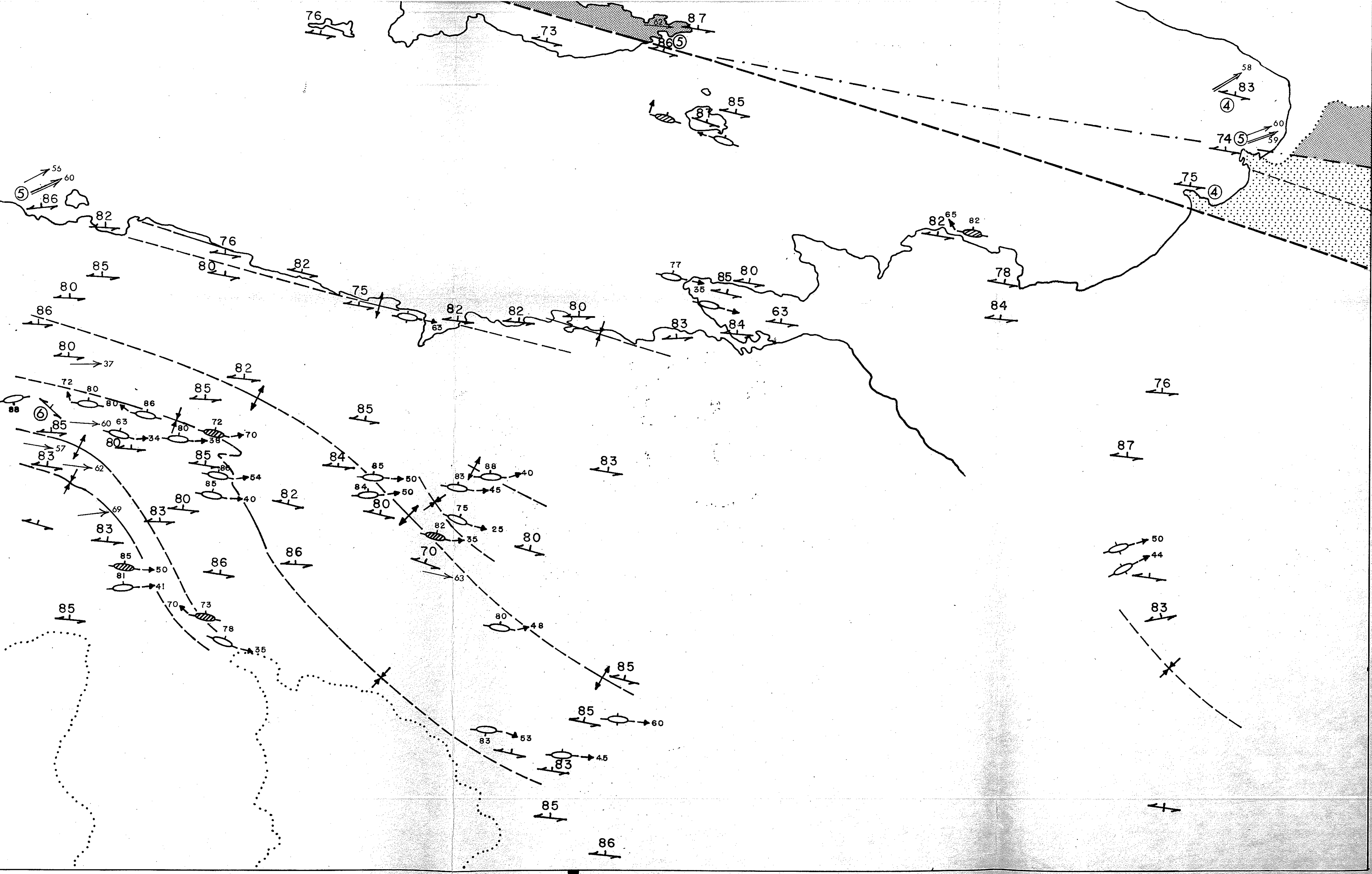
rface)
4:1
7:1
16:1



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