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AEROMAGNETIC STUDY OF THE REGIONAL GEOLOGY OF THE WESTERN HALF OF THE NORTHERN PENINSULA OF MICHIGAN

By

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ABSTRACT

AEROMAGNETIC STUDY OF THE REGIONAL GEOLOGY OF THE WESTERN HALF OF THE NORTHERN PENINSULA OF MICHIGAN

By Wafik M. Meshref

U.S. Geological Survey aeromagnetic maps of the western portion of the Northern Peninsula of Michigan from Wisconsin border to Keweenawán Bay and the Amasa Oval have been compiled to a common arbitrary magnetic base level and horizontal scale.

This study has shown conclusively that aeromagnetic interpretation is an extremely useful tool in determining the regional structure of a Precambrian terrain consisting of widely diverse magnetic formations. The complexity of magnetic rock properties restricted the interpretation to a semi-quantitative approach based upon the integration of the surface geology, Bouguer gravity anomalies, and the results of analytical studies of the magnetic data.

The near surface contact between the Northern Trap Range lavas and the Jacobsville sandstone is believed to have a southerly dip along most of its extent west of longitude 89° 20' W. This dip probably originates from cross-faulting and/or sliding of a block of Keweenawan lavas over the Jacobsville sandstone after the major thrust of the Northern Trap Range lavas along the Keweenawan fault. A

time break in deposition of the Jacobsville sandstone is believed to have taken place during the period of tectonism associated with the Keweenawan fault.

The structure in the Porcupine Mountains area and the origin of the Iron River syncline is interpreted to be the result of a lopolithic intrusion of rhyolite.

The structure of the Middle Trap Range is interpreted as an upfaulted block of lava in form of a horst. These volcanics are burried beneath 1250 to 2500 feet of sandstone. This variation in depth to the Middle Range is believed to be due to several cross faults of considerable vertical displacement.

The thickness of the Michigamme slate varies between 1500 and 4000 feet in different portions of the basin. However, a magnetic source underlying the Michigamme slate was recorded at a depth of about 7000 feet. This is the deepest magnetic source in the study area.

The Wolf Lake granite outcropping south of the Barb Lake fault is believed to be of Lower Precambrian age as the granitic basement rocks in the center of the Marenisco anticline. The magnetic strata of the Marenisco Range, mapped to be of uncertain stratigraphic position, are interpreted as the Ironwood iron formation of the Tyler slate series on the south limb of the Marenisco anticline.

A magnetic trend analysis indicated that the acting stress on the Pre-Keweenawan rocks was of a non-rotational nature and that the principal stress axis was north-south. It also indicated that the acting stress during the Keweenawan time was of a rotational nature due to a shear couple which was shifting in time and space.

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CHAPTER I

INTRODUCTION

The U.S. Geological Survey in cooperation with the Geological Survey Division of the Michigan Department of Conservation conducted a comprehensive restudy of the mineral-bearing districts of Michigan. As a part of this program aeromagnetic surveys have been conducted over the majority of the Northern Peninsula of Michigan. The geologic interpretation of portions of these surveys have been published by Balsley and others (1949), Wier and others (1953), and Case and others (1965).

A portion of these aeromagnetic maps has been selected for geologic interpretation. The area chosen for this study covers about 5,000 square miles, including most of the western half of the Northern Peninsula of Michigan. It includes Ontonagon, Gogebic, Iron, and parts of Baraga and Houghton Counties. The area shown in Figure 1 is located south of latitude 47° 00' N, west of longitude 88° 07' 30" W and is bounded on the west and south by the Michigan-Wisconsin border. The geology of the area of investigation is varied and highly complex, and although it has been studied for nearly a century, the regional geology has not been completely defined primarily

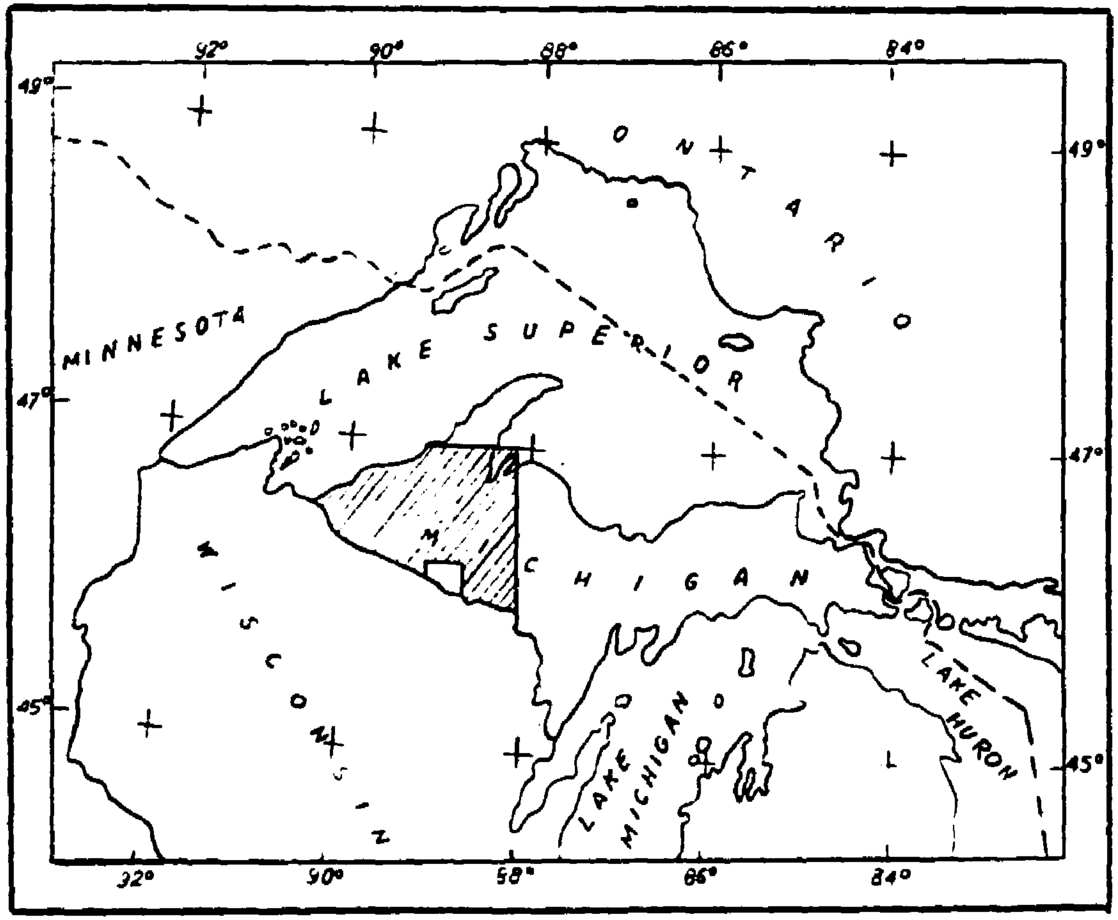

Fig.1. Index map of area of investigation.

because of the surficial covering of sediments and Pleistocene glacial drift. Due to the varied magnetic properties of the Precambrian rocks, the magnetic method should provide an excellent tool for delineating the regional geology and structural patterns of the area.

Rocks of Lower, Middle (Animikie), and Upper (Keweenawan) Precambrian age underlie most of the area. The Lower Precambrian rocks form the basement and consist of granite, gneisses, greenstones, and other metavolcanic rocks. One or more periods of metamorphism and deformation occurred before the end of Early Precambrian time. These basement rocks are separated from the overlying metasedimentary rocks of Middle Precambrian age (Animikie), by a major unconformity. Widespread deformation and regional metamorphism occurred at the close of Middle Precambrian time. Prior to that time intrusive bodies of both Lower and Middle Precambrian age were emplaced.

The Keweenawan rocks are separated from the underlying Animikie rocks by another major unconformity. These rocks include the Keweenawan lava flows, conglomerates, sandstone, and shales. During Late Precambrian (Keweenawan) diabase dikes, which have a dominant westward trend, intruded the older rocks. These Precambrian rocks are unconformably overlain in the central part of the area by flatlying Jacobsville sandstone and generally are concealed by glacial debris of Pleistocene age.

The general purpose of this study is to map the regional structure and lithology of the Precambrian rocks in the area, using the aeromagnetic data as the main source of geophysical information.

The specific objectives of this study are:

1. To map the Precambrian rocks where information is sparse due to the lack of outcrops and/or the inaccessibility of the area.
2. To trace the location of the Keweenaw fault in the area.
3. To delineate the structure of the Keweenawan rocks in the area and the basement structure that underlies the Animikie sediments.

The primary objective in magnetic interpretation is to draw inferences about the attitude, depth, configuration, and lithology of the subsurface structure. To accomplish this, information must be obtained about the regional geology and the induced and remanent magnetization of the underlying basement complex. Therefore, geologic information about the area of investigation was compiled on one map of the same scale as the aeromagnetic map of the area (1:62,500). The purpose of this map is to facilitate the correlation of the known geology with major magnetic anomalies and broad areas that have characteristic magnetic patterns. The character of these magnetic anamalies was used to interpret the geology of areas which have not been previously mapped. Rock samples were collected representing most of the lithologies in the area for the purpose of determining their magnetic properties.

Qualitative and quantitative magnetic interpretation was accomplished using the following interpretation tools:

1. Published depth determination techniques were applied to the study area in order to interpret adequately the geology and structure of the basement rocks.
2. A magnetic trend analysis was conducted to help define the major structural trends in the area under investigation, and correspondingly the direction as well as the nature of the tectonic forces involved in developing these trends.
3. A second vertical derivative map of the total magnetic intensity was prepared for the central portion of the study area to aid in the depth determinations and to isolate the boundaries of magnetic units.
4. Theoretical magnetic profiles were calculated for assumed geologic bodies and compared with the observed magnetic profiles.

In addition, the magnetic interpretation was checked against the regional gravity map of the study area.

For the purpose of facilitating the discussion of the geology and the results of interpretation, the area of investigation is divided into two areas. This division is based primarily on geologic considerations as shown in Figure 2. The first area includes rocks of the Keweenawan age, as well as younger rocks. The second area is characterized by both Lower and Middle Precambrian rocks, i.e., Pre-Keweenawan rocks. This area constitutes the southern part of the study area and is further subdivided into an eastern and a western protion. The western protion covers mainly the area to the west and south of Lake Gogebic. The eastern protion includes the Iron River-Crystal Falls district and the Amasa Oval.

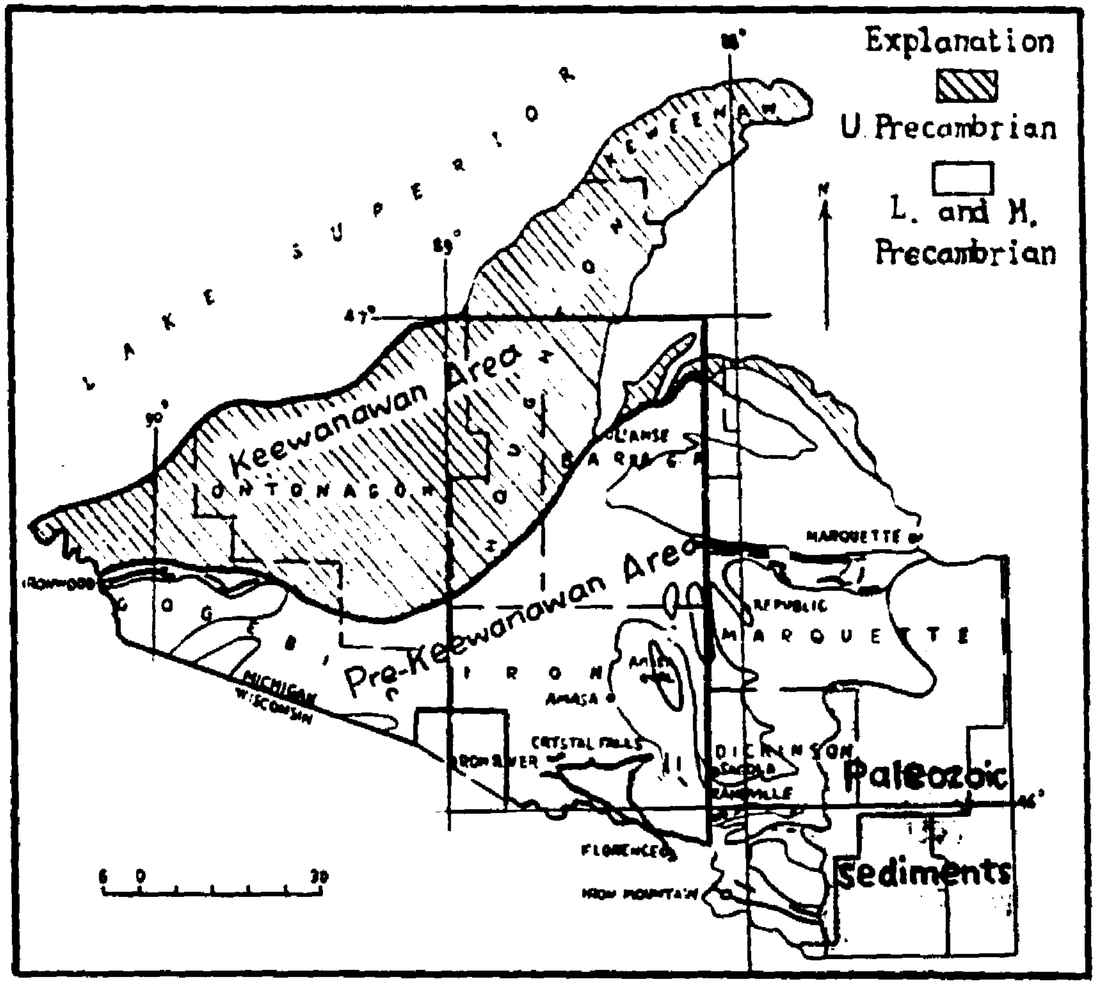

Fig. 2. Division of study area into two subareas according to regional geology.
(After Gair, 1956)

CHAPTER II

PHYSIOGRAPHY OF THE AREA

A comprehensive description of the physiography of selected protions of the area is presented in U.S. Geological Survey Monograph 52 (Van Hise and Leith, 1911) and in previous U.S. Geological Survey publications.

The study area is a part of the highland topographic province of the Lake Superior region. This is contrasted with the remainder of the Northern Peninsula of Michigan from Marquette eastward to Sault Ste. Marie, which is considered to be a lowland nowhere rising more than 900 feet above sea level or 300 feet above Lake Superior. The relief of the highland area varies between 1000 and 1700 feet with some exceptions as in the Porcupine Mountains area, which lies in the northwest part of the study area. The mean elevation of the Porcupine Mountains is about 1500 feet, but in some areas it exceeds an elevation of 1950 feet above mean sea level. One of the major topographic features in the area is the depression occupied by Lake Gogebic.

The highland forms a broad upland cut by valleys that lie 100 to 400 feet below the general ground level and it is diversified by monadnocks and other ridges.

The upland is made up chiefly of the Lower Precambrian rocks, that include greenstones, granites, and other coarse grained rocks together with schists and gneisses, most of which are homogeneous over broad areas in their resistance to weathering and erosion. Where folding and faulting occurs, the Animikie schists, gneisses, and quartzites and the Keweenawan lavas usually present homogeneous resistance to weathering over narrow linear belts, thus, resulting in ridges and monadnocks.

The Northern Trap Range, composed mainly of Keweenawan lavas, extends across the northern and northwestern parts of the area. It is a northeastward trending homoclinal ridge, dipping to the northwest. It has rugged topography as a result of the differential erosion of the more resistant lavas and the less resistant surrounding sedimentary rocks. The average local relief is about 300 feet. A broad, relatively flat plain, occurs south of the Northern Trap Range. It has an average elevation of 1300 feet above mean sea level. This plain is covered with the Jacobsville sandstone. Uralitized basalt flows outcrop within this plain at Silver Mountain which is located in sections 1 and 12 of T49N, R36W, and section 6 of T49N, R35W, Houghton County. Limestone Mountain, an outlier of Ordovician limestone is located about 10 miles north of Silver Mountain.

The South Trap Range outcrops occasionally along the southern edge of the Jacobsville sandstone plain. East of Lake Gogebic the South Trap Range dips to the northwest at about 15°, but it dips about 70-80° west of Lake Gogebic.

A narrow lowland area skirts the south shore of Lake Superior in the study area. This area is underlain by rocks of Upper Keweenawan age, mainly the Outer Conglomerate of the Copper Harbor group, Nonesuch shale and Freda sandstone of the Oronto group.

The most important topographic feature in the southwestern part of the area is the Penokee-Gogebic Range, which extends from west of Lake Gogebic to the western border of the study area. The Penokee-Gogebic Range rises to elevation of 1500 to 1800 feet (Irving, 1880) which is 100 to 300 feet above the lower land to the south.

Extending along the southern border of the Animikie rocks is a prominent ridge. This ridge is not continuous, but rather consist of a series of disconnected linear highlands, the crest of which in some parts of the district is formed by the Ironwood formation. In other parts of the district the highlands are formed by the granitic rocks of the Lower Precambrian which occur as rather rugged hills.

The topographic characteristics of the Lower Precambrian rocks in the extreme northeastern portion of the study area has been described in great detail by Van Hise and Bayley (1895) as follows:

North Complex--which constitutes the Huron Mountains, the southern part of which is exposed in the northeastern part of the area. In this complex isolated remnants of schists form rugged hills, while granite and syenite form rounded knobs.

South Complex--primarily consists of knobs as in the northern granite areas.

The topography of the Crystal Falls district has been described by Clements and others (1899). The topography is typical of the glaciated Lake Superior uplands. Low, swampy areas, alternate with undulating plains, knobs, and kettle terrains. In most areas the topography is controlled by the bedrock. The uplands are predominantly massive igneous and volcanic rocks or silicious facies among the sedimentary rocks. The low swampy tracts, generally are underlain by slates and schists as in the Michigamme slate plain, west of the Crystal Falls area. The average relief is about 200 feet. Michigamme Mountain which reaches an elevation of 1600 feet is the highest topographic feature in this district.

CHAPTER III

GEOLOGY OF THE AREA

General

The geology of the Precambrian terrain of the Northern Peninsula of Michigan has been described in early publications of the U.S. Geological Survey, and the Michigan Geological Survey (Irving and Van Hise, 1892; Van Hise and Bayley, 1897; Clements and Smyth, 1899; Van Hise and Leith, 1911; Allen and Barrett, 1915; Barrett, Pardee, and Osgood, 1929; Leith, Lund and Leith, 1935; Martin, 1936; and many others).

Unlike the situation with respect to post-Precambrian time, there exists no widely accepted reference framework of eras and periods to which Precambrian lithologic units and geologic events can be related. James (1958) introduced new formal names and summarized the stratigraphic nomenclature used by the U.S. Geological Survey for the Precambrian rocks that occur in this part of Northern Michigan. His nomenclature is shown with previous investigator's classification in Table 1.

The three subdivisions of the Precambrian as used by the U.S. Geological Survey are separated at most places by major unconformities. They are overlain in places by

TABLE 1.--Comparison of major subdivisions of Precambrian rocks of Northern Michigan with previously used terminology.

	Van Hise & Leith (1911)		Leith, Lund & Leith (1935)	Grout et al (Minnesota) (1951)	Present U.S. Geological Survey Usage for N. Mich.
	Algonkian		Algonkian type	Late Precambrian	Upper Precambrian
Proterozoic	Archean	Precambrian	Archean type	Middle Precambrian	Middle Precambrian (Animikie)
				Early Precambrian	Lower Precambrian

Paleozoic rocks and generally are concealed by glacial debris of Pleistocene age.

The author will follow the terminology currently used by the U.S. Geological Survey. The Lower Precambrian rocks, "Archean", consist predominantly of granites, gneisses, greenstones, and other metavolcanic rocks. These rocks are widely exposed in the western portion of the study area, as compared to the eastern portion.

The Animikie rocks are represented by a thick sequence of metasedimentary and metavolcanic rocks. These rocks have been referred to as the "Huronian Series" for over 70 years, but this designation has been changed to the Animikie series. James (1958) showed that the correlation of the Middle Precambrian rocks of Northern Michigan with the Animikie group of northeastern Minnesota is more valid than their correlation with the Huronian rocks of Ontario. He divided the Animikie series into four typical groups and applied them to his study of the Precambrian rocks of Iron and Dickinson Counties.

Widespread deformation and regional metamorphism occurred at the close of Middle Precambrian time. Prior to that time intrusive bodies of both Lower and Middle Precambrian age were emplaced. The largest and most abundant of these were irregular and tabular masses of gabbro and diabase that were highly altered during the subsequent metamorphism.

Irving (1883) recognized an unconformity between the Keweenawan "Upper Precambrian" and the underlying Animikie series, as well as an unconformity above with the Jacobsville sandstone. There is no definite and clear agreement in the previously published reports, concerning the divisions of the Keweenawan rocks. In most reports these rocks are divided into two main groups, either Upper and Lower or Upper and Middle Keweenawan. In more recent reports, the Keweenawan rocks are divided into three groups, Upper, Middle, and Lower. The author will follow this division of the Keweenawan rocks through the course of this study.

The Keweenawan Area

Stratigraphy

The Keweenawan rocks and Jacobsville sandstone underlie the area defined here as the Keweenawan area. Table 2 shows the generalized geologic column of this area.

Lower Keweenawan Rocks

Hubbard (1967) pointed out that the Keweenawan volcanic rocks in the western portion of the Northern Peninsula of Michigan should be divided into two sequences. A younger sequence, about 15,000 feet thick, is equivalent to the Portage Lake Lava Series of the Keweenawan Point. A second, older series of traps which

TABLE 2.--Generalized geologic column for the Keweenawan area.

Cenozoic		
	Quaternary	
		glacio-fluvial deposits
____ ____ ____	Unconformity	____ ____ ____ ____
Paleozoic		
	Cambrian	
		Jacobsville Sandstone
____? ____? ____?	Unconformity	____? ____? ____? ____?
Upper Precambrian		
	Keweenawan	
	Upper:	
		Oronto Group
		Freda Sandstone
		Nonesuch Shale
		Copper Harbor Group
		Outer Conglomerate
		Lake Shore Trap
		Great Conglomerate
	Middle:	
		Portage Lake Lava Series
		Eagle River Group
		Ashbed Group
		Central Mine Group
		Bohemian Group
	Lower:	
		South Trap Lavas
		Quartzite Member
____ ____ ____	Unconformity	____ ____ ____ ____
Middle Precambrian		
	Animikie	

are exposed in the South Range are about 8,000 feet thick. He suggested that the two series are separated by more than 7,000 feet of sedimentary rocks.

Hubbard's studies indicate that the upper flows of the South Range contain groundmass feldspars that are uniformly more sodic and generally finer grained than the Portage Lake flows. A few of the upper South Range flows are porphyritic, having feldspar phenocrysts that range from one half of an inch to one inch in length. The lower most South Range flows are interbedded with a few well-sorted Lower Keweenawan type sandstones. West of Bessmer, the lowest flow is a "pillow" lava whose emplacement locally contorted the upper few inches of the underlying even-bedded sandstone layer. These features indicate that the Lower Keweenawan sandstones in the South Trap Range probably are an uninterrupted sequence. The thickness of this lower quartzite member is about 500 feet (Reed, 1968).

Kenneth Book of the U.S. Geological Survey has found that the paleomagnetic field directions of the Portage Lake lava series near Ironwood are similar to those of the lavas of the Keweenawan Point and that the paleomagnetic field directions of the South Range Traps are distinctly different. The paleomagnetic properties of the rocks within each sequence are internally consistent.

Based on petrological, as well as magnetic properties differences between the two sequences, an age difference seems to be certain. The South Range lavas is believed to be of Lower Keweenawan age.

Middle Keweenawan Rocks

The Portage Lake Lava Series

The Portage Lake lava series is a thick sequence of basalt and andesite flows, with a few interbedded rhyolitic conglomerates and local rhyolites (White, 1953). It comprises the following four groups (Irving, 1883):

(a) The Bohemian Range Group.--The Bohemian Range group is a sequence of amygdaloidal basalt flows. It contains subordinate conglomeratic beds and rhyolites. It attains a thickness of 10,000 feet. A basal conglomerate rests unconformably on the Animikie of Middle Precambrian rocks (Allen, 1915).

(b) The Central Mine Group.--The Central Mine group is a similar sequence characterized by thick lava flows. Associated with these flows are minor interbedded rhyolitic conglomerates and thin ash beds.

(c) The Ashbed Group.--The Ashbed group is described as a series of interbedded lava flows and subordinate coarse, sedimentary rocks. In the Porcupine Mountains, the lower part is a thick sequence of rhyolite (Thaden, 1950).

(d) The Eagle River Group.--The Eagle River group is a 2,000 foot sequence of basic lava flows, interbedded with minor amounts of rhyolitic conglomerates.

Upper Keweenawan Rocks

The Copper Harbor Group

The Copper Harbor group is the thickest and most persistent conglomerate of the Keweenawan sequence. It can be traced from Keweenawan point to Black River near the Michigan-Wisconsin border and further west. It is 5,000 feet thick in the Porcupine Mountains and comprises three distinct units, known in the older literature as: the Great and Outer Conglomerates which are separated by the Lake Shore Traps.

Lithologically the sedimentary units are poorly stratified conglomerates, containing minor interbedded, medium to coarse grained arkosic sanstones. These units interfinger and pinch out in relatively short distances. The ratio of sandstone to conglomerate is unknown due to absence of continuous exposures.

The Lake Shore Traps are a 300 to 400 feet thick series of basic lava flows. They form the escarpment overlooking Lake of the Clouds in the Porcupine Mountains.

The Oronto Group

A sharp lithologic break separates the Copper Harbor conglomerate from the overlying Nonesuch shale and

Freda sandstone. These units are a series of silty shales, siltstones and sandstones, several thousands of feet thick.

(a) The Nonesuch Shale.--The Nonesuch shale is predominately a flaggy, grey to reddish-grey siltstone, 800 feet thick, with interbedded grey to greenish-grey, silty shales. The presence of ripple marks and mud cracks indicate a shallow marine or continental environment, possibly deltaic. Nonresistant heavy mineral suites and angular detritus suggest deposition near source. The contact between the Nonesuch shale and the Freda sandstone is gradational.

(b) The Freda Sandstone.--The Freda sandstone is a well-sorted, fine to medium grained, red to greenish-grey arkose. It contains minor amounts of red to green micaceous shales and siltstones. Accurate measurements of its thickness are not available, however, data from scattered exposures near the Porcupine Mountains indicate a thickness of 14,000 feet (Hamblin, 1958).

(c) The Jacobsville Sandstone.--The Jacobsville sandstone comprises the rock unit southeast of the Keweenaw fault. It is medium to fine grained, red to white, arkosic sandstone. It is 4,000 feet thick (Hamblin, 1961). Its relationship with the underlying Freda sandstone is still conjectural, however, Hamblin places it in the Cambrian.

Structure

Lake Superior occupies a great synclinal structure, the Lake Superior basin, in the Southern Canadian Shield. The periphery of the western half of the basin is composed of rocks of Keweenawan age. Except for a subordinate fold in the Porcupine Mountains, the beds dip toward the center of the basin. They are steeper on the south than on the north limb. A general flattening of dip occurs from the base to the top of the Keweenawan section, with thickening of the units down-dip.

Folds

The south limb of the Lake Superior basin is quite irregular with broad transverse anticlines and synclines that plunge down-dip toward the center of the basin. The Porcupine Mountains is an arcuate dome, parallel to Lake Superior and is connected to the Northern Trap Range by a saddle. Thaden (1950) confirmed the presence of rhyolite in the center of the Porcupine Mountains as previously mentioned by Butler and Burbank (1929).

The Iron River syncline lies between the Porcupine Mountains and the Keweenawan Trap Range. It is assymetric, strikes northeast, and is truncated on the northeast by the White Pine fault. The beds on the north limb are near vertical and locally overturned. The Presque Isle River syncline which plunges to the northwest is on the west flank of the Porcupine Mountains.

Several other folds exist, many are the result of drag along faults. They vary in size from a few feet to several miles in magnitude.

Faults

The Keweenaw fault is a high angle reverse fault, which in the study area strikes northeast and dips northwest. It has been mapped along the southern edge of the Keweenawan Trap Range from the end of the Northern Peninsula to the northern edge of Lake Gogebic. A broad trough like area exists between the Keweenaw fault on the north and the South Trap Range and Precambrian highlands to the southeast.

The rocks are offset in many places by other faults. The White Pine fault, the major transverse fault, strikes northwest and dips steeply northeast. It is a right-handed transverse fault with a lateral displacement of about one mile and vertical displacement of only a few hundred feet (White, 1954).

The Pre-Keweenawan Area

Stratigraphy

This area is underlain by the Middle and Lower Precambrian rocks. The Lower Precambrian rocks are widely exposed in the western protion of the area, west of Lake Gogebic. Table 3 shows the lithologic sequences of the Middle and Lower Precambrian rocks and their correlative

TABLE 3.--Generalized geologic column for Pre-Keweenawan rocks as distributed in different districts of the area.

Upper Precambrian	Keweenawan series			diabase dikes and sills
	Iron River-Crystal Falls area (James, 1958)		Marquette district (Van Hise & Leith, 1911)	Lake Gogebic area (C.E. Fritts, 1967)
	Granitic intrusive rocks			
			Intrusive Contact	
	Metadiabase and Metagabbro			
			Intrusive Contact	
	Paint River group	Fortune Lake slate Stambaugh formation Hiawatha graywacke Riverton iron formation	absent	absent
Middle Precambrian (Animikie series)	Baraga group	Badwater greenstone Michigamme slate Fence River and Amasa formation Hemlock formation Goodrich quartzite Dunn Creek slate	Michigamme slate Upper slate member Bijik iron formation member Lower slate member {Clarksburg volcanics {Greenwood iron formation member Goodrich quartzite	Gray slate near Paulding Metavolcanic, Metasedimentary rocks Graywacke near Banner Lake (iron formation) Metatuff and tuffaceous graywacke Tyler slate (intercalated iron formation)
	Menominee group	Vulcan iron formation Felch formation	Negounee iron formation {Siamo slate {Ajibik quartzite	Ironwood iron formation Palms formation
	Chocolay group	Randville dolomite } Sanders formation Sturgeon quartzite } Sanders formation	{We We slate {Kona dolomite Mesnard quartzite	Bad River limestone Sunday quartzite
Lower Precambrian	Syenite granites, gneisses and greenstones			

names in the different districts as described by previous investigators.

Lower Precambrian Rocks

These are the oldest rocks in the area. They form the basement and consist of gneisses, granites, greenstones and other metavolcanic rocks. Granites and granite gneisses predominate. One or more periods of metamorphism and deformation occurred before the end of Early Precambrian time.

Middle Precambrian Rocks "Animikie"

The Chocolay Group

The Chocolay group and its correlatives as defined here are equivalent to the Lower Huronian of earlier reports. From Table 3 it is clear that it comprises two major units, a thick basal quartzite (the Sturgeon, Mesnard, and Sunday quartzites of the different localities), and an equally thick dolomite (the Randville, Kona, and Bad River dolomite). Both units contain some slaty members. The quartzite formation is made up of a basal conglomerate which is overlain by the rather coarse grained quartzite. The quartzite member is separated from the underlying "Archean" rocks by a major unconformity. The quartzite grades upward into the dolomite member. The aggregate thickness of the two units is typically about

4,000 feet, but in many places these strata are absent because of non-deposition or post-dolomite erosion.

The Menominee Group

The Menominee group and its correlatives as described here are equivalent to Middle Huronian of preceding reports. The type locality of this group consists of two formations, a basal clastic formation (Felch formation and Ajibik and Palm quartzites) overlain by iron formation. These commonly are conformable or nearly so with the underlying Chocolay group. The base of this group is marked by a thin conglomerate, one to three feet thick. Where the formation is in contact with the "Archean," as in parts of the Gogebic area, the pebbles are granite gneiss and greenschist, but where the underlying formation is the dolomite member of the Chocolay group, the conglomerate also include fragments of chert and limestone. The basal clastic formation ranges from 10 to 800 feet in thickness and from vitreous quartzite to graywacke and slate (or schist) in lithology.

This clastic formation grades upward into the iron formation which consists primarily of alternating thin layers of chert and iron minerals. Siderite, hematite, iron silicates, or magnetite are predominant. The Negaunee iron formation of the Marquette Range attains a maximum thickness of 2,000 feet, whereas the Ironwood iron formation of the Penokee-Gogebic Range rarely exceeds 800 feet.

The Baraga Group

The Baraga group and its correlatives comprise most of the strata referred to as Upper Huronian of previous reports. It is made up chiefly of graywacke, slate, and basic volcanic rocks, but conglomerate, quartzite, and iron formation are common particularly in the lower part. The principal stratigraphic unit is the Michigamme slate and its correlatives in the Penokee-Gogebic Range area. The exposed parts of the Michigamme slate and its correlatives consist of graywacke and slate in about equal proportions. The graywackes are dark gray, massive, and fine to medium grained. The slates are light to dark gray and transitional in grain size into the graywackes with which they are interbedded. Bedding is commonly indistinct or subordinate to slaty cleavage as the obvious structure. Most graywacke beds show no cleavage.

The Michigamme slate and its correlatives and probably 5,000 to 10,000 feet of basic volcanic rock, now mainly greenstones (Hemlock formation and its correlatives) form several thick units in the Baraga group. Much of this rock shows agglomeratic or pillow structures and submarine origin is probable.

Fritts (1967) published a geologic map of the area around Lake Gogebic (Marenisco-Watersmeet) and presented the geologic column on that map. This sequence of rocks includes at its base a metatuff and tuffaceous metagraywacke member which consist of minor quartzite, conglomerate, and magnetic iron formation in the lower part. It also possibly includes pillow lavas, east of Cup Lake, dipping at 60° to the southeast. This is overlain by the Graywacke series developed near Banner Lake, the upper part of which includes magnetic iron ore especially south of the Barb Lake fault. This is overlain by a metavolcanic and metasedimentary formation which crops out north of the Barb Lake fault. This could be separated into two units north of the fault, the metatuff and magnetic iron formation and the pillow lava and fragmental volcanic rocks. This is overlain by the uppermost member of this group which is labeled by Fritts as the graywacke slate near Paulding.

The Paint River Group

The Paint River group and its correlatives in previous reports, which include productive iron formation, generally were considered part of the Michigamme slate (Leith, Lund, and Leith, 1935). The Iron River-Crystal Falls district is a deep tightly folded major synclinal structure incompletely bounded by Badwater greenstone. In the area immediately east of Crystal Falls, greenstone is absent and the strate of the district rest directly on the Michigamme slate, which doubtless is the reason they were previously considered an extension of that unit. Recognition of the stratigraphic position of the Badwater greenstone forms the basis for the definition of the Paint River Group.

In the Iron River-Crystal Falls area this group includes a basal sequence of siltstone and slates named the Dunn Creek slate, which ranges in thickness between 400 and 800 feet. Much of the Dunn Creek is graywacke and slate that are physically indistinguishable from the Michigamme slate.

This is overlain by the Riverton iron formation which consist dominantly of interbedded chert and siderite. In places the upper part of the formation is absent because of erosion prior to the deposition of the overlying Hiawatha graywacke which is clastic in nature, mainly graywacke with considerable interbedded slate. This is overlain by the Stambaugh formation which is an iron-rich rock that ranges from chlorite mudstone and slate to a laminated cherty siderite-magnetite rock. This is overlain by the Fortune Lake slates which consists primarily of slate and minor graywacke.

The aggregate thickness of the group is at least 4,000 feet.

<u>Middle Precambrian Igneous Rocks</u>

The Middle Precambrian igneous rocks in the area fall into two principal groups, metadiabase and metagabbro of Animikie or post-Animikie age, and granite and allied rocks that are younger than the metadiabase and metagabbro.

The metadiabase and metagabbro were metamorphosed during the post-Animikie, Pre-Keweenawan interval (James, 1955). The existence of post-Animikie granite in Northern Michigan has been known almost since geologic work began more than a hundred years ago, but considerable debate has arisen as to its extent. The results to date, of work on absolute ages, suggest that the age of the Post-Animikie, Pre-Keweenawan epoch of diastrophism, metamorphism, and granite instusion is more than 1,400 million years, as compared with 1,100 million years for the Keweenawan (Duluth Gabbro and related rocks). James (1955) used the term Killarney to the post-Animikie, Pre-Keweenawan granite rocks in Michigan, but its validity is uncertain.

Structure

The major structure in the eastern portion of the Pre-Keweenawan area is a large faulted syncline which widens and plunges to the southwest. The north limb is continuous to Iron River. The south limb of the syncline has been subjected to a greater degree of deformation. Secondary folds on this limb maintain a northwestward trend and generally plunge in that direction. Transverse faulting has occurred subparallel to the secondary folding. The beds have been tightly folded producing a very irregular outcrop pattern. To the northeast of this area the major structure is the Amasa Oval which is a domal uplift. The long axis of the Amasa Oval plunges north-northwest and south-southeast. The major structures in the far eastern portion of the area and to the east of it are three Precambrian metasedimentary synclinoriums; the Marquette syncline, the Felch trough and the Gwinn trough. The first two generally trend east-west, while the third trends northwest-southeast. These are considered areas of extremely complex folding and faulting, probably the result of a period of a major orogeny.

The major structural feature in the western portion of this area is the Penokee-Gogebic Range. It is a steeply northward dipping monocline. The most noticeable features are the great thrust fault at Wakefield and the Barb Lake fault which strikes east-west. With the exception of the general northward tilting, the folding and faulting of the Animikie rocks took place prior to Keweenawan time and after the deposition and induration of the Middle Animikie Series. The structure around Lake Gogebic is very complicated. In this area the Animikie rocks are believed to be compressed into a syncline with the axial plane striking northeast-southwest and dipping to the northwest.

CHAPTER IV

PREVIOUS GEOPHYSICAL STUDIES

Balsley, James and Weir (1949) published a geophysical report including some preliminary interpretations of an aeromagnetic survey of parts of Baraga, Iron, and Houghton Counties. They concluded that the correlation of the magnetic data with the known geology is good in most parts of the area. They also pointed out that the use of aeromagnetic data is one of the fastest and most reliable methods for outlining the areal distribution of the magnetic rock units as well as their structure.

Campbell (1952) investigated the vertical component of the magnetic field and the gravitational field in the Silver Mountain area. He considered the subsurface structure to be quite complex.

Bacon and Wyble (1952) conducted a gravity investigation in the Iron River-Crystal Falls mining district of Michigan. The purpose of their study was to determine the merits of the gravity methods in iron ore exploration. They concluded that there is some possibility that gravity methods may be able to differentiate between large iron ore bodies and the iron formation in the Iron River-Crystal Falls district. They stated that the regional gravity work outlines quite clearly the major structural features of the Iron River-Crystal Falls synclinal basin. They also pointed out that a large anomaly occurring about fifteen miles west of Iron River may well be associated with a structurally similar basin and consequently may be another potential iron ore district.

Thiel (1956) and Bacon (1957) illustrated the relationship of Bouguer gravity anomalies to geology of the south shore of Lake Superior. Thiel correlated the "Mid-continent gravity high" with the gravity anomalies over the Keweenawan of Wisconsin. The regional gravity study by Bacon showed a similar high in the Northern Peninsula of Michigan.

Bacon (1960) advanced the hypothesis that a major fault parallel to the Keweenaw fault exists in approximately the central poriton of the Jacobsville sandstone. Bacon (1966) on the basis of geophysical data explored more fully some of the structure in the area to the east and south of the Keweenaw fault. He suggested that a Middle Range of basalts lies beneath the Jacobsville sandstone, and that it may be either the northern limb of a shallow symmetrical syncline plunging to the west, with the South Range as the southern limb, or that the Middle Range lavas are a horst. He also indicated the possibility of another fault parallel to the Keweenaw fault in the graben area between the Middle Range and Northern Trap Range.

Wold (1966) flew 7,500 miles of magnetic traverses over the Lake Superior region. This survey consisted of 37 north-south oriented profiles, spaces at six mile intervals (Figure 3). Some portions of these profiles cover the area of investigation. Flight elevation was at 3,000 feet above sea level as determined by a standard aneroid altimeter. A U.S. Navy P2V-5 (Neptune) aircraft, instrumented with a Wold (1964) digital recording proton precession magnetometer system was used for the survey. He only correlated in general the results of his survey with the Keweenawan lavas and clastics.

Case and Weir (1965) in their aeromagnetic study of parts of Marquette, Dickinson, Baraga, Alger, and Schoolcraft Counties, Michigan, covered a small strip of the extreme eastern portion of the investigation area. They correlated the major magnetic anomalies and broad areas that have characteristic magnetic patterns with the geology as determined from published reports. They defined the following six district group of anomalies or anomaly patterns:

1. The iron formation in the Animikie series is shown by magnetic highs of large amplitude up to 27,000 gammas.
2. Westward-trending reversely magnetized diabase dikes of Keweenawan age are shown by prominent elongate magnetic lows of moderate to high amplitude.

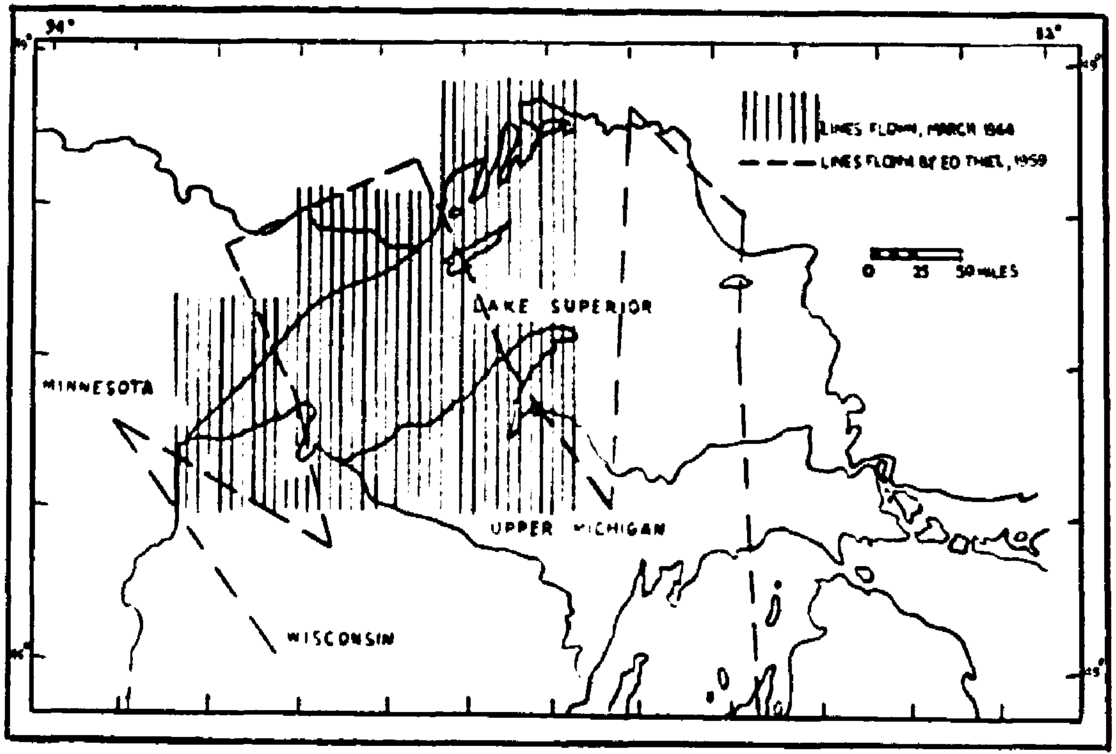

Fig. 3. Aeromagnetic flight lines flown by the University of Wisconsin. (After Wold, 1966)

3. Mafic intrusions into Pre-Animikie basement rocks northwest of Ishpeming are the source of a group of large magnetic highs.
4. The basement gneiss is characterized by a pattern of discontinuous highs and lows of low to moderate amplitude.
5. Intrusive greenstone in the basement gneiss causes, in some places, isolated magnetic highs of moderate amplitude, but in other places, it is apparently only weakly magnetic.
6. Where Precambrian rocks are covered by 2,000 feet of Lower Paleozoic sedimentary rocks, large magnetic highs and lows with relatively flat magnetic gradients predominate.

Miller (1966) conducted a gravity investigation of Porcupine Mountains and adjacent area. He concluded that, in general, the gravity map correlates very well with the geology as mapped by White (1962). He further indicated from gravity profiles observed over the Keweenaw fault that there is a decrease in the throw of the fault from northeast to southwest, varying from 6,000 feet north of Ewen, to 3,000 feet west of Lake Gogebic. He also indicated that the dip of the fault appears to be to the south, instead of to the north as previously postulated.

Several reports have been published by the U.S. Geological Survey on limited portions of the area, involving aeromagnetic studies and their geologic interpretation; these include:

1. Gair and Weir (1956) in their study of geology of the Kiernan Quadrangel, Iron County, Michigan.
2. Bayley (1959) in his study of the geology of Lake Mary Quadrangle, Iron County, Michigan.
3. Weir (1967) studied the geology of Kelso Junction Quadrangle, Iron County, Michigan, based partly on the aeromagnetic map of the area.
4. Prinz (1967) studied the Pre-Quaternary geology of part of the eastern Penokee-Gogebic Range, Michigan, utilizing results from ground magnetic surveying.

CHAPTER V

AEROMAGNETIC MAPS

Aeromagnetic maps of the area of investigation were obtained from the U.S. Geological Survey through the Geological Survey Division of the Michigan Department of Conservation.

The aeromagnetic maps are divided into two groups. The first group that covers the area east of longitude 88" 30' W, west of longitude 88° 07' 30" W, and south of latitude 46° 25' N, was mapped at a scale of 1:31,680. The flight traverses for this area were flow in an east-west direction because in this area most of the geologic units and structures, such as the Amasa Oval and the rocks of the Lower Precambrian of the South Marquette Range, strike approximately north-south.

The second group of maps cover the rest of the study area. These maps were mapped at a scale of 1:62,500 and the flight traverses were flown in a north-south direction which is perpendicular to the general strike of the trend of the geologic structures in this part of the area.

The contour interval of these maps varies between 50 gammas, which is the basic unit, to 1000 gammas depending on the intensity of the magnetic field.

A constant flight elevation of 500 feet from the ground surface was maintained throughout the study area, although this might deviate in areas of rugged relief. Traverses were spaced at intervals of approximately one-quarter of a mile. The flight path of the aircraft was recorded by a gyrostabilized continuous strip camera, and the elavation was continuously recorded by a radio-altimeter.

Magnetic measurements were made by an AN/ASQ-3A fluxgate magnetometer. Base lines were flown perpendicular to the flight traverses in two directions to obtain data to correct for diurnal magnetic variations.

The aeromagnetic maps for the area were assembled and compiled together to a common arbitrary magentic base level, and one common scale of 1:62,500 (Plate I). Available geologic information about the area, also was compiled to this scale, in order to facilitate the correlation of the magnetic anomalies with the areas of known geology.

CHAPTER VI

MAGNETIC PROPERTIES OF ROCKS

Introduction

The purpose of this chapter is to discuss and summarize the magnetic properties of the rock types in the area as a basis for the analysis of aeromagnetic data.

The most important magnetic property of a rock is its magnetic susceptibility (K), the ease with which the substance is magnetized. Magnetic susceptibility is affected by many different factors but the major factor is the volume fraction of the magnetic minerals in the rock. Other factors such as field strength, state of magnetization, grain size, fabric of rock, temperature and pressure, may affect the magnetic susceptibility. However, they are of limited consequence in practical application.

The magnetic susceptibilities of rocks exhibit a very wide range. Sediments, excluding iron formations, are relatively nonmagnetic and are considered to have zero magnetic susceptibility. The magnetic susceptibility of igneous rocks generally range between 100×10^{-6} c.g.s. units as represented by the lowest rank in the acidic group of rocks such as granite, and $10{,}000 \times 10^{-6}$ c.g.s. units for basic rocks.

The magnetic polarization (I) of a rock unit is determined not only by its magnetic susceptibility, but also by the strength of the inducing geomagnetic field (H). Thus,

$$I = K H \tag{1}$$

where,

H is the earth's magnetic field which is 0.595 oersteds in the study area.

In the last decades, it was discovered that the remanent magnetization (I_{RM}), which may be present in rocks, greatly affects the magnetic properties of the rock. In such cases, the total magnetic polarization of the rock is given by:

$$\overrightarrow{I_{total}} = \overrightarrow{I_i} + \overrightarrow{I_{RM}} \tag{2}$$

where,

$\overrightarrow{I_i}$ is the induced magnetic polarization

$\overrightarrow{I_{RM}}$ is the remanent magnetic polarization

The ratio of remanent magnetization (I_{RM}) to the induced magnetization (KH), is given by Q, which is known as the Konigsberger ratio.

Induced Magnetic Properties

Rock samples representing most of the lithologies in the area were collected for magnetic susceptibility measurements. In collecting these samples, the following two conditions were taken in consideration:

a. Only unweathered samples were collected.

b. Representative samples were collected from different outcrops of the same rock type and samples of each rock type in an outcrop were selected for analysis.

Magnetic susceptibility measurements for 120 samples were conducted in the laboratory using MS-3 magnetic susceptibility bridge, manufactured by the Geophysical Specialties Company. The calibration range of this instrument extends from approximately $2X10^{-6}$ to $40{,}000X10^{-6}$ c.g.s. units of volume magnetic susceptibility, which covers the ranges of susceptibility of the rocks encountered in the area. The upper limit can be extended to beyond 100,000 $X10^{-6}$ c.g.s. units by simple techniques.

Relative accuracy on a homogeneous sample is about one per cent. The absolute accuracy is somewhat lower, of the order of five to ten per cent. The MS-3 magnetic susceptibility bridge does not measure remanent magnetization nor will measurements taken with the MS-3 be affected by the presence of remanent magnetization.

The principal of operation may be understood by reference to Figure 4, which shows a cutaway view of the sample holder. Three co-axial coils are spaced vertically along a cylindrical form. This form is machined from phenolic resin which has been selected for its high thermal and mechanical stability. Alternating current at an audio frequency flows through coils A and C in series in a direction such that the magnetic fields which they produce will be effectively cancelled at the position of coil B.

From Figure 4 it may be seen that the sample holder opening passes through coil A and downward to Coil B. When a rock sample is introduced into the sample holder, the magnetic coupling between coils A and B will be increased, whereas the coupling between coils C and B will be relatively unaffected.

The amount of the unbalance will depend upon the susceptibility (K) of the sample and can be measured by means of an alternating current bridge. An oscilloscope was used in place of the headphones as a means for detecting the condition of balance. The amount of balance is measured in terms of (ΔR) which is converted to magnetic susceptibility either by a calibration curve when (ΔR) was greater than 500 ohms, in other cases for values of (ΔR) less than 500 ohms, the magnetic susceptibility (K) was obtained by:

$$K = 3.57 \times \Delta R \times 10^{-6} \text{ c.g.s.} \qquad (3)$$

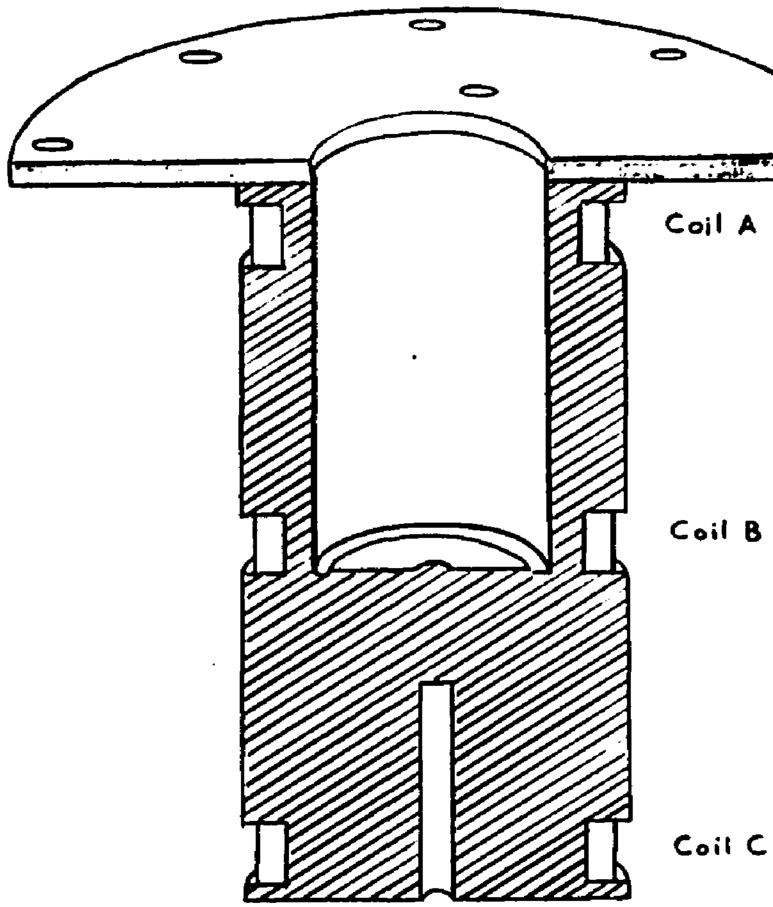

Fig. 4. Cutaway view of the sample holder.

This quantity which has been computed is the apparent susceptibility. To obtain the true value of "K" these values were corrected for:

a. Diameter correction: The calibration curve applies only to a solid sample of diameter 1.187 of an inch, and of length 3 inches or greater. Since a sample tube of 1.08 inch internal diameter was used, all the readings (ΔR) were multiplied by:

$$\frac{(1.187)^2}{(1.08)^2} = \frac{1.413}{1.166} = 1.212$$

b. Air space correction: The reading corrected for diameter was multiplied by the correction factor (C), where

$$C = \frac{\text{True density of sample material}}{\text{Apparent sample density}} \quad (4)$$

Instead of measuring the true sample density and the apparent density directly, a volumetric method was used for determining the ratio of the two quantities. Table 4 shows the range of magnetic susceptibilities as well as the average value for most of the Precambrian rocks in the area.

The following conclusions can be drawn from this table:

TABLE 4.--Magnetic susceptibility measurements of Precambrian rocks in the area.

Rock Type	No. of Samples	Range of Volume Susceptibility (K) $10X^{-6}$ c.g.s.	Average Volume Susceptibility ($X\ 10^{-6}$ c.g.s.)
II. Keweenawan rocks			
a. sediments	18	11-48	32
b. acidic flows	5	143-1000	438
c. basic flows	4	1220-1773	1561
d. basic intrusives	6	1881-9730	5683
e. acidic intrusives	2	31-56	43
I. Pre-Keweenawan rocks			
1. Animikie rocks			
a. metasediments	44	21-112	58
b. limonitic & hematitic iron ore	12	64-752	141
c. metamorphosed iron formation	1	4230	4230
d. stambaugh formation	1	10260	10260
e. metabasic intrusives	2	72-79	76
f. acid intrusives	9	8-1000	121
2. "Archean" rocks			
a. acid intrusives and gneiss	9	11-86	40
b. greenstones	8	10-57	37

1. Sediments (excluding iron ores), greenstones and acid intrusives have the lowest magnetic susceptibility values in the area. All sediments and greenstones have a susceptibility of less than $100X10^{-6}$ c.g.s. units.
2. Due to visible magnetite content in a hand specimen of granite the volume susceptibility value reached $1000X10^{-6}$ c.g.s.
3. Limonitic and hematitic iron ores and acidic lava flows have rather moderate values of magnetic susceptibility.
4. Basic flows and intrusives and metamorphosed iron formations have relatively high magnetic susceptibility.
5. The Stambaugh formation which is mainly a magnetic slate has the highest value of magnetic susceptibility.
6. Metabasic intruxives show remarkably low magnetic susceptibility values.

Remanent Magnetic Properties

The magnetic properties of the Keweenawan rocks of the Lake Superior region have been studied in more detail than the Pre-Keweenawan rocks due to the heterogeneity of the latter. Cox and Doell (1960) and Irving (1964) have compiled the results of these studies.

Dubois (1957) showed that cobbles of basalt of Keweenawan age have random magnetic orientation, and that they have acquired a stable magnetization. He also showed that the main cause of the magnetization is thermoremanent magnetization.

By reconstructing the original dip of the Keweenawan volcanics, Dubois (1962) and Jahren (1965) gave an average inclination of +45° and a declination of approximately 285° for the remanent magnetic field of the Keweenawan lavas. These are the values used for quantitative interpretation of magnetic profiles in this study.

Graham (1953) has reported on the paleomagnetism of certain dikes from Baraga County, Michigan. These and similar dikes occur in the eastern part of the study area as an east-trending swarm. The dikes were found to have consistent magnetization with declination of 90° and steep upward dip of -87°. Graham explained the origin of the reverse magnetization of these dikes to be due to partial oxidation of the magnetite of magnetite-ilmenite intergrowth to maghemite which has been magnetized in the demagnetizing field of the magnetite. Subsequent easier demagnetization of the residual magnetite on account of its larger grain size took place.

Dubois (1962) correlated these dikes with the Logan sills of Canada due to their common computed pole positions. Due to the fact that the dikes intrude Animikie type rocks and are overlain by the Jacobsville sandstone, he considered them to be of Keweenawan age.

Hinze, O'Hara, Secor, and Trow (1966) summarized the magnetic properties of the rocks of the Lake Superior region reported in literature including the studies of Mooney and Bleifuss (1953), Bath and Schwartz (1960), Cox and Doell (1960), Jahren (1960-1963), Bath (1962), Irving (1964) and Case and Gair (1965). Their compilation is given in Table 5. The measured values shown in Table 4 agree well with the ranges of magnetic susceptibilities shown in Table 5.

From the previous discussions and by analysis of the aeromagnetic maps, the following generalizations appear valid for the rocks in the area.

1. High amplitude anomalies are expected to be associated with iron formations and basic intrusives.
2. All sediments of all ages should give the lowest magnetic intensity level in the area.
3. Keweenawan lava flows are expected to give high magnetic response but not as high as magnetic iron formations.
4. Acidic intrusives and greenstones are expected to show some magnetic irregularities.

TABLE 5.--Summary of magnetic properties (after Hinze, O'Hara, Secor and Trow, 1966).

	Rock Type	Susceptibility $KX10^{-6}$ c.g.s	Konigsberger Ratio $Q = I_{RM}/KH$ $H = 0.6$ Oersted
IV.	Paleozoic sediments	Negligible	Negligible
III.	Keweenawan Rocks:		
	a. sediments	Negligible	Negligible
	b. basic flows	10,000-1,000	3.0-1.0
	c. basic intrusives	9,000-2,000	2.0-1.0
	d. acid intrusives and flows	3,000-100	-------
II.	Pre-Keweenawan Rocks:		
	a. acid intrusives and gneisses	3,000-100	Generally Low
	b. metabasic intrusives and flows	4,000-200	2.0-0.5
	c. iron formations	900,000-500	10.0-0.0
	d. metasediments	200-0	Negligible
I.	Undifferentiated Precambrian	Variable	Variable

CHAPTER VII

METHODS OF INTERPRETATION

Introduction

Many methods of interpreting magnetic data have been developed over the past thirty years. Some of these methods are applicable only under certain conditions. Others are "Rule of Thumb" methods that apply only where certain assumptions are known to hold true.

In this study, selected depth determination techniques were used in interpreting the aeromagnetic anomalies. These included the half-width method (Nettleton, 1942), D. W. Smellie's method (1956), Peters' slope method (1949), and Vacquier's method (1951).

A second vertical derivative map of the total magnetic intensity was constructed for the central portion of the study area using the method of Henderson (1960). The purpose of the second vertical derivation map is to aid in determining depths by Vacquier's method and to assist in locating the contacts of magnetic rock units.

A magnetic trend analysis also was carried out to define the major tectonic trends in the area.

Depth Determinations

The depth to causative geological bodies is one of the most important parameters that must be determined in order to interpret adequately the geology and the structure of an area. A variety of magnetic depth determination techniques have been discussed in the geophysical literature. Each method has its own assumptions, as well as limitations.

The half-width technique, D. W. Smellie's method and Peters' slope method were applied to most of the anomalies in the study area. Vacquier's method was applied to only a relatively few anomalies. All of the methods are based on the assumption that the magnetization of rocks is only induced, i.e., no remanent component is present. Therefore, the depth determinations may be subject to error because most of the basic intrusives and extrusives, and iron formations in the area have a strong remanent magnetic component.

Methods

The Half-Width Method

The half-width method utilizes a magnetic profile, the principal profile, taken perpendicular to the strike of the anomaly at or near its maximum amplitude. The depth to the causative body is related to the "half-width" of the profile curve at one-half the maximum amplitude. This distance is marked $X_{1/2}$ on Figure 5.

In general $X_{1/2}$ must be multiplied by a constant factor depending upon the shape and length of the body and its depth extent. The factors for the idealized bodies that were used to approximate the causative masses in the study area are as follows:

<u>Dipole Approximations</u>:

Sphere	2.00
Horizontal Cylinder	2.05

<u>Pole Approximations</u>:

Narrow Vertical Dikes	1.00
Vertical Cylinders	1.00

This method is based upon vertically induced magnetic polarization. This condition is not exactly met in the survey area, but is approximated due to the high magnetic inclination (76°). Great care must be exercised in determining the zero level of the anomaly which will affect the maximum amplitude and accordingly the $X_{1/2}$ measurements. Also interference from neighbouring anomalies will have a profound effect on the measured $X_{1/2}$ distance.

Smellie's Method

Henderson and Zeitz (1948) studied the relationship between the total magnetic field intensity anomalies and the point pole and line of poles sources. Theoretical

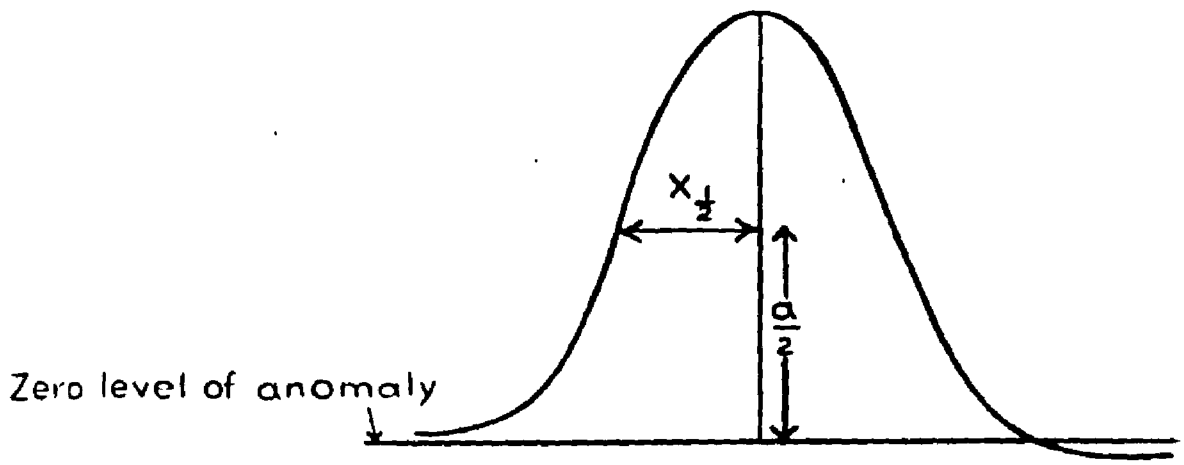

Fig.5. Half-width method of depth determination.

profiles were examined for maxima and minima and it was established that the depth is a linear function of the half-maximum abscissa. They calculated factors for depth determinations based upon this parameter.

Smellie (1956) modified this work and derived the total magnetic expressions for four simple sources: the point pole, line of poles, dipole, and line of dipoles. He also worked out theoretical curves for depth factors for all these cases. These curves were established for different geomagnetic latitude (I), for bodies parallel to the magnetic meridian and those at an angle (β) to it. In this regard, Smellie's method can be looked upon as the half-width method corrected for both magnetic latitude and orientation with respect to the magnetic meridian.

Magnetic bodies of limited horizontal extent, but of great depth extent can be approximated with a point pole. However, narrow dikes which have great horizontal and vertical extent are approximated with a line of poles. The dipole approximations are used for spherical bodies and line of dipoles for bodies which approximate a horizontal cylinder in shape. For the pole approximations the estimated depth is to the top of the body causing the anomaly, whereas for the dipole it is the depth to the center of the body. As a general rule, the interpretation of anomalies characterized by nearly circular contours may be approximated using a pole or dipole, and elongated anomalies can be interpreted using a line of poles or line of dipoles approximation. The dipole or line of dipoles approximation is used in those cases where the anomalies exhibit a definite negative magnetic anomaly associated with the positive anomalies.

The applicability of these approximations depends to a large extent on the dimensions of the source. Sources which are wide, compared with their depth will give depths that are too great. This is also the case with complex sources consisting of several closely spaced anomalous bodies, whose effects merge to give a single anomaly. In cases where the isolation of anomalies is not complete, error is anticipated because of the difficulty in determining the relative maximum amplitude of the anomaly. Serious error also may be caused by making the wrong approximation to the shape of the source. Errors also may rise in original plotting or contouring of the data.

<u>Peters' Slope Method</u>

L. J. Peters (1949) has developed several methods of depth determinations. The most commonly used of his methods is the "slope" method. It relates the maximum gradient of the anomaly to the depth of the top of its source. Peters' method is based mainly on two assumptions:

1. The anomalous mass is in the shape of an infinitely long slab with vertical sides, extending infinitely downward. However, it

has been found that the sides can deviate from the vertical by 10 degrees without introducing serious errors in estimated depths.

2. The source of the anomaly is vertically polarized.

Peters' method is applied to the principal profile of the anomaly, Figure 6 illustrates this technique. The inflection point is located at the maximum slope of the anomaly profile. A tangent is drawn to the inflection point (Line A), and measures its slope and two tangents (C,D) are drawn to the anomaly curve which are parallel to B. The horizontal separation "S" is approximately related to the depth (Z) by the formula

$$S = 1.6\ Z \tag{5}$$

This relation only holds true, where Z and T (the width), are about the same magnitude, i.e., $T/Z \approx 1$.

$$\text{When } T = 0, \qquad S = 1.2\ Z \tag{6}$$

$$\text{When } T = \infty, \qquad S = 2.0\ Z \tag{7}$$

Equation (5) is generally used in cases where "T" is neither zero nor infinity. The accuracy using equation (5) is as follows:

(a) If $0 < T/Z \leq 0.5$ Poor results are obtained.

(b) If $0.5 < T/Z \leq 1.1$ Good results are obtained.

(c) If $1.1 < T/Z$ Excellent results are obtained.

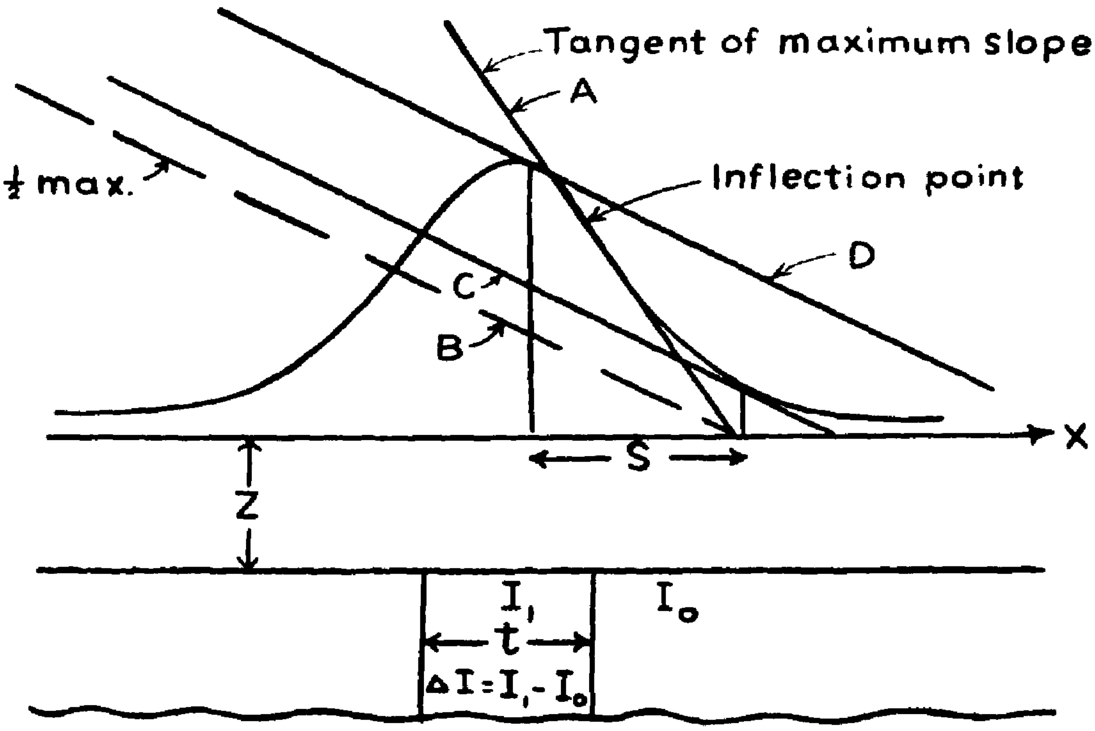

Fig. 6 Peters' slope method of depth determination.

Greater depth values are expected from Peters' method in cases where the sides of the rock mass are sloping downward and outward. Shallower values of depth are expected in cases where the sides are inward-sloping or where it is applied to anomaly slopes between two adjacent masses that overlap. Any inaccuracy in contouring will have a great effect on the slope of the anomaly, as well as the inflection point, which affect the results accordingly.

In spite of the previously mentioned limitations, Peters' method utilizes data fairly close to the apex of the anomaly, thereby avoiding some of the influence of neighboring anomalies. Another advantage to it, is that it does not require definition of the zero-level of the anomaly.

Vacquier's Method

A second vertical derivative map for an area of about 3,700 square miles in the center of the study area was constructed from the total magnetic intensity map. The numerical analysis procedure of calculating derivatives developed by Henderson (1960) was used with a mesh interval of one-half mile. The main purpose of the second derivative map was to carry out depth determinations using Vacquier's method. Also the derivative map was used as a guide for mapping lithologic contacts because the zero curvature approximates the boundary of the geologic source.

Vacquier's method is initiated by comparing the observed with the computed magnetic effect of idealized bodies, which are rectangular prisms with vertical sides extending infinitely downwards. The prisms are considered similar to large lithologic units in crystalline rock with polarization in the direction of the present earth's magnetic field. The susceptibility contrast (K) is assumed constant for the magnetized bodies. The models are measured in terms of depth of burial to the top of the prism. Dimensions are expressed in terms of "n x m", where n is the side of the prism more nearly parallel to magnetic meridian and m is the side of the prism, perpendicular to n.

Depth indices are determined by measuring the horizontal extent of the steepest gradient on the total magnetic intensity map and the second vertical derivative map. The same procedure is used to measure the depth indices of the prism model. The depth is estimated by dividing the depth indices of the observed anomaly by the depth indices from the prism model. The A and G indices were determined for most anomalies from the second vertical derivative and total intensity maps, respectively, because of their independence of the size of the prism model.

The magnetic susceptibility (K) of the anomalous prism was calculated by applying the relation

$$K = \Delta T_m / \Delta T_c \; T \qquad (8)$$

where

K is the magnetic susceptibility contrast

ΔT_m is the maximum amplitude of the observed anomaly in gammas

ΔT_c is the maximum amplitude of the prism model anomaly in gammas, and

T is the earth's magnetic field intensity in gammas.

Results

The half-width method and Smellie's method were applied to most of the anomalies in the study area. Peters' slope method was applied only to those anomalies which approached two dimensionality. The location of all the anomalies used for depth determinations is shown in Plate II. The results obtained from the methods, the assumed source for the causative mass, and the bedrock geology of each anomaly are shown in Table 6.

It is clear from Table 6 that the depth estimates by the various methods are in a fairly good agreement. The differences can be attributed to natural conditions which differ markedly from the assumptions on which the methods are based.

TABLE 6.--Depth determinations.*

(1) Anomaly No.	(2) Half-width method (feet)	(3) L. D. Smellie's method (feet)	(4) Peter's slope method (feet)	(5) Vacquier's method (feet)	(6) source assumed	(7) Bedrock geology
1	655	513	--	--	L.P.[a]	Northern Trap Range
2	550	473	--	--	L.P.	" " "
3	445	294	--	--	L.P.	" " "
4	1285	1305	1281	--	L.P.	Jacobsville sandstone (Middle Trap Range)
5	1600	1267	--	1369	L.P.	" " " " "
6	1600	1709	1928	--	P.P.[b]	" " " " "
7	1390	1486	1797	--	L.P.	Michigamme slate
8	550	323	--	--	L.P.	" "
9	130	553	--	--	L.P.	" "
10	445	237	--	--	L.P.	" "
11	--	3595	3240	--	L.D.P[c]	" "
12	4540	3798	3240	--	L.D.P.	" "
13	2230	2298	2120	--	L.D.P.	" "
14	1390	1777	1156	--	L.D.P.	" "
15	3910	3864	3110	--	L.D.P.	Jacobsville sandstone (South Trap Range)
16	235	396	--	--	L.P.	Badwater greenstone
17	235	258	--	--	L.P.	" "
18	865	563	--	--	L.P.	" "
19	655	387	--	--	L.P.	" "
20	550	556	616	--	L.P.	" "
21	340	146	--	--	L.P.	" "
22	445	469	550	--	L.P.	" "
23	3910	4505	3700	--	L.D.P.	Riverton iron formation
24	445	471	550	--	L.P.	Stambaugh formation
25	2755	2201	2120	--	L.D.P.	Michigamme slate
26	2020	2167	2120	2064	L.D.P.	" "
27	445	498	420	--	L.P.	" "
28	3280	3395	2848	2636	L.D.P.	" "
29	655	661	747	928	L.P.	" "
30	4010	4239	3897	--	L.D.P.	" "
31	4120	4025	4094	--	L.D.P.	" "
32	7900	6399	7111	--	L.D.P.	" "
33	760	493	680	841	L.P.	Hemlock formation
34	550	472	--	--	L.P.	" "
35	655	568	--	--	L.P.	Michigamme slate
36	5170	4733	4750	--	L.D.P.	Fortune Lake slate
37	2860	2610	2912	--	L.D.P.	" " "
38	3070	2715	2912	--	L.D.P.	" " "
39	235	165	--	--	L.D.	Badwater greenstone
40	655	591	--	--	L.P.	Hemlock formation
41	340	311	--	--	L.P.	" "
42	550	535	--	--	L.P.	" "
43	2440	2459	2190	--	L.D.P.	Fortune Lake slate
44	1075	1023	1340	--	P.P.	Hemlock formation
45	1390	1249	1600	--	L.P.	" "
46	865	989	--	--	L.P.	" "
47	760	763	747	--	L.P.	" "
48	760	670	812	--	L.P.	" "
49	25	40	--	--	L.P.	" "
50	235	273	--	--	L.P.	" "
51	3280	3400	2200	--	L.D.P.	" "
52	445	535	--	--	L.P.	" "
53	2335	2353	2450	--	L.D.P.	Michigamme slate
54	1920	1443	1732	--	L.P.	" "
55	655	653	--	--	L.P.	" "
56	550	592	500	--	L.P.	" "
57	1380	1416	1010	--	L.P.	" "
58	172	225	--	--	L.P.	Metatuff and metasediments
59	130	150	--	--	L.P.	" "
60	235	261	--	--	L.P.	" "
61	655	833	--	--	L.P.	" "
62	235	303	--	--	L.P.	" "
63	288	416	--	--	L.P.	" "
64	1390	1984	1797	1485	L.D.P.	" "
65	2020	1975	1403	--	L.D.P.	" "
66	393	472	--	--	L.P.	" "
67	340	493	--	--	L.P.	" "
68	235	493	--	--	L.P.	" "
69	445	524	--	--	L.P.	" "
70	135	493	--	597	L.P.	" "
71	78	166	--	824	L.P.	" "

TABLE 6.--Continued.

(1) Anomaly	(2) Half-width method (feet)	(3) L.P. Smellie's method (feet)	(4) Peter's slope method (feet)	(5) Vacquier's method (feet)	(6) Source assumed	(7) Bedrock geology
72	[illegible]	[illegible]	--	680	L.P.	Metatuff and metasediments
73	[illegible]	1146	[illegible]	--	L.P.	" "
74	[illegible]	268	--	--	L.P.	Granitoid gneiss
75	235	311	--	--	L.P.	" "
76	1390	1306	1600	1146	L.P.	Iron formation
77	1075	1224	1140	1120	L.P.	Granitoid gneiss
78	235	276	615	958	L.P.	Graywacke near Bonner Lake
79	235	592	--	--	L.P.	" " " "
80	235	592	--	--	L.I.	" " " "
81	550	412	--	632	L.P.	" " " "
82	235	209	--	--	L.P.	Metatuff and metasediment
83	1390	1239	1469	--	L.D.P.	" "
84	183	221	--	--	L.P.	" "
85	392	380	--	--	L.P.	" "
86	550	830	682	--	L.P.	" "
87	3910	3592	2912	--	L.D.P.	Jacobsville sandstone
88	3175	3047	3240	--	L.P.	" "
89	5275	5664	5734	--	L.P.	" "
90	2650	2562	2843	--	P.P.	" "
91	918	517	945	824	L.P.	Northern Trap Range
92	655	592	811	--	L.P.	" " "
93	970	900	[illegible]	--	L.P.	" " "
94	865	587	--	--	L.P.	" " "
95	235	109	--	--	L.P.	" " "
96	865	792	1140	--	L.P.	" " "
97	655	592	747	--	L.I.	" " "
98	550	534	--	--	L.I.	" " "
99	2755	2148	2781	--	P.P.	" " "
100	2230	2545	2781	--	P.P.	" " "
101	1600	1324	--	--	L.P.	" " "
102	1495	1313	--	--	L.P.	" " "
103	[illegible]	810	--	--	L.P.	" " "
104	[illegible]	1024	--	--	L.P.	" " "
105	[illegible]	[illegible]	--	--	P.P.	" " "
106	[illegible]	[illegible]	--	--	P.I.	" " "
107	[illegible]	653	--	--	L.P.	" " "
108	[illegible]	[illegible]	--	--	L.P.	" " "
109	77	[illegible]	--	--	L.P.	" " "
110	[illegible]	[illegible]	--	--	L.P.	" " "
111	540	[illegible]	--	--	L.I.	" " "
112	[illegible]	135	--	--	L.P.	" " "
113	[illegible]	[illegible]	--	--	L.P.	" " "
114	615	451	--	--	L.P.	" " "
115	760	443	--	--	L.P.	" " "
116	550	[illegible]	--	--	L.P.	" " "
117	[illegible]	[illegible]	--	--	L.P.	South Trap Range
118	[illegible]	196	--	--	L.P.	Ironwood iron formation
119	970	268	--	--	L.P.	" " "
120	[illegible]	2732	2387	--	L.D.P.	" " "
121	[illegible]	470	--	--	L.P.	Northern Trap Range
122	183	213	--	--	L.P.	" " "
123	--	--	--	754	Model 2x8	" " "
124	--	--	--	493	Model 2x8	" " "
125	--	--	--	858	Model 2x6	" " "
126	--	--	--	493	Model 2x8	" " "
127	--	--	--	991	Model 2x6	" " "
128	--	--	--	1276	Model 2x6	" " "
129	--	--	--	2827	Model 2x8	" " "

* Depth values obtained from half-width and Smellie's methods are from the ground surface to the top of the causative mass for pole approximations, while it is to the center of the mass in case of the dipole approximations.

Depth values obtained from Peters' and Vacquier's methods indicate the depth from the ground surface to the top of the causative mass.

(a) L.P. = Line of poles
(b) P.P. = Point pole
(c) L.D.P. = Line of Dipoles

The depth determinations for anomalies number 123 to 129 were calculated using Vacquier's method alone. These anomalies are not sufficiently well-defined on the total magnetic intensity map, to utilize the other depth determination methods. However, they are well-defined on the second vertical derivative map and, therefore, could be analyzed by Vacquier's method.

Table 7 shows the calculated volume magnetic susceptibility of the causative source for the anomalies analyzed by Vacquier's Method assuming only induced polarization.

It is to be noted that the magnetic susceptibility values obtained from this method are quite high compared to the values obtained from laboratory determination or the previously published data. The reason for this is mainly attributed to the fact that in these calculations, the amplitude of the observed anomaly (ΔT_m) was assumed to be only due to induced magnetization. This is not true because most of the magnetic formations in the study area have a remanent magnetization component.

Correlation of Estimated Depth Values with Bedrock Geology

General

It is interesting and informative to correlate the depth determinations with the bedrock geology. This correlation has been made for both the Keweenawan and the Pre-Keweenawan rocks and the results are summarized in Table 8.

TABLE 7.--Magnetic susceptibilities determined by Vacquier's method.

Anomaly Number	Model Used	ΔT_c	ΔT_m	Volume magnetic Susceptibility (K) in 10^{-6} c.g.s. units
5	2x6	2.75	200	1,200
26	2x6	2.75	4500	27,300
28	2x6	2.75	3250	14,500
29	2x6	2.75	450	2,700
33	2x8	2.00	2100	17,500
64	2x6	2.75	4750	28,800
70	2x8	2.00	2250	18,800
71	2x6	2.75	1250	8,100
72	2x8	2.00	400	3,300
76	2x8	2.00	2500	20,800
77	2x8	2.00	560	4,700
78	2x8	2.00	1500	12,500
81	2x8	2.00	250	2,100
91	2x8	2.00	450	3,800
123	2x8	2.00	2250	13,700
124	2x8	2.00	800	6,700
125	2x6	2.75	750	4,500
126	2x8	2.75	750	4,500
126	2x8	2.00	300	2,500
127	2x6	2.75	350	2,100
128	2x6	2.75	200	1,200
129	2x8	2.00	200	1,700

*A value of 59,500 gammas was considered for T (Earth's magnetic field).

TABLE 8.--Correlation of depth determinations with bedrock geology.

Pole Approximation					Dipole Approximation				
Depth Range in Feet	Number of Anomalies				Depth Range in Feet	Number of Anomalies			
	Keweenawan Rocks		Pre-Keweenawan Rocks			Keweenawan Rocks		Pre-Keweenawan Rocks	
	No.	%	No.	%		No.	%	No.	%
0- 500	12	31.6	36	59.0	0-1000	0	0.0	0	0.0
501-1000	6	42.1	17	27.8	1001-2000	0	0.0	4	19.0
1001-2000	6	15.8	8	13.2	2001-3000	0	0.0	9	42.9
2001-3000	2	5.3	0	0.0	3001-4000	2	100.00	3	14.3
3001-4000	1	2.6	0	0.0	4001-5000	0	0.0	4	19.0
4001-5000	0	0.0	0	0.0	5001-7000	0	0.0	0	0.0
5001-6000	1	2.6	0	0.0	> 7000	0	0.0	1	4.8
TOTAL	38	100.0	61	100.0		2	100.0	21	100.0

It should be noted that the source of anomalies that are at a depth of less than 500 feet could be outcropping. This error in depth determinations may be attributed to errors in measuring anomaly characteristics or may originate in deviations from the 500 foot flight elevation, especially in areas of rough topography.

Keweenawan Rocks

It is evident from Table 8 that most of the Keweenawan rocks in the study area could be approximated by either a point pole or a line of poles. This suggests that such rocks are mainly in form of narrow dikes that extend to a considerable depth or in form of thin sheet like bodies. The Keweenawan lavas of the Northern Trap Range occur at or near the surface along its entire length across the northern portion of the study area. However, they may reach a depth of 1400 to 2500 feet at the southern border of the Iron River syncline. South of the Keweenaw fault, in the central and western portions of the study area, a narrow band of Keweenawan rocks of the Northern Trap Range appear to be covered by a thin wedge of sediments.

The volcanics of Middle Trap Range are buried beneath 1250 to 2500 feet of Jacobsville sandstone. However, they outcrop in the Silver Mountain area. This variation in depth to the Middle Range is believed to be due to several cross faults with considerable vertical displacements.

The South Trap Range is outcropping in the western portion of the study area (west of Lake Gogebic). East of Lake Gogebic it outcrops occasionally along its extension while in some other parts it is covered by 3,000 to 5,000 feet of Jacobsville sandstone.

Pre-Keweenawan Rocks

Table 8 shows that sources of anomalies within the Pre-Keweenawan rocks can be approximated either by poles or dipoles and that, although the majority of the depth estimates are shallow, the sources have a wide range of depths.

The Michigamme slate contains more than one possible source of anomalies at different depth levels. Those causative masses that are near to the surface could be either a magnetiferrous slate member or outcropping basic intrusives. Another group of anomalies has a depth range between 1500 and 4000 feet. The source of these anomalies is believed to be due to basic intrusives and extrusives that lie at the base of the Michigamme slate. It is worth noting that the Michigamme slate includes the anomaly with the deepest source in the entire study area. This source reaches an approximate depth of 7000 feet.

The metatuff and metavolcanic rocks that occur in the western portion of the area around Lake Gogebic are mostly outcropping or at few hundred feet from the surface. However, due to local structures these rocks produce anomalies which originate at depths up to 1500 feet from the surface.

The source of anomalies in the Hemlock formation and Badwater greenstone are either outcropping or lie very near to the surface. However, in the Hemlock formation some anomalous sources occur at a depth of 1400 to 2000 feet. The Fortune Lake slate seems to include a deep magnetic source that has a depth range between 2500 and 4500 feet.

There are other scattered anomalies due to sources of limited extent such as those occurring over the Stambaugh formation, Riverton iron formation, Ironwood iron formation, graywacke near Banner Lake, and granitoid gneiss. The source rock in most of these cases is either outcropping or very near to the surface.

Magnetic Trend Analysis

The use of what has come to be known as "character" in magnetic maps, is a common quantitative approach to magnetic interpretation. The term "character" is based upon the wavelength, amplitude, grouping of anomalies, and their magnetic trend pattern. It has been shown that trend patterns can be used to define magnetic provinces which reflect tectonic provinces (Affleck, 1963).

The study area was divided into two areas on the basis of regional geology; the Pre-Keweenawan and the Keweenawan areas. On the basis of magnetic properties of rocks, depth determinations, and examination of the aeromagnetic maps, the magnetic anomalies in the study area were divided into the following three main groups, according to amplitude:

1. First order anomalies, with amplitudes greater than 2500 gammas, which are indicative of:
    a. Pre-Keweenawan basic intrusives and extrusives.
    b. Pre-Keweenawan iron formations.
2. Second order anomalies, with amplitudes between 500 and 2500 gammas, which are indicative of:
    a. Keweenawan acidic and basic extrusives.
    b. Near surface Pre-Keweenawan basic intrusives.
3. Third order anomalies, with amplitudes less than 500 gammas, which are indicative of:
    a. Westward trending, reversely magnetized diabase dikes of Keweenawan age.
    b. Keweenawan extrusives buried beneath Keweenawan sediments.
    c. Basement gneisses, intrusive greenstones and near surface, slightly magnetic rocks, of Pre-Keweenawan age.

The rock types ascribed to each anomaly group is necessarily a generalization. Anomalies associated with specific rock types may fall within more than one group due to varying depths, magnetization or volume of the source.

In general, the anomalies align themselves along definite axes, forming "trends." The trends for the three groups of anomalies were traced out and marked according to the amplitude classification (Plate II). A simple and standard method of portraying the two-dimensional magnetic trend patterns is to construct a frequency plot showing the number of elements lying in various direction ranges (Miller and Kahn, 1962). The study area was divided into squares of two miles on a side. The squares serve to define "elements" of the pattern. The number of elements is equal to the number of squares in which a particular trend occurs. The directions of the element was measured as an azimuth, clockwise from north, and each element contributed a separate measurement of azimuth. An element that changed its azimuth by more than 5 degrees along its length was broken into two or more separate elements. The number of elements within each area and amplitude group, in each five degrees of azimuth, was tabulated and their frequency percentages calculated. These data are shown in Table 9. The frequency percentage of the total number of elements in the entire survey area as well as in the Keweenawan and the Pre-Keweenawan areas for each five degrees of azimuth also was calculated. These data are shown in Table 10.

TABLE 9.--Distribution of magnetic trend elements of different anomaly orders in the Keweenawan and the Pre-Keweenawan areas.

Range of azimuth in degrees	Keweenawan Area				Pre-Keweenawan Area					
	500-2500 gammas		<500 gammas		>2500 gammas		500-2500 gammas		<500 gammas	
	Number of trends	Frequency in %	Number of trends	Frequency in %	Number of trends	Frequency in %	Number of trends	Frequency in %	Number of trends	Frequency in %
0- 5	2	1.26	23	1.64	7	4.14	12	2.73	25	3.63
6- 10	2	0.32	12	0.86	2	1.18	1	0.23	10	1.45
11- 15	3	0.47	9	0.64	4	2.37	4	0.91	5	0.73
16- 20	6	0.95	17	1.21	4	2.37	2	0.46	8	1.16
21- 25	5	0.79	14	1.00	1	0.59	5	1.14	2	0.29
26- 30	9	1.42	13	0.93	5	2.96	5	1.14	2	0.29
31- 35	14	2.21	24	1.71	1	0.59	2	0.46	3	0.44
36- 40	16	2.52	20	1.43	2	1.18	3	0.68	2	0.29
41- 45	33	5.21	26	1.86	3	1.78	6	1.36	6	0.88
46- 50	27	4.26	49	3.50	1	0.59	10	2.27	12	1.74
51- 55	40	6.31	50	3.57	1	0.59	8	1.82	16	2.32
56- 60	43	6.78	67	4.79	1	0.59	22	5.00	27	3.92
61- 65	48	7.57	56	4.00	3	1.78	24	5.46	23	3.34
66- 70	60	9.46	72	5.14	2	1.18	37	8.41	31	4.50
71- 75	55	8.68	102	7.29	5	2.96	35	7.96	48	6.97
76- 80	46	7.26	133	9.50	4	2.37	22	5.00	24	3.48
81- 85	57	8.99	190	13.57	6	3.55	28	6.36	25	3.63
86- 90	97	15.30	277	19.79	21	12.43	58	13.18	84	12.19

91- 95	18	2.84	45	3.21	4	2.37	5	1.14	27	3.92
96-100	17	2.68	54	3.86	2	2.18	20	4.55	40	5.81
101-105	4	0.63	28	2.00	14	8.28	18	4.09	33	4.79
106-110	6	0.95	10	0.70	11	6.51	17	3.86	25	3.63
111-115	8	1.26	9	0.64	4	2.37	14	3.18	32	4.64
116-120	3	0.47	20	0.14	8	4.73	6	1.36	18	2.61
121-125	--	--	10	0.70	8	4.73	6	1.36	15	2.18
126-130	2	0.32	7	0.50	4	2.37	4	0.91	11	1.60
131-135	--	--	6	0.43	2	2.18	3	0.68	27	3.92
136-140	1	0.16	4	0.29	6	3.55	3	0.68	12	1.74
141-145	--	--	6	0.43	3	1.78	8	1.82	20	2.90
146-150	2	0.32	1	0.07	--	--	5	1.14	10	1.45
156-160	--	--	6	0.43	4	2.37	14	3.18	12	1.74
161-165	1	0.16	15	1.07	4	2.37	7	1.59	23	3.34
166-170	2	0.16	9	0.64	7	4.14	6	1.36	6	0.88
171-175	1	0.32	8	0.57	7	4.14	9	2.05	6	0.88
176-180	--	0.16	5	0.36	2	2.37	--	--	10	1.45

TABLE 10.--Distribution of magnetic trend elements in the Keweenawan area, Pre-Keweenawan area, and the survey area.

Range of azimuth in degrees	Keweenawan Area		Pre-Keweenawan Area		Total Survey Area	
	Number of trends	Frequency in %	Number of trends	Frequency in %	Number of trends	Frequency in %
0- 5	31	1.52	44	3.39	75	2.25
6- 10	14	0.69	13	1.00	27	0.81
11- 15	12	0.59	13	1.00	25	0.75
16- 20	23	1.13	14	1.08	37	1.11
21- 25	19	0.93	8	0.62	27	0.81
26- 30	22	1.08	12	0.93	34	1.02
31- 35	38	1.87	6	0.46	44	1.32
36- 40	36	1.77	7	0.54	43	1.29
41- 45	59	2.90	15	1.16	74	2.22
46- 50	76	3.74	26	2.00	102	3.06
51- 55	90	4.43	24	1.85	114	3.42
56- 60	110	5.41	50	3.85	160	4.80
61- 65	104	5.11	50	3.85	154	4.62
66- 70	132	6.49	70	5.39	202	6.06
71- 75	157	7.72	88	6.78	245	7.35
76- 80	179	8.80	50	3.85	229	6.87
81- 85	247	12.14	59	4.55	306	9.18
86- 90	374	18.39	163	12.56	537	16.12
91- 95	63	3.10	36	2.77	99	2.97
96-100	71	3.49	62	4.78	133	3.99

101-105	32	1.57	65	5.0	97	2.91
106-110	16	.79	53	4.08	69	2.07
111-115	17	.84	50	3.85	67	2.01
116-120	23	1.13	32	2.47	55	1.65
121-125	10	0.49	29	2.23	39	1.17
126-130	9	0.44	19	1.46	28	0.84
131-135	6	0.30	32	2.47	38	1.14
136-140	5	0.25	21	1.62	26	0.78
141-145	6	0.30	31	2.39	37	1.11
146-150	3	0.15	15	1.16	18	0.54
151-155	6	0.30	30	2.31	36	1.08
156-160	3	0.20	26	2.00	29	0.84
161-165	16	0.79	34	2.62	50	1.50
166-170	11	0.54	19	1.46	30	0.90
171-175	9	0.44	22	1.70	31	0.93
176-180	5	0.25	12	0.92	17	0.51

Figure 7 shows the frequency distribution per five degrees of azimuth of the total survey area, the Pre-Keweenawan area, and the Keweenawan area. Figure 8 shows the frequency distribution per five degrees of azimuth of the magnetic trend patterns of the three amplitude groups within the Pre-Keweenawan area. Figure 9 shows the corresponding distribution within the Keweenawan area. It is to be noted that the elements of magnetic trend patterns associated with the Keweenawan diabase dikes were tabluated with other elements of the Keweenawan area, though most of these dikes occur within the Pre-Keweenawan area.

From Figures 7, 8 and 9 it is clear that there is a dominant east-west trend through the study area for all groups of anomalies. This east-west trend can be regarded either as a basic tectonic trend or as an overprinted pattern on previous ones. Figure 7-C shows two subsidiary peaks on either side of the major east-west peak associated with the Pre-Keweenawan area. They occur roughly at N 72° E and N 102° E and are comparable to two shear planes. This fact suggests that the acting stress on these rocks at the time of their formation or right after was probably of a nonrotational nature (pure shear). Assuming that the rocks were ductile, as evidenced by folding, it can be concluded that the direction of the principal stress axis was north-south. Figure 9-B shows that the subsidary peak at N 72° E is more developed than the other subsidary

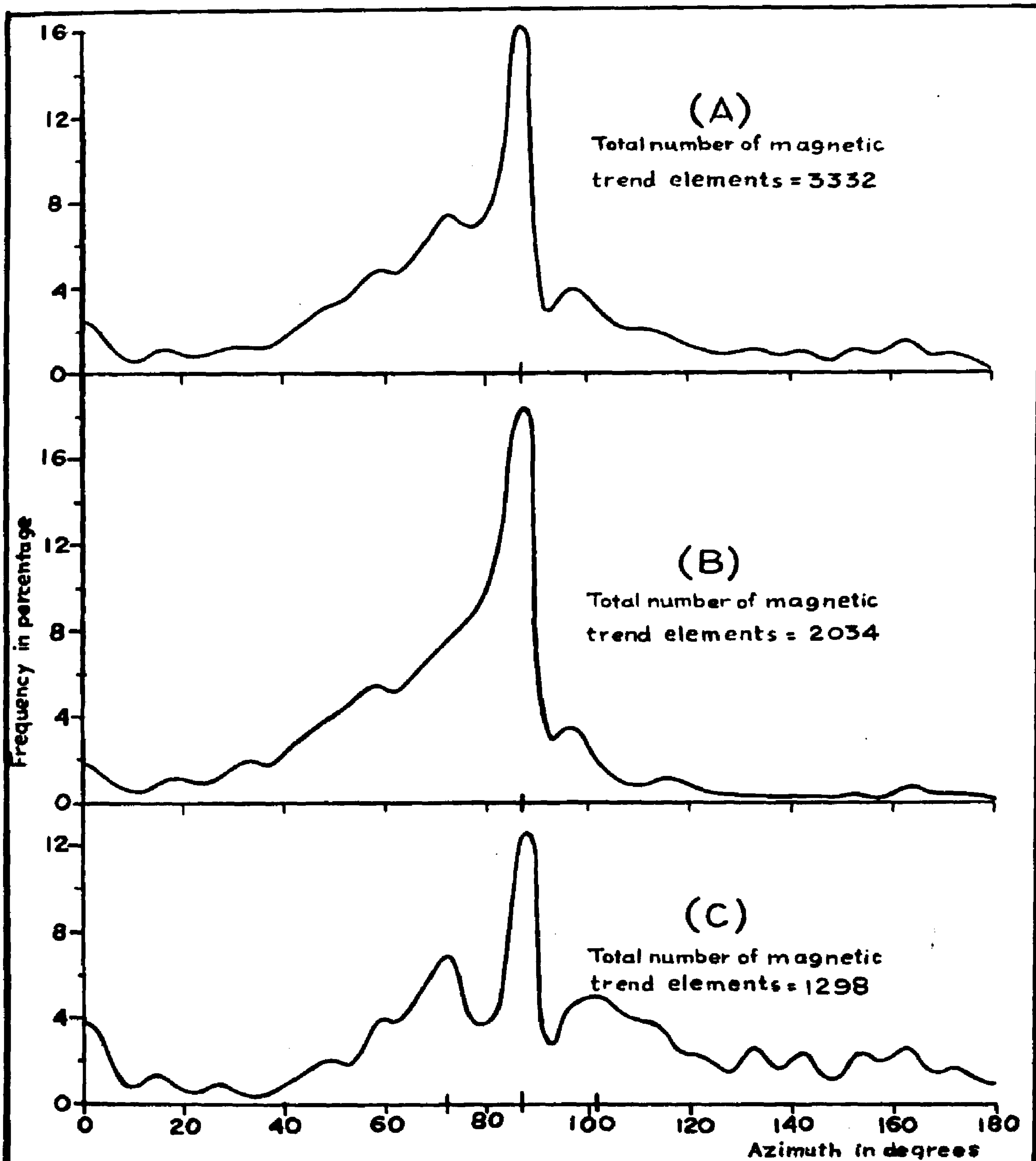

Fig. 7. Distribution of magnetic trend elements in (A) Total survey area (B) Keewanawan rocks (C) Pre - Keewanawan rocks .

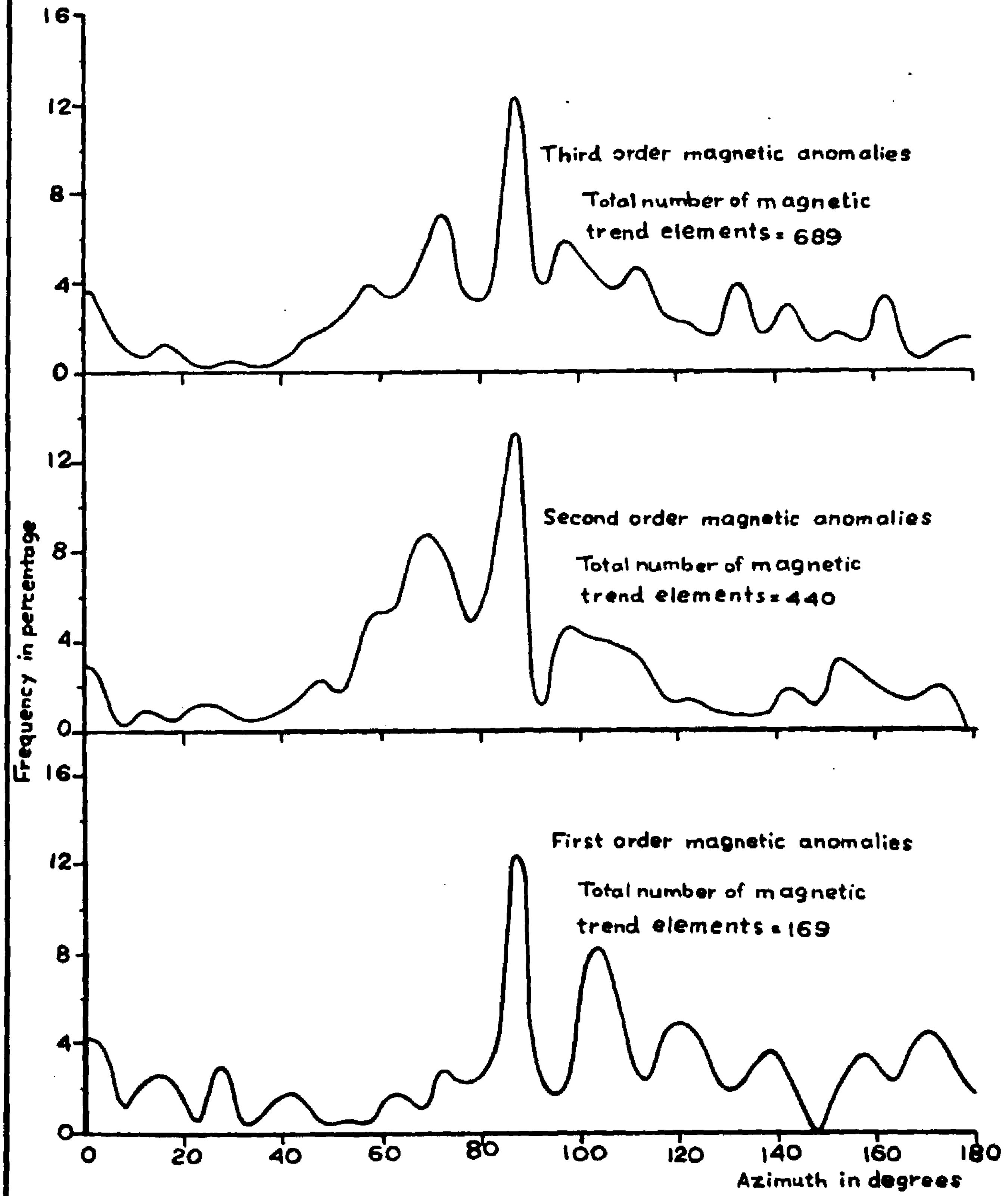

Fig. 8. Distribution of magnetic trend elements within Pre-Keewanawan rocks according to order of magnetic anomalies.

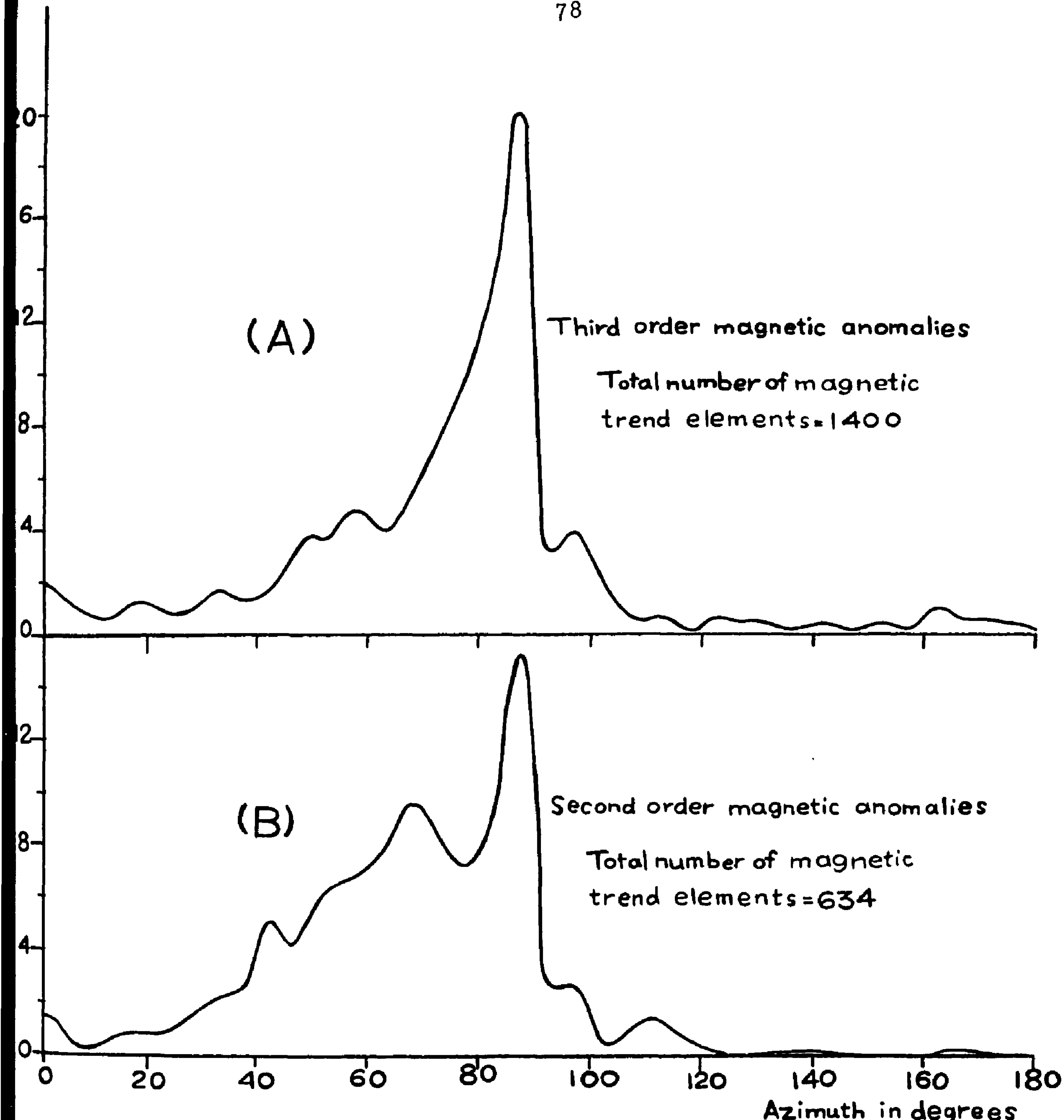

Fig.9. Distribution of magnetic trend elements within the Keewanawan rocks according to order of magnetic anomalies.

peak. This may suggest that the acting stress during the Keweenawan time was of a rotational nature (simple shear) due to a shear couple. Figure 7-B shows a gradual increase in frequency of magnetic elements that have an azimuth between 40 and 85 degrees that resulted in an asymmetry of the major east-west peak for the Keweenawan area. This may reflect a gradual shift in both time and space of the acting shear couple.

CHAPTER VIII

INTERPRETATION

General

Heiland (1940) states that

> Most interpretation of magnetic data is of a qualitative nature. This is due to several factors, (1) The magnetic methods lack depth control, (2) Most quantitative interpretation is indirect, (3) Magnetic properties of geologic formations, particularly of igneous and metamorphic rocks, are subject to great horizontal and vertical variations and are dependent on the thermal and mechanical history, the effects of which are difficult to evaluate, and (4) Magnetism is the only physical rock property which is of a bipolar nature, and variability of polarization adds another unknown. Quantitative interpretation is further handicapped because the proportion of induced and remanent magnetism is rarely known.

Although these conclusions are about 30 years old, they still hold true in general for an area with complex Precambrian geology such as the Northern Peninsula of Michigan.

Assuming that the overlying sediments show no magnetic effect, the broad range of magnetic anomalies can be interpreted as reflecting changes in the composition of the igneous and metamorphic basement rocks. Geological features such as faults, extrusives, and intrusives can frequently be identified by observing the shape and extent of the anomalies over a contact between rock units, together with the known regional geology. Abrupt shifts of the magnetic contour pattern is often an indication of a fault or an unconformity.

The ultimate purpose of magnetic interpretation is to deduce the geometry of magnetic bodies causing the anomalies. Unfortunately, an infinite number of subsurface distributions of magnetization can explain a set of magnetic field observations on the earth's surface. This holds true even if the field is known with perfect precision at every point on the surface. It follows that magnetic anomalies alone are not sufficient for uniquely determining the bodies or structures causing the anomalies. Therefore the indirect method of interpretation utilizing theoretical anomalies, calculated from bodies of plausible shape and magnetic characteristics, plus the extrapolation and interpolation of known geology was the principal approach used in this study. The geological interpretation of the aeromagnetic maps is presented in form of bedrock geology map (Plate III) and geological profiles (Plate IV).

Aeromagnetic Maps

Introduction

It is highly desirable to initiate the interpretation by discussing the aeromagnetic maps. The aeromagnetic maps depict a wide range of magnetic intensity which is characteristic to the Lake Superior region. Positive anomalies range from few tens of gammas to about 8,000 gammas. Negative anomalies seldom reach a value of 1000 gammas. These anomalies are superimposed on the normal magnetic variation which averages about four gammas per mile over the study area, as computed from the U.S. Coast and Geodetic total intensity map (1955). The normal magnetic variation increases from south to north. The following discussion involves the qualitative interpretation of the aeromagnetic maps, based upon the previous division of the study area.

The Keweenawan Area

Several lineations within the Keweenawan area are immediately apparent from the aeromagnetic map (Plate I). These lineations are associated with the Keweenawan lavas of the Northern, Middle, and Southern Trap Ranges. In the northwestern portion of the area and extending across it, skirting the south shore of Lake Superior, is a major multipeak magnetic anomaly. This anomaly is composed of alternating positive and negative peaks that reach a maximum amplitude of 750 to 2000 gammas along its extension. It coincides with and is caused by the outcropping Keweenawan lavas of the Northern Trap Range. The width and amplitude of the anomaly are relatively uniform within the area, which suggests that the source is a single geologic formation. The elongate shape of the anomaly suggests the trace of a dipping sheet-like mass. The steep magnetic gradient of this anomaly and its narrowness is indicative of the outcrop of the source rock. This anomaly reaches its maximum breadth in the Porcupine Mountains area. The broadening could be explained by a local increase in the volume of the extrusives and or due to doming in the area.

Another major elongate anomaly is shown in the central portion of the area. It extends from west of the Keweenawan Bay southwestward toward Lake Gogebic and to the west of it. The amplitude, ranging from 500 to 900 gammas and the discontinuous nature of this anomaly, reflect variations in depth to its source. This anomaly is interpreted to be due to buried Keweenawan lavas of the Middle Trap Range. The Middle Range only outcrops at Silver Mountain which is located in sections 1 and 12 of T49N, R36W and section 6 of T49N, R35W, Houghton County. The Middle Trap Range reaches its steepest magnetic gradient and highest amplitude at Silver Mountain. According to Roberts (1940), this outcrop is composed of at least fourteen uralitized basalt flows. The flows strike N 20° E and dip 15° to the northwest. They are fine grained amygdaloidal extrusive rocks, and according to Lane (1909), are typical Keweenawan basalts. The structure of this range is interpreted to be the result of upfaulted blocks in the form of a horst. Some magnetic patterns cut through the Middle Trap Range anomaly and are believed to be associated with transverse faults that transect the Range. The difference in elevation of the Middle Range along its extension is attributed to these faults. The abrupt termination of the Middle Range anomaly at the northern end is interpreted to be the result of an east-west striking crossfault. The Bouguer gravity map of the area (Bacon, 1957) and the magnetic second vertical derivative map substantiate this conclusion. A negative magnetic anomaly to the south and east of the Middle Trap Range correlates with the Jacobsville sandstone which terminates at the outcropping of the unconformity between the Jacobsville sandstone and the Pre-Keweenawan rocks. Along the western protion of T50 and 51N, R34W, a north-south striking fault is believed to have dropped the lavas to a considerable depth to the east of it. The contact between the Jacobsville sandstone and the Pre-Keweenawan rocks east of this fault can be traced out by the increased wavelength of the magnetic anomalies associated with the mapped Jacobsville sandstone.

West of Lake Gogebic, at longitude 89° 50' W, the anomaly associated with the Middle Trap Range, joins with a subparallel anomaly south of it. The southern anomaly is believed to be due to the South Trap Range which outcrops occasionally at the southern edge of the Jacobsville sandstone. The outcrops of the South Trap Range east of the junction point are associated with no definite magnetic character in contrast to situation west of the junction point. This can be explained by a difference in magnetic polarization of the lavas in these two localities due to a remanent component and/or due to differences in the dip of the lavas. To the east of the junction point some lava outcrops were found to dip at an angle of 15° to the northwest, while to the west of the junction point, outcrops of lava dip at 70 to 80° to the north.

Between the Northern Trap Range and the Middle Trap Range there is a relative magnetic low area which is characterized by low magnetic gradients. This is believed to be associated with the basalt flows in the downthrown block buried beneath the Jacobsville sandstone. In T50N and to the east of R36W there is a positive magnetic anomaly that reaches an amplitude of 500 gammas which is probably due to an anticlinal flexure in the lavas. In T48N, R38 and 39W the magnetic pattern indicates a fault which may have brought some parts of the lava nearer to the surface.

A well-defined magnetic low of roughly 1100 gammas magnitude exist over the Iron River syncline. Another magnetic minimum of much lower magnitude occurs over the Presque Isle syncline and extends to the northwest out of the study area. A positive anomaly of about 300 gammas magnitude surrounds the Iron River syncline anomaly from the west and north. This anomaly is correlated with a rhyolite extrusive body that roughly parallels the base of the Nonesuch shale. In sections 5, 6, 7 and 8 of T49N, R44W, this anomaly reaches a maximum amplitude of about 1500 gammas. The high magnitude anomaly may be due to remanent polarization of the rhyolite. Another positive magnetic anomaly of 1500 gamma amplitude and of large areal extent occurs east of the Iron River syncline and centers in T50N, R42W. This anomaly has been interpreted to be due to an upfaulted block of a previously folded anticlinal structure of the Keweenawan lavas that underlie the rhyolite and the Nonesuch shale.

A negative magnetic anomaly in T40N, R42W, within the Northern Trap Range, correlates with a rhyolite body mapped by Wright (1909). Rhyolite is found in drill holes south and within the Iron River syncline and in the Porcupine Mountains area. Miller (1966), on basis of quantitative interpretation of gravity profiles across the Porcupine Mountains area, concluded that the rhyolite is about 2000 to 3000 feet thick under the syncline, 15,000 feet thick in the Porcupine Mountains and extends for some distance to the south of the syncline. The structure in the Porcupine Mountains area and the origin of the Iron River syncline could be the result of the lopolithic intrusion of rhyolite. In this case, basining has been contemperaneous with the intrusion, with the overlying sediments sagging downward while masses of rhyolite are being withdrawn from the underlying magma reservoir. Billings (1959), states,

> In fact, some geologists consider this contemperaneous basining, an essential part of the definition of a lopolith. If a large, concordant sheet injected into flat sedimentary rocks were deformed into a basin, during some later orogenic period, these geologists would use the term sill rather than lopolith.

Near the western end of the Northern Trap Range in the study area, there is an elongated negative anomaly of about 200 gamma amplitude centered at the border between T48N and T49N and extends across the area from the western border of R47W, eastward to the eastern border of R43W. This anomaly correlates with outcrops of felistic conglomerate.

Pre-Keweenawan Area

Lake Gogebic Area

Strong magnetic highs are associated with the eastern end of the Gogebic Range. They are mainly due to the Tyler slate which includes the Ironwood iron formation as its lower most member. In sections 7, 8, and 9 of T47N, R45W, the anomaly reaches its highest magnitude of about 6000 gammas. At this location an apparent thickening of the Ironwood iron formation ends at the center of T47N, R43W. The magnetic anomaly associated with the Tyler slate wraps around the nose of an eastward plunging anticline, the Marenisco anticline. West of Lake Gogebic near Marenisco, Michigan, the magnetic anomaly associated with the upper members of the Tyler slate disappear and the magnetic high associated with the Ironwood iron formation appears on the south limb of the Marenisco anticline. This anomaly lies in the center of T46N and extends from the eastern border of R43W to western border of R45W, on the upthrown side of the fault and extends across the Michigan-Wisconsin border.

To the south of the Ironwood iron formation anomaly, along the northern limb of the Marenisco anticline, there is a negative magnetic gradient of about 250 gammas per mile that extends southward for about four miles at the extreme western border of the study area and averages about one mile in width at the eastern end of the Gogebic Range. This negative, uniform magnetic gradient is interpreted to be due to greenstones and greenschists that underlie the Tyler slate. West of T47N, R46W, there are some granite rocks that outcrop through the greenstones. These outcrops are not reflected in the magnetic map.

The center of the Marenisco anticline, west of Lake Gogebic is occupied by a very large number of weak magnetic anomalies that strike about N 70° E. These anomalies are associated with granitic rocks mapped by Fritts (1965), namely granite and banded gneiss. The boundary mapped by Fritts between the banded gneiss and the granite is apparent from the magnetic pattern east of T47N, R44W. To the west of that point the boundary is not apparent on the magnetic map and the two units are mapped as one unit.

The complexity of the magnetic character of the Animikie rocks on the north limb of the Marenisco anticline and east of T47N, R44W reflects a higher degree of deformation than the same rocks west of that point. According to Prinz (1967), to the west of that point, the period of major deformation of these rocks postdated the Keweenawan basalt flows, whereas to the east of it the deformation is Pre-Keweenawan.

The Tyler slate anomaly on the south limb of the anticline is located in T46N and extends from western portion of R41W to western portion of R43W. To the south of the Tyler slate anomaly, a positive magnetic high that reaches about 1500 gammas in amplitude lies in the southeast portion of T46N, R42W. This anomaly is related to the iron formation in the lower part of the metatuff and tuffaceous metagraywacke that Fritts (1967) has mapped. Skirting the magnetic anomaly associated with this iron formation is a small negative anomaly that reaches a magnitude of 250 gammas in some places. This anomaly is correlated with the upper parts of the metatuff and tuffaceous metagraywacke, minor quartzite and clomgomerate. At the upper contact of this formation with the graywacke near Banner Lake, there is another narrow negative anomaly of higher magnitude that ranges between 350 and 500 gammas.

There is a discontinuity in this anomaly at the border between T46N and T45N, R43W which may be attributed to Barb Lake fault. At the upper part of this formation, on the south side of the fault, there is a magnetic high that reaches an amplitude of 4000 gammas. This is correlated with the magnetic iron formation in the upper part of the graywacke member. This is bordered to the southeast by a magnetic low and then a magnetic high. The magnetic low ranges between 300 and 500 gammas and is believed to be associated with the pillow lava and fragmental volcanic rocks. The magnetic high which has an amplitude of 200 gammas is believed to be associated with the metatuff and magnetic iron formation. The discontinuity of these anomalies is also attributed to the Barb Lake fault which strikes east-west across the center of the Lake Gogebic area.

It is clear from the aeromagnetic map of this area and from the geologic information that the principal structure to the north of the Barb Lake fault is a south-dipping monocline. North of the Barb Lake fault and in T46N and extending eastward from R40W and south of the upper contact of the metatuff formation, there is a decreasing uniform magnetic gradient that averages about 500 gammas per mile. This uniform magnetic gradient is correlated with the Michigamme slate.

From the aeromagnetic map (Plate I-d), it is clear that the structure south of the Barb Lake fault is more complex and highly folded. Fritts (1965) reported that diamond drilling near Banner Lake indicated a synclinal flexure. The character and magnitude of the magnetic high associated with the metatuff helped in delineating the fold structures south of the Barb Lake fault. The folding of these rocks is believed to have taken place after their deposition over the erosional surface of the Wolf Lake granite. The Wolf Lake granite to the south of the Barb Lake fault is considered to be the oldest rock in the area, and occurs at the center of the anticlines and is associated with weak negative magnetic anomalies.

There are two more broad negative anomalies that occur south of the Barb Lake fault. The first occupies the center of T45N and extends from the eastern border of R43W to the center of R41W. The second occupies T44N and extends from the center of R40W to the western border of R38W. These two anomalies reach an amplitude of about 600 gammas and are correlated with the Michigamme slate. The Michigamme slate in this area is named the graywacke formation near Paulding by Fritts (1967). These magnetic lows lie along the axes of synclines in that area.

The Iron River-Crystal Falls Area

The Iron River-Crystal Falls area is characterized by widely-contrasting magnetic anomalies. One of the most dominant features is a group of remarkably sharp, long negative anomalies which cut across all other magnetic anomalies. This group of anomalies occurs between latitude 46° 15' and 46° 45' N and east of longitude 85° 05' W, with greatest concentration in T48N and T49N. All of these anomalies are related to reversely magnetized diabase dikes. These dikes intrude strata as young as Michigamme slate, while other dikes intrude the Margenson Creek gneiss, which is mainly a granitic rock, generally foliated and gneissic. The age of the Margenson Creek gneiss is believed to be Lower Precambrian. Some negative magnetic anomalies associated with the diabase dikes extend through the area overlain by the Jacobsville sandstone, and they may intrude the Keweenawan lavas of the South Trap Range. These dikes occur in T48N, R37W and western portion of R36W.

The anomalies associated with the diabase dikes that occur to the west of the contact between the Jacobsville sandstone and the Pre-Keweenawan rocks have a greater wavelength than those associated with the diabase dikes occurring east of this contact. This suggests that these dikes do not reach the bedrock surface and thus does not intrude the Jacobsville sandstone.

The second dominant feature in this area is a group of large positive anomalies that occur within the Michigamme slate. There are two anomalies of this group in Plate I-c. One occurs in T48N, R32W and the other one centers approximately on the south border of T48N, R34W. These anomalies are believed to be due to deep seated mafic rocks of unknown origin. Other anomalies of this type are shown on Plate I-e. They are located in T45, 46, and 47N, R33, 34, and 35W. These anomalies were studied by Balsley and others (1949) and are believed to be mainly due to dark magnetic slate of volcanic origin on crests of anticlinal folds. The fact that these anomalies become weaker and broader westward indicates the presence of a series of west plunging anticlines, on which the magnetic rock becomes progressively deeper.

The third group of anomalies occurs in T42, 43N and extends from the western border of R32W to the eastern border of R36W. This group of moderately strong positive anomalies reach amplitudes of 2500 gammas. The major part of the Iron River basin is located within this area. Most of these anomalies are caused by a strongly magnetic slate known as the Stambaugh formation. This magnetic slate is exposed in some places in this area, notably on the hill on which the town of Stambaugh is located. The slate is composed of fine-grained, intergrown chert and siderite, with abundant tiny crystals of magnetite throughout. This group of anomalies appears erratic in both trend and intensity. This indicates that the Stambaugh formation is contained in tightly folded synclines of highly variable trend and plunge, characteristic of the Iron River-Crystal Falls area.

Another group of positive anomalies of moderate magnitude occur in T42N, R34, and 35W. The source of this group of anomalies lies within the Badwater greenstone. It is composed of flows, tuffs, and agglomerates. The Brule River anomaly (Balsley, 1949) which occurs to the south of the Randville dolomite is associated with another belt of greenstone, called the Brule River greenstone. This formation is exposed in a number of places in the southern part of Sections 20, 21 and 22, T42N, R35W. It is a massive metabasalt, locally agglomeratic and ellipsoidal.

Another dominant magnetic feature in this area is the strong positive anomaly bordering the Amasa Oval. This anomaly reaches a magnitude of 6000 gammas in several places. It is caused by the upper part of the Animikie Hemlock formation which is composed mainly of volcanic breccia and basaltic flows. On the eastern side of the Amasa Oval, the anomaly exhibits a north-south strike and also may be due in part to the Fence River formation. This formation is a fine-grained, magnetite-bearing quartzite. On the western and northern sides of the Amasa

Oval, the anomaly is generally broader and discontinuous due to faulting. The Amasa formation which is chiefly a martite slate with layers of cherty-iron formation is non-magnetic. This fact has been verified by Weir (1967) as a result of a ground magnetic survey that has been made along the southwestern protion of the inferred belt of the iron-bearing Amasa formation. The group of anomalies north and west of the Amasa Oval are interpreted to be due to the same volcanic breccia and basaltic flow member of the upper Hemlock formation that underlies the Michigamme slate. The positive anomalies that occur in the center of T47, 46N, and the northeast portion of 45N, R31, and 32W, bordering the two granitic intrusions are believed to have their source within the Hemlock formation.

A large, broad negative magnetic anomaly in T46N, R31W, extends southeastward along the eastern border of the Amasa Oval. This anomaly correlates with the non-magnetic graywacke of the Michigamme slate. Within the Amasa Oval, the lower members of the Hemlock formation show two weaker magnetic zones that trend northwest. The source of these anomalies may be a magnetic volcanic rock within the Hemlock formation. Moderate to strong anomalies occur along the eastern border of the West Kiernan sill. Similar anomalies are associated with the metagabbro dikes in the area.

A broad, positive belt of magnetic anomalies extending northwest-southeast in T43N, R31W is interpreted by Bayley (1959) to be due to the magnetite-bearing volcanic schist that underlies the Randville dolomite. A broad negative magnetic anomaly roughly parallels the inferred belt of Randville dolomite within the Amasa Oval.

The magnetic anomaly associated with the Margenson Creek granite gneiss at the center of the Amasa Oval is not clearly defined as those associated with the two Margenson Creek granite gneiss outcrops to the northeast of the Oval. This can be explained by the fact that the magnetic contrast between the volcanic breccia and basaltic flows and the granitic rocks outside of the Oval is much higher than that between the granite and the peripheral dolomite within the Oval.

The granitic rocks north of the Marquette Range cover a large area from the center of T48N to T50N, and from R33W to the eastern border of the study area. The granite is characterized by a pattern of discontinuous highs and lows of varying orientation and of low to moderate magnitude. It seems that the magnetic character of these granites is highly affected by the Marquette Range anomaly to the south of it and by the several diabase dikes that cut across it. The northern contact of the granite which is an erosional surface is mapped primarily on basis of geologic information because there is no sharp and definite magnetic contrast between the granite and the Michigamme slate north of it. The magnetic anomalies associated with the Michigamme slate north of this granite are of higher frequency and of more irregular strike than those associated with the Michigamme slate at the center of the basin. This reflects the thinning of the Michigamme slate in this area and that the magnetic character of the underlying granite shows through the overlying Michigamme slate.

A large positive magnetic anomaly of 8,000 gamma amplitude occurs in the center of T48N, R31W. This anomaly is associated with the iron formation at western end of the Marquette Range. Another distinct positive anomaly in the northeast portion of T49N, R34W, correlates with the iron formation at Tyler mine. Another positive anomaly to the west of Tyler mine anomaly is believed to be due to an iron formation. Several small, positive anomalies which occur in the eastern portion of T49N, R33W, and T50N, R32W, are believed to be due to either local iron formations or small knobs of basic extrusives.

Discussion of Profiles

General

In this study fourteen profiles (Plate IV, A-N) were chosen across the area for quantitative interpretation. The geographic position of these profiles is shown on Plate III. They are laid out as closely as possible to cross at right angles the major geological features in the area and are positioned in areas where some geological control is available in order to extrapolate from and interpolate between the known geology utilizing the magnetic data. The topography of the ground surface along the profiles was taken from the U.S. Geological Survey topographic maps.

The general purpose of the quantitative magnetic interpretation was to determine the geologic relationship along the vertical cross-section. In particular, the quantitative interpretation was used to study the geological relations along the Keweenaw fault and to determine the structure of the Keweenawan lavas of the Middle Trap Range below the Jacobsville sandstone.

Many of the geologic bodies and structures of interest in the area of investigation are horizontally linear and thus can be approximated by the two-dimensional form of analysis. A two-dimensional magnetic program outlined by Talwani, Worzel, and Landisman (1959) was used in these computations utliizing the Michigan State University C.D.C. 3600 computer. This program is based on the assumption that the boundary of the vertical cross-section of a two-dimensional body can be approximated by a polygon. This approximation can be made as accurate as one wishes by increasing the number of sides of the polygon. The total magnetic intensity due to the polygon can be obtained at any given point and there are no limits on the size or position of the body.

Initially several trials were conducted to compute anomalies from bodies of assumed geometric configuration and magnetic polarization contrasts to fit the observed anomalies along three of the fourteen profiles. The assumed forms of these bodies were selected on the basis of available geologic information. All other available information concerning the parameters of the bodies such as depth, length, dip and magnetic polarization also were used in the calculations. Unfortunately, little success was achieved in matching theoretical anomalies with the observed magnetic profiles. The inability to match theoretical with observed anomalies is believed to stem from the complexity of magnetic rock properties.

As a result, a qualitative approach was made to the interpretation of the profiles utilizing the surface geology information, depth determinations, second vertical derivative magnetic map, Bouguer gravity map (Bacon, 1957), plus the results of one profile, H-H' (Plate IV-D) in which a reasonable match was obtained between the theoretical and observed anomalies.

<u>Profile A-A'</u>

The magnetic gradient at the northern end of Profile A-A' is related to the dip of the Keweenawan lavas into the

Lake Superior basin at depth and the thickening of the Keweenawan sediments. There is a low magnitude positive anomaly of about 150 gamma amplitude that lies over the outcrop of Copper Harbor sandstone. This anomaly may be due to a conglomeritic member of the Copper Harbor sandstone which contains abundant basalt pebbles. To the immediate south of this anomaly there are two positive peaks separated by a large negative anomaly. The two positive peaks reach an amplitude of about 500 gammas and are related to the Keweenawan lavas of the Northern Trap Range. The negative anomaly reaches an amplitude of about 400 gammas and is associated with felsitic, concordant intrusion within the Northern Trap Range. A negative anomaly occurs to the immediate south of the positive anomaly associated with the Northern Trap Range lavas. This negative anomaly is believed to be attributed to loss of magnetism of the lavas near the Keweenaw fault or to the complications of remanent magnetization in the neighborhood of the fault. Hemming (1965) in a typical cross section across the Keweenawan fault near Portage Lake mapped the Keweenawan fault at a distance of about one mile to the south of the positive anomaly associated with the Keweenawan lavas. Accordingly the Keweenawan fault throughout the study area has been mapped at the center of this negative anomaly at the southern margin of the Northern Trap Range.

The Jacobsville sandstone to the south of the Keweenaw fault yields a magnetic low. At the southern margin of the Jacobsville sandstone there is a magnetic high of about 2400 gamma magnitude which is associated with the outcropping lavas of the South Trap Range. It is to be noted that although the width of the outcrop of the South Trap Range is less than that of the Northern Trap Range, the South Trap Range anomaly has a much higher amplitude. This may be attributed to the higher angle of dip along this profile and/or higher magnetic polarization of the South Trap Range lavas.

To the immediate south of the South Trap Range anomaly there is a positive anomaly of 500 gamma amplitude associated with the Ironwood iron formation. The anomaly associated with the greenstones that underlie the iron formation seems to be partially masked by the local strong regional effect resulting from the iron formation anomaly. The granite and banded gneiss at the center of the Marenisco anticline is associated with a magnetic low that includes narrow positive anomalies which have amplitudes generally less than 100 gammas. To the south of the granite there is a magnetic high of about 1500 gamma amplitude associated with the iron formation on the south limb of the Marenisco anticline. The contact between the granite and this iron formation is considered to be an unconformity, as evidenced by the erosion of the greenstones on the south limb of the Marenisco anticline. To the south, the iron formation is overlain by the metatuff and tuffaceous metagraywacke which is associated with a magnetic low.

Profile B-B'

The prominant feature at the northern portion of profile B-B' is the positive magnetic anomaly associated with the rhyolite outcrop. This anomaly is of higher magnitude than that associated with the Northern Trap Range lavas. This may be the result of strong magnetic polarization of the rhyolite due to a remanent component. The negative anomaly associated with the felsite intrusion within the Northern Trap Range also occurs on this profile. The negative anomaly immediately south of the positive anomaly associated with the Northern Trap Range lavas suggests a southerly dip of the contact between these lavas and the Jacobsville sandstone. There are two positive anomalies that occur within the area of the Jacobsville sandstone outcrop. The anomaly that lies to the immediate south of the Keweenaw fault has a steeper magnetic gradient than the one that lies further to the south. The latter is interpreted to be caused by a horst structure associated with the Middle Trap Range.

The anomaly to the immediate south of the Keweenaw fault is interpreted to be due to a block of Keweenawan lavas which is separated from the main body of the

Northern Trap Range by faulting. This anomaly continues for about fifty miles across the study area and lies immediately south and parallel to the interpreted position of the Keweenaw fault. This suggests an association of the origin of this block with the thrusting of the Northern Trap Range along the Keweenaw fault. The author suggests that the origin of this block may be due to either one of two possibilities. One possibility stems from the assumption that faulting took place across the southern portion of the Northern Trap Range (Figure 10-B). Due to the thrust with rotation along the Keweenaw fault, the wedge of sediment north of the fault has been brought nearer to the surface with the Middle Trap Range lavas assuming a greater angle of dip in relation to the South Trap Range (Figure 10-C). Differential erosion followed and resulted in separation of the smaller block of lava from the main body of the Northern Trap Range (Figure 10-D). Still later a younger sandstone formation was deposited (Figure 10-E) leading to the present geologic structure.

Another explanation of this anomaly is based upon the assumption that faulting took place along the contact of the sandstone and the lavas of the Northern Trap Range or parallel to it. As illustrated in Figure 11-C, a crossfault developed within the Northern Trap Range lavas approximately at right angles to the Keweenaw fault plane and sliding of the faulted block took place (Figure 11-D).

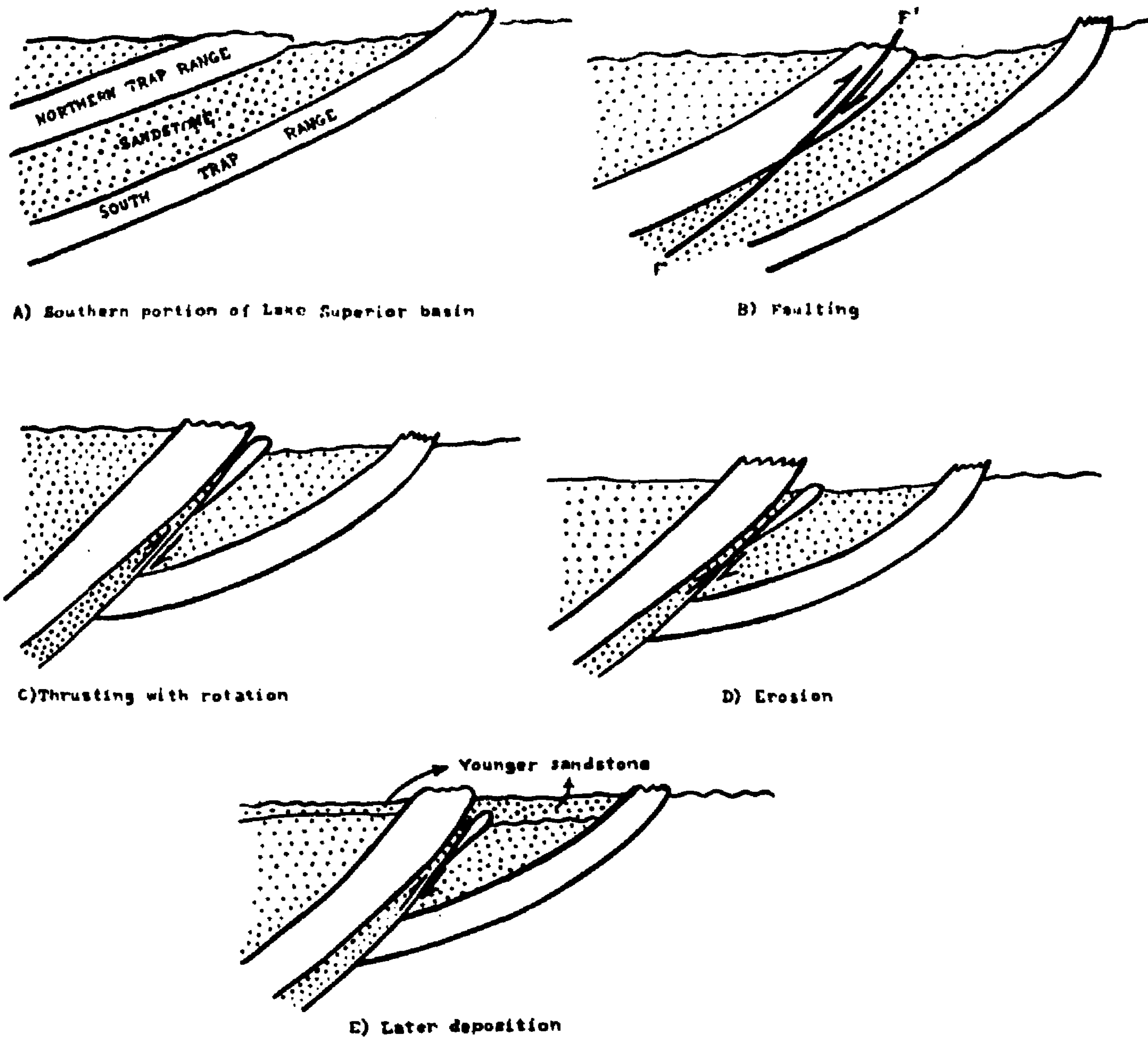

Fig.10.Possible development of structural relations along the Keewanaw fault

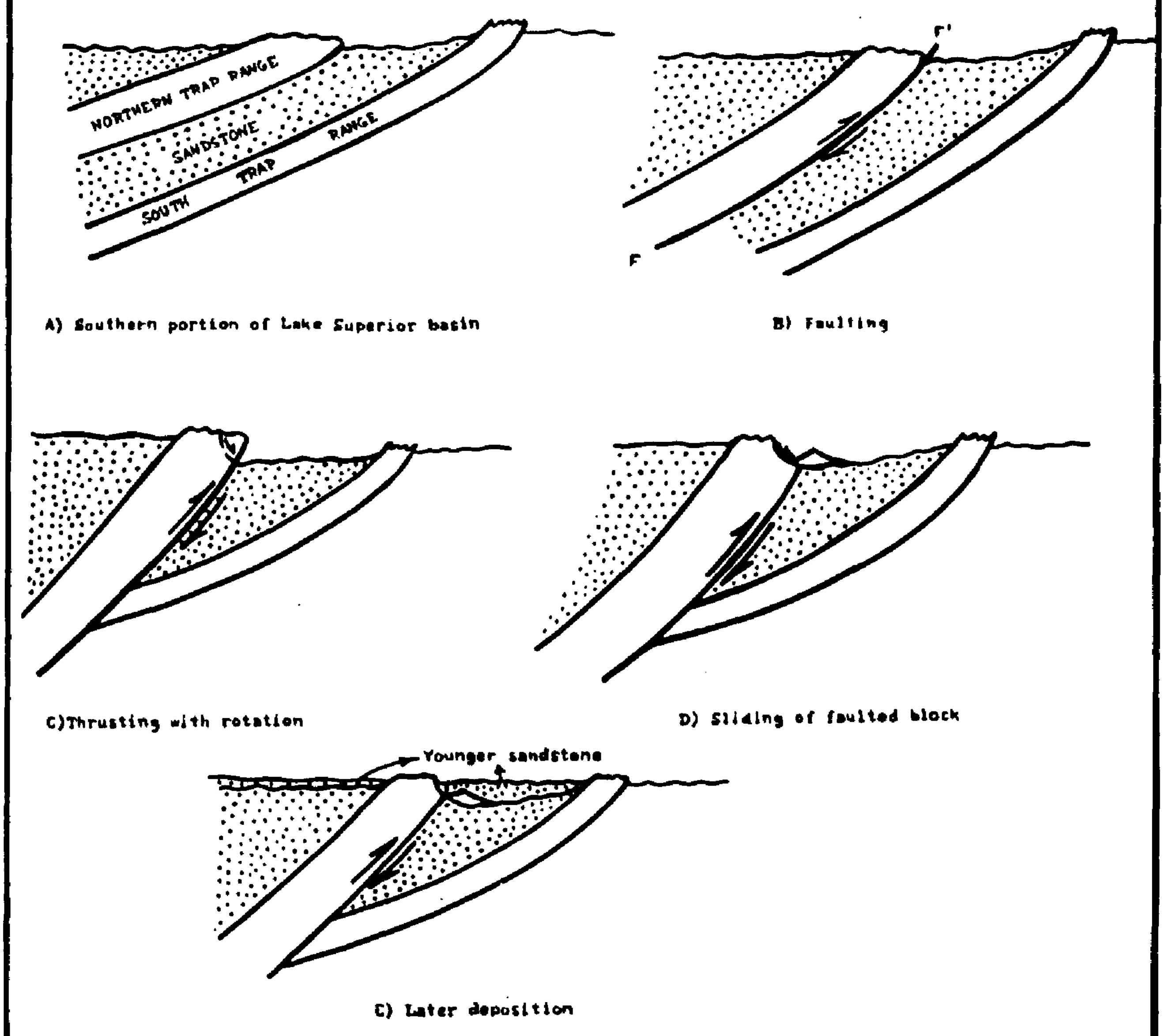

Fig.11. Possible development of structural relations along the Keewanaw fault

The cross-faulting and/or sliding may have been facilitated by insufficient support of the Northern Trap Range lavas by the underlying sandstone. Later deposition of a younger sandstone formation followed, leading to the present geologic structure (Figure 11-E).

Results obtained from quantitative magnetic interpretation substantiates the configuration along the Keweenaw fault shown in Figure 11-E. Also Miller (1966), as a result of his gravity investigation of the Porcupine Mountains area concluded that the southern margin of the lavas where they are in contact with the sandstone dips to the south rather than the north as previously postulated. He came to this conclusion as a result of quantitative interpretation of gravity profiles across the Keweenaw fault.

A third possible origin of the positive anomaly to the immediate south of the Keweenaw fault is an intrusion into the sandstone that did not reach the surface. This possibility seems unlikely due to the persistance of this feature for a distance of about fifty miles.

The anomaly associated with the South Trap Range reaches an amplitude of about 2000 gammas and is separated from the iron formation anomaly on the northern limb of the Marenisco anticline by a magnetic low. This low is associated with the upper member of the Tyler slate which is nonmagnetic. The anomaly associated with the greenstones along this profile is more pronounced than that shown on the previous profile and reaches an amplitude of 500 gammas. The positive magnetic anomaly associated with the iron formation on the south limb of the Marenisco anticline reaches an amplitude of about 1000 gammas.

To the south of the Marenisco anticline there is a syncline that includes rocks of the Upper Animikie series. A graywacke slate formation occurs at the center of this syncline and is correlated with the Michigamme slate to the east. The graywacke slate formation is associated with a a magnetic low and overlies the metavolcanics and metasediments near Blair Lake which is slightly magnetic. The metavolcanics and metasediments are underlain by the graywacke near Banner Lake which includes a magnetic iron formation in its upper parts. The two anomalies associated with the metavolcanics and iron formation member of the graywacke at the northern limb of the syncline merge into one anomaly that reaches about 200 gamma magnitude. The low magnitude and breadth of this anomaly can be attributed to the small angle of dip of these formations. The graywacke is underlain by the metatuff and tuffaceous metagraywacke which thickens along this profile due to repitition by faulting. At the extreme southern protion of the profile the granitic basement rocks of Lower Precambrian age outcrop at the surface.

Profile C-C'

The northern portion of Profile C-C', associated with the Keweenawan rocks, is similar to the corresponding portion of profile B-B'. However, the Northern Trap Range anomaly includes more magnetic lows. These lows are attributed to a number of felsite conglomerates of the Upper Middle Keweenawan Great Conglomerate and Outer Conglomerate. These conglomerates are estimated (Bulter and Burbank, 1929) to have maximum thickness of 2200 and 3500 feet respectively. Within the area of Pre-Keweenawan rocks the anomaly associated with the iron formation at the base of the Tyler slate on the south limb of the Marenisco anticline is not present probably as result of faulting. Further to the south there is a large positive anomaly of about 3500 gamma magnitude associated with the iron formation in the upper series of the graywacke near Banner Lake. The anomaly over the metavolcanic and metasedimentary rocks divides into a magnetic low and a magnetic high. The magnetic low lies to the immediate south of the iron formation anomaly and is associated with the pillow lavas and fragmental volcanic rocks. The magnetic high reaches a magnitude of about 500 gammas and is associated with the metatuff and magnetic metasedimentary rocks. The granitic basement rocks outcrop at the extreme southern portion of this profile.

Profile D-D'

Along Profile D-D' the Northern Trap Range anomaly reaches its maximum amplitude of 2000 gammas and the magnetic gradient north of it reflects a thickening of the sediments over the center of the Iron River syncline. The steep gradient anomaly to the south of the Keweenaw fault and the anomaly associated with the Middle Trap Range lavas is shown on this profile as in previously discussed profiles. It is to be noted that the South Trap Range does not outcrop along this profile and is assumed to underlie Lake Gogebic.

There is a small positive magnetic anomaly of about 200 gamma magnitude associated with the iron formation at the base of the metatuff and tuffaceous metagraywacke. Further to the south, an asymmetrical anomaly of about 600 gamma magnitude occurs along this profile. This is related to the combined effect of the outcropping metavolcanics and metasediments and the underlying iron formation in the upper part of the graywacke near Banner Lake. The steeper gradient of this anomaly on the northern side is attributed to the Barb Lake fault. The gentler slope of the southern side of this anomaly reflects the low angle of dip of the magnetic formations. There is another small positive anomaly of 200 gamma magnitude associated with the outcrop of the matavolcanics and metasediments at the southern limb of the syncline. At the southern portion of this profile and within the granitic basement rocks, there are two positive anomalies associated with two outliers of the metavolcanics and metasediments.

Profile E-E'

The portion of the profile E-E' associated with the Keweenawan rocks is similar to the corresponding portion of the profile D-D'. However, the South Trap Range anomaly is present along this profile and reaches a magnitude of about 500 gammas. Immediately to the south of the South Trap Range volcanics, the metatuff and tuffaceous metagraywacke outcrops and is intruded by a younger granite, probably of late Animikie age. This younger granite outcrops along this profile and in several other places south of Lake Gogebic and north of the Barb Lake fault. To the south of this granite there is a broad magnetic low associated with the upper members of the metatuff and tuffaceous metagraywacke, the graywacke near Banner Lake, and the metavolcanic member of the younger rocks. There are four positive magnetic anomalies associated with the outcrops of the metatuff and magnetic iron formation on both sides of the Barb Lake fault. The magnitude of these anomalies differ due to local thickening of this formation as a result of minor folding. The two magnetic lows that lie to the immediate south of the Barb Lake fault and at the southern portion of the syncline are associated with the graywacke slate formation. The central negative magnetic anomaly is due to local thinning of the metatuff and magnetic iron formation at that location. At the southern portion of this profile and within the granitic basement rocks, there is a broad positive anomaly of about 250 gamma magnitude associated with an outlier of the metavolcanics and metasediments.

Profile F-F'

The magnetic gradient at the northern end of Profile F-F' reflects a doming of the buried Keweenawan lavas. This doming is mainly related to folding. It is to be noted that there is a sharp decrease in the magnetic gradient at the northern end of this profile which is attributed to faulting of the Keweenawan lava. The steep gradient positive anomaly to the immediate south of the Keweenaw fault reaches its maximum amplitude of about 850 gammas along this profile.

The positive magnetic anomaly associated with the South Trap Range lavas reflect a thinning of these lavas due to erosion along its outcrop. South of the South Trap Range anomaly there is a sharp positive anomaly of about 600 gamma magnitude which is associated with the iron formation which occurs in the upper parts of the graywacke near Banner Lake. This anomaly is followed by a broader and stronger positive anomaly associated with the outcrop of the metavolcanics and metasediments. The Michigamme slate on the downthrown side of the Barb Lake fault is associated with a magnetic low. The granitic basement rocks are outcropping along the southern portion of the profile on the upthrown side of the Barb Lake fault. Several positive magnetic anomalies of varying amplitudes are associated with outliers of metavolcanics and metasediments in the granitic basement rocks.

Profile G-G'

The anomalies associated with the Keweenawan rocks along profile G-G' are generally similar to the corresponding anomalies along profile F-F'. However, the magnetic gradient at the northern portion of the profile reflects a thickening of the Keweenawan sediments along this profile as result of the disappearance of the domal uplift encountered along the previous profile. It is to be noted that the South Trap Range is associated with a negative anomaly along its outcrop which reflects a change in the magnetic polarization of the South Trap Range lavas. The negative anomaly is emphasized by the positive anomaly immediately to the south of it and associated with the metavolcanics and metasediments. The gentler gradient on the south side of the positive anomaly is attributed to a lower angle of dip of the metavolcanics and metasediments and due to thickening of the Michigamme slate toward the center of the syncline. The granitic basement rocks outcrop immediately to the south of Barb Lake fault and are associated with a small positive magnetic anomaly.

South of the Barb Lake fault, a strong positive magnetic anomaly of 5500 gamma amplitude is associated with the outcrop of the metavolcanics and metasediments on the northern limb of the syncline. The outcrop of the same formation on the south limb of the syncline is associated with another anomaly of much lower magnitude. This decrease in amplitude of the anomaly is attributed to thinning and gentler angle of dip of the metavolcanics and metasdeiments at the south limb of the syncline. Another positive magnetic anomaly at the southern end of this profile is related to outcropping or very near surface metavolcanics and metasediments.

Profile H-H'

The portion of Profile H-H' associated with the Keweenawan rocks has been interpreted quantitatively. Separate body configurations were utilized to approximate the Northern Trap Range, and the combined Middle and South Trap Ranges.

The magnetic program utilized in the quantitative interpretation is based on calculating the combined induced and remanent field vector. Both the induced and remanent field vectors are resolved into orthogonal components. These components are then added algebraically. The sums specify the coordinates of the end point of the combined field vector. The combined angles of declination and inclination are then calculated. An inclination of +45°, a declination of 285°, and a total magnetic intensity of 0.00354 c.g.s. units were used for the remanent magnetization vector of the Keweenawan volcanics. These are the approximate values given by Dubois (1962) and Jahren (1965) for the remanent magnetic polarization vector of the basic Keweenawan plutons and extrusives. These values are given for the remanent magnetic vector assuming that the lavas lie in a horizontal position. A structural correction of 50° dip was applied to the remanent vector applied for the Northern Trap Range body, and a correction of 20° dip was applied for the remanent vector used for the other body representing the Middle and South Trap Ranges. Consequently, the resultant magnetization vector for each body was calculated by the vector summation of the induced and remanent magnetization values. A magnetic inclination of +71°, a magnetic declination of 0°, and a total field intensity of 59,500 gammas were the magnetic elements utilized for the induced vector in the calculations. The resultant magnetic vector used in the calculation of the magnetic effect for the Northern Trap Range body has a magnetic inclination of +74°, a magnetic declination of 143°, and a combined field intensity of 527 gammas. The resultant magnetic vector used for calculating the magnetic effect for the other body has a magnetic inclination of +63°, a magnetic declination of 127°, and a combined field intensity of 513 gammas.

The value of magnetic susceptibility used for the combined vector for both bodies was unity and the combined intensity was read, in gammas, into the computer in place of the total magnetic field. The units of the dimensions of the bodies, the flight elevation (500), and station spacing (200), were in feet. The assumption has been made in the magnetic program that the inclination and declination do not vary as the magnitude of the anomaly increases. This assumption allows the summations of the effects of individual bodies along the profile.

Repeated trials with reasonable configurations bringing the Keweenaw fault to the surface greatly distorted the theoretical anomaly as compared to the observed anomaly. However, a reasonable match between the theoretical and the observed anomalies was achieved over this portion of the profile by assuming the configuration shown for the Northern Trap Range body in profiel H-H' (Plate IV-D). The steep gradient anomaly to the south of the Keweenawan fault is not present along this profile. A close correlation over the Middle Trap Range is obtained between the theroretical anomaly and the observed magnetic profile. The estimated depth from the quantitative interpretation for the Middle Trap Range is about 2000 feet. This value is in close agreement with the value of 2300 feet obtained from a borehole drilled at latitude 46° 31' N and longitude 89° 16' W through sandstone (Bacon, 1966).

This location is about 2.7 miles west of this profile. It is evident from the theoretical profile that no match for the negative anomaly associated with the outcrop portion of the South Trap Range has been achieved. This necessitates the assumption of a different magnetic polarization for the South Trap Range which in turn casts suspicion on the configuration of the Middle Trap Range anomaly determined by the calculation. It is significant to mention that the thickness of the Keweenawan lavas below the Jacobsville sandstone is not predictable from the magnetics. However, a minimum thickness of about 2000 feet is reasonable to assume.

To the immediate south of the South Trap Range anomaly there is an asymmetrical positive magnetic anomaly associated with the outcropping portion of the metavolcanics and metasediments. The gentle gradient on the south side of this anomaly is attributed to the thickening of the overlying non-magnetic Michigamme slate toward the center of the syncline. The granite outcrop to the south is associated with a magnetic low. At the southern portion of this profile another asymmetrical positive magnetic anomaly is associated with another metavolcanic outcrop to the south of the granitic basement rocks.

<u>Profiles I-I' and J-J'</u>

The profiles I-I' to N-N' are primarily aimed toward the discussion of the Keweenawan geology in the northeastern portion of the study area. This is justified by the fact that the Precambrian geology to the southeast of these profiles has been discussed in detail by the U.S. Geological Survey. The results of these studies are published by Wier and others (1953), Gair and others (1956), Bayley (1959), and Wier (1967).

Due to the general similarity between Profiles I-I' and J-J', they are discussed together. It is to be noted that the Northern Trap Range in both profiles is associated with a multiple peak positive anomaly which decreases in magnitude due to the thinning of the lava flows along this portion of the study area. The southern most peak is of a smaller amplitude and separated from the main Northern Trap anomaly by a negative anomaly. This anomaly is related to outcrops of felsitic intrusions within the Northern Trap Range. There is a possibility that the smaller amplitude anomaly to the south of the negative may be due to the continuation of the block of volcanics along the south edge of the Keweenaw fault.

It is to be noted that the Middle Trap Range is cut by three normal faults which bring the volcanics nearer to the surface. Along Profiel J-J' there is a peculiar negative anomaly associated with the Middle Trap Range. This negative anomaly is attributed to tilting of the faulted blocks of the Middle Trap Range. Also, it is to be noted that no South Trap Range anomaly is present along the southern end of the Keweenawan portion of these profiles on Profile J-J' or the profiles to the northeast. This is attributed to the feathering edge of the South Trap Range lavas due to erosion. It is important to mention that the thinning of the South Trap Range lavas shown on these profiles as well as the following ones is only a schematic representation.

Along the southern portion of these profiles diabase dikes cut through the older formation. The northwestern most dike along these profiles is believed to cut through the erosional wedge of the South Trap Range, but does not continue through the overlying Jacobsville sandstone. This is evidenced by the broader negative anomalies associated with these dikes as compared to the dikes outcropping in the southeastern portion of these profiles.

<u>Profiles K-K' to N-N'</u>

Profiles K-K' to N-N' are discussed together because of their general similarity. The Northern Trap Range anomaly along these profiles range in amplitude from 250 to 1000 gammas which reflects local change in the volume of the lavas along these profiles. The steep gradient positive anomaly to the immediate south of the Keweenaw fault is not present along these profiles. It is to be noted that there is a very broad positive anomaly of low magnitude that lies over the Jacobsville sandstone outcrop to the south of the Keweenaw fault. This anomaly is attributed to an anticlinal flexure of the Keweenawan lavas at depth. The Middle Trap Range anomaly reaches its maximum amplitude of about 750 gammas and its steepest gradient along profile K-K' where it appears to be very near to the surface. This observation is substantiated by the fact that the Keweenawan volcanics of the Middle Trap Range outcrop nearby at Silver Mountain. The Middle Trap Range anomaly is not present along Profile N-N' because this profile passes north of an east-west cross-fault along which the Middle Trap Range terminates. In all of these profiles there is no magnetic anomaly associated with the erosional wedge of the South Trap Range lavas.

Several diabase dikes along the southeastern portion of these profiles cut across Pre-Keweenawan formation. None of these dike anomalies cut across the erosional wedge of the Keweenawan volcanics. There is a positive magnetic anomaly of about 2500 gamma magnitude that occurs along the southeastern portion of the Profile K-K'. This anomaly is related to an anticlinal flexure of the metavolcanics and metasediments that underlie the Michigamme slate. Several other positive anomalies of smaller amplitude along the southeastern portion of the profile are associated with local anticlinal flexures along the metavolcanics and the metasediments.

It is worth noting that the portion of the magnetic profile overlying the Michigamme slate is leveling off in an easterly direction from profile K-K' to profile N-N'. This is mainly attributed to the thinning of the meta-volcanics and metasediments, possibly due to erosion before the deposition of the younger Michigamme slate.

CHAPTER IX

SUMMARY

This study has shown conclusively that aeromagnetic interpretation is an extremely useful tool in determining the regional structure of a Precambrian terrain consisting of widely diverse magnetic formations. It is evident, however, that the complexity of the magnetic rock properties restricts the interpretation to a semi-quantitative approach based upon the integration of the surface geology, Bouguer gravity anomalies, and the results of analytical studies of the magnetic data. Analytical studies that have proven useful in the interpretation include magnetic depth determinations and trend analysis, second vertical derivative total magnetic intensity anomalies, and correlation of theoretical magnetic anomalies with the observed magnetic data.

The magnetic interpretation has confirmed some geological relations and suggested new valid solutions to the major structural problems of the western portion of the Northern Peninsula of Michigan. The near surface contact between the Keweenawan lavas of the Northern Trap Range and the Jacobsville sandstone has a southerly dip along most of its extent west of longitude 89° 20' W. This dip probably originates from cross-faulting and/or sliding of a block of Keweenawan lavas over the Jacobsville sandstone to the south after the major thrust of the Northern Trap Range lavas along the Keweenaw fault. This explains the previous difficulty in tracing the Keweenaw fault on the surface along this portion of the study area.

A time break in deposition of the Jacobsville sandstone is suggested which results in two major series of sandstone. The lower series of this formation is believed to have been deposited before extrusion of the Northern Trap Range lavas and the upper series of sandstone after the major Keweenaw faulting. The author believes that this break in deposition of the sandstone during the period of tectonism associated with the Keweenaw fault is the main reason for the present ambiguity about the age of the Jacobsville sandstone. It is evident that the earlier sandstone series is not older than Middle Keweenawan age and that post-faulting series can be either of Late Keweenawan or Early Cambrian age, depending on the magnitude of the unconformity that separates the two series of sandstone.

The structure in the Porcupine Mountains area and the origin of the Iron River syncline are interpreted to be the result of a lopolithic intrusion of rhyolite. The sagging of the overlying sediments is believed to be contemperaneous with the withdrawal of the rhyolite from the underlying magma reservoir.

The structure of the Middle Trap Range is interpreted as an uplifted block of lava in the form of a horst. The volcanics of the Middle Trap Range generally are buried beneath 1250 and 2500 feet of Jacobsville sandstone. However, they outcrop in the Silver Mountain area. This variation in depth to the Middle Range is believed to be due to several cross-faults of considerable vertical displacement. The Keweenawan lavas in the graben between the Northern Trap Range and the northern portion of the Middle Trap Range exhibit an anticlinal flexure that extends parallel to the strike of the Middle Trap Range. A thinning of the Jacobsville sandstone in the central portion of Houghton County is indicated from quantitative interpretation of the aeromagnetic map. This thinning is suggestive of another anticlinal flexure of the Keweenawan lava. The lavas of the Middle Trap Range are interpreted as younger members of the South Trap Range lavas that have been separated from the South Trap Range east of longitude 89° 50' W. The older members of the South Trap Range lavas extend along the contact between the older Animikie rocks and younger Keweenawan rocks. The South Trap Range lavas occasionally outcrop, but in general these volcanics are buried beneath 3000 to 5000 feet of sandstone.

The Wolf Lake granite outcropping south of the Barb Lake fault and mapped by Fritts (1966) as of Late Animikie age is believed to be of Lower Precambrian age as the granitic basement rocks in the center of the Marenisco anticline. The basement rocks are believed to have been tilted to the north during early Precambrian time and were subjected to erosion, thus resulting in a greater angular unconformity between the basement and the overlying sediments. The northerly tilt of the basement rocks resulted in a thickening of the sediments toward the north. This fact is evident in the study area where younger Animikie rocks, metavolcanics, and metasediments exposed south and west of Watersmeet, unconformably overlie the granitic basement rocks, while the older Tyler slate unconformably overlies the granitic basement rocks outcropping near Marensico.

The magnetic strata of the Marenisco Range, as mapped by Fritts (1966) to be of uncertain stratigraphic position, are interpreted as the Ironwood iron formation of the Tyler slate series on the south limb of the Marenisco anticline.

The volcanic breccia and basaltic flows in the upper part of the Hemlock formation, which are associated with a group of strong positive anomalies surrounding the Amasa Oval, are believed to underlie the Michigamme slate basin across the study area. These rocks were mapped as metavolcanics and metasediments by Fritts (1966) at the western portion of the Michigamme slate basin.

The thickness of Michigamme slate varies between 1500 and 4000 feet in different portions of the basin. However, a magnetic source underlying the Michigamme slate was recorded at a depth of about 7000 feet. This is the deepest magnetic source in the study area.

The magnetic trend analysis results suggest that the stress acting on the Pre-Keweenawan rocks was of a non-rotational nature, and that the principal stress axis was north-south. However, the stress acting on the Keweenawan rocks is believed to be of a rotational nature due to a shear couple which was shifting in time and space during Keweenawan tectonism.

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20′

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46° 45′

15'

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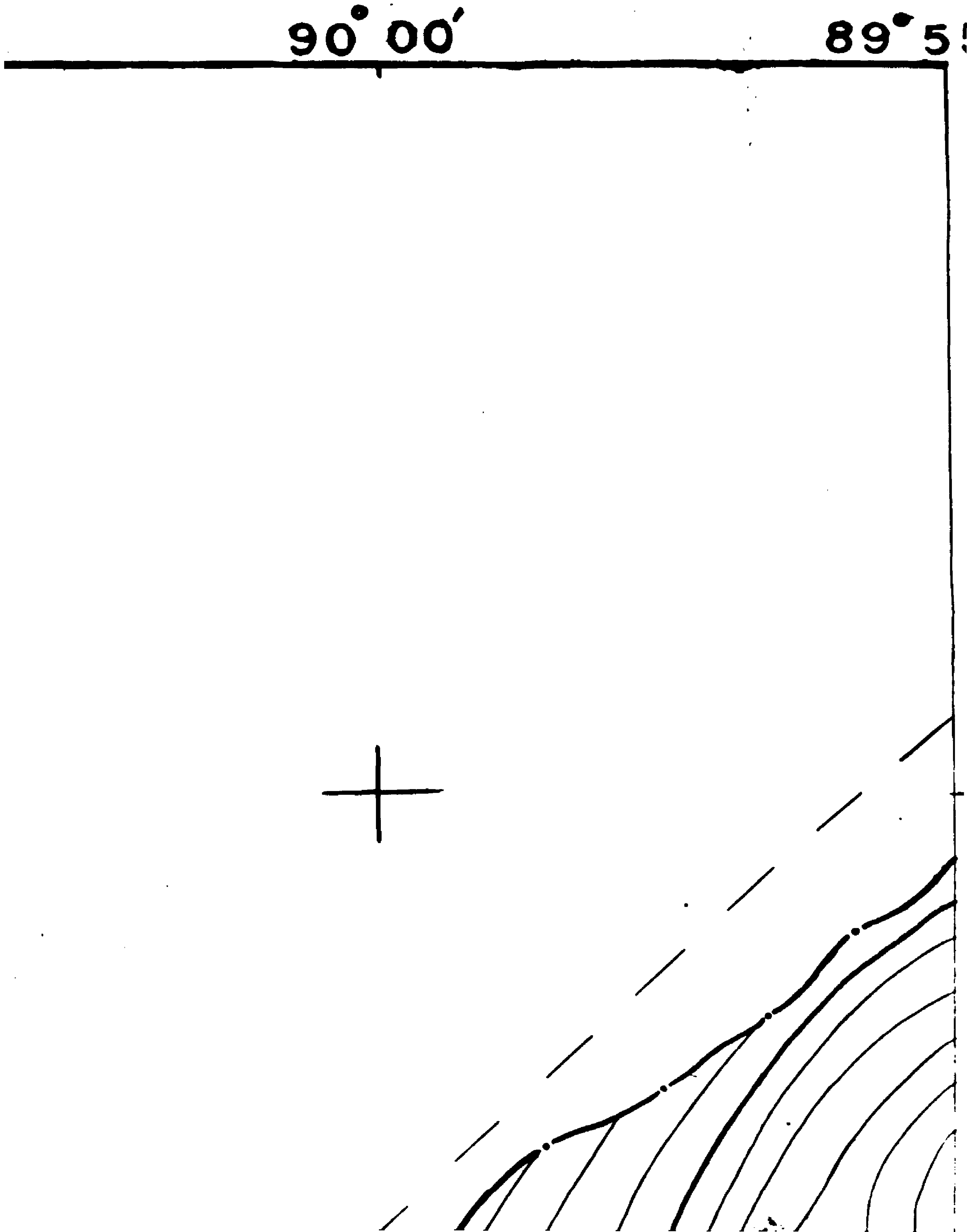
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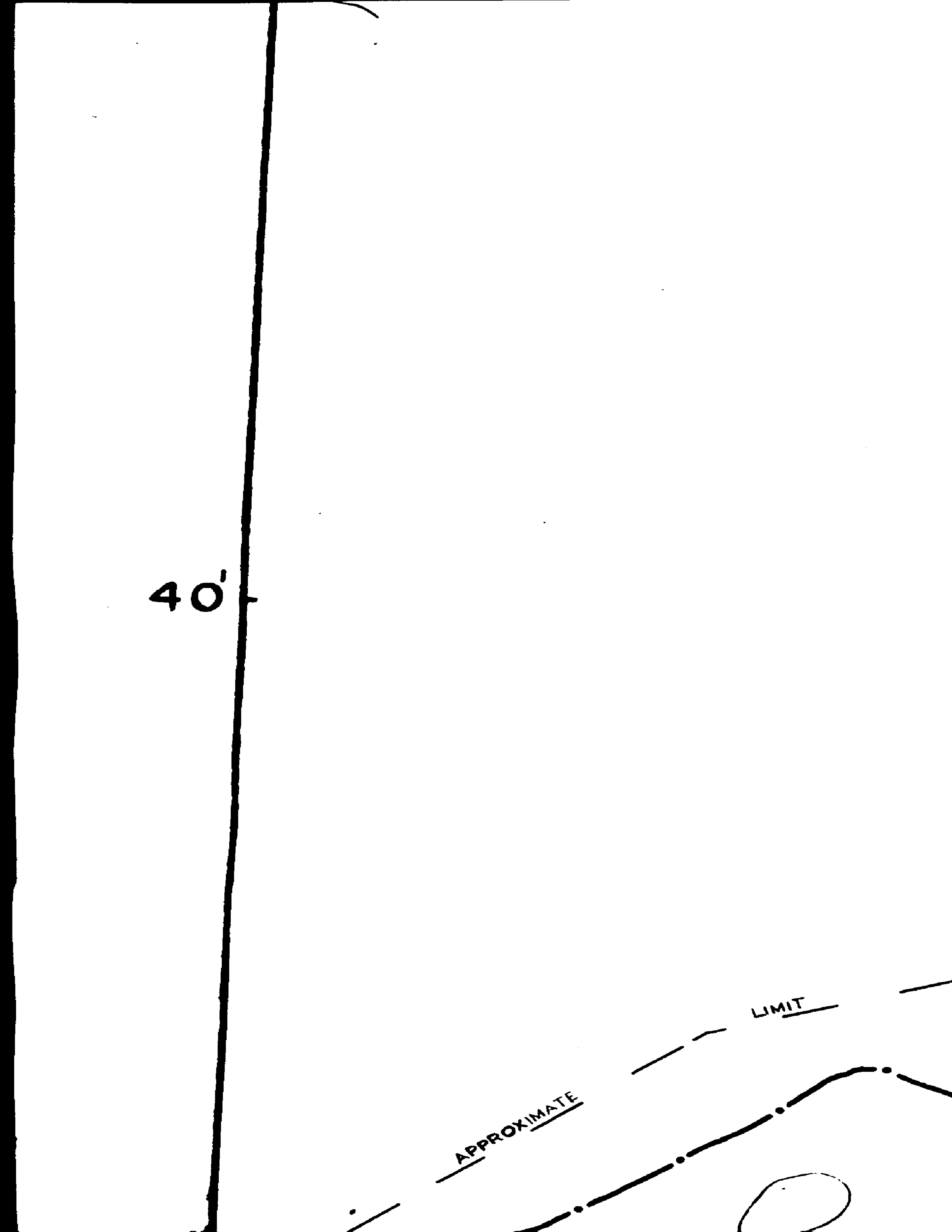
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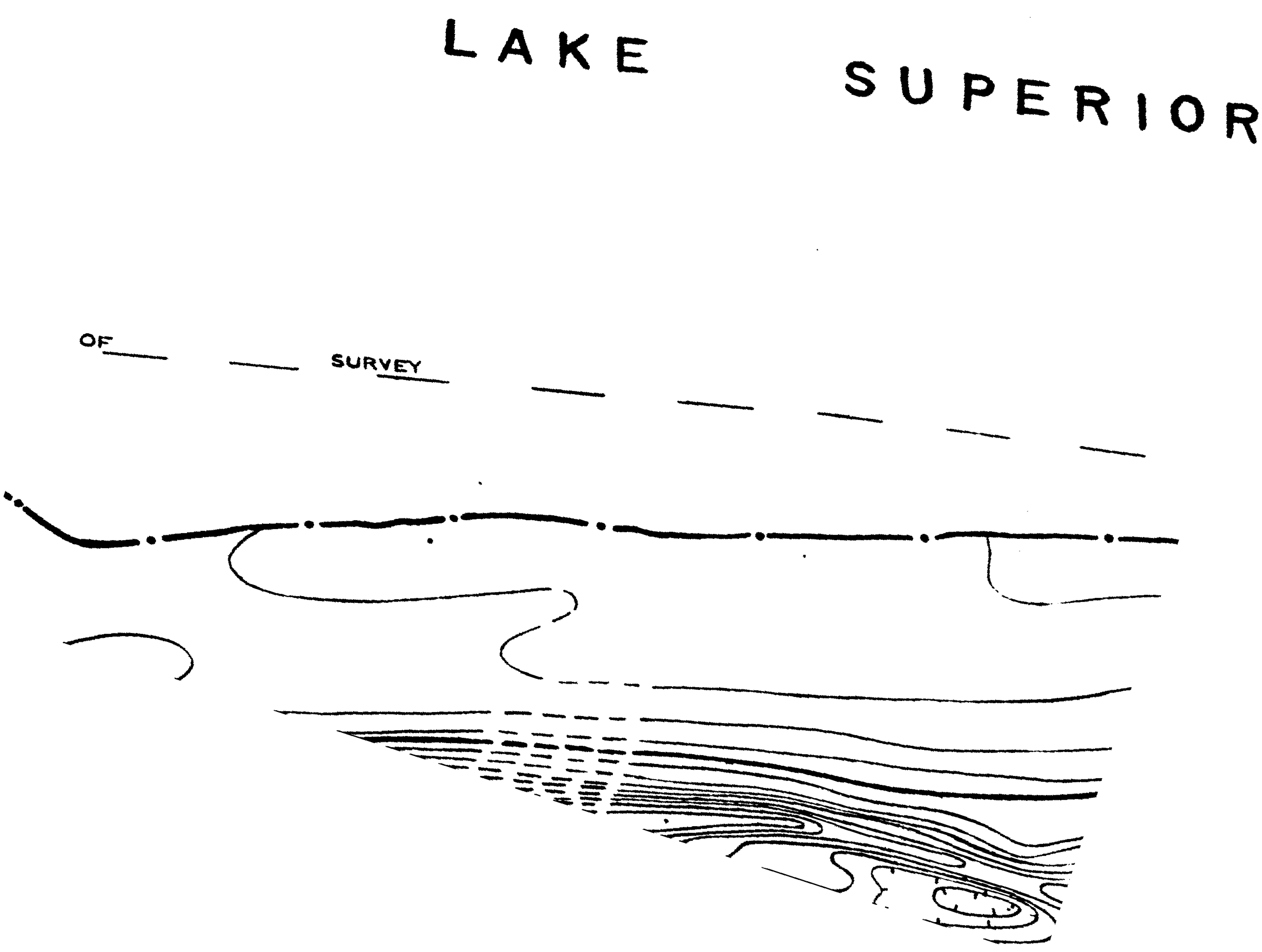
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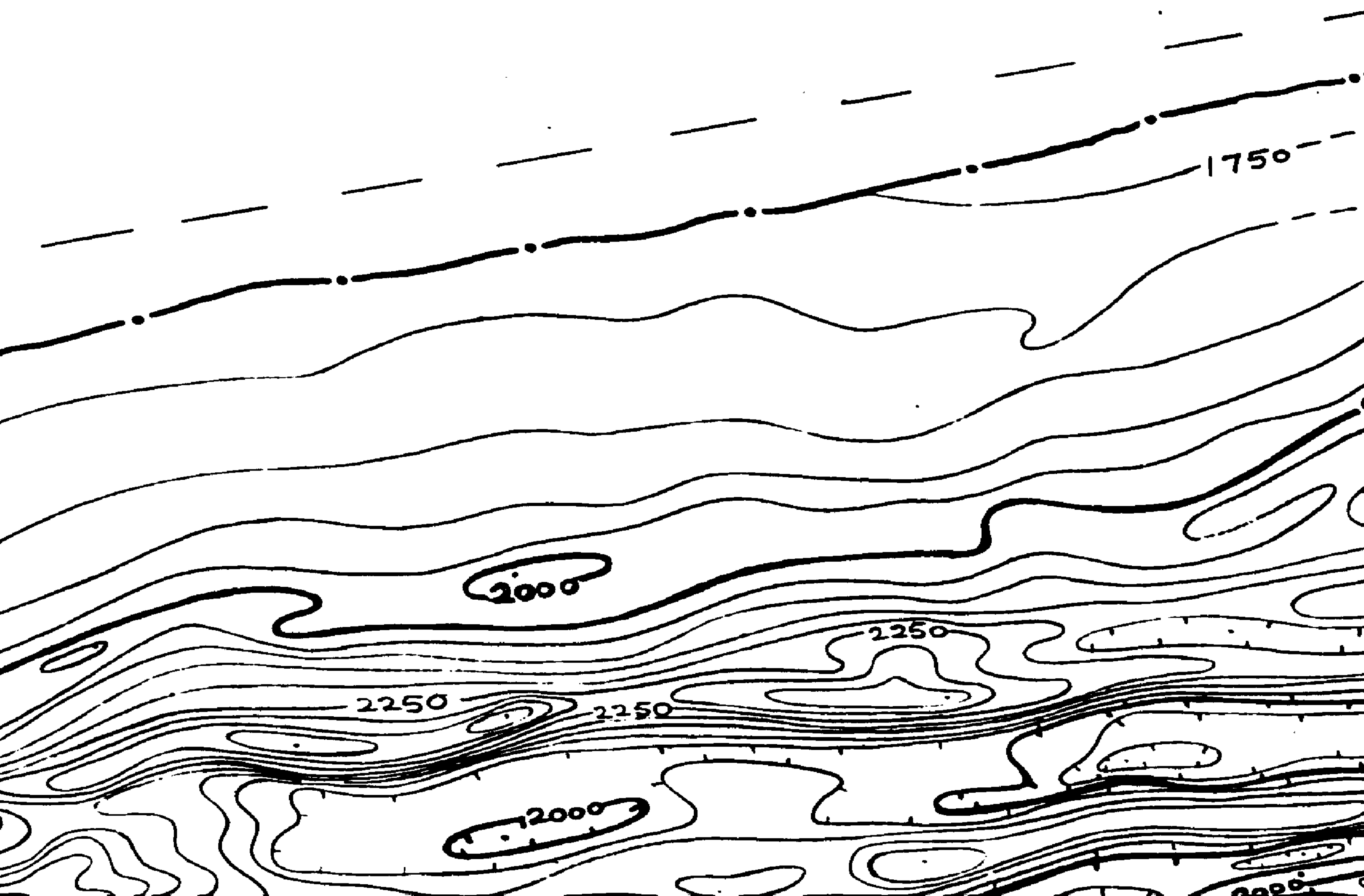

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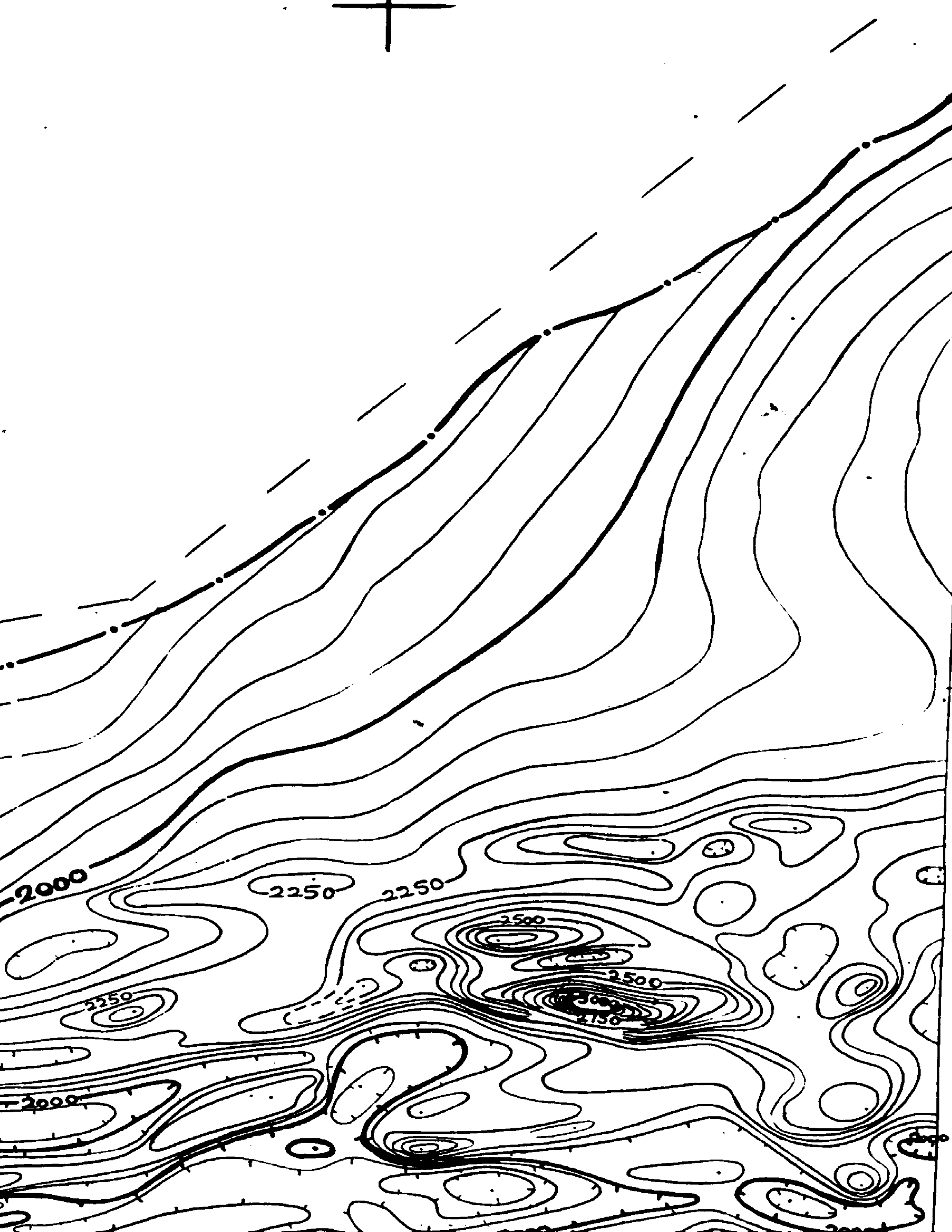
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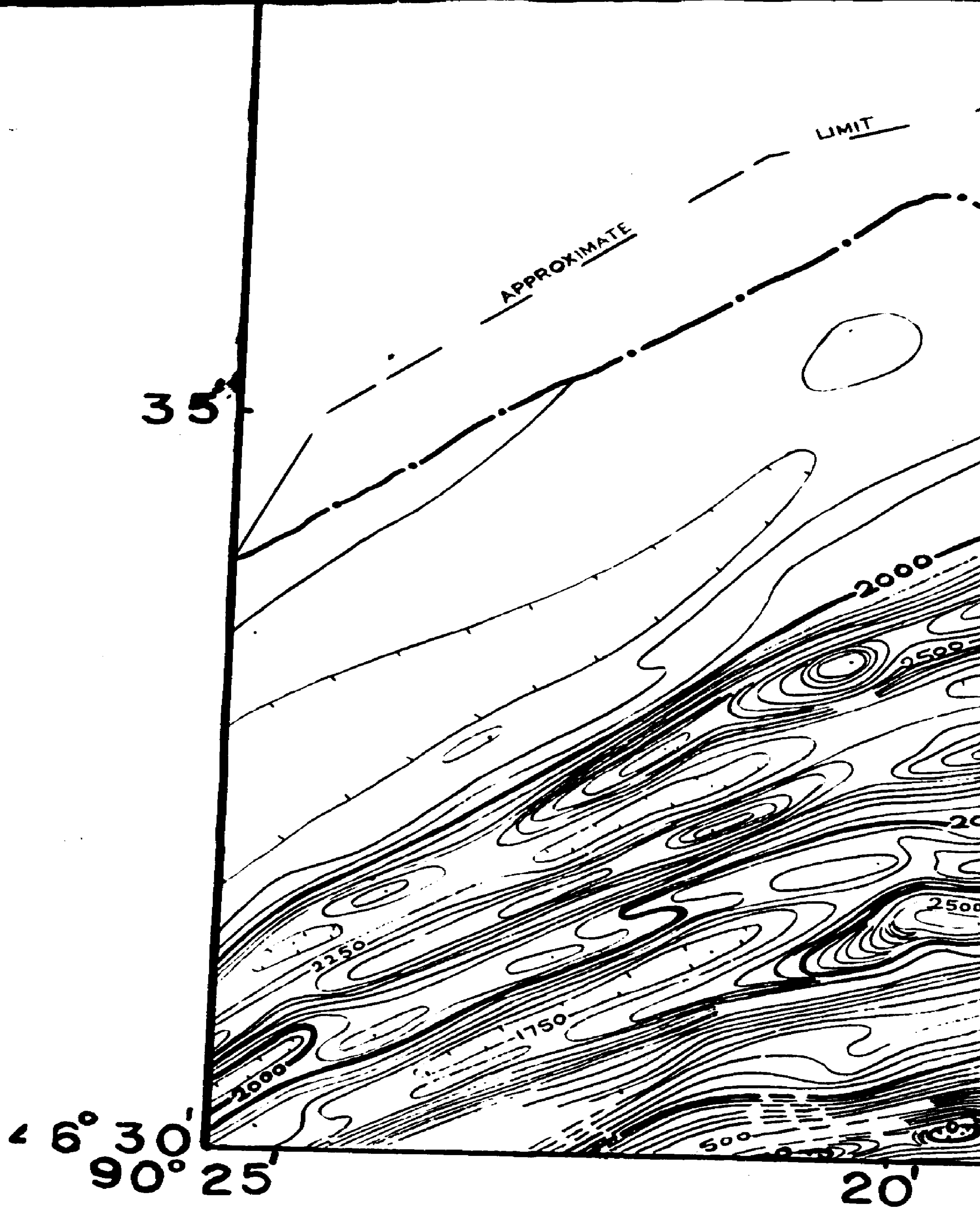
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90° 25'
20'

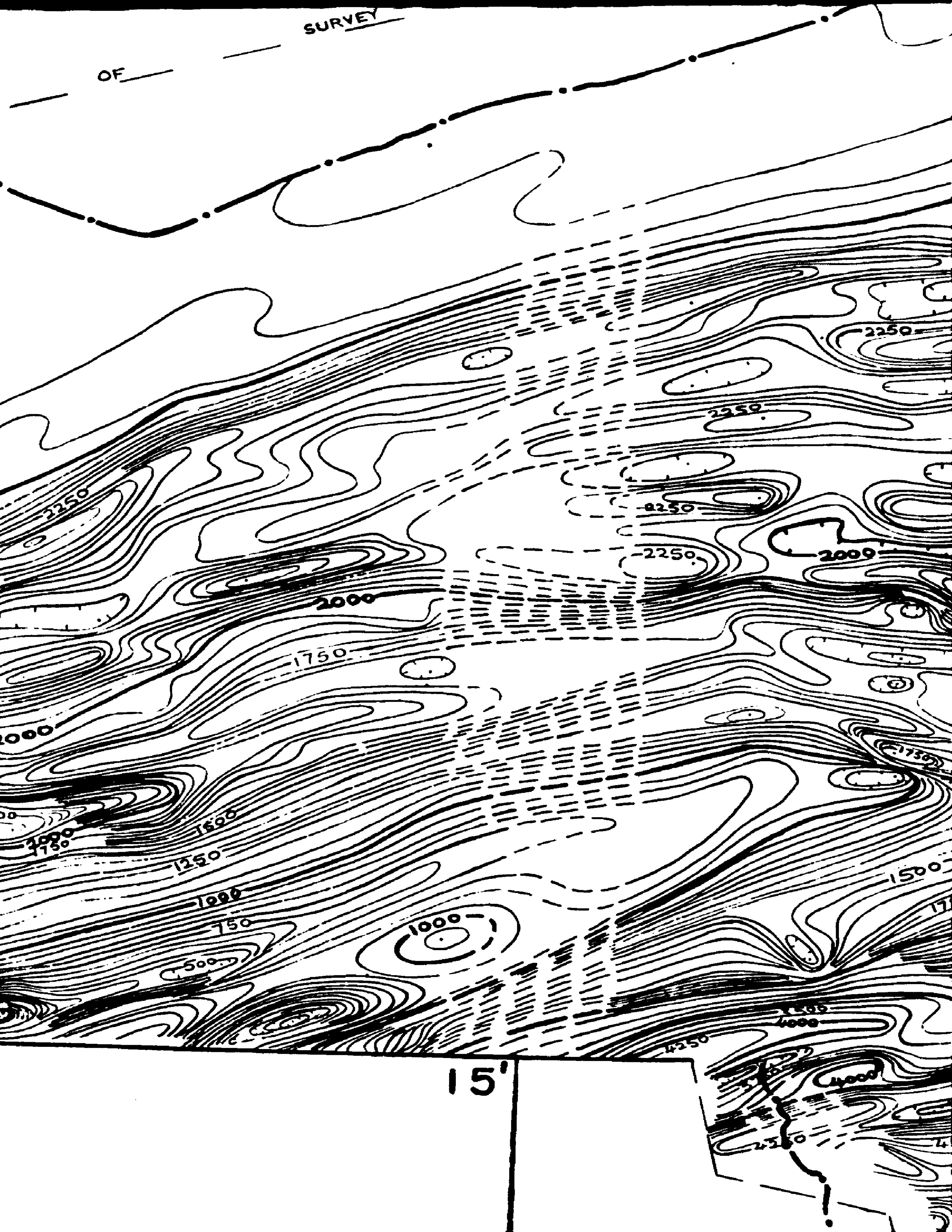

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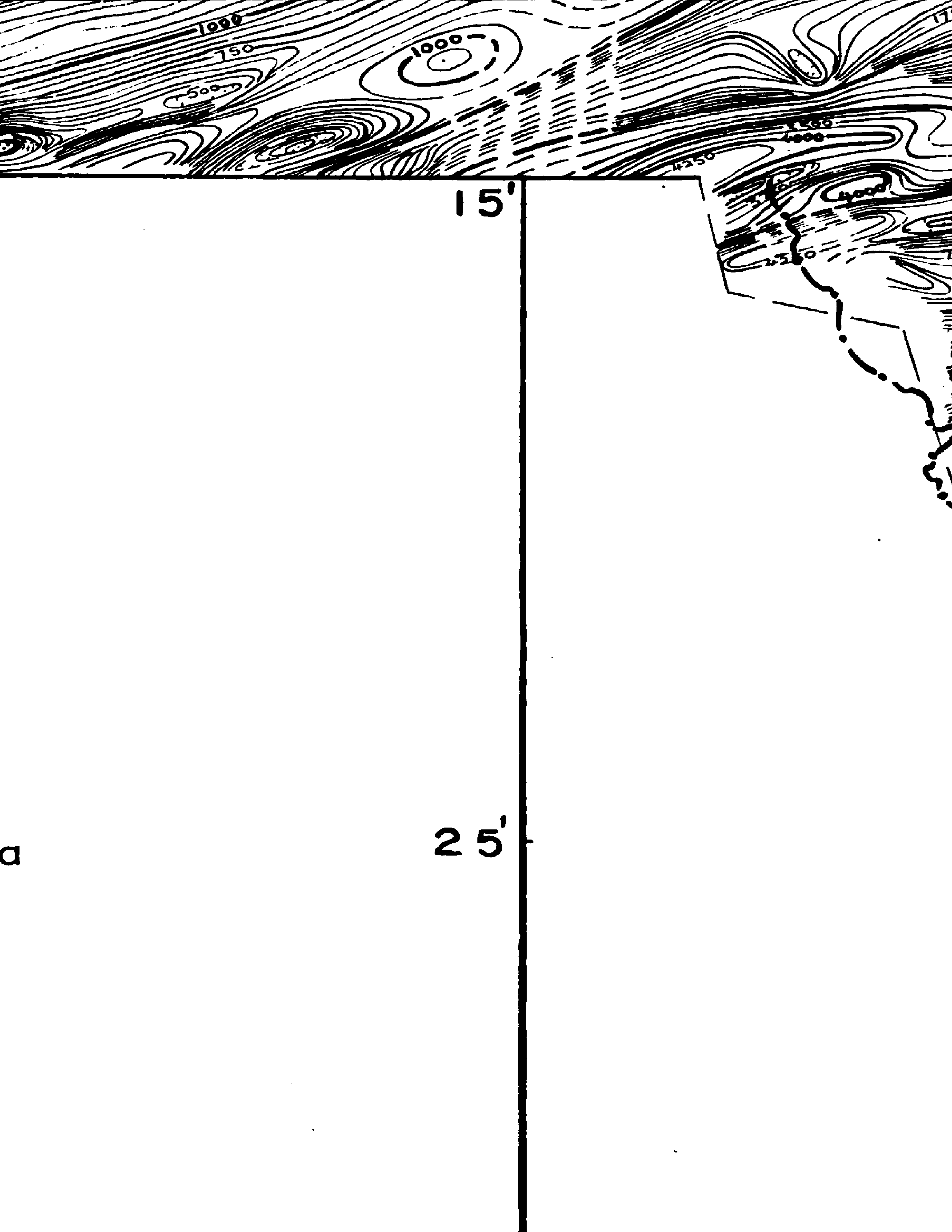
PLATE I



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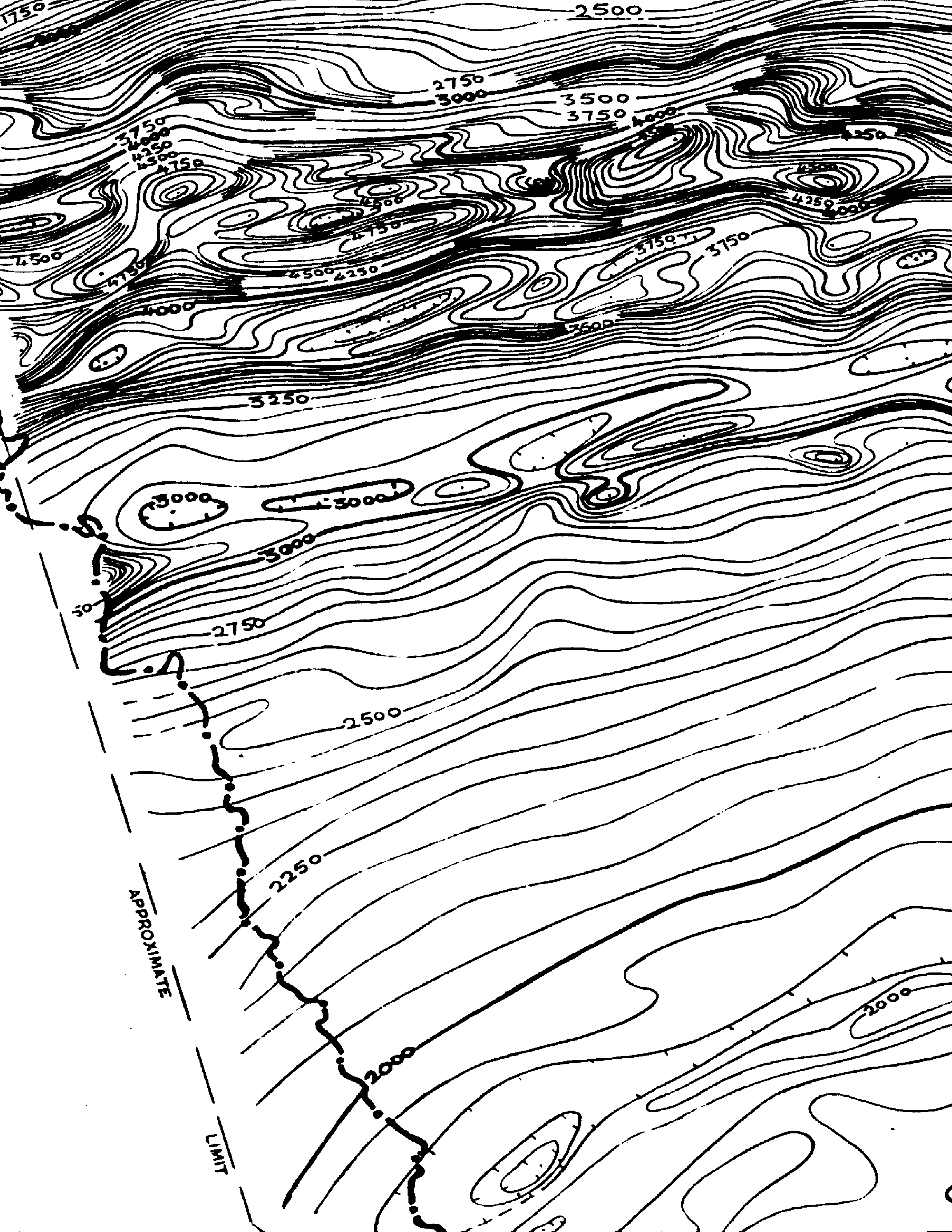
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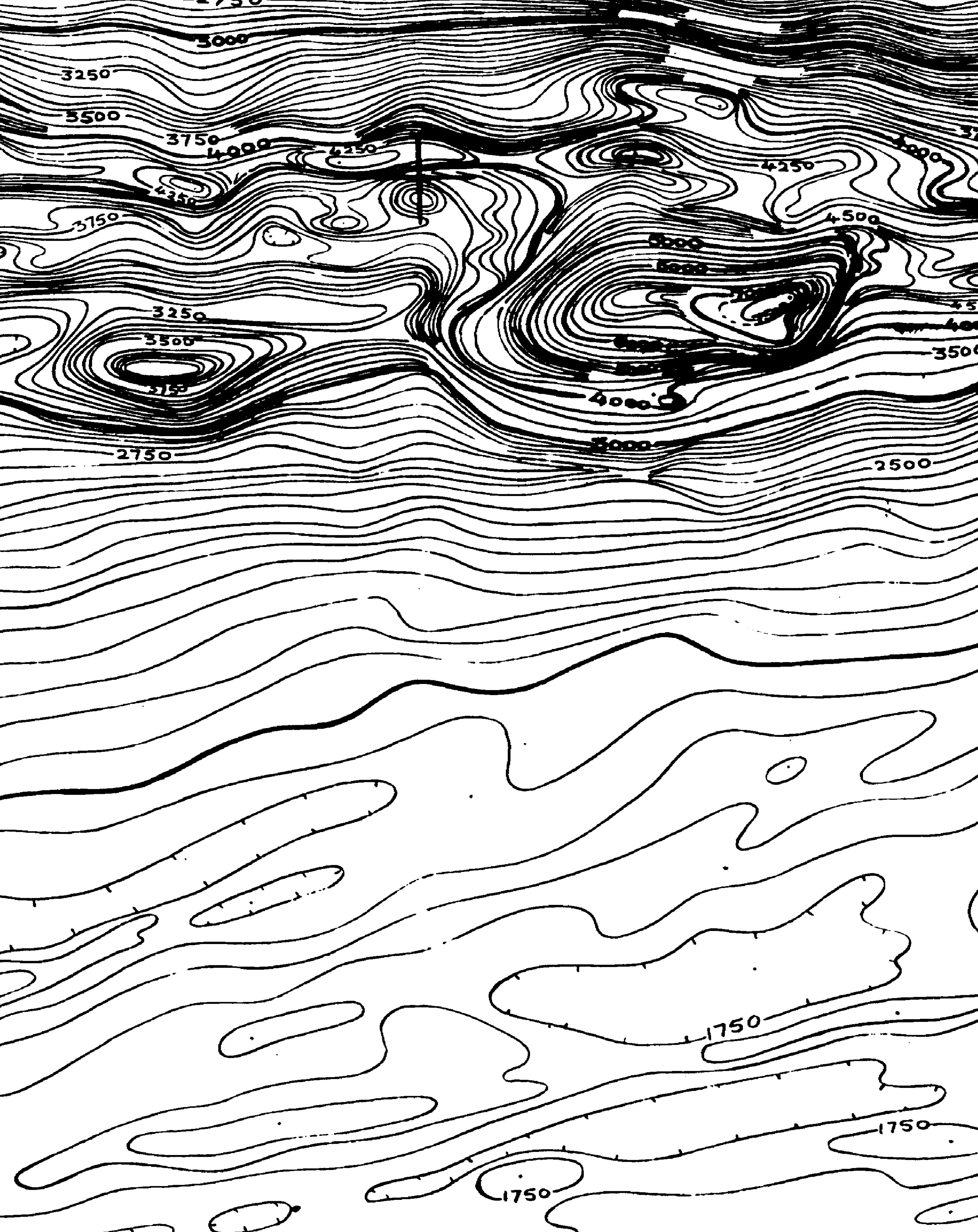
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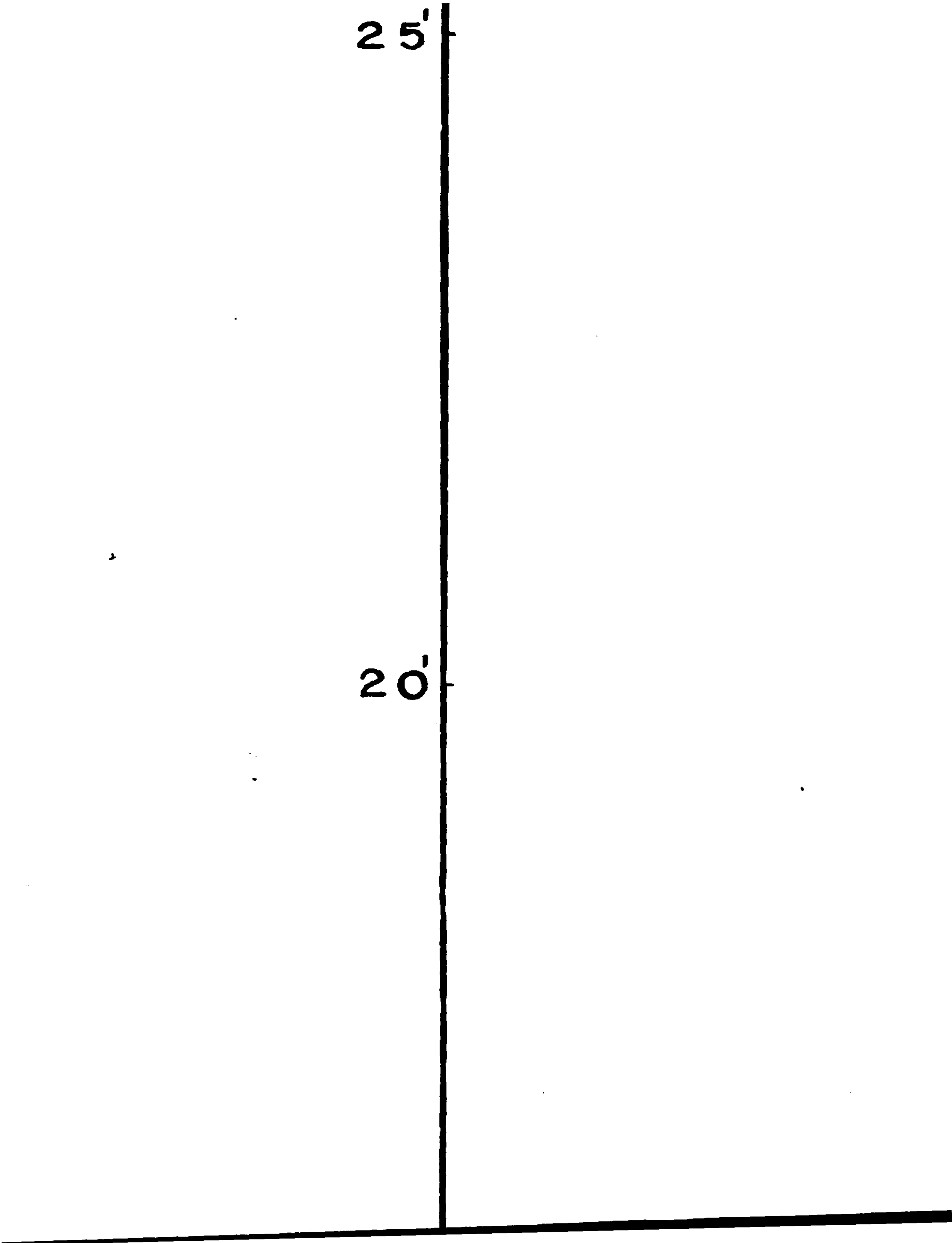
1750

PLATE I-a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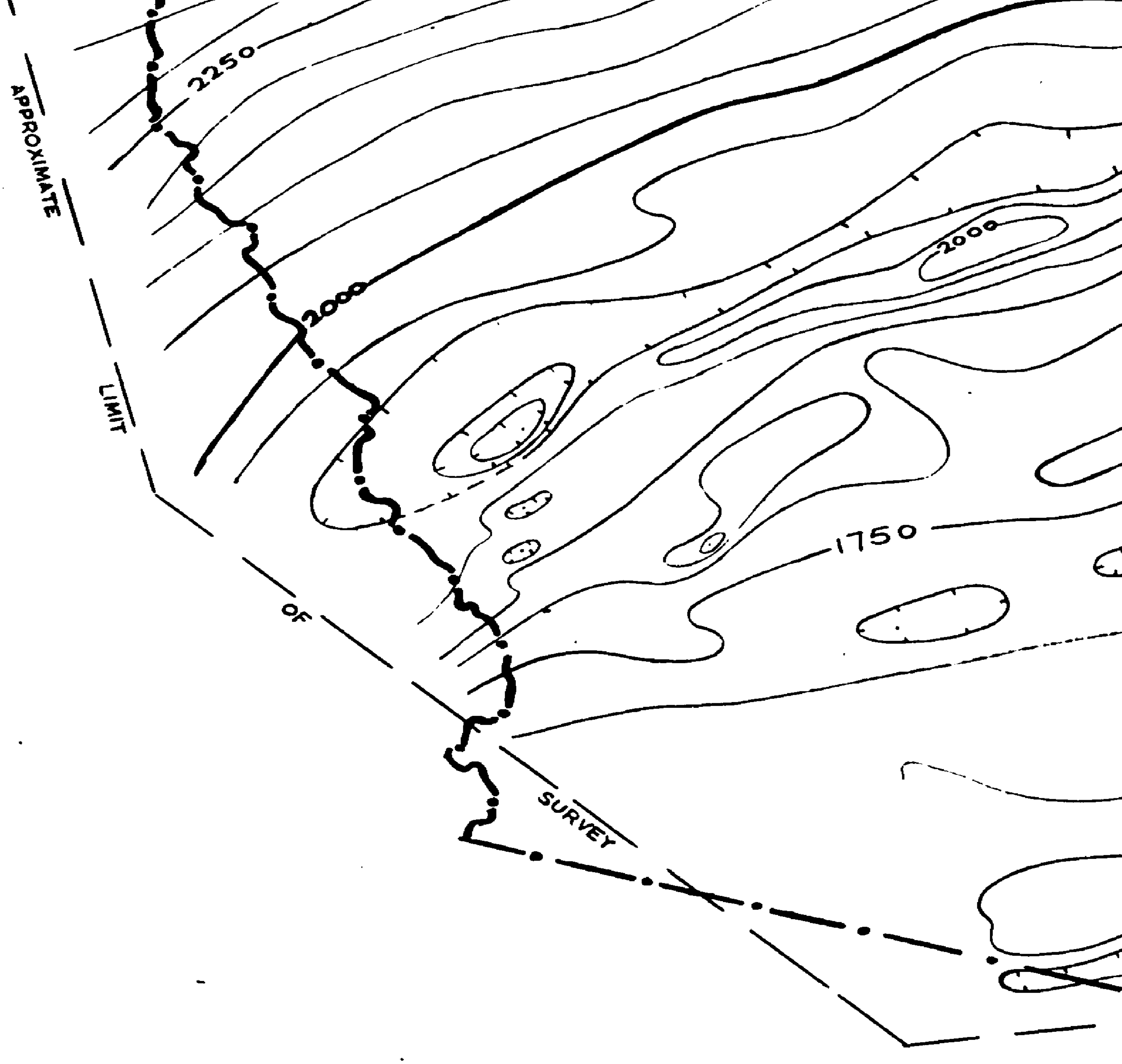

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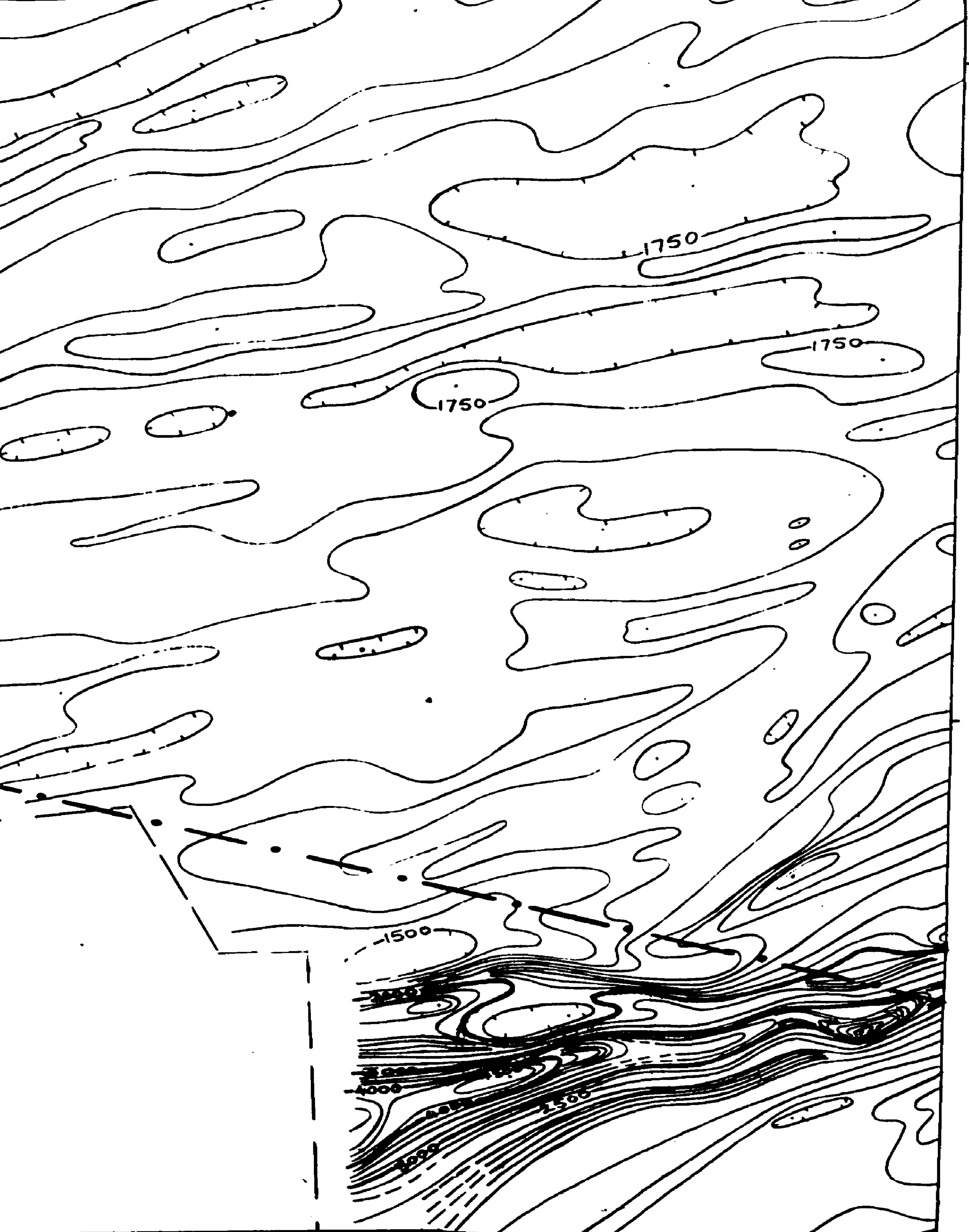

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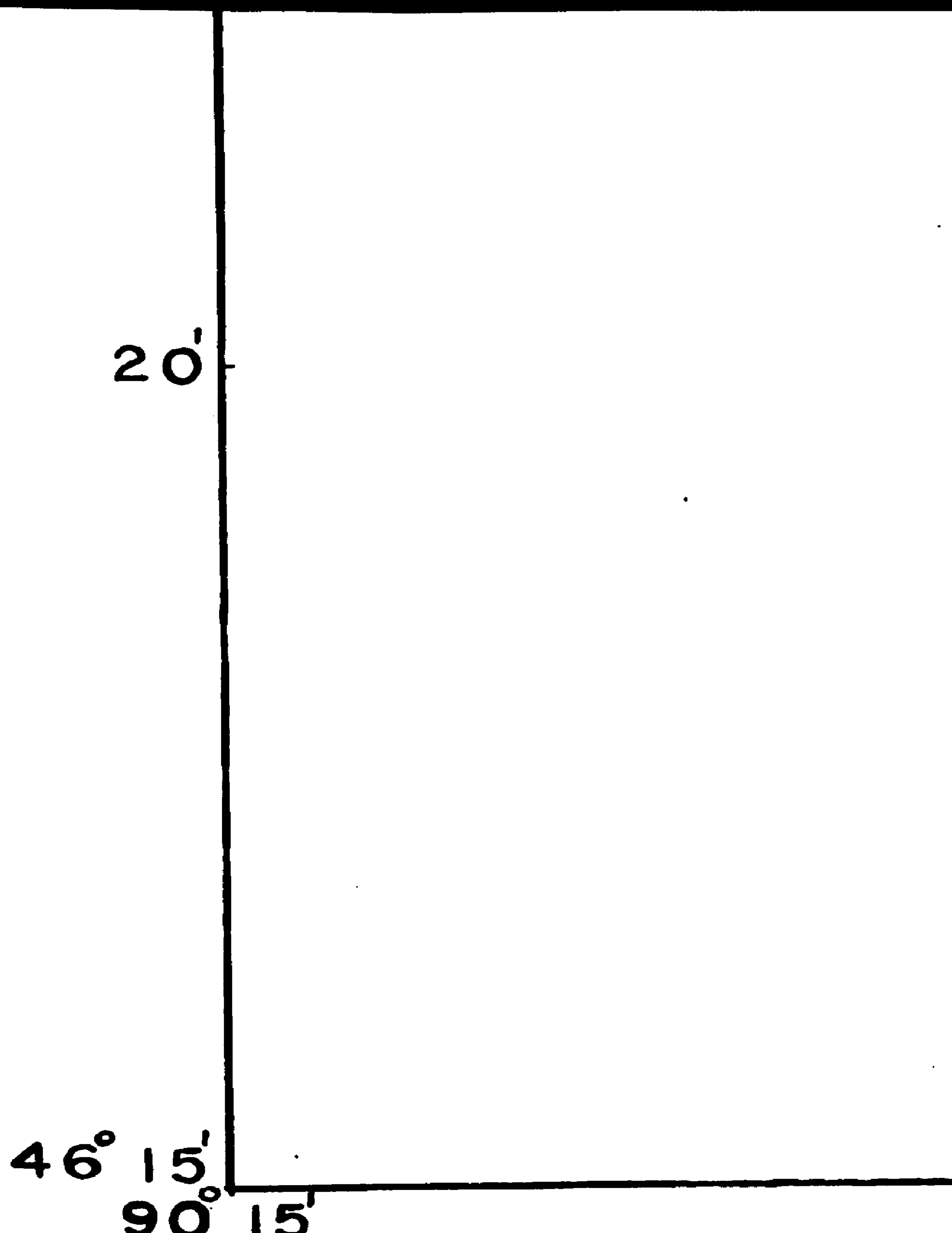

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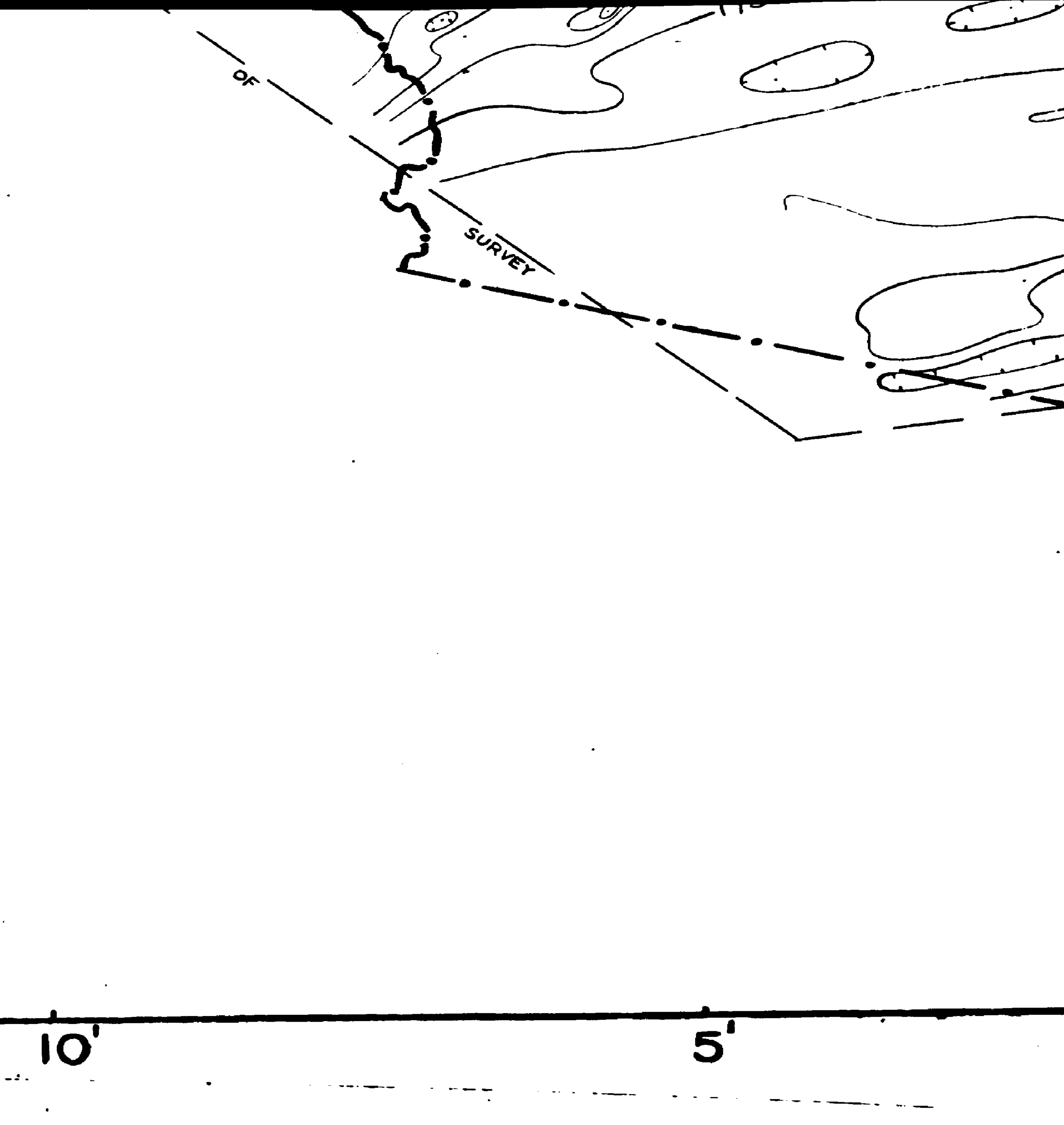
OF
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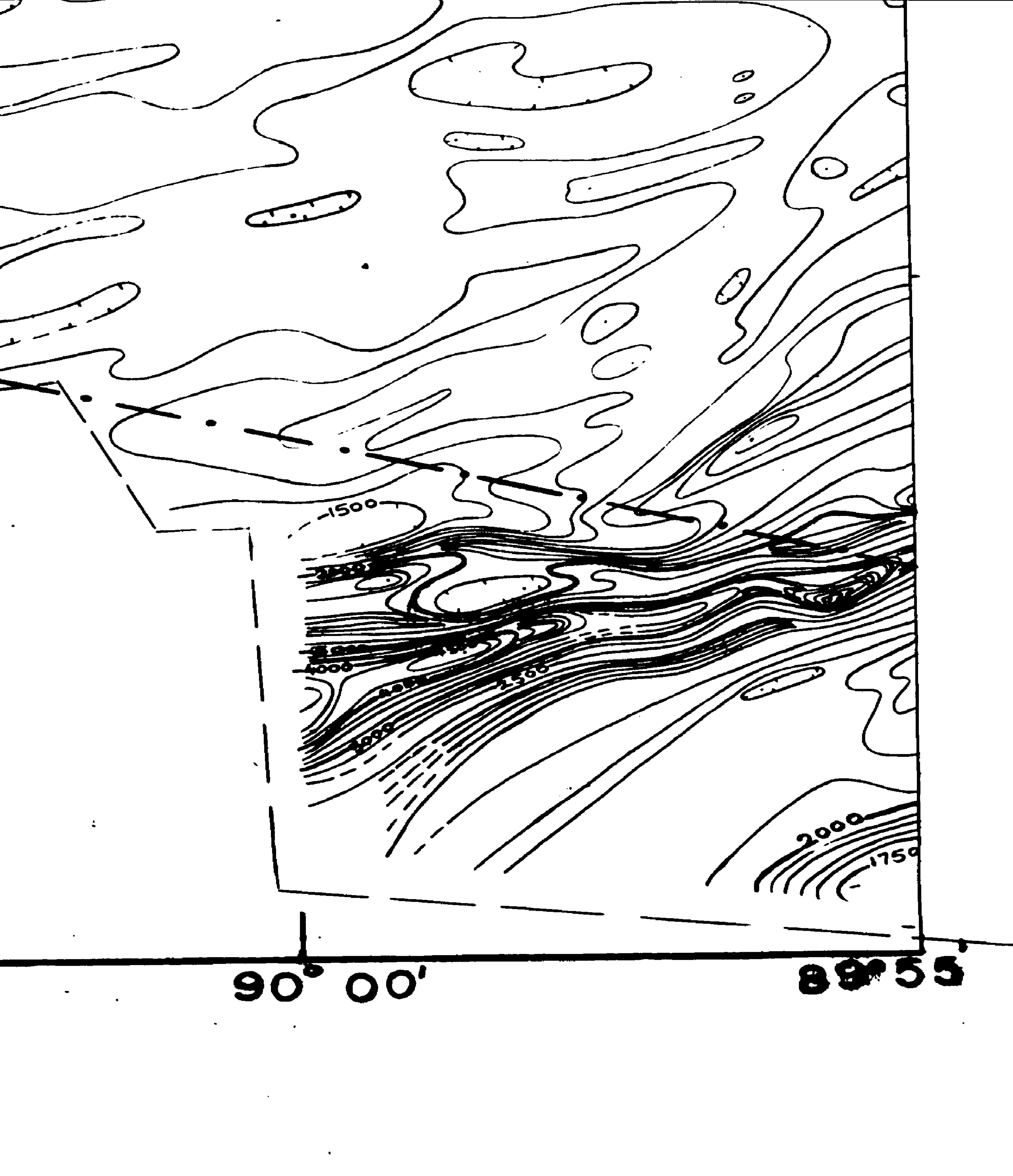
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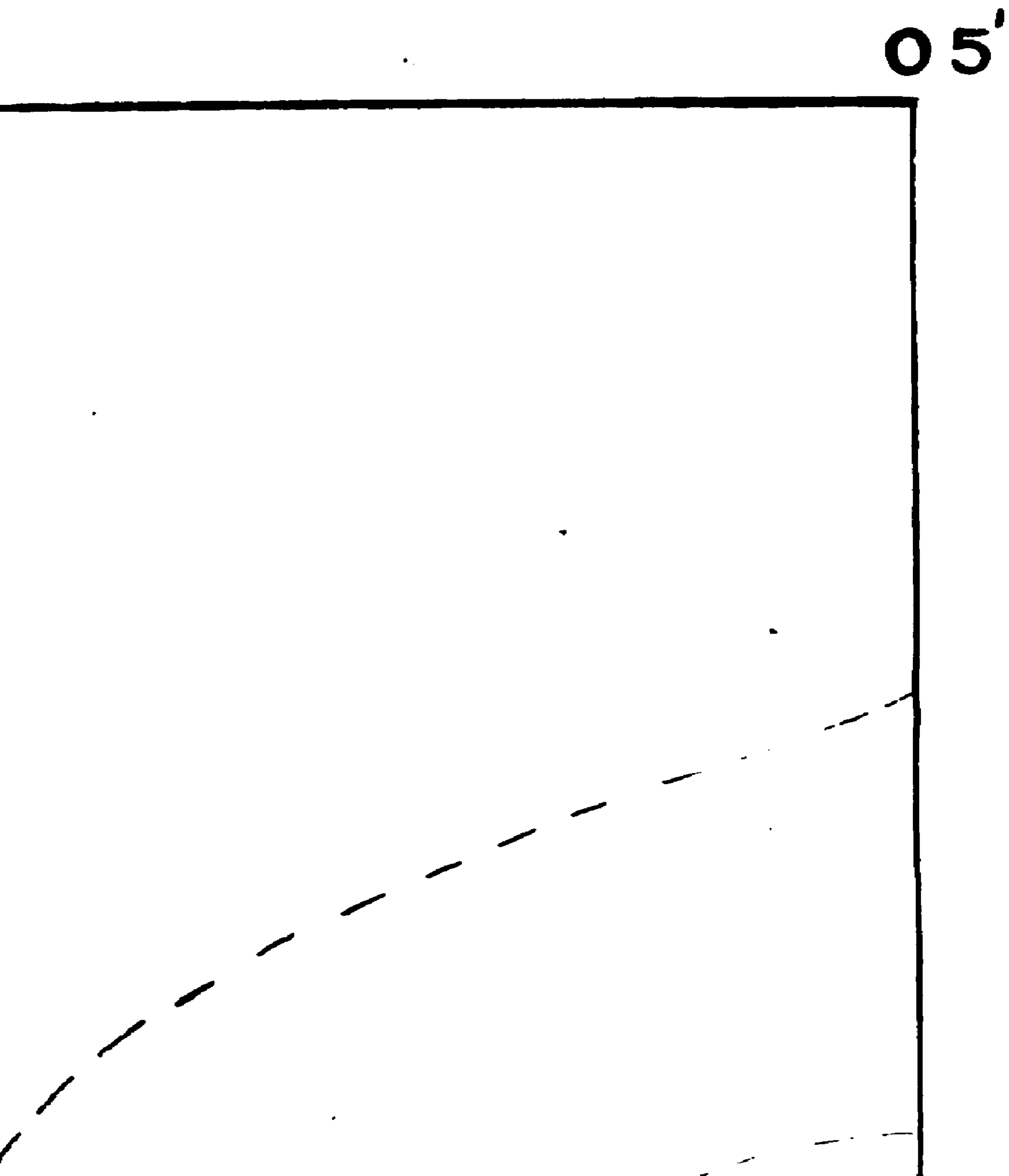
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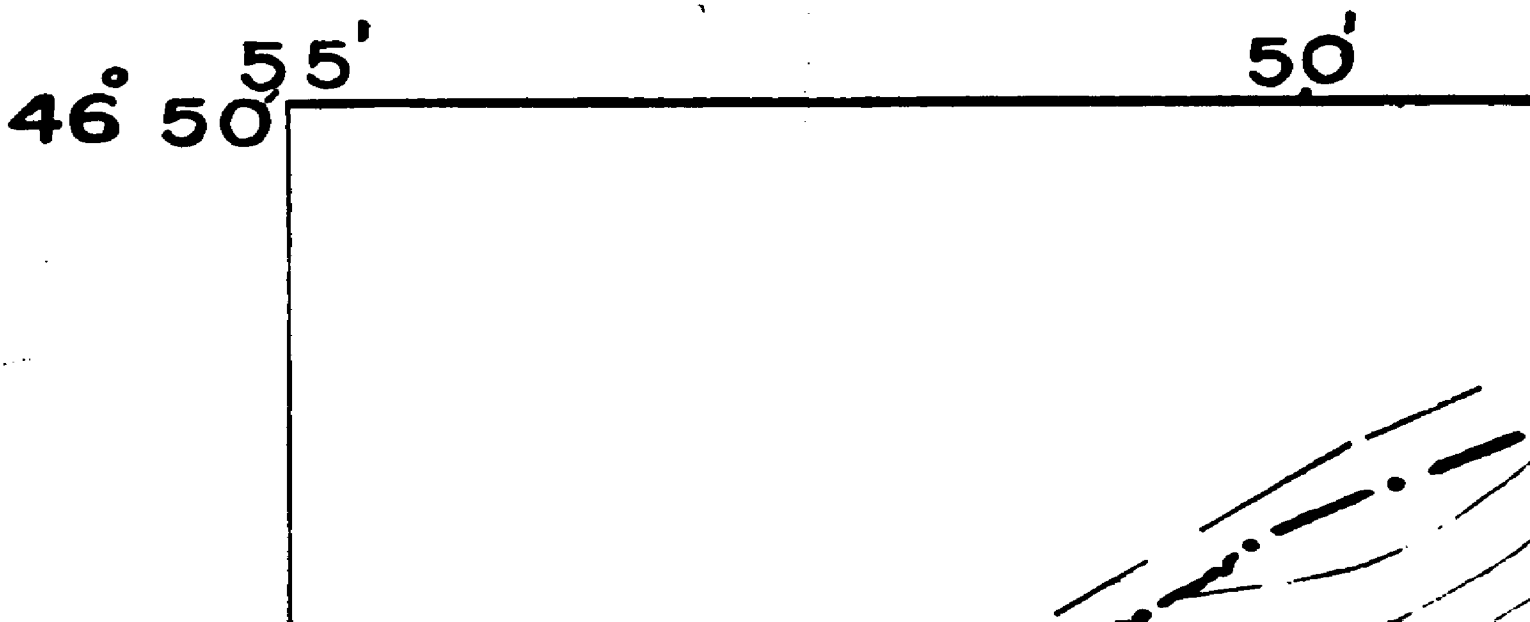

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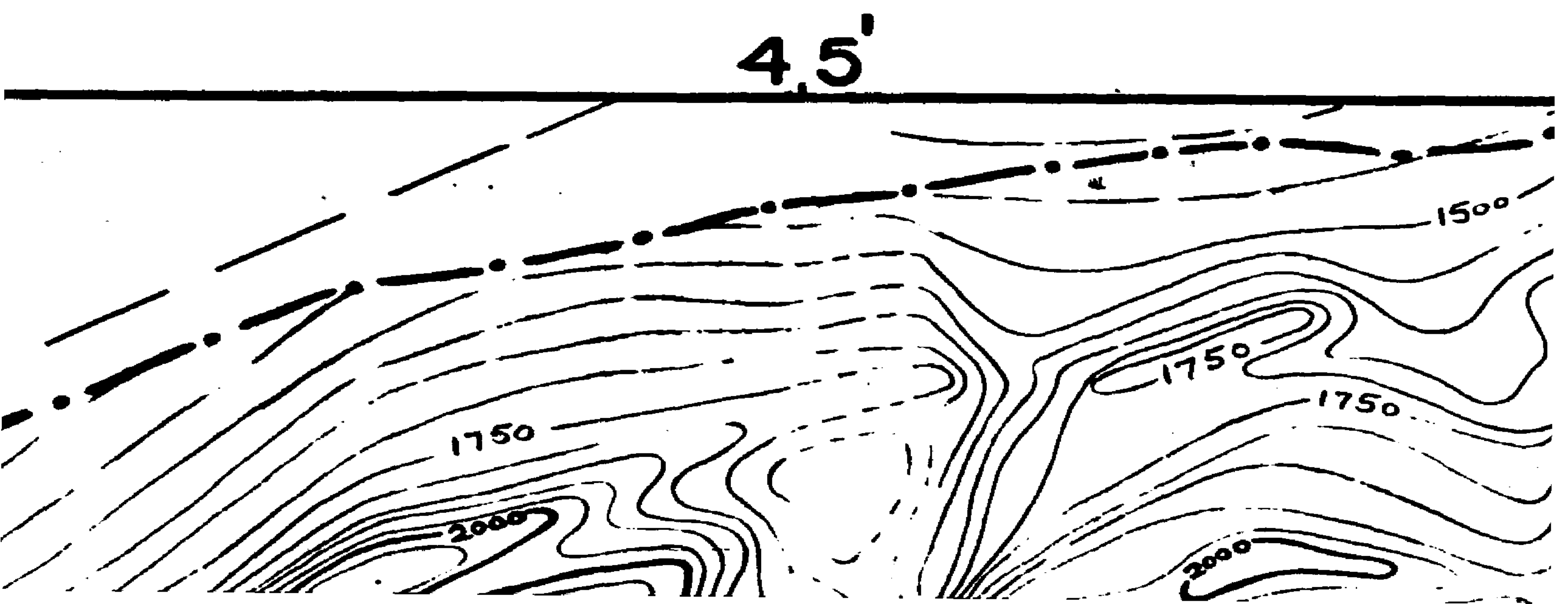
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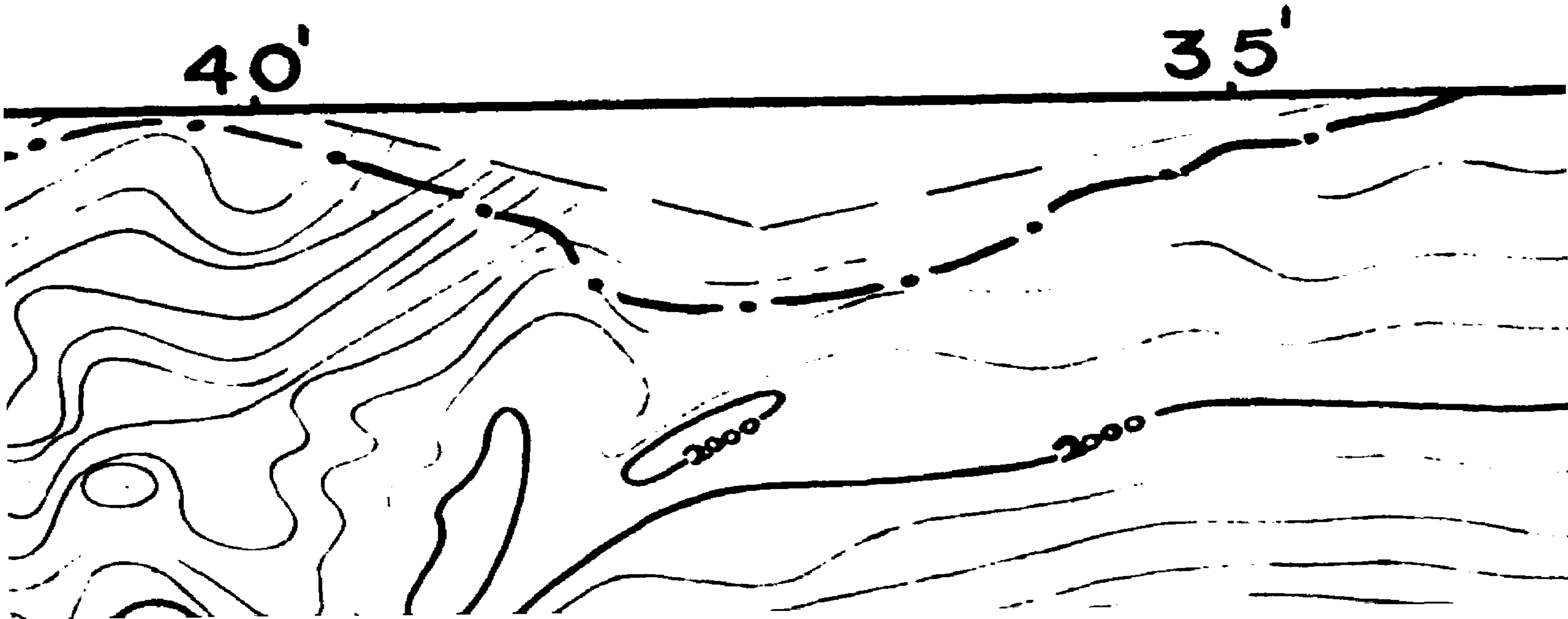

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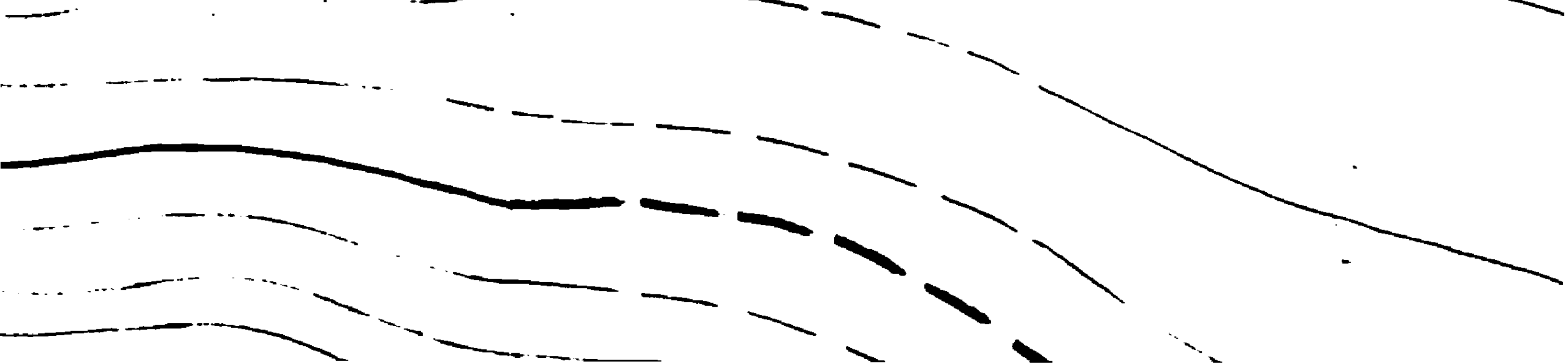

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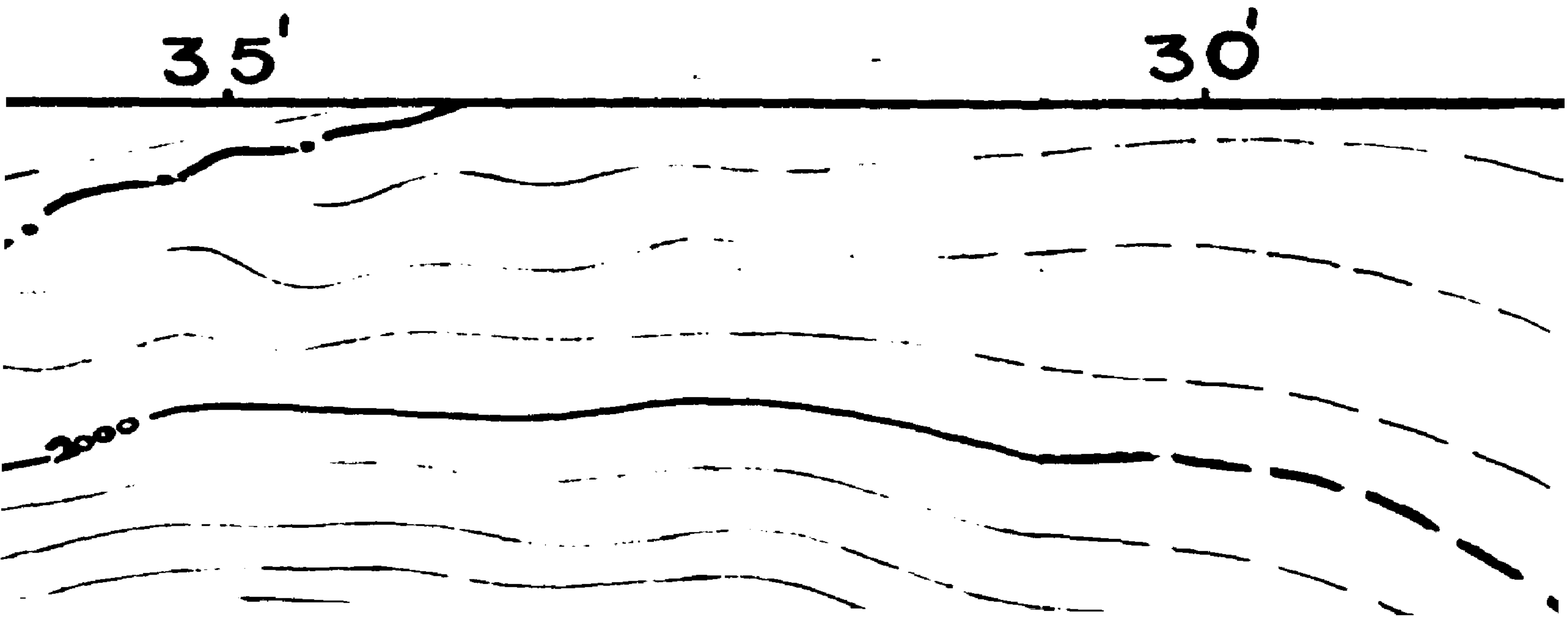

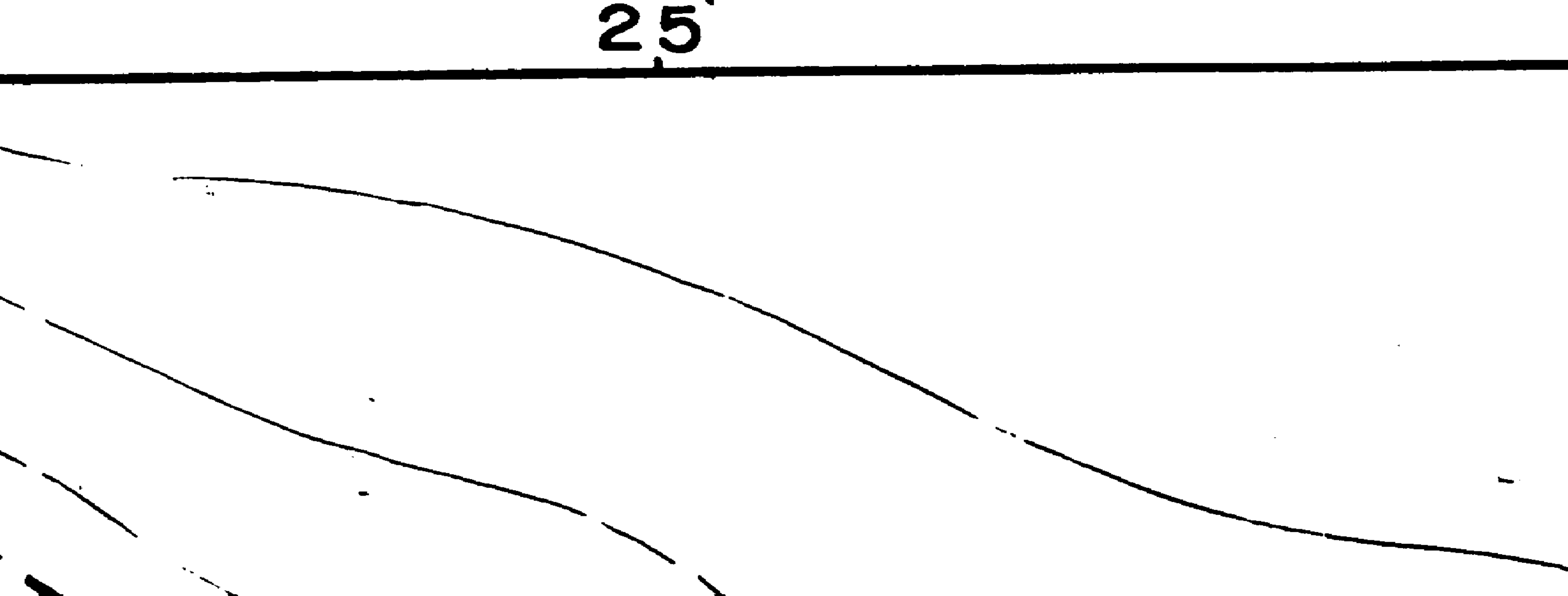
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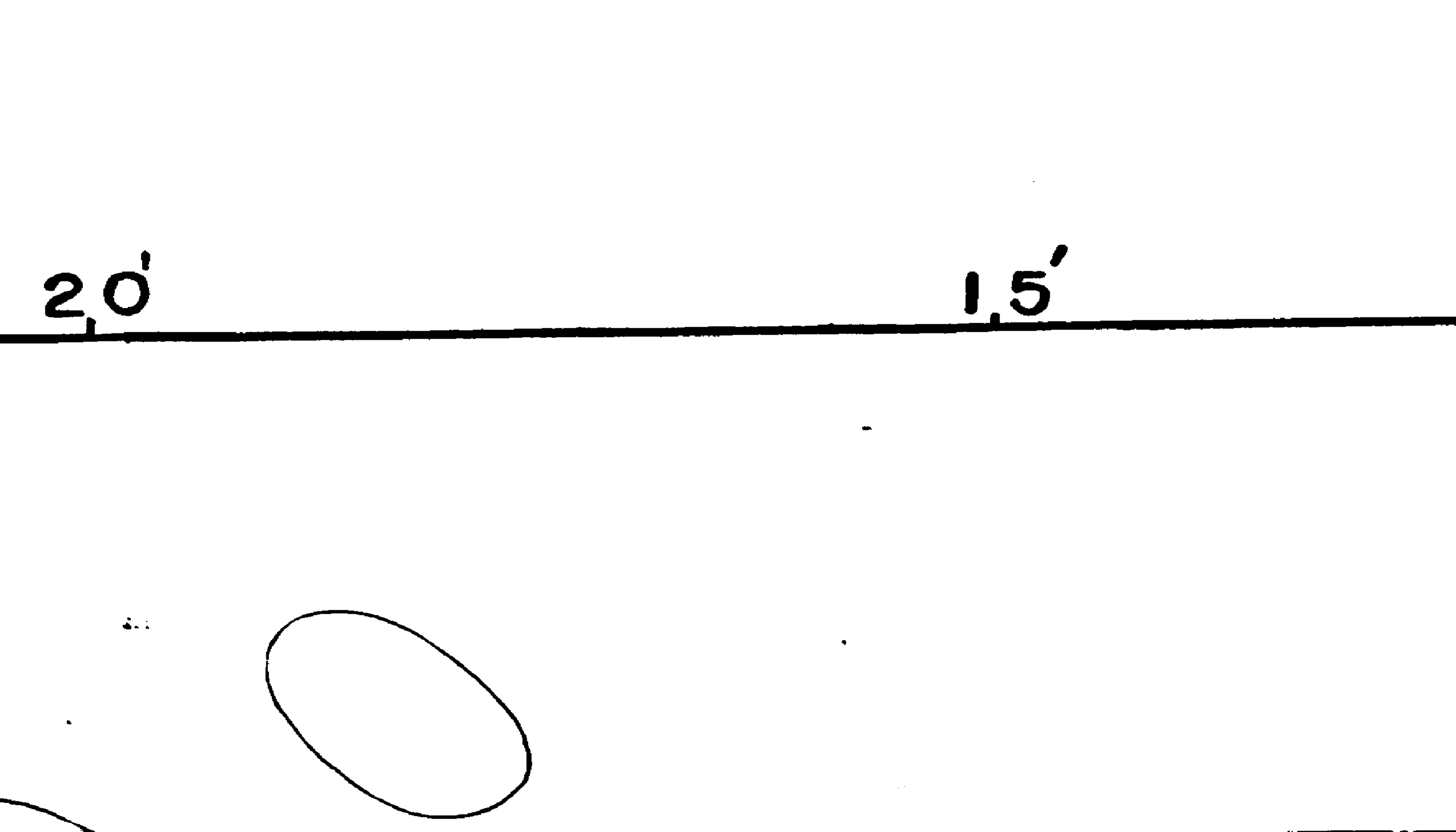
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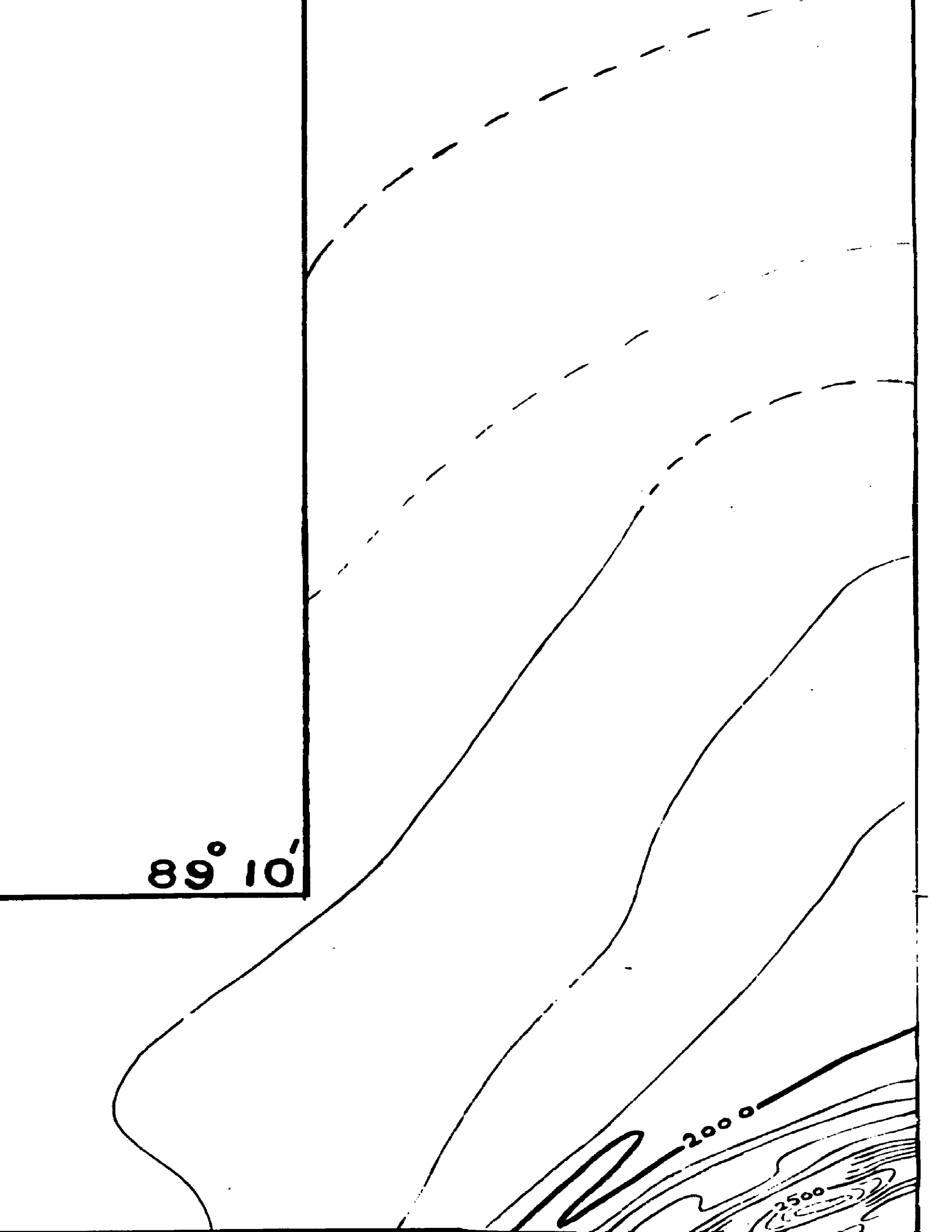

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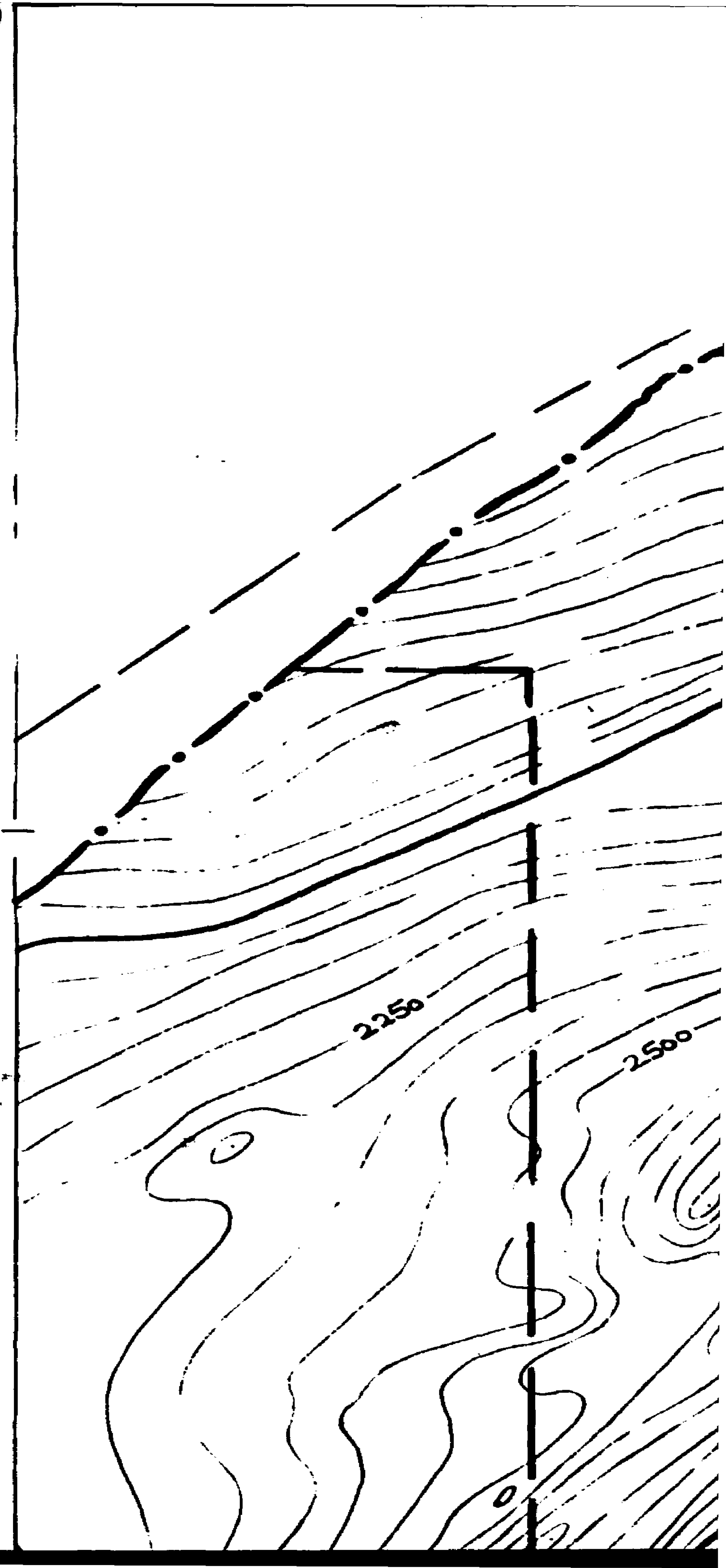

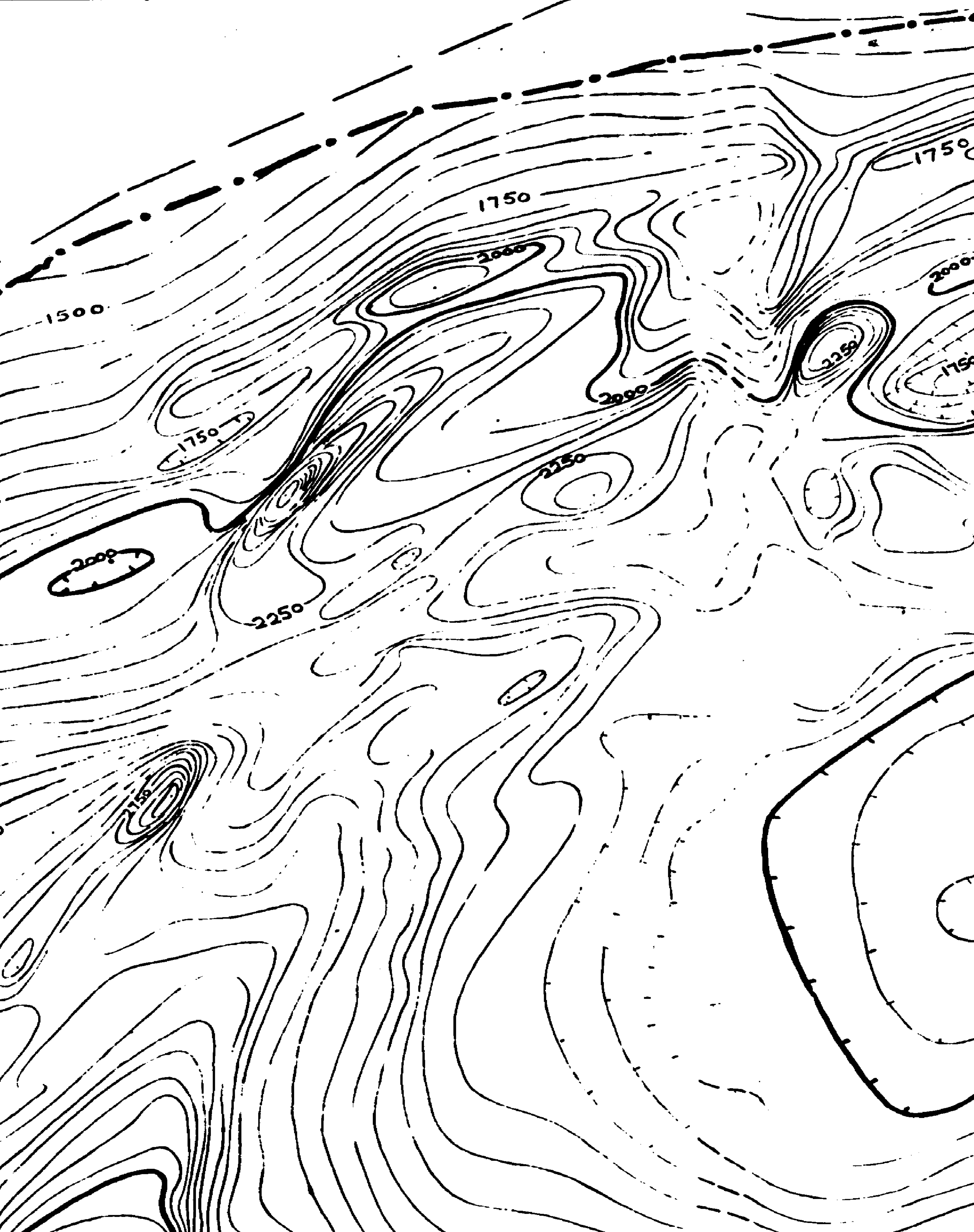

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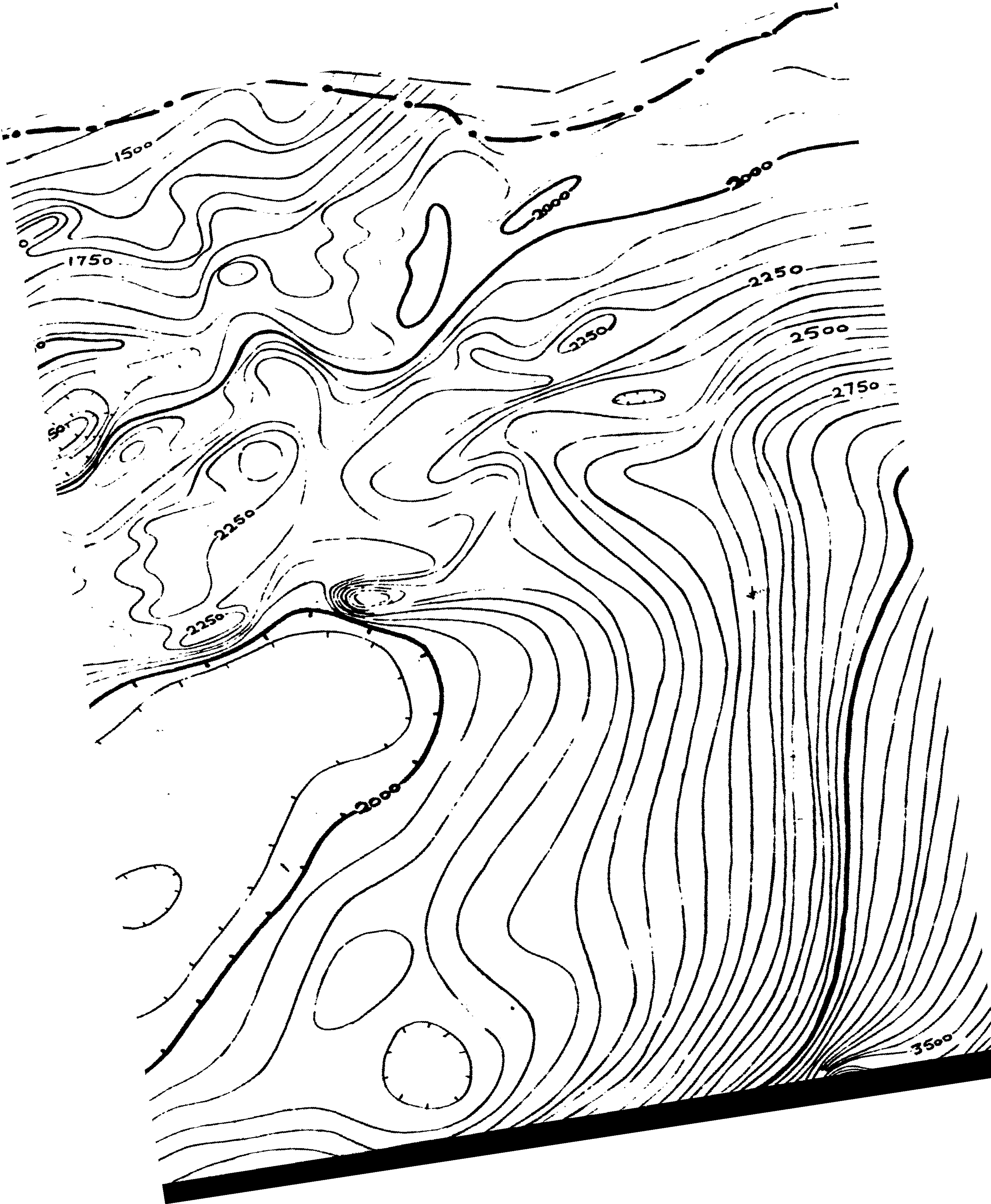
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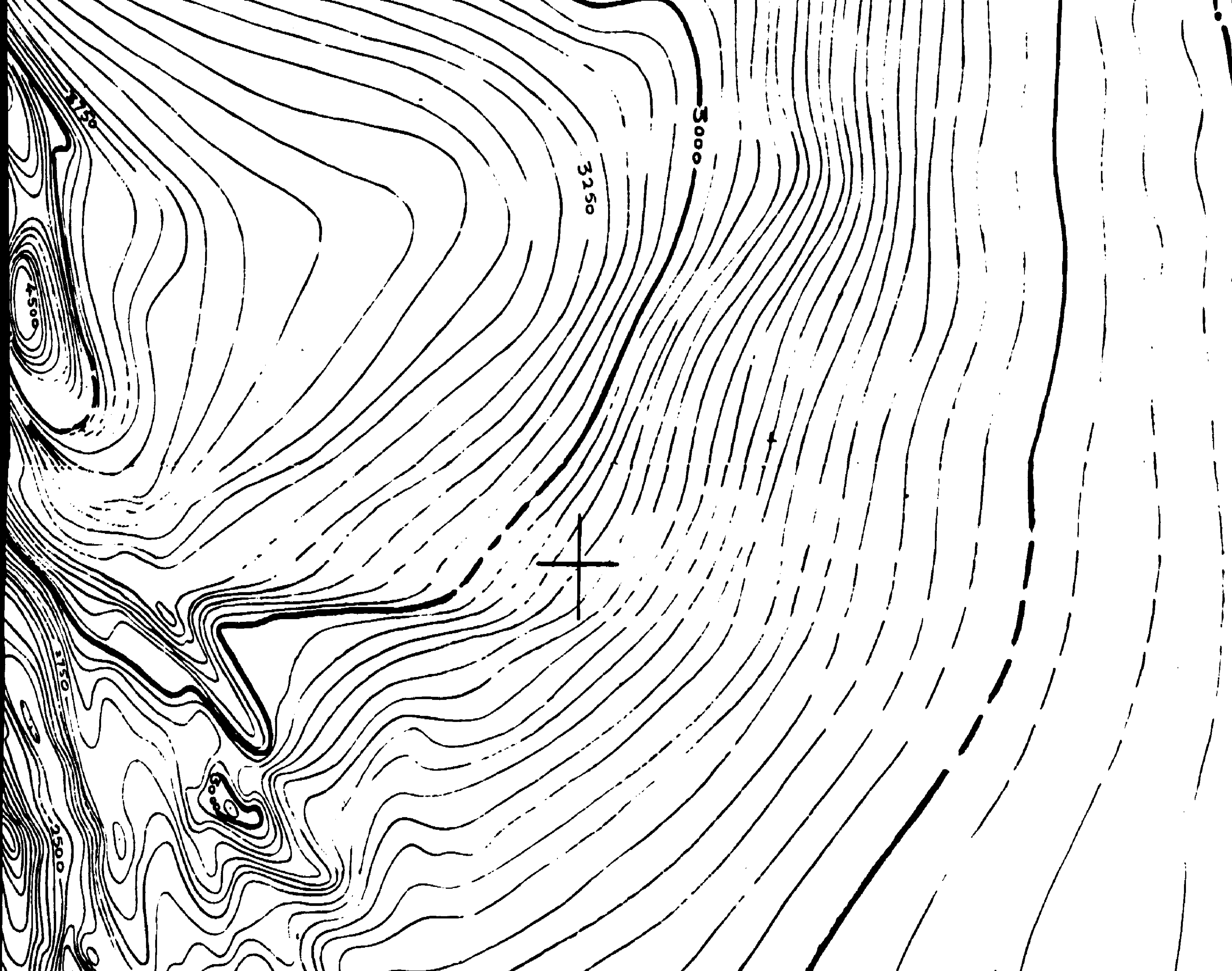
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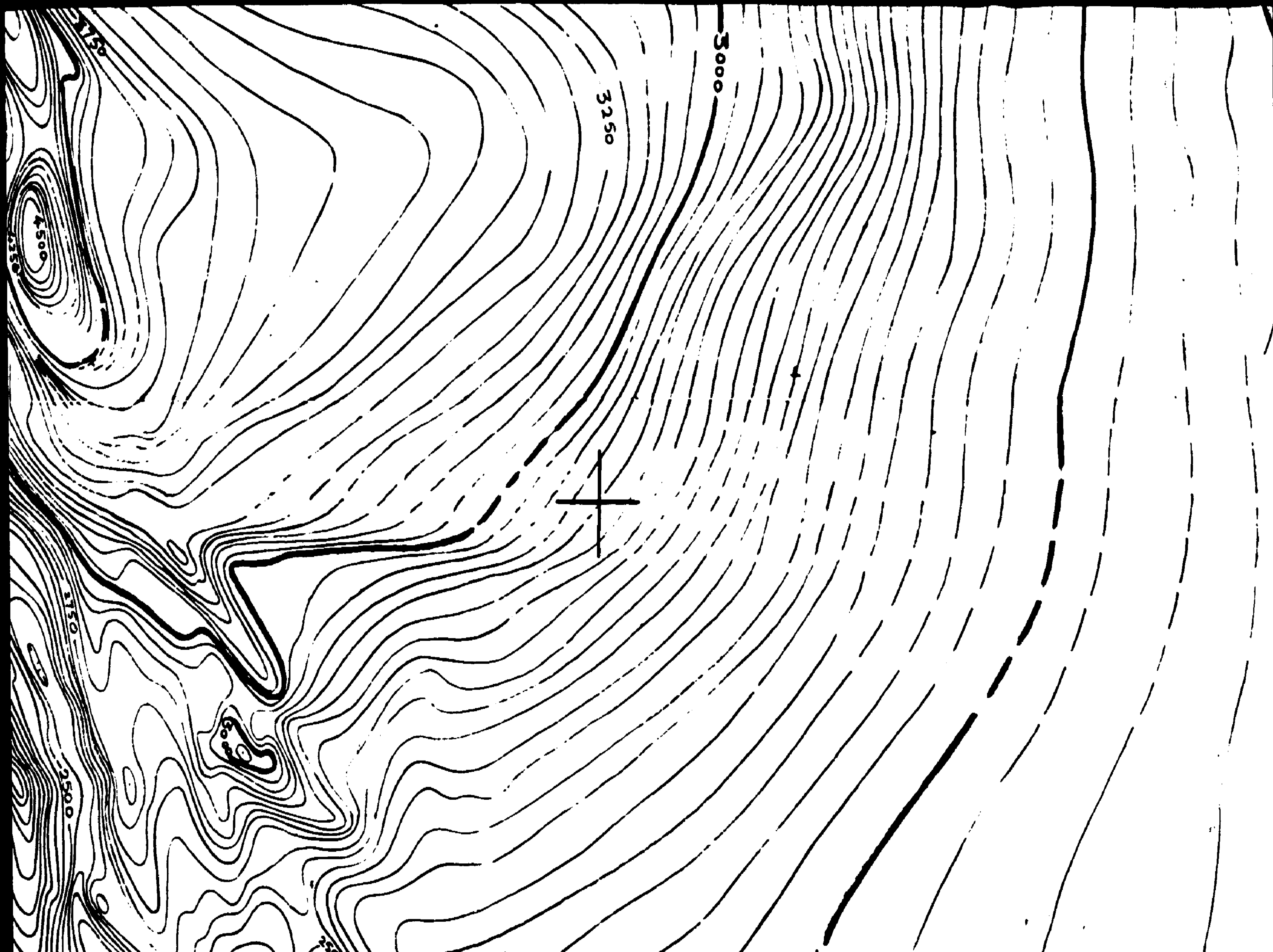

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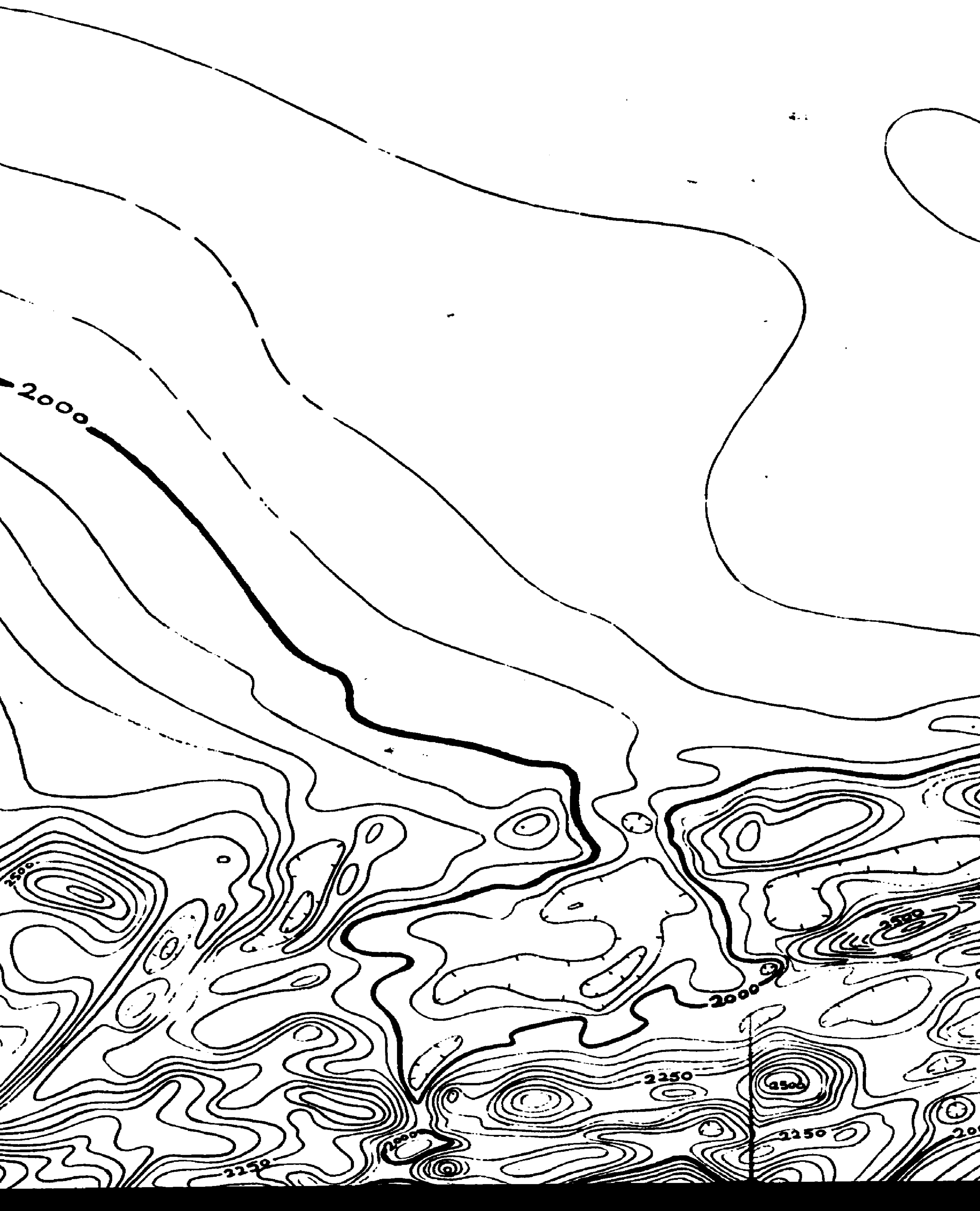
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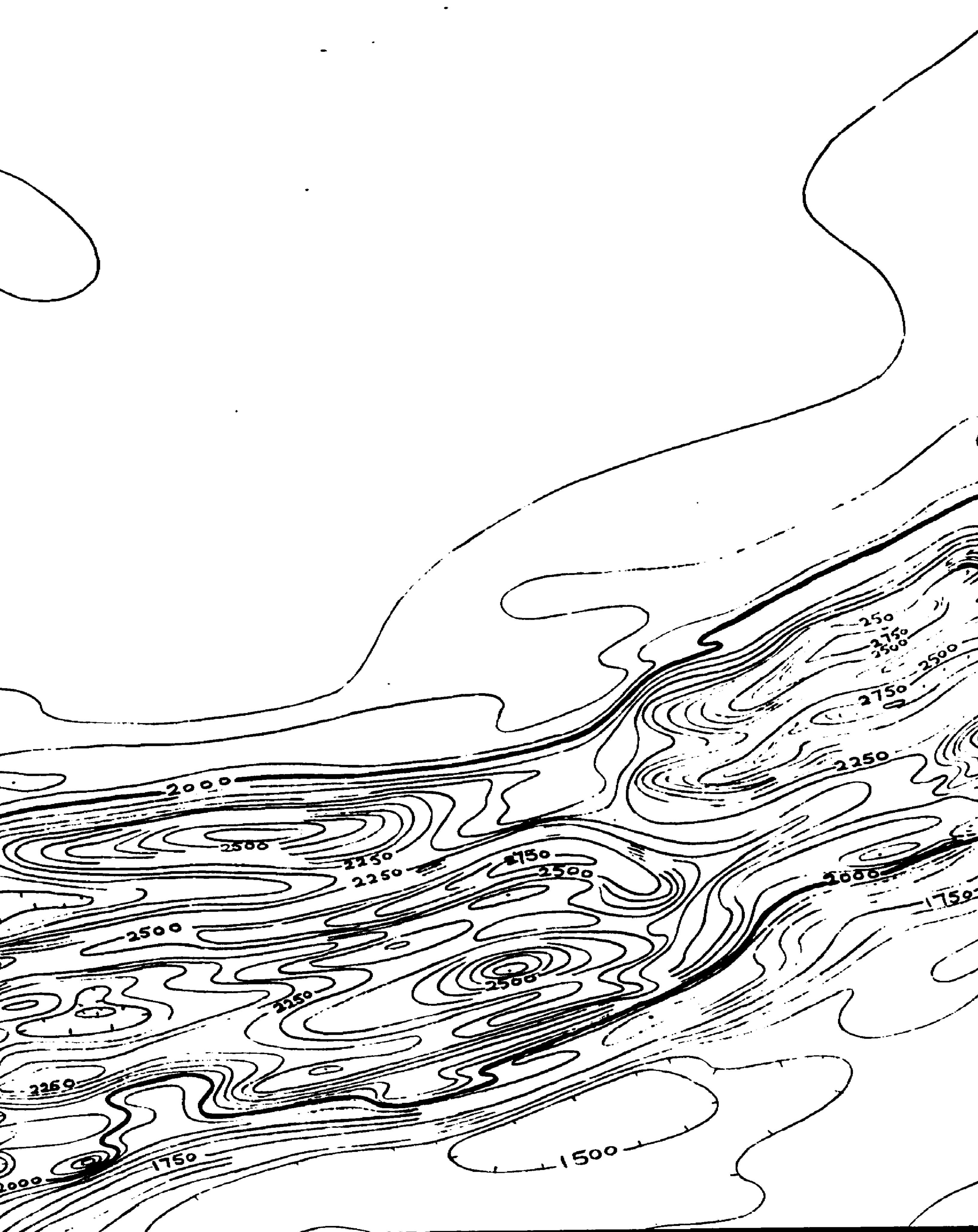

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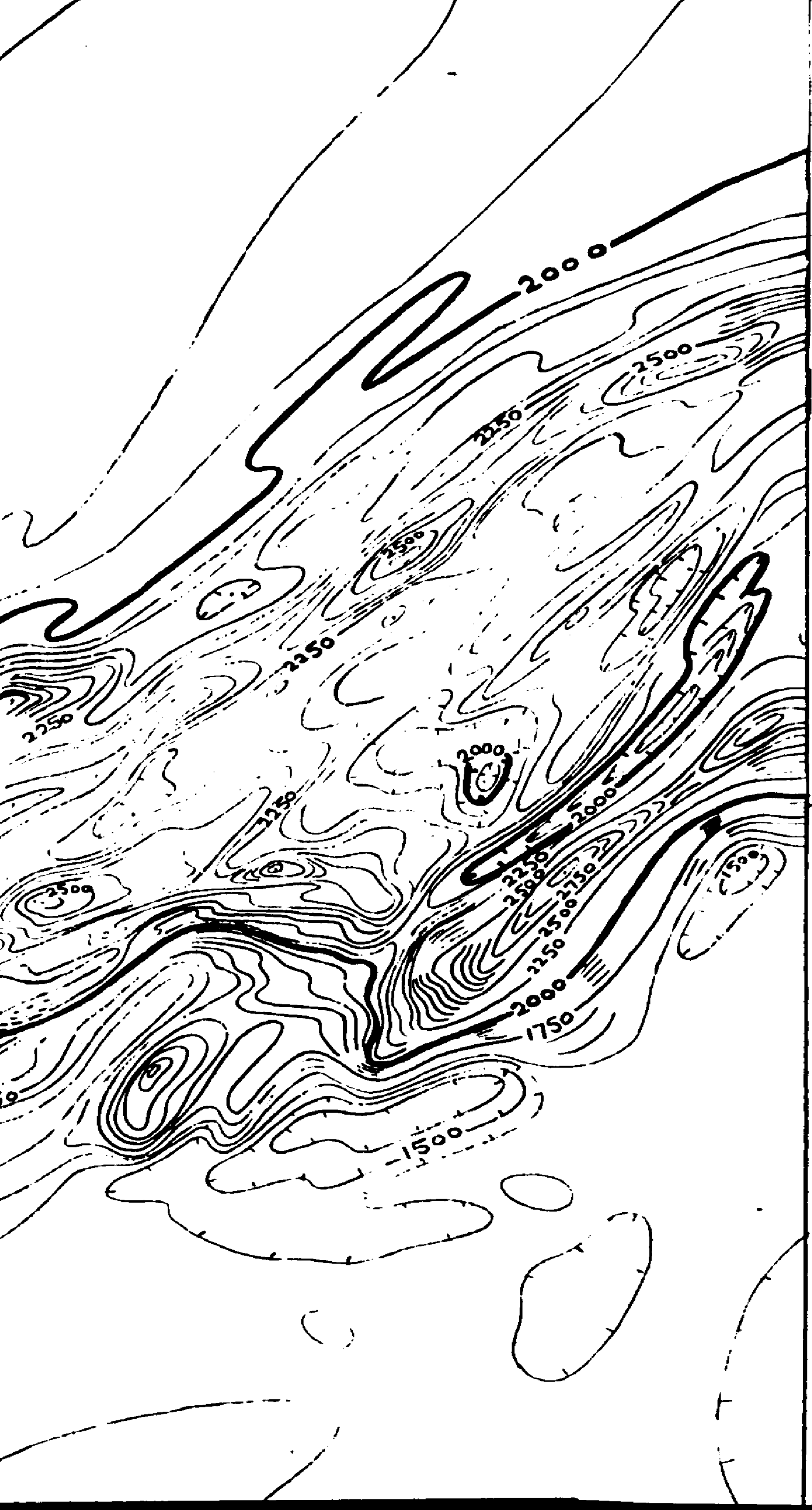

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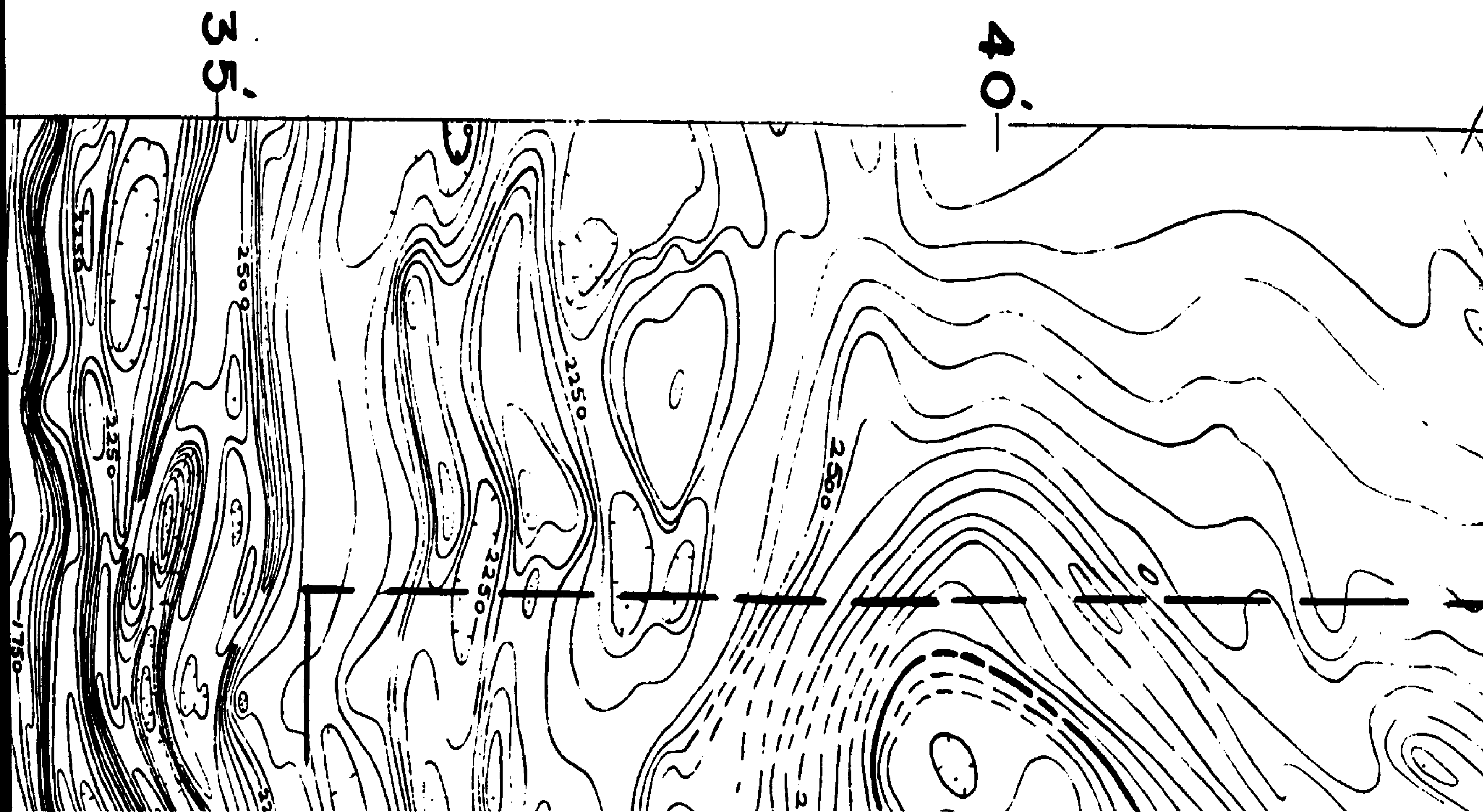
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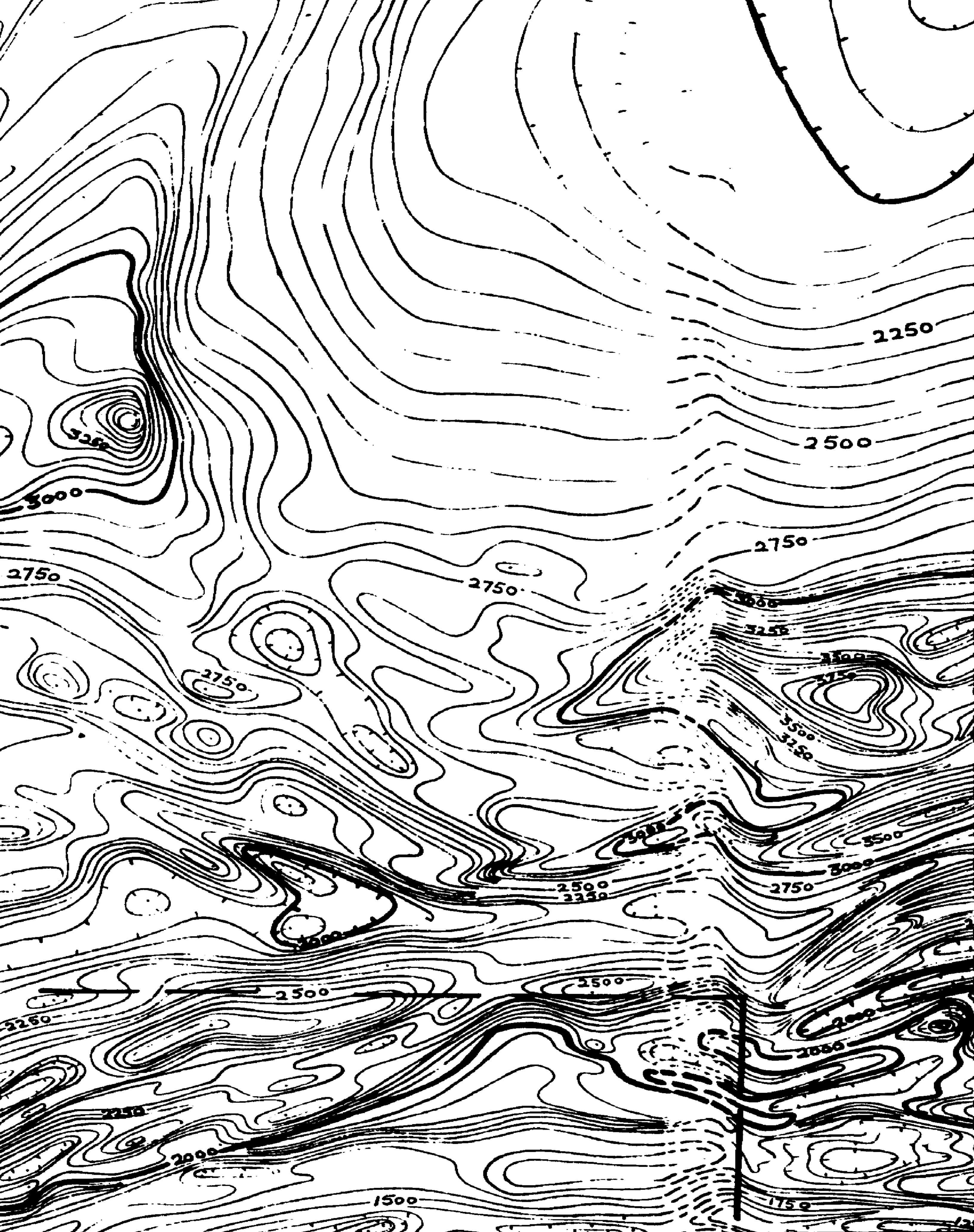

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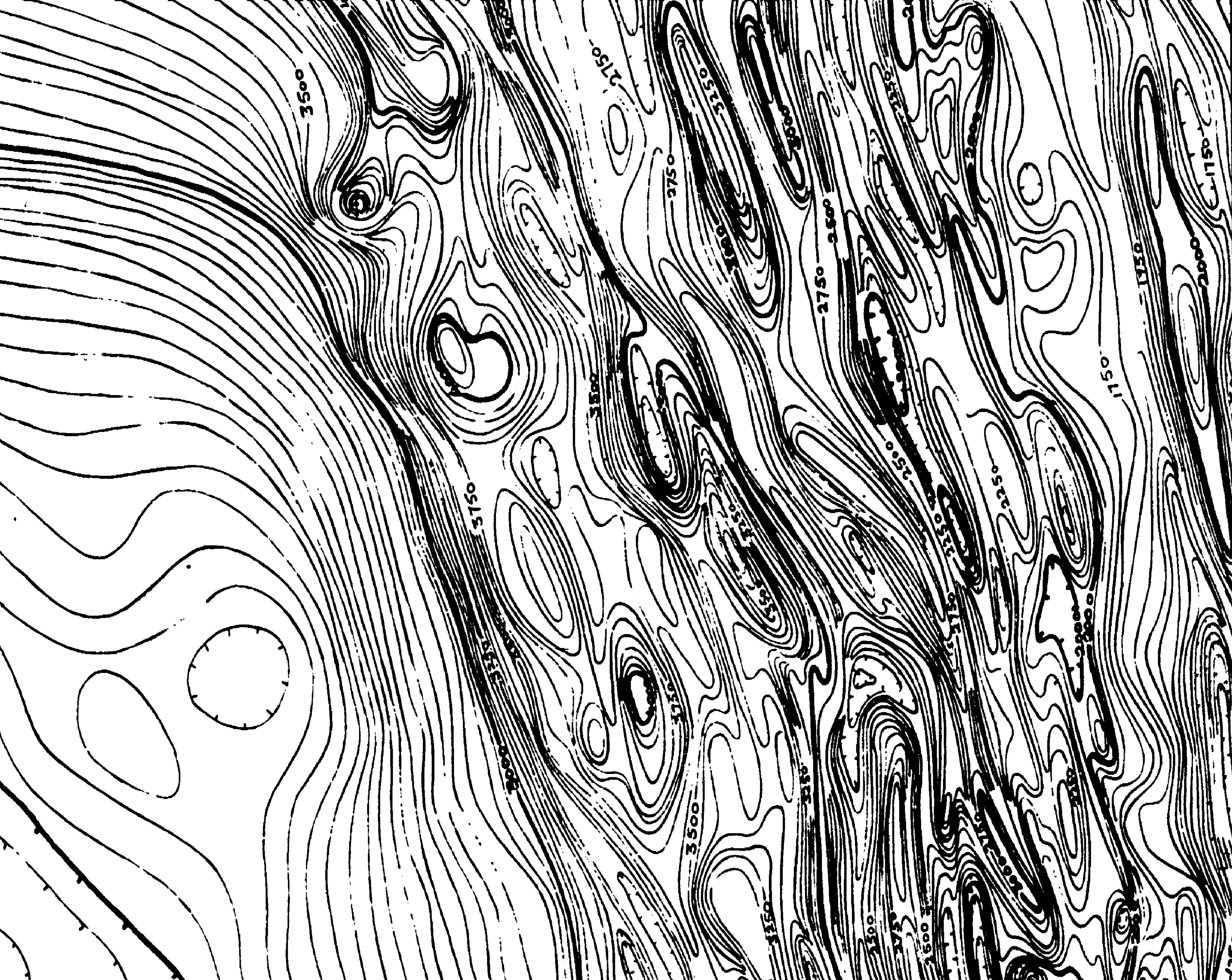
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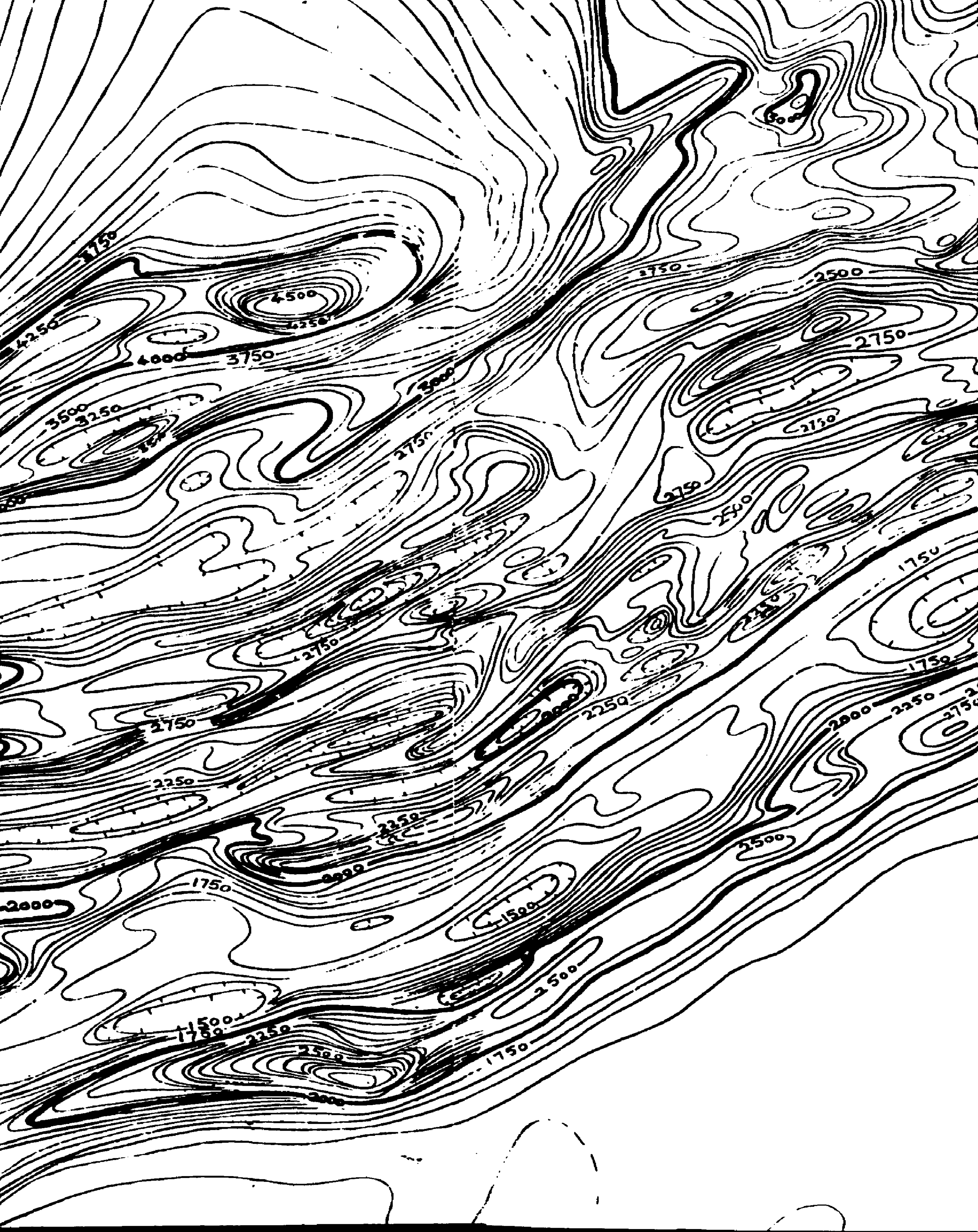

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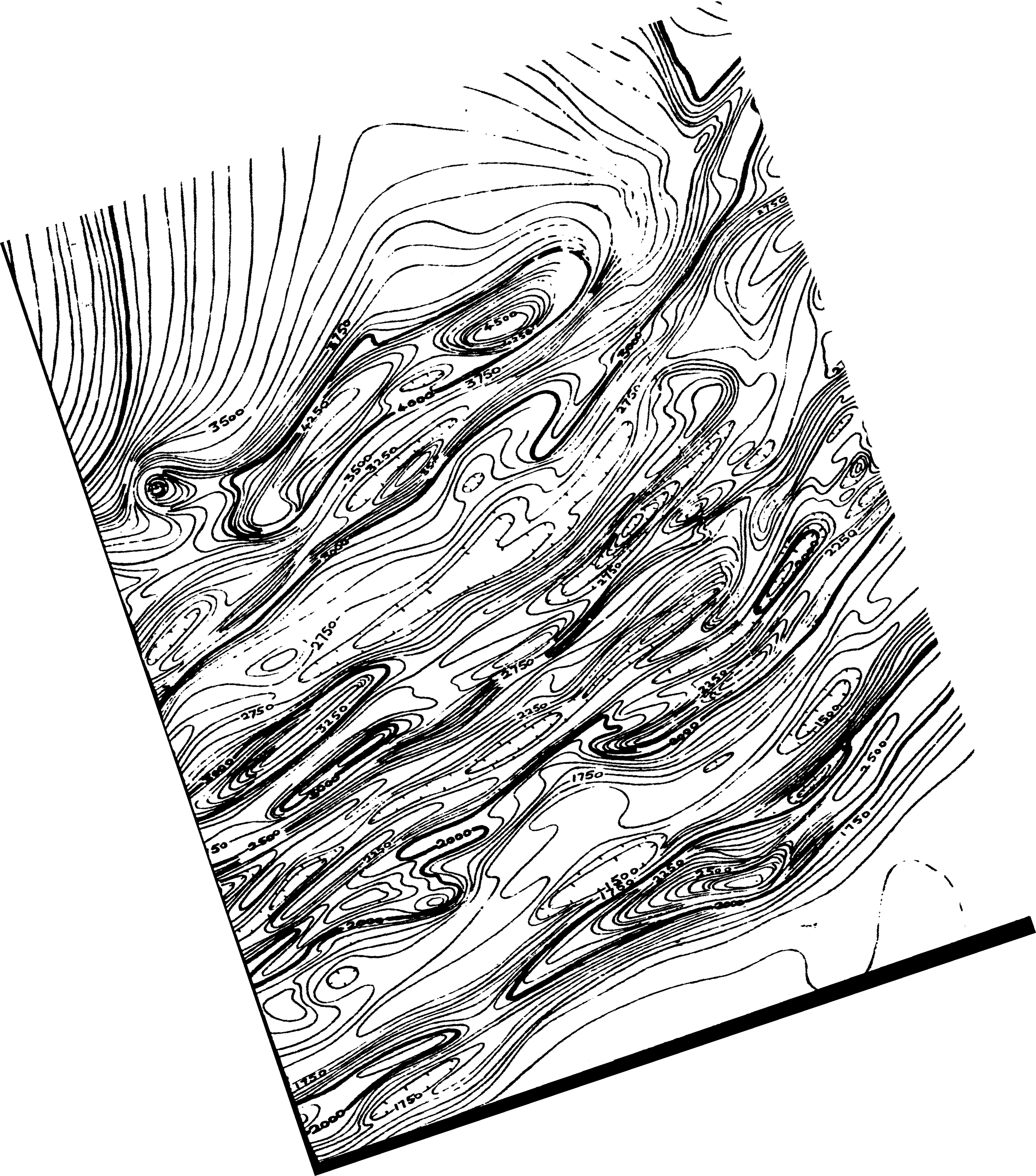
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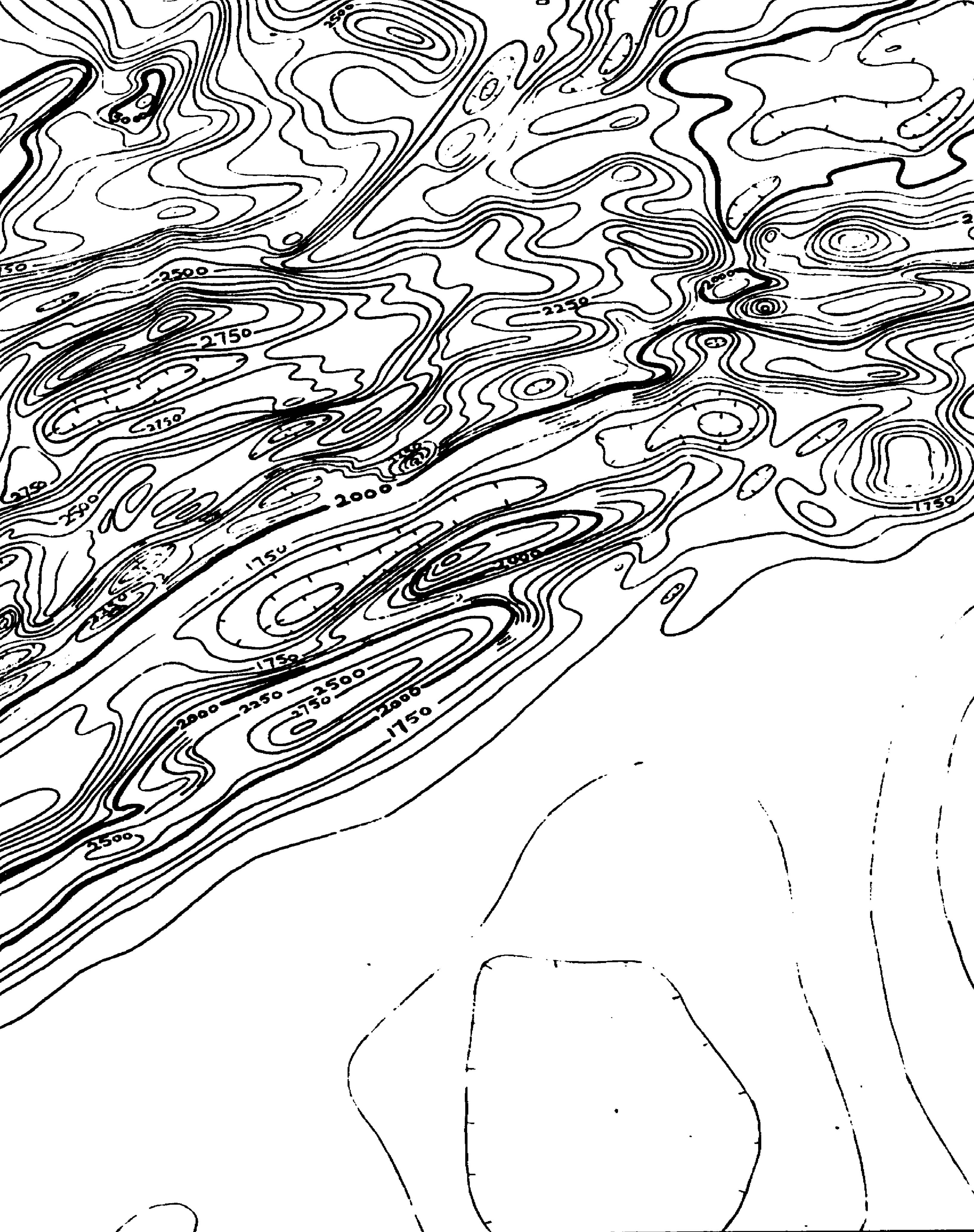

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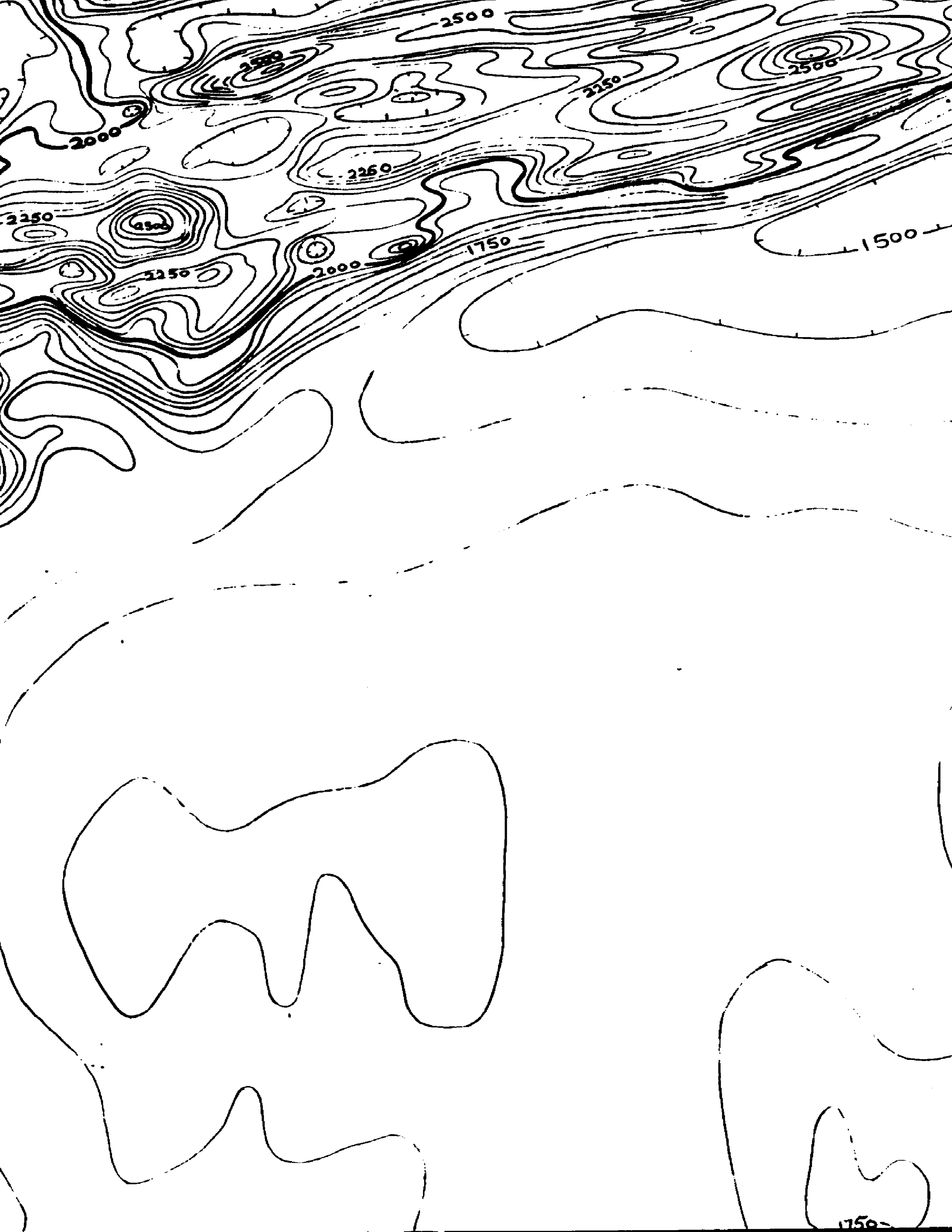
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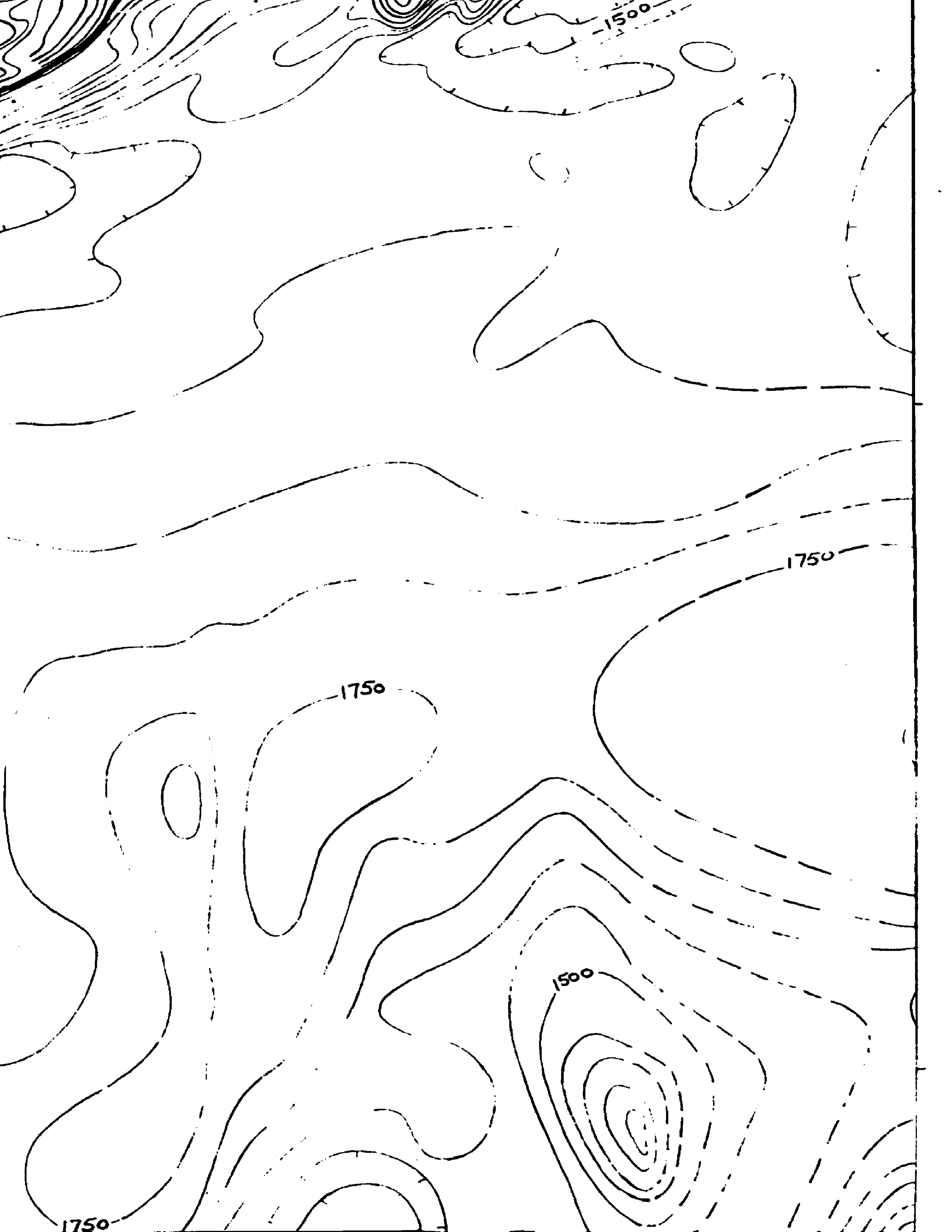

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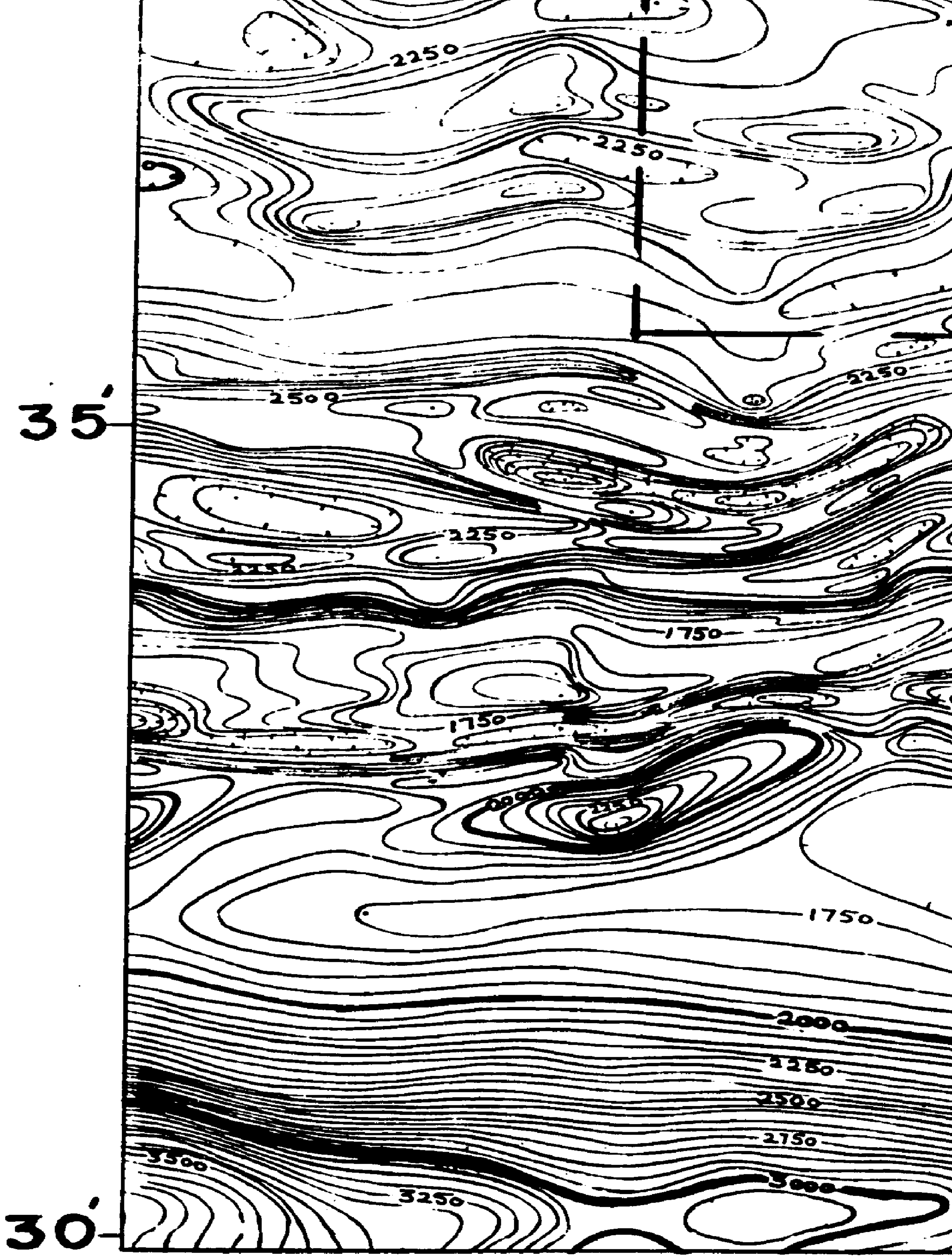

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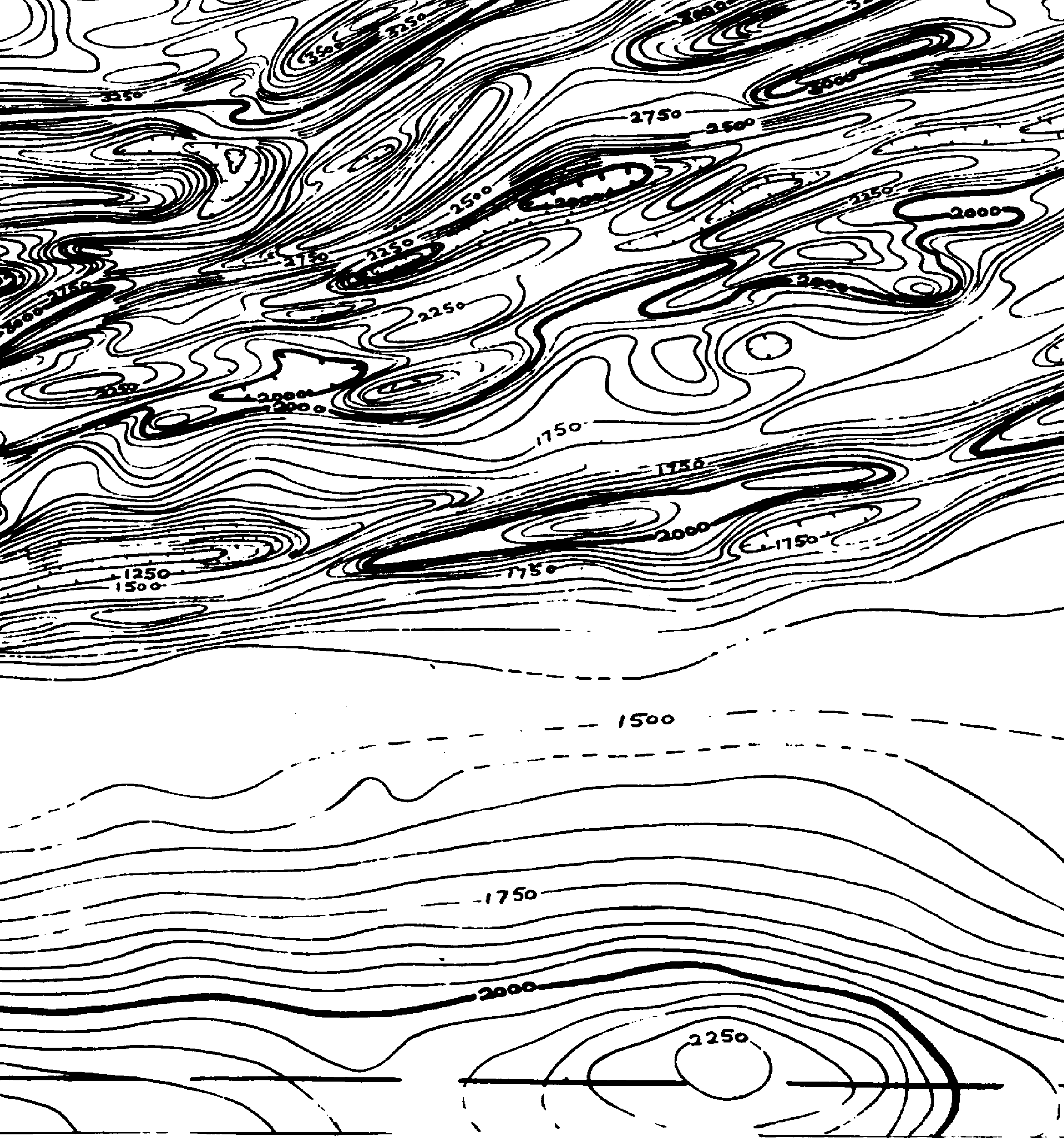

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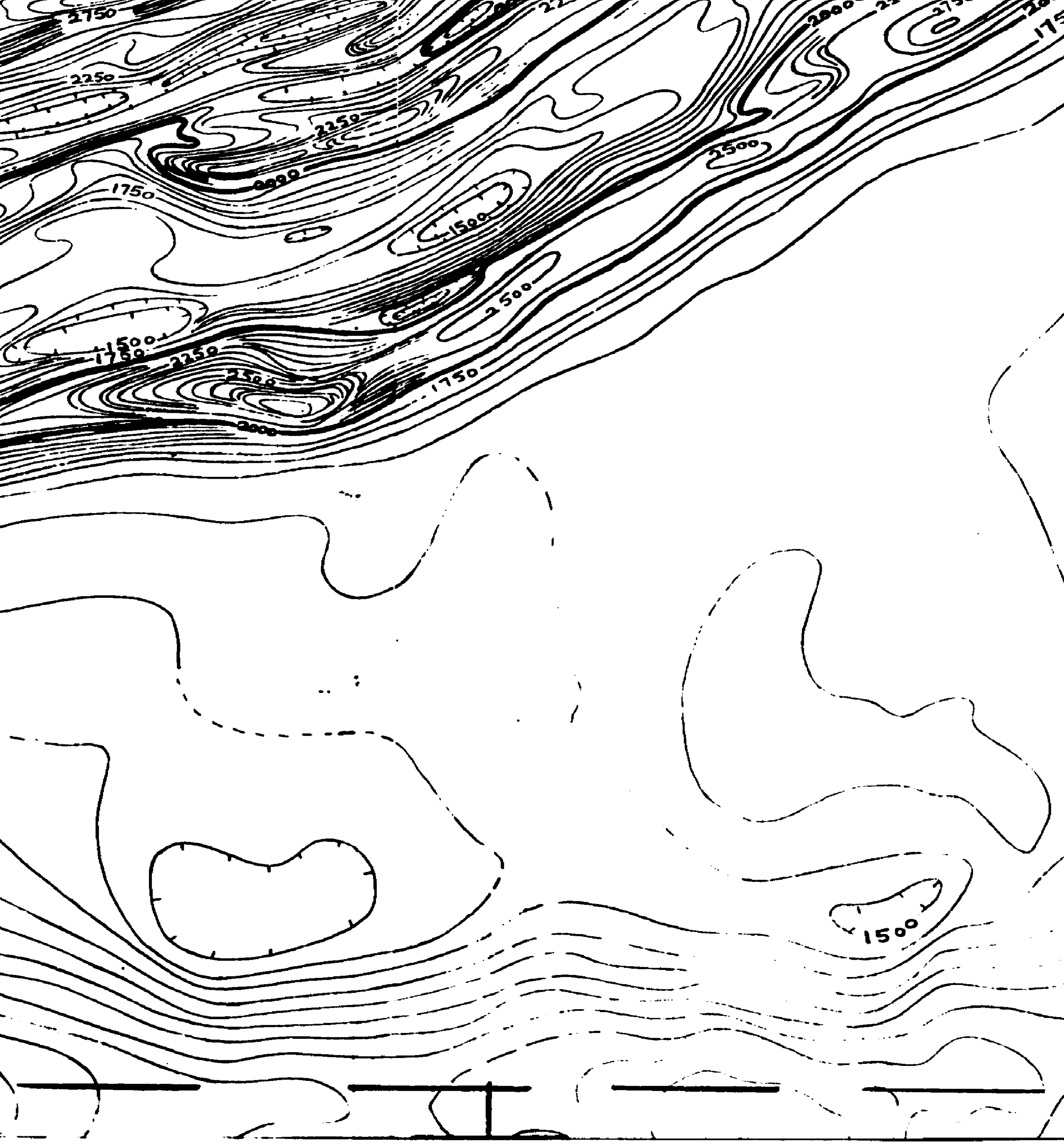
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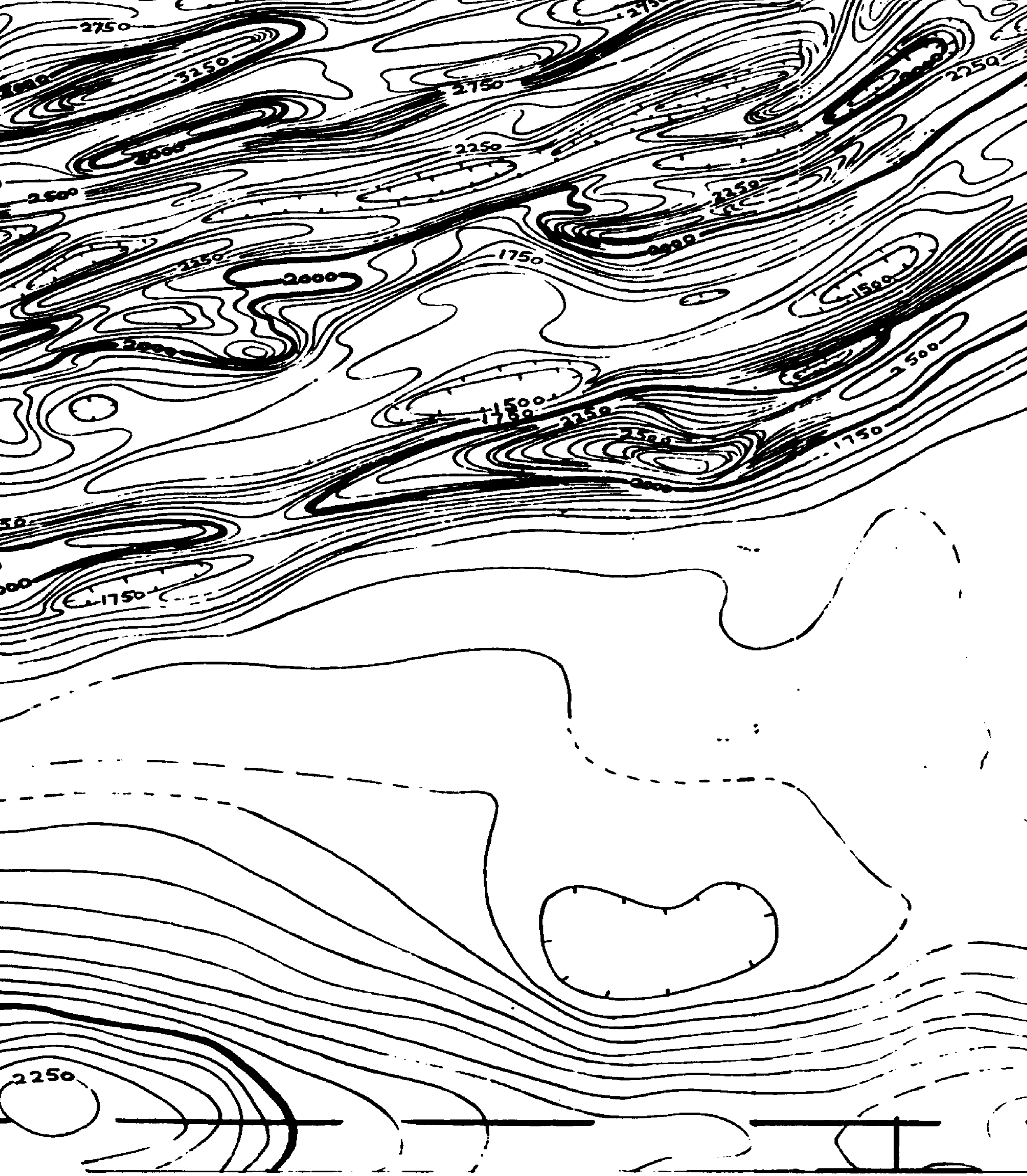
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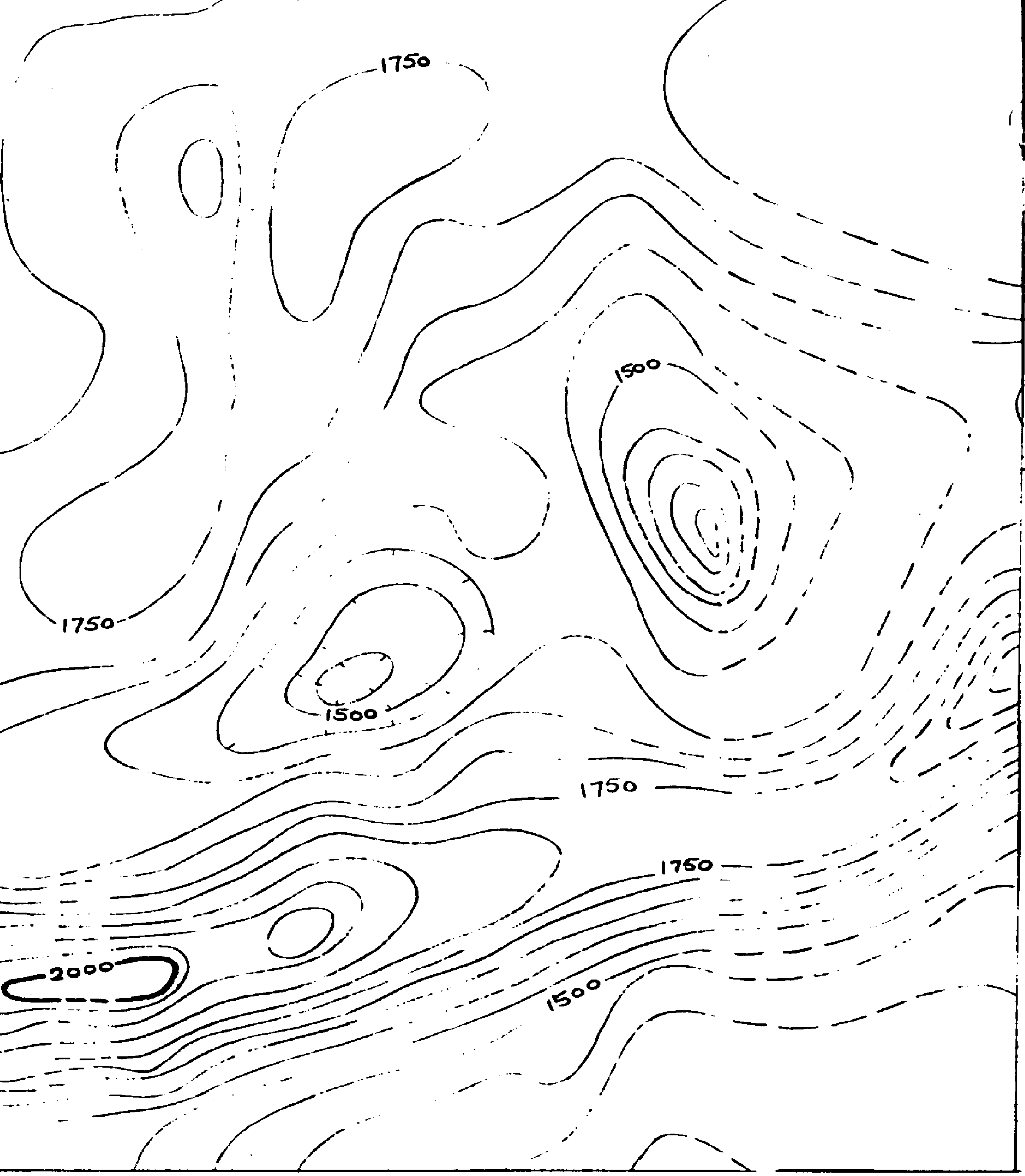
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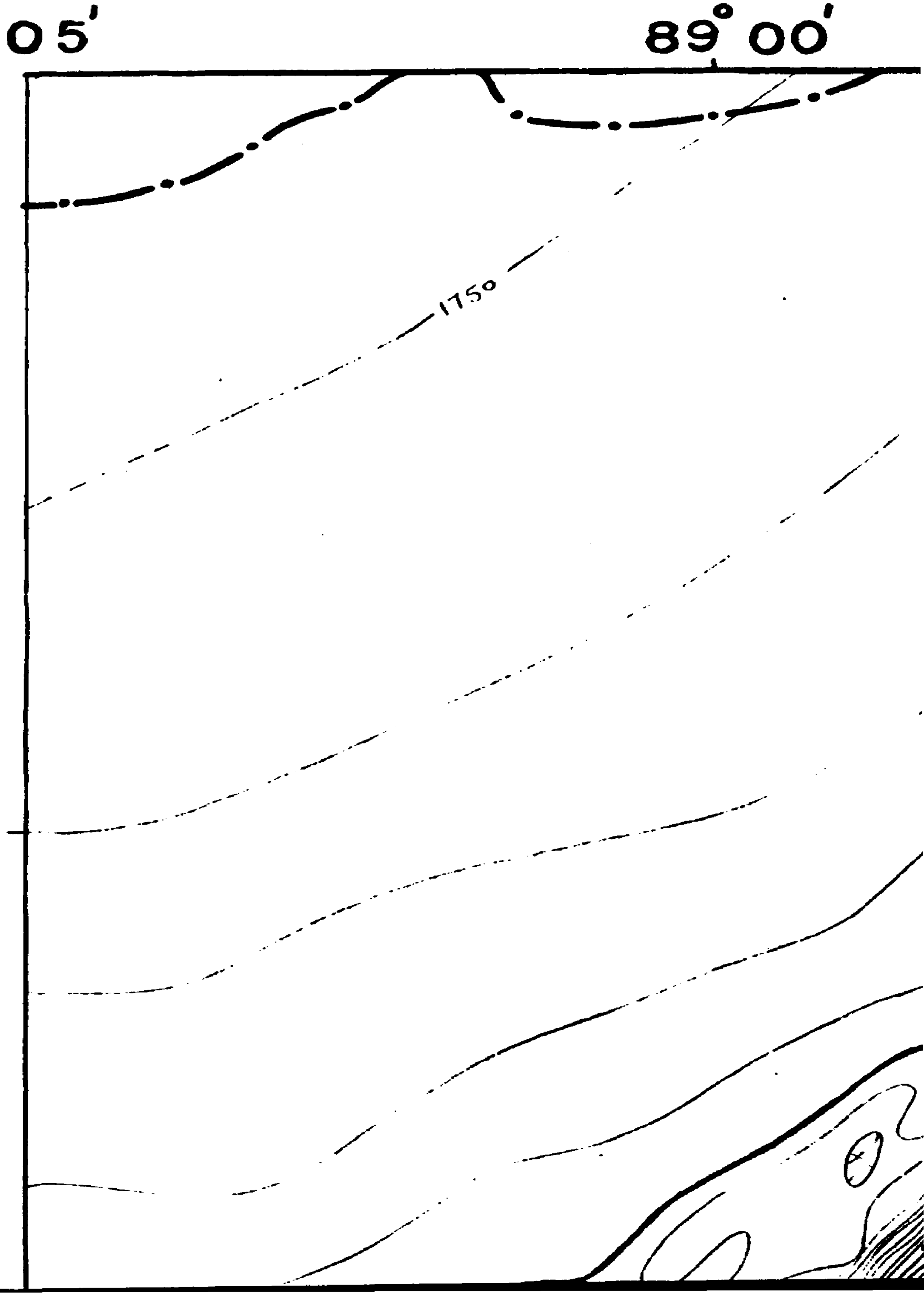
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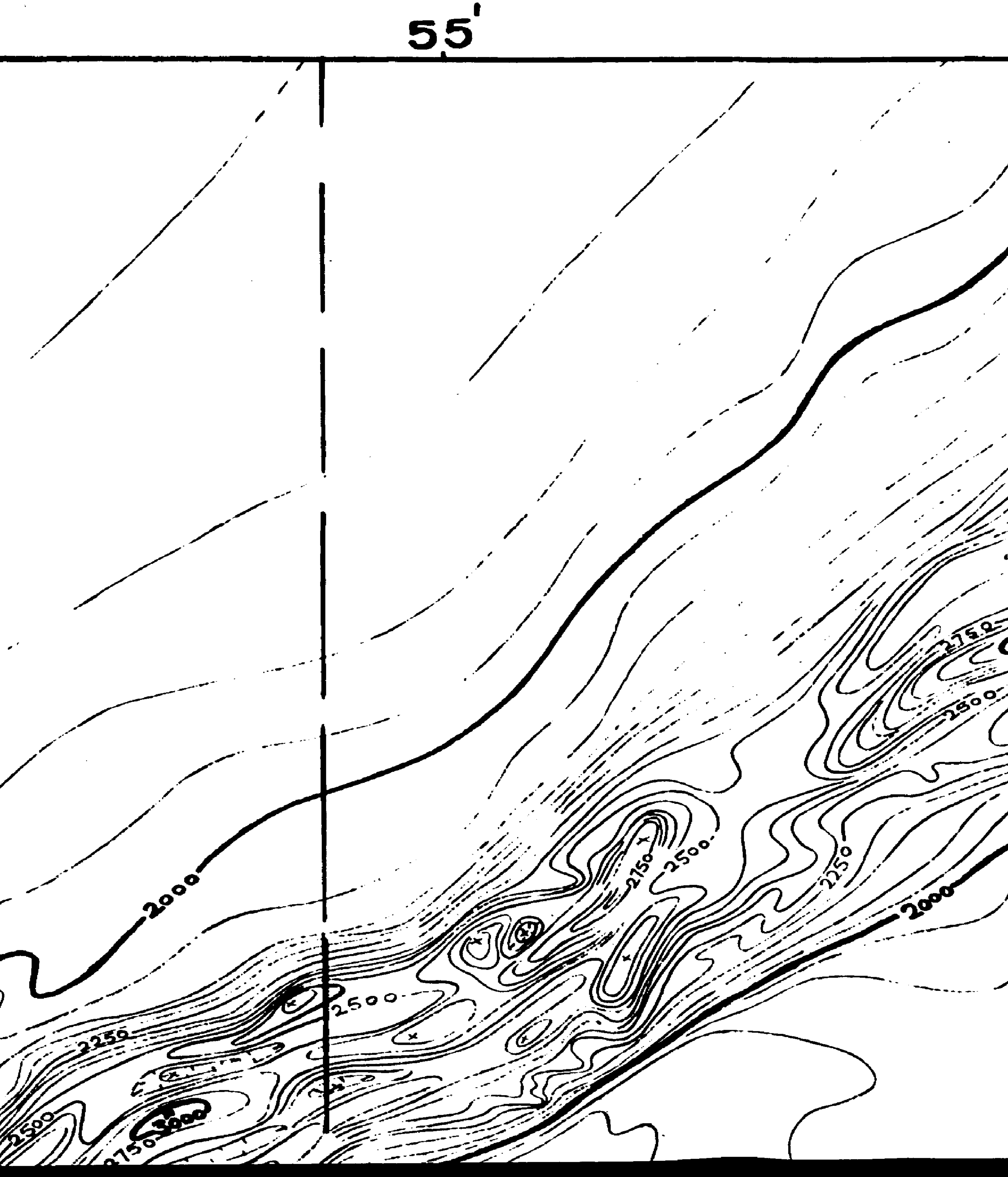

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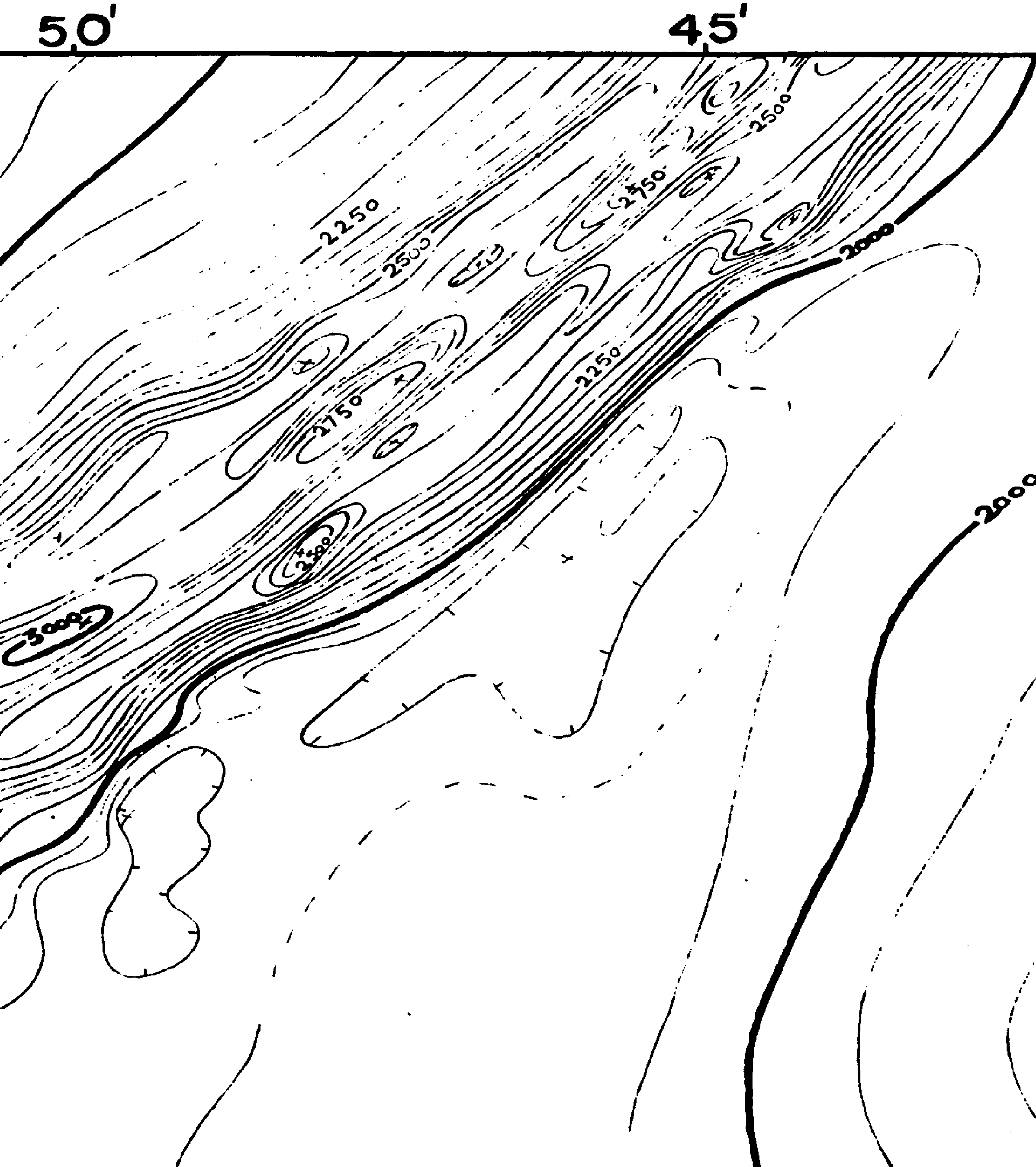

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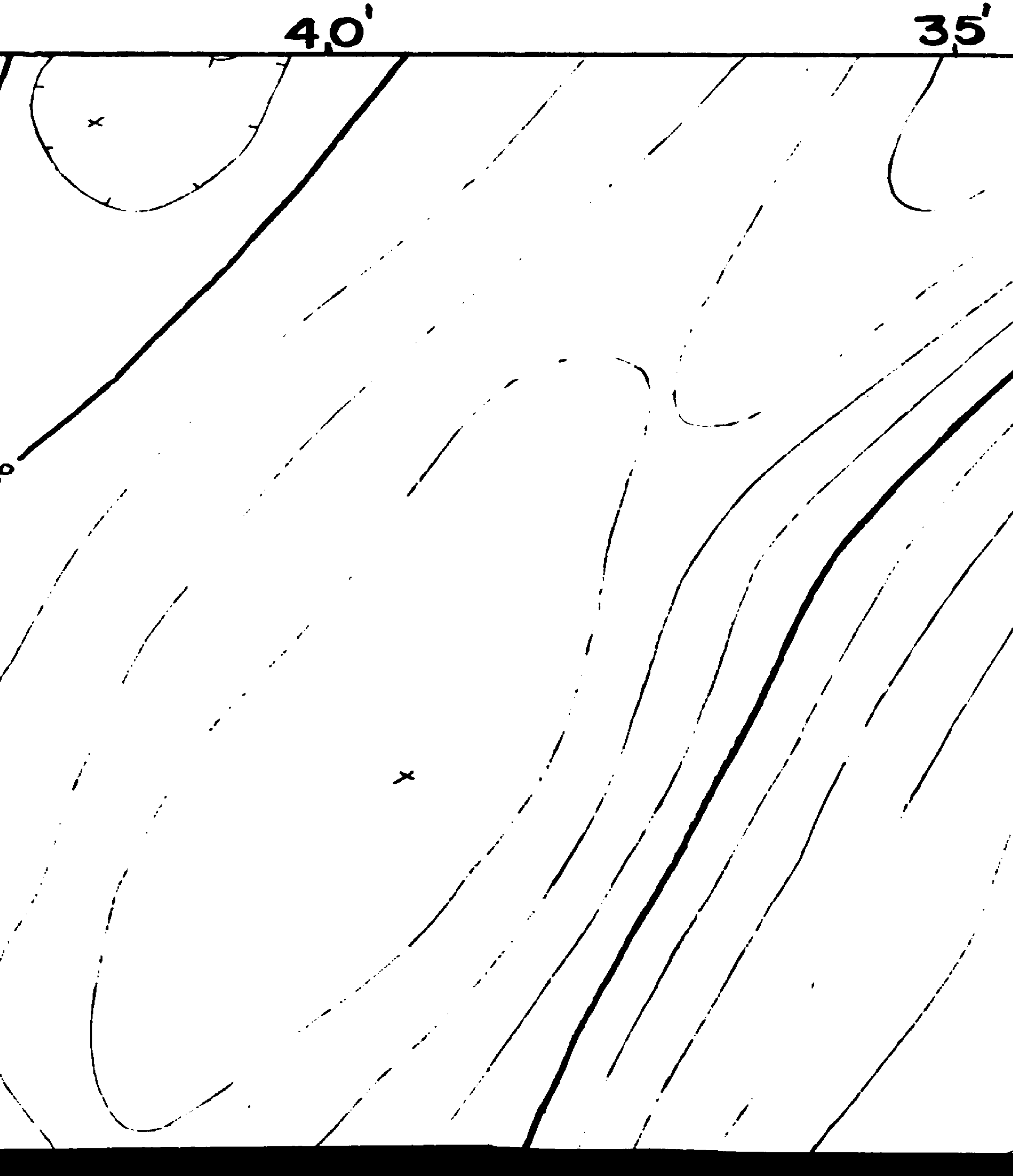
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35'


35'
88
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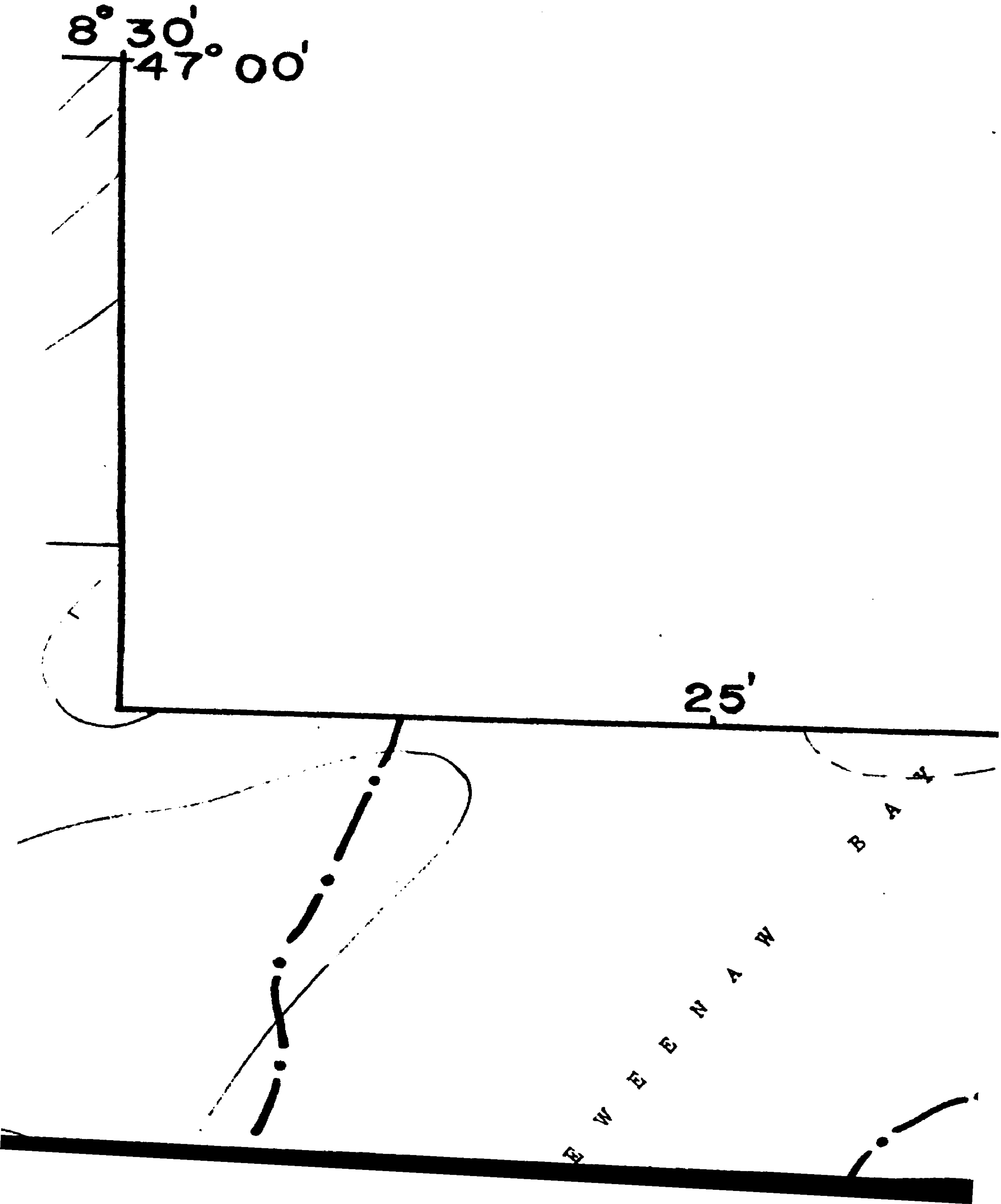
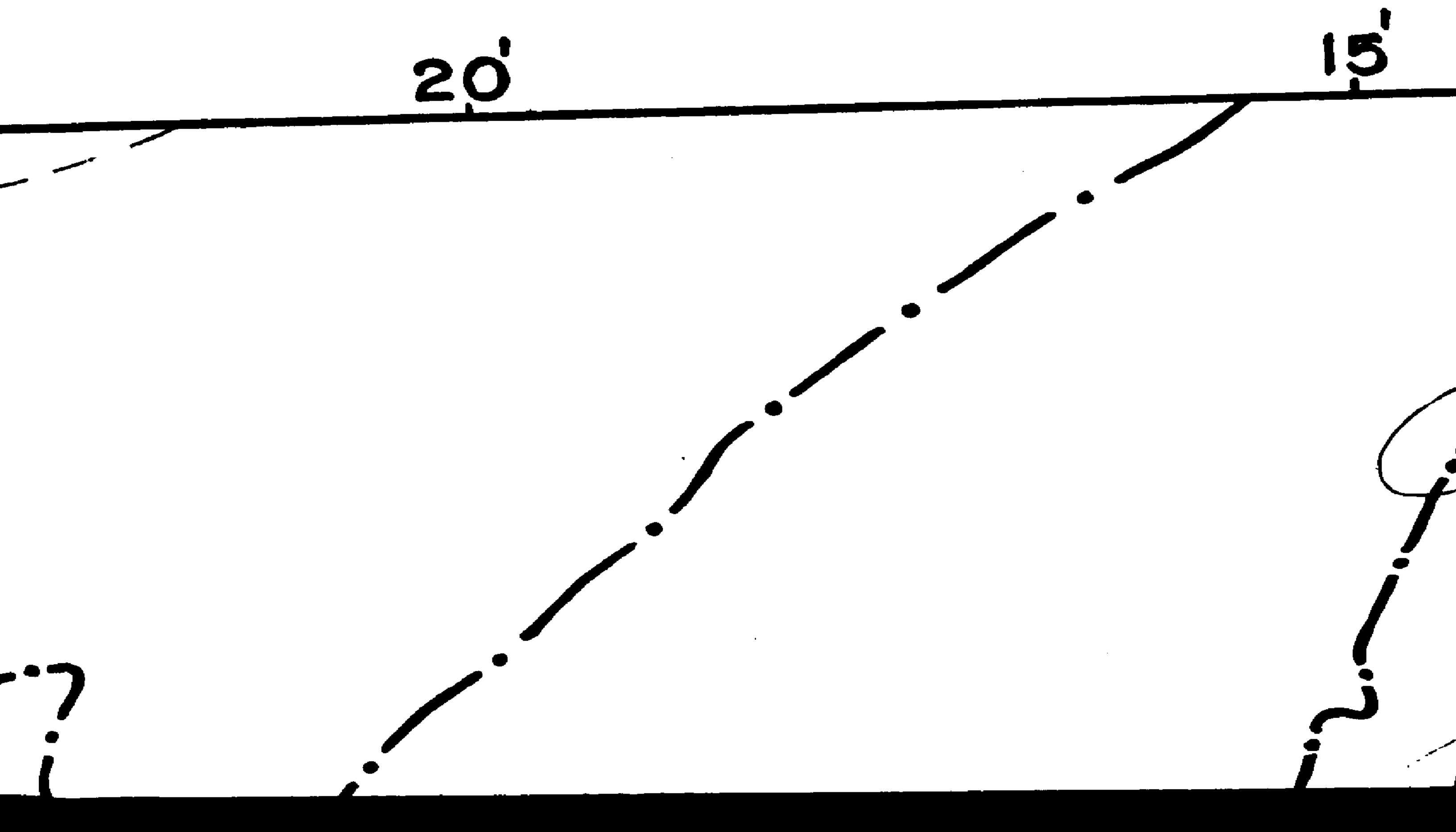
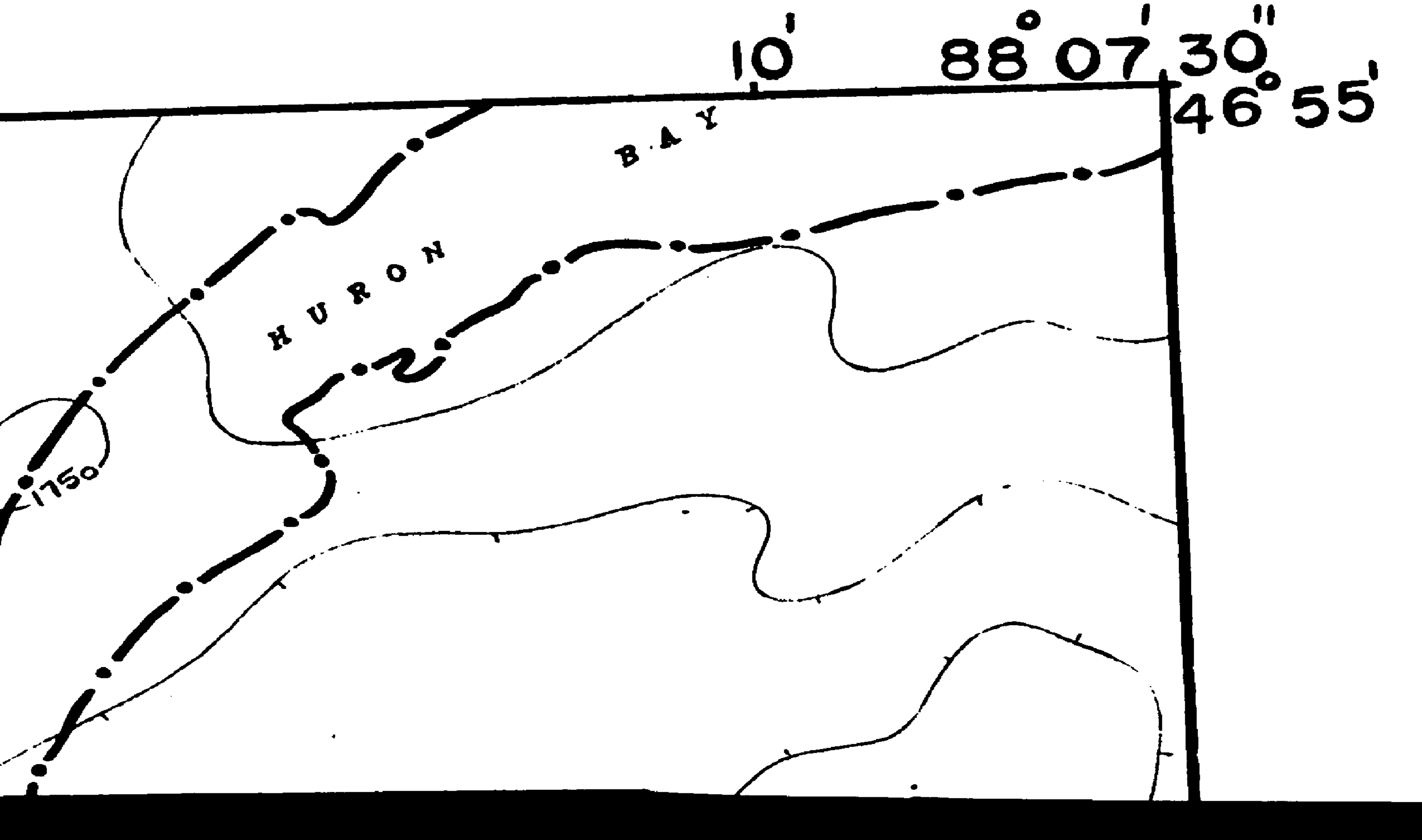
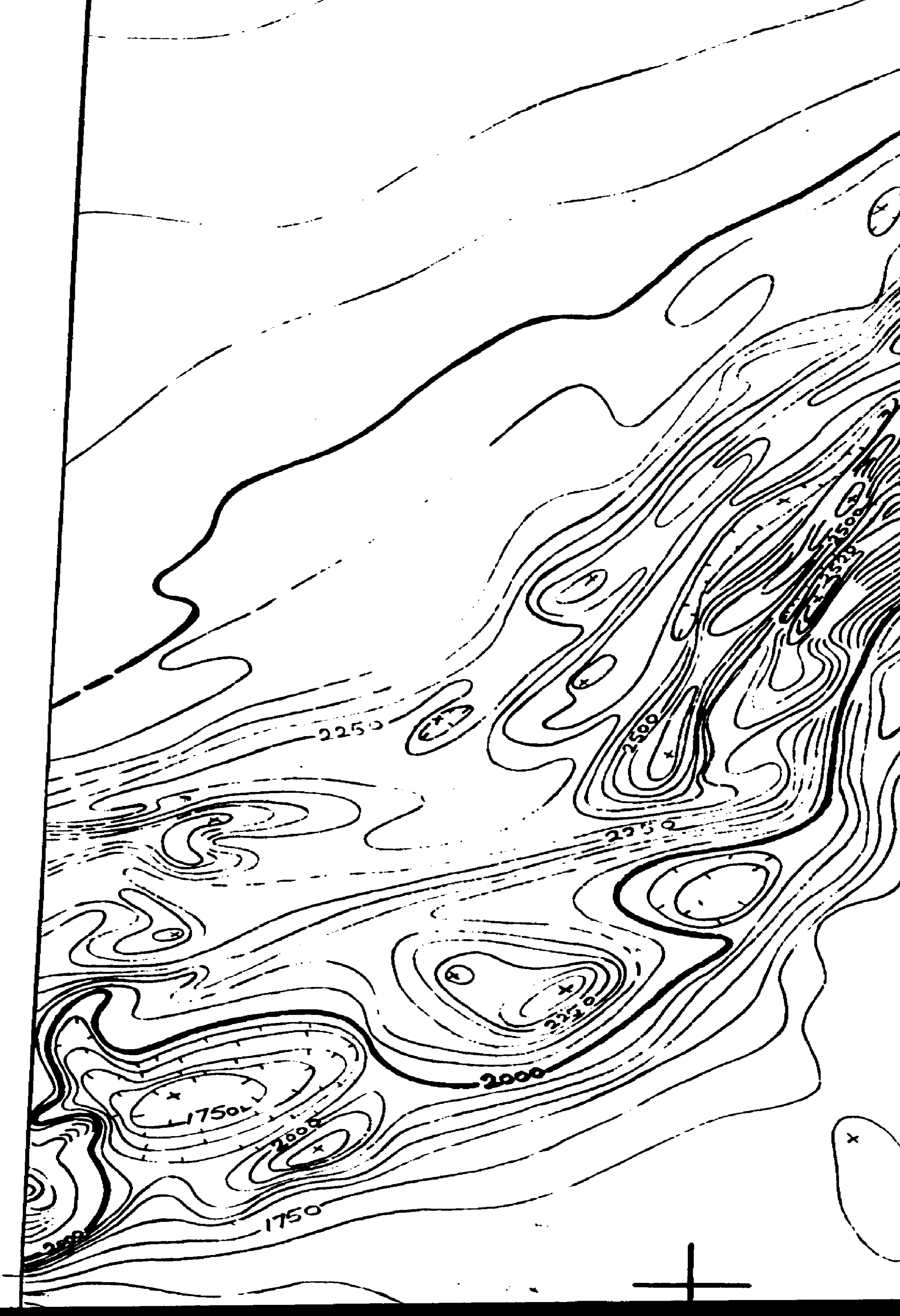

8° 30'
47° 00'
25'
EWEENAW BAY

PLATE I-c




10'
88° 07' 30"
46° 55'
HURON BAY
1750



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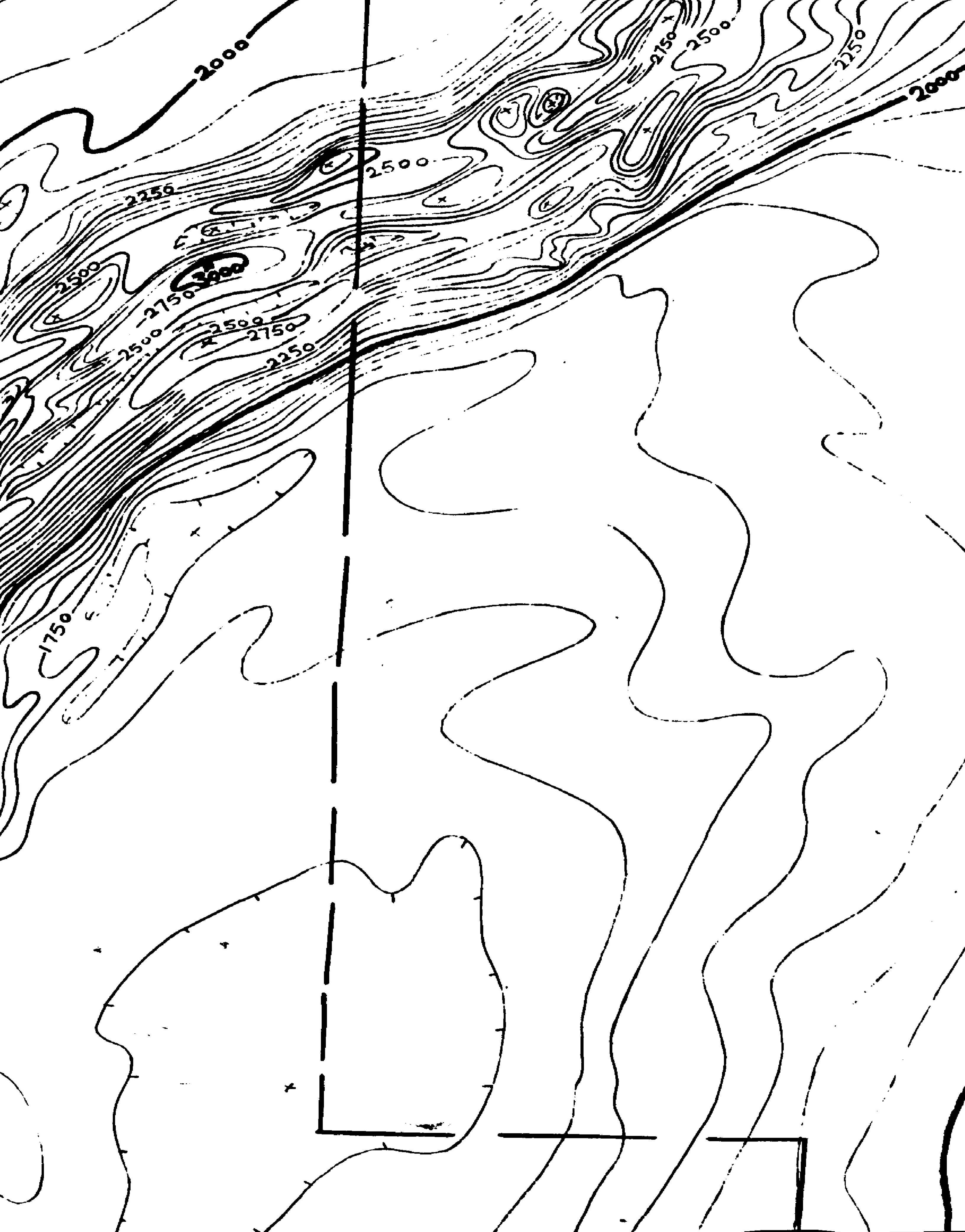

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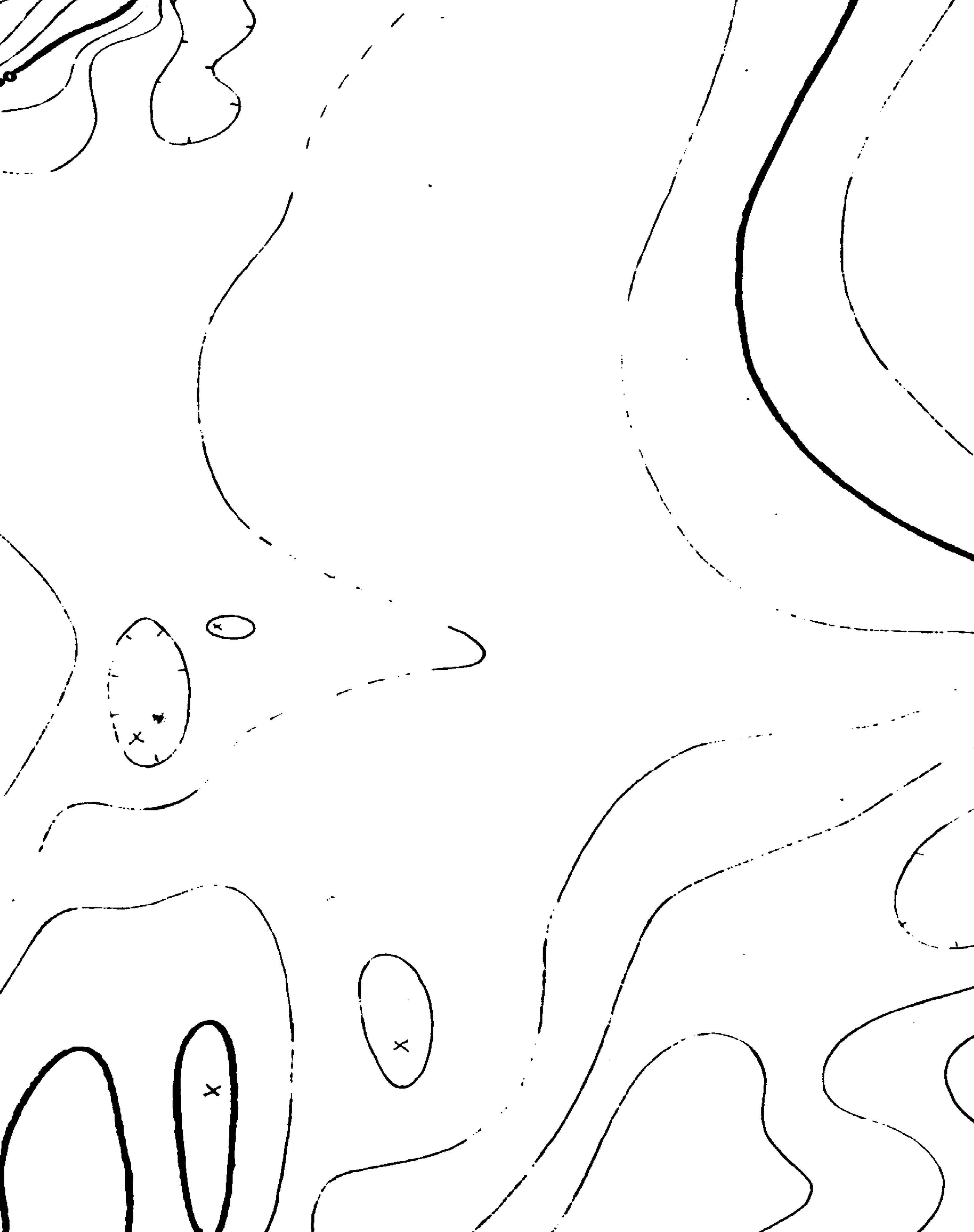

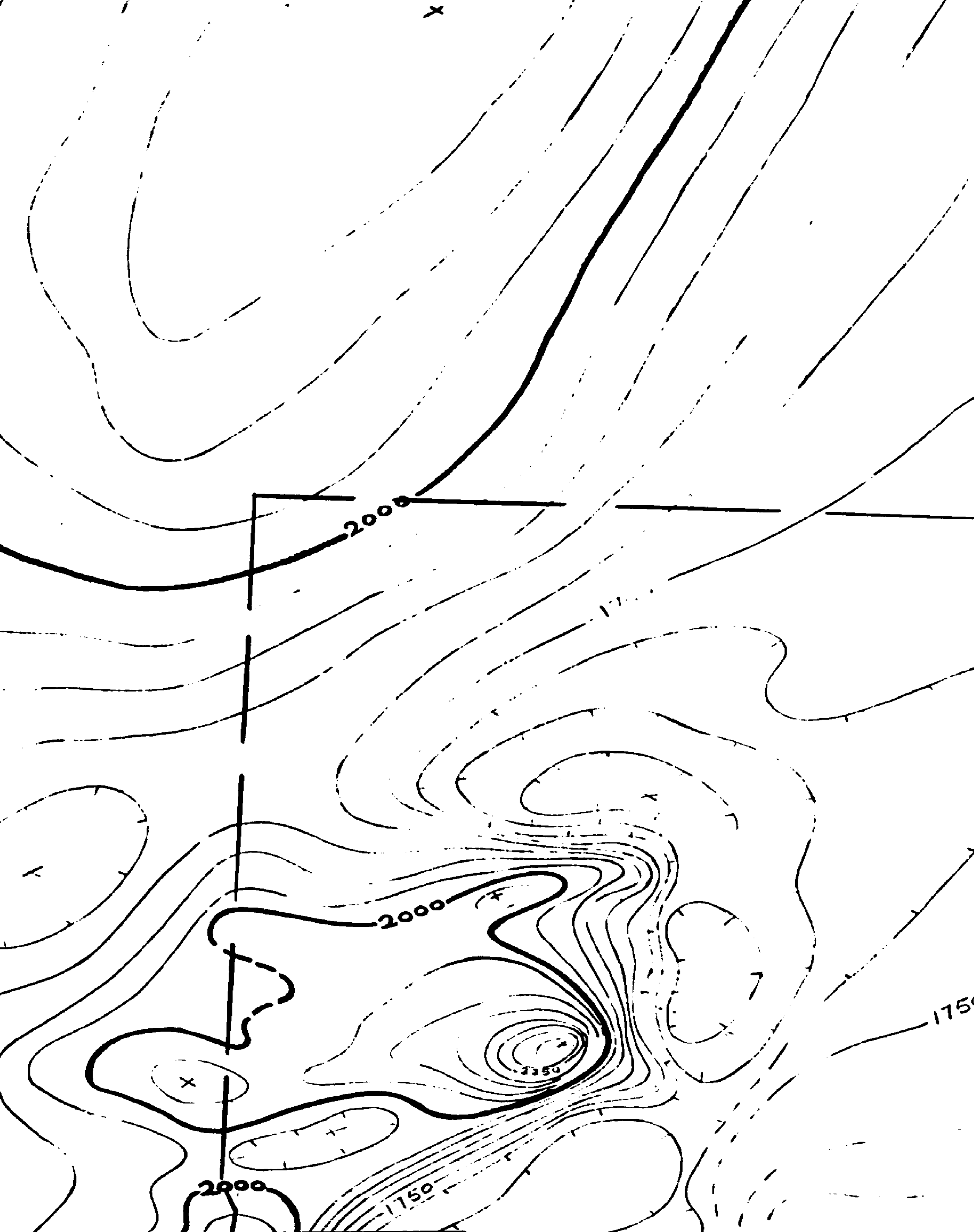

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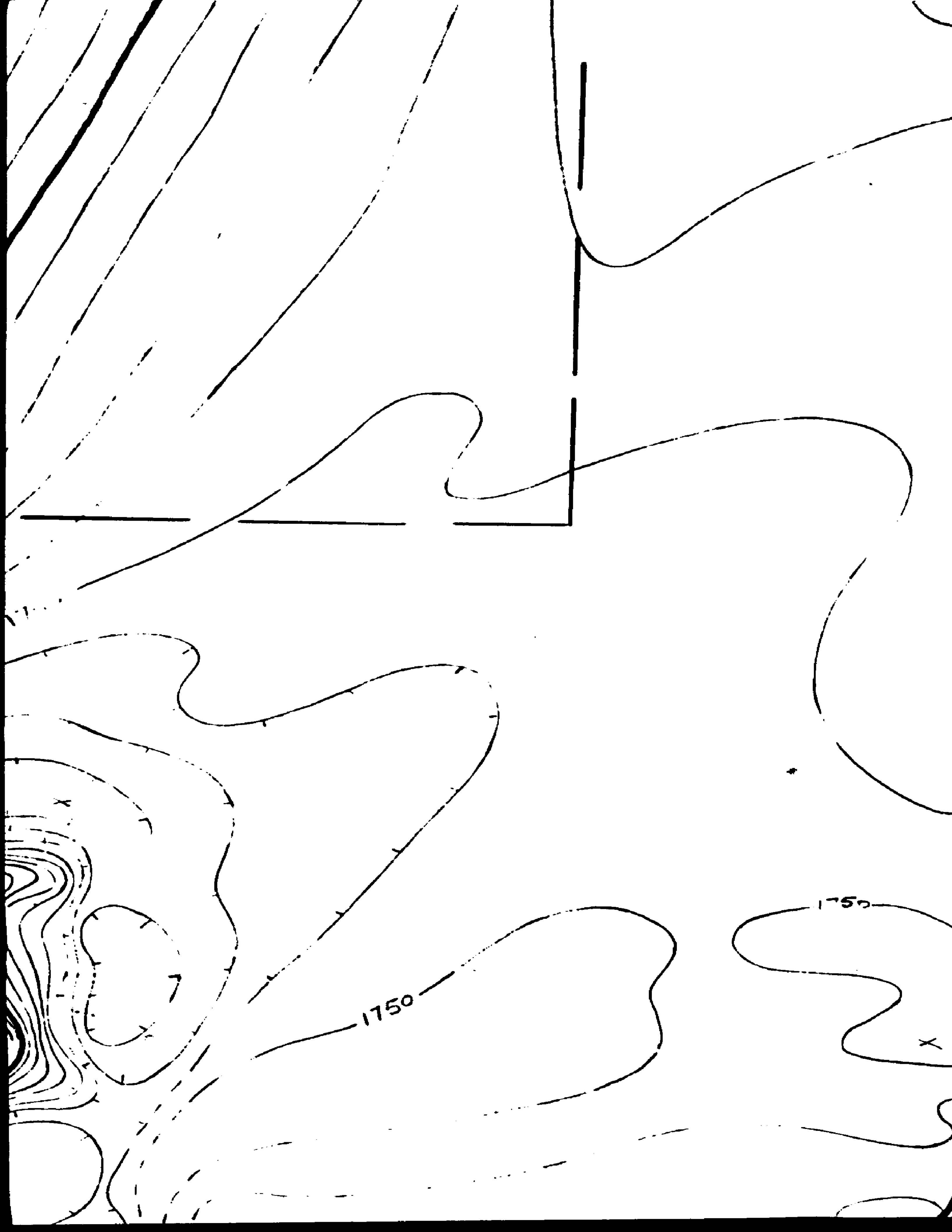
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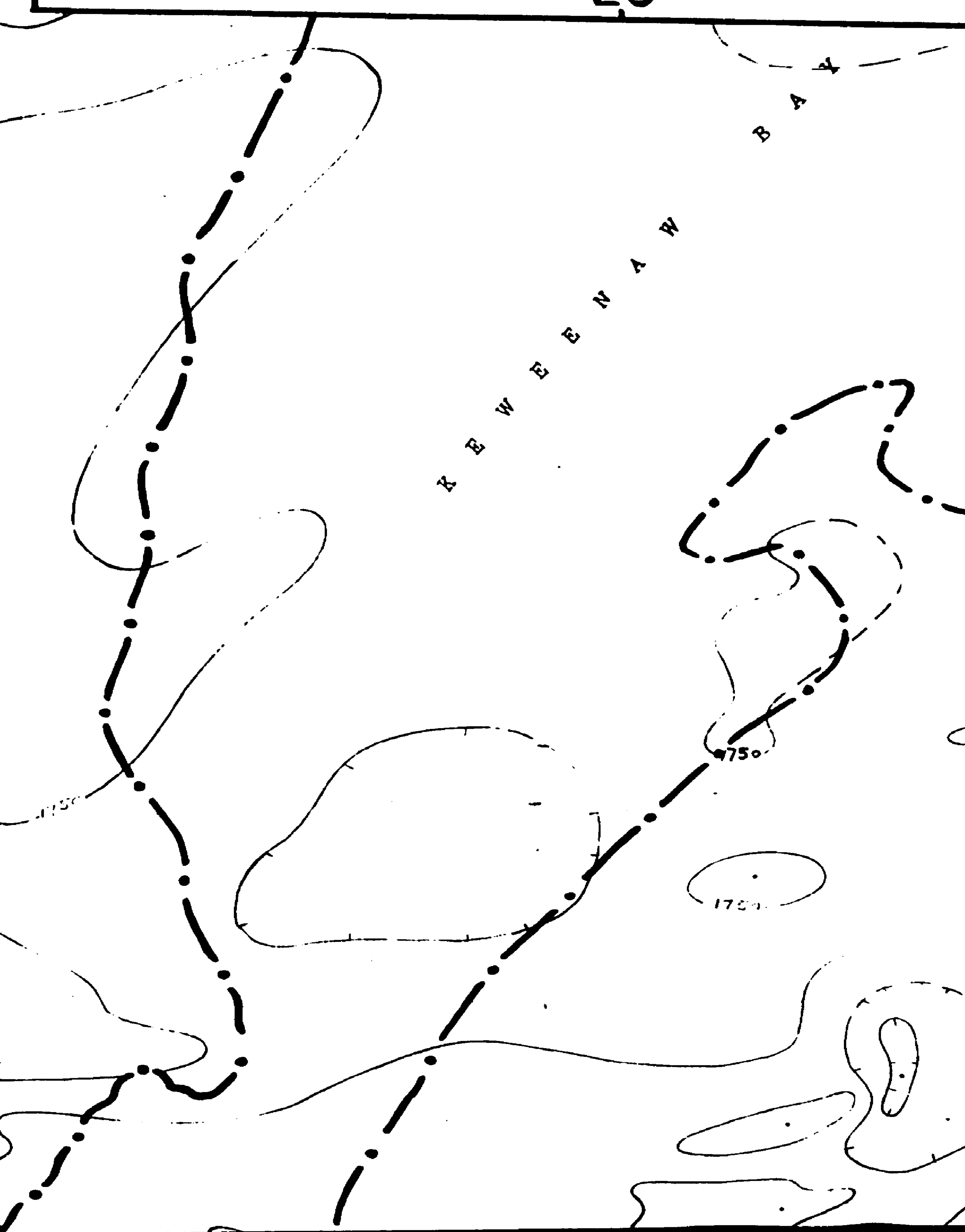

KEWEENAW BAY
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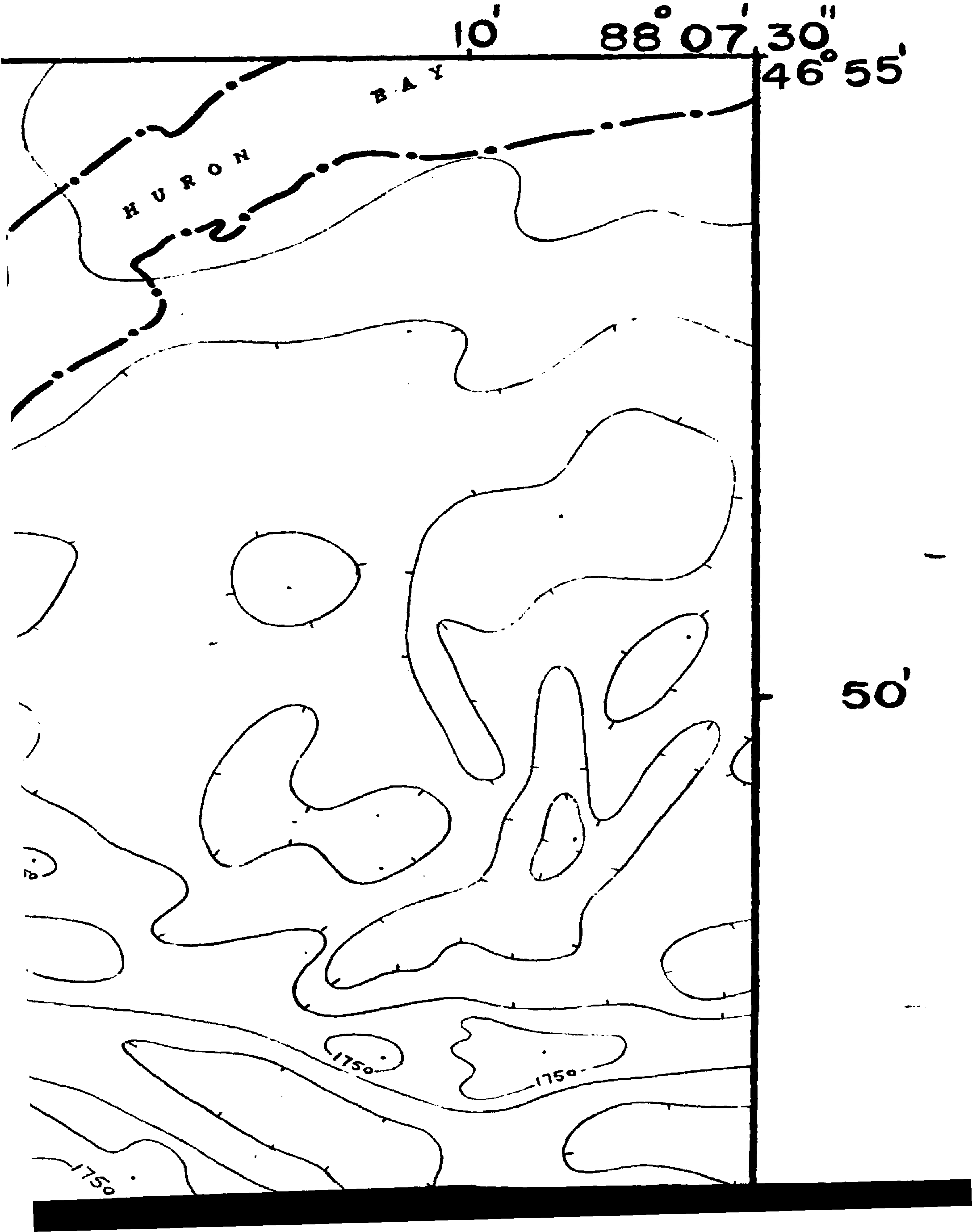

10'
88° 07' 30"
46° 55'
HURON BAY
50'
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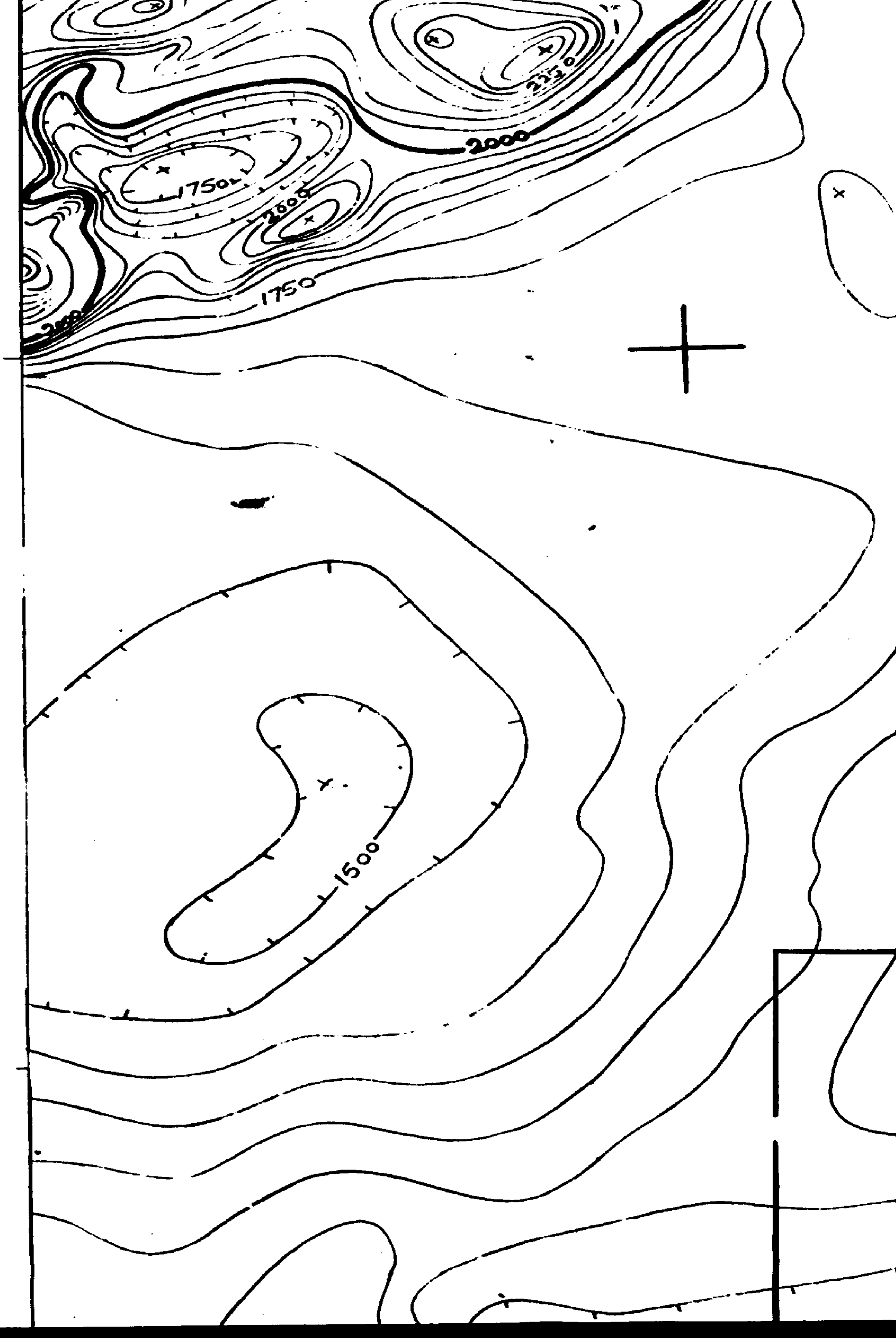

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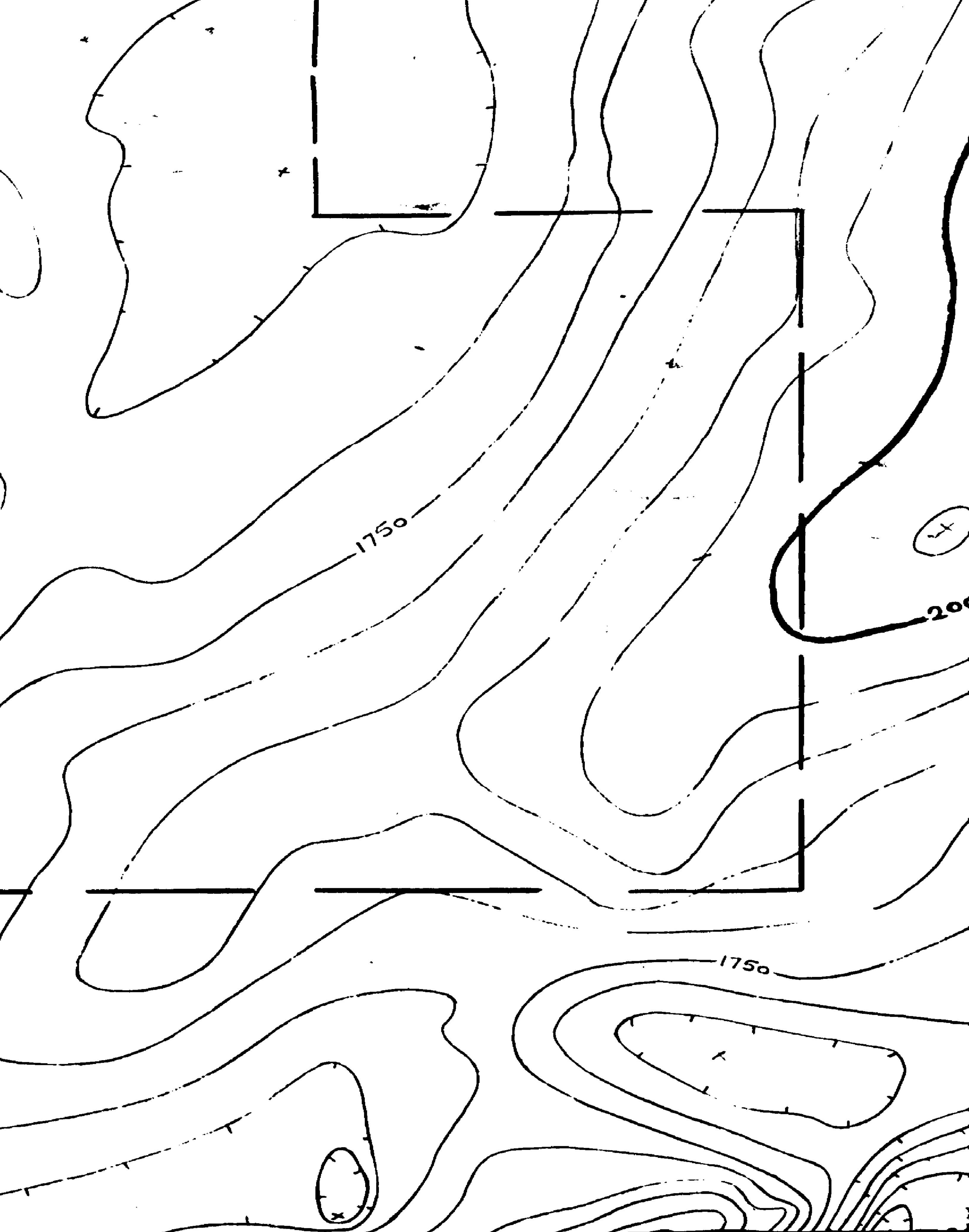
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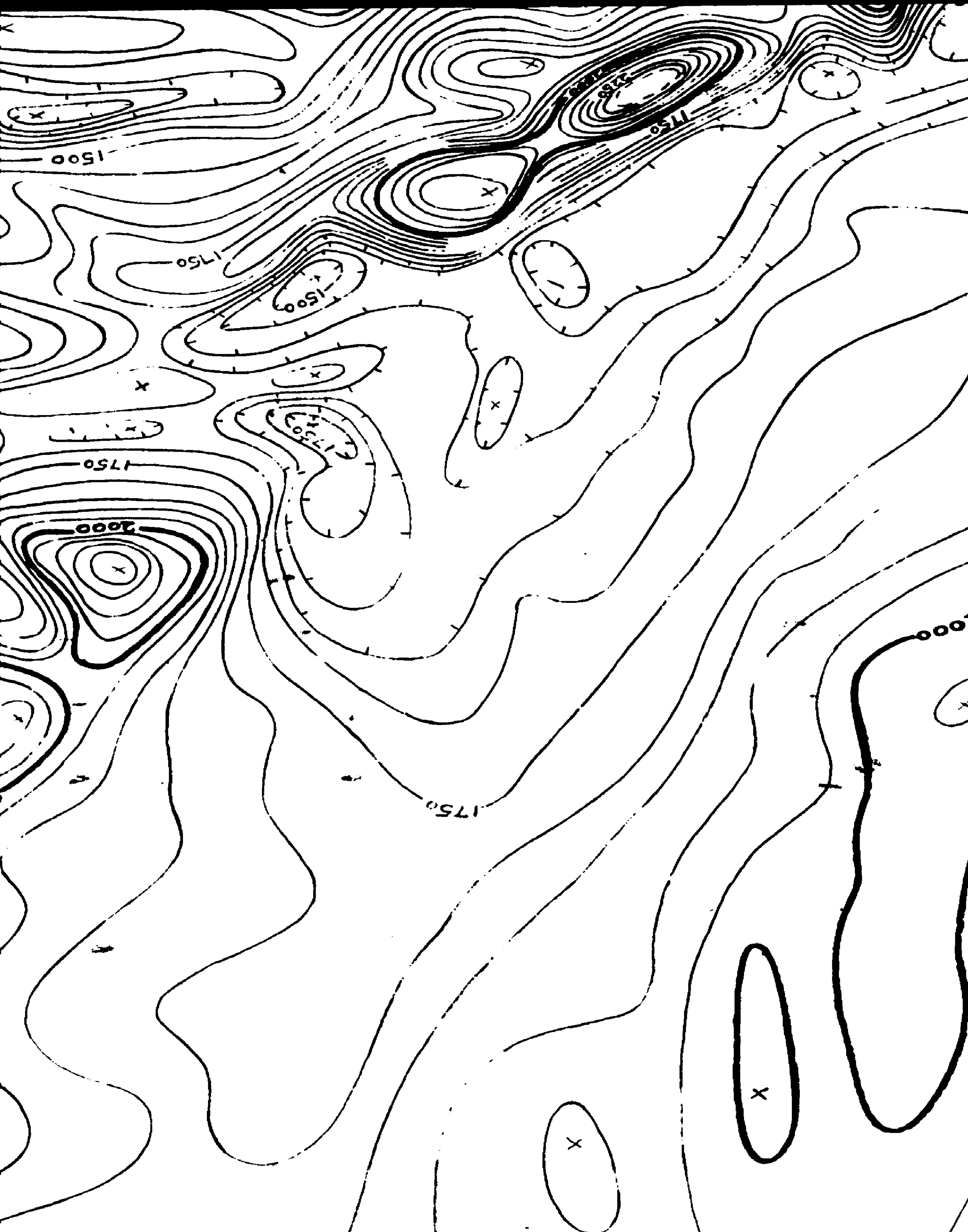
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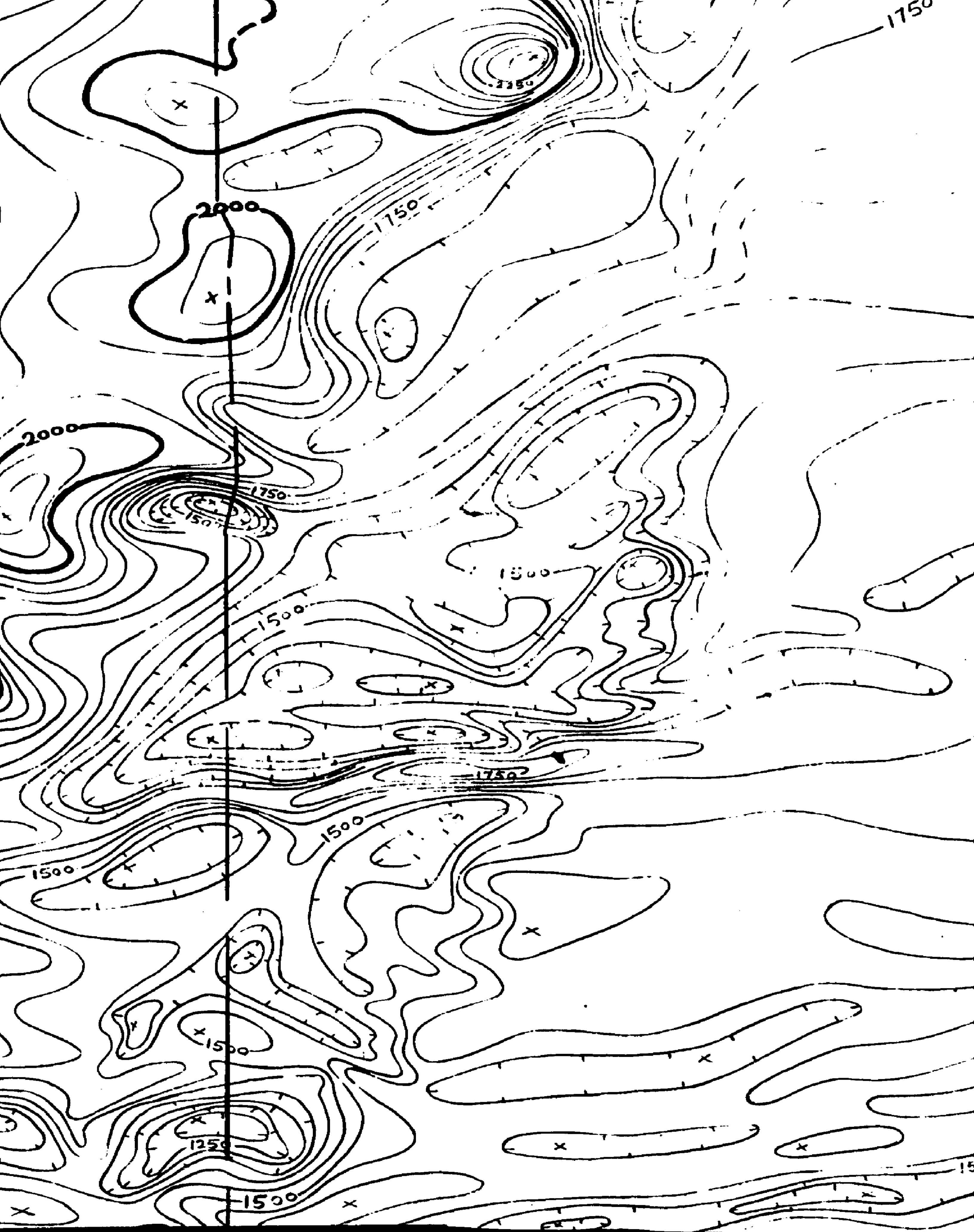

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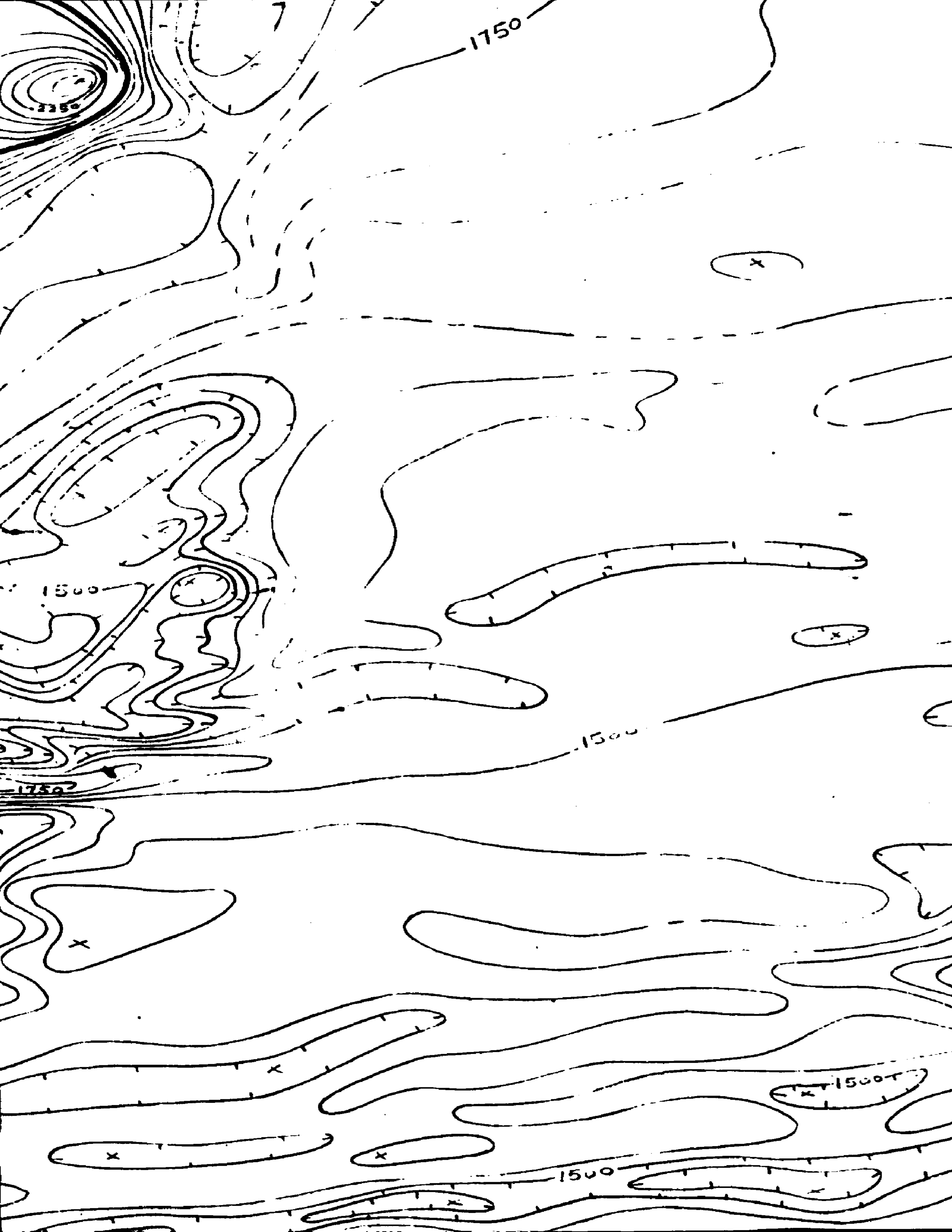

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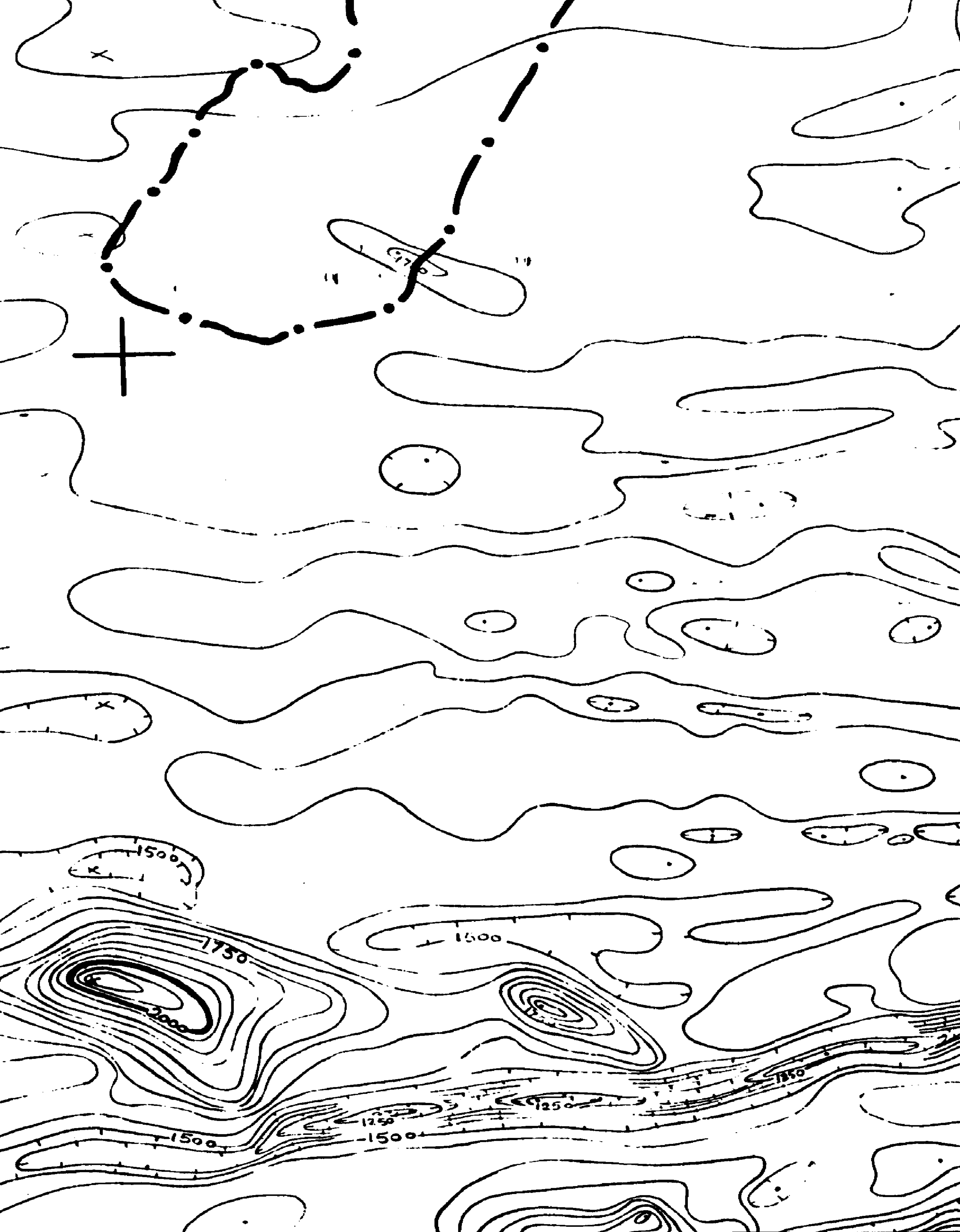

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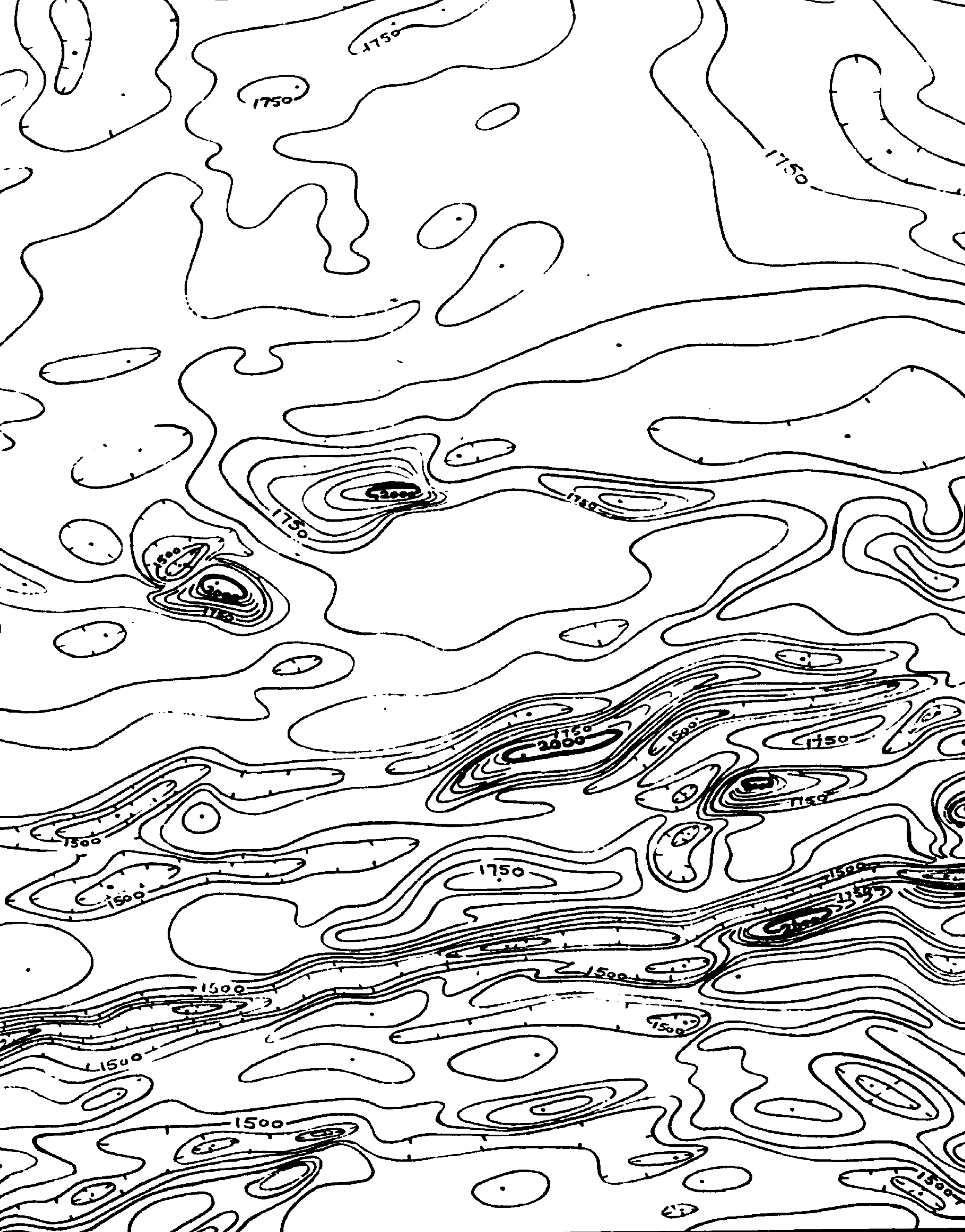

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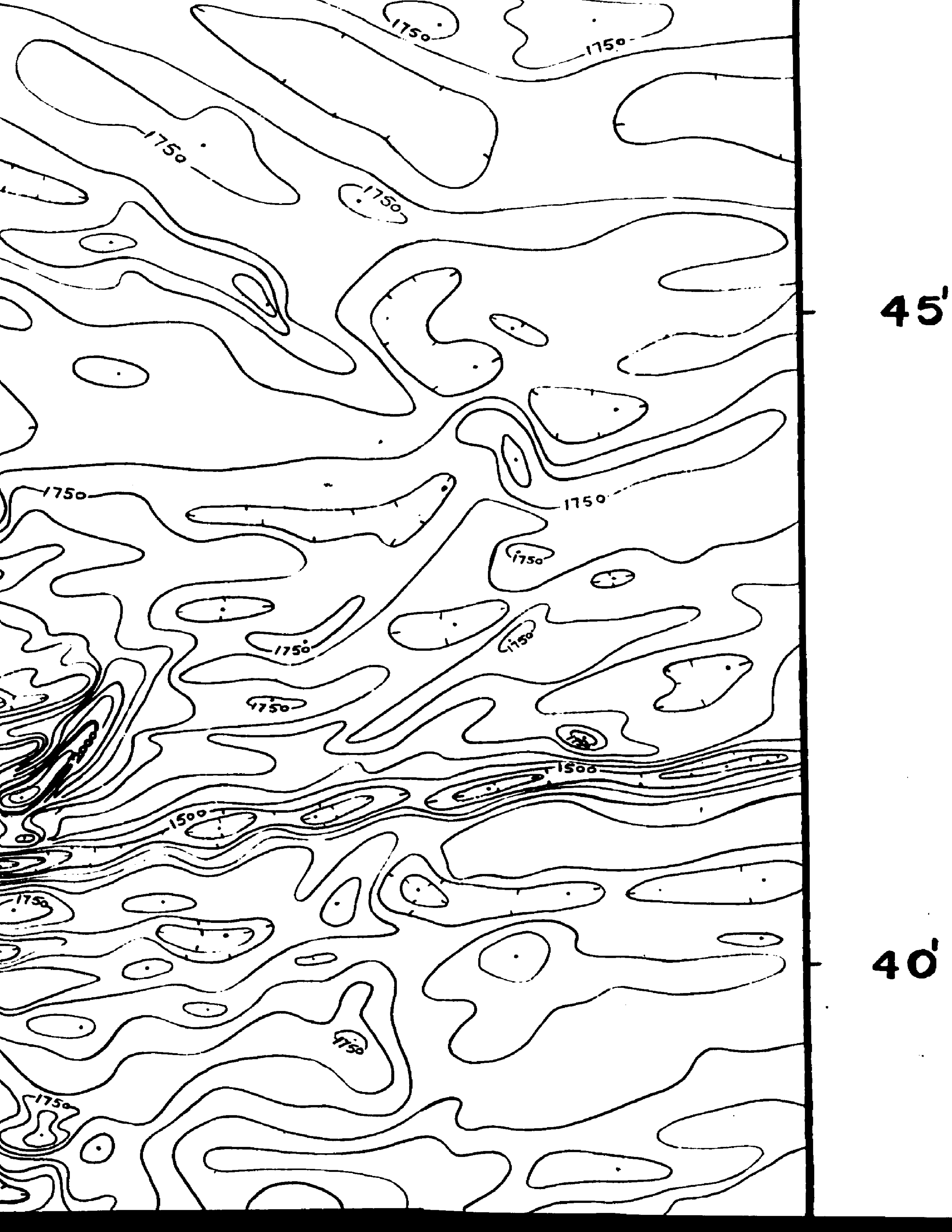

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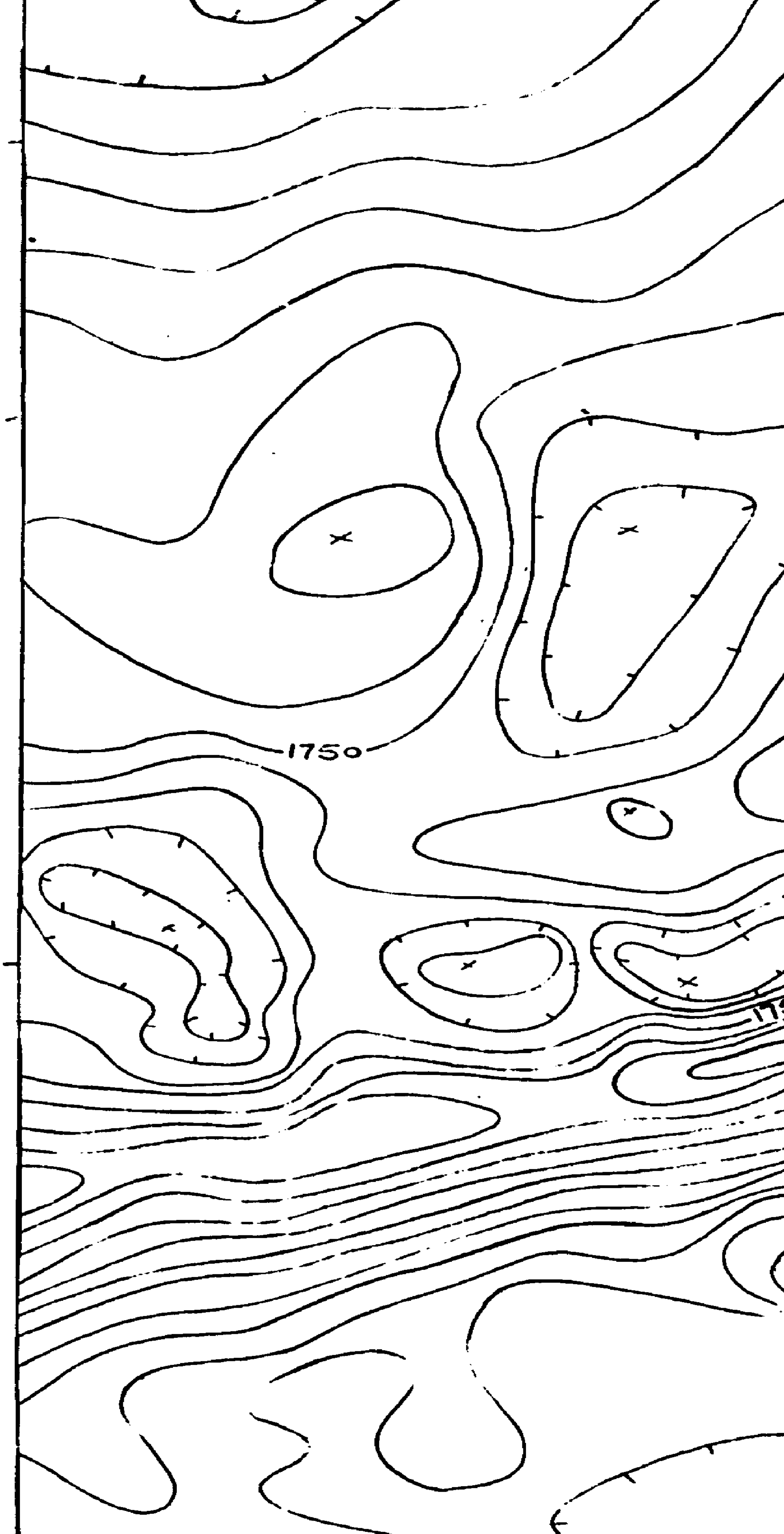
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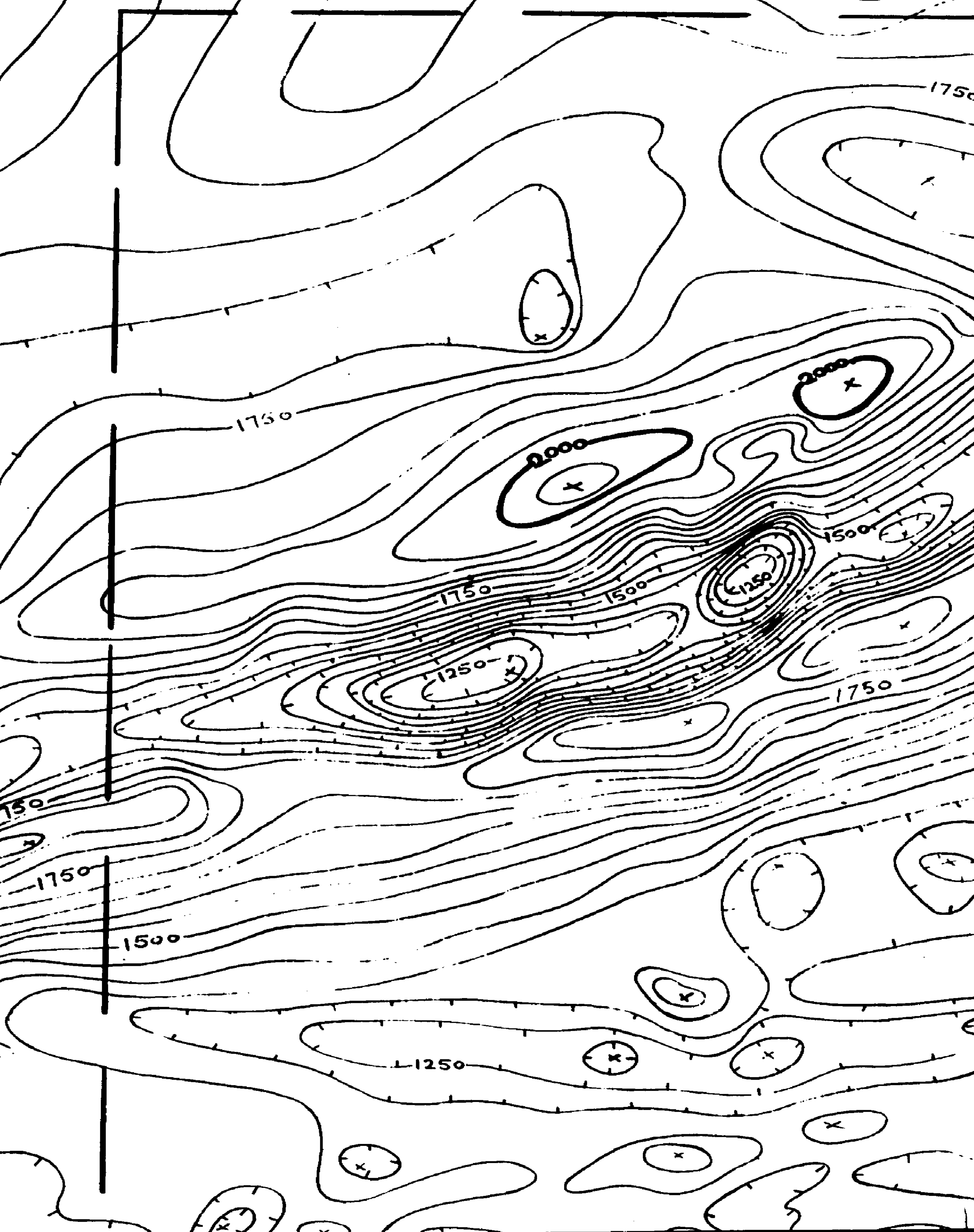

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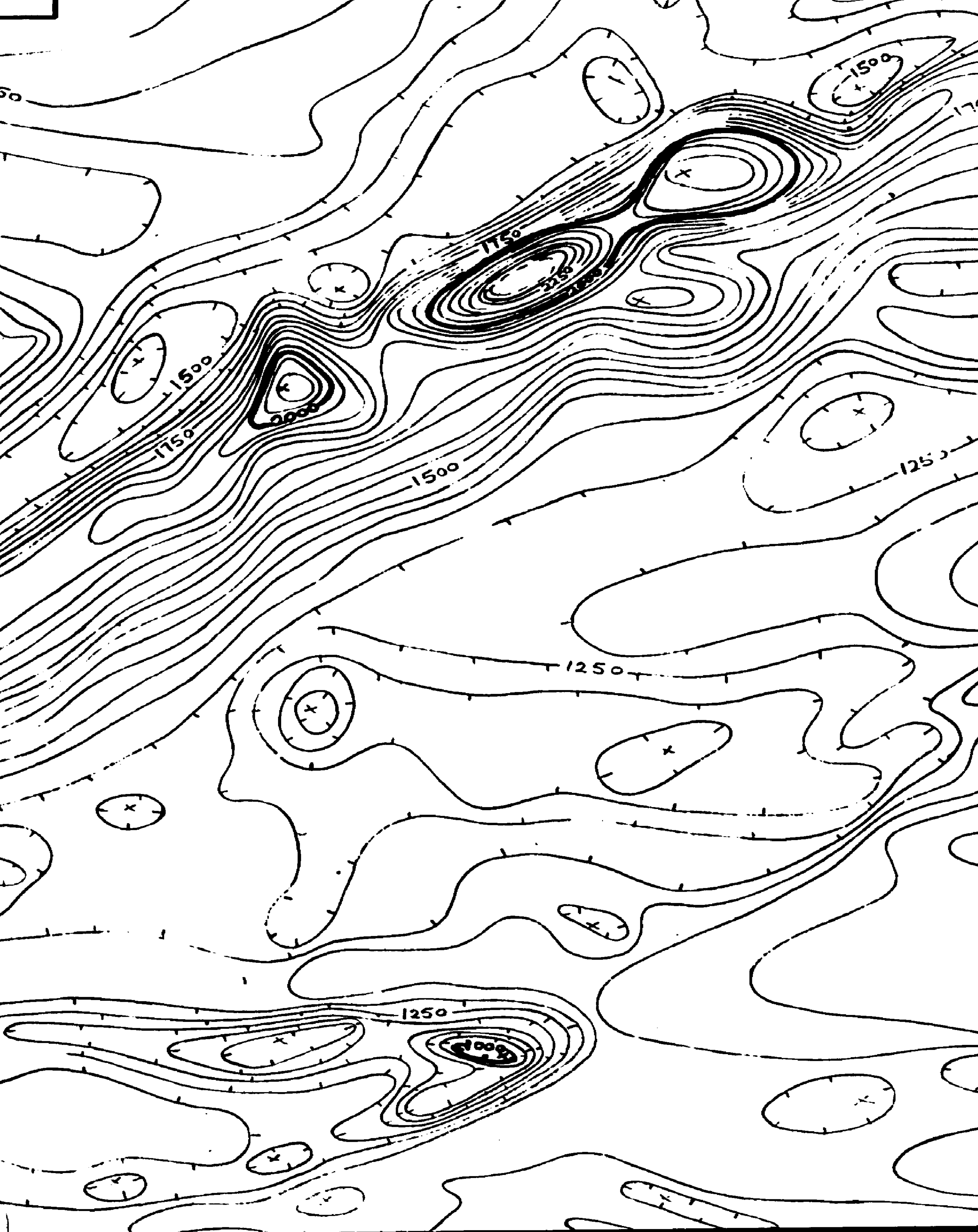
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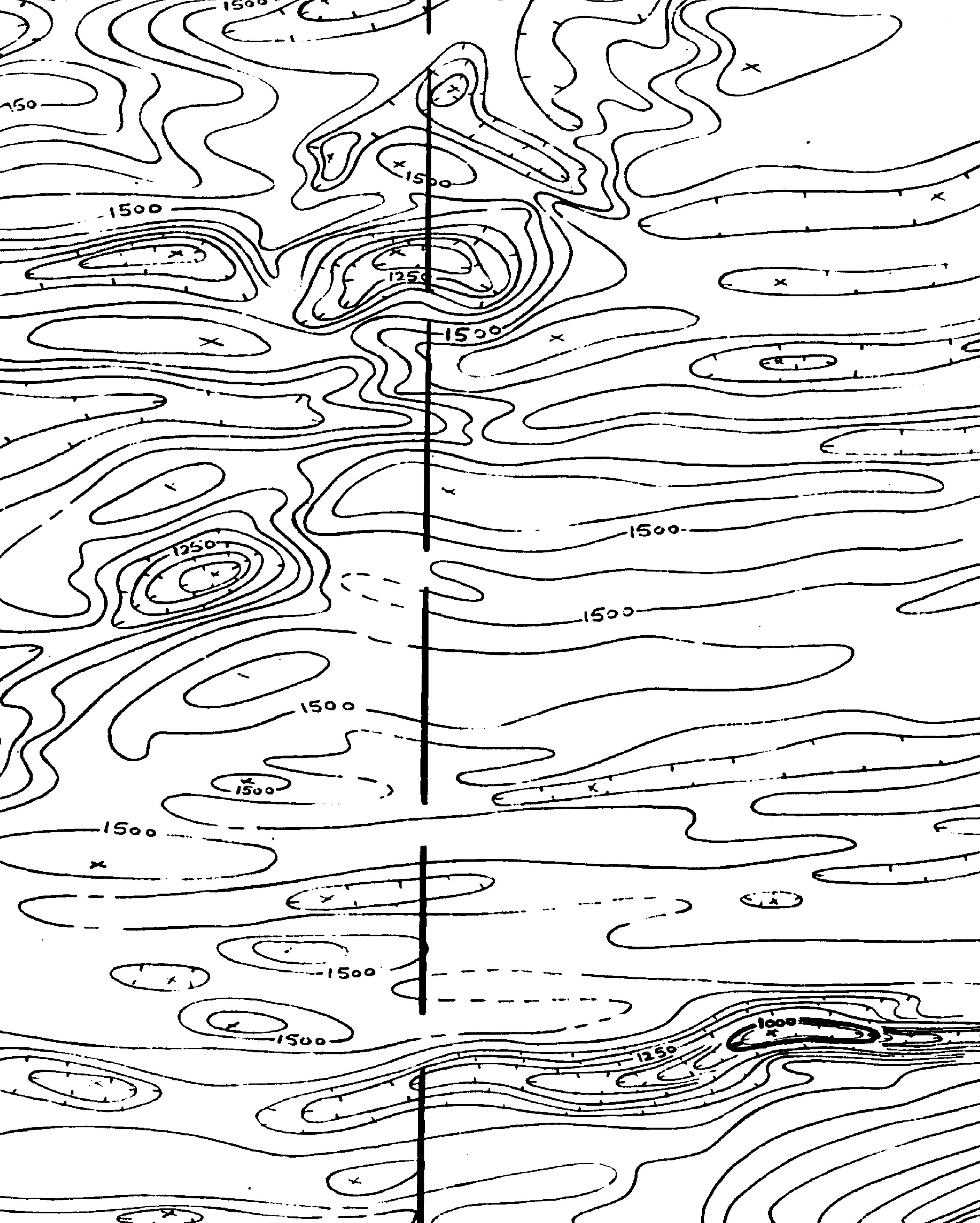
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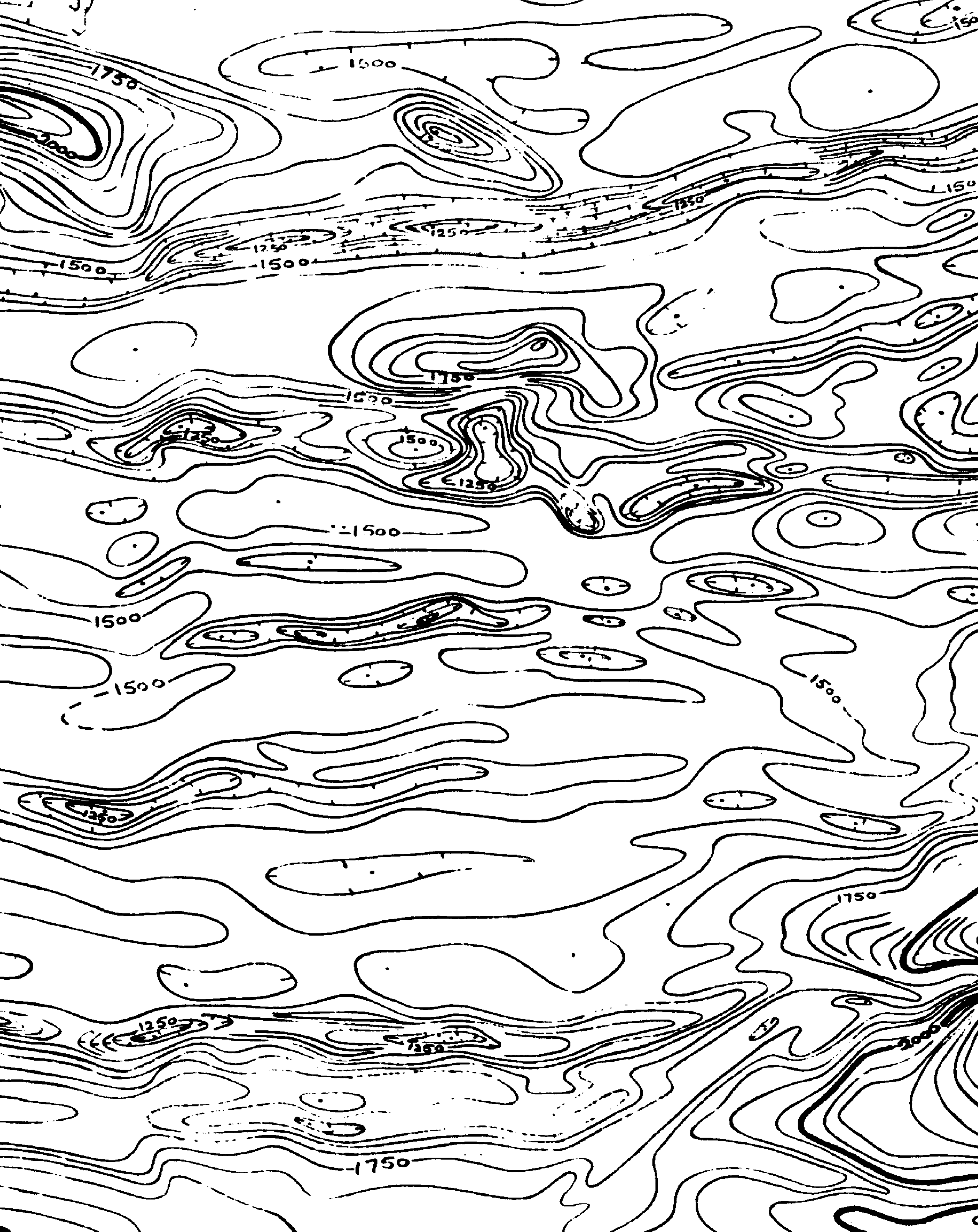
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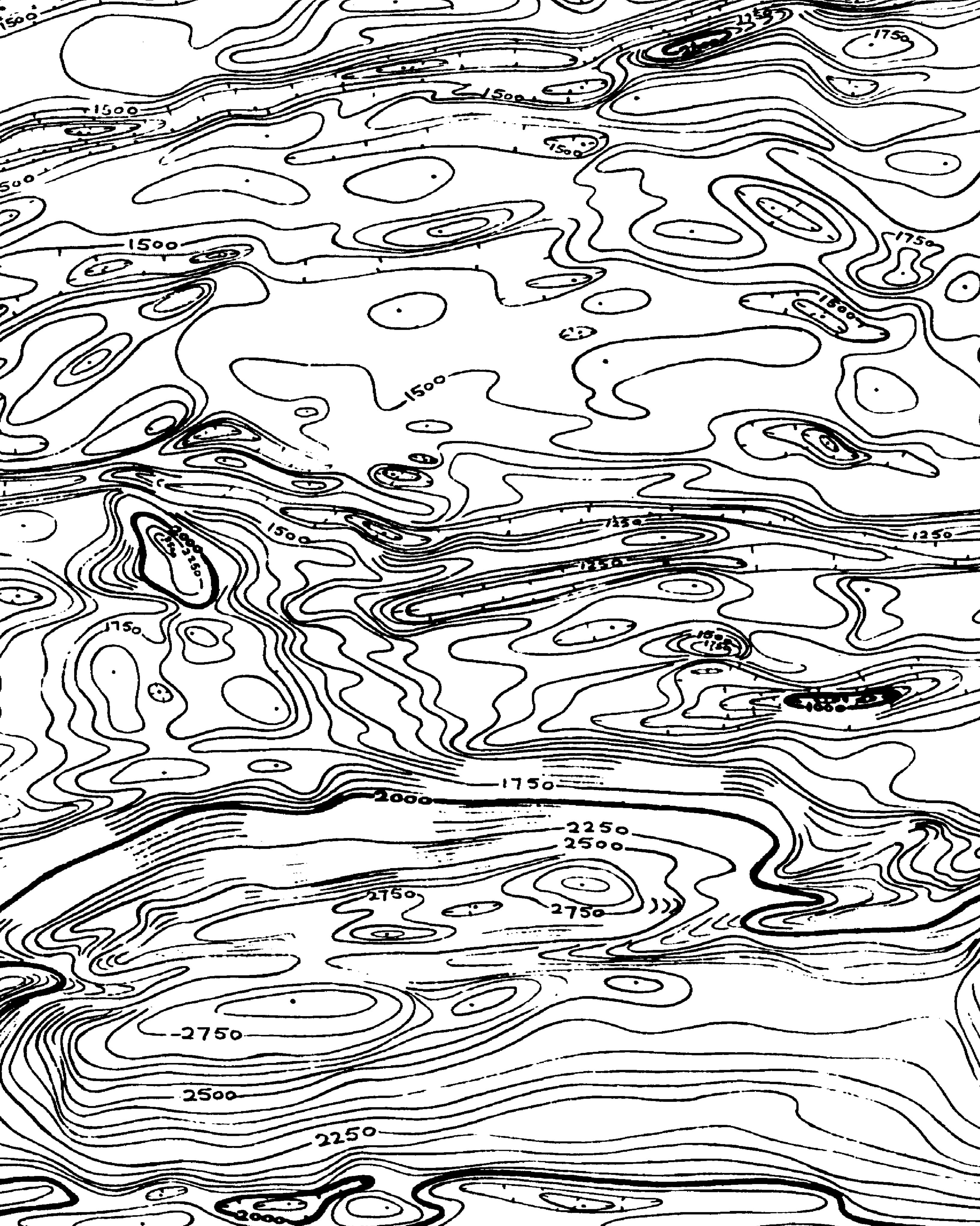

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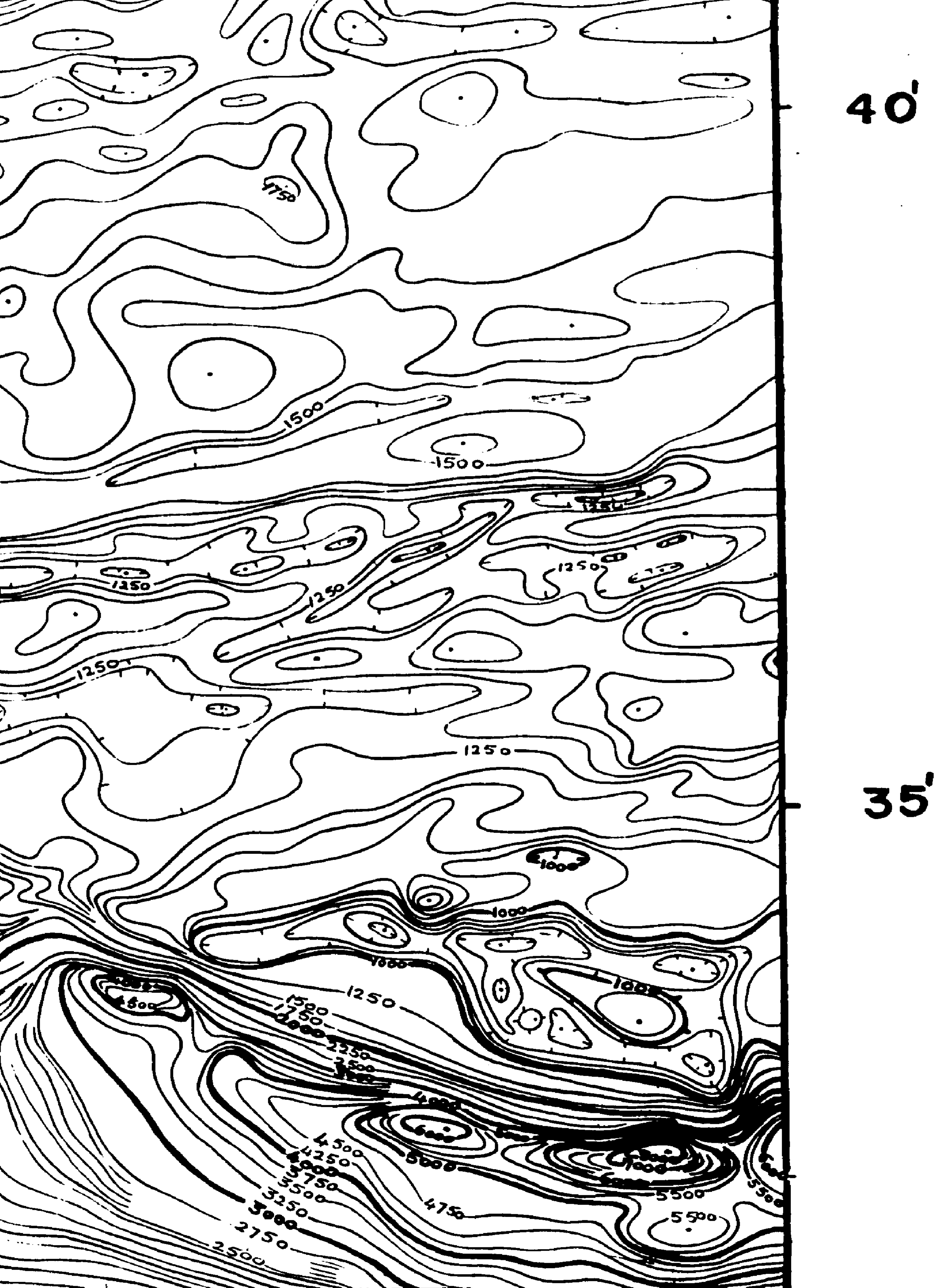
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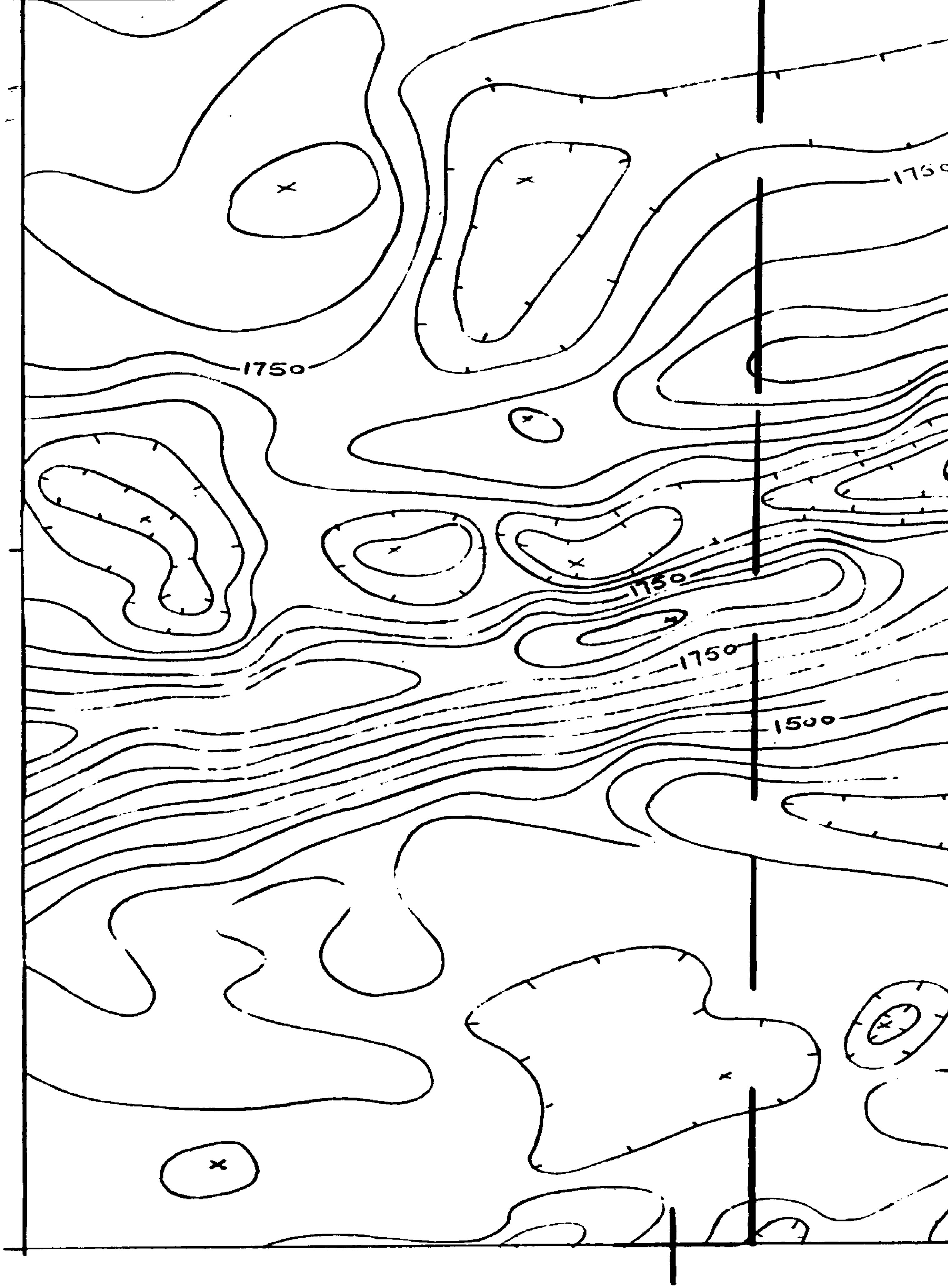
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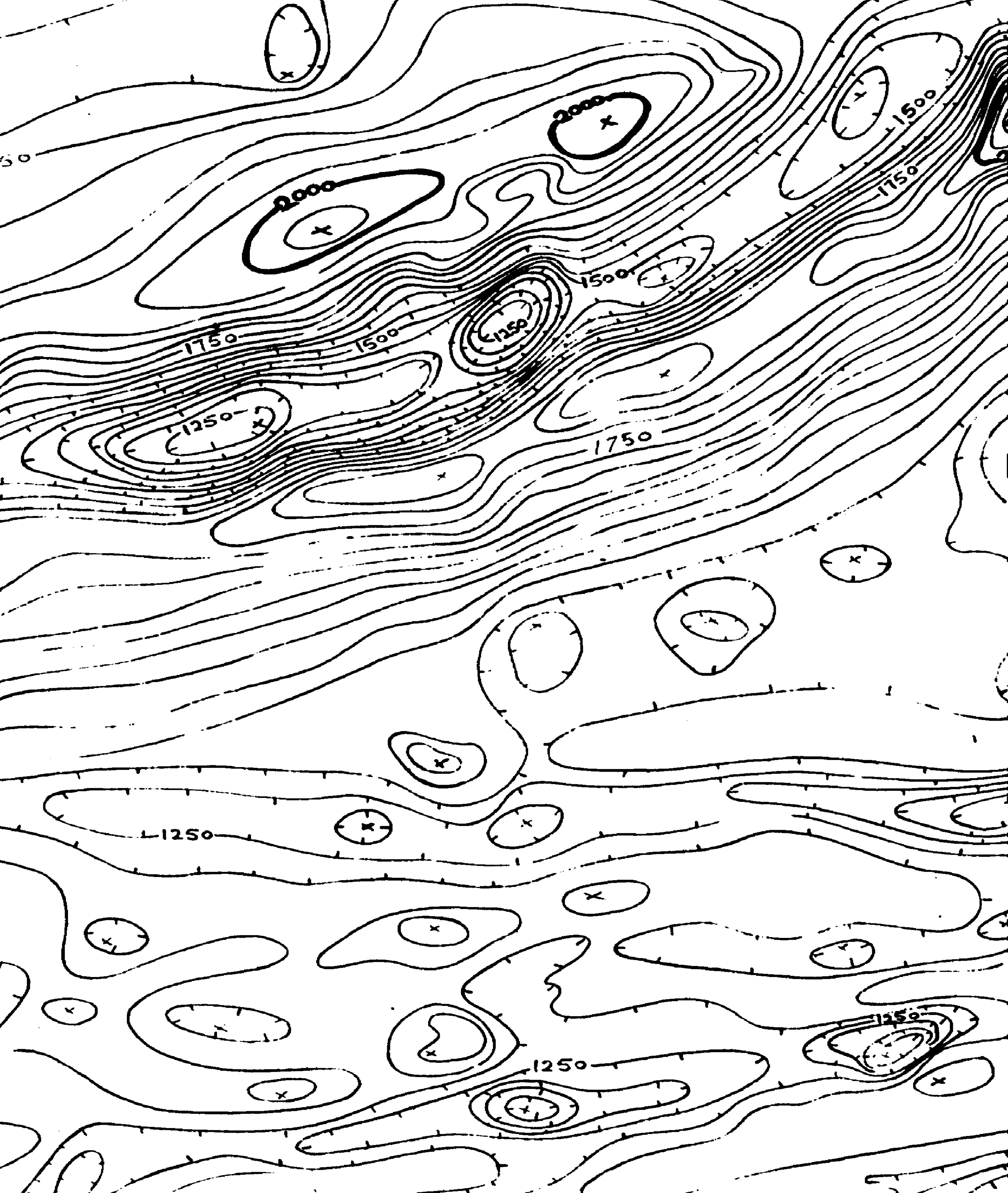
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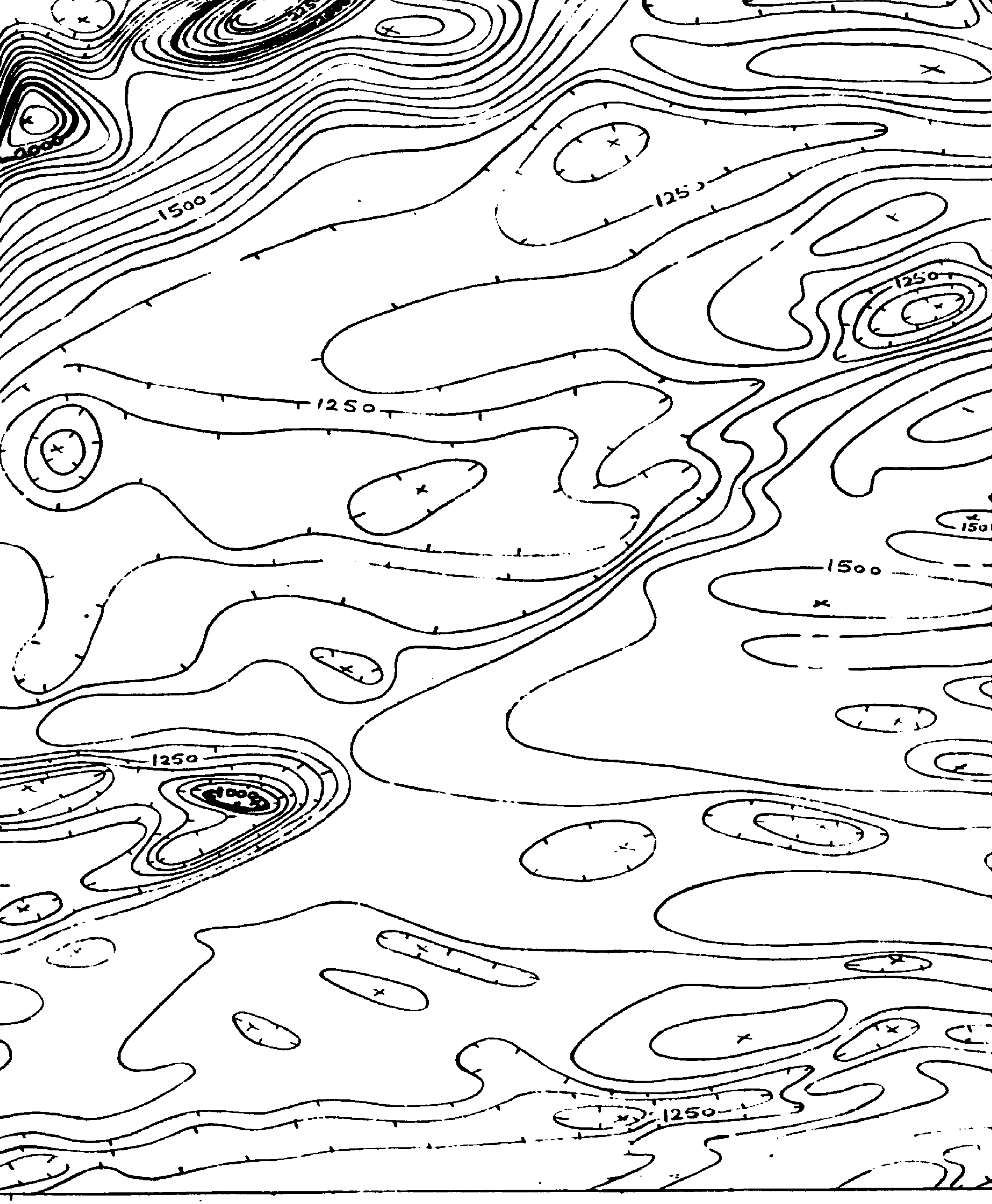
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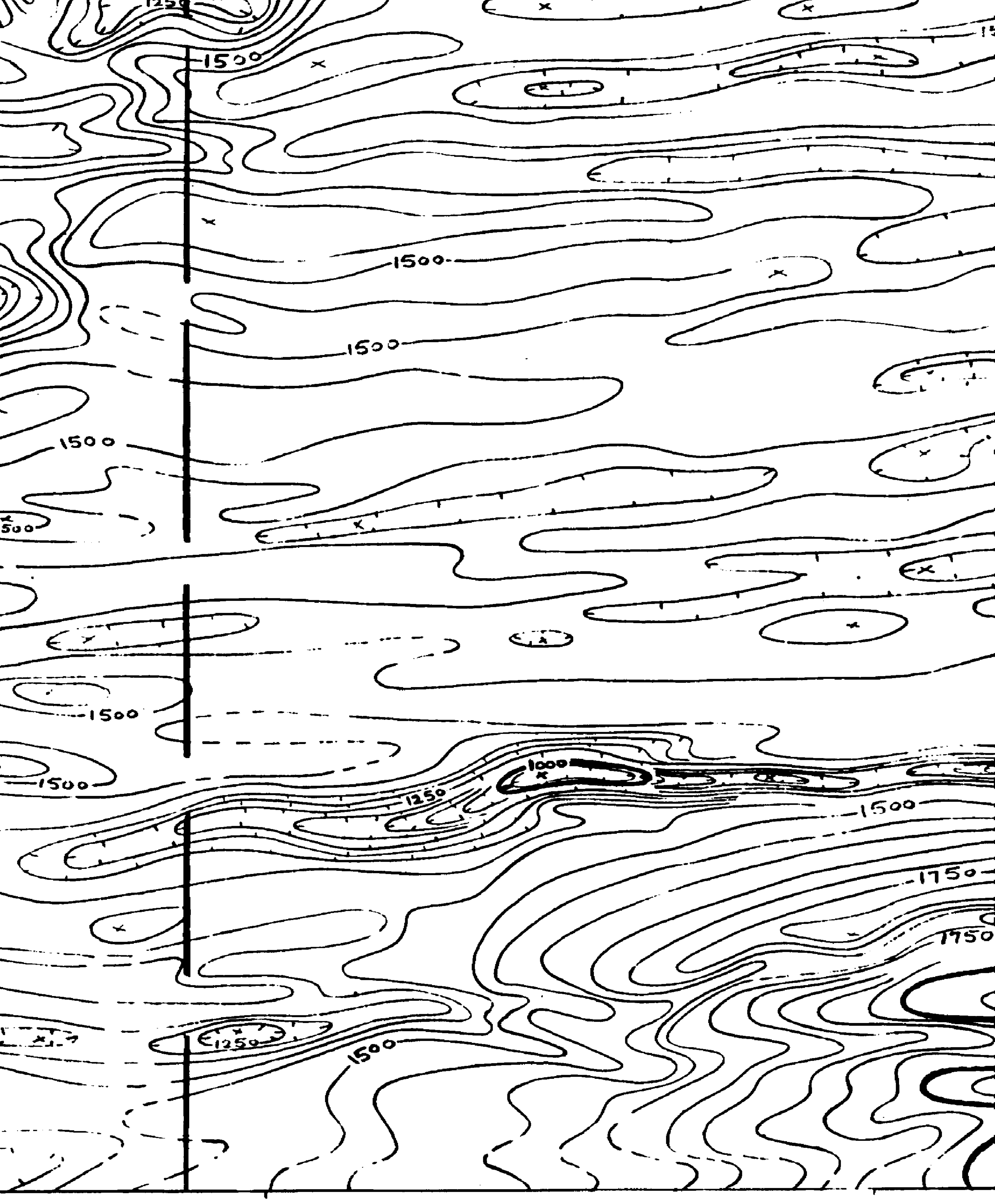
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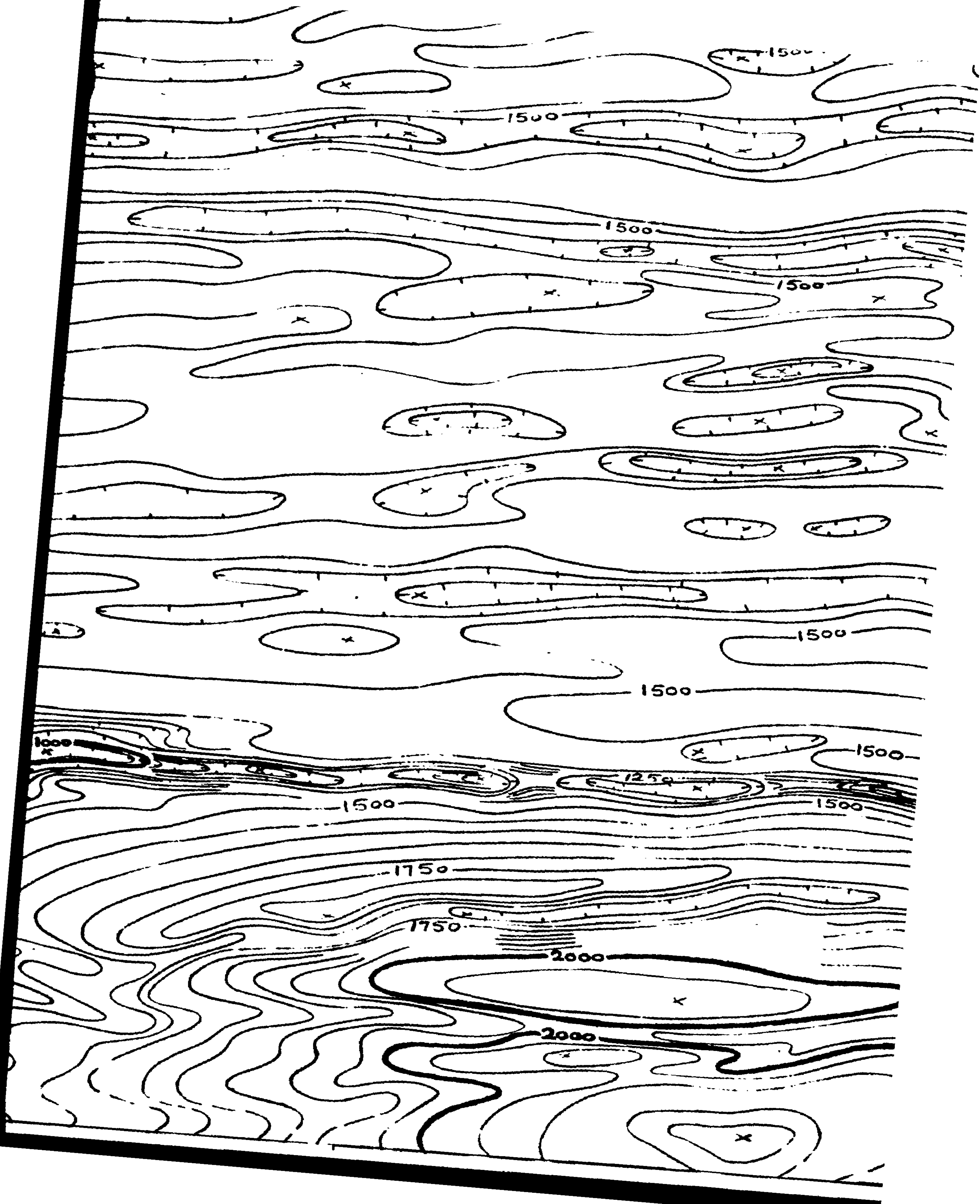
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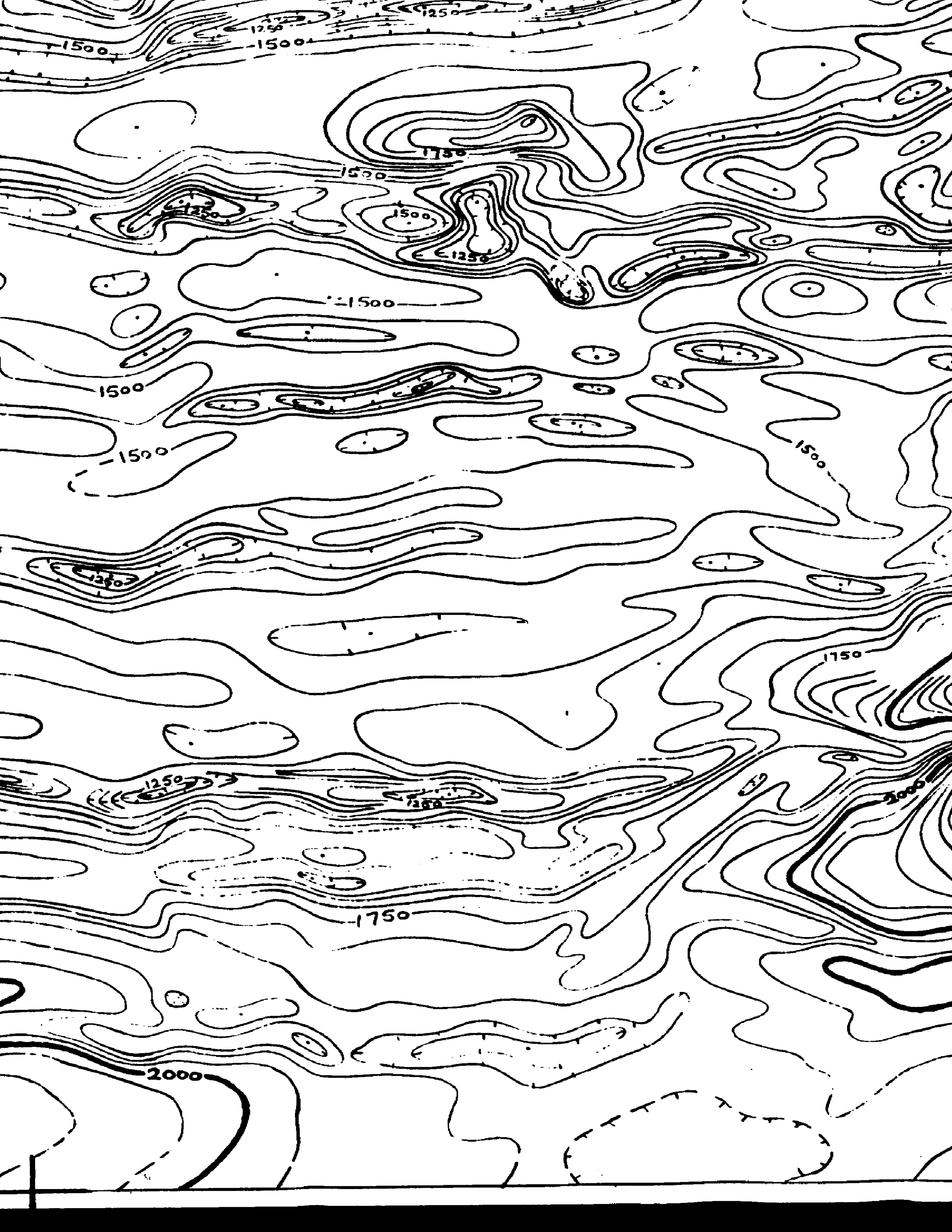
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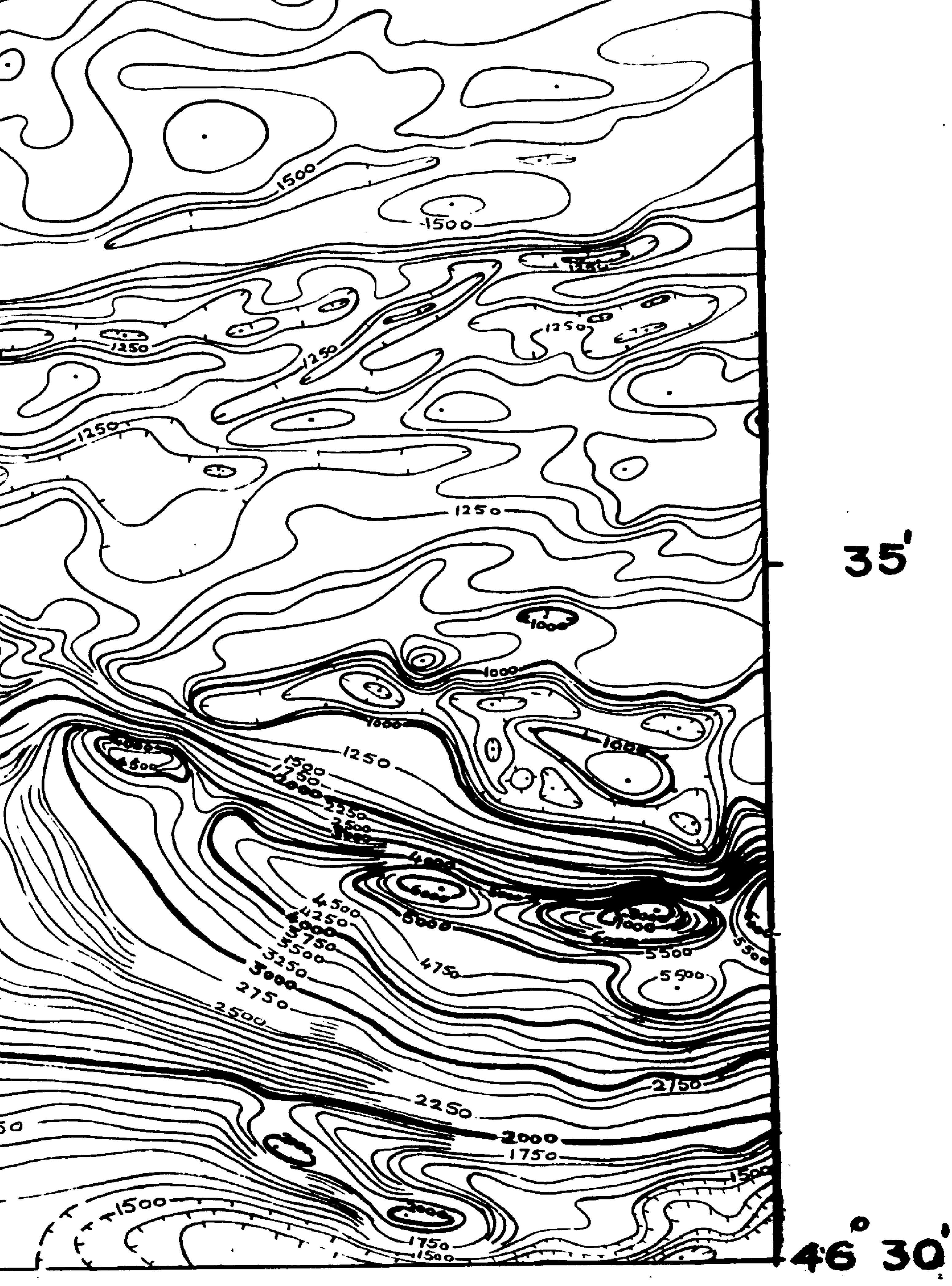

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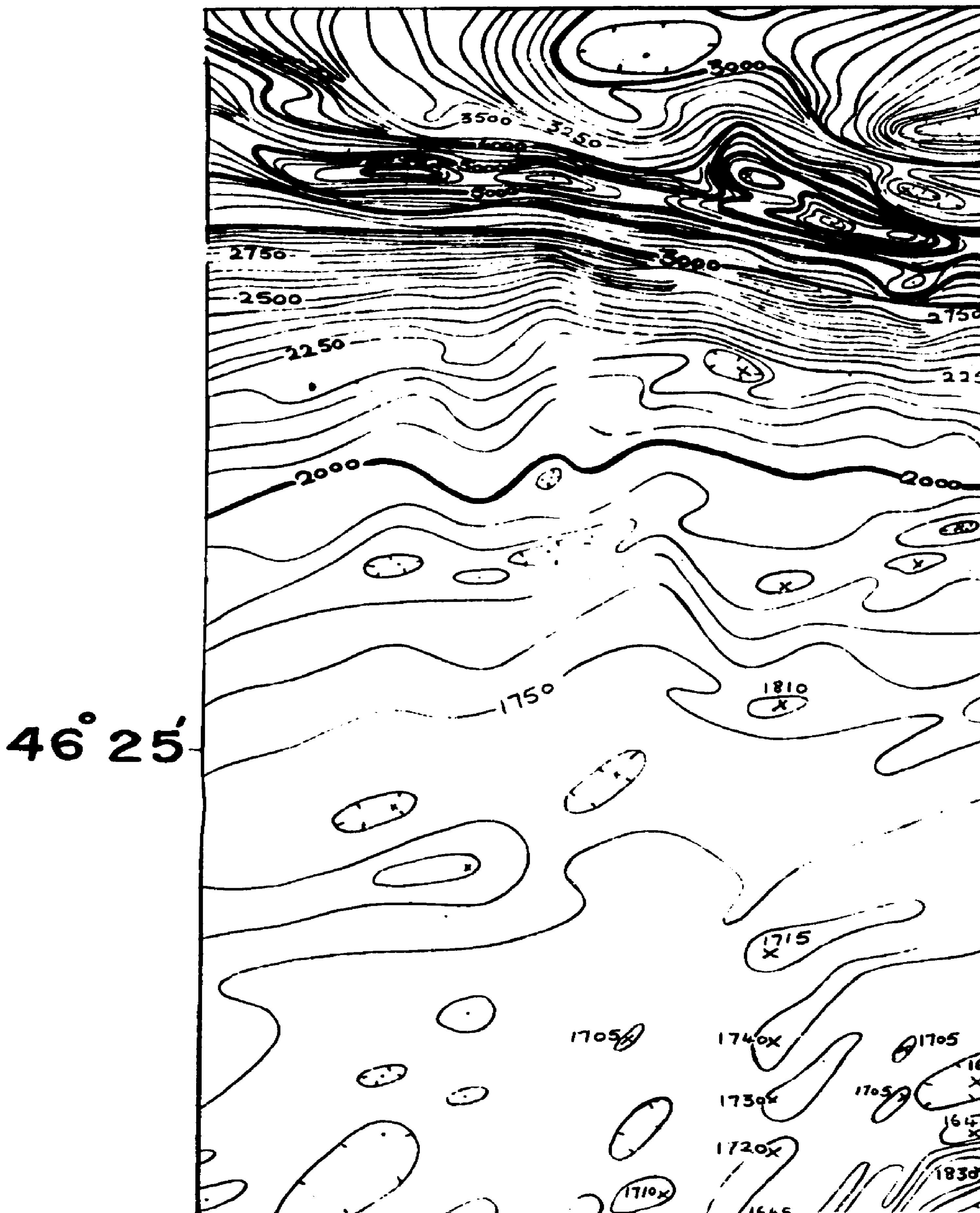
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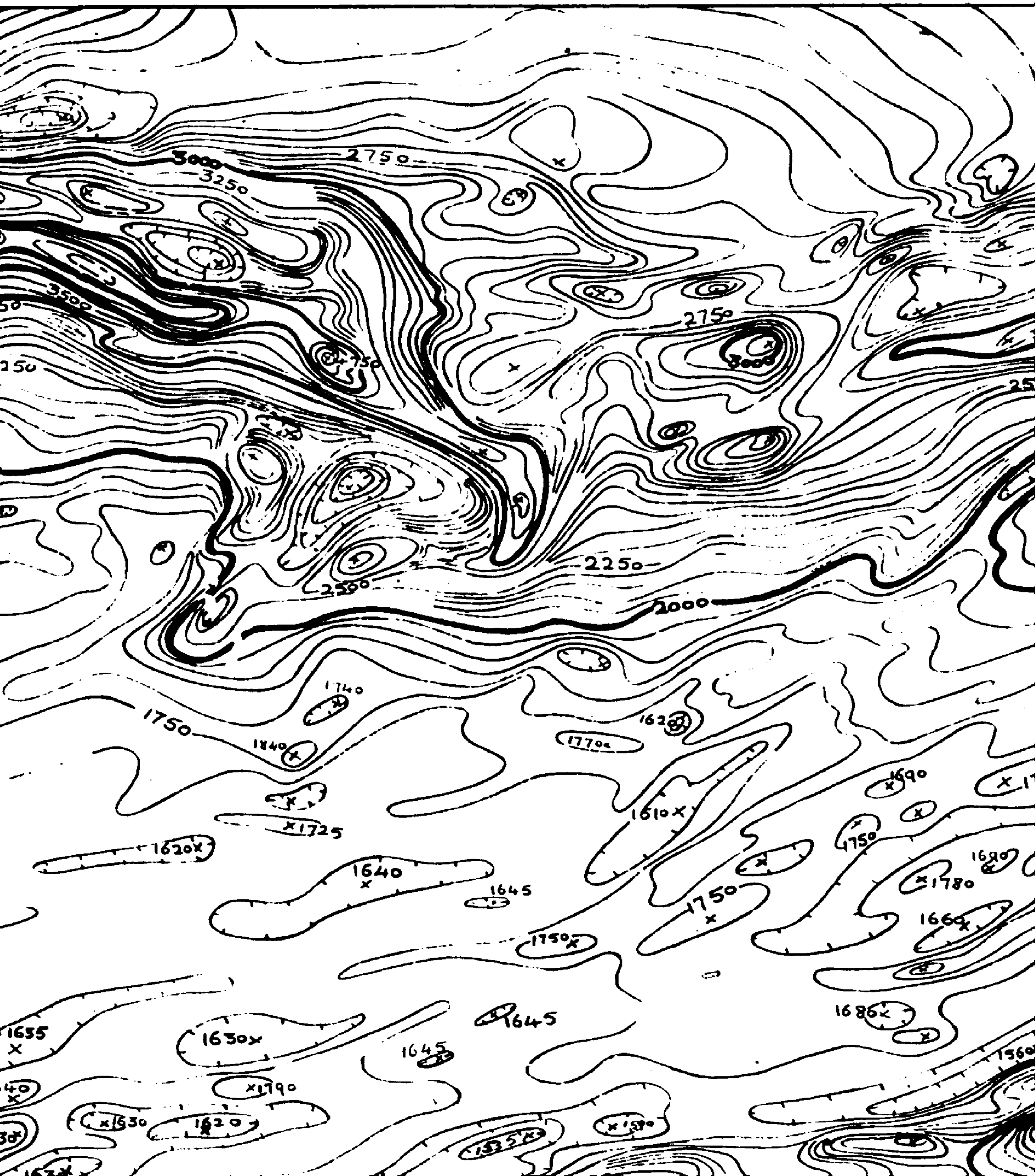

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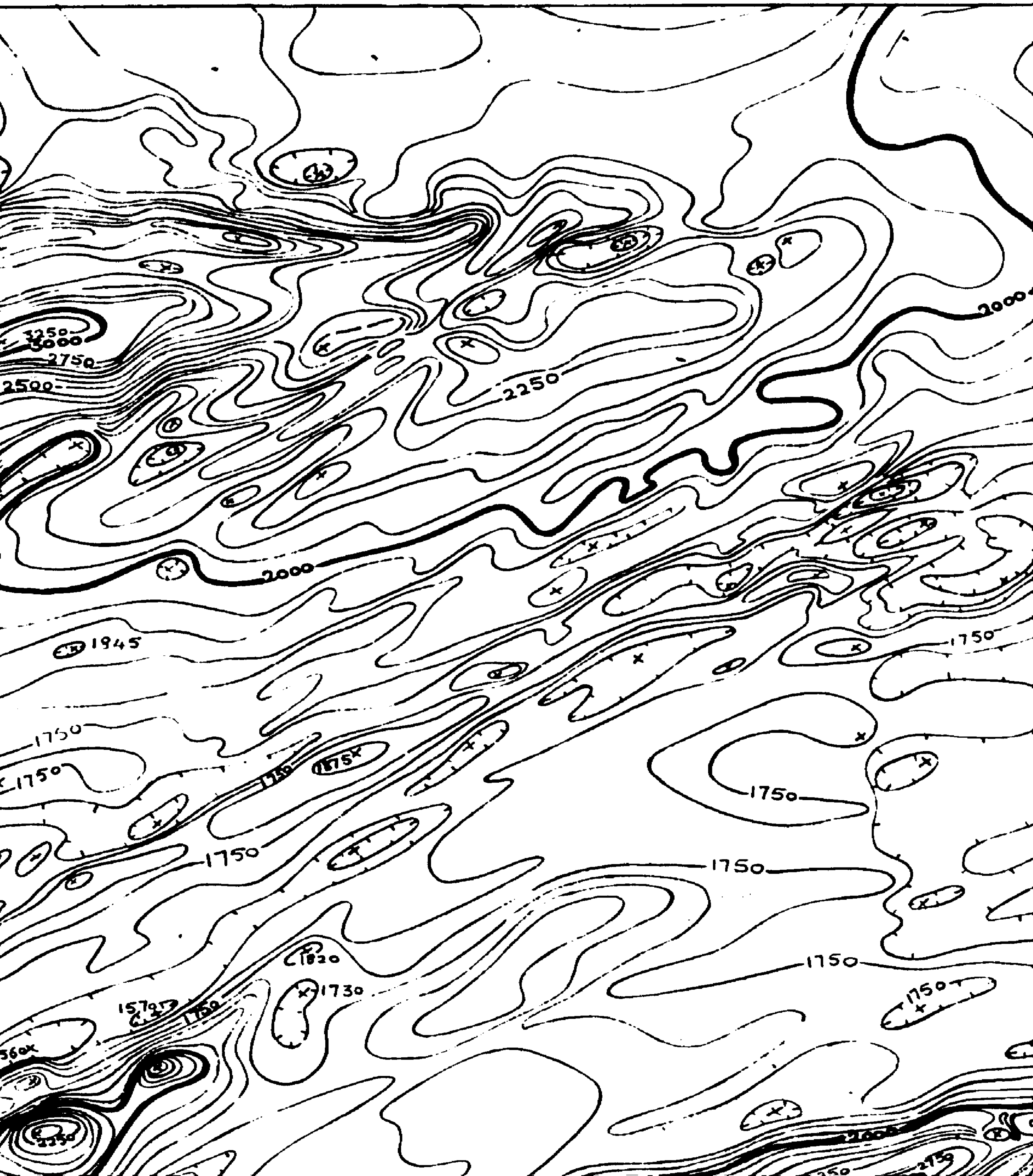
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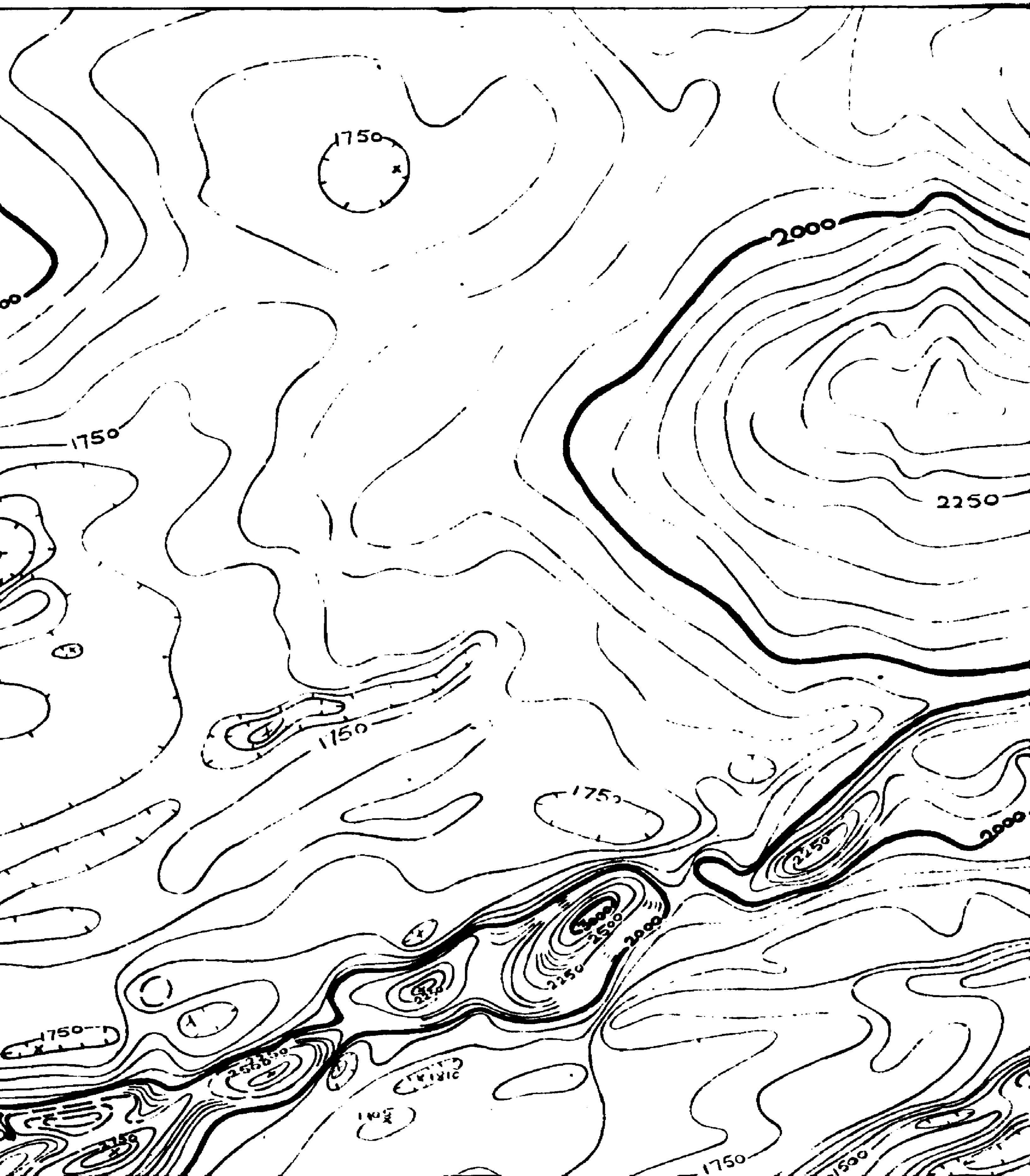
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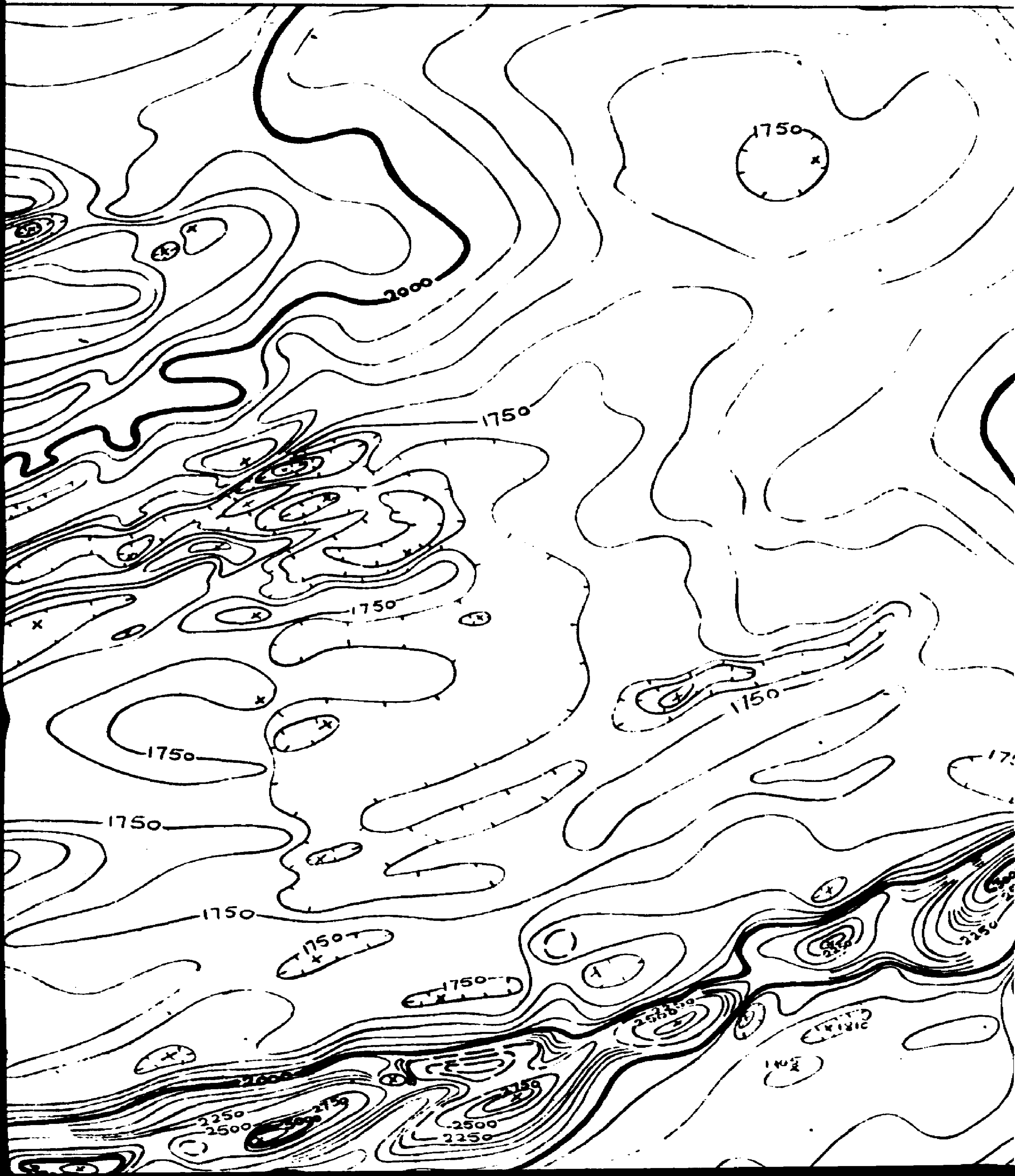
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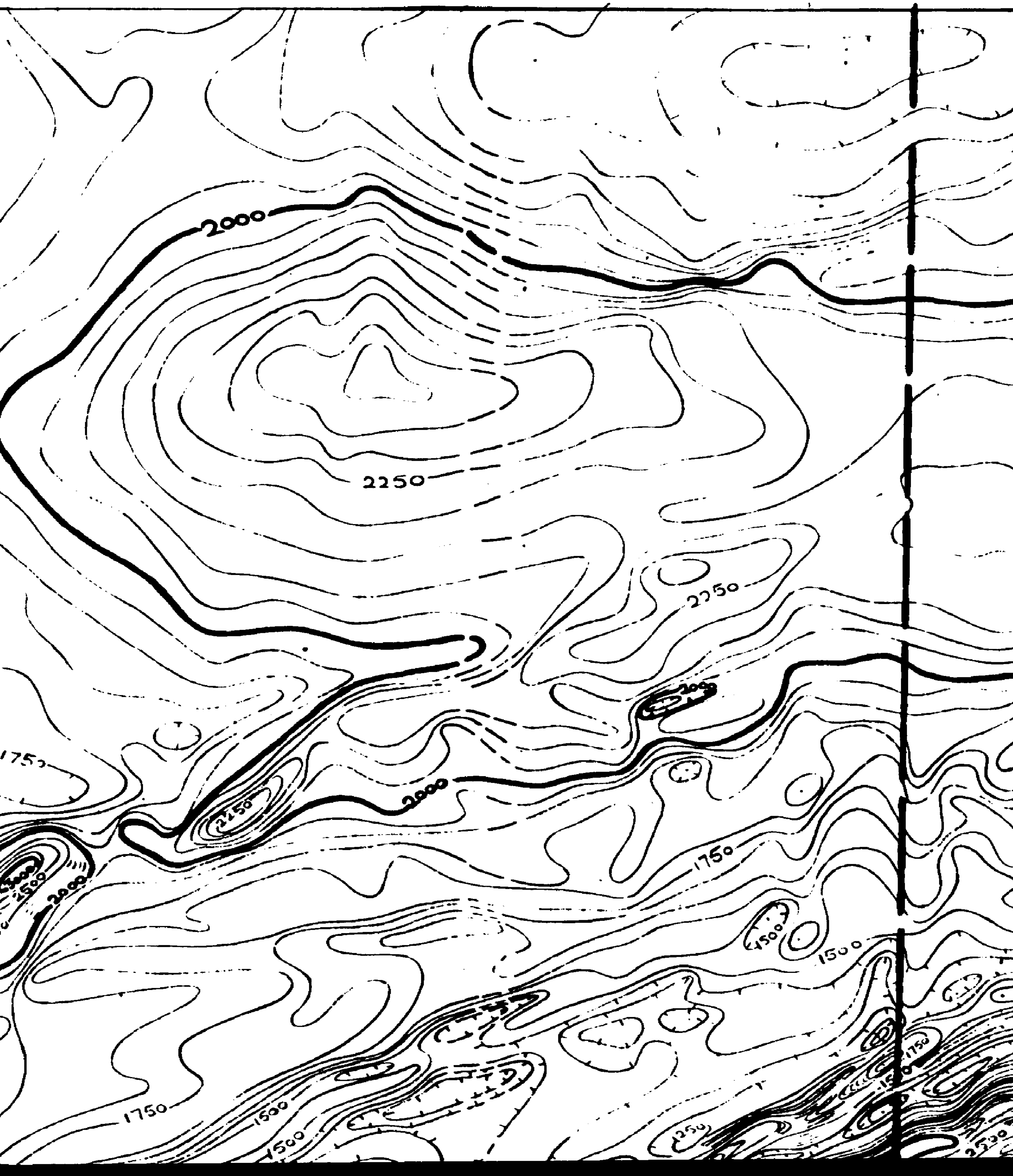
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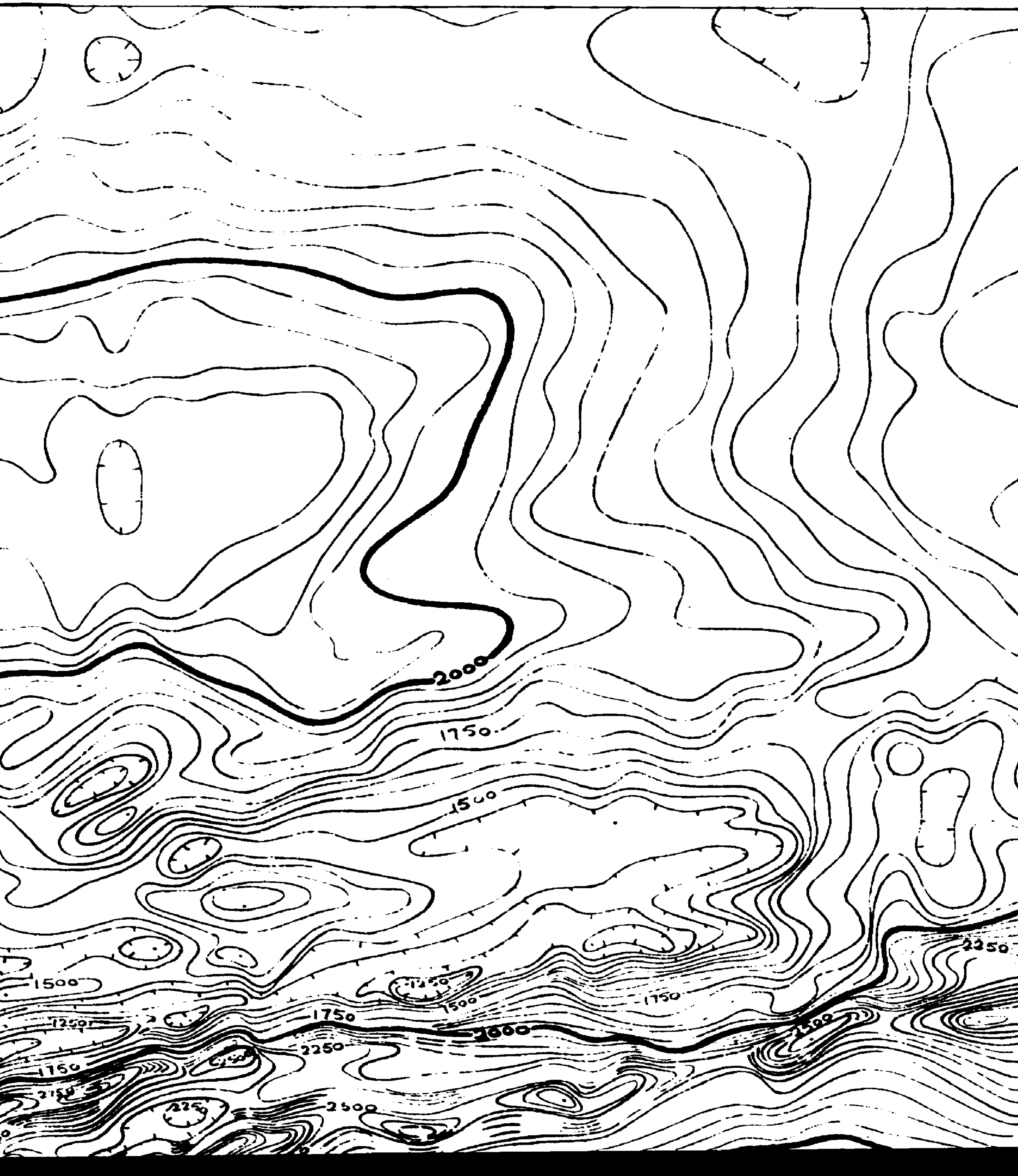

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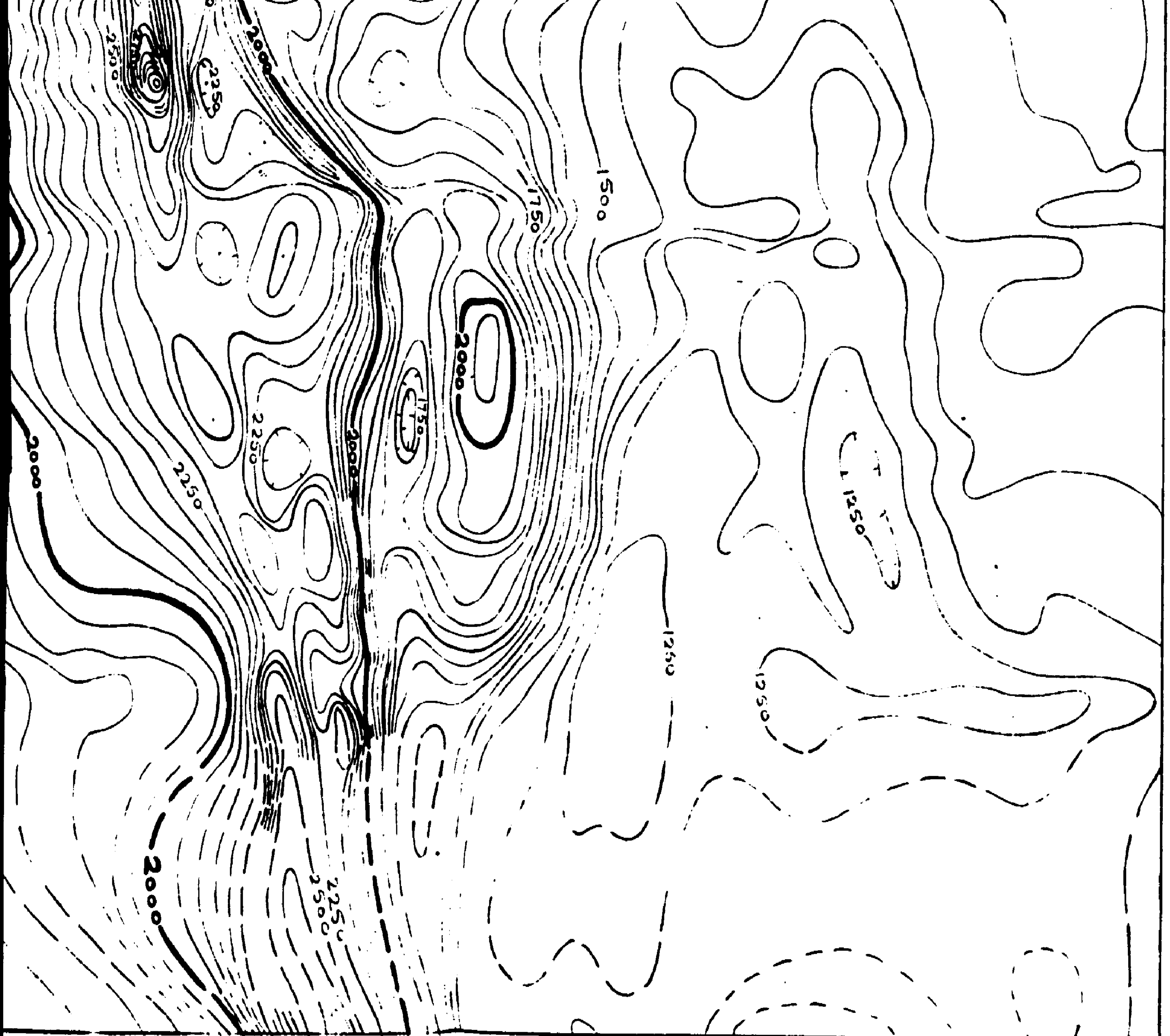
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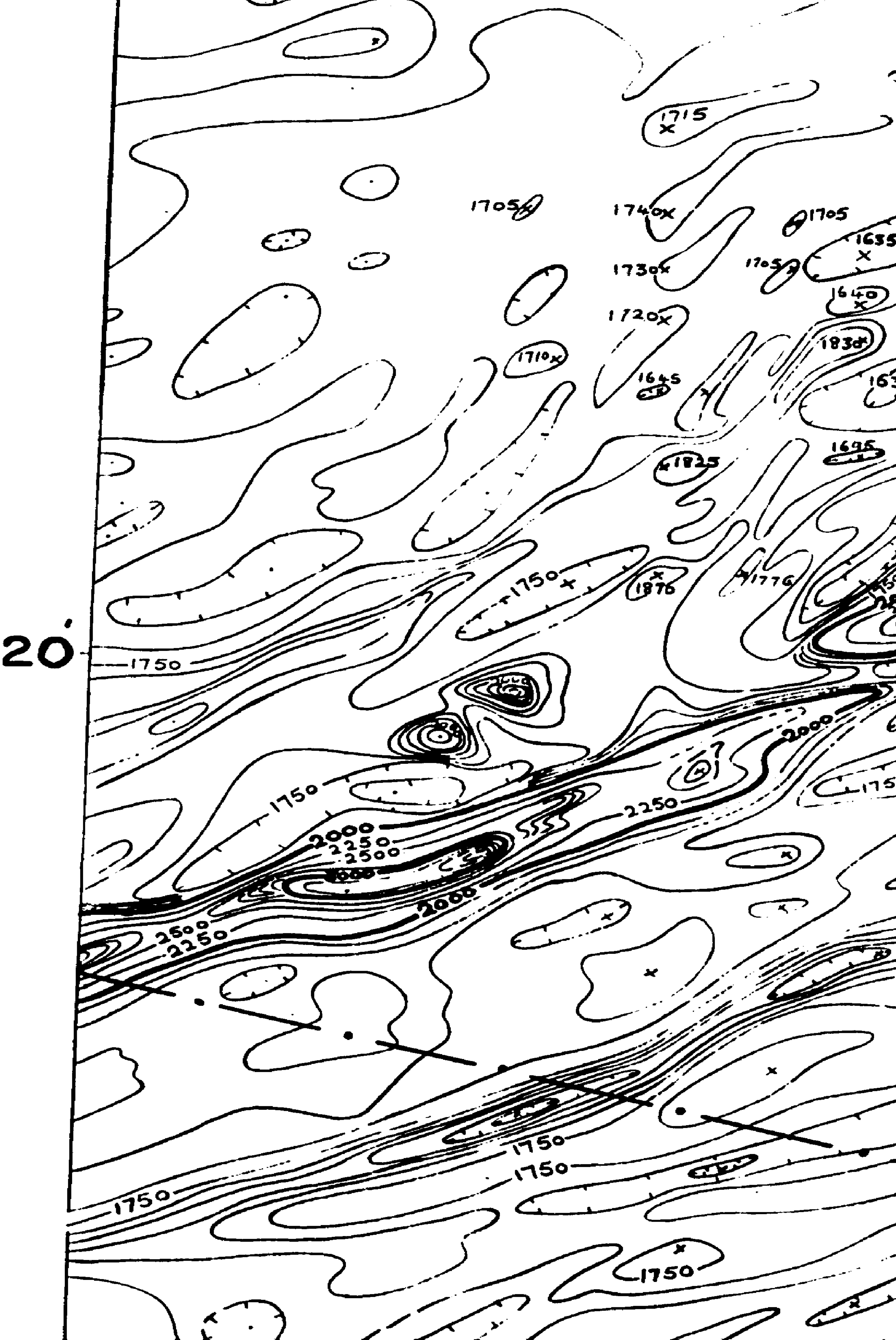
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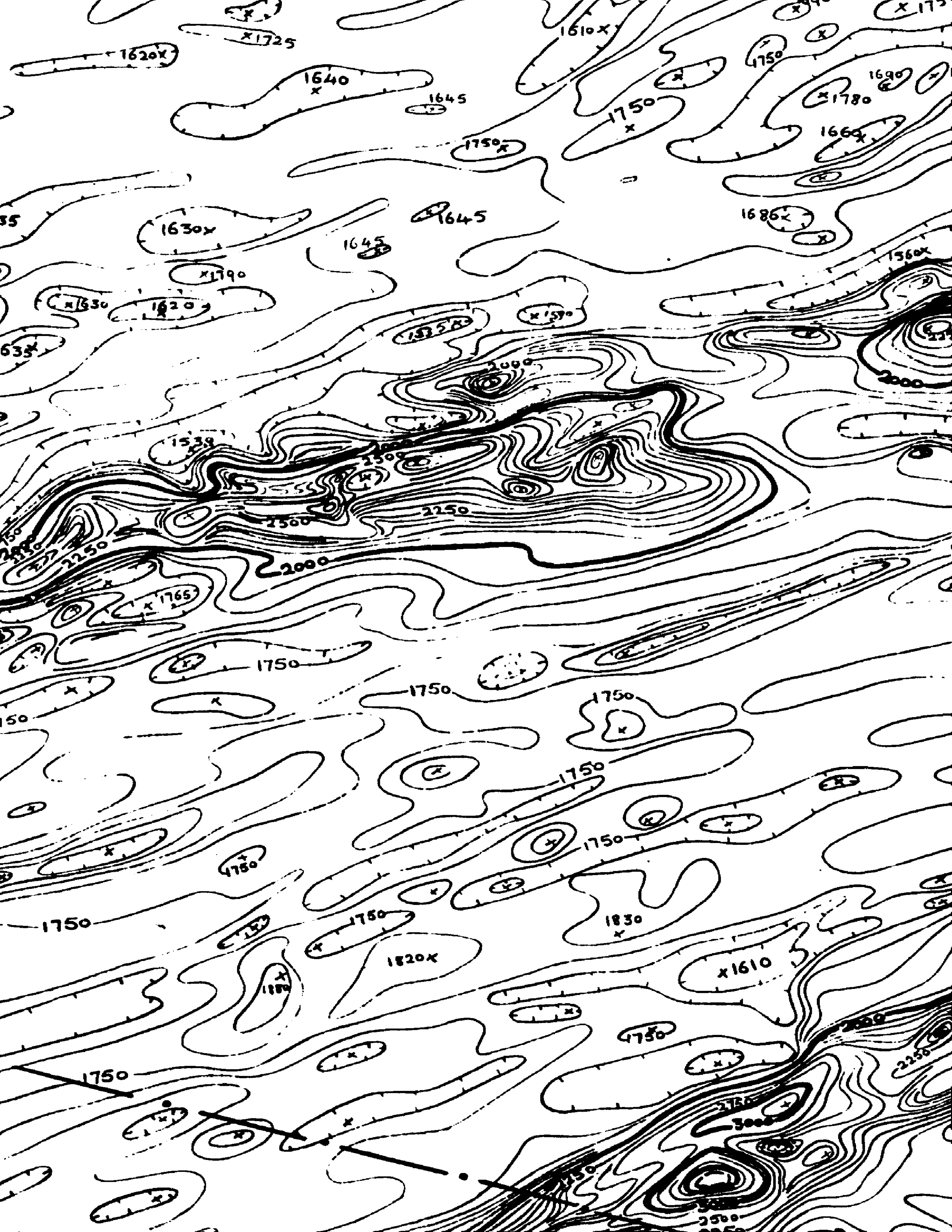

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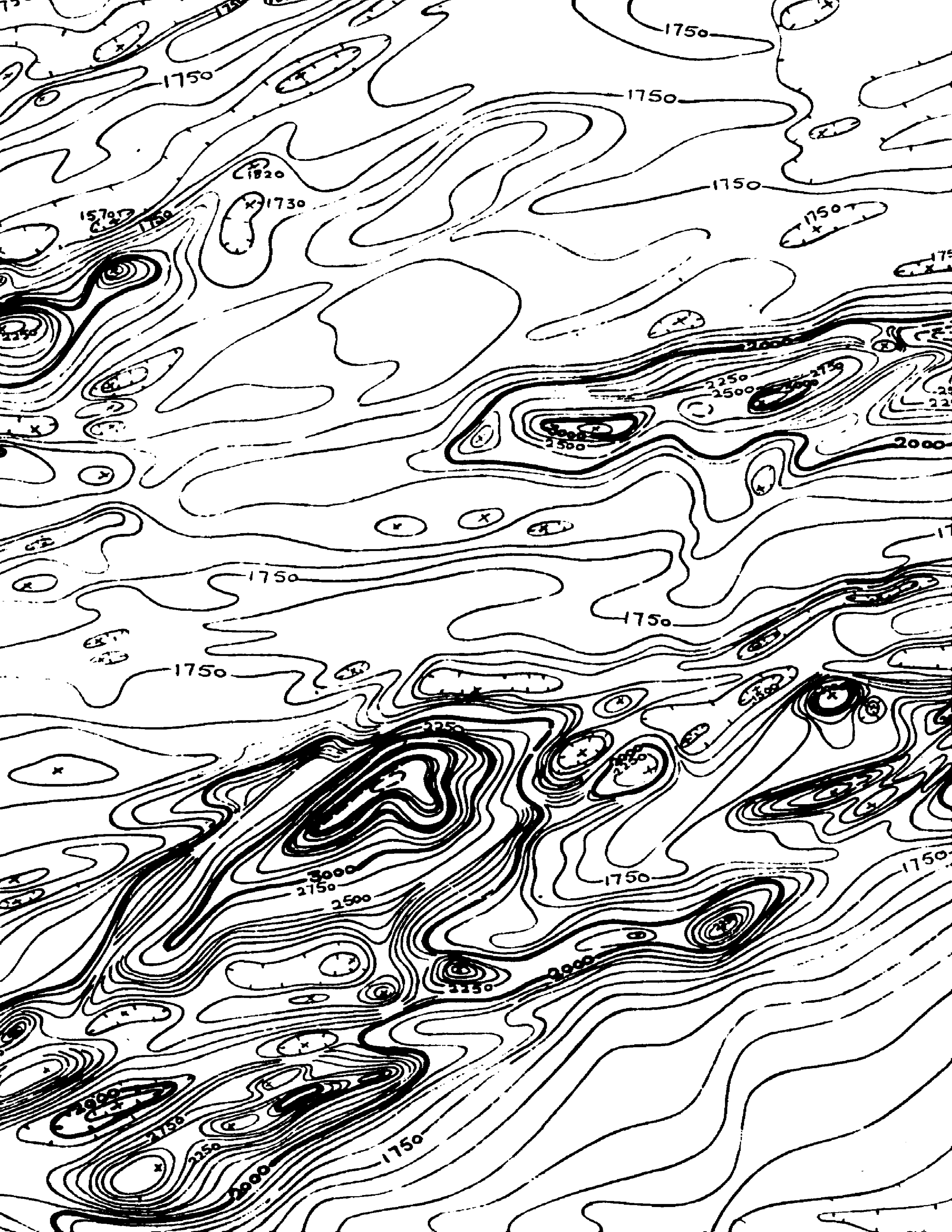
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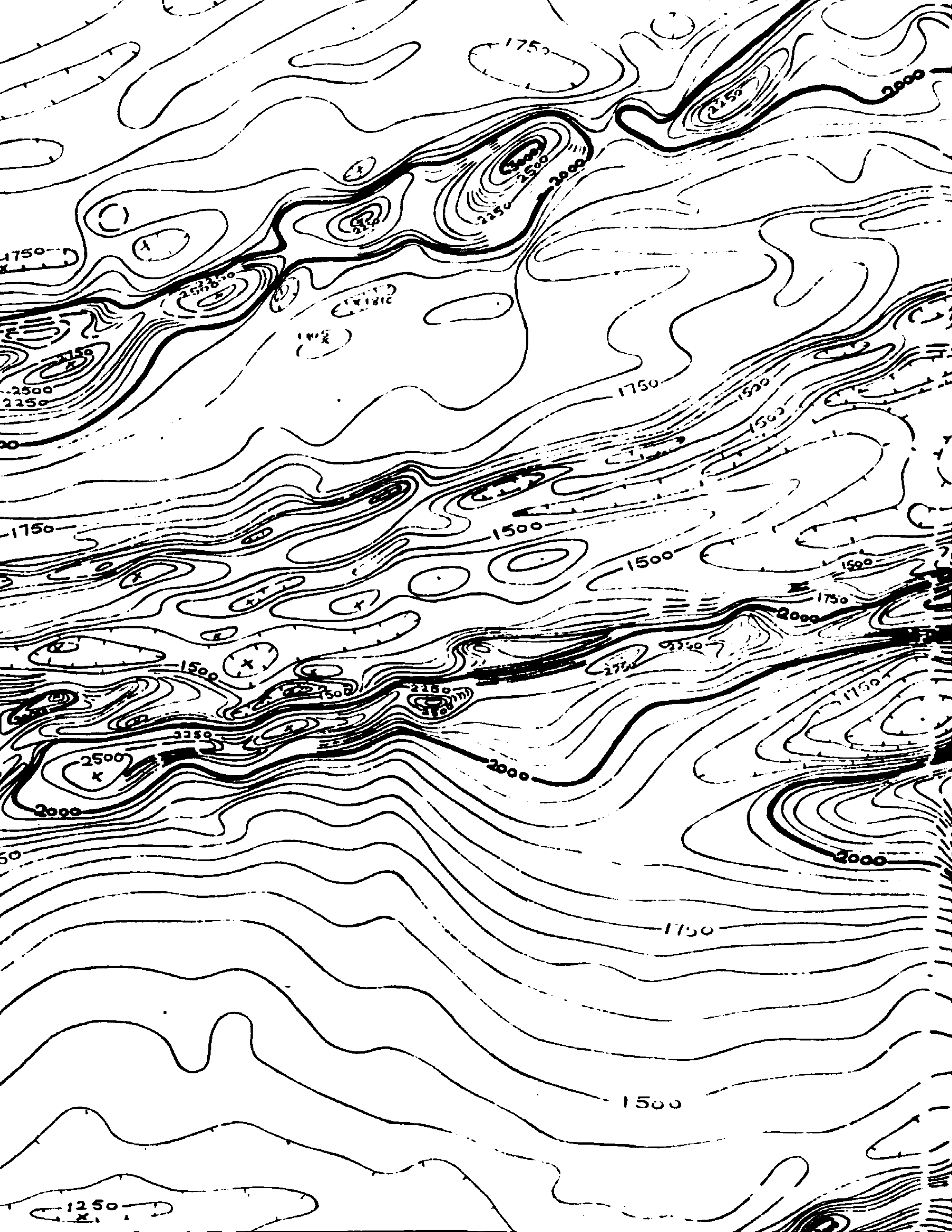

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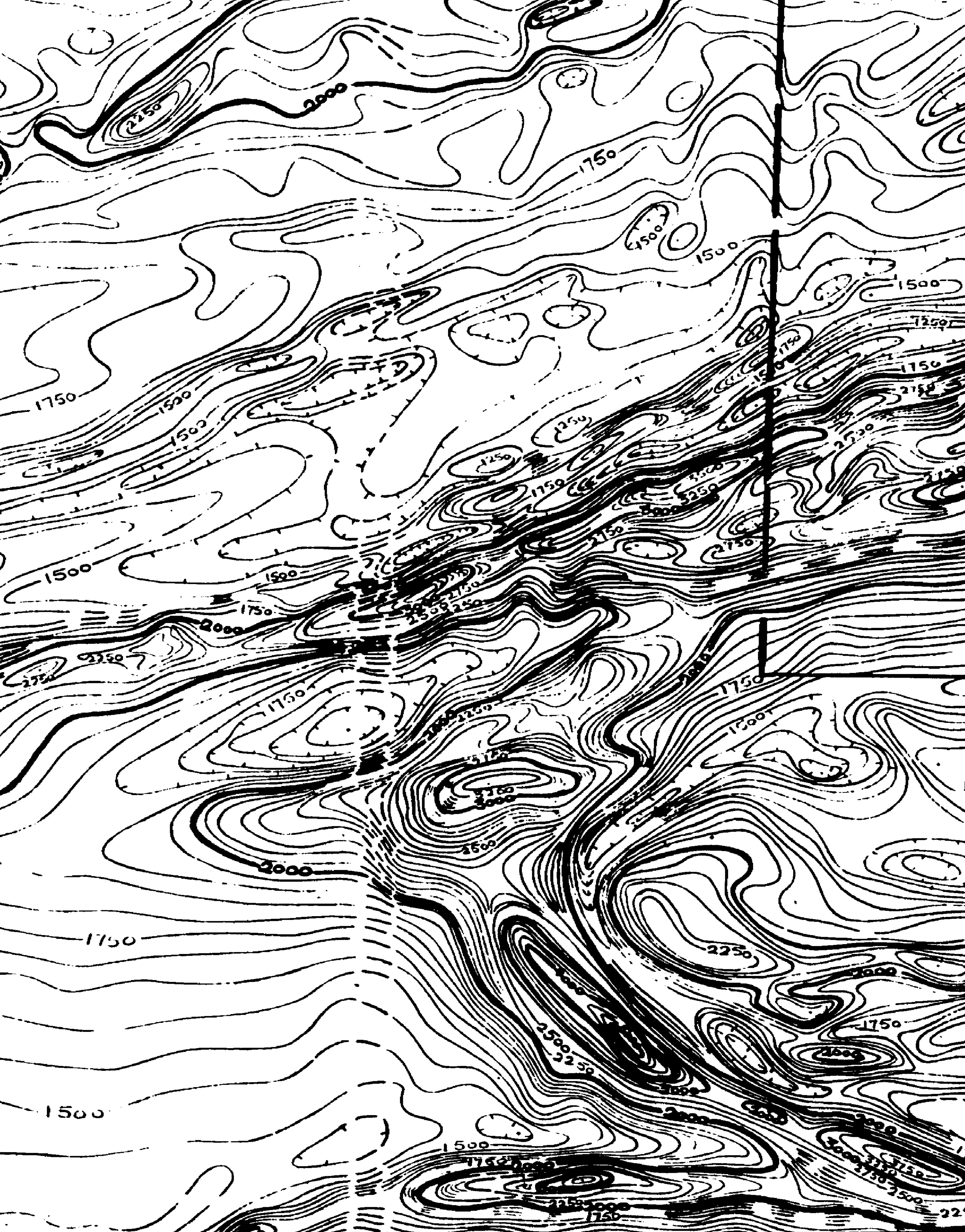

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1500
1750
1500
1500
1250
1250
1750
3000
2250
2750
1500
1500
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1750
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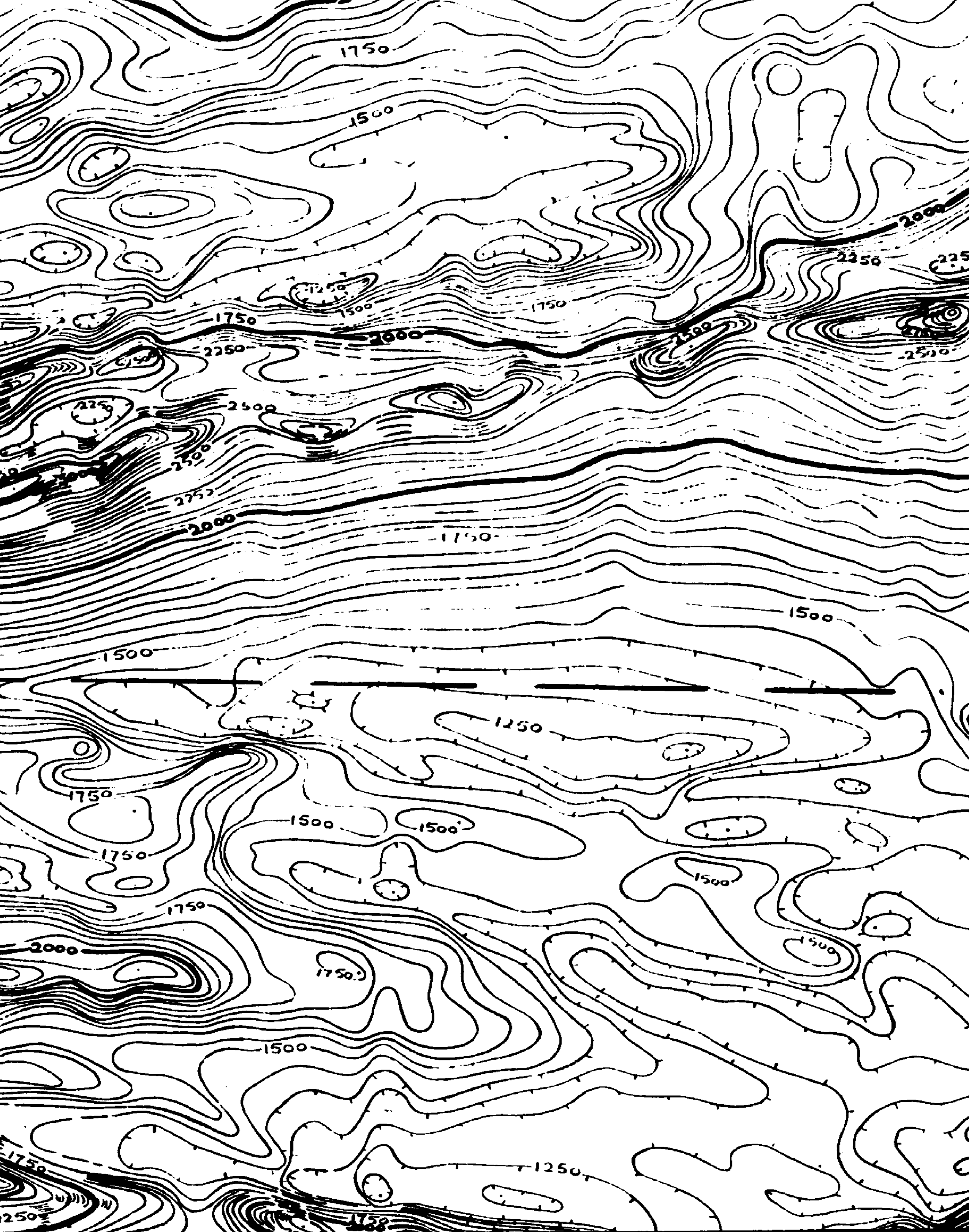
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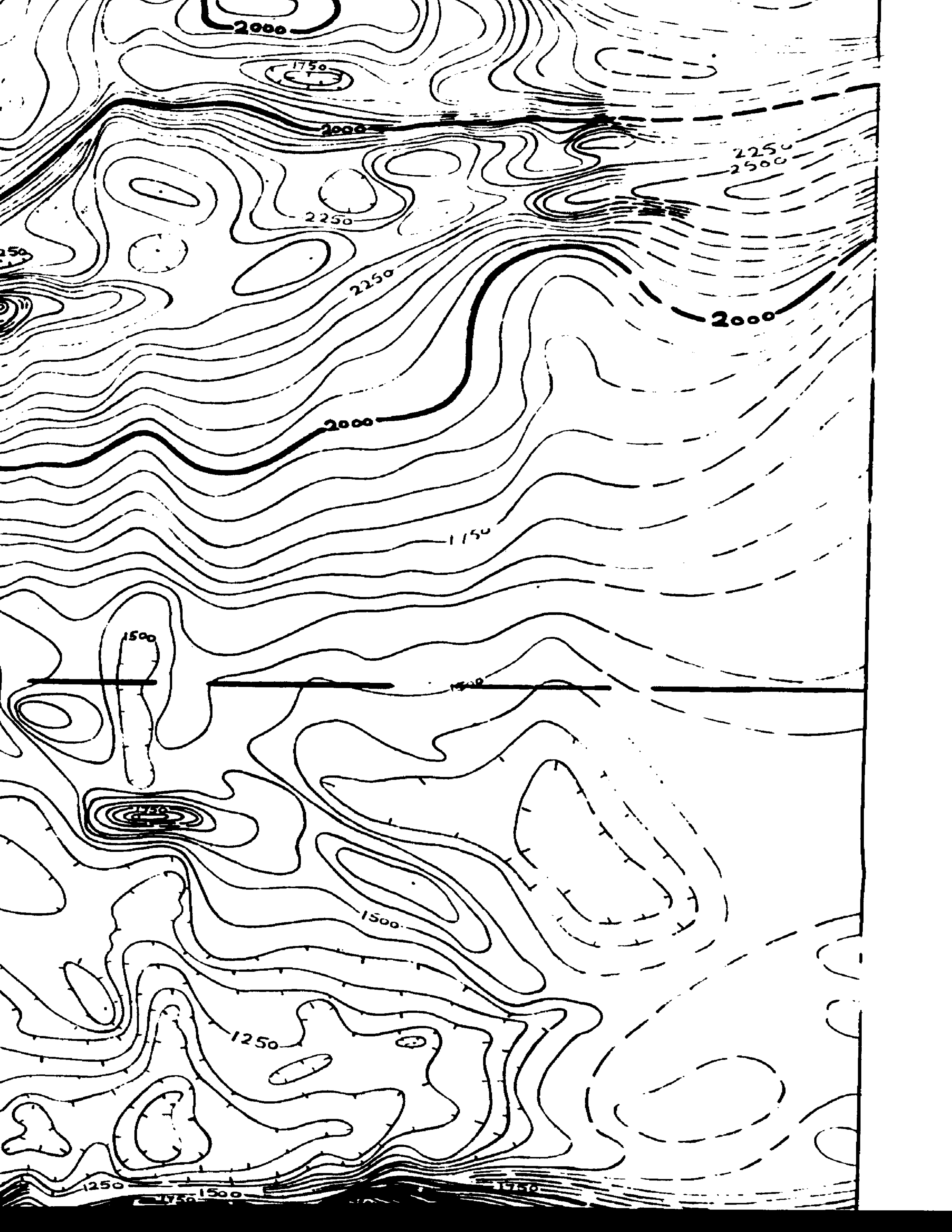
2250
2500



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2250
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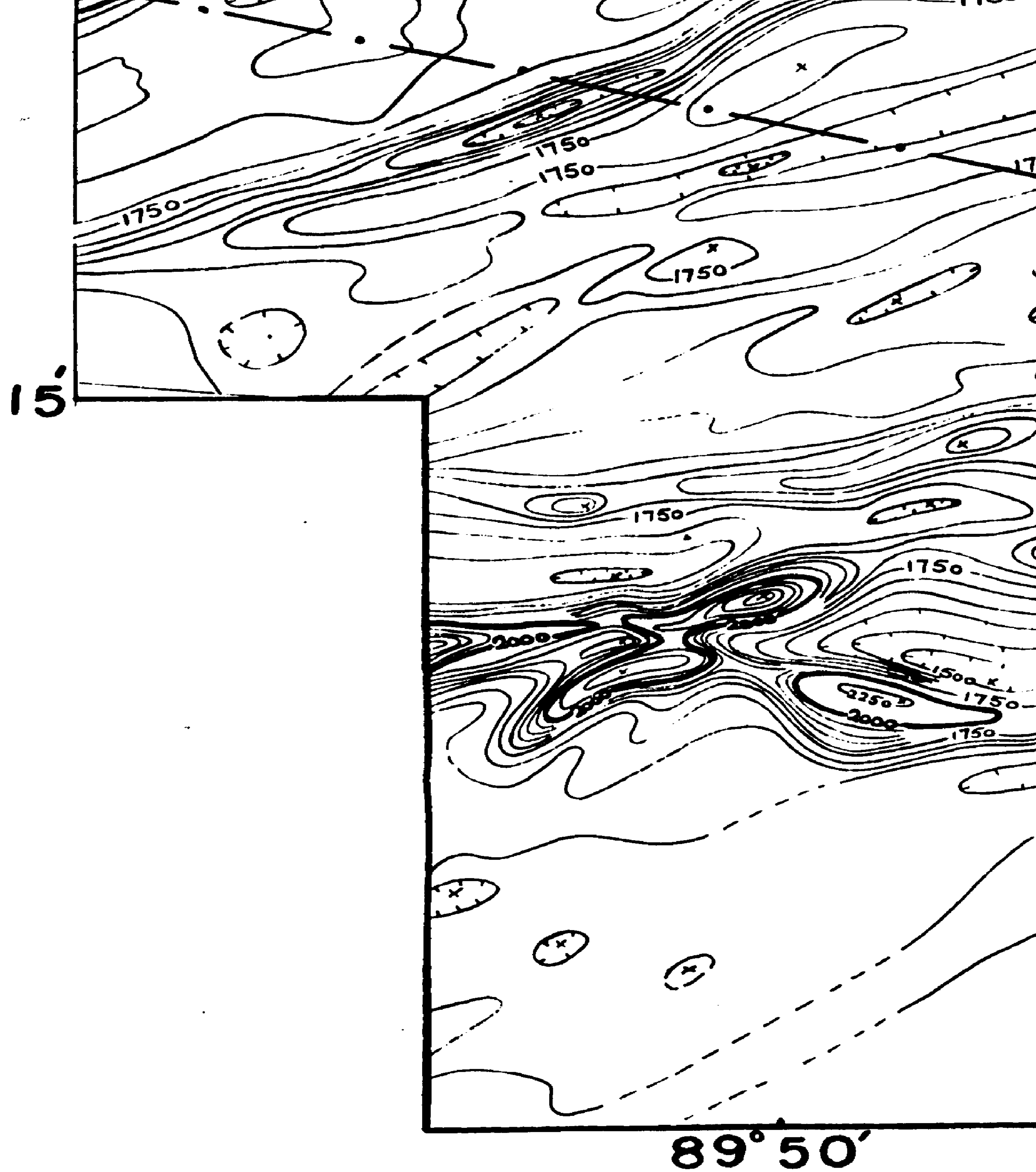
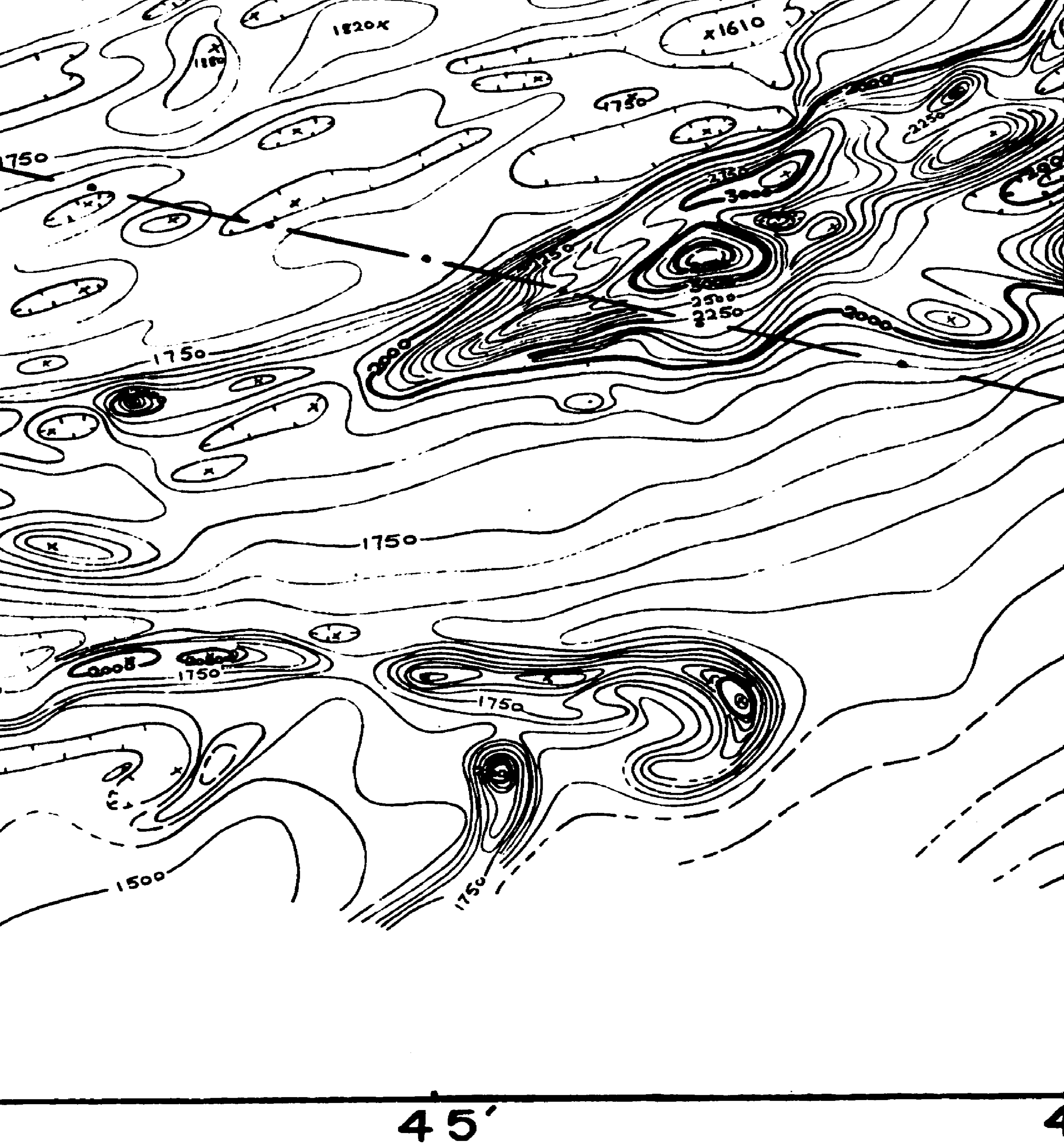
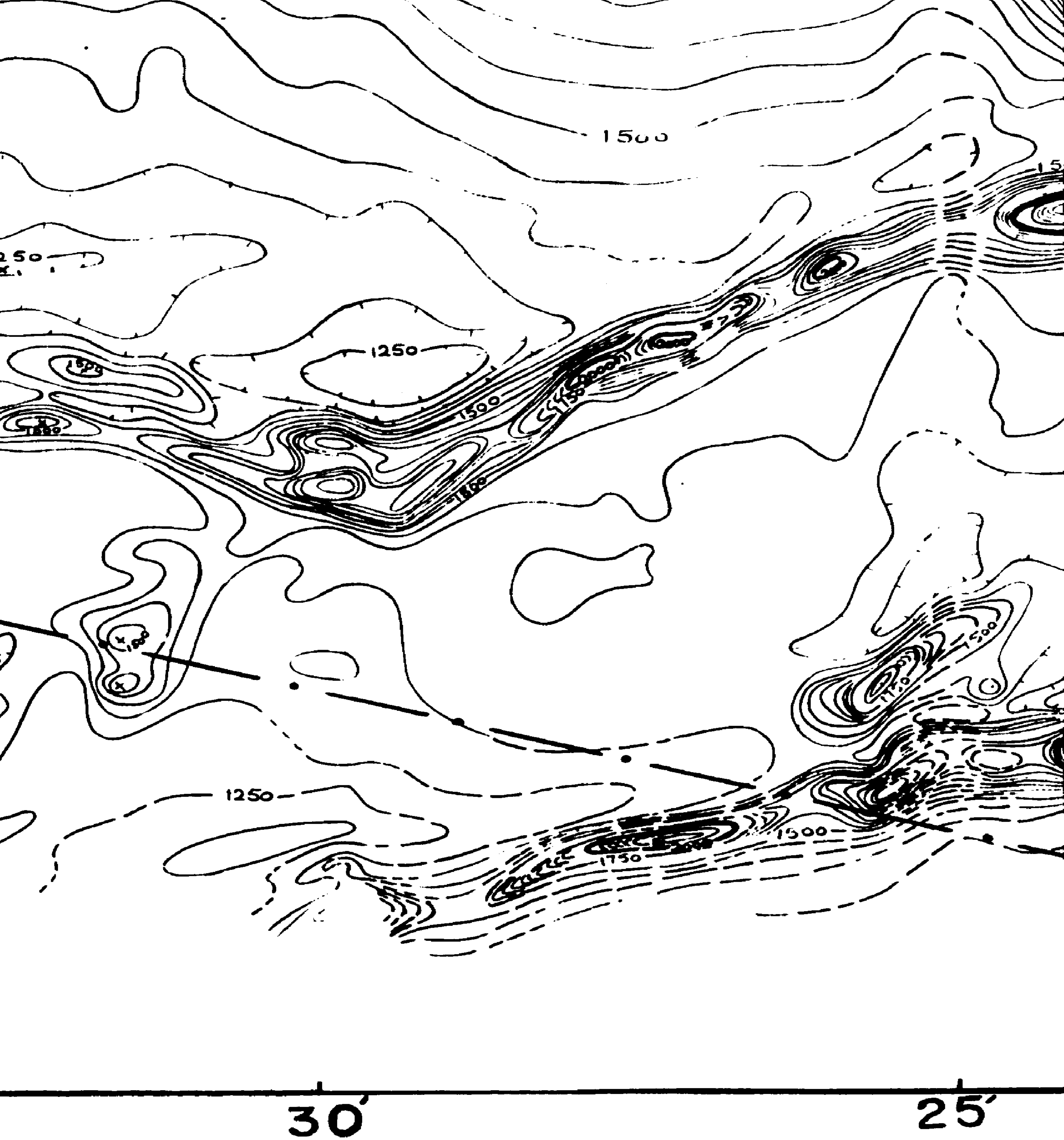
1750


15′
89°50′
1750
2000
2250
1500



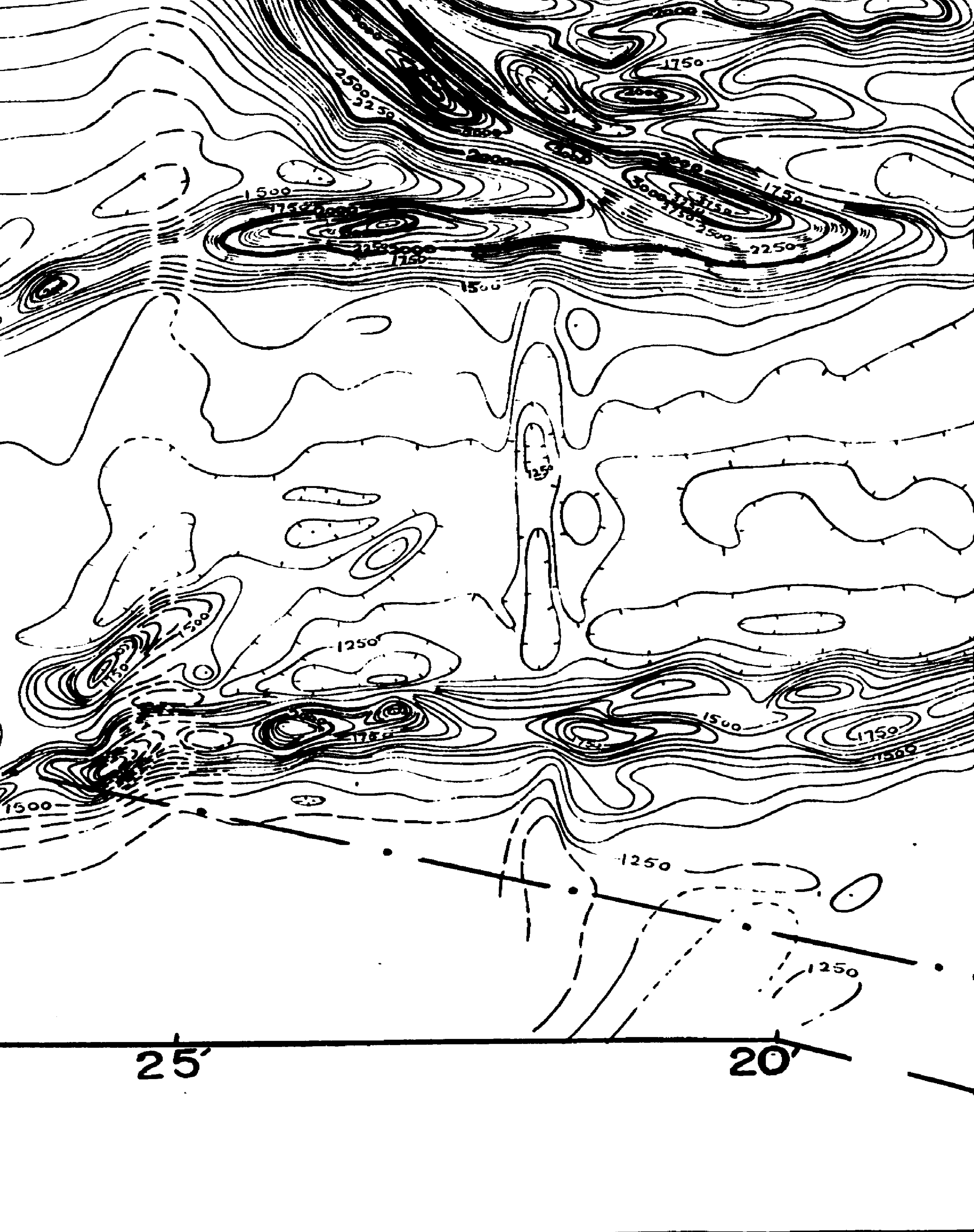
1820x
x1610
1750
2000
2250
2500
3000
1500
45′

PLATE



E I-d

PLATE I-d



25′
20′
1250
1500
1750
2000
2250
2500

1500
1250
1750
2250
2000
1500
1250
1750
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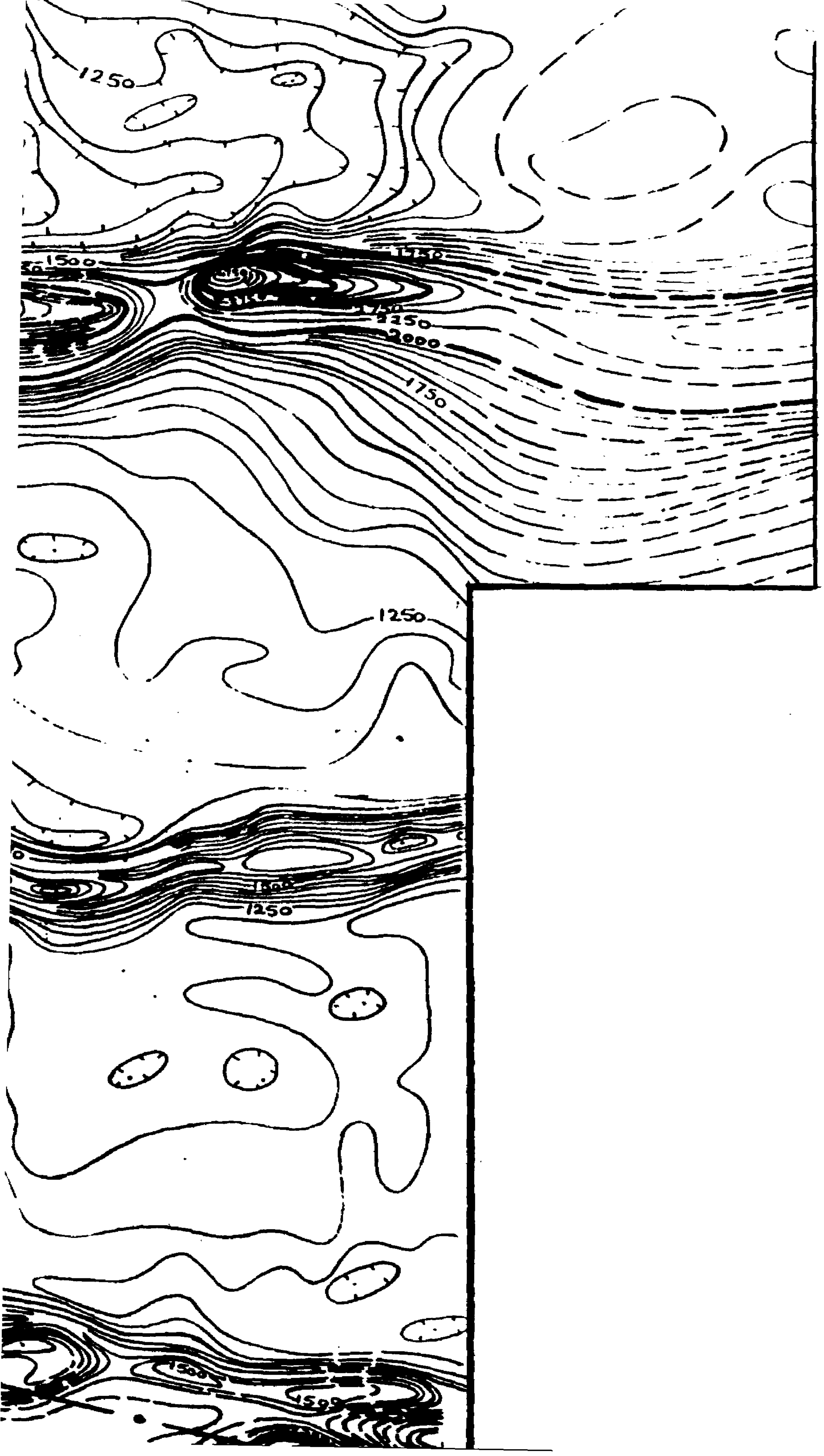
1250
1500
1250
15'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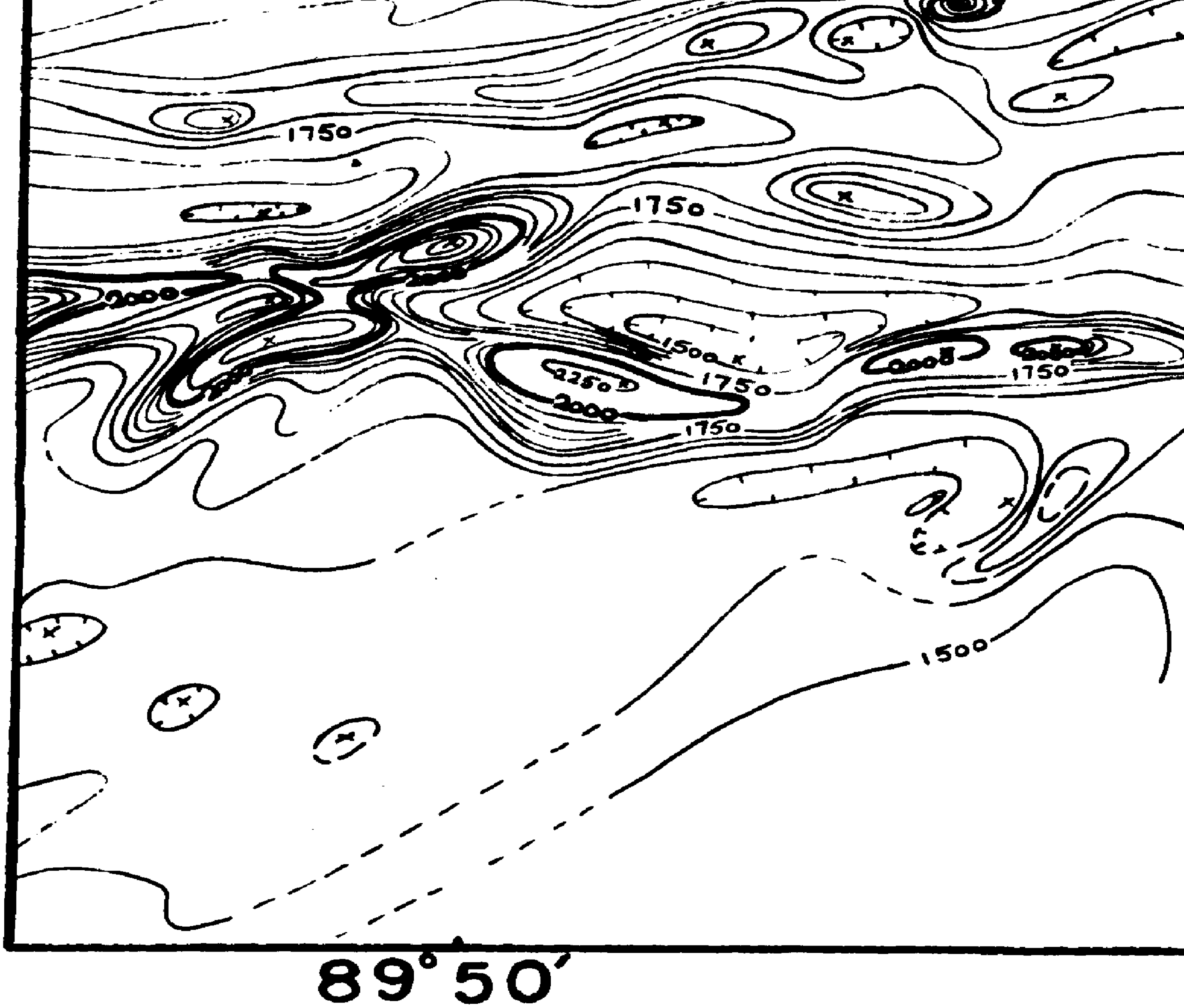
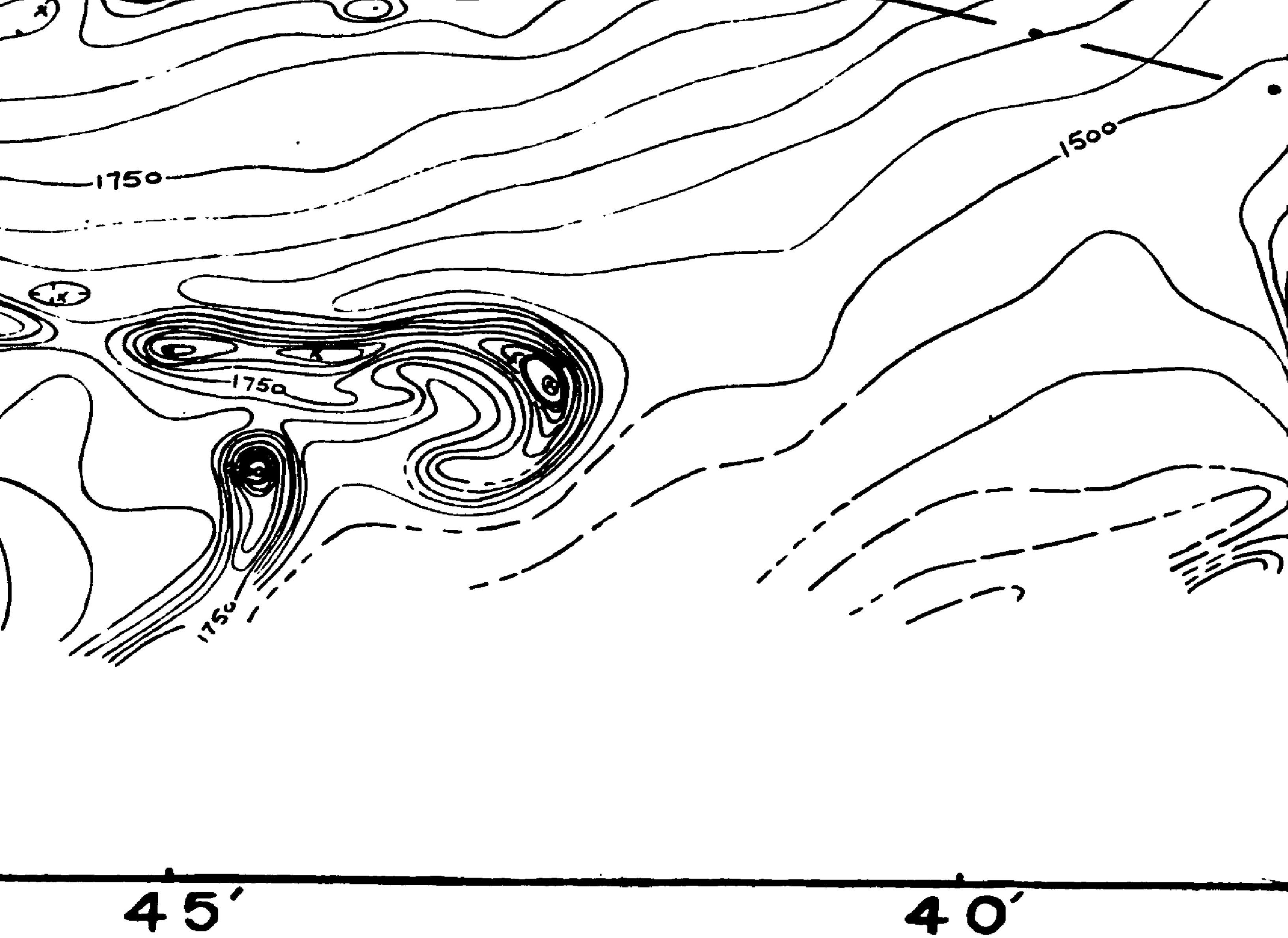
1500
1750
2250
2000
1750
1250
1250
1500
1500



1750
1750
2000
1500
1750
2250
2000
1750
2000
2000
1750
1500
89°50′


1750
1500
1750
1750
45′
40′

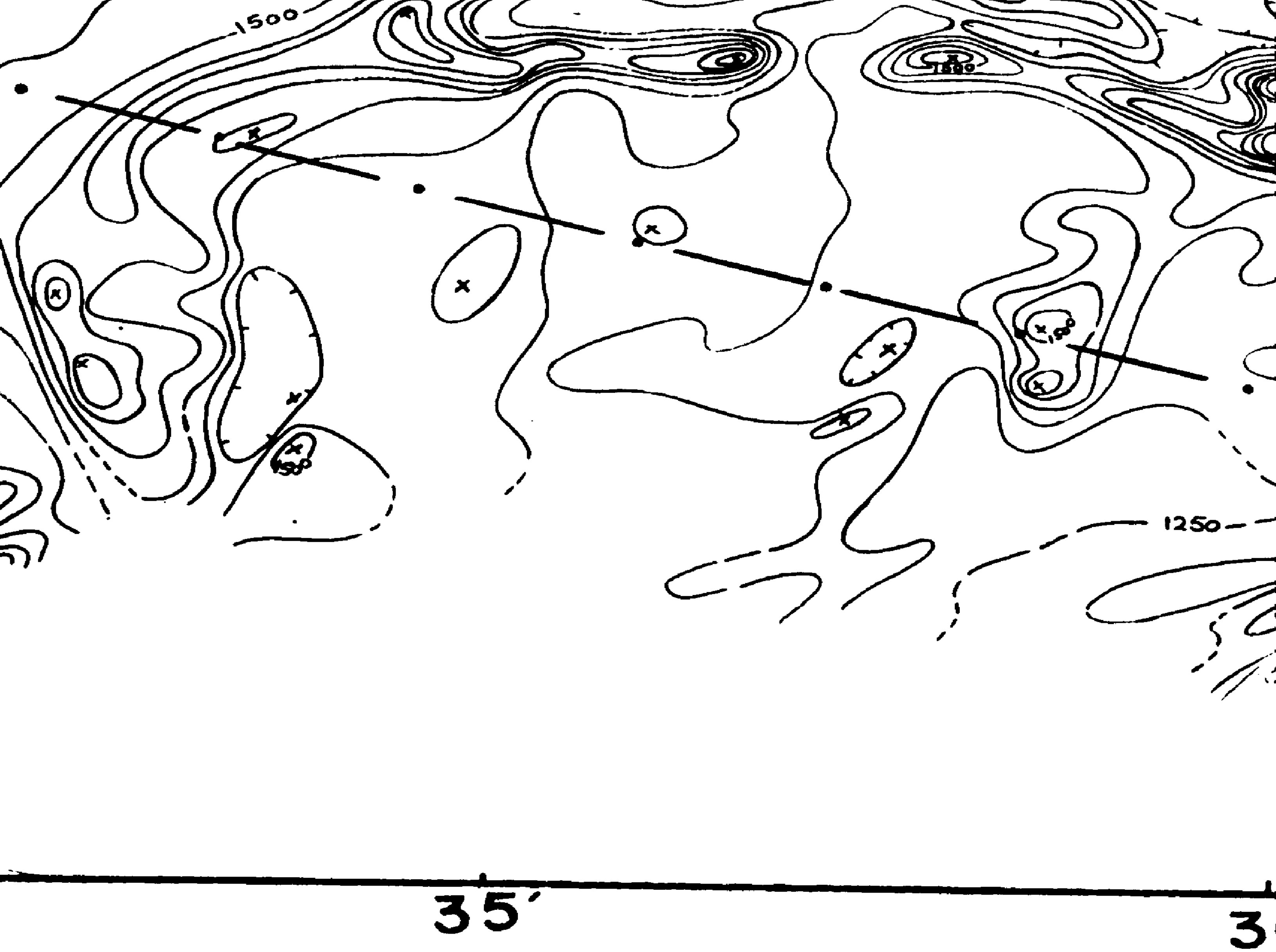
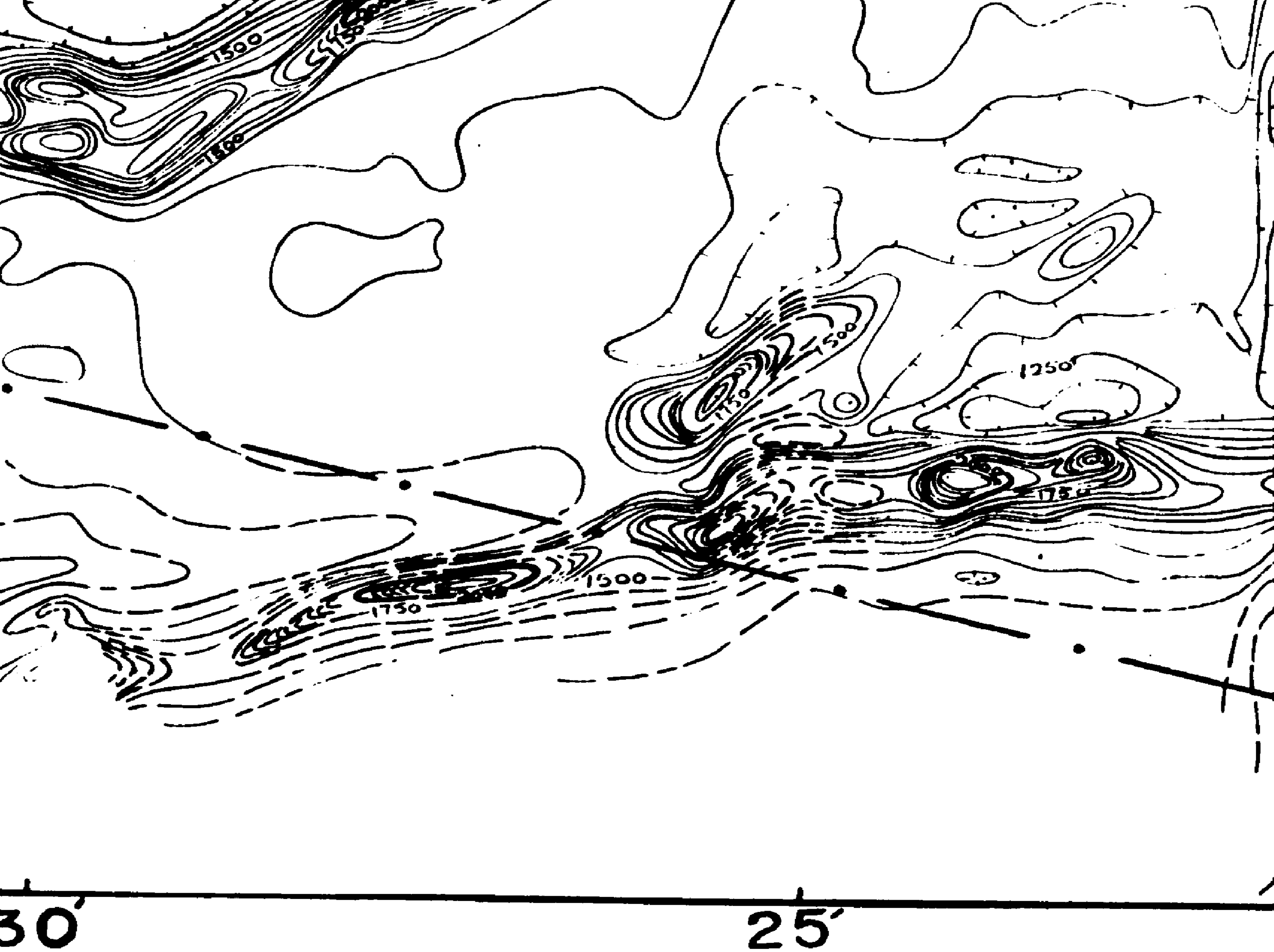


PLATE I-d



1500
1500
1500
1500
1250
1750
1750
1750
1500
1750
30′
25′

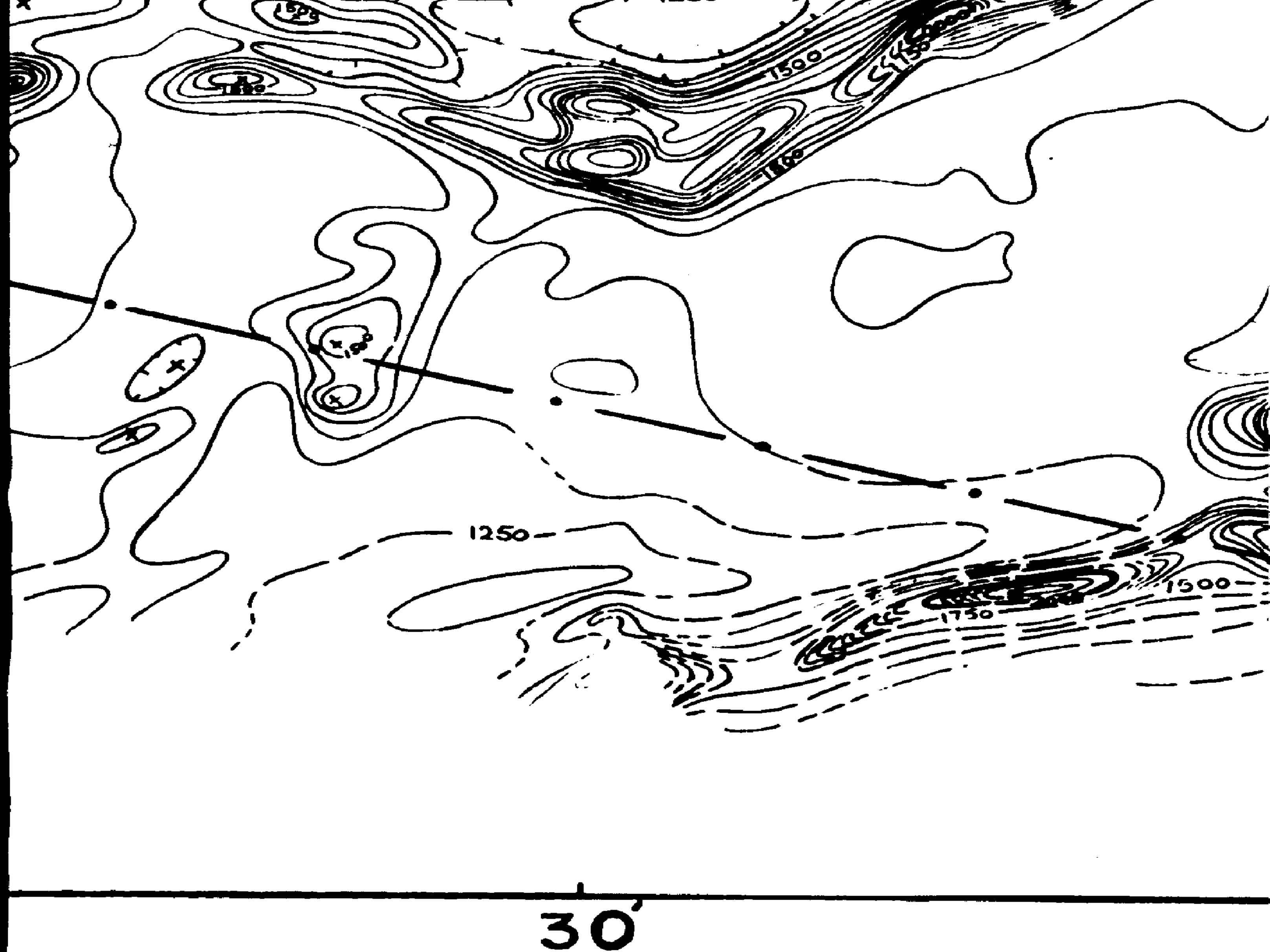
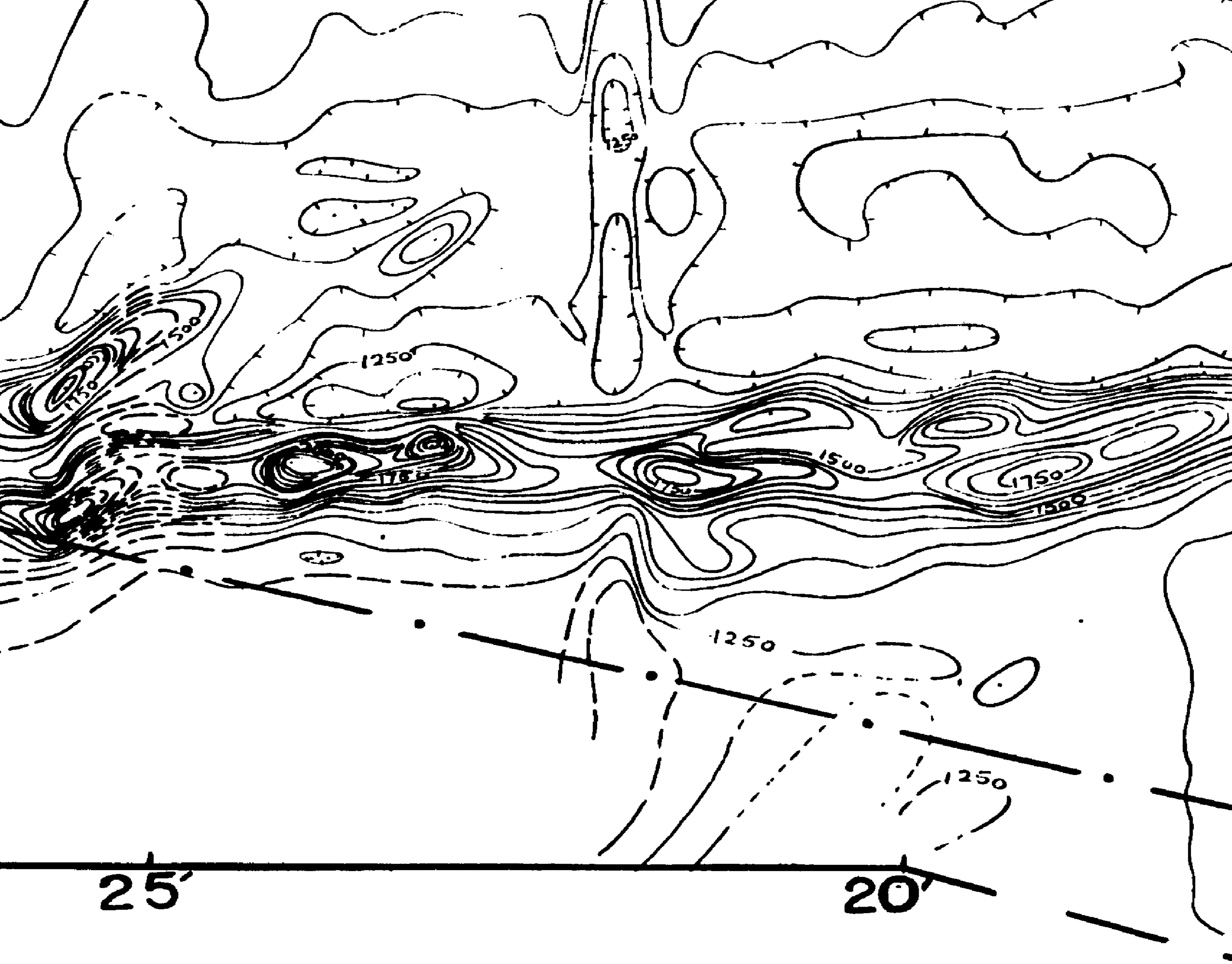
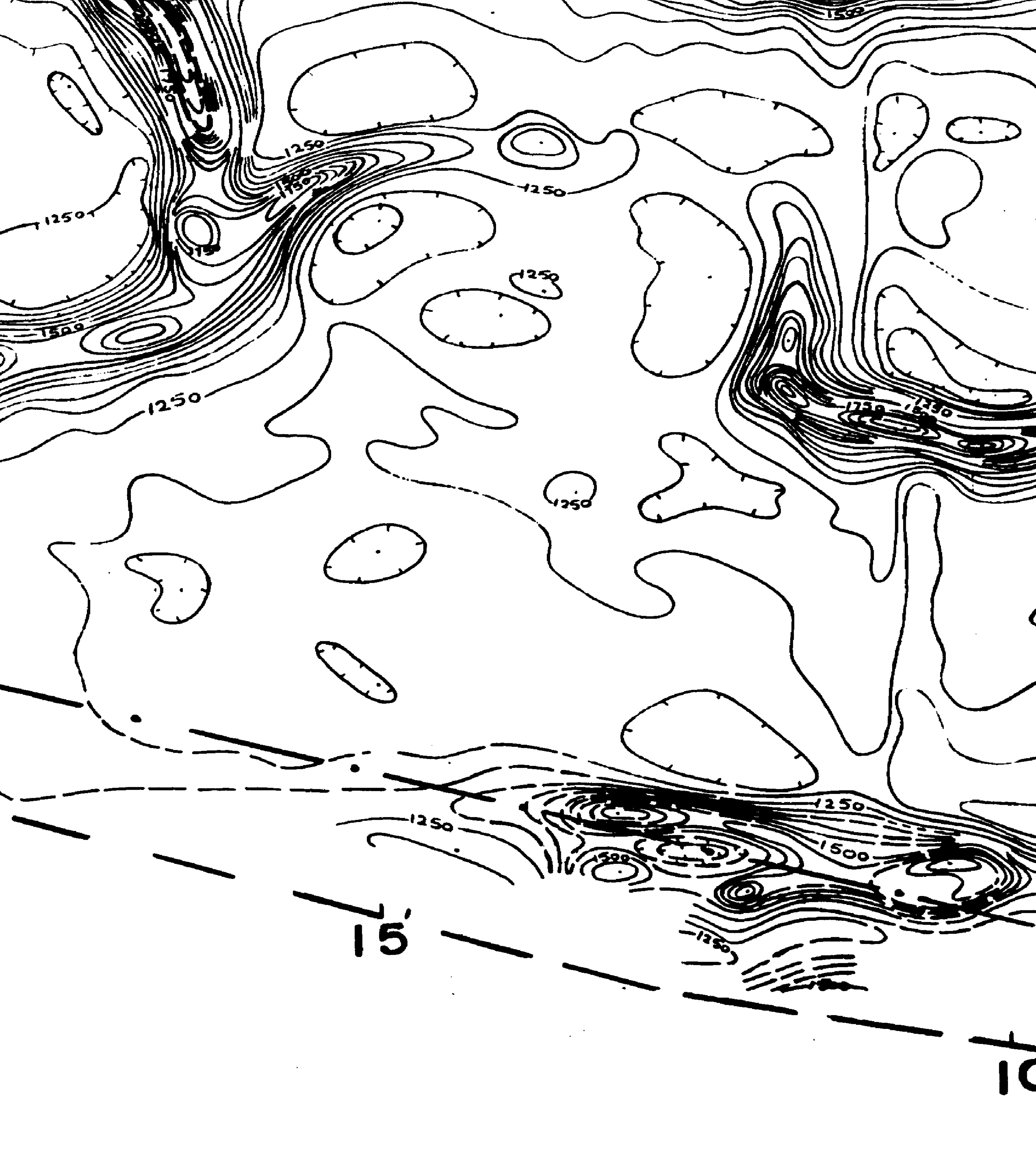
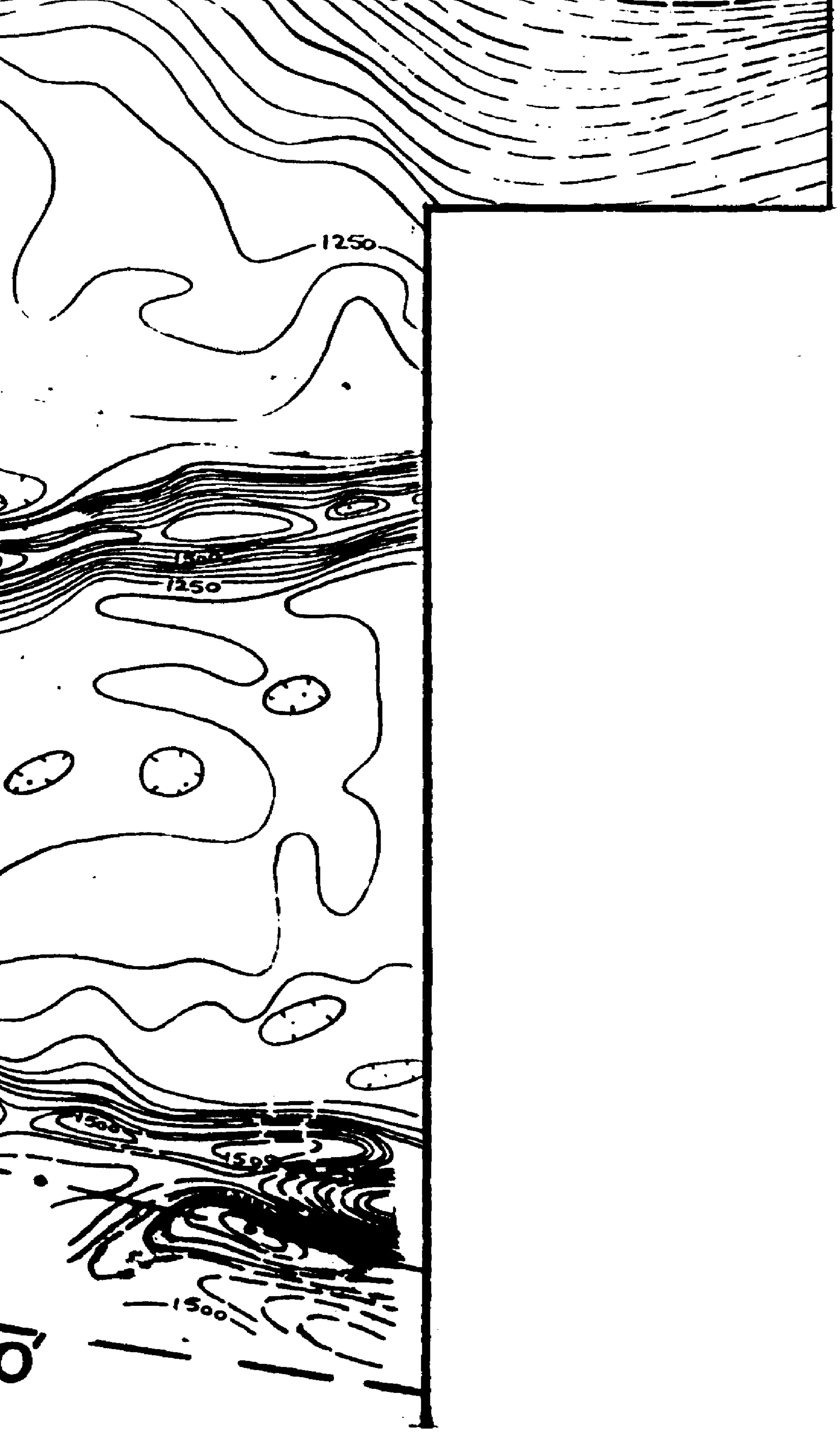


PLATE I-d

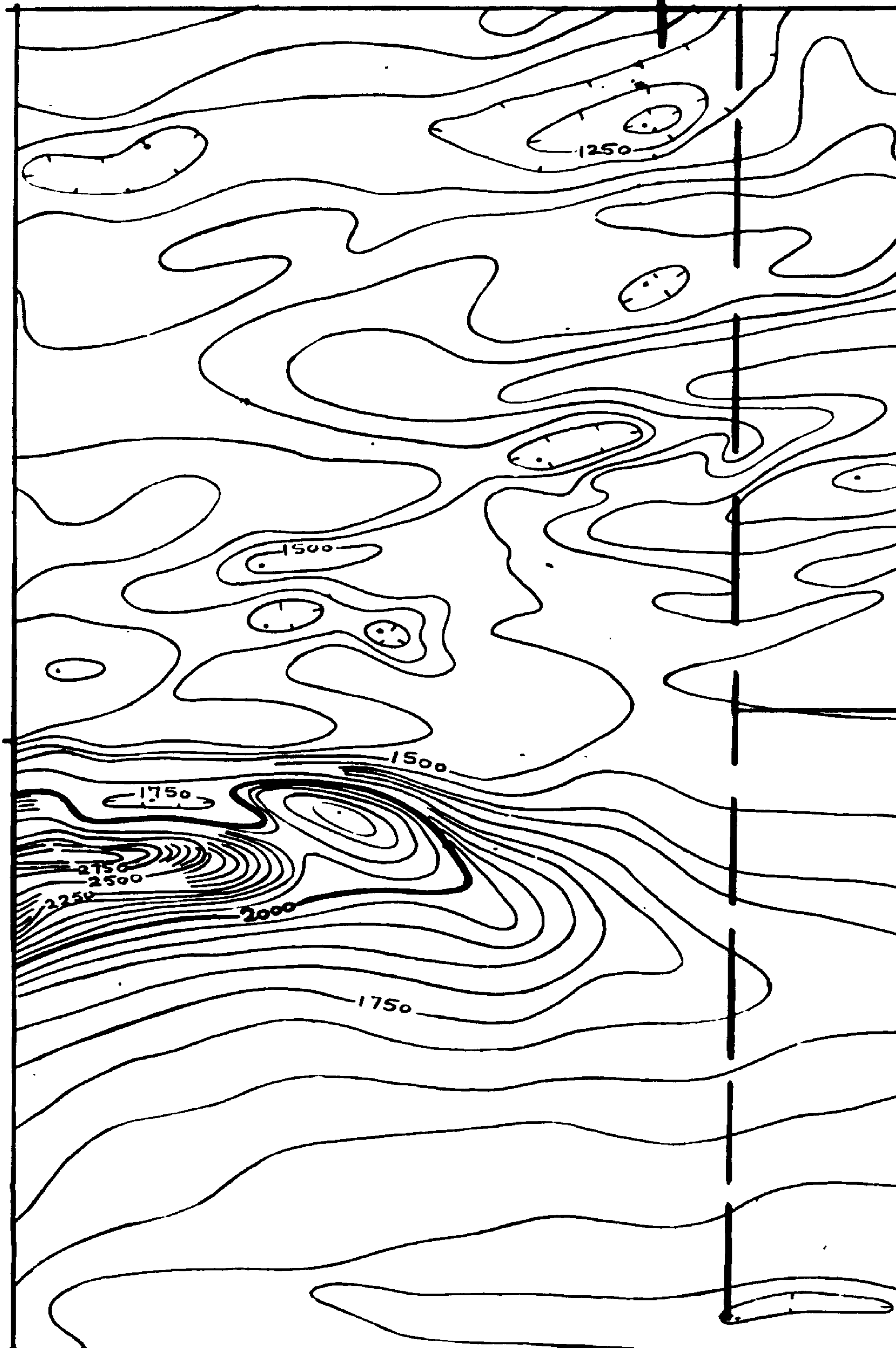


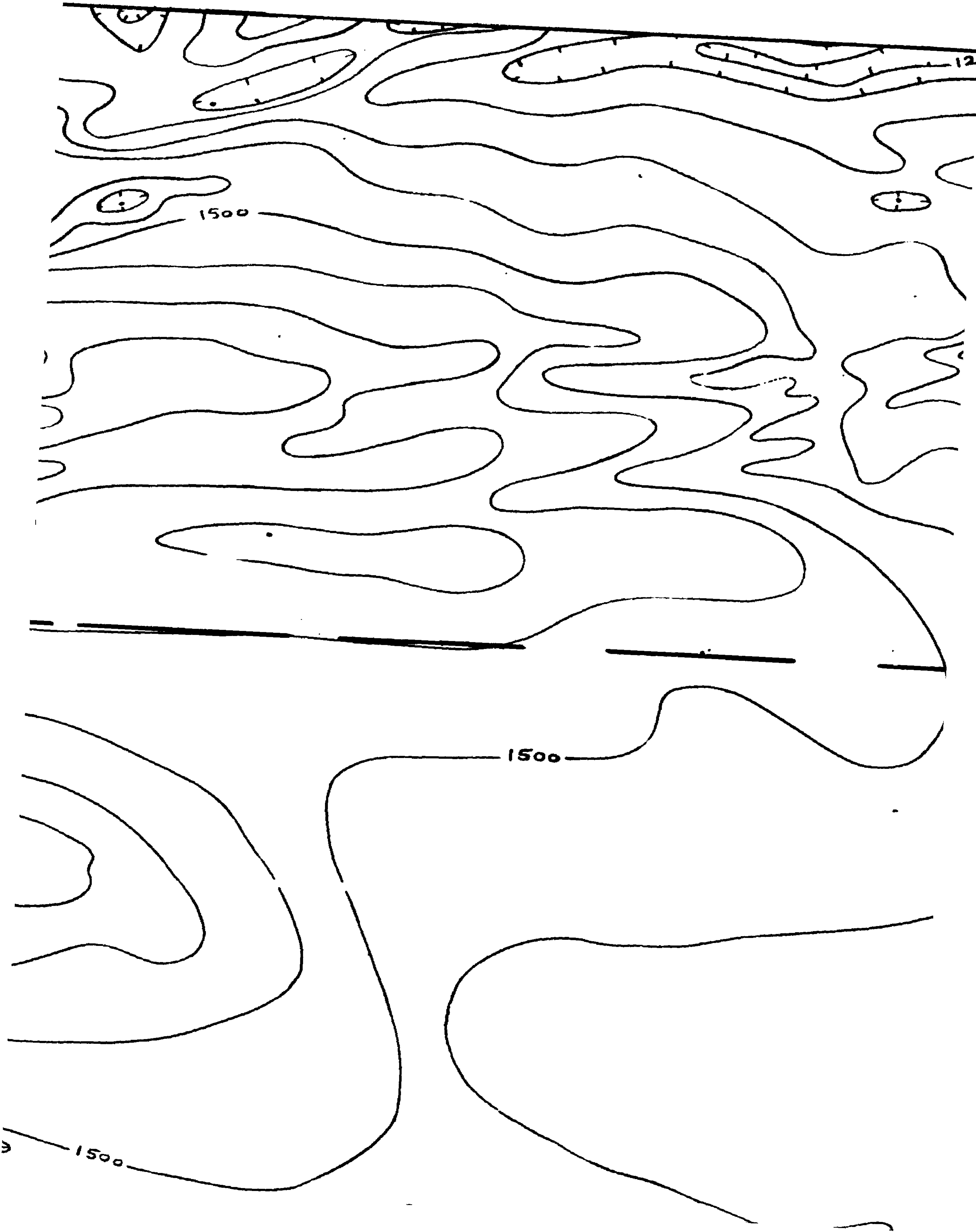
125
1250
1500
1750
1500
1750
1500
1750
1500
1750
1500
1250
1250
25′
20′


15'
10
1250
1500

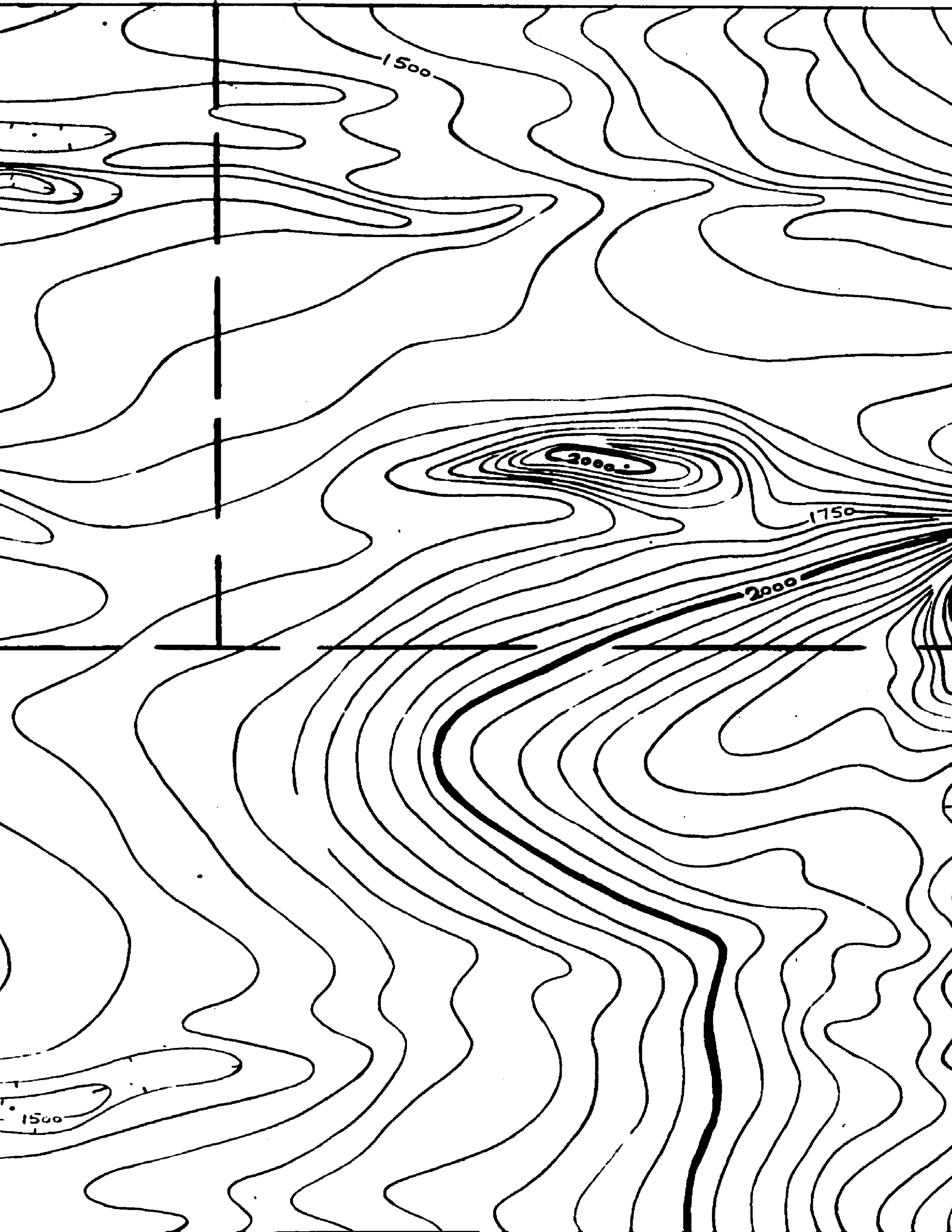


1250
1250
1500
1500

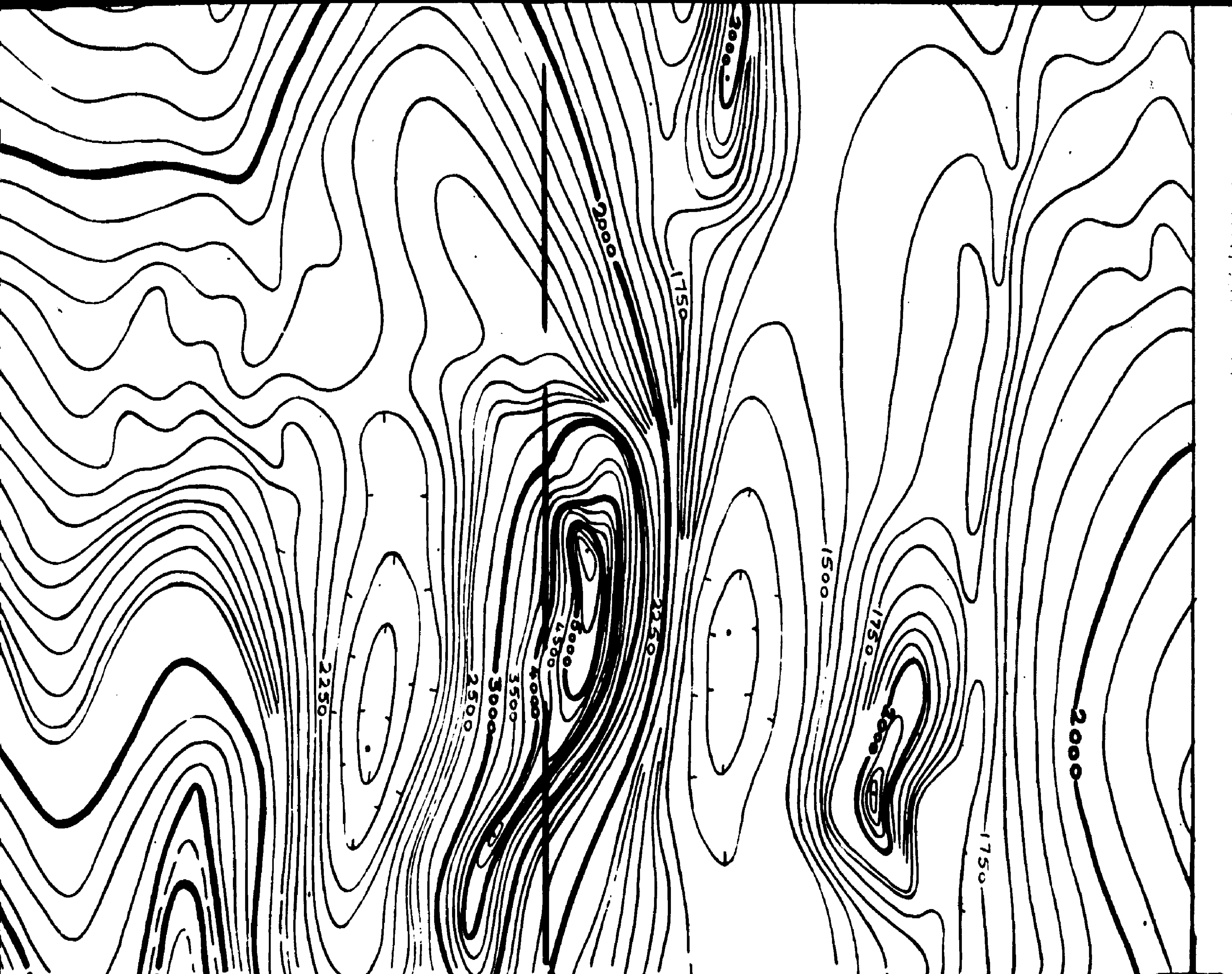

1250
1500
1500
1750
2750
2500
2250
2000
1750


1500
1500
1500

1250
1250
1250
1500
1750



1500
2000
1750
2000
1500



2000
2000
1750
2250
2250
2500
3000
3500
4000
4500
1500
1750
2000
1750


1750
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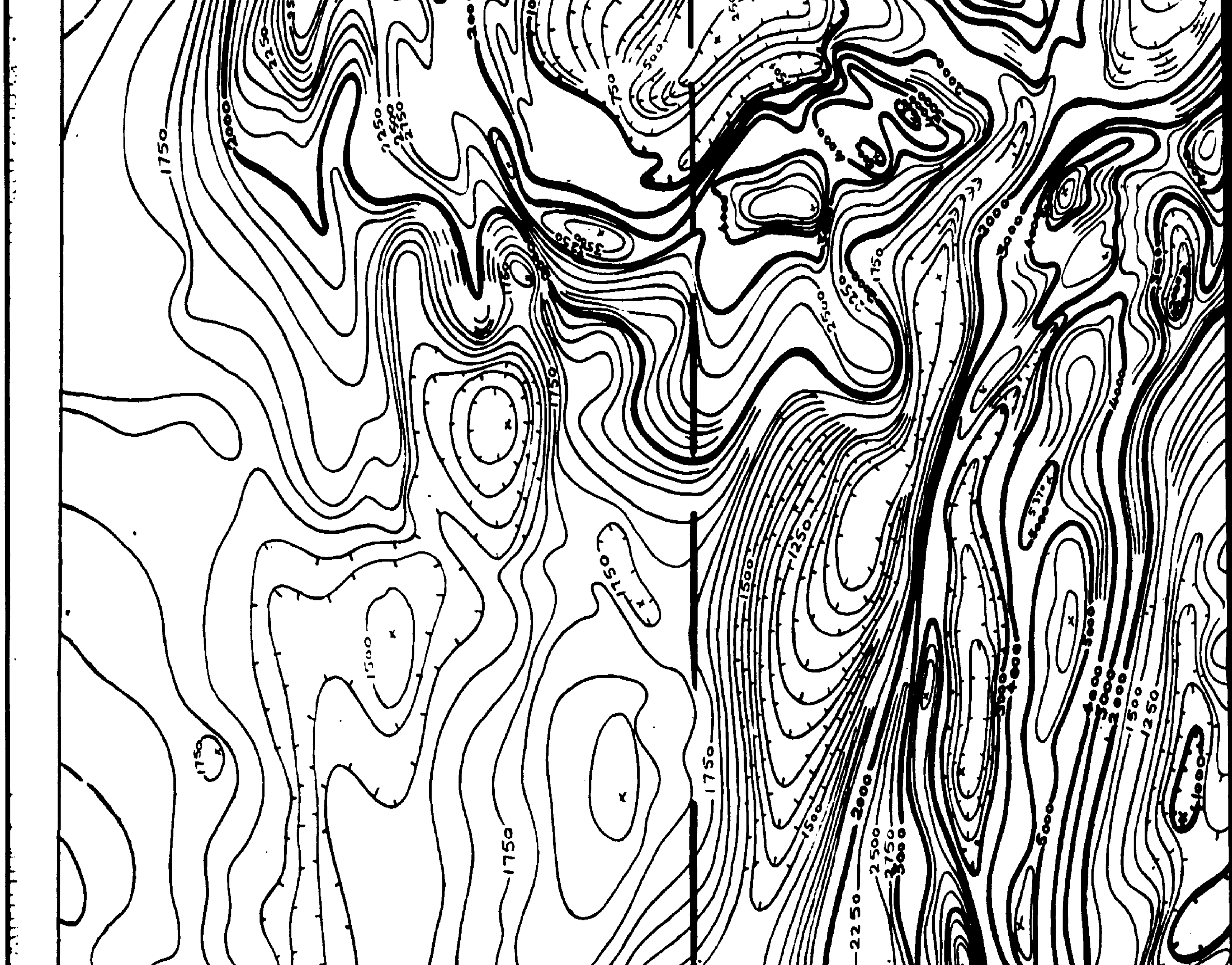
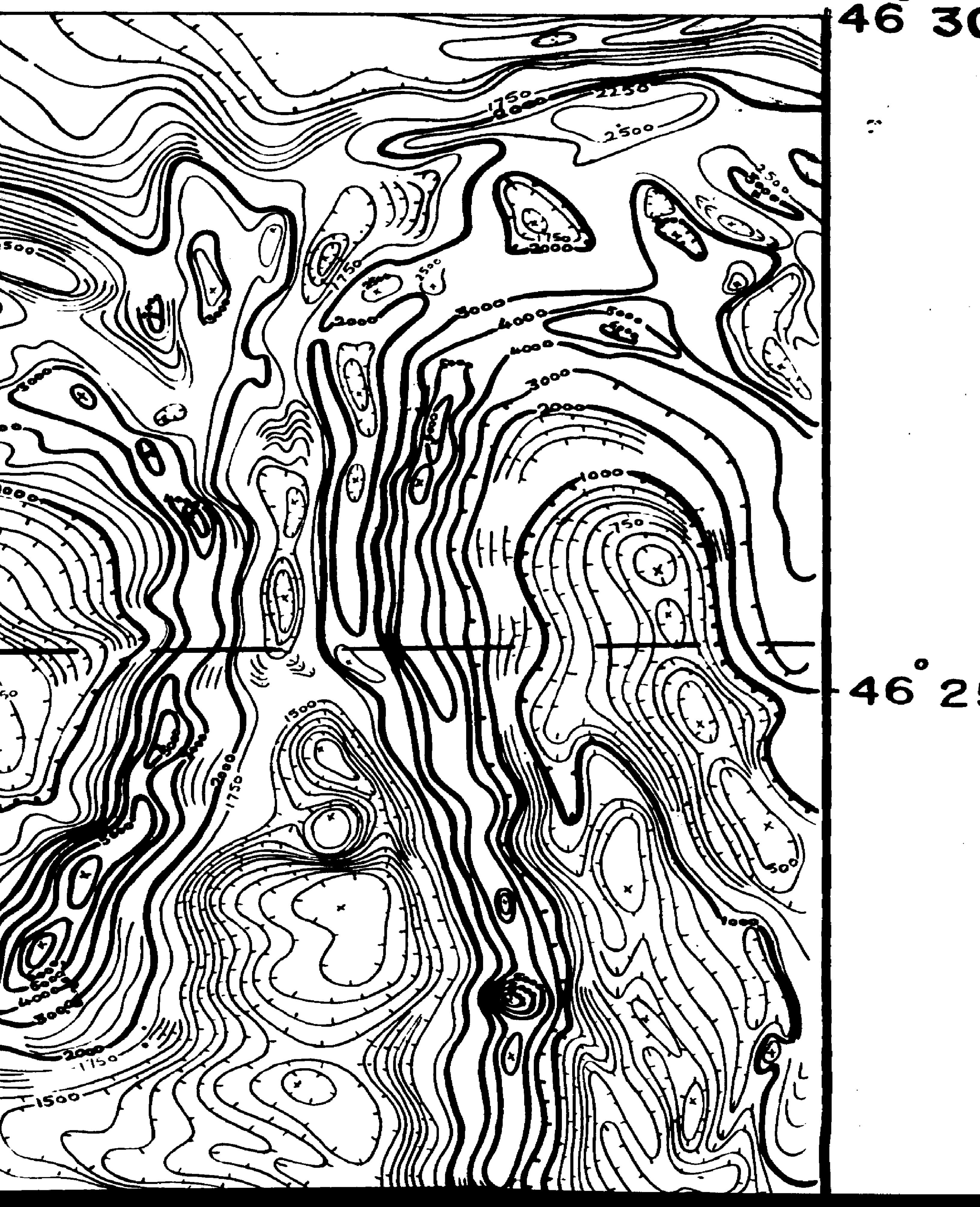
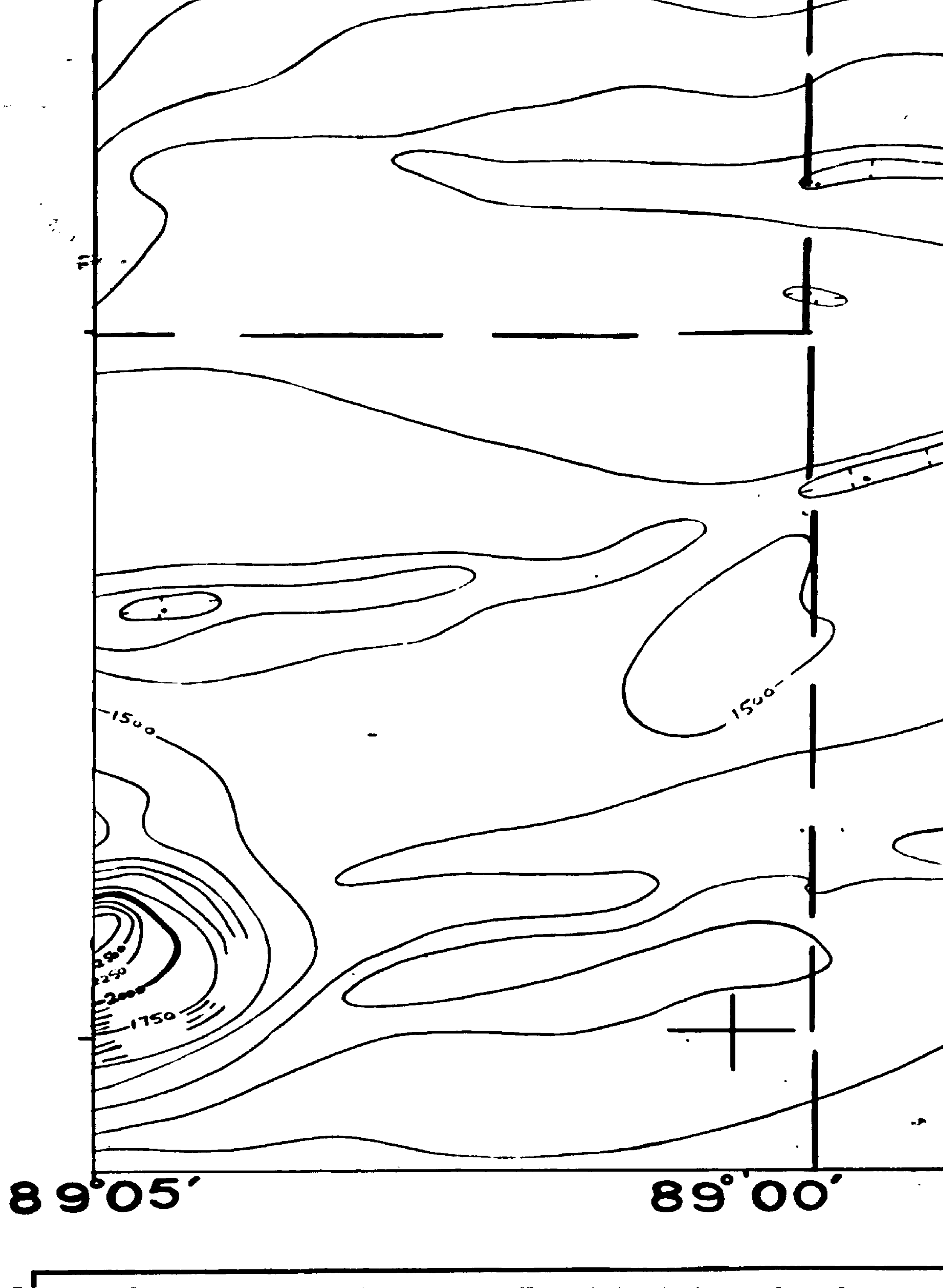
2000
2500
2750
3000
3500
4000
4500
5000
4000
5000
2750
2500
2250
4000

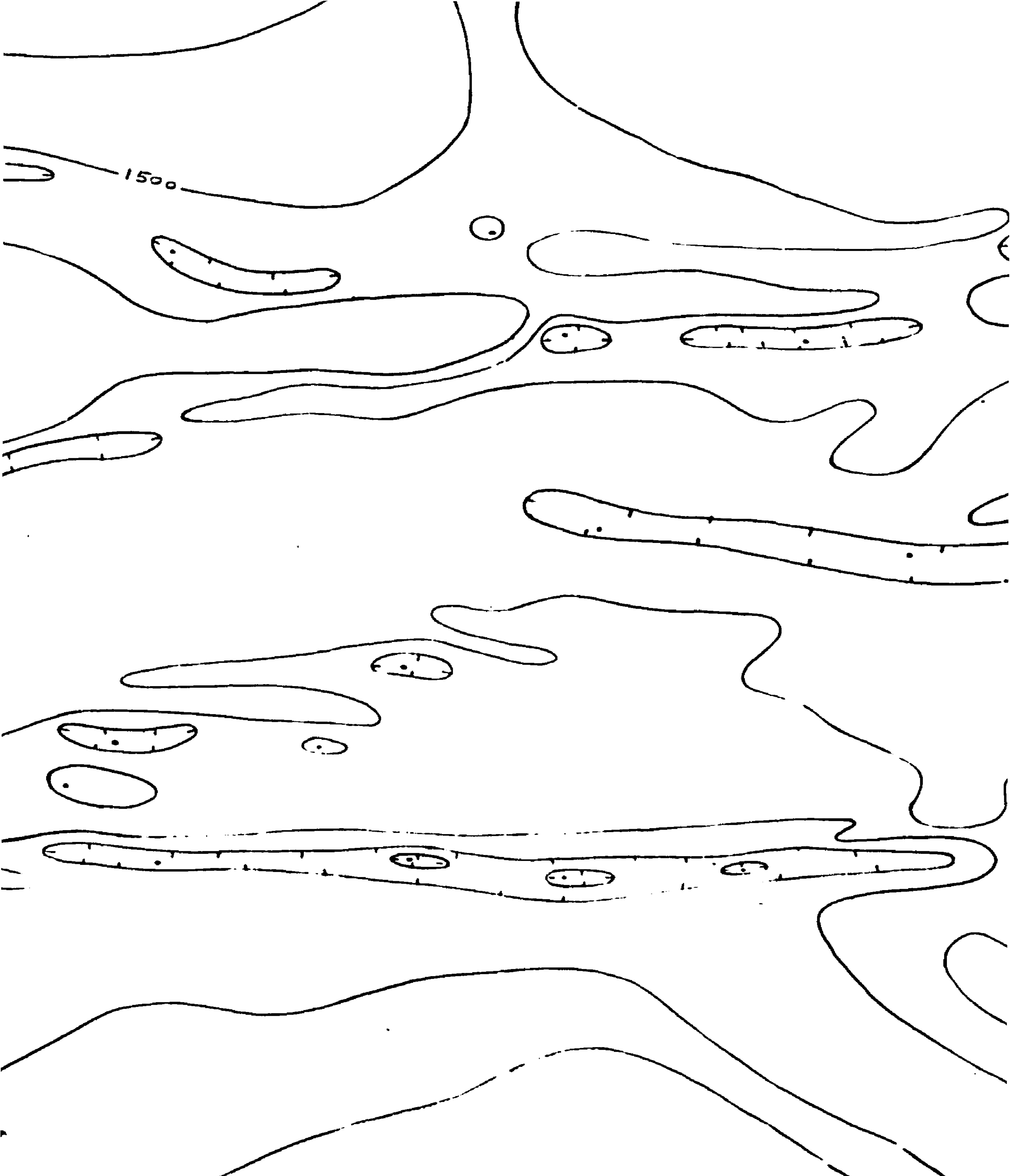


1750
2000
2250
2500
2750
750
500
3250
1500
1250
3000
4000
5000



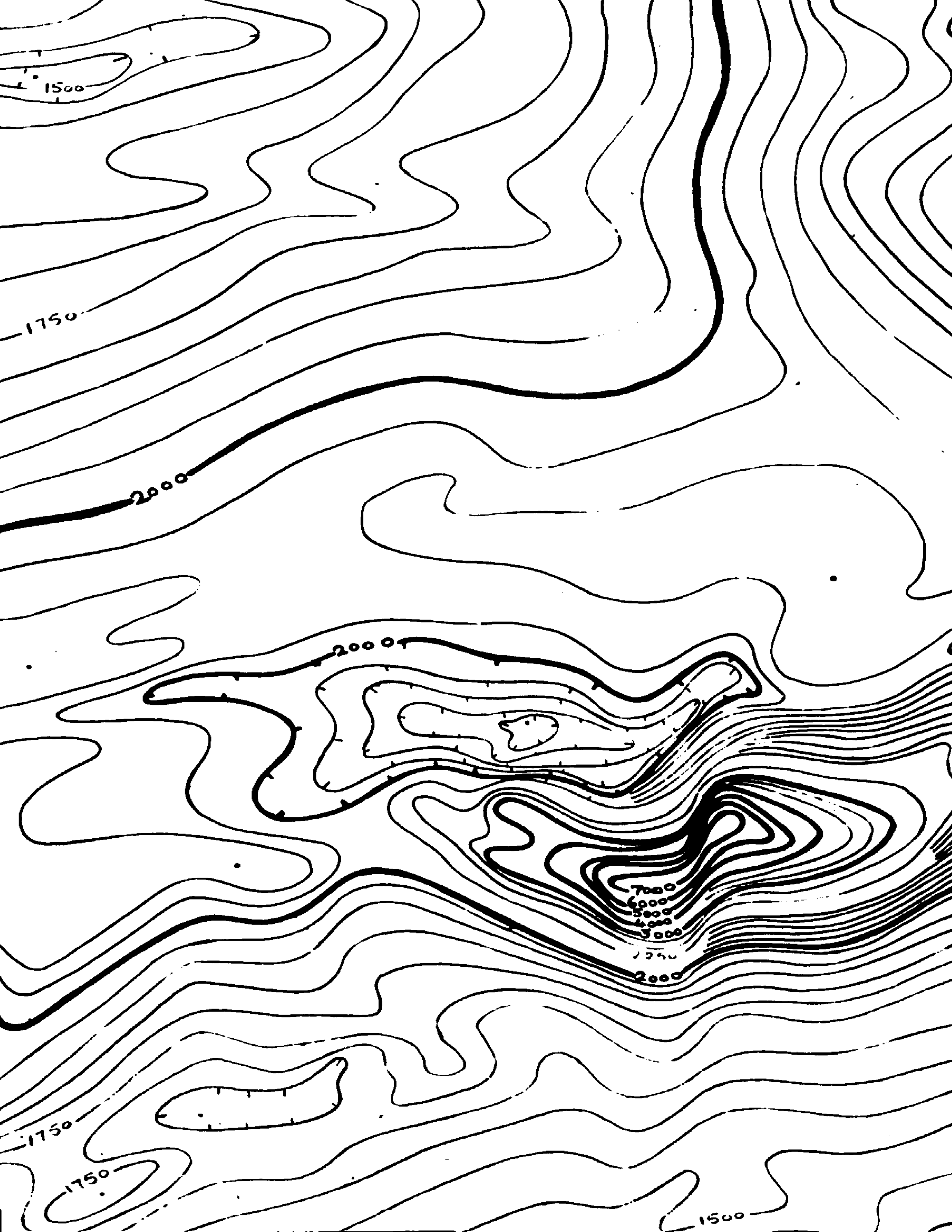
46° 30
46° 25
1750
2000
2250
2500
3000
4000
5000
1000
750
1500
500


1500
1500
1750
2000
2250
2500
89°05′
89°00′



88°55' 8


1750
1500
88°50′


1500
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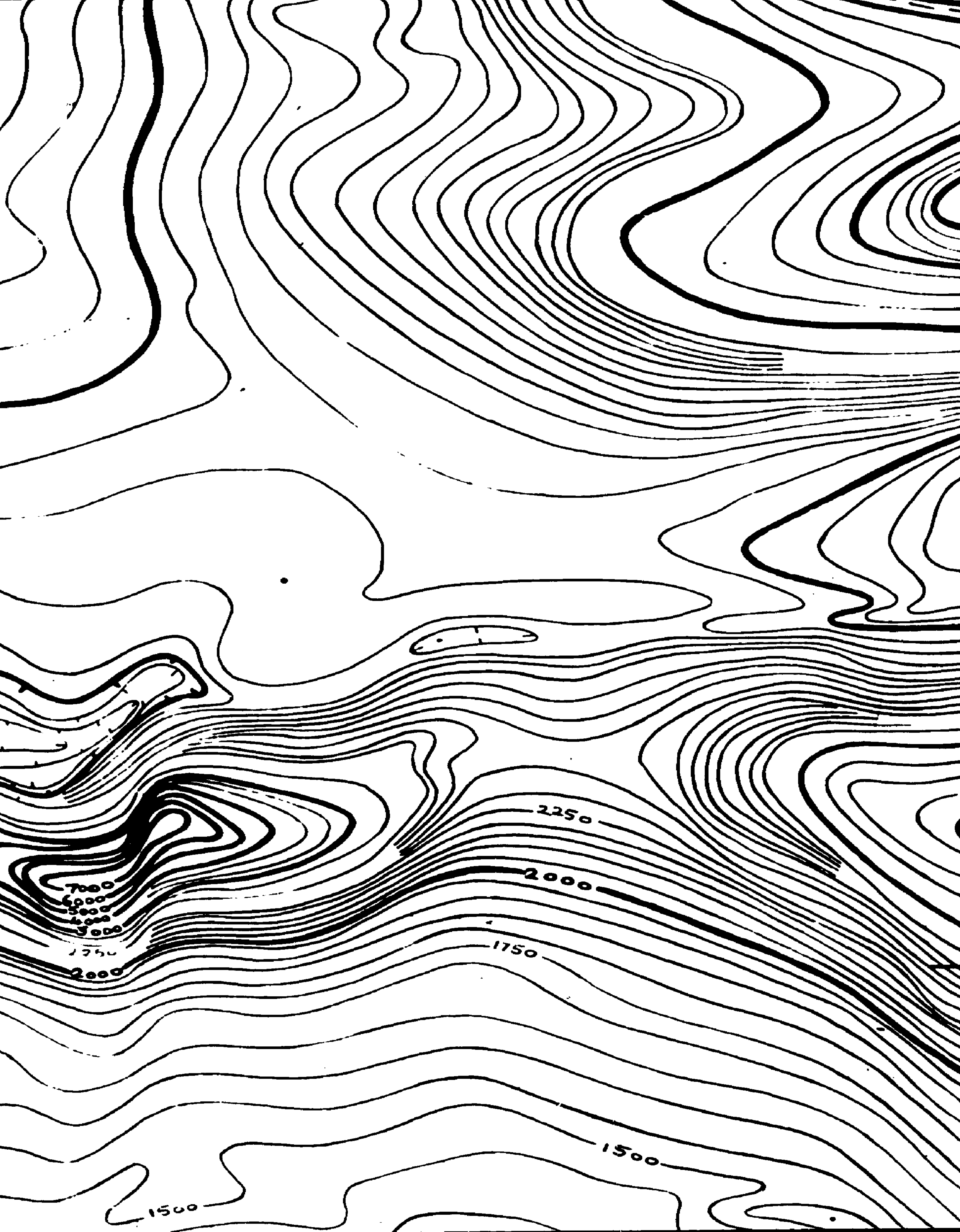
2000
7000
6000
5000
4000
3000
2250
2000
1750
1750
1500


2250
2000
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6000
5000
4000
3000
2000
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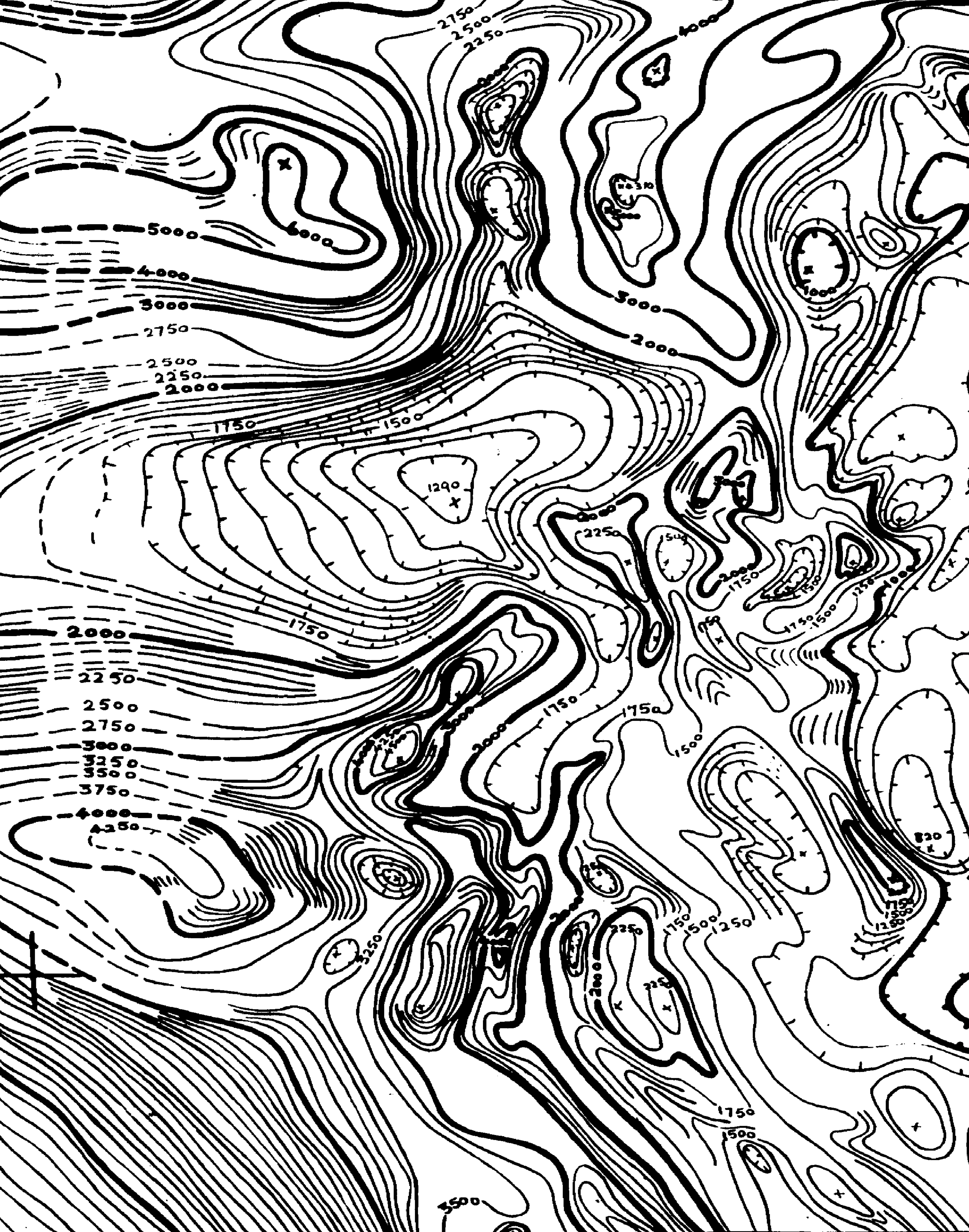
1500
1500



2750
2500
2250
4000
5000
6000
4000
3000
2750
2500
2250
2000
3000
2000
1750
1500
1290
2000
2250
1750
2000
2250
2500
2750
3000
3250
3500
3750
4000
4250
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3250
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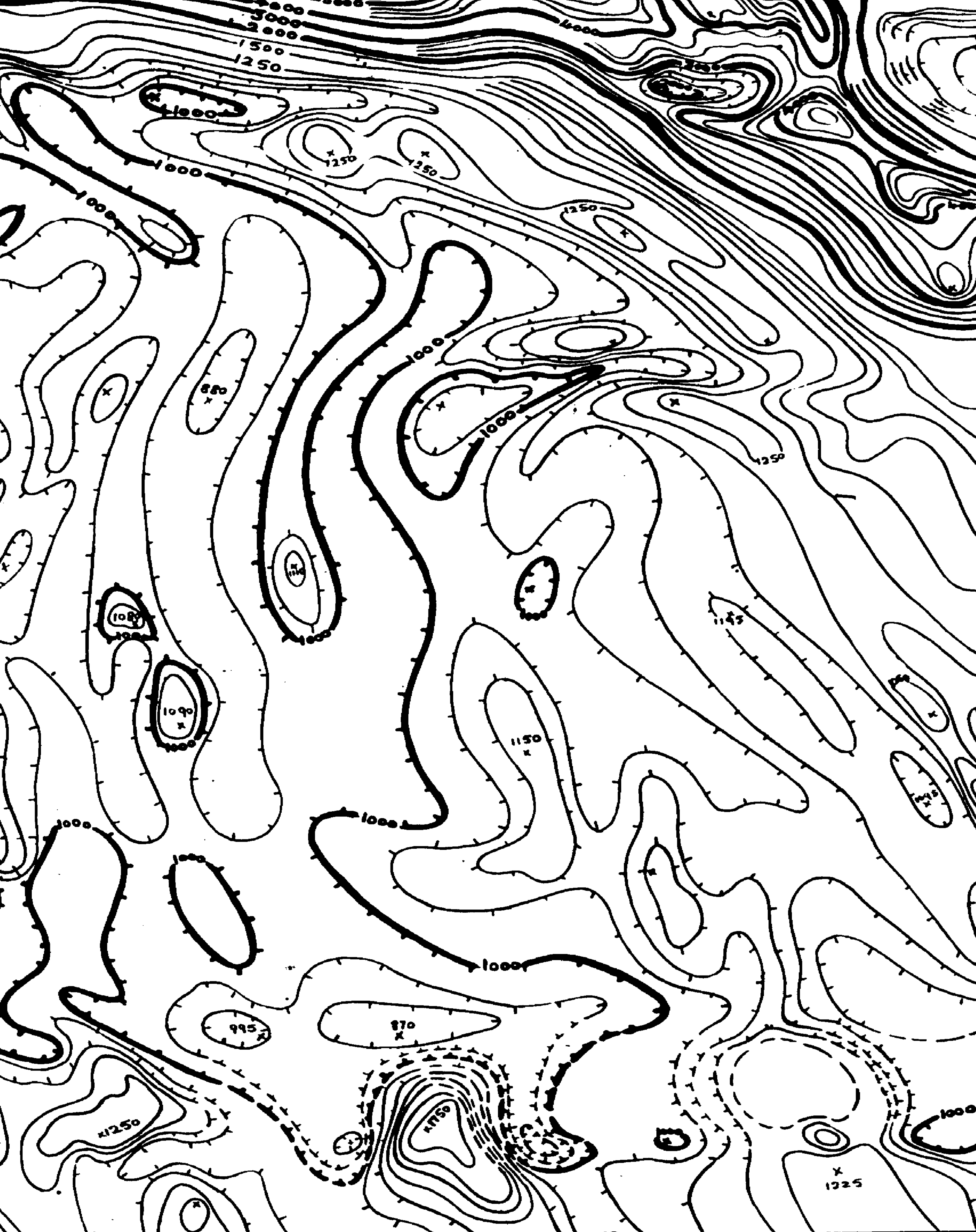
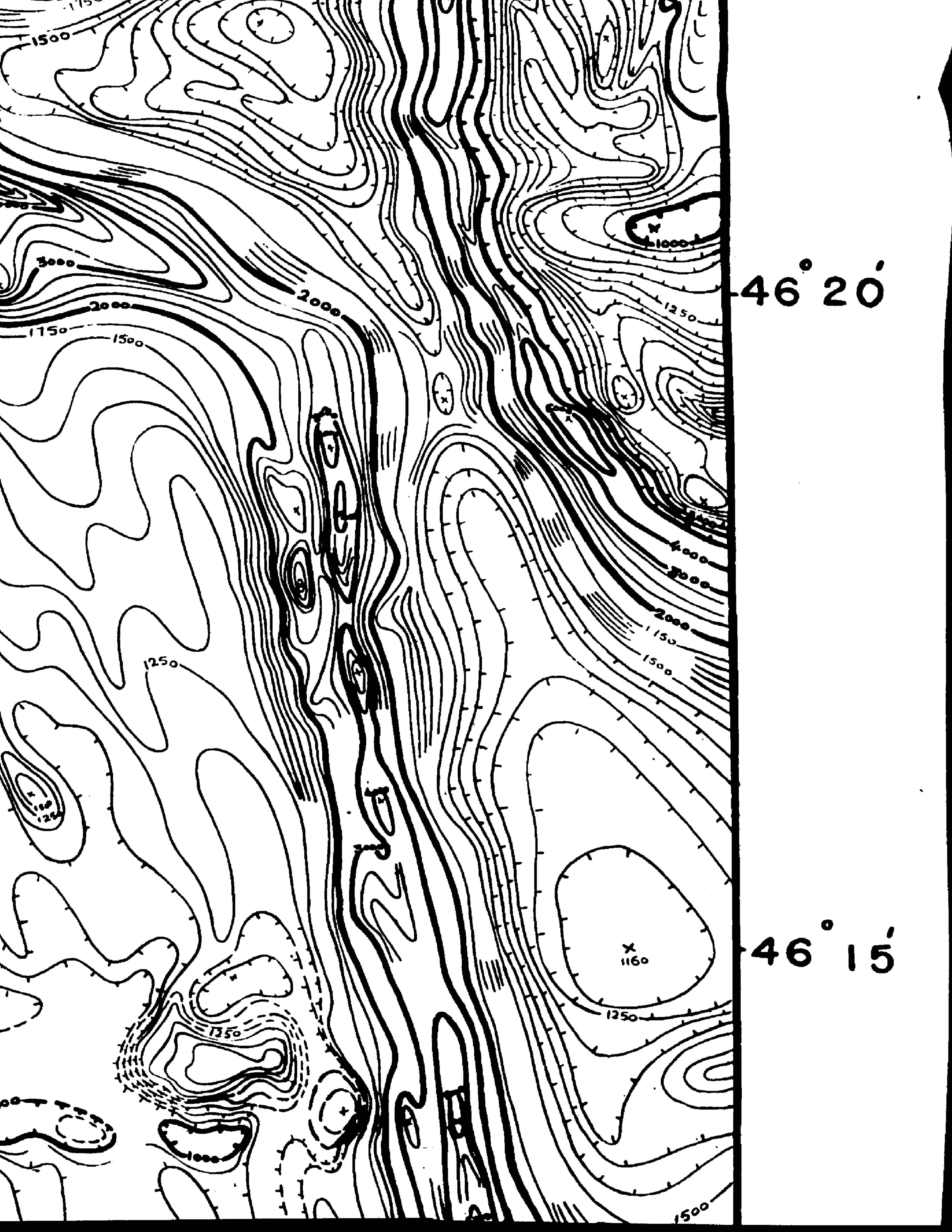
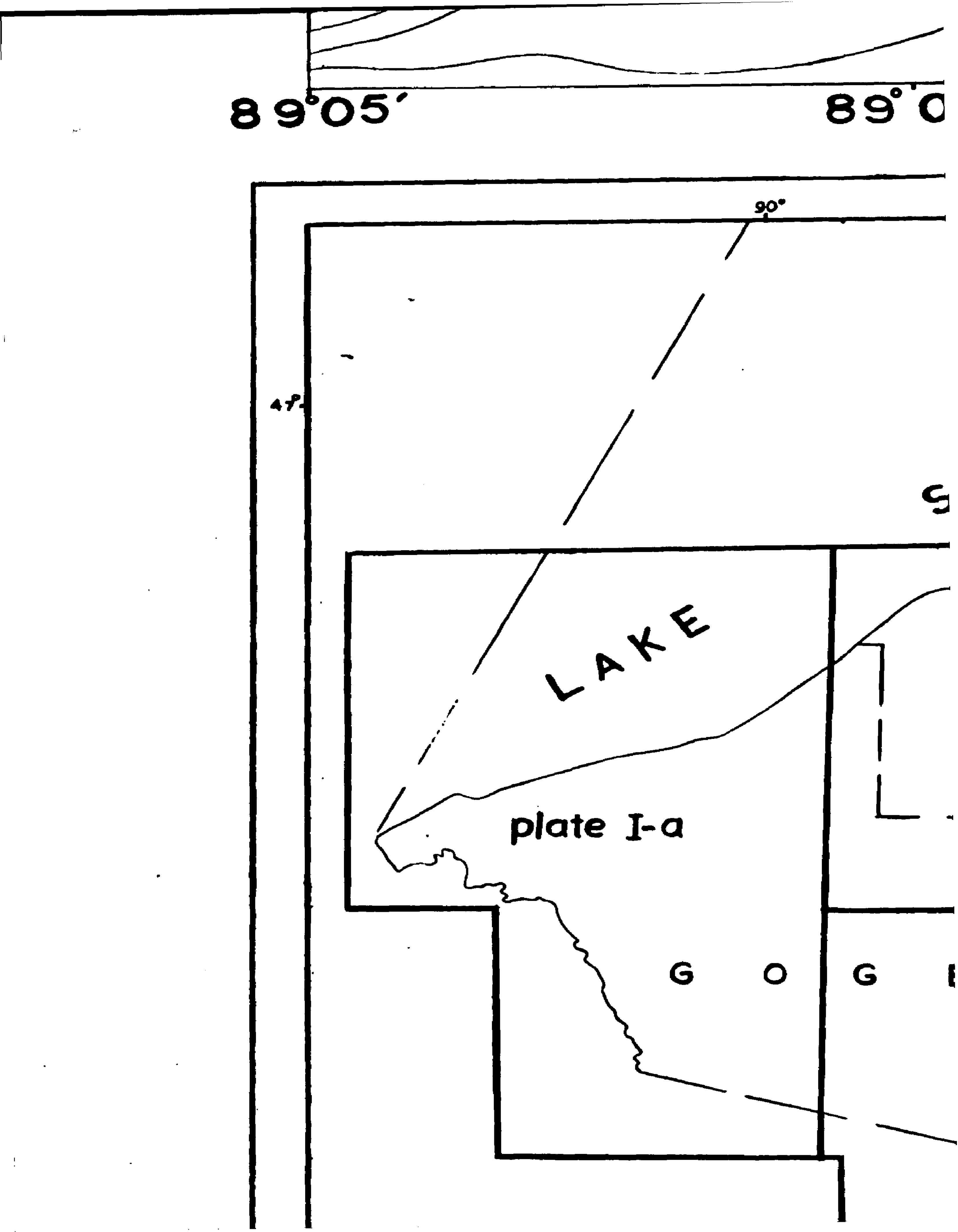
1500
3500



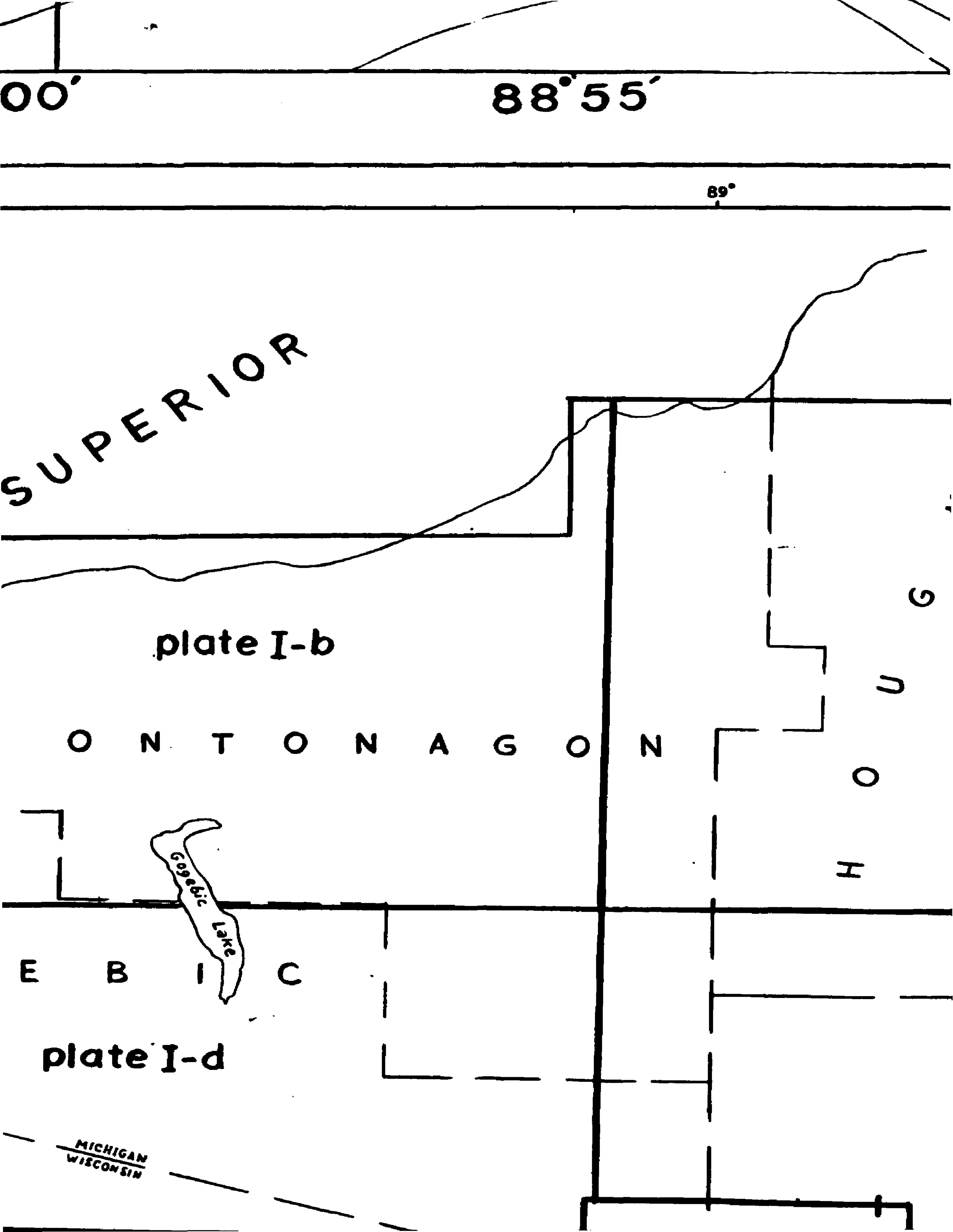
4000
3000
2000
1500
1250
1000
880
1090
1150
1145
870
995
1250
1225

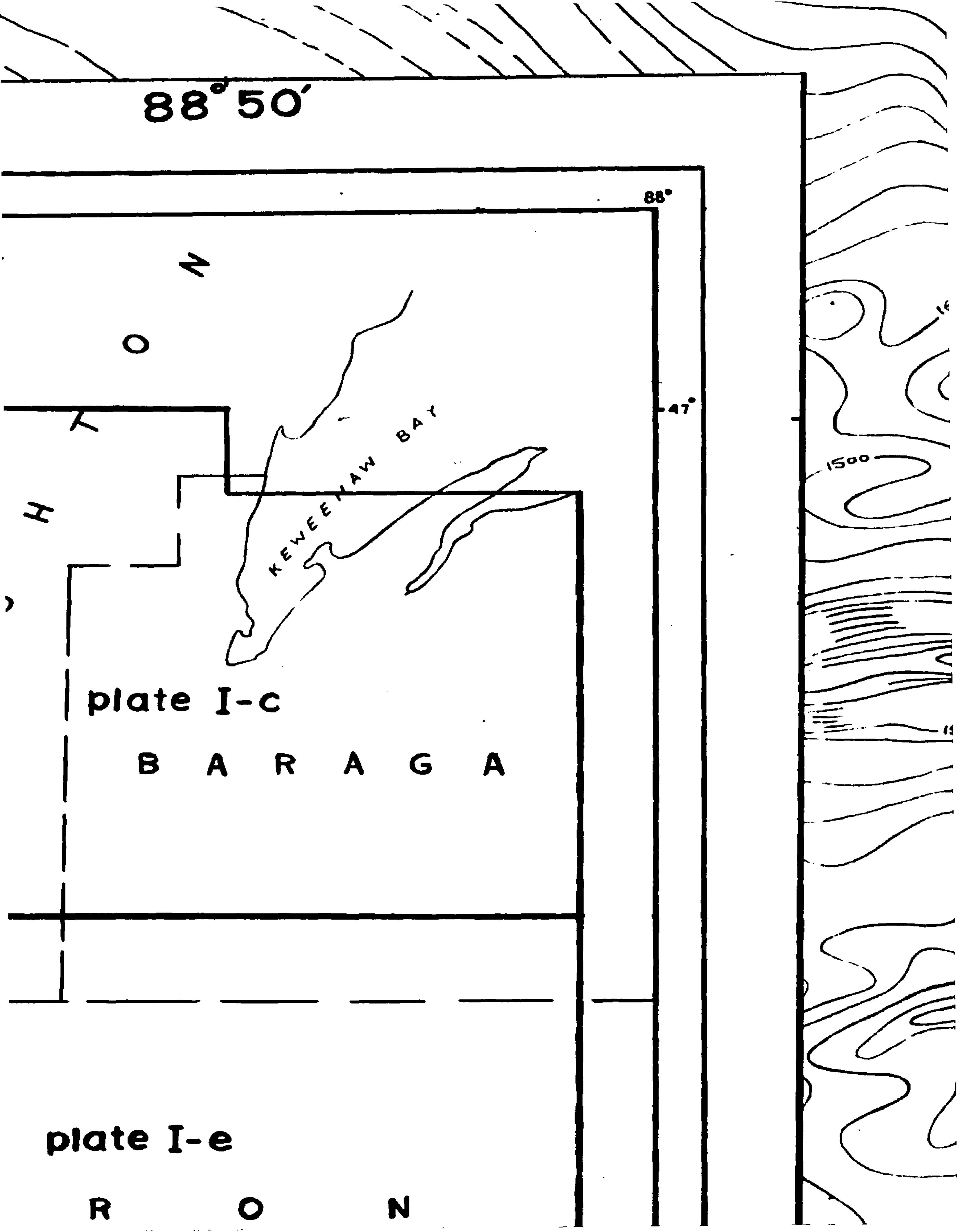


46°20′
46°15′
1500
3000
2000
1750
1250
1000
4000
1160



89°05′
89°0
90°
47°
LAKE
plate I-a
G O G E


00′
88°55′
89°
SUPERIOR
plate I-b
O N T O N A G O N
H O U G
Gogebic Lake
E B I C
plate I-d
MICHIGAN
WISCONSIN


88°50'
88°
47°
KEWEENAW BAY
1500
plate I-c
B A R A G A
plate I-e
R O N

1750
1750
1500
1600
1600
1500
1500
1500
1500
1750
1750
1500
1500


1500
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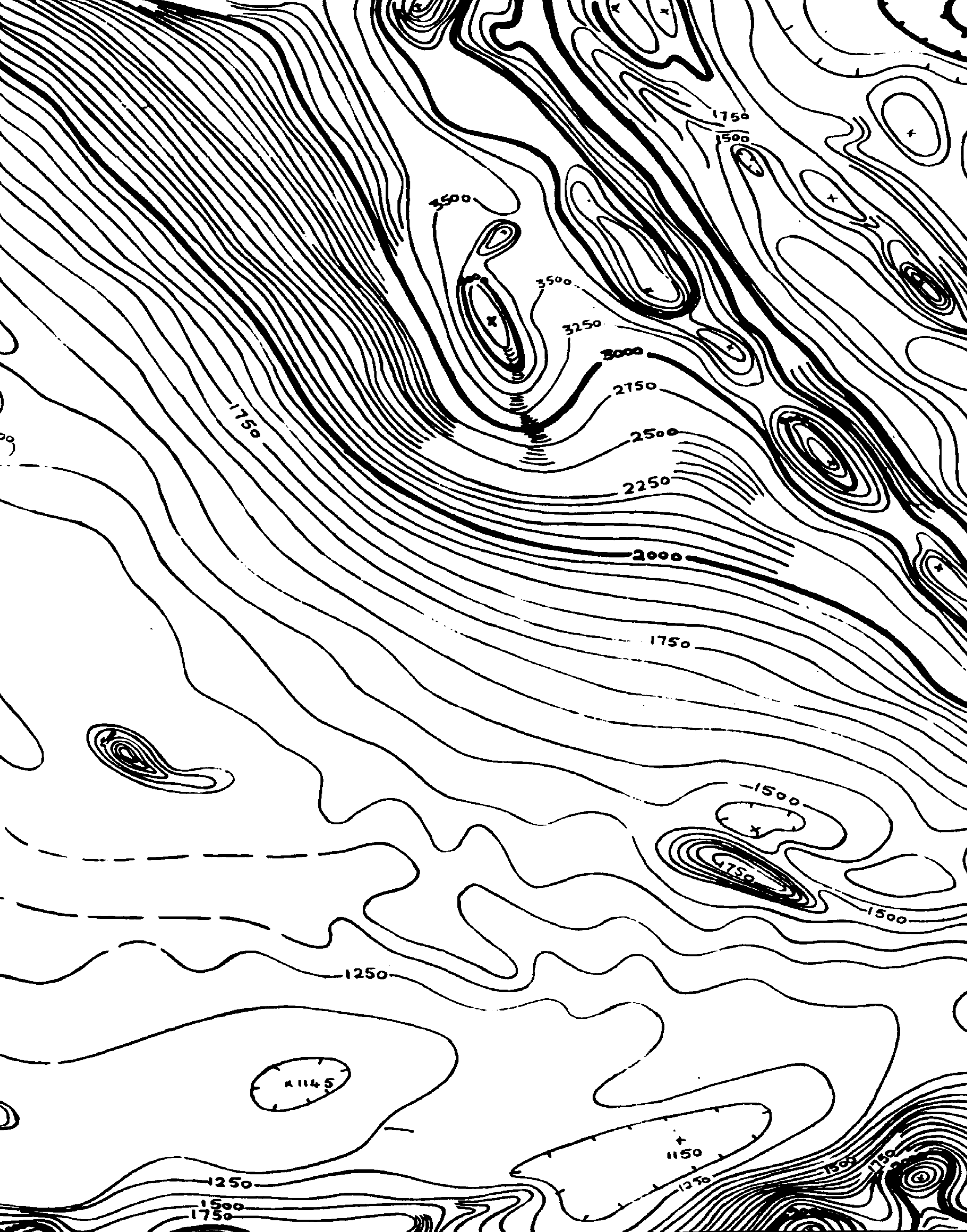
1500
1350
1300
1250
1250
1250
1500
1500



1750
1500
3500
3500
3250
3000
2750
1750
2500
2250
2000
1750
1500
1750
1500
1250
1145
1150
1250
1500
1750
1250
1500
1750

995
970
1250
1750
1000
1225
1250
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1250
1250
1500
1250
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2000
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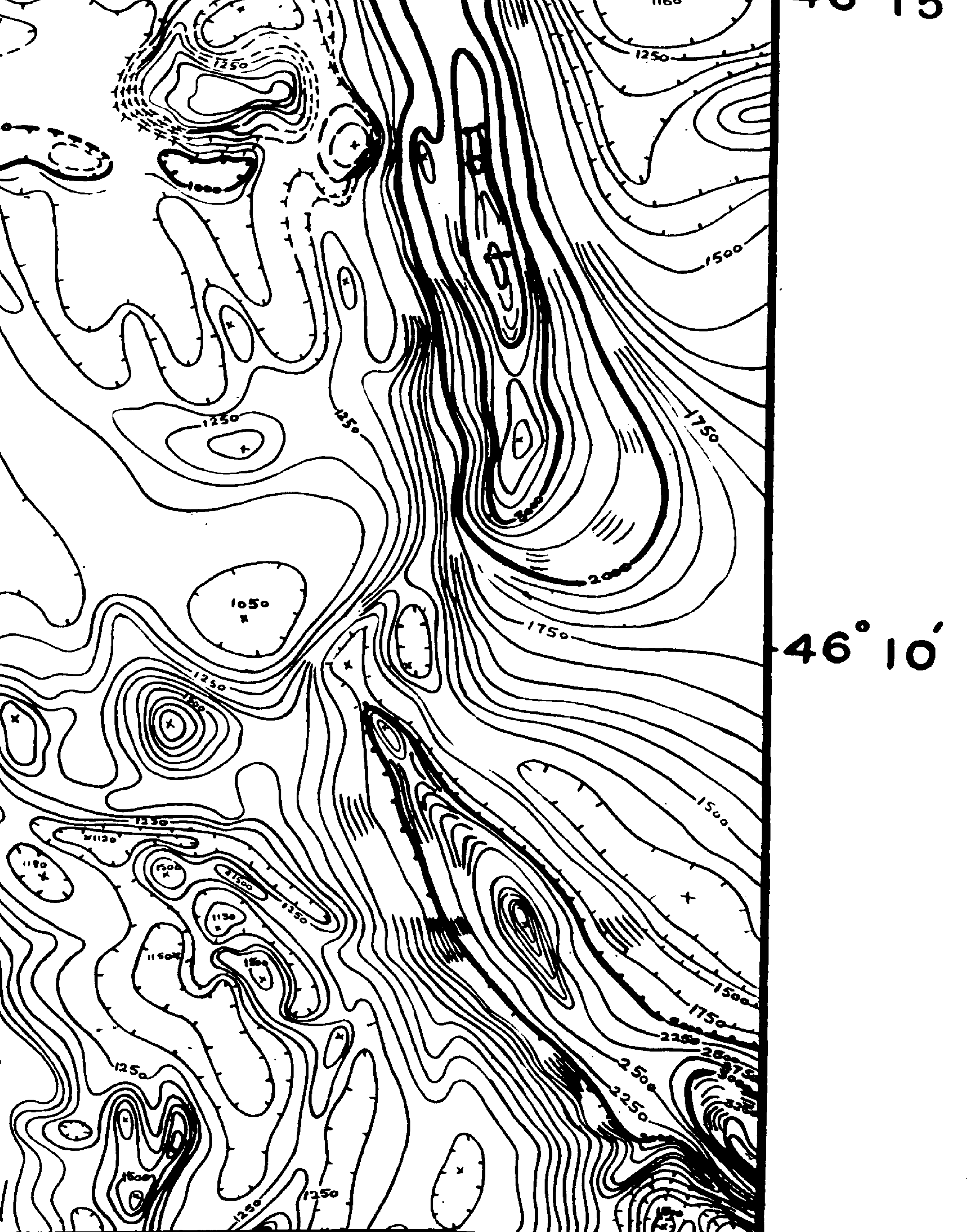
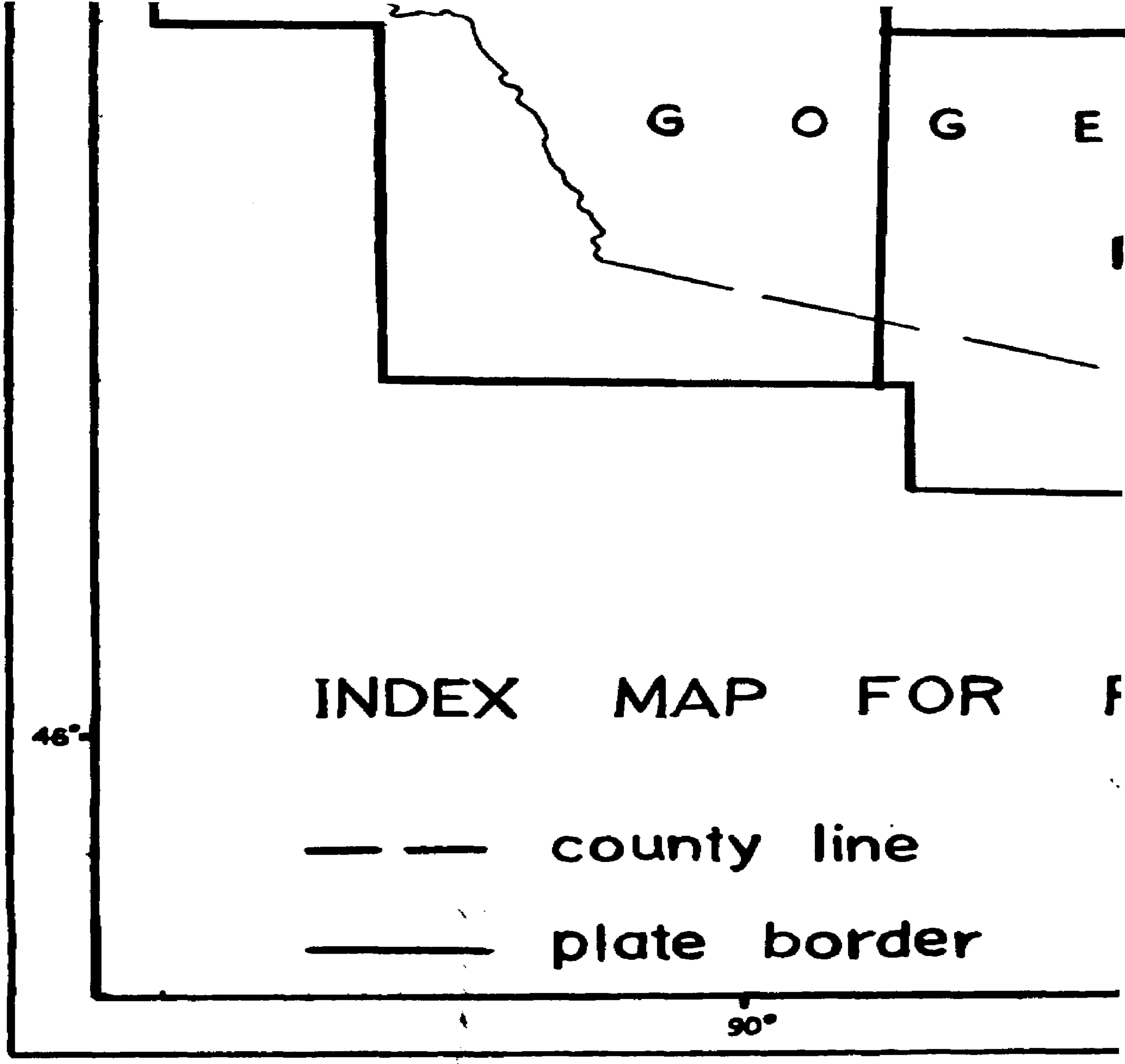
1500
1250
1750
1750

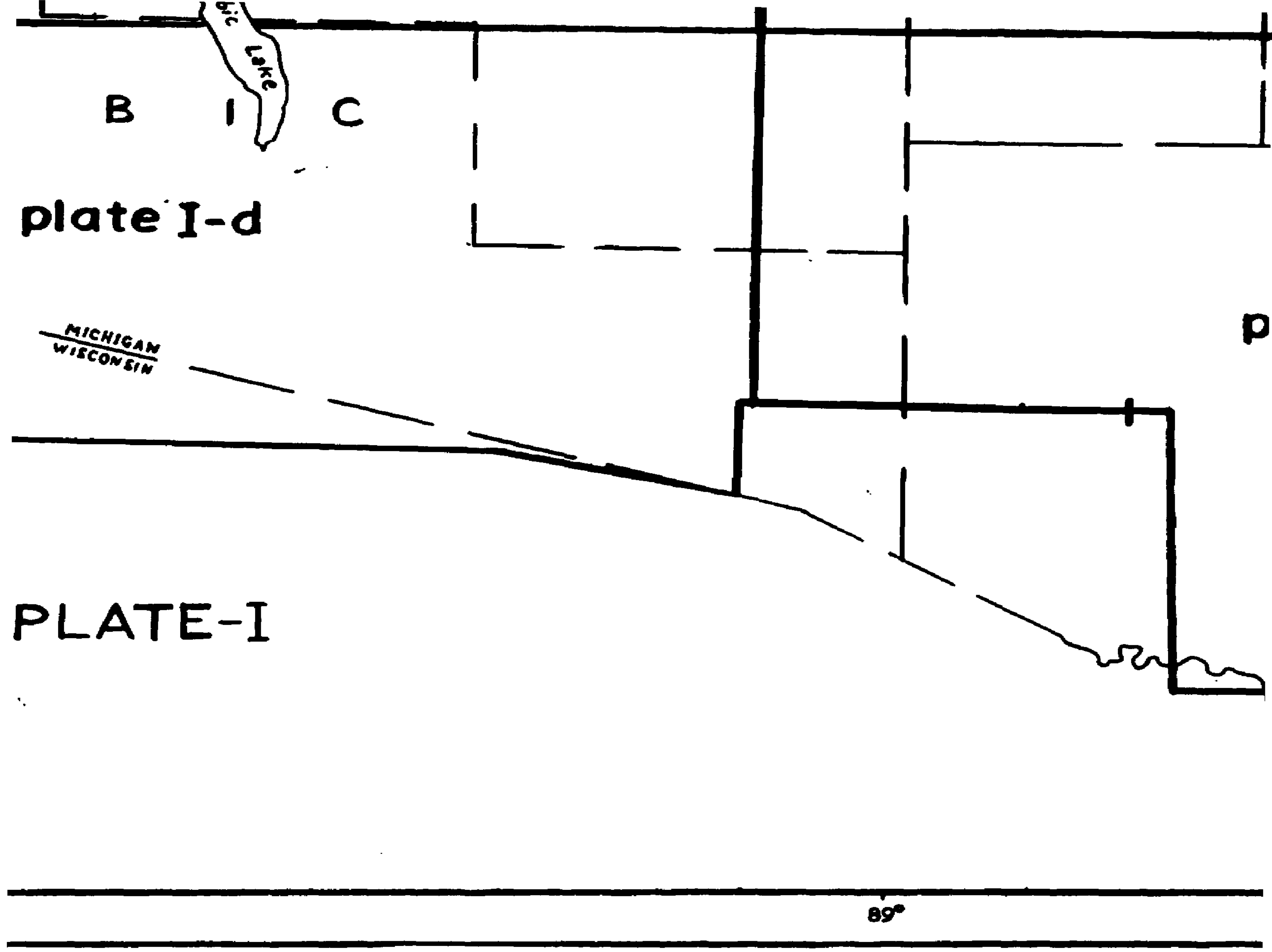


46°10′
1250
1500
1750
2000
1050
1000
2250
2500



AEROMAGNETIC M

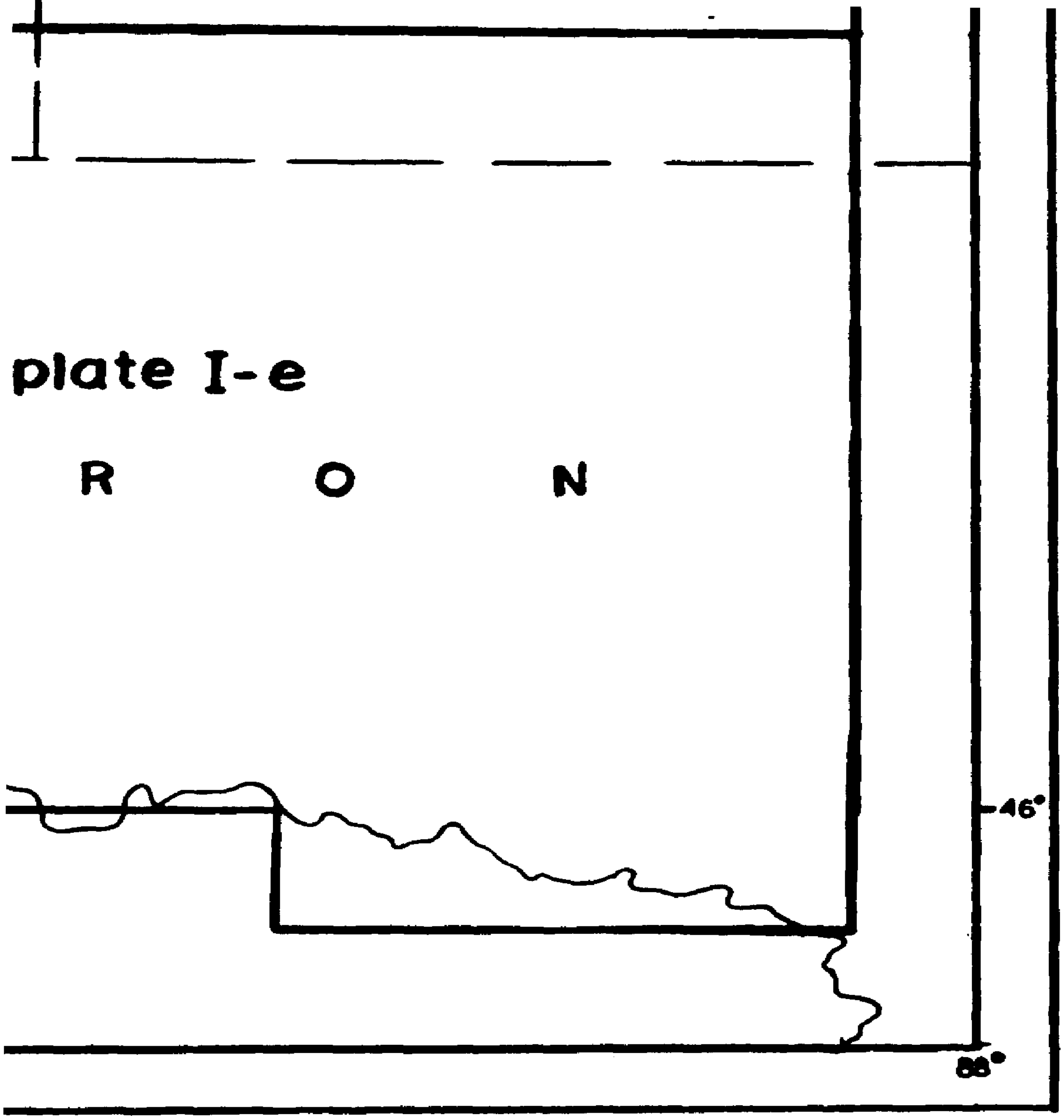
THE NORTHE



MAP OF THE WESTE

OF

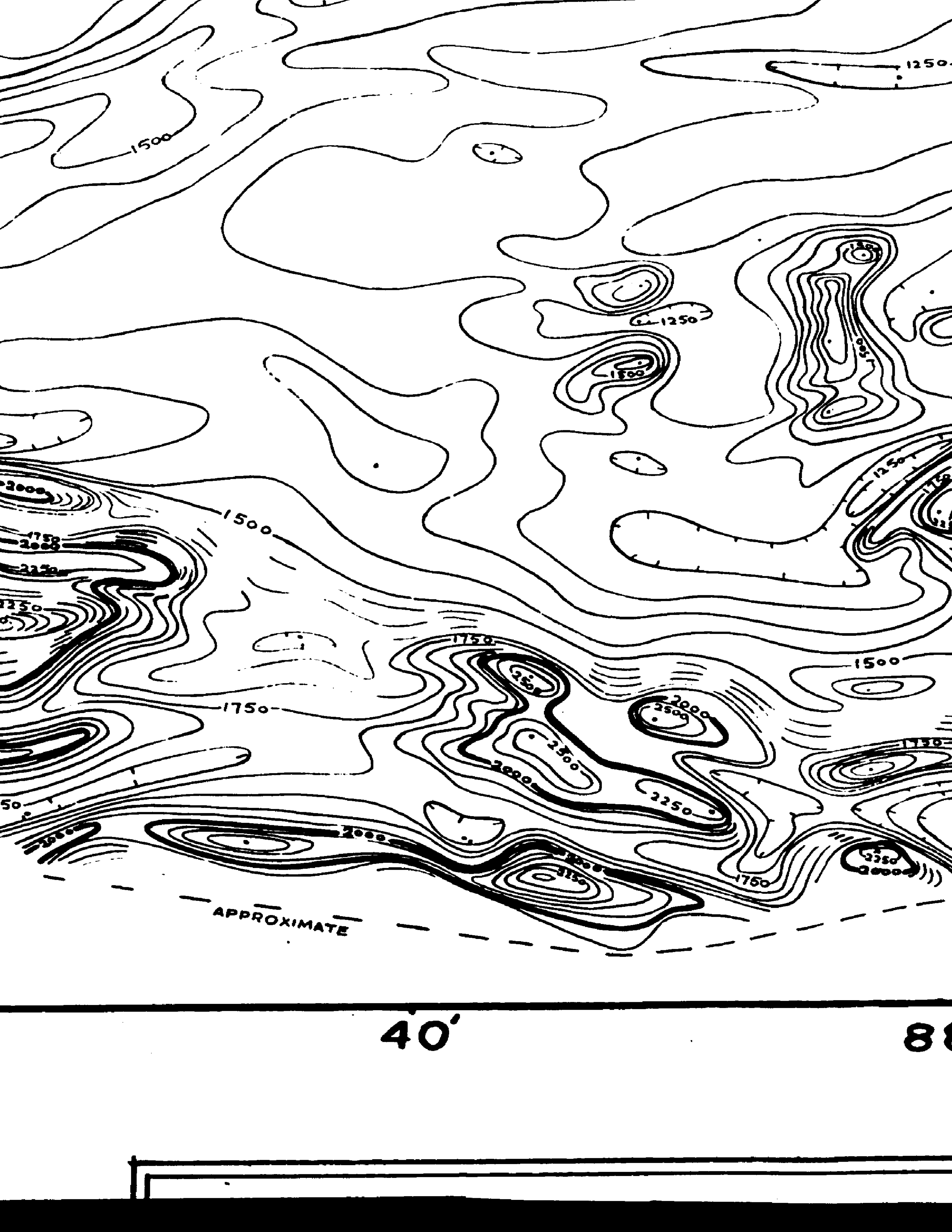
RN PENINSULA OF

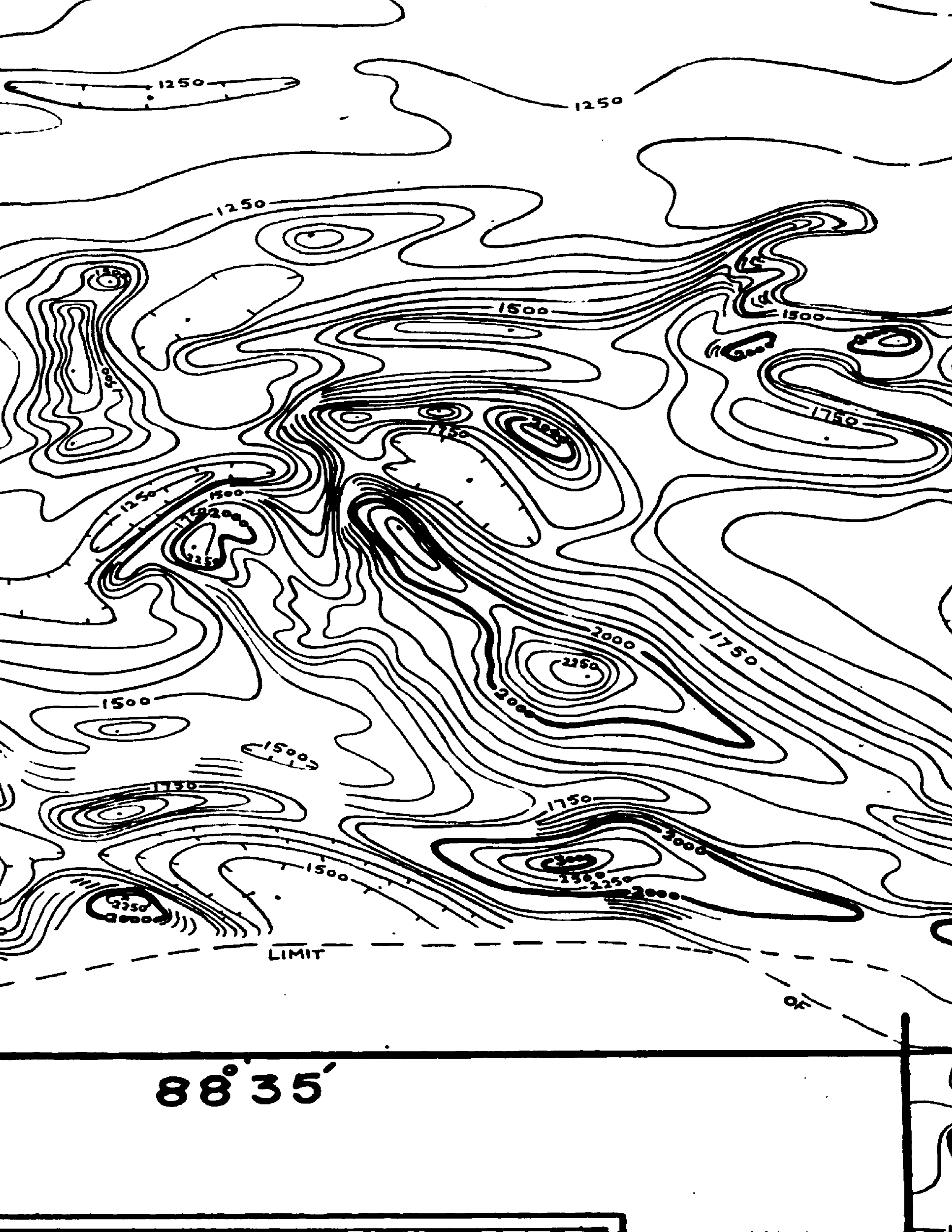


88°45′

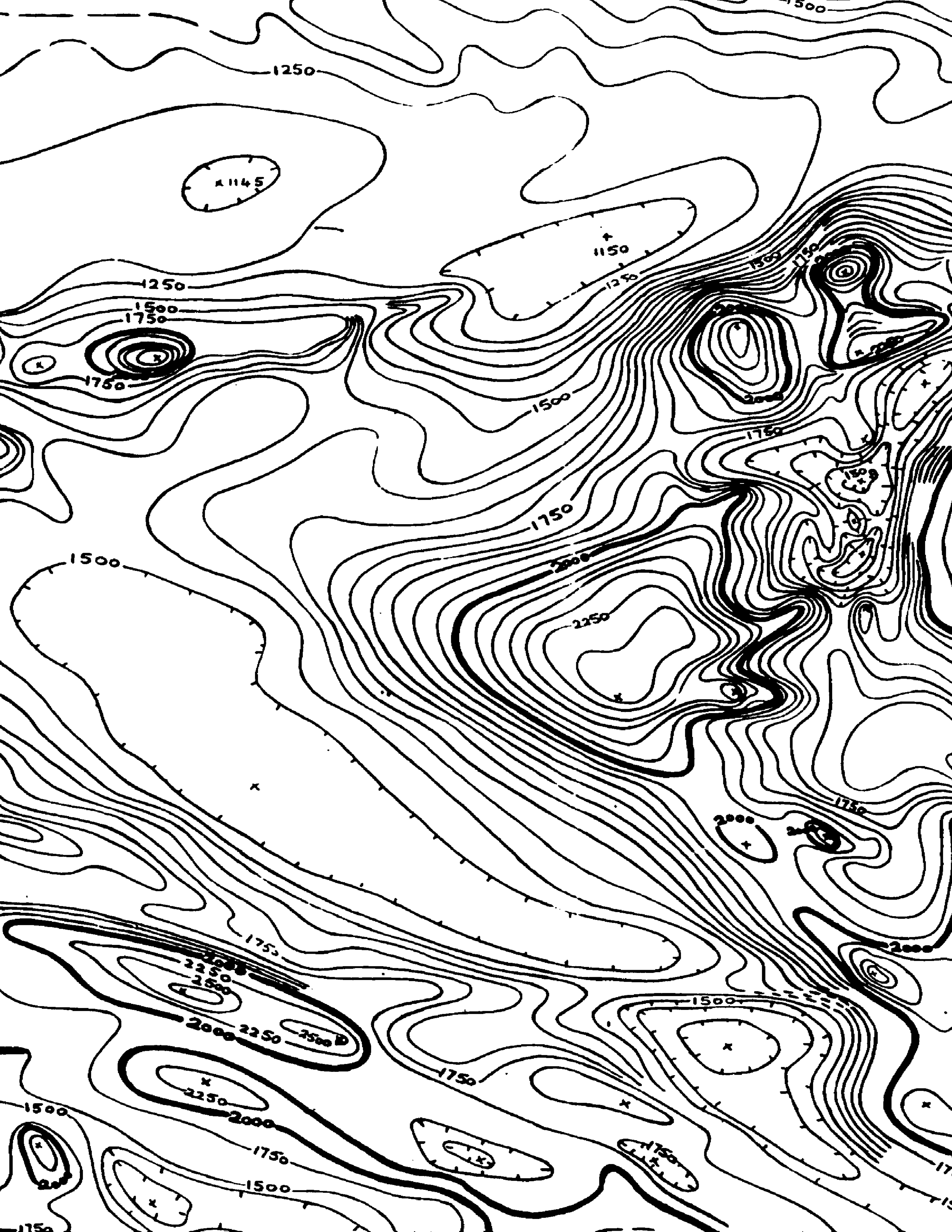
ERN HALF

MICHIGAN


APPROXIMATE
1500
1750
2000
2250
2500
1250
40'
88



1250
1250
1250
1500
1500
1500
1500
1500
1750
1750
1750
1750
2000
2000
2000
2000
2250
2250
2500
3000
LIMIT
OF
88°35′



1250
1500
1145
1150
1250
1500
1750
1750
1500
1750
2000
2250
1750
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2000
2250
2500
2000
2250
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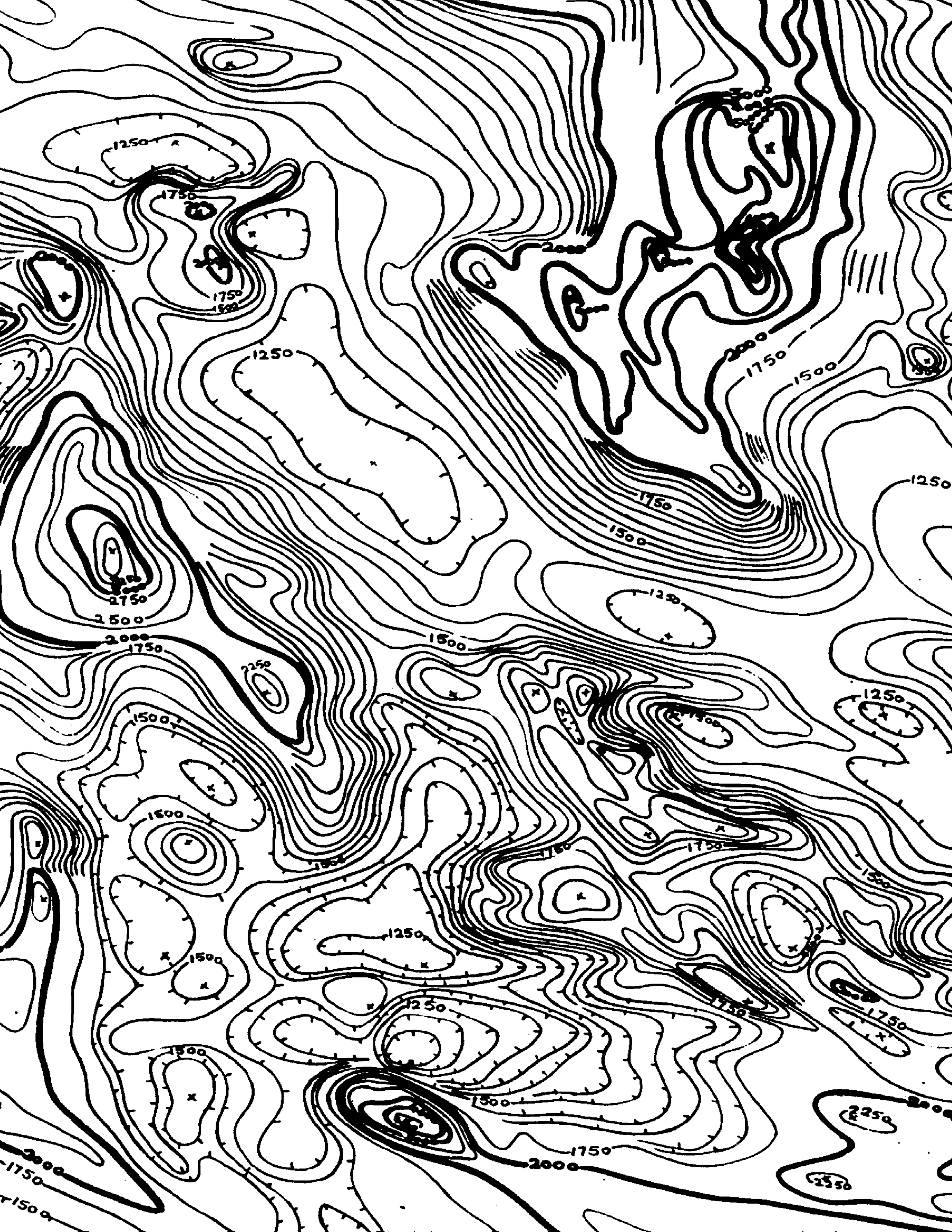
1750
2250
2000
1500
1750
1500
1750



1250
1750
2000
1750
1500
1250
1750
1500
2500
2000
1750
2250
1500
1500
1250
1500
1750
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1250
1500
1250
1750
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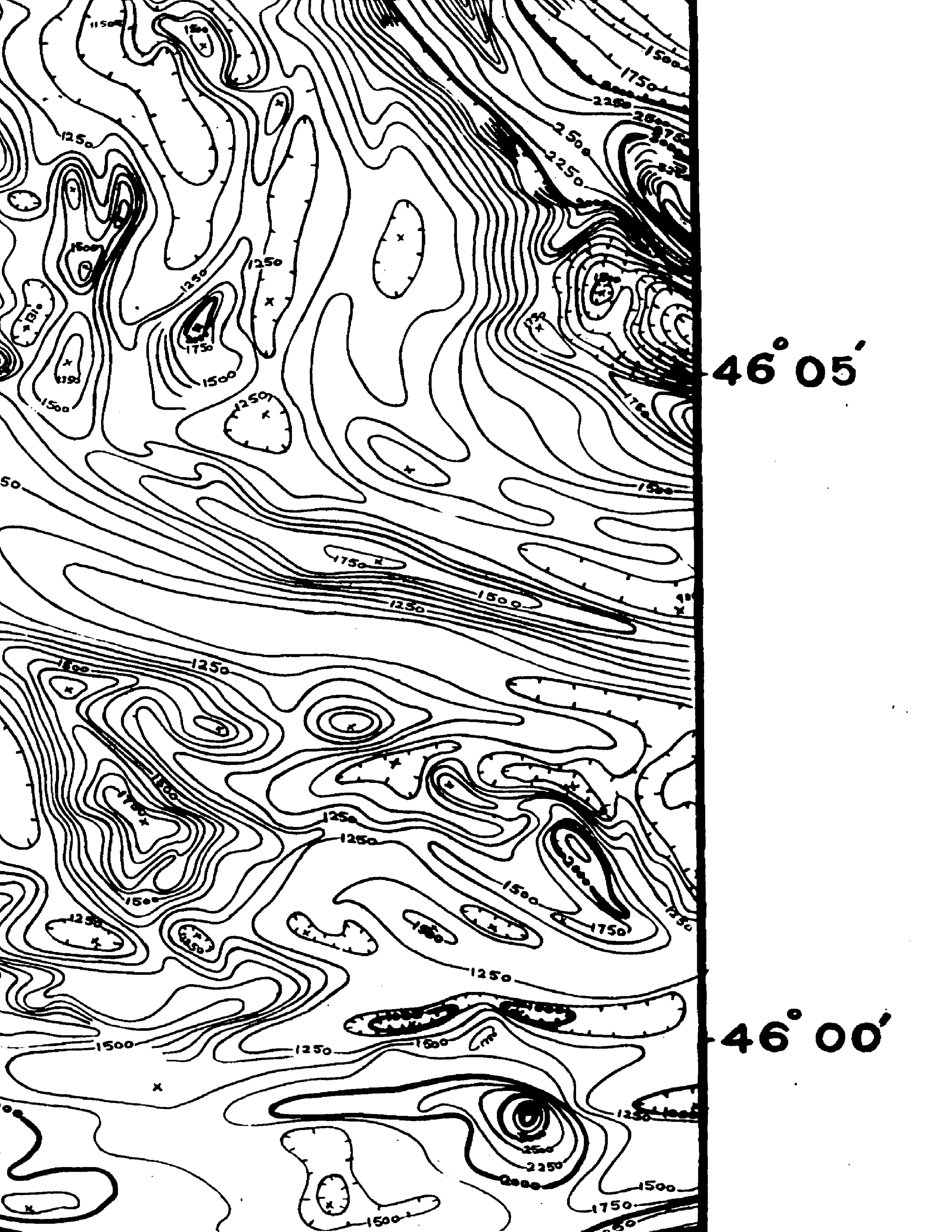
2000
1750
1500
2250



46°05′
46°00′
1250
1500
1750
2250
2500

plate border

90°

AEROMAGNETIC M

THE NORTHER

89°

MAP OF THE WESTE

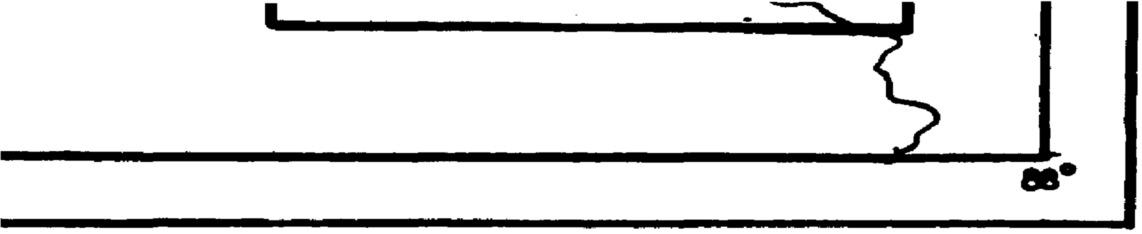
OF

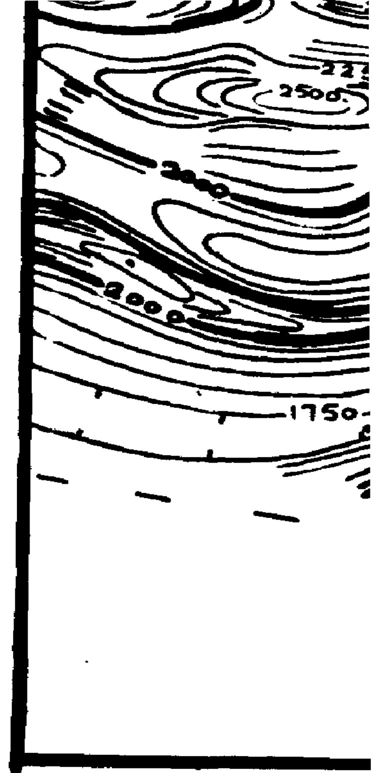
RN PENINSULA OF M

SCALE 1: 62500

0 1 2 3 4 MILES

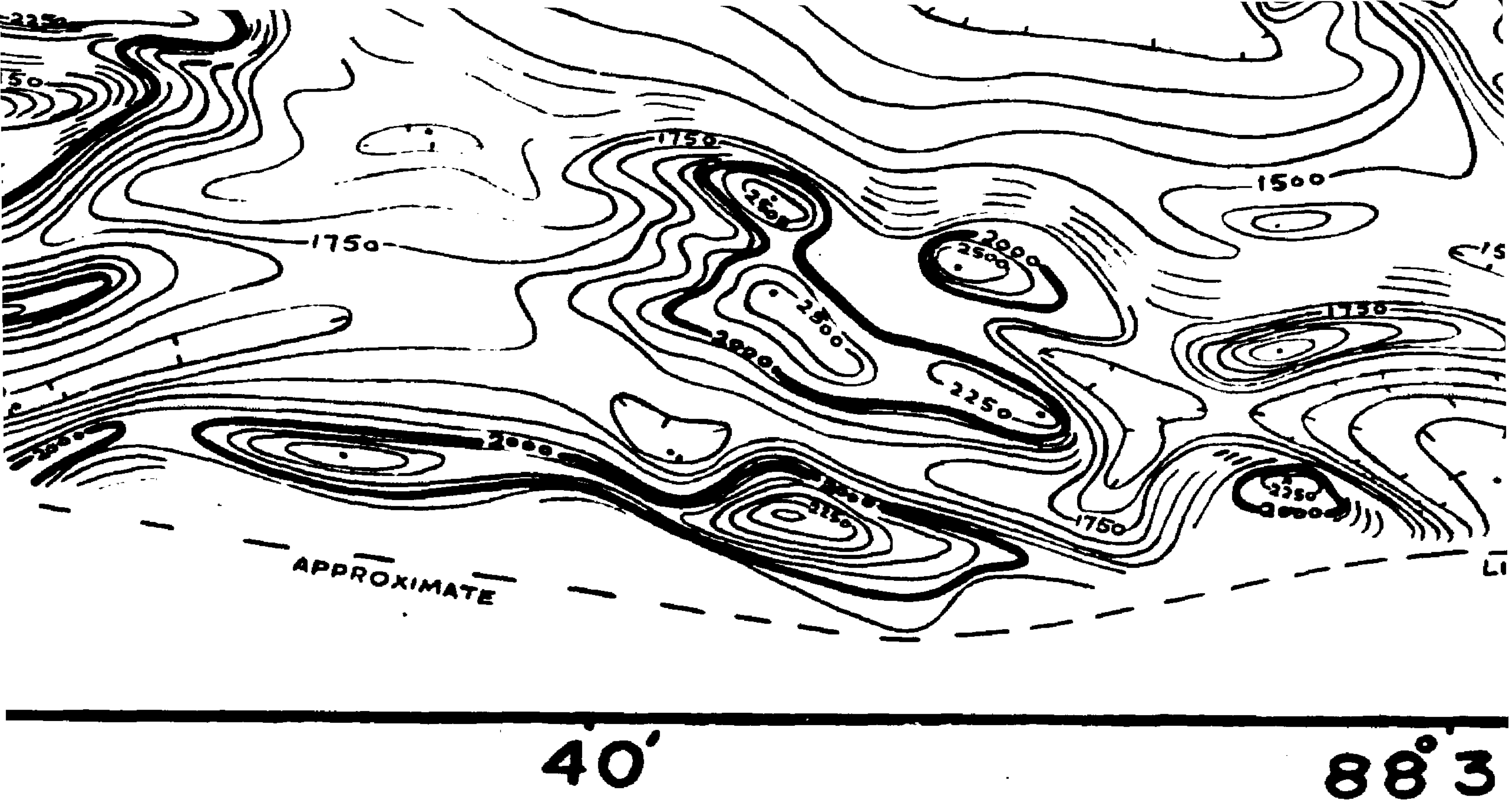
PLATE I-e





ERN HALF

MICHIGAN



LEGEND

CONTOUR INTERVAL 50.-1000 gammas.

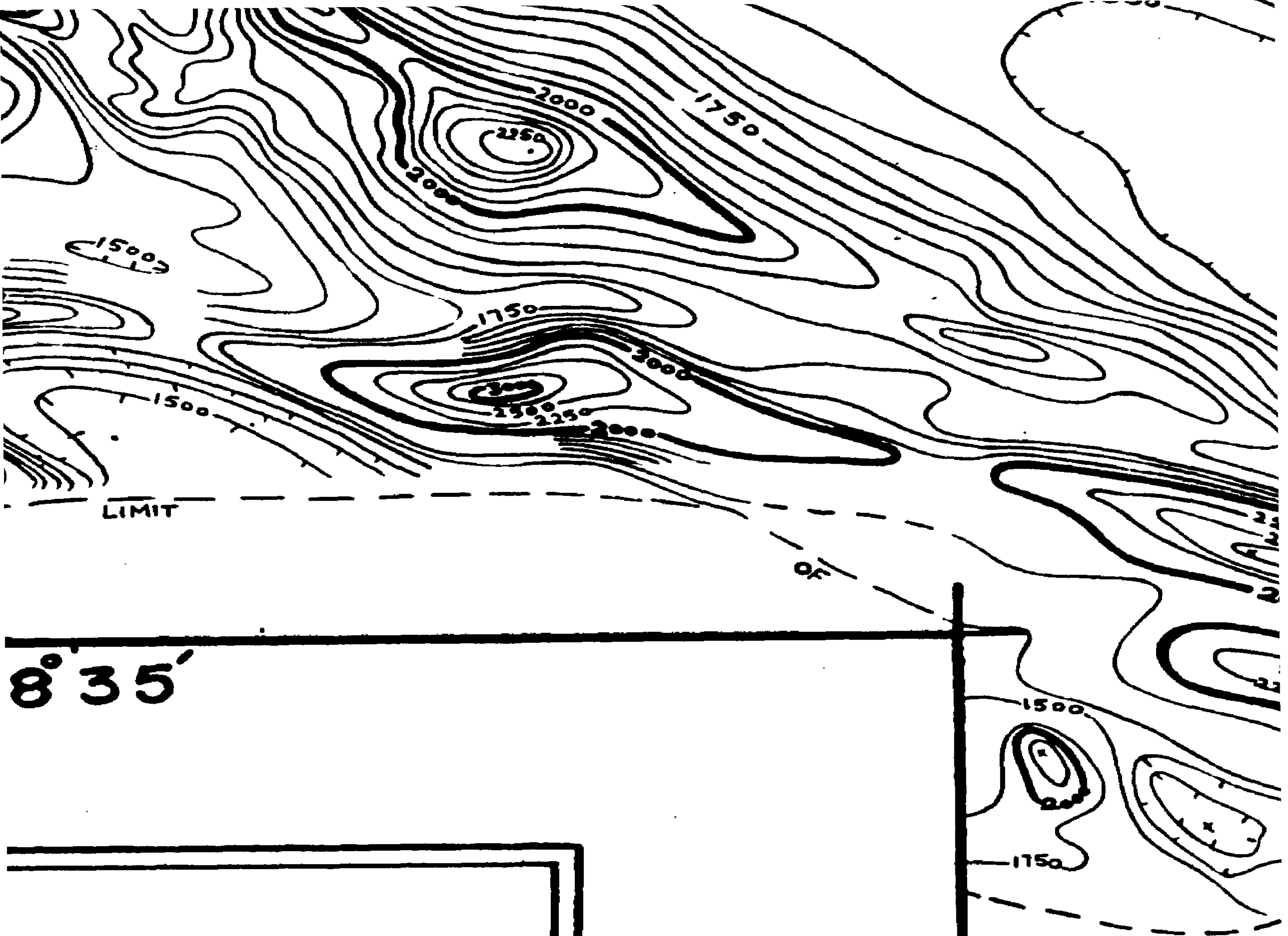
FLIGHT ELEVATION 500 ft. from ground surface.

50, 250, 500 gamma contour. Mag

1000 gamma contour. State or na

Source: These maps were compiled from the U.S. Geologi

file maps.



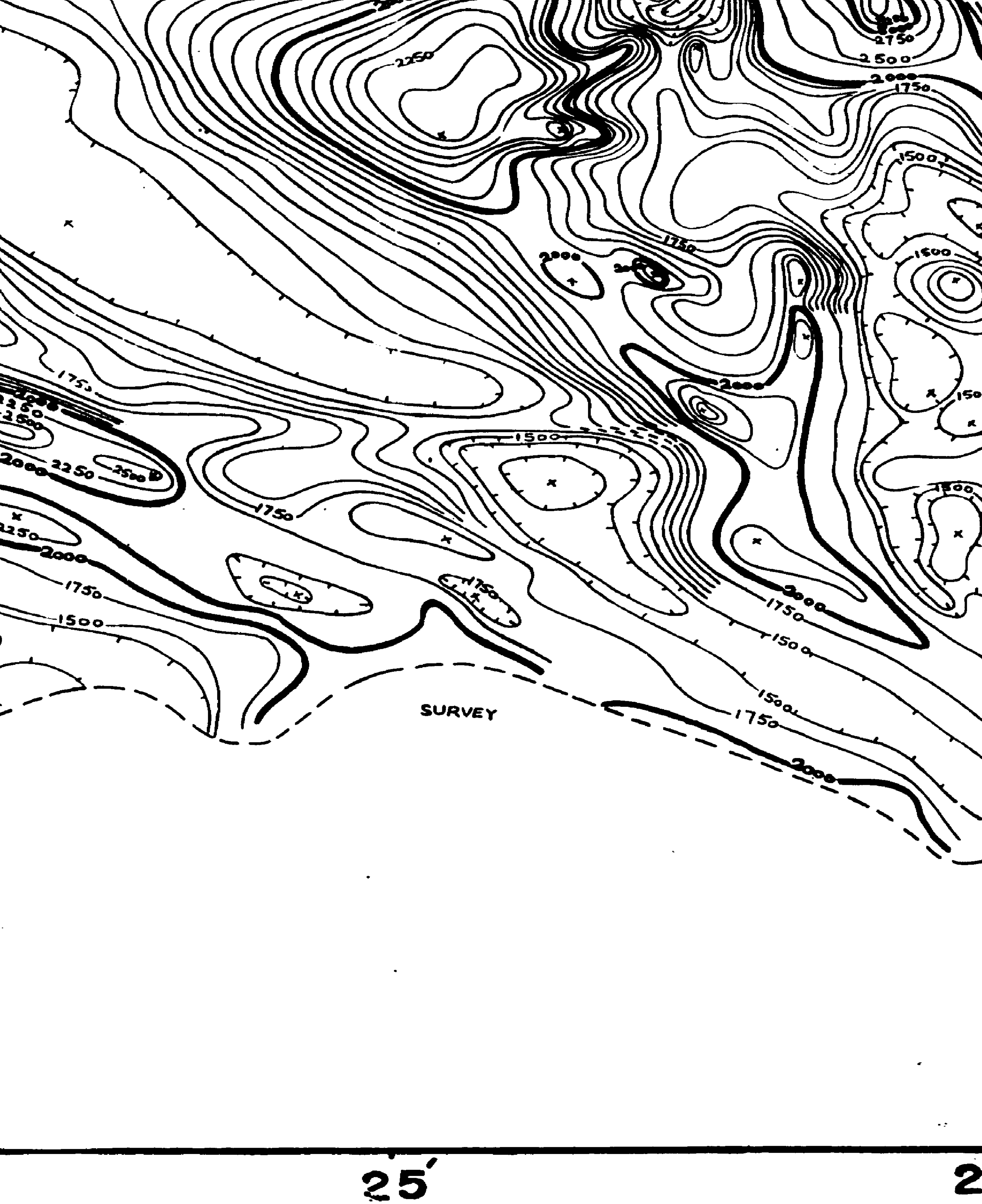
8°35′

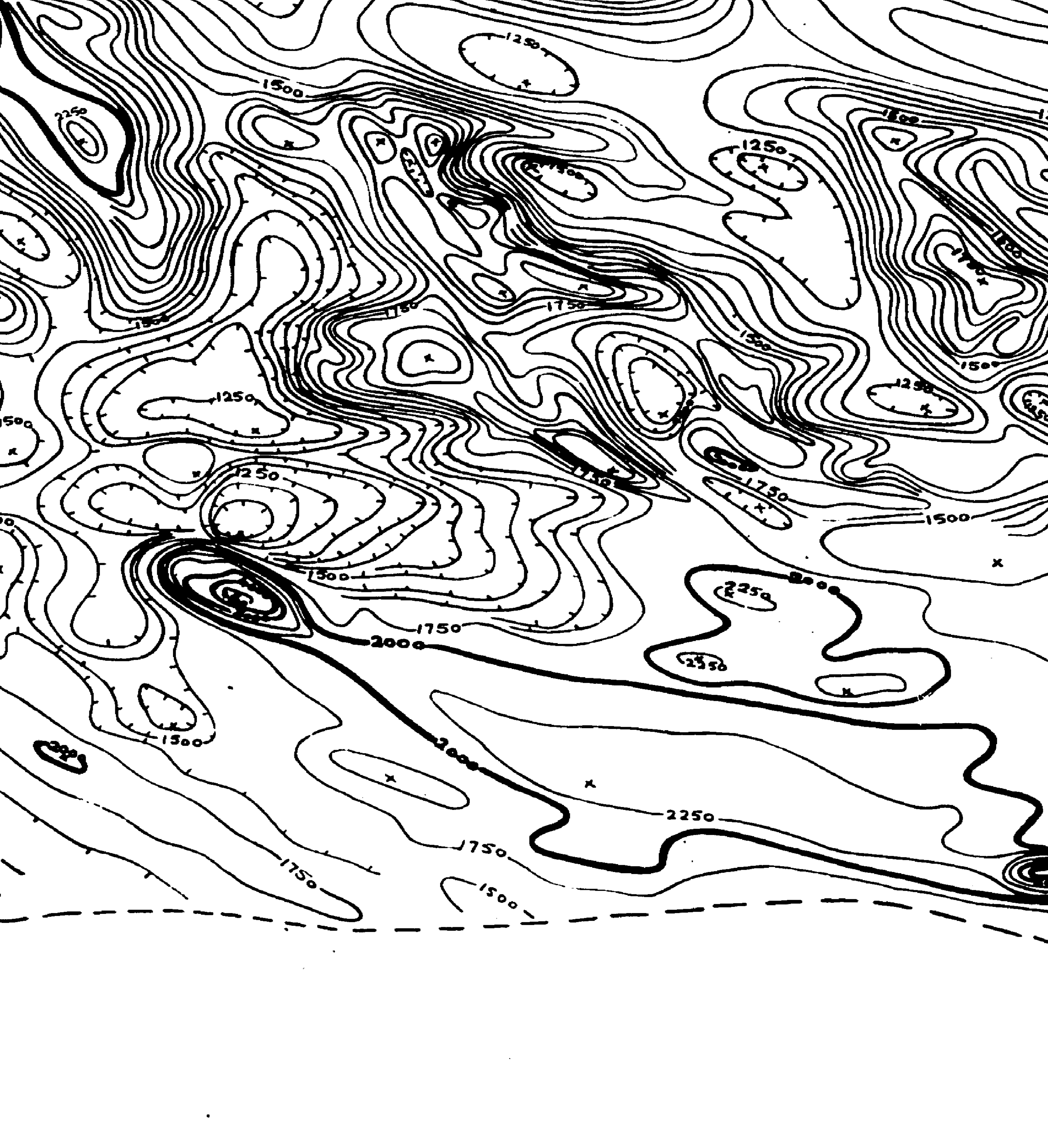
Magnetic low.

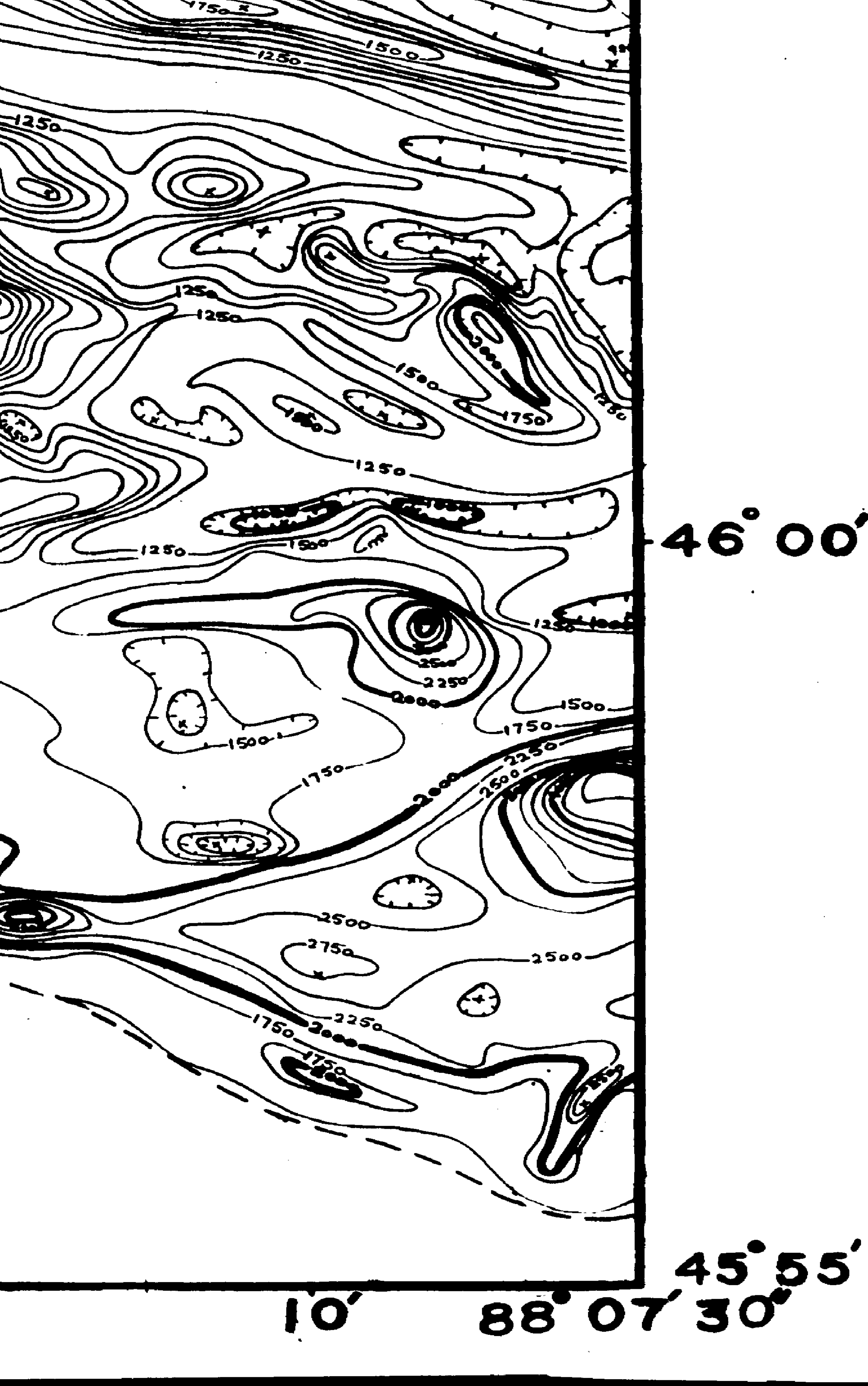
e or natural border.

ieological Survey open-

88°30′


SURVEY
2250
2500
2750
2000
1750
1500
25′


1250
1500
1750
2000
2250
20'
15'


1750
1500
1250
1250
1250
1250
1500
2000
1750
1250
1250
1250
1500
1250
2500
2250
2000
1500
1500
1750
2250
2500
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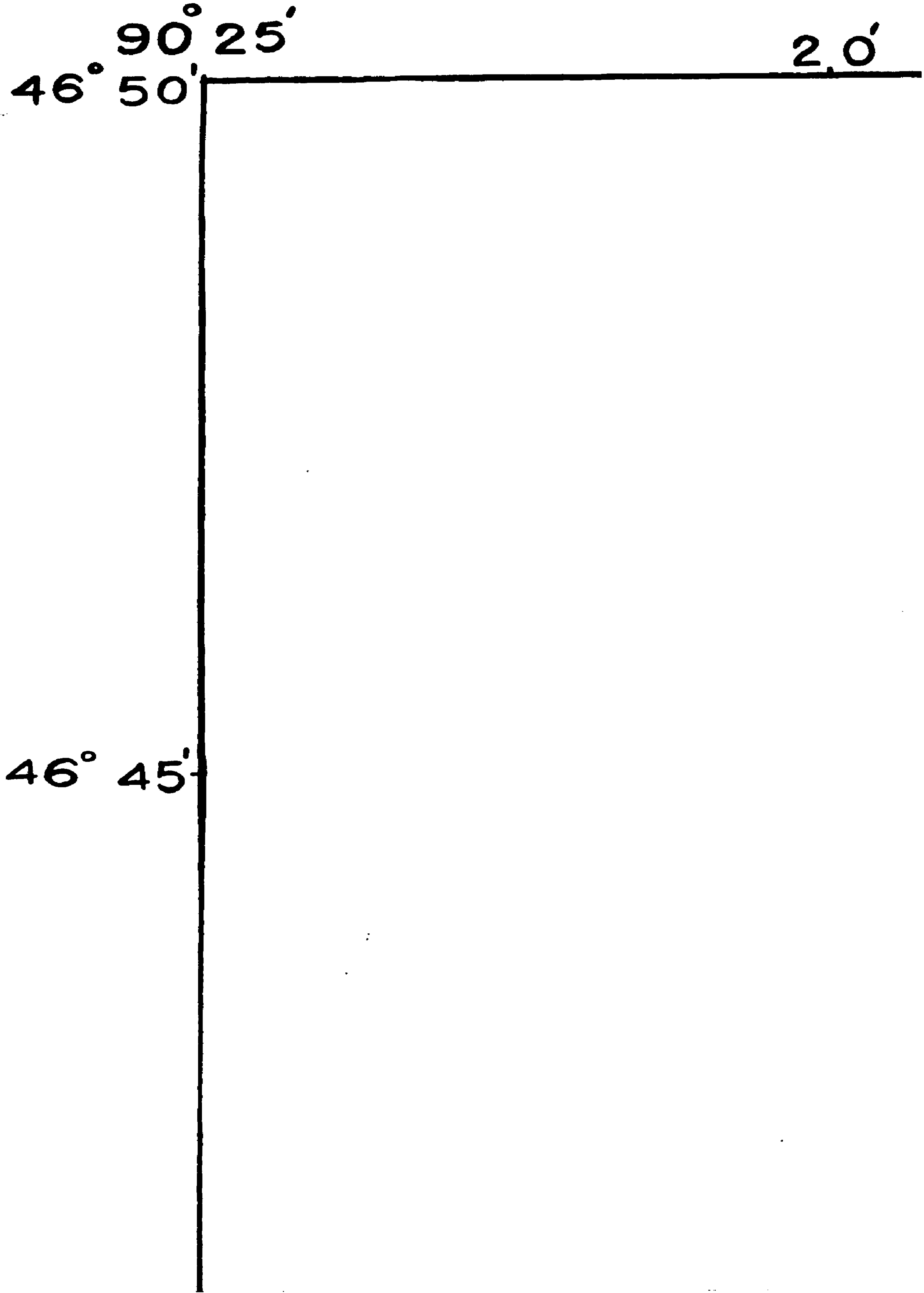
2750
2500
2250
1750
2000
1750
46°00'
45°55'
10'
88°07'30"

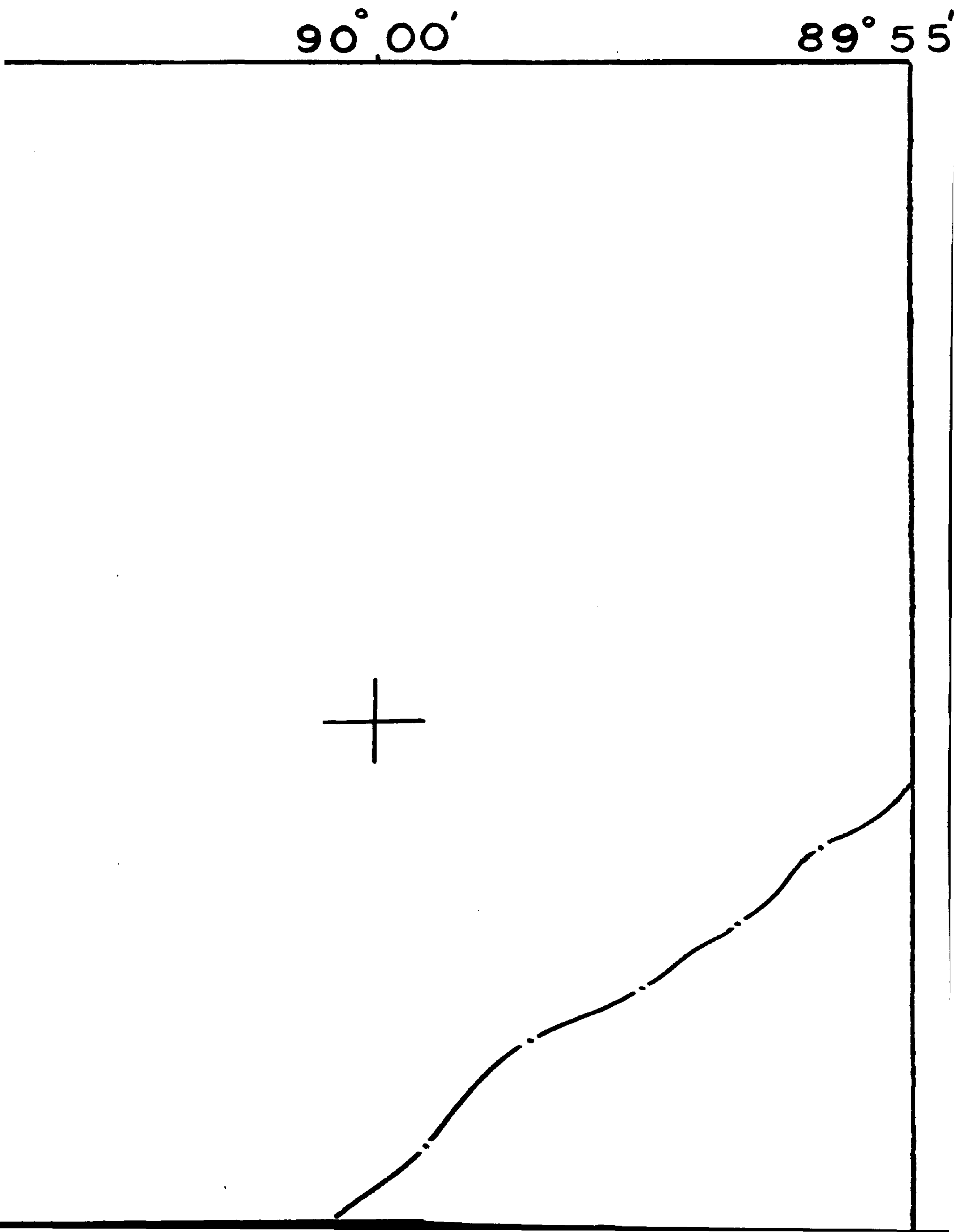

90° 25'
2.0'
46° 50'
46° 45'

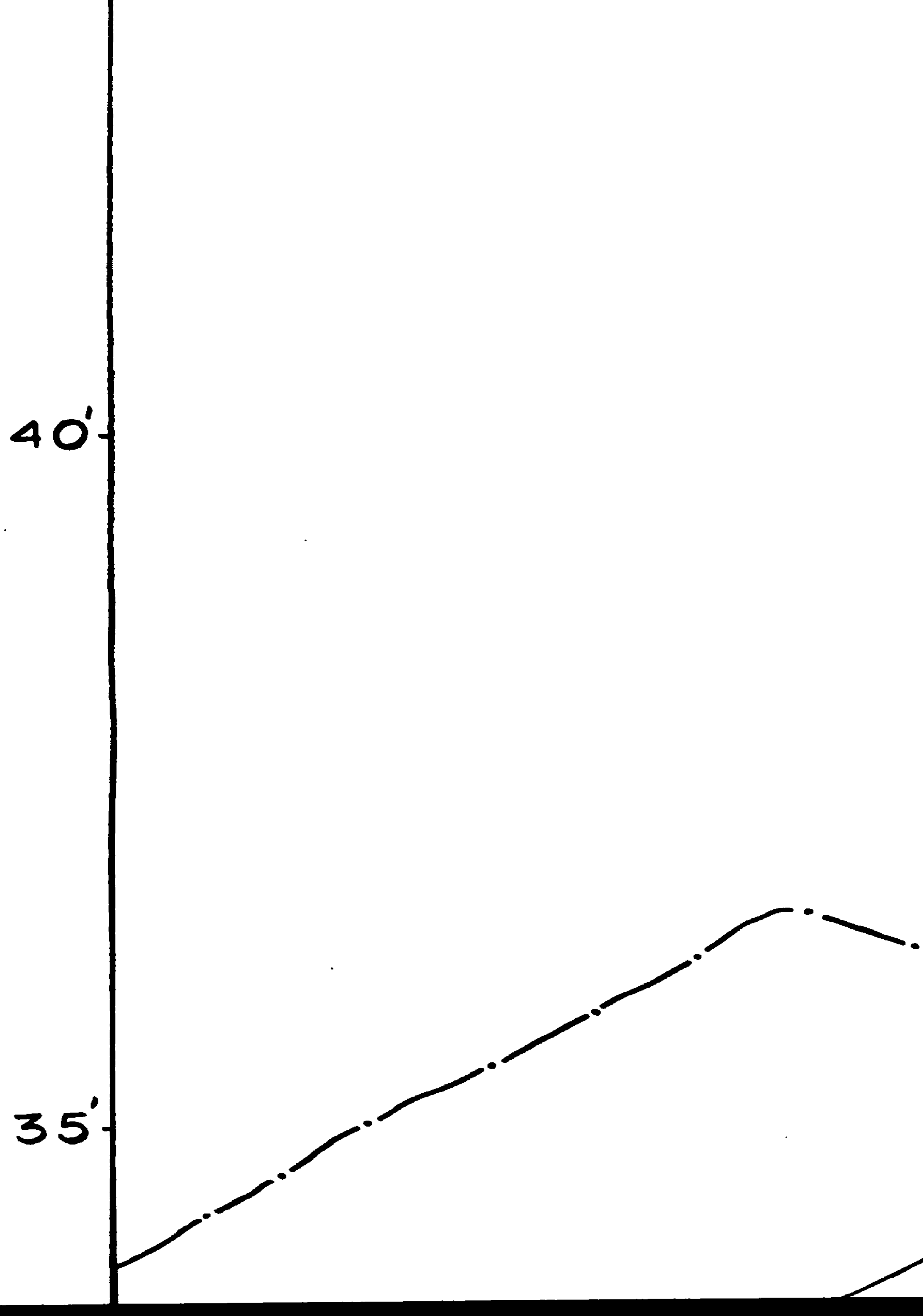
15'

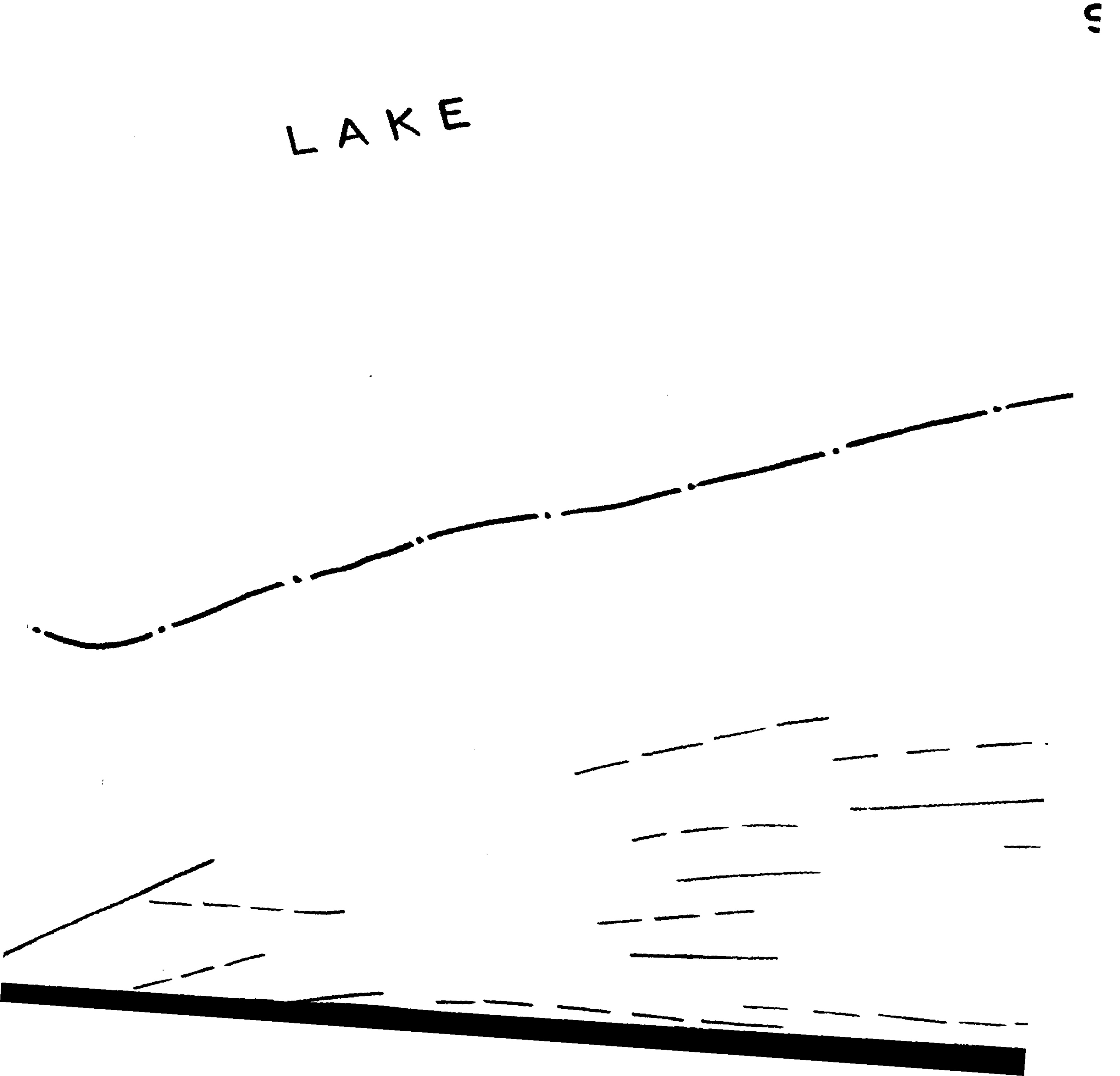
10'

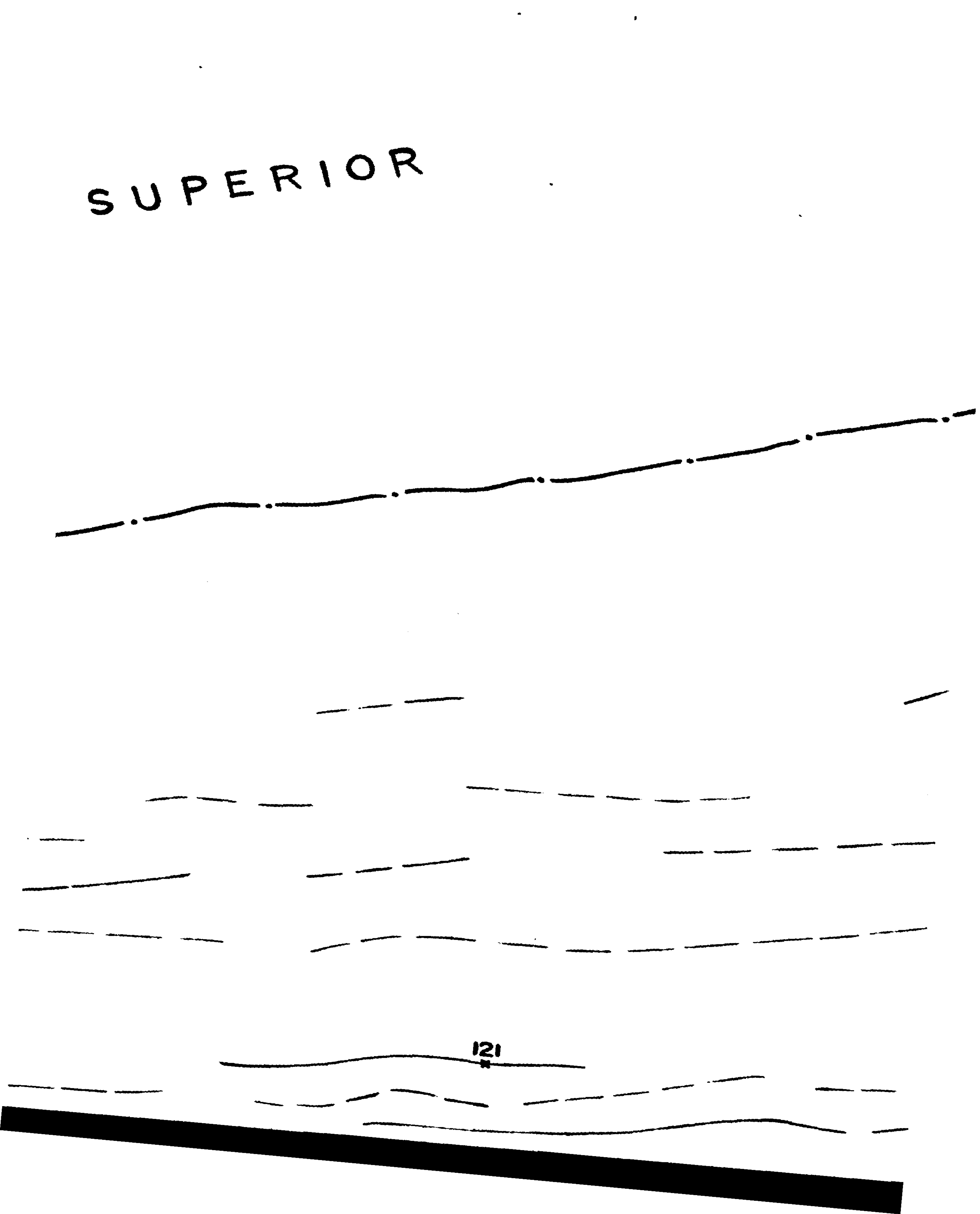
5'

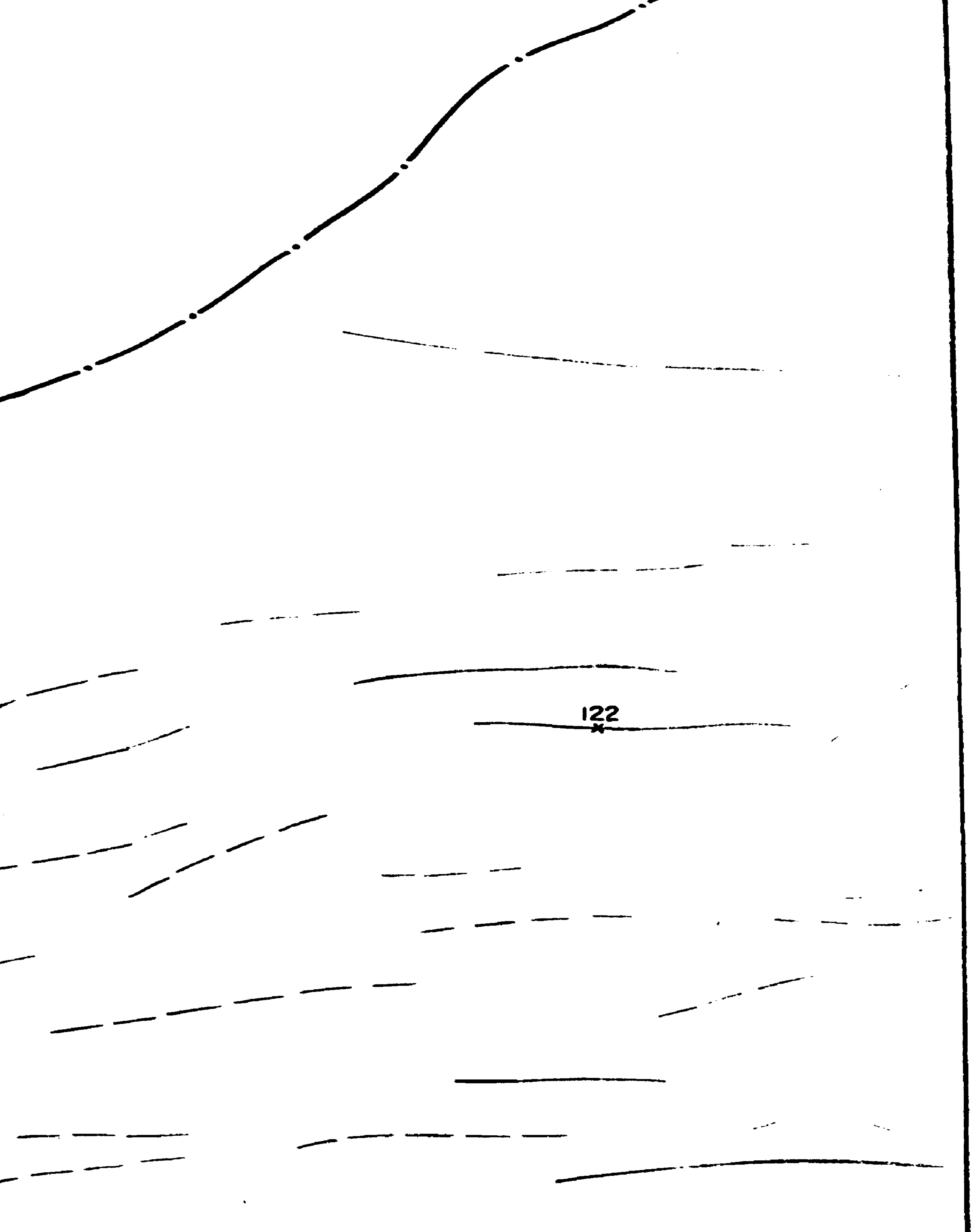
SUPERIOR

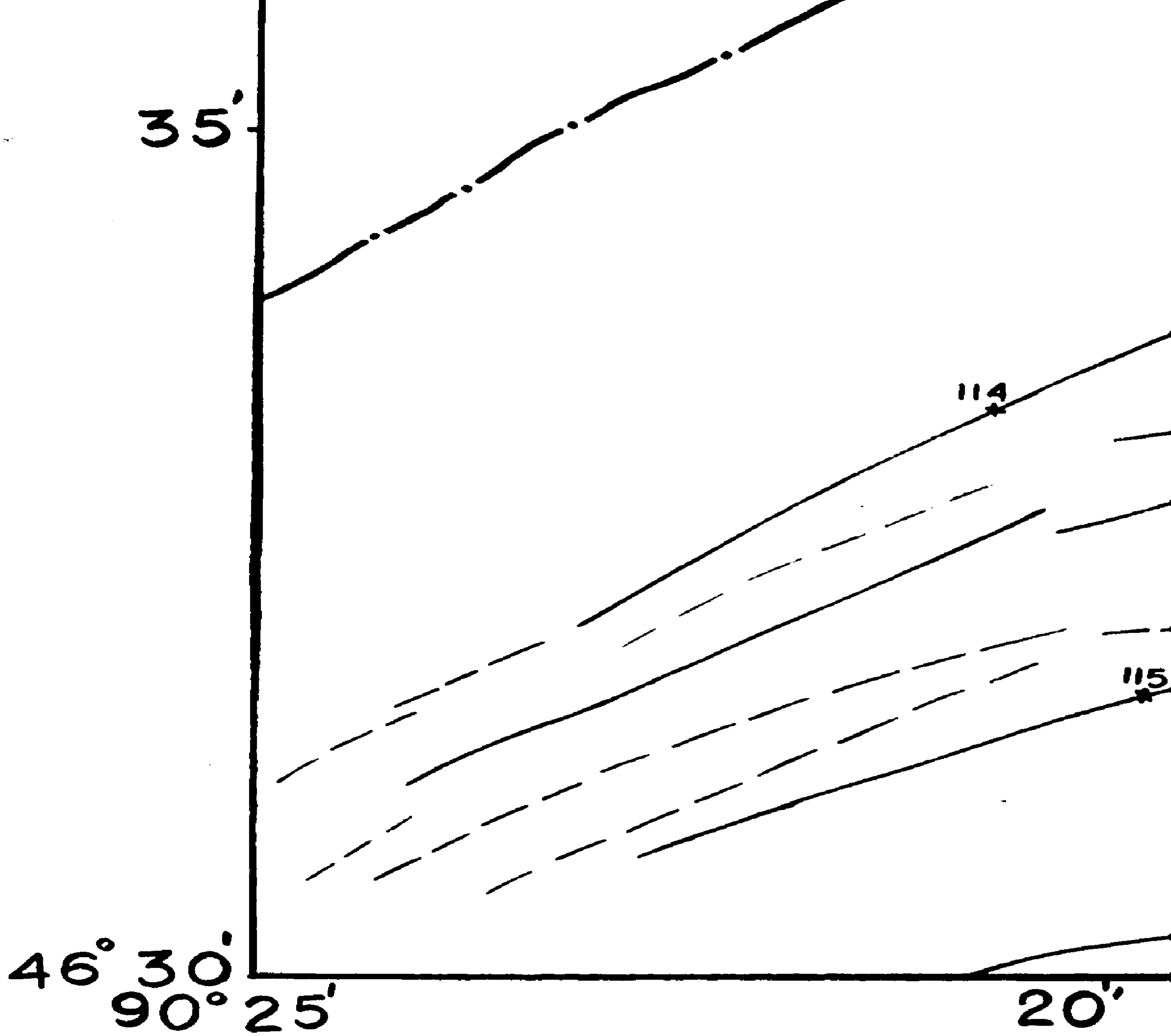

90°00′
89°55′


40'
35'

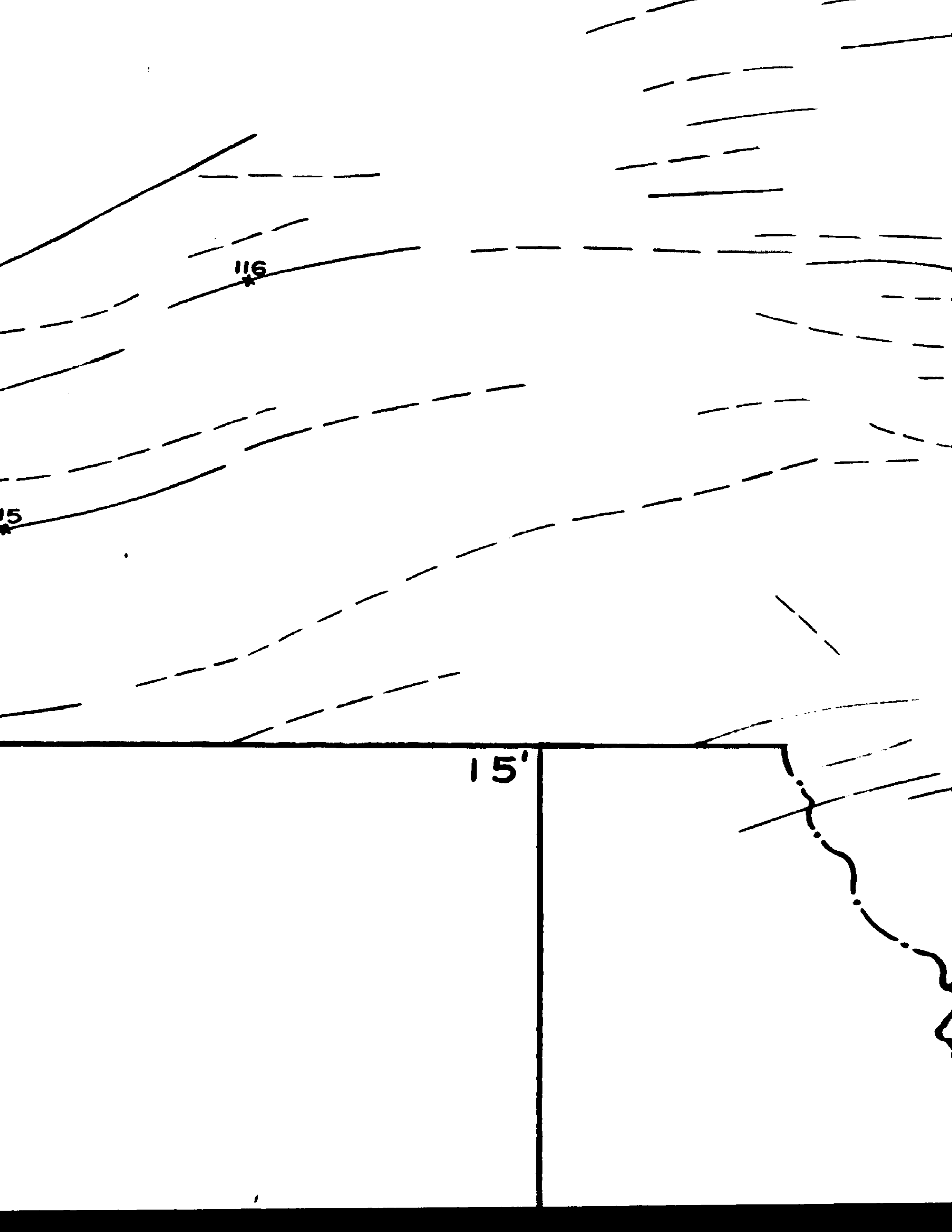

LAKE

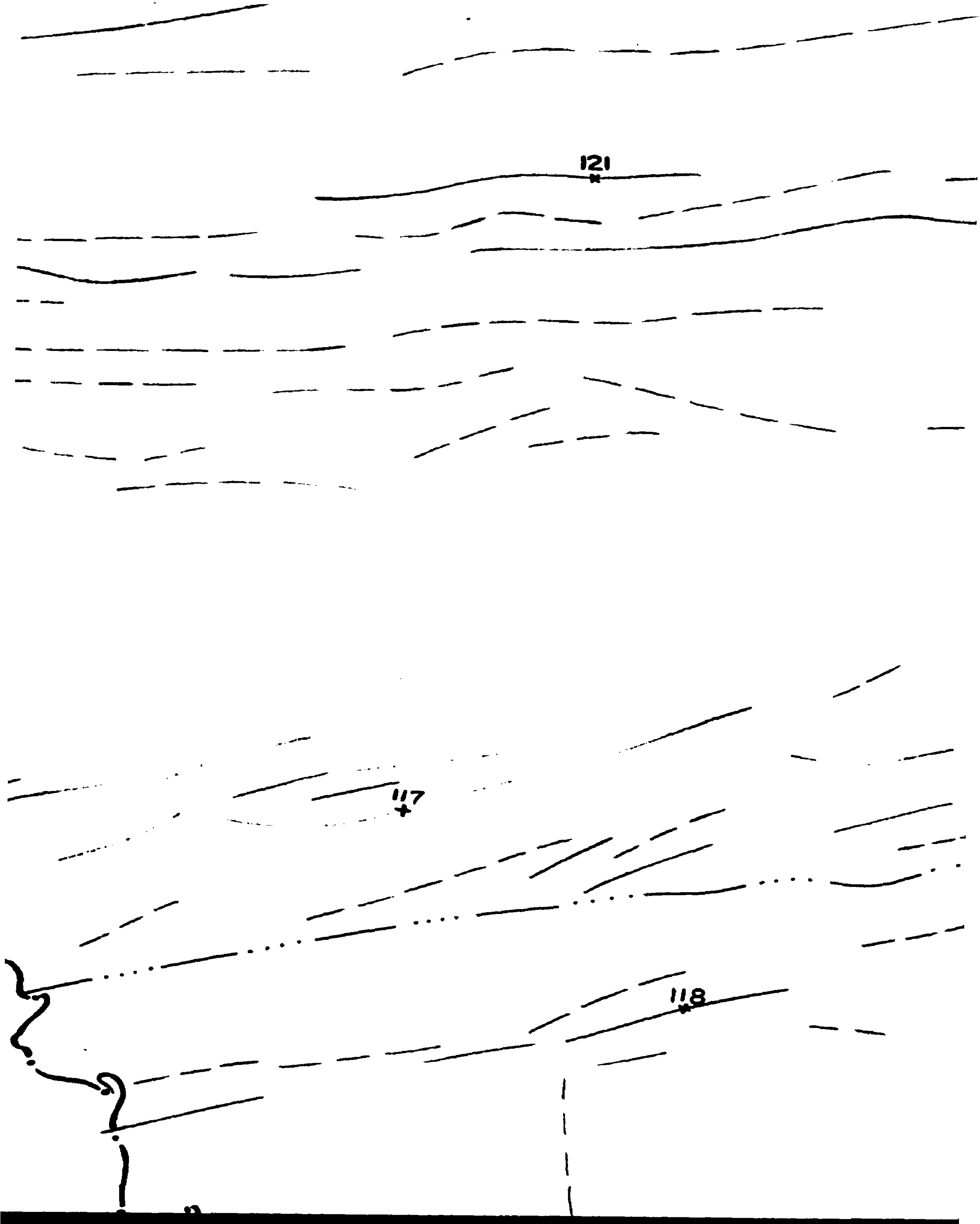

SUPERIOR
121


122



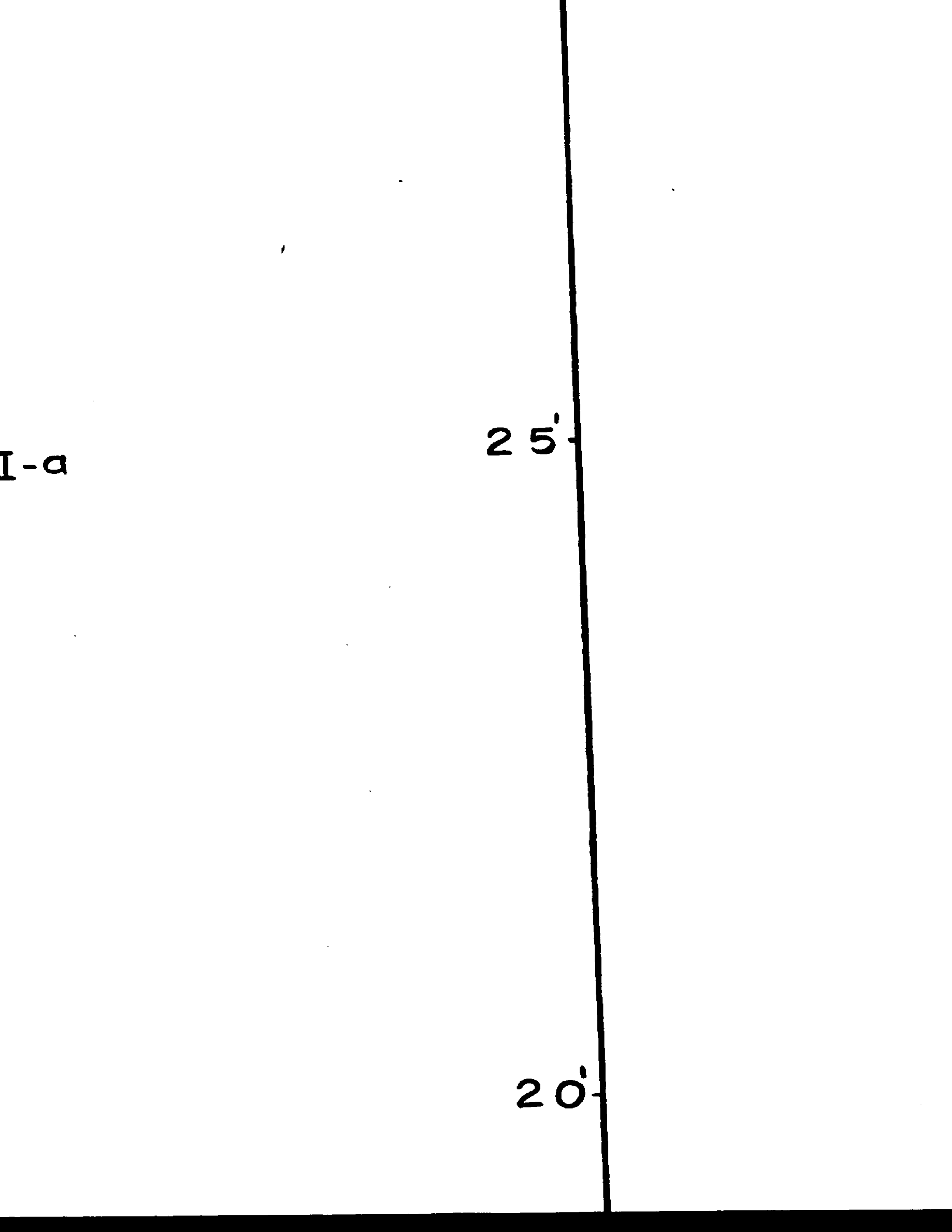
35'
114
115
46°30'
90°25'
20'

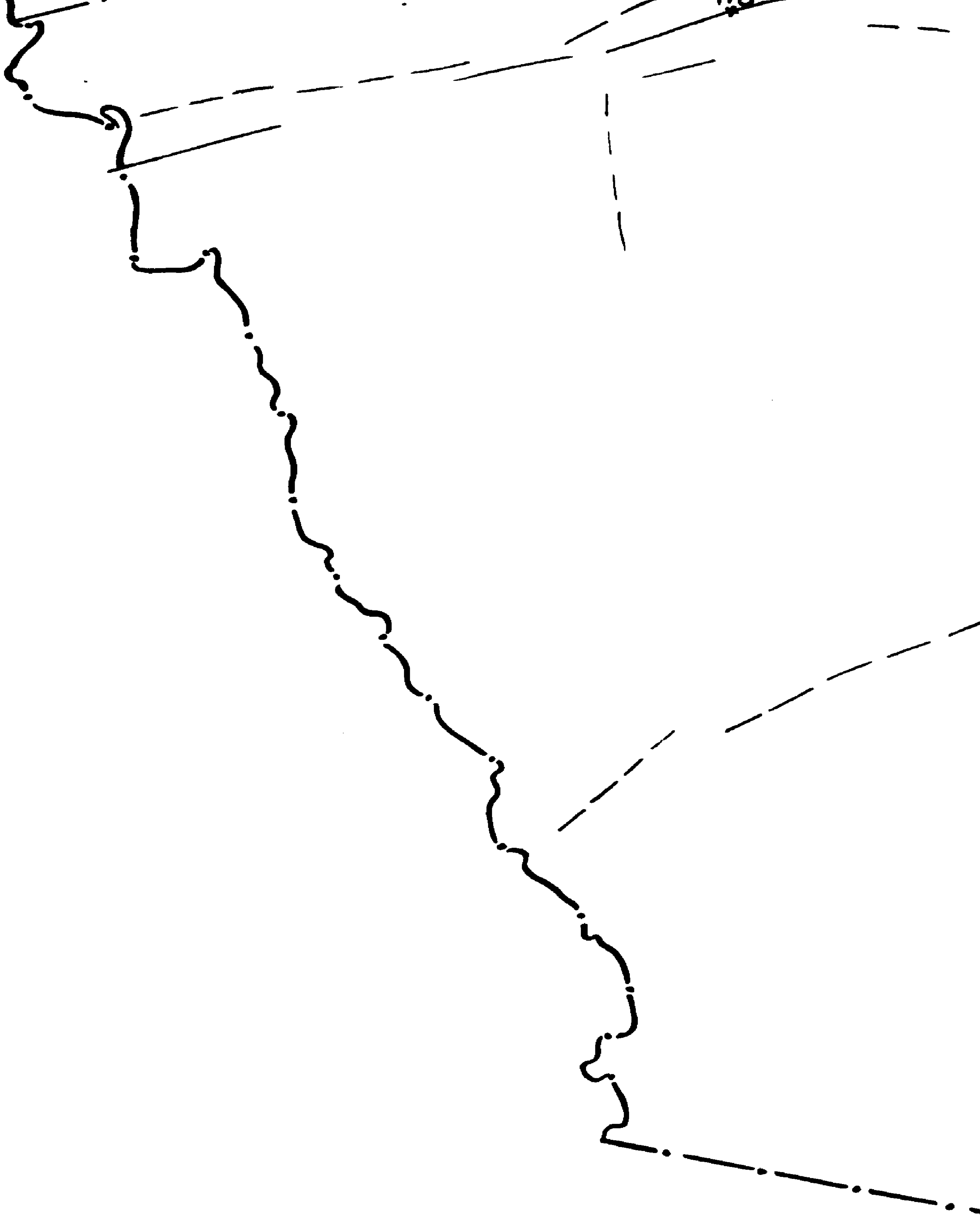

116
15
15'

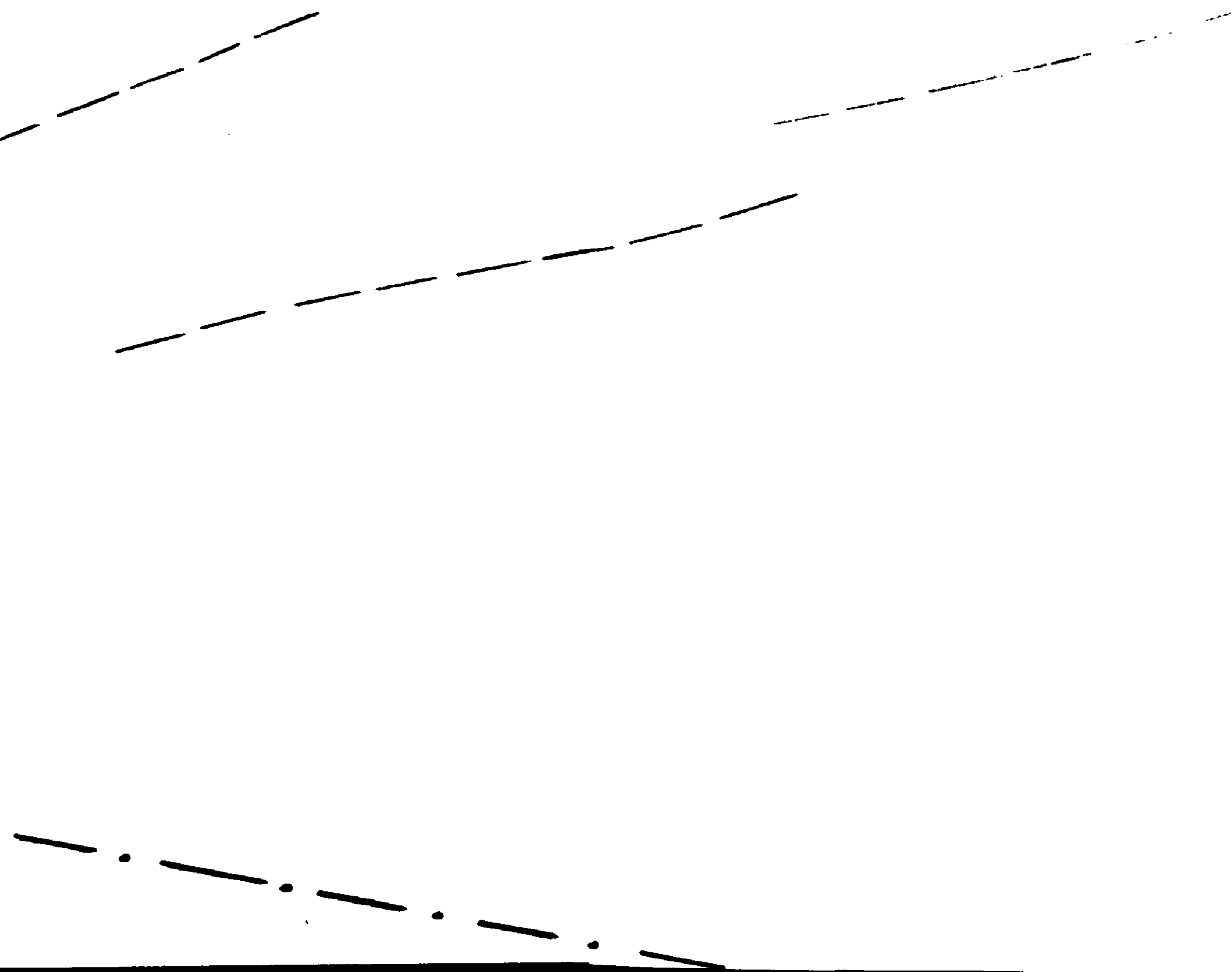

121
117
118

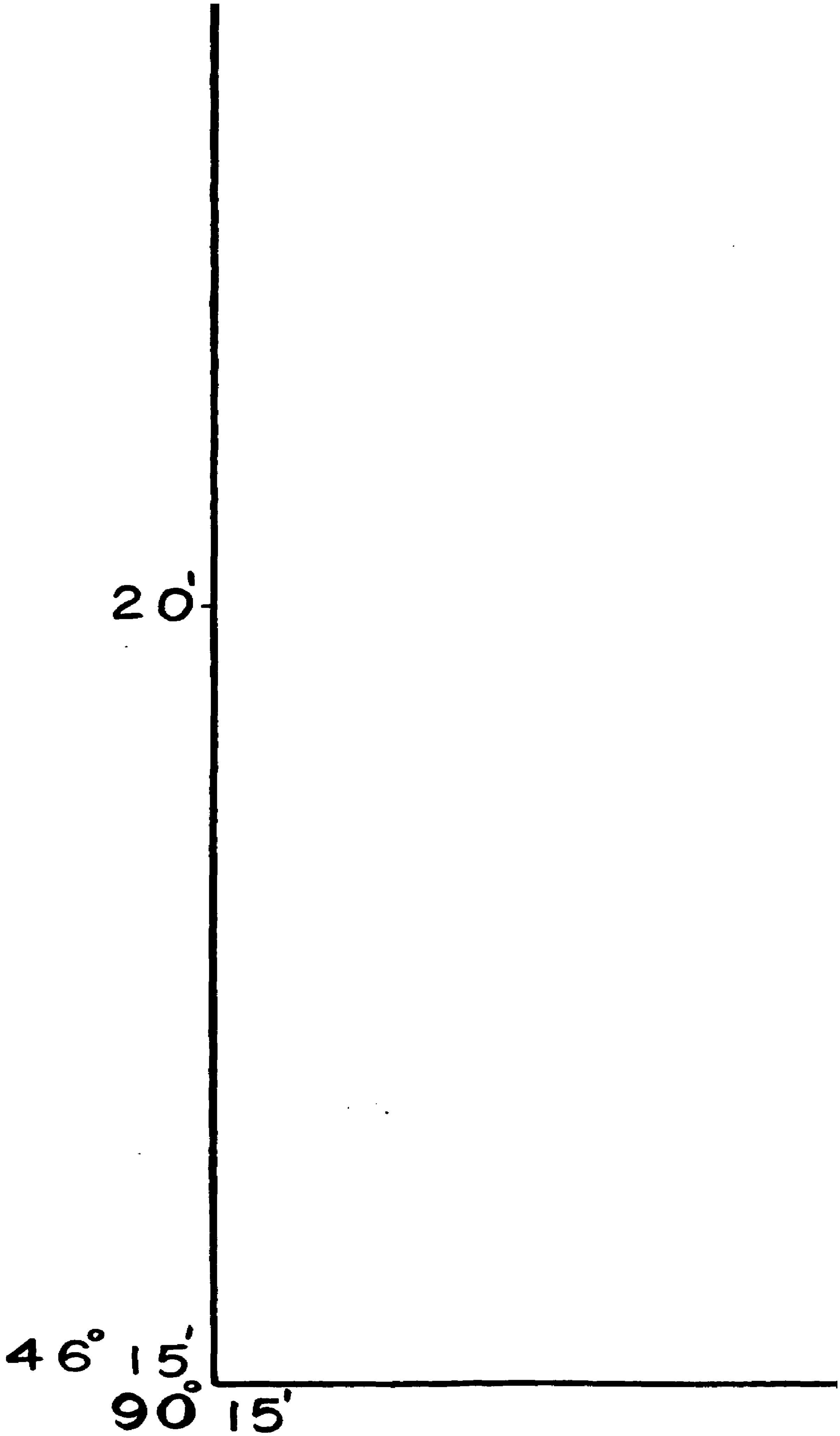

119
120

PLATE II

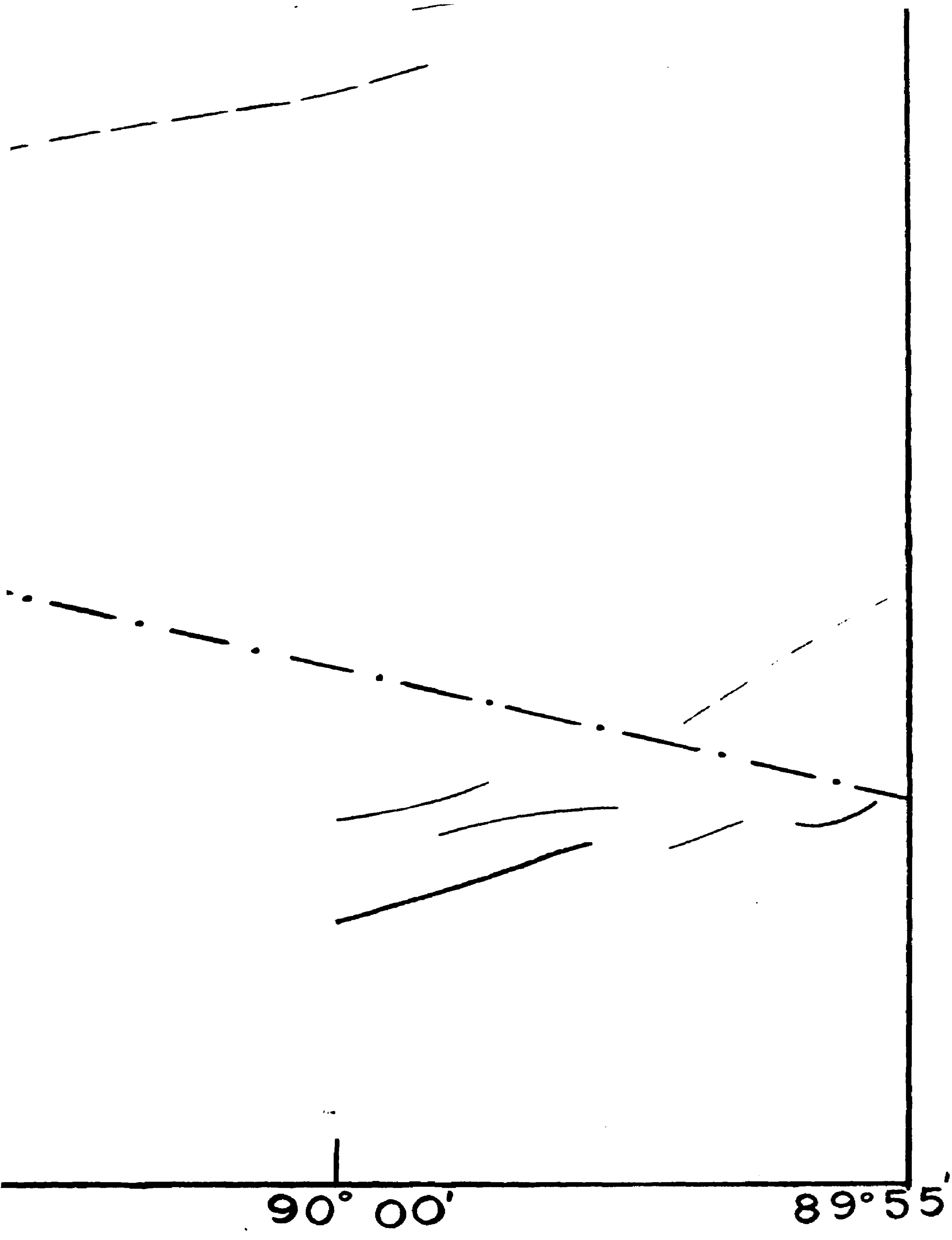

I-a
25'
20'






20'
46° 15'
90° 15'


10'
5'

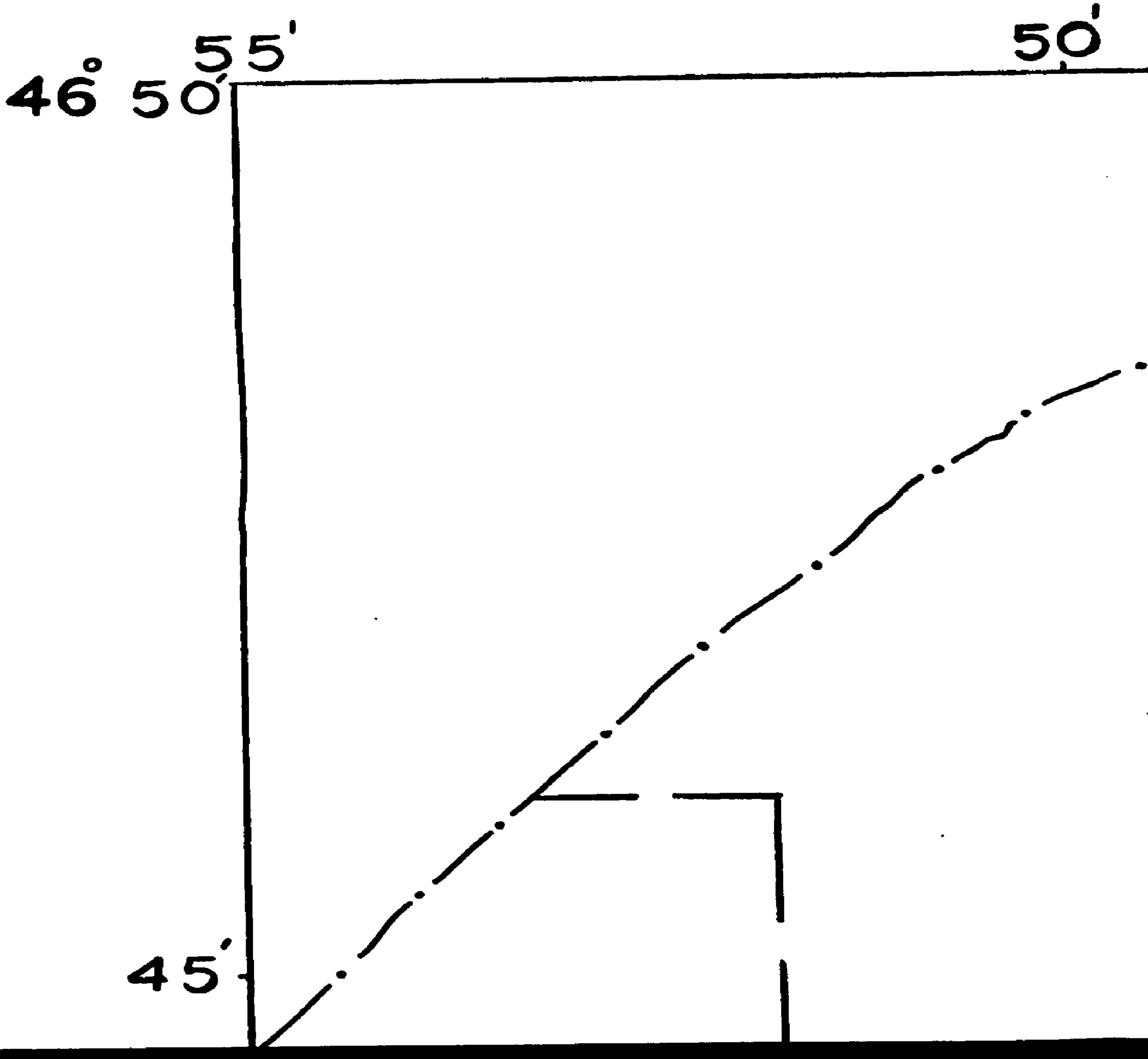

90° 00'
89°55'

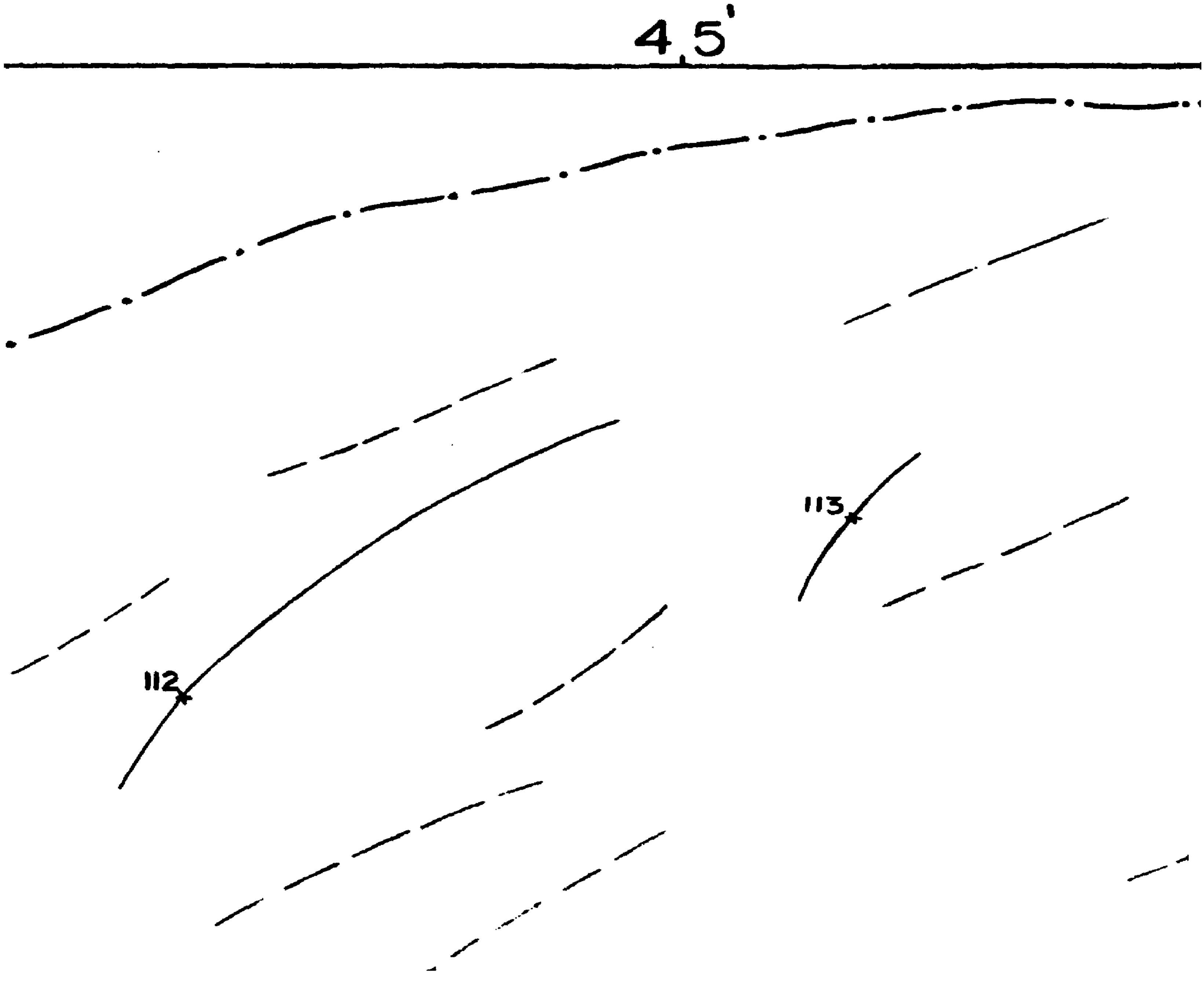
PL

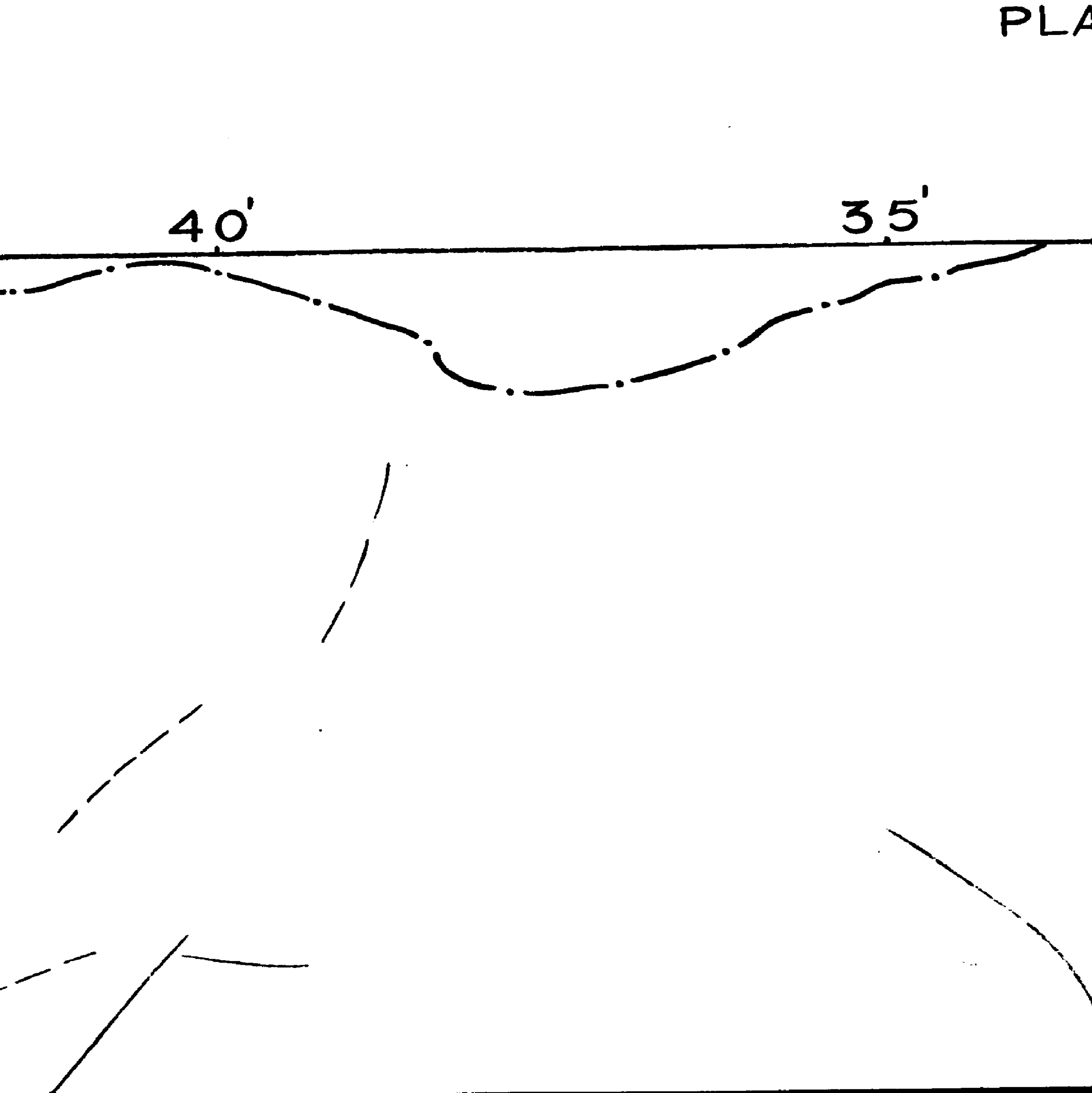
_ATE II-b

PLATE II-b

05'


55'
50'
46° 50'
45'


4.5'
112
113


PLA
40'
35'

.ATE II-b

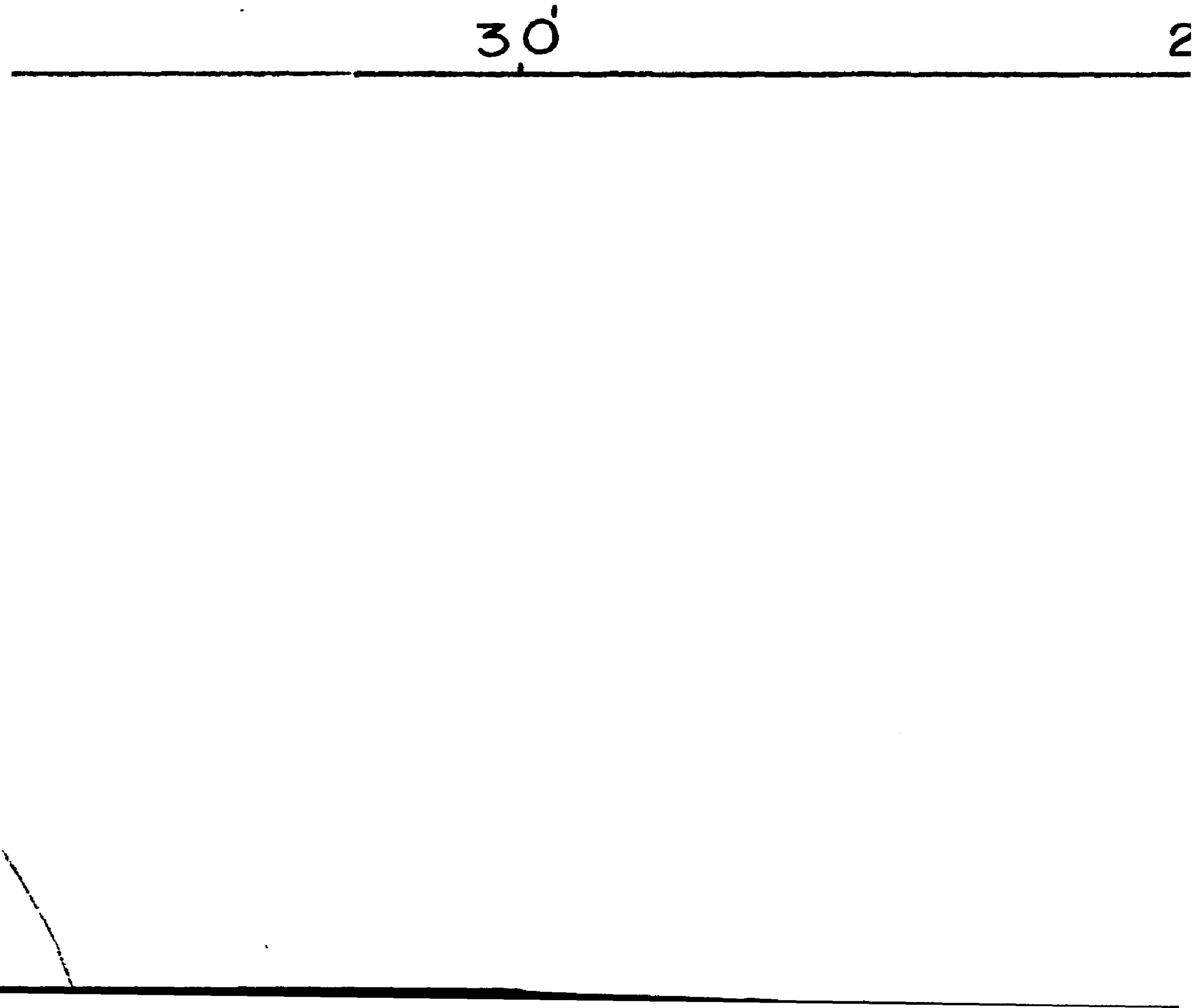
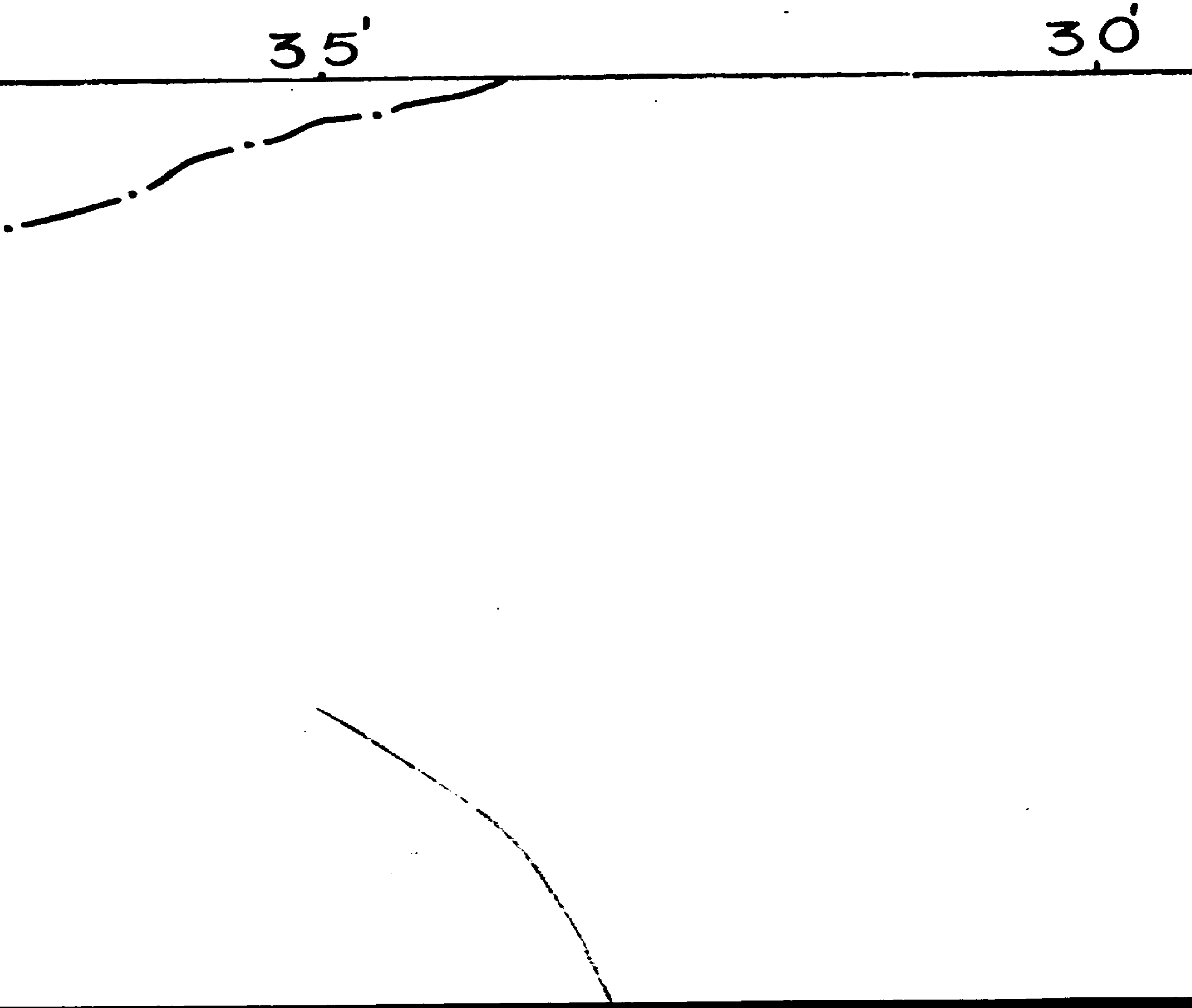
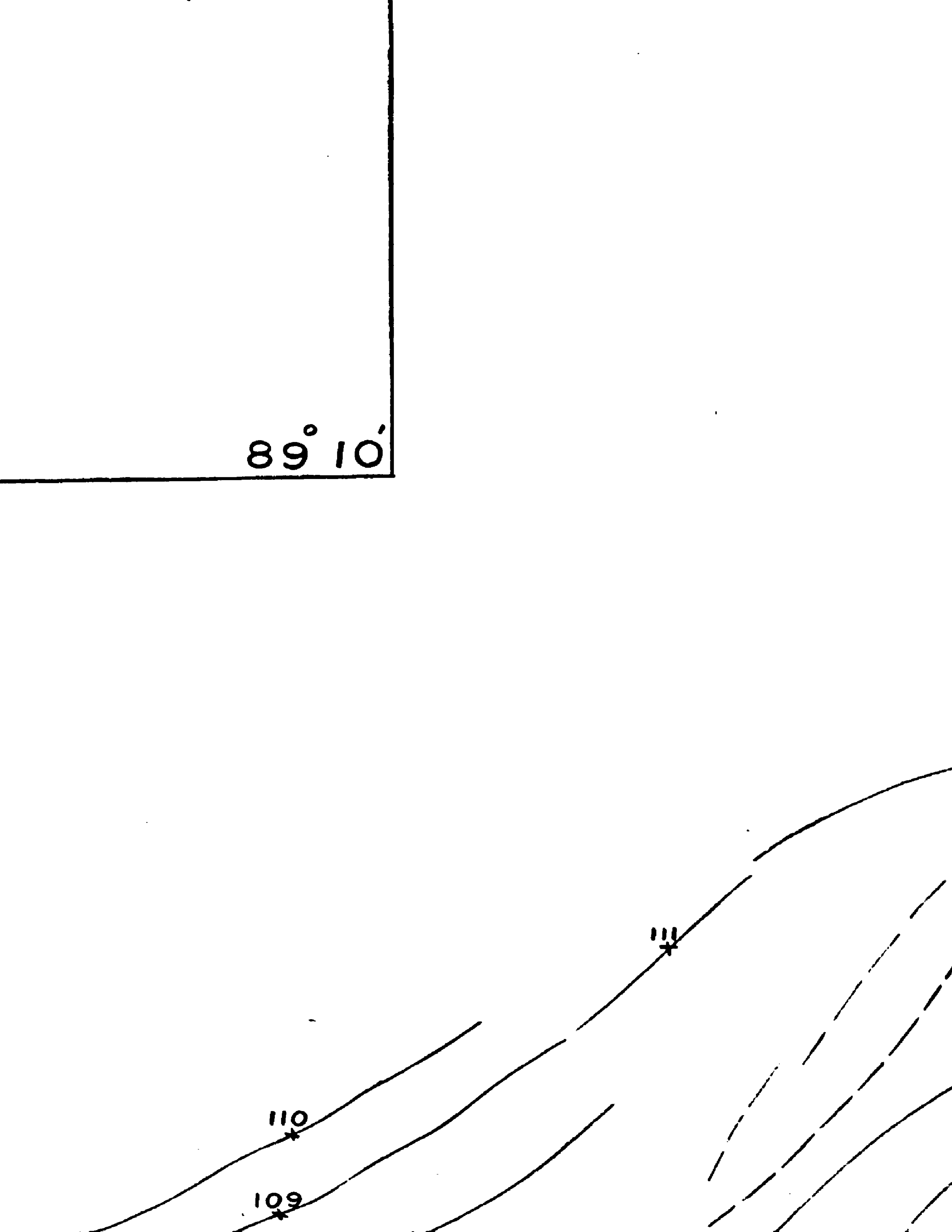


PLATE II-b

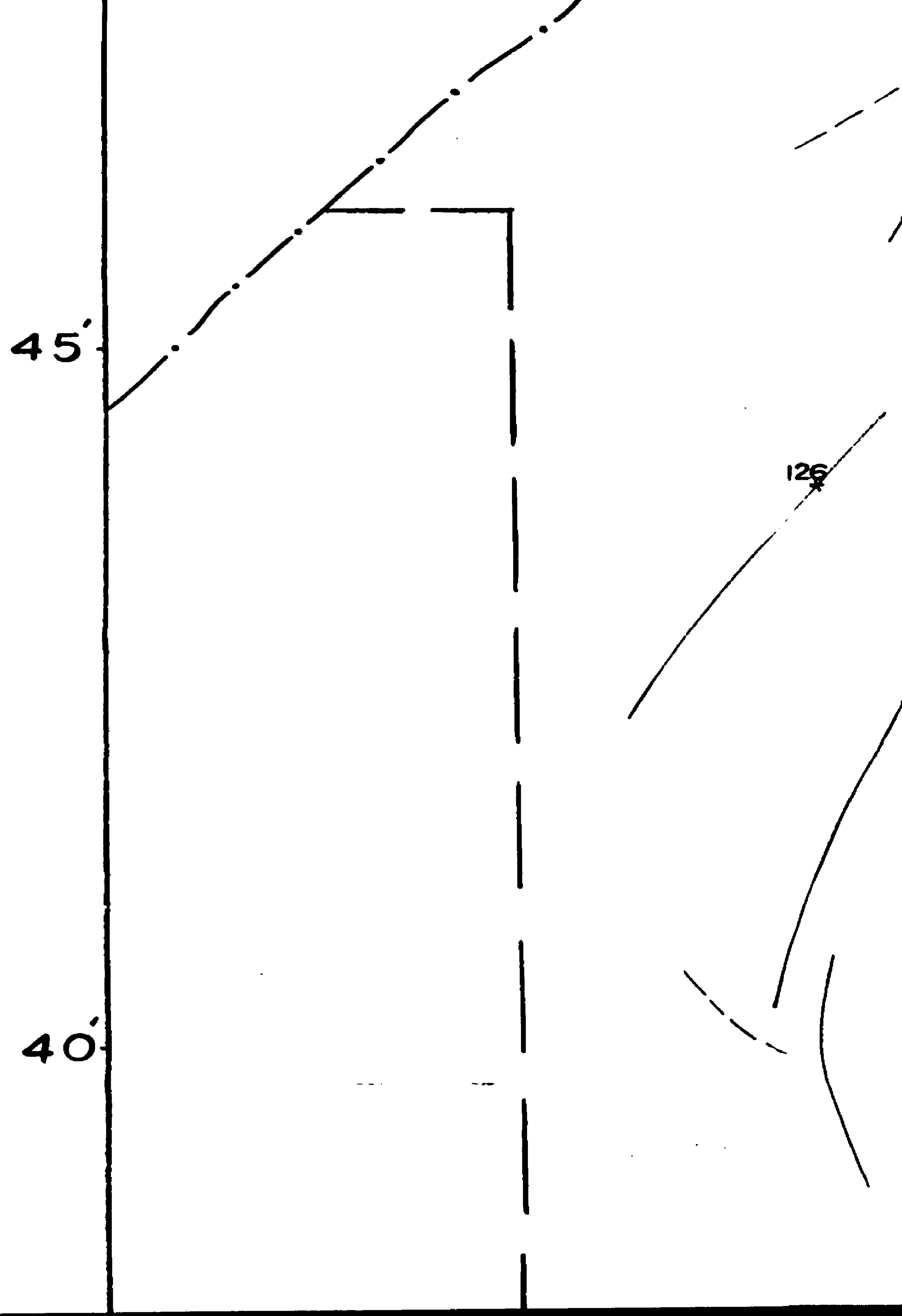


25'

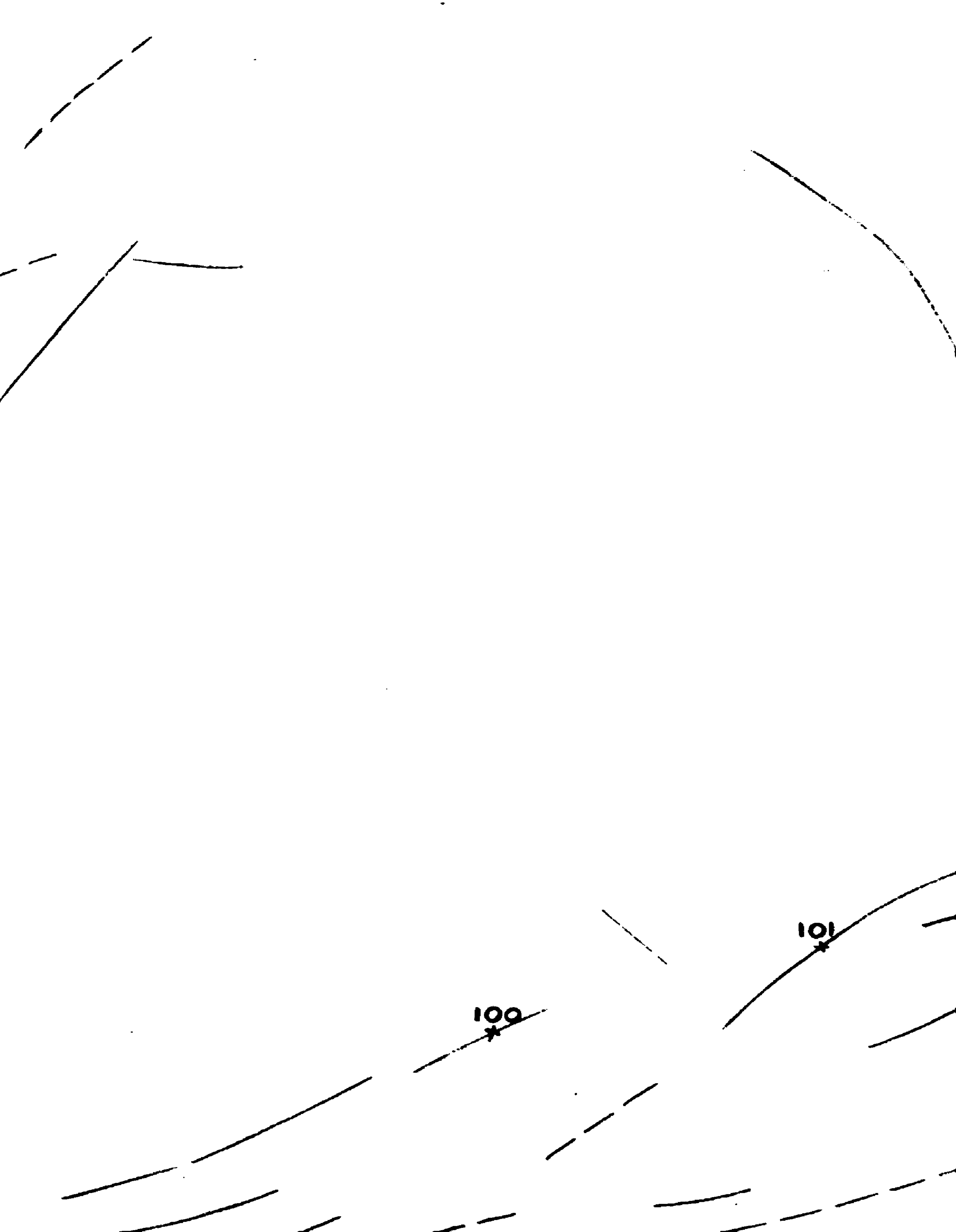
20′ 15′

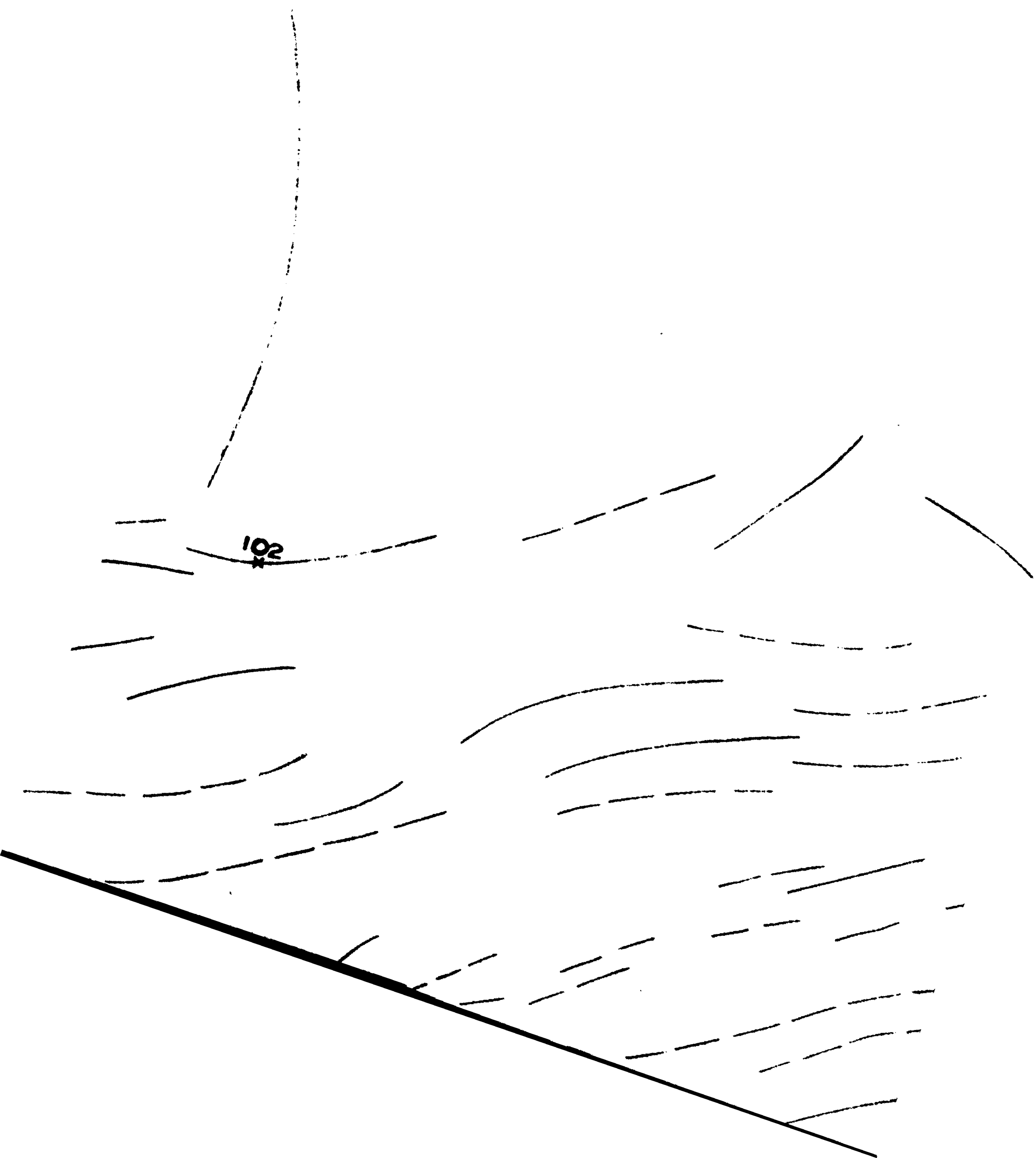


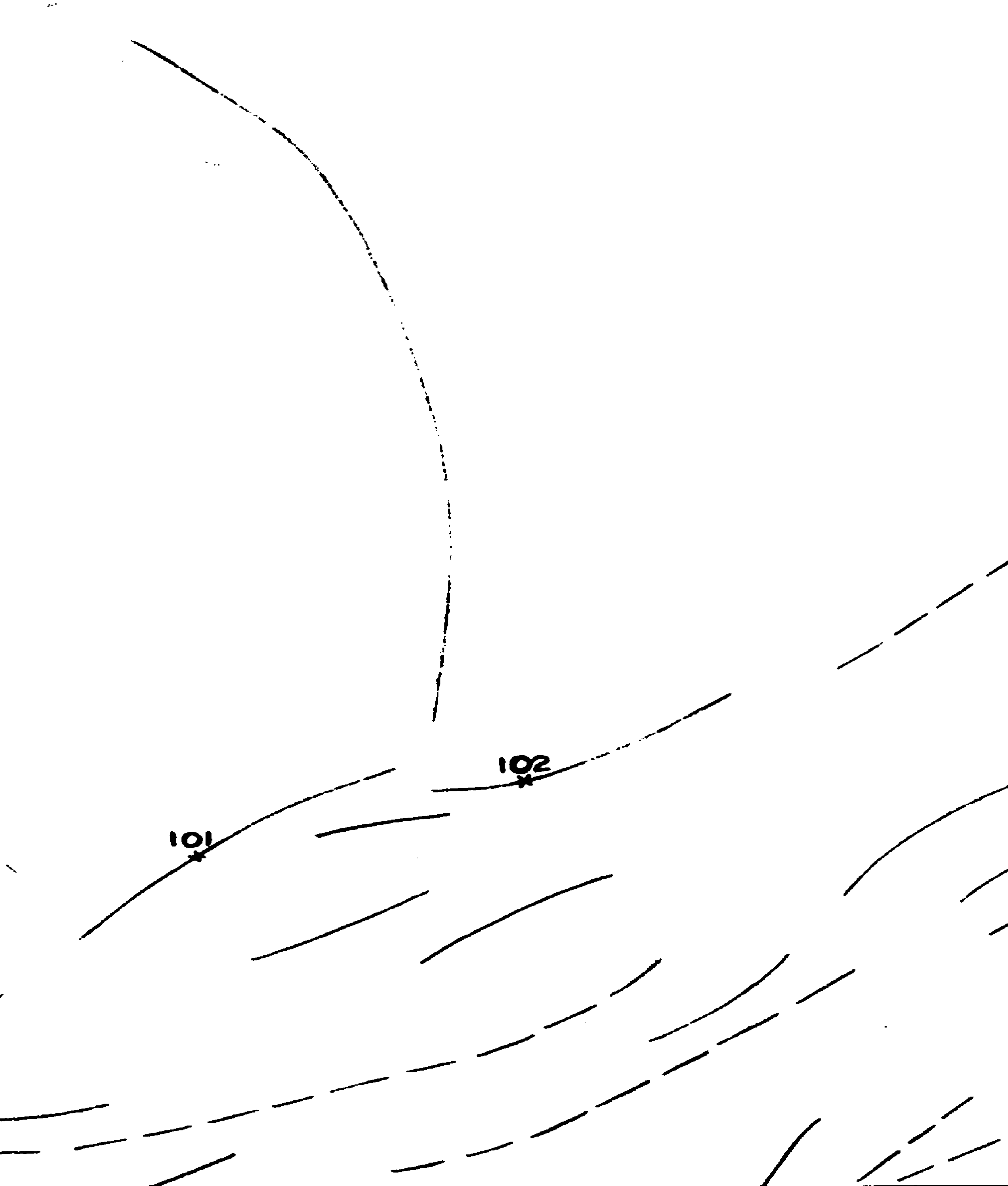
89° 10'
111
110
109

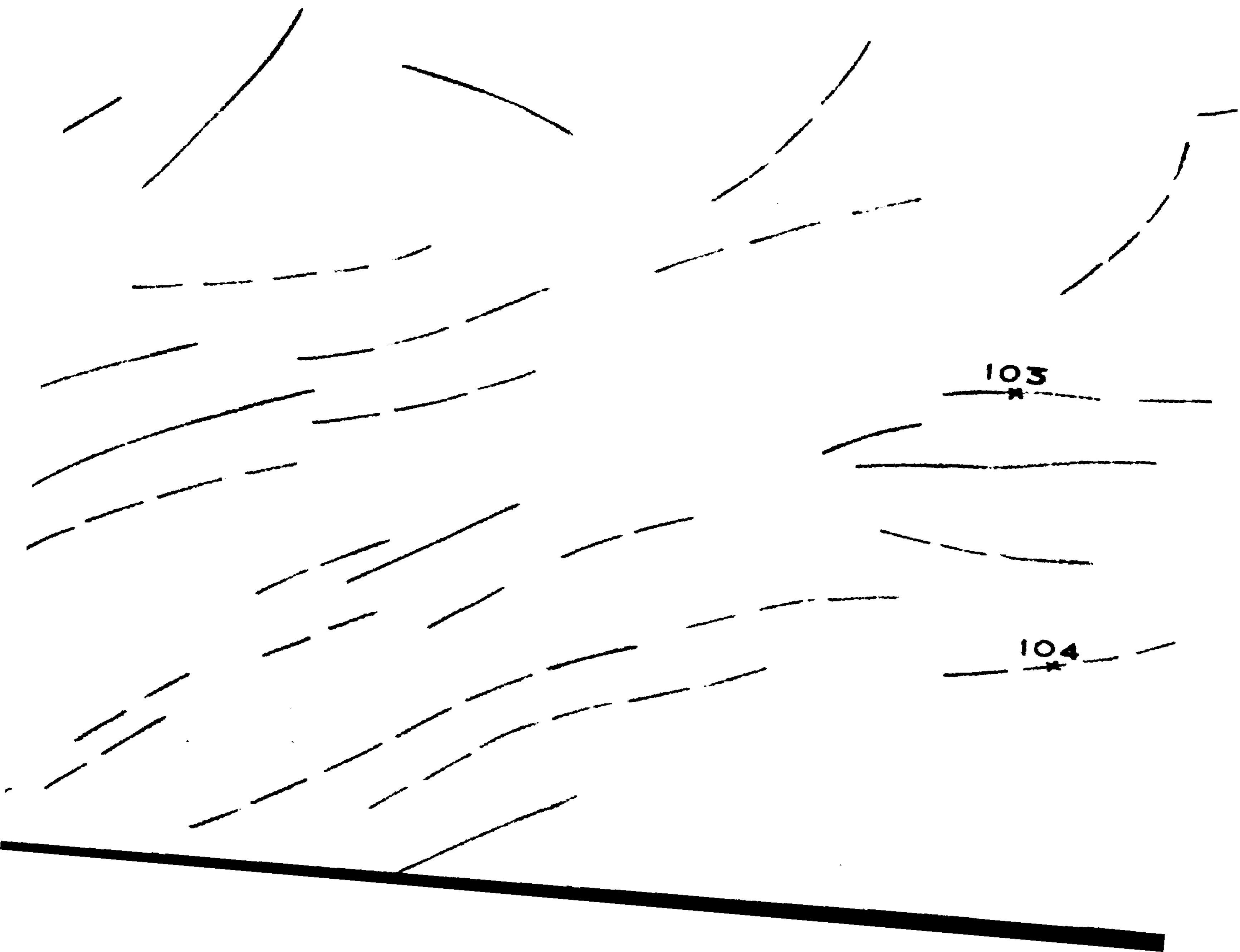

45′
126
40′

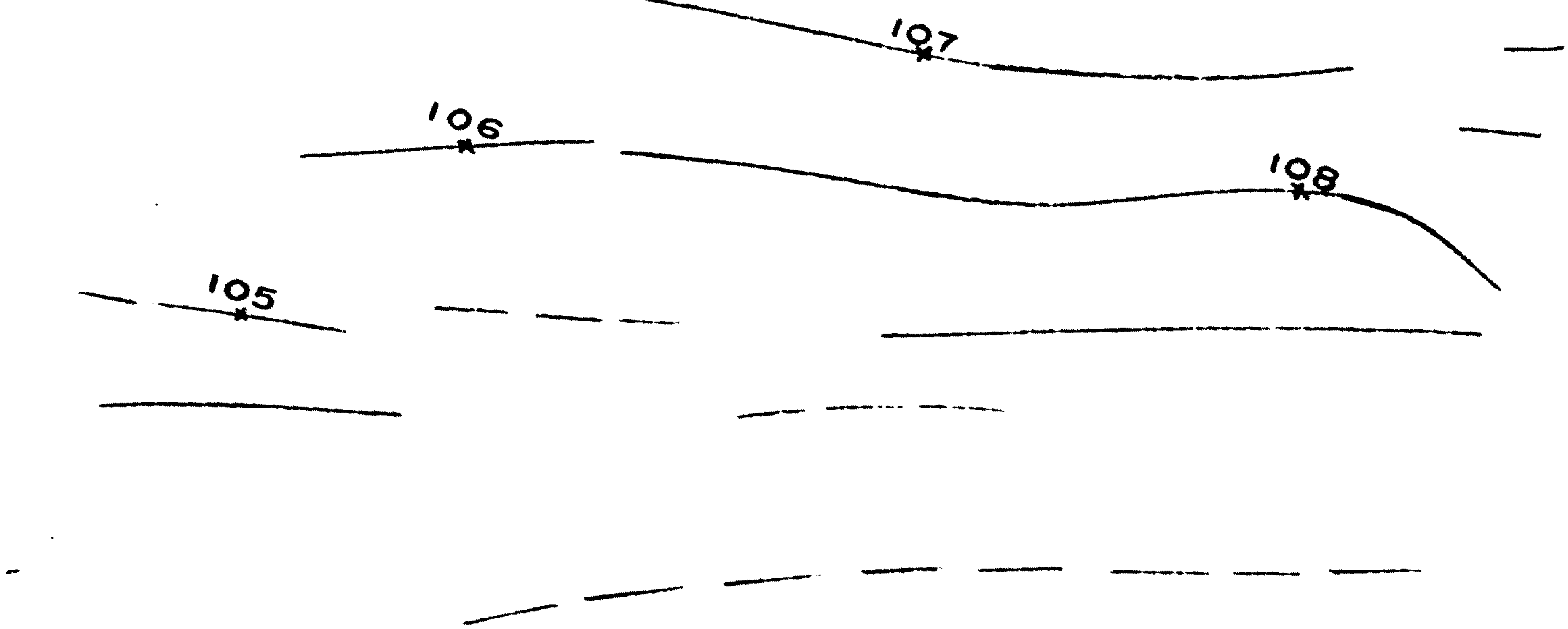

112


100
101

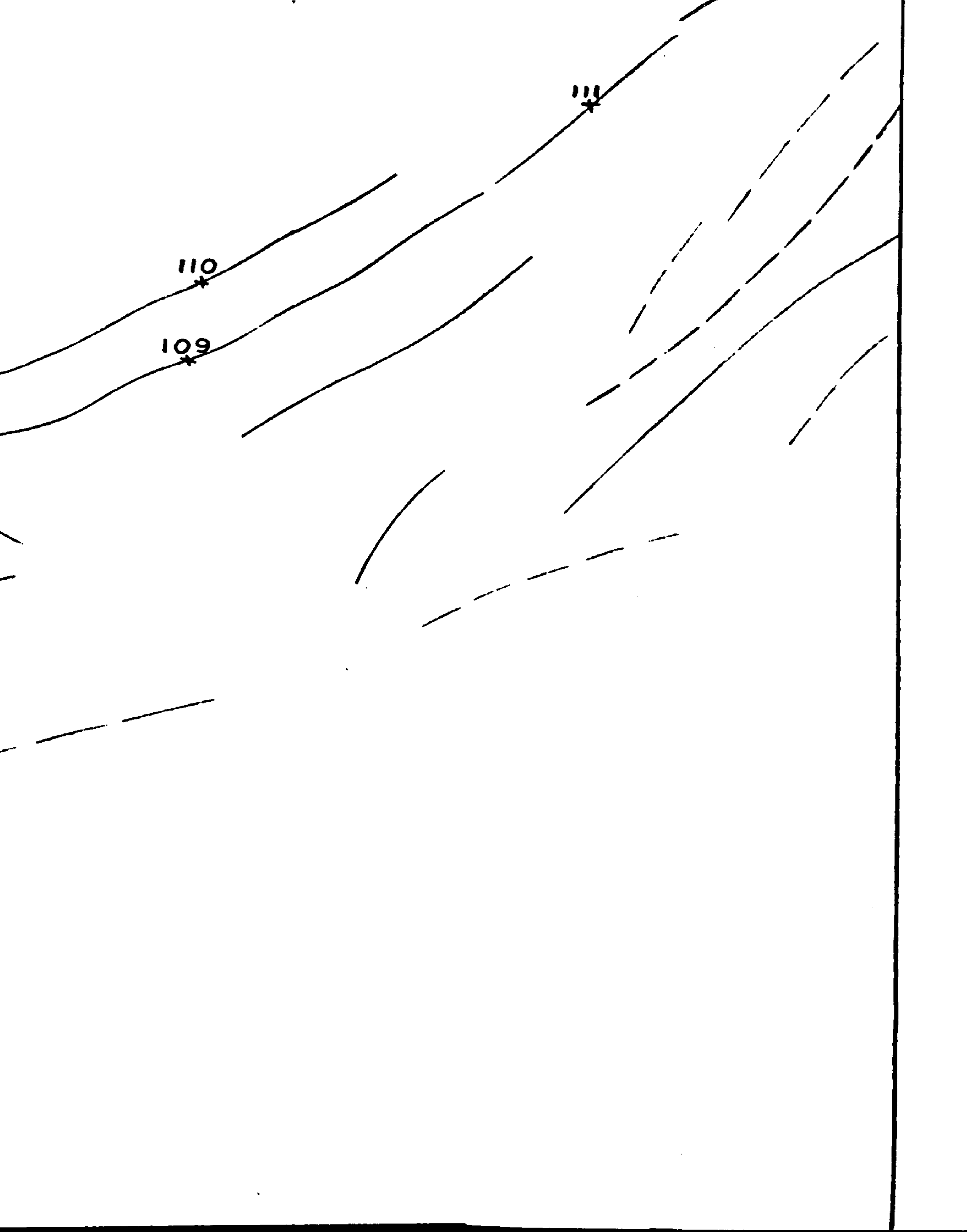

102

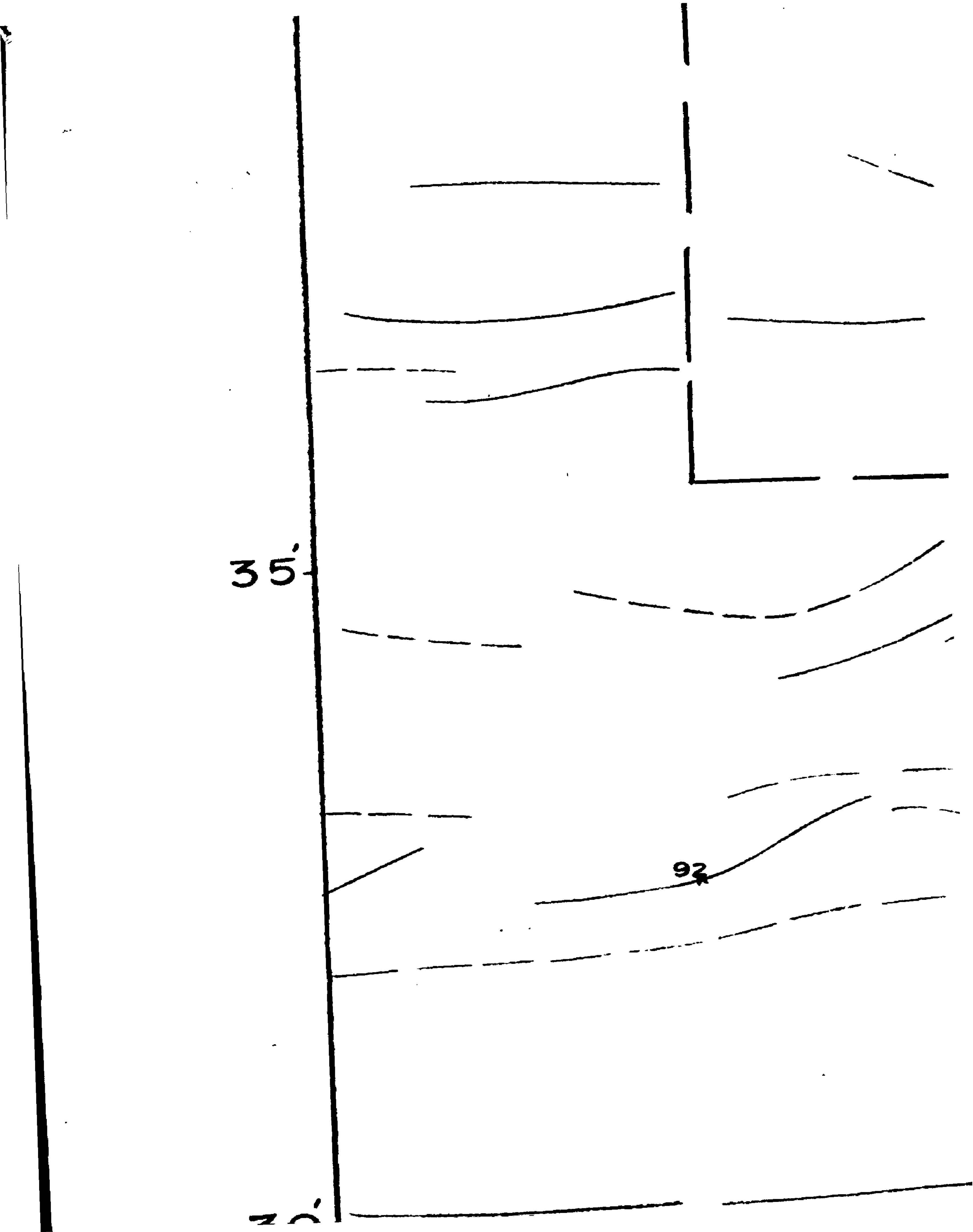

102
101

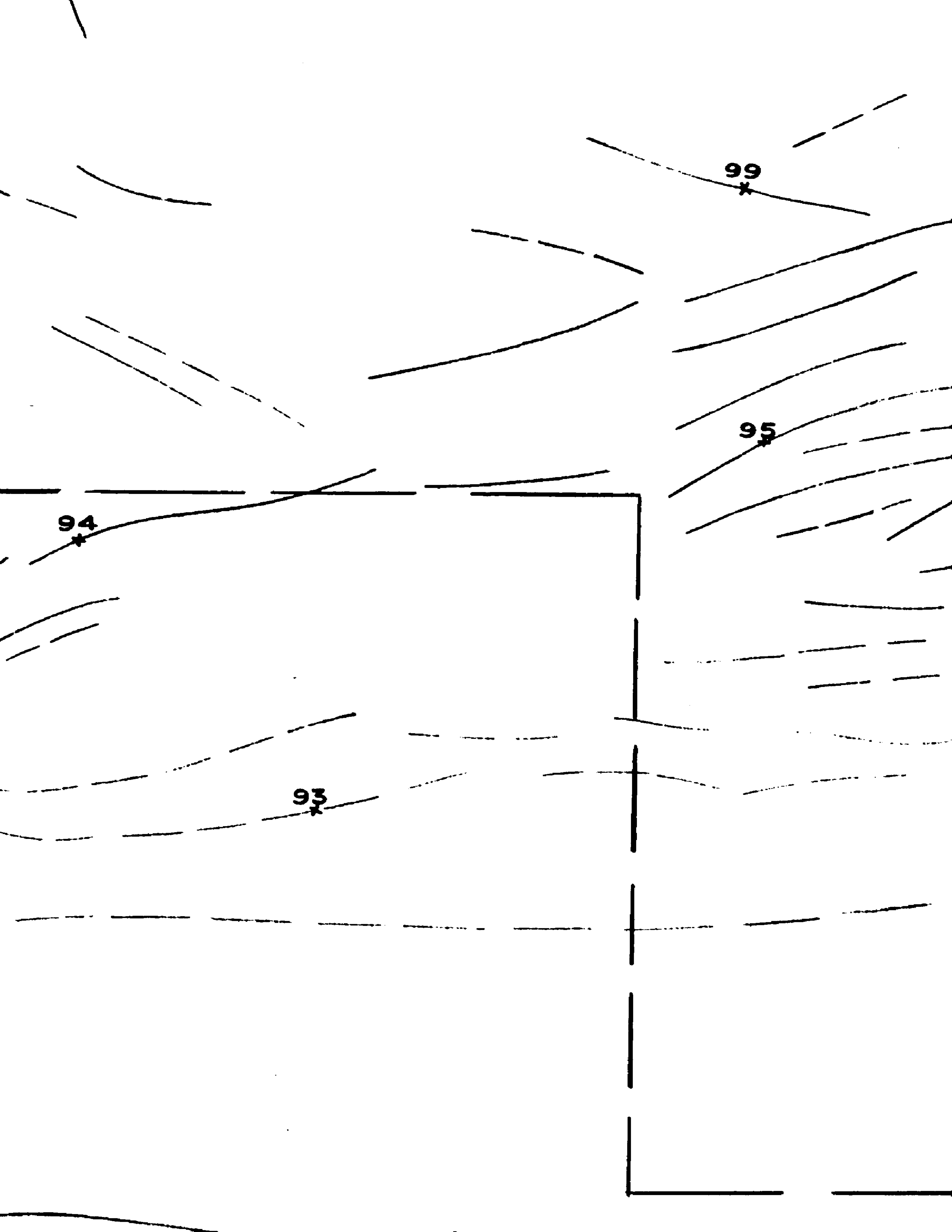

103
104

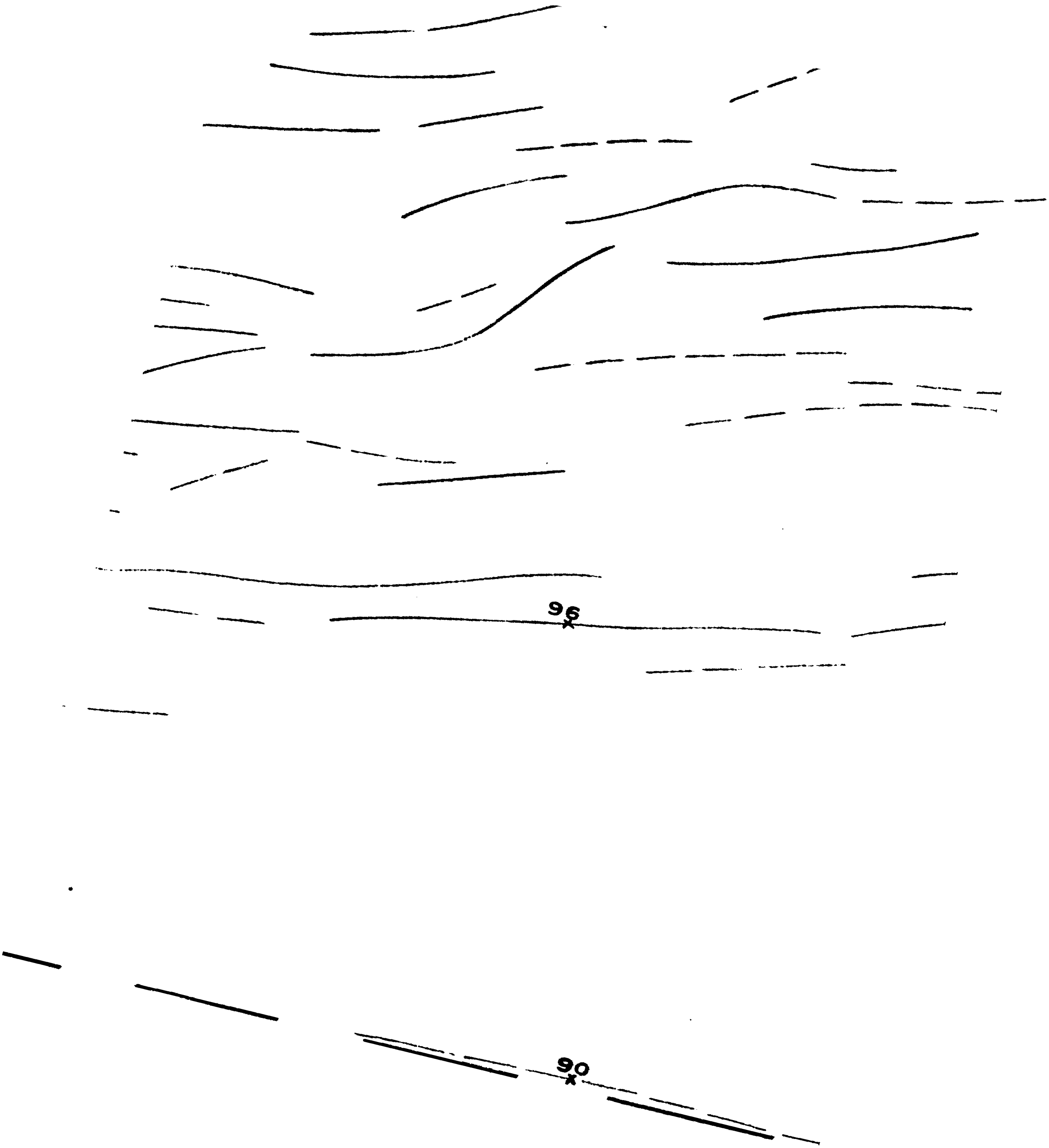


107
106
108
105


111
110
109

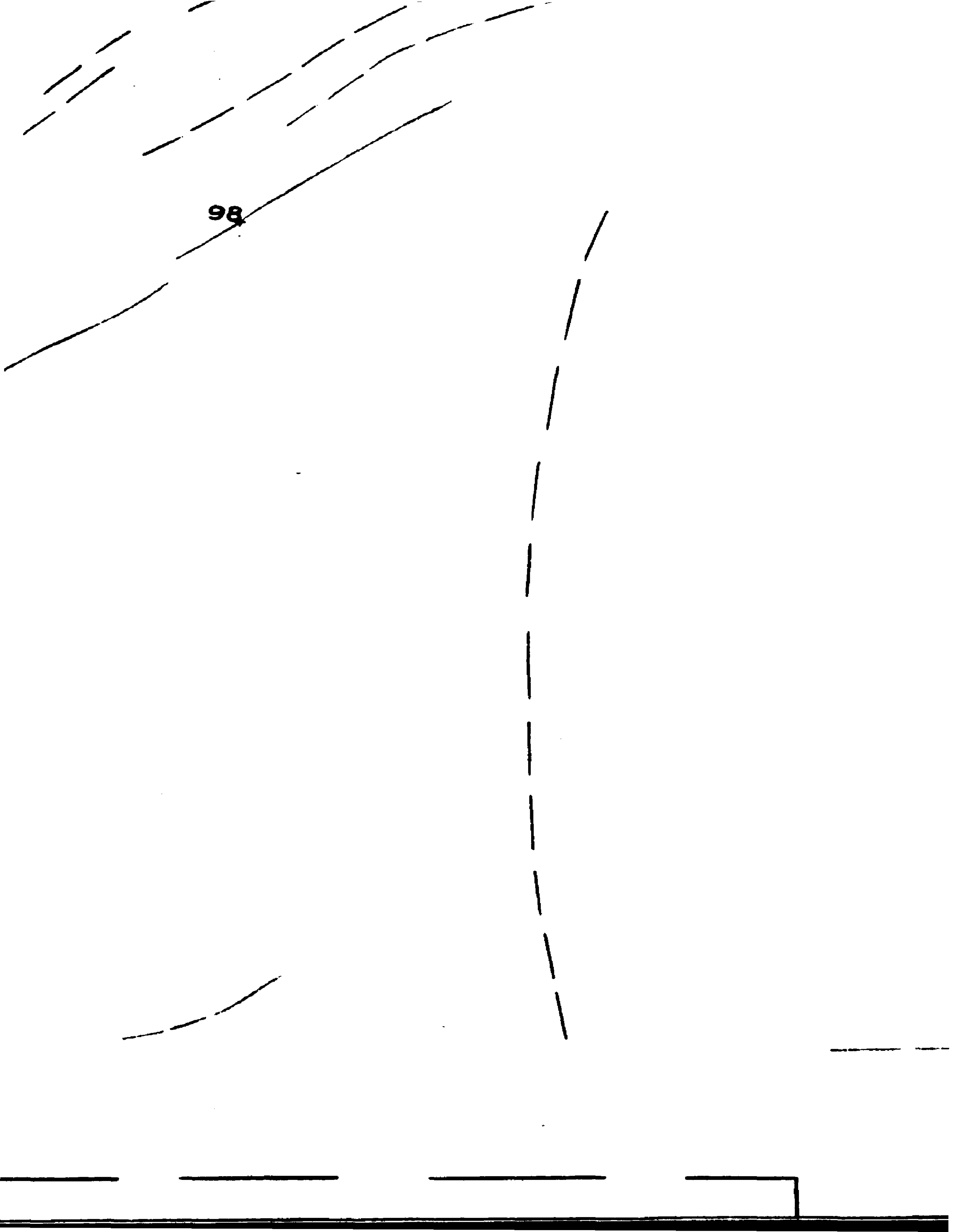

35′
92


99
95
94
93

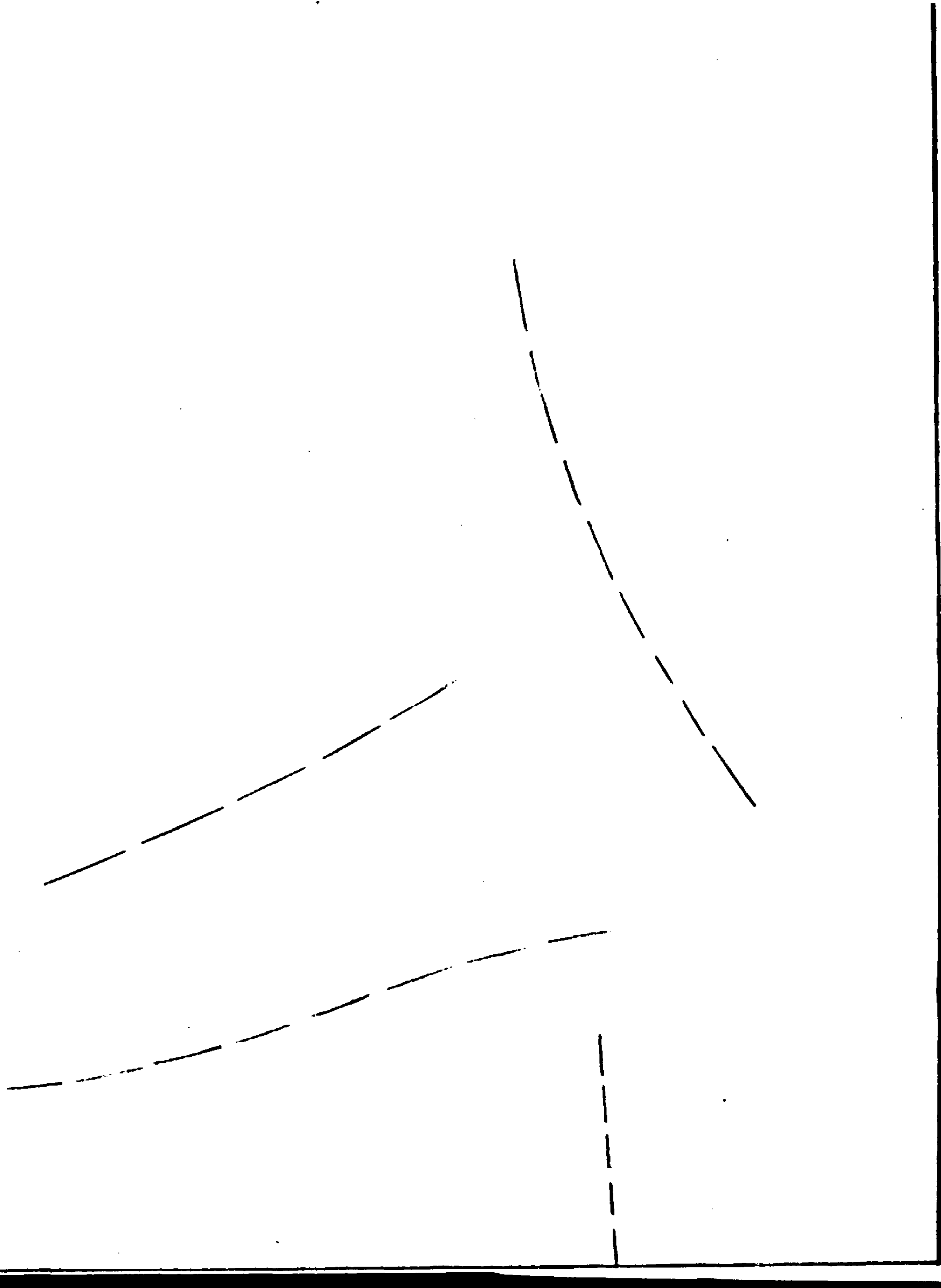

96
90

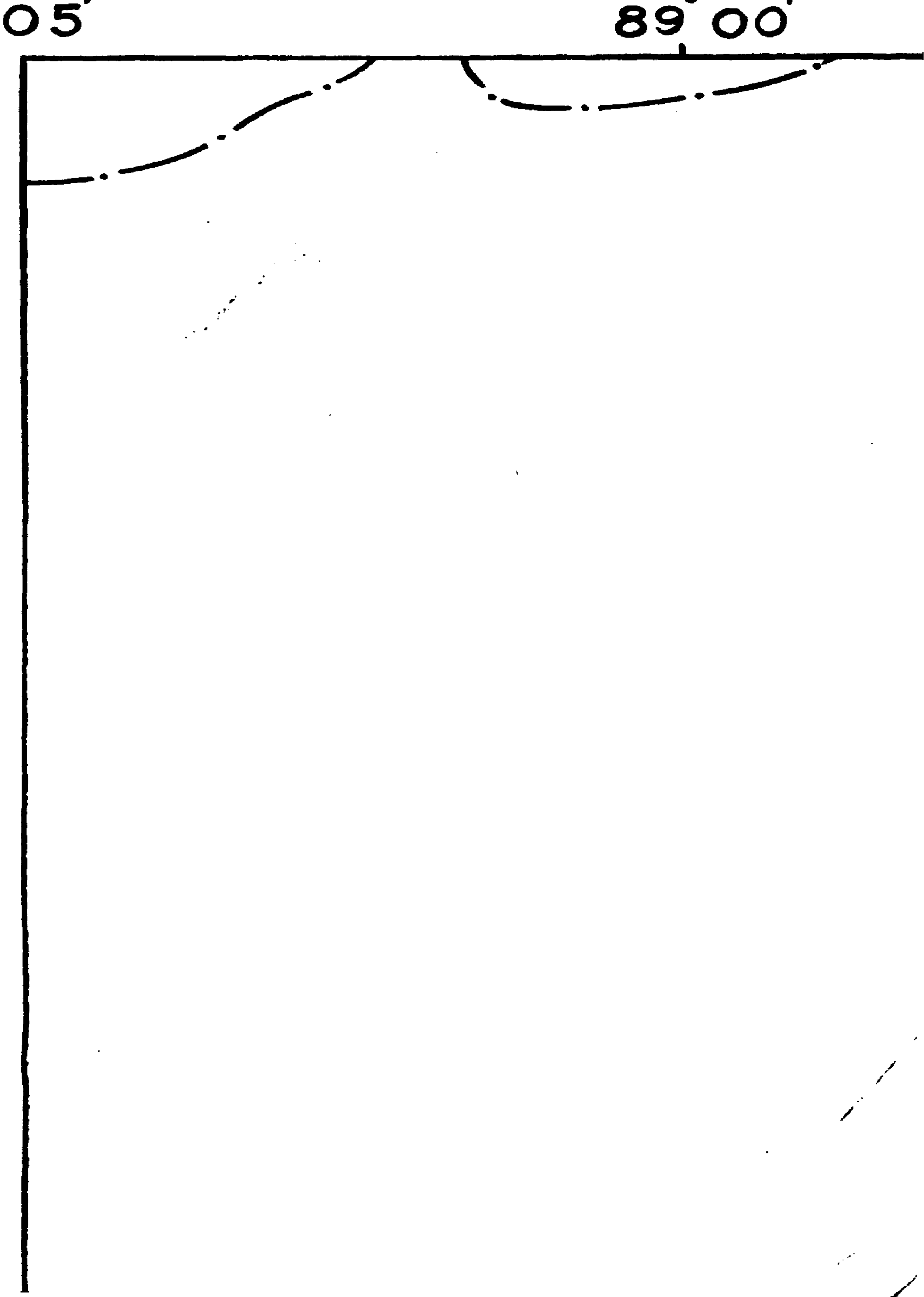

97
98

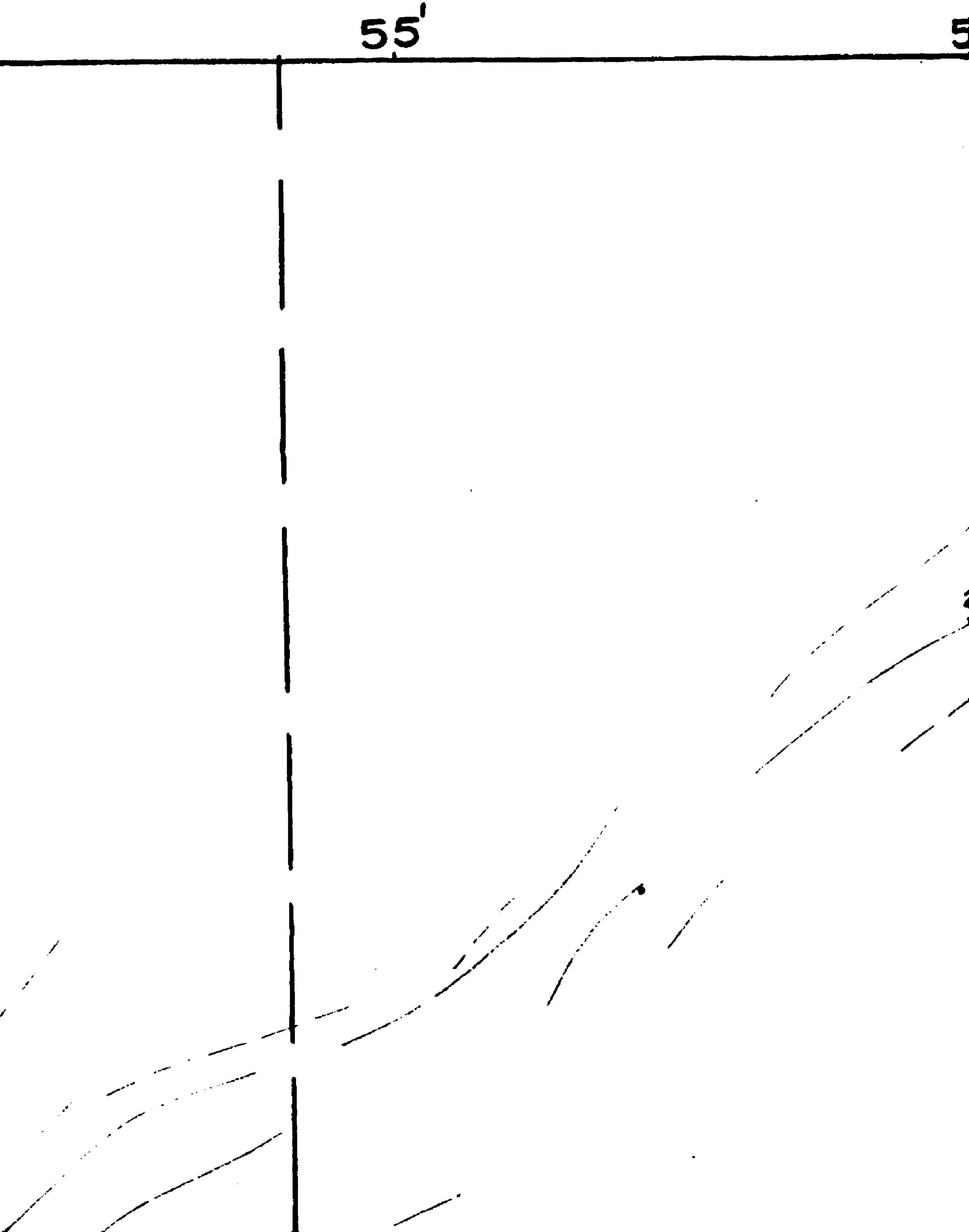

97


98

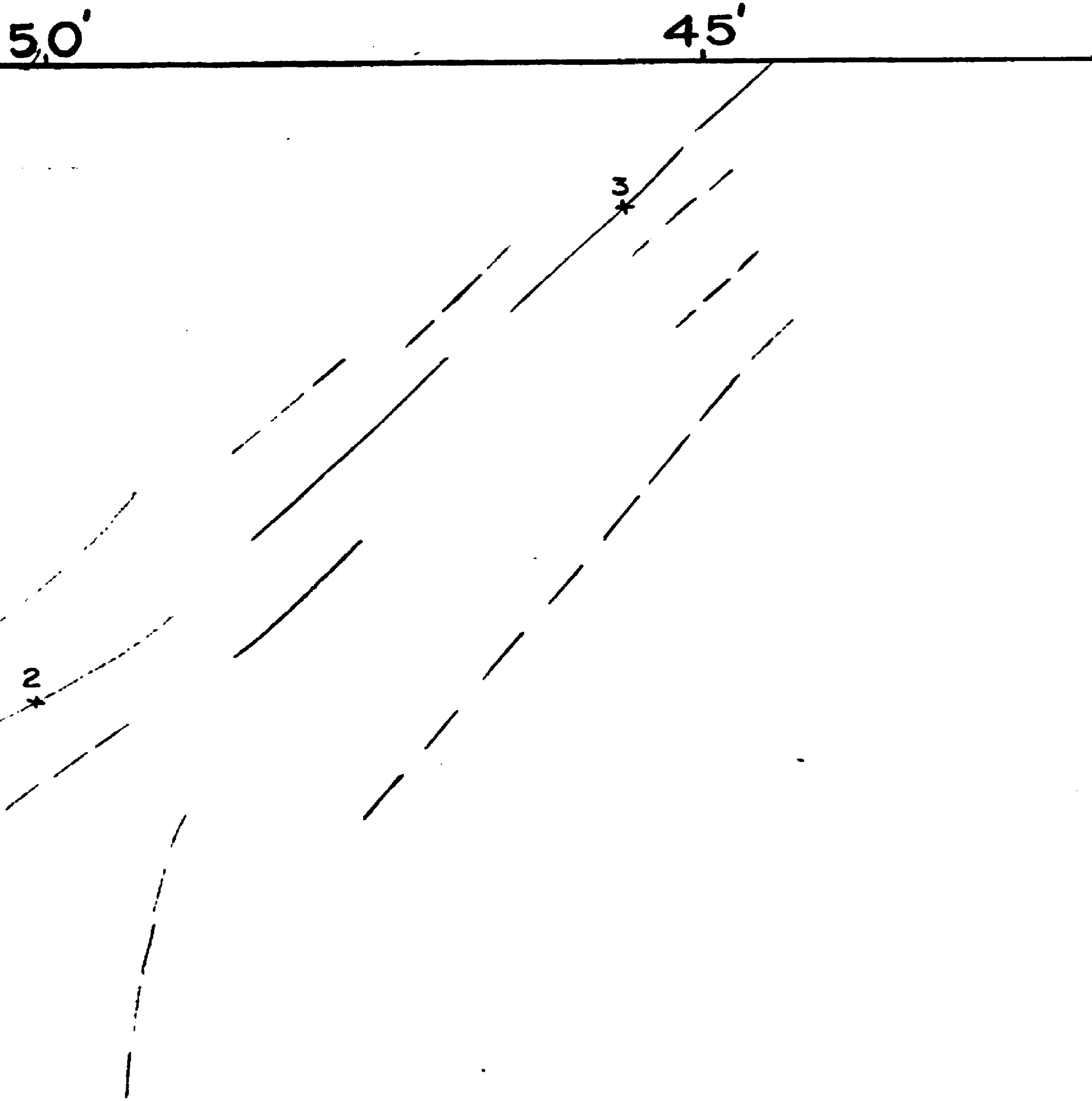

88



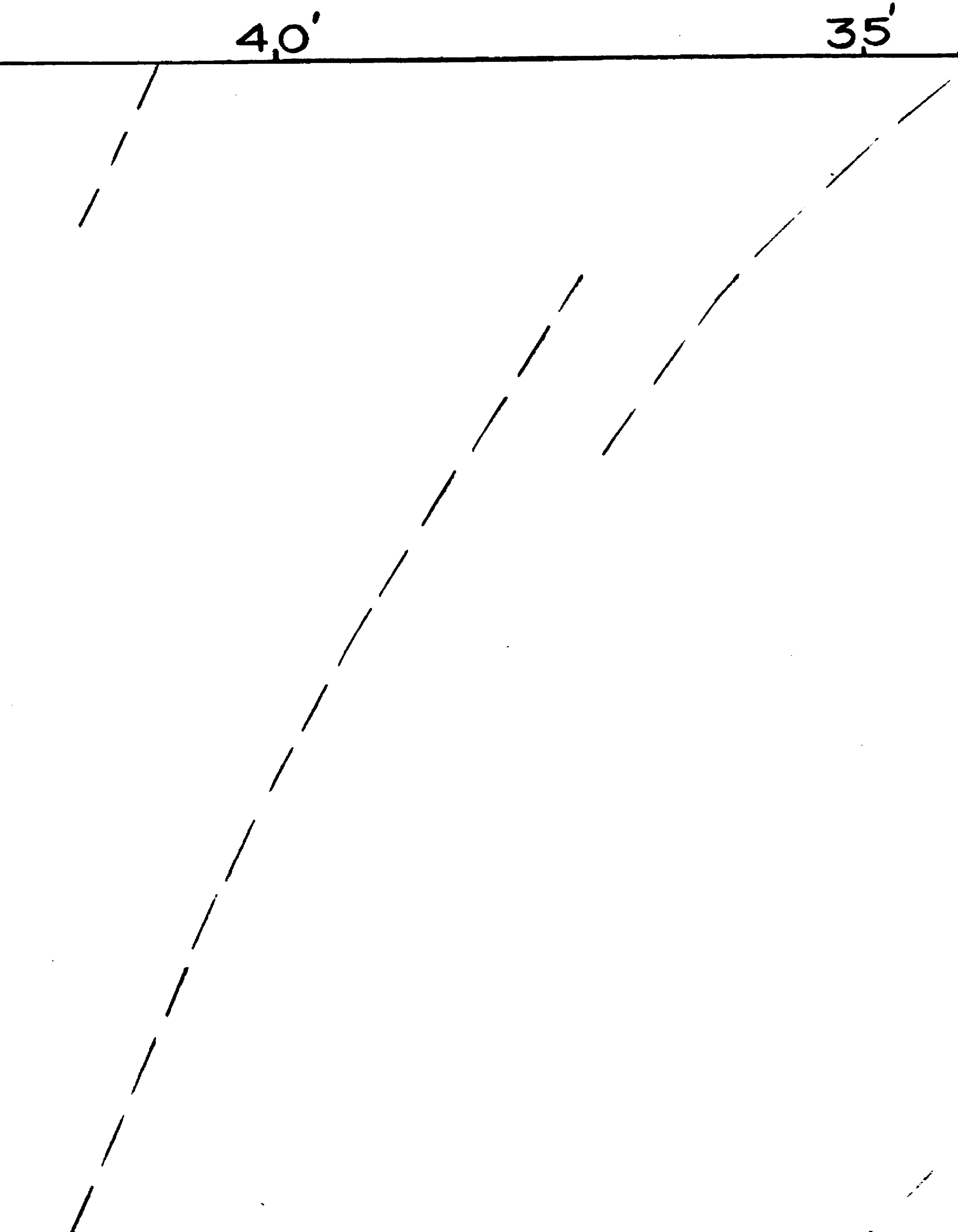

05'
89° 00'

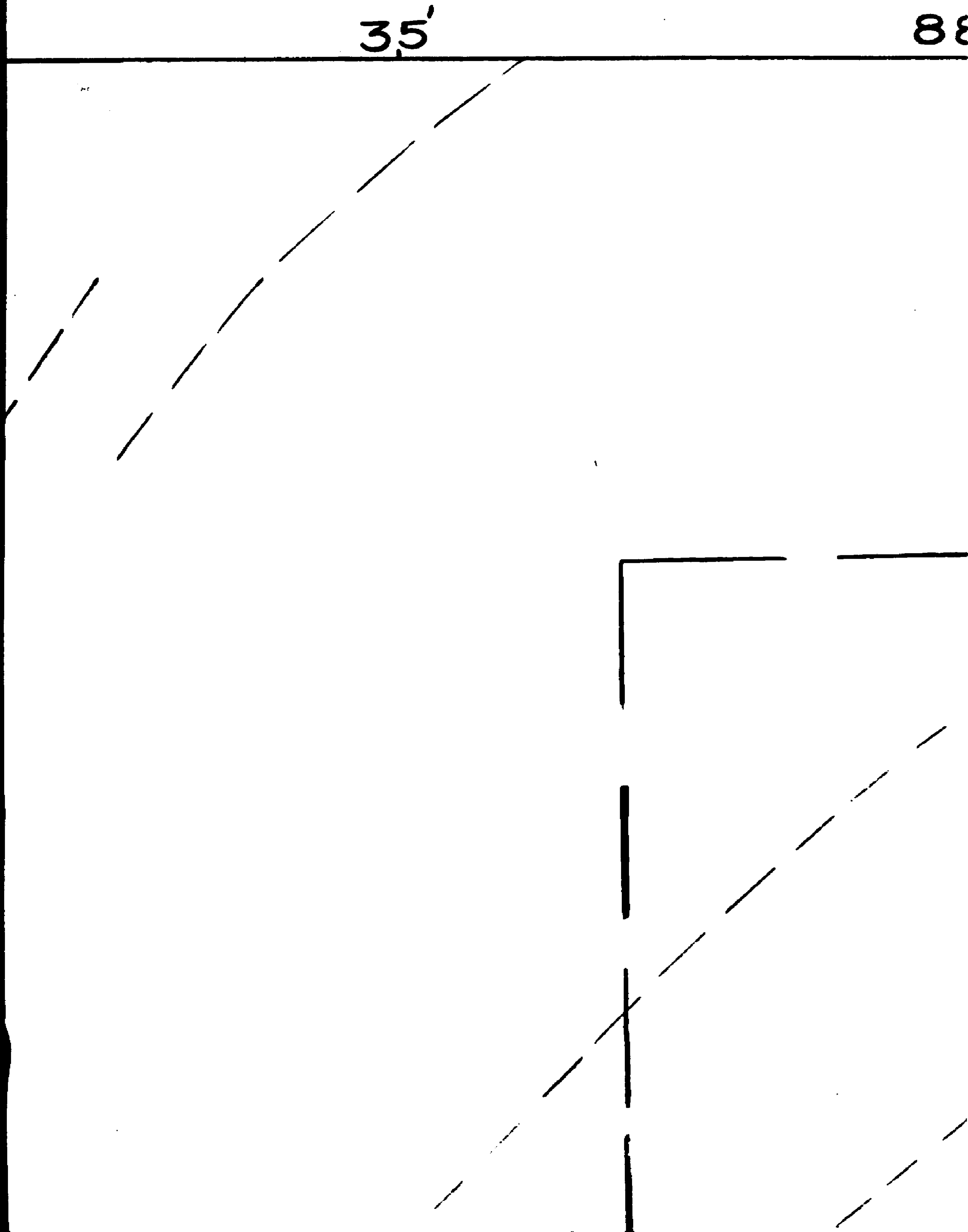


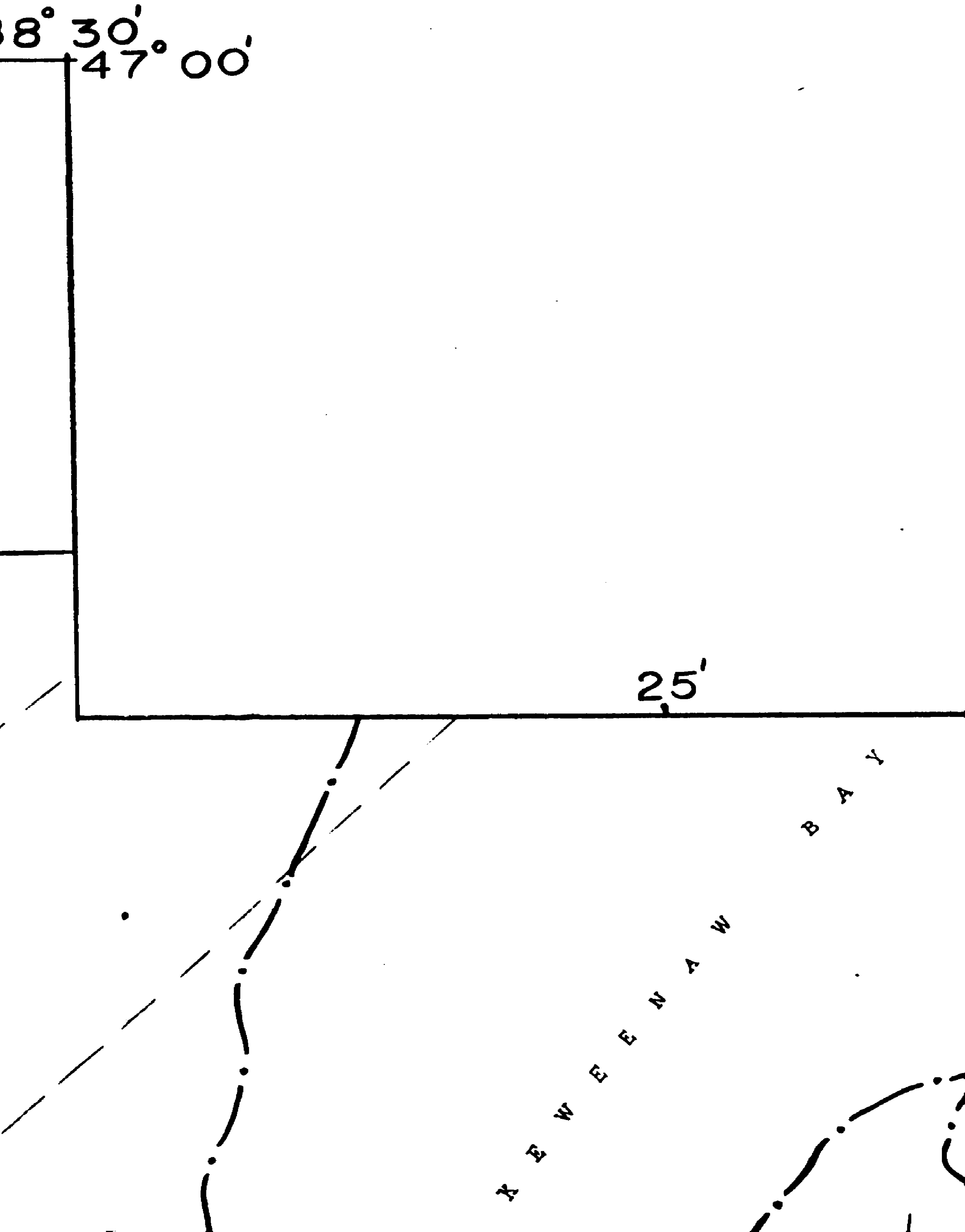
55'



50'
45'
3
2

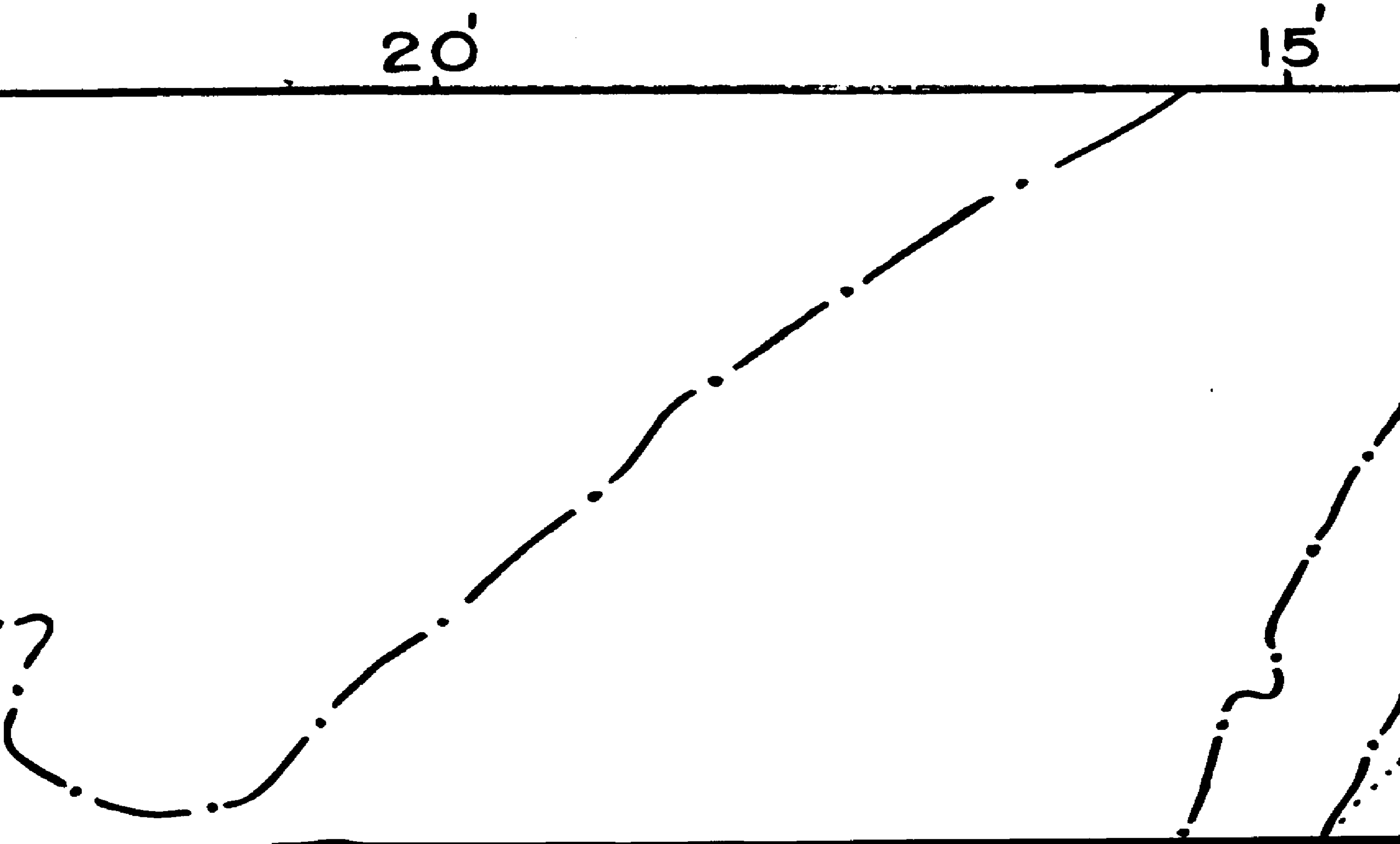

40'
35'

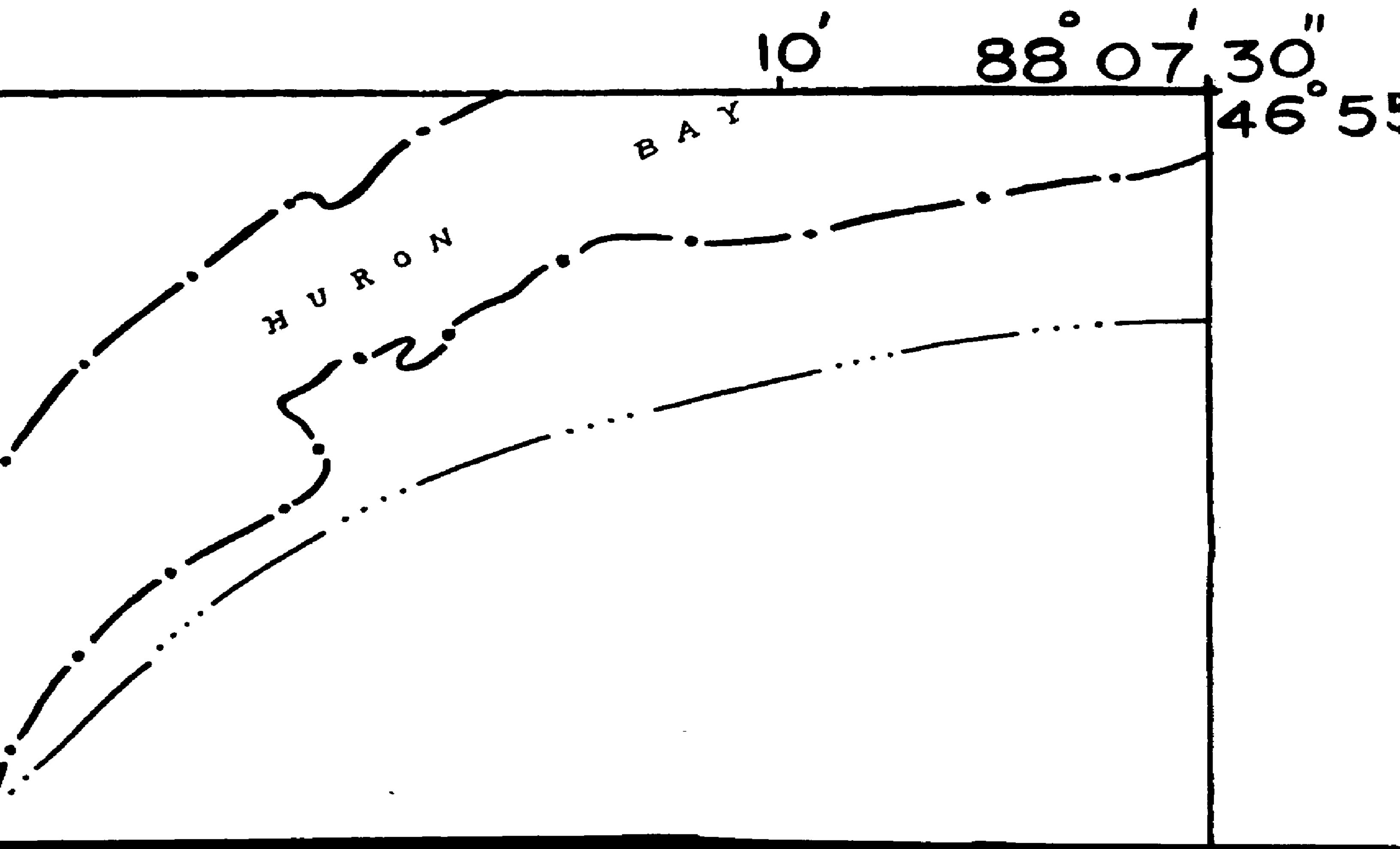

35'
88



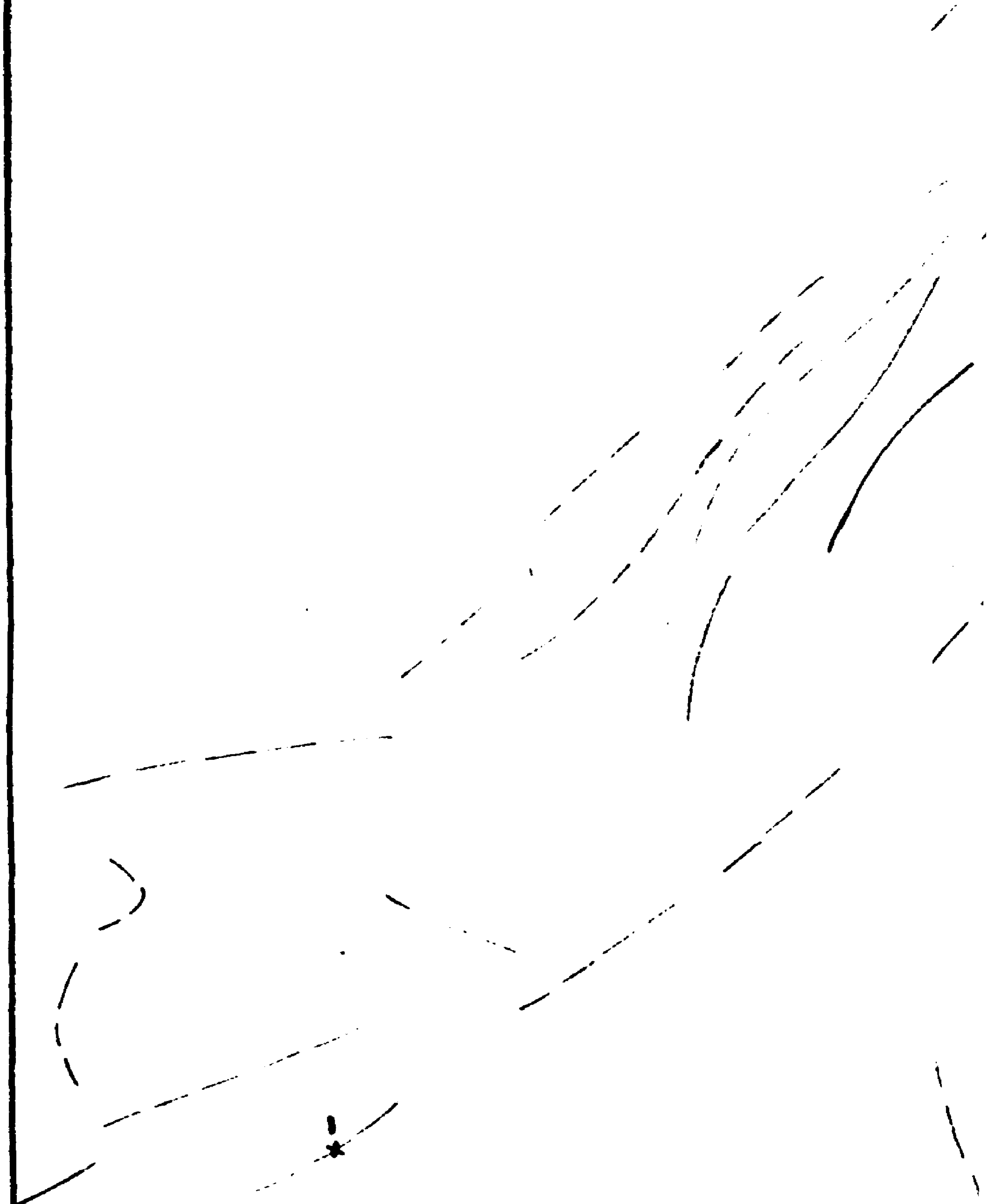
88° 30'
47° 00'
25'
KEWEENAW BAY

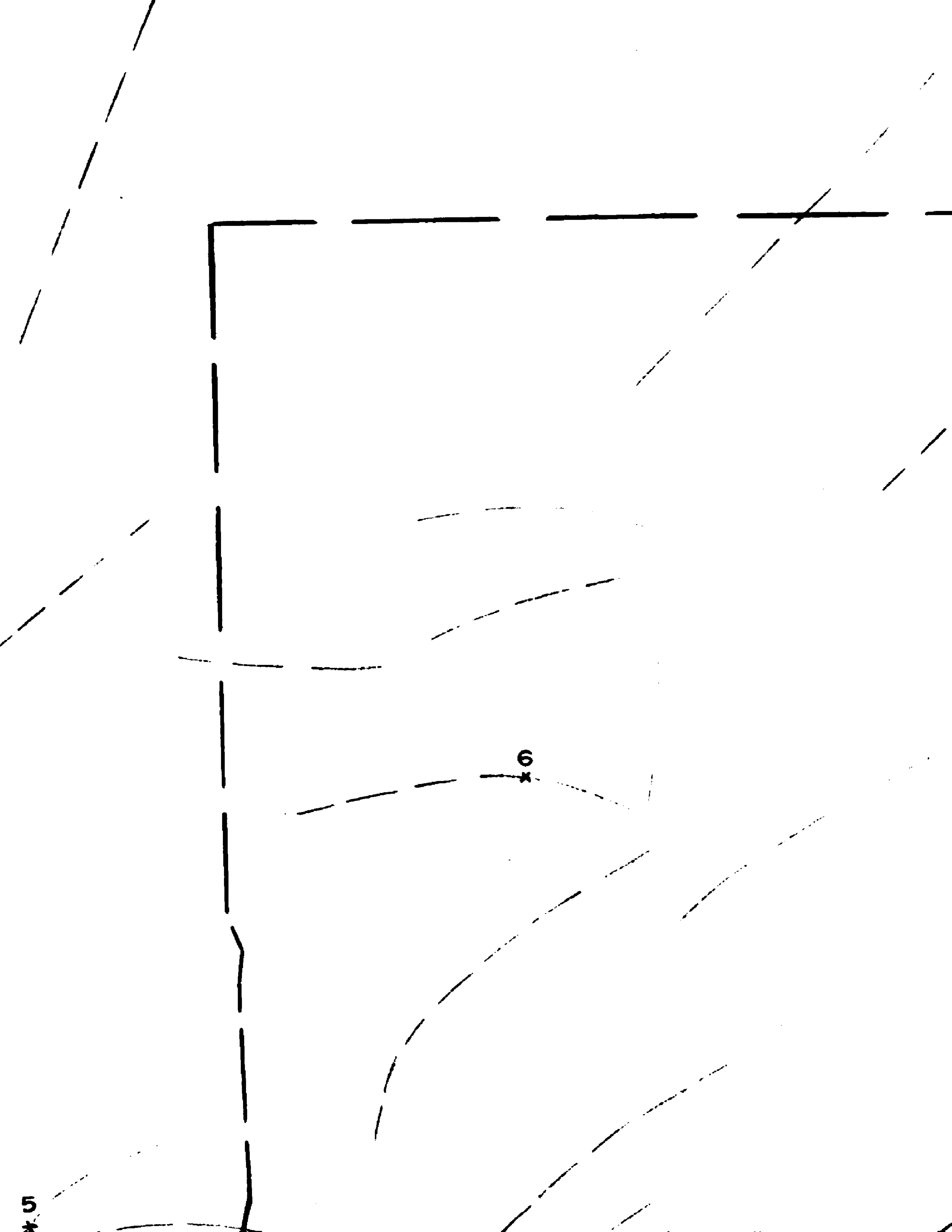
PLATE II-c

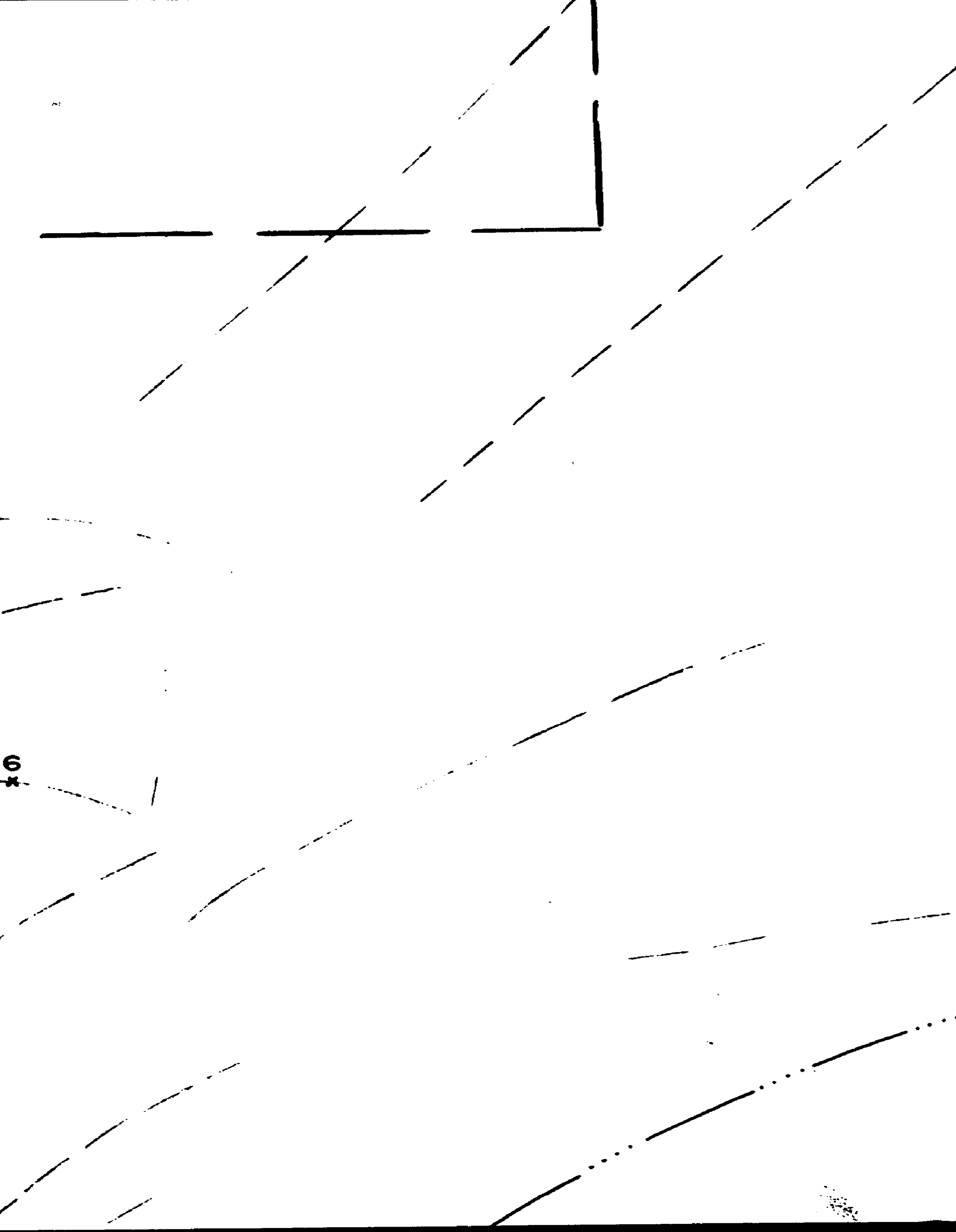




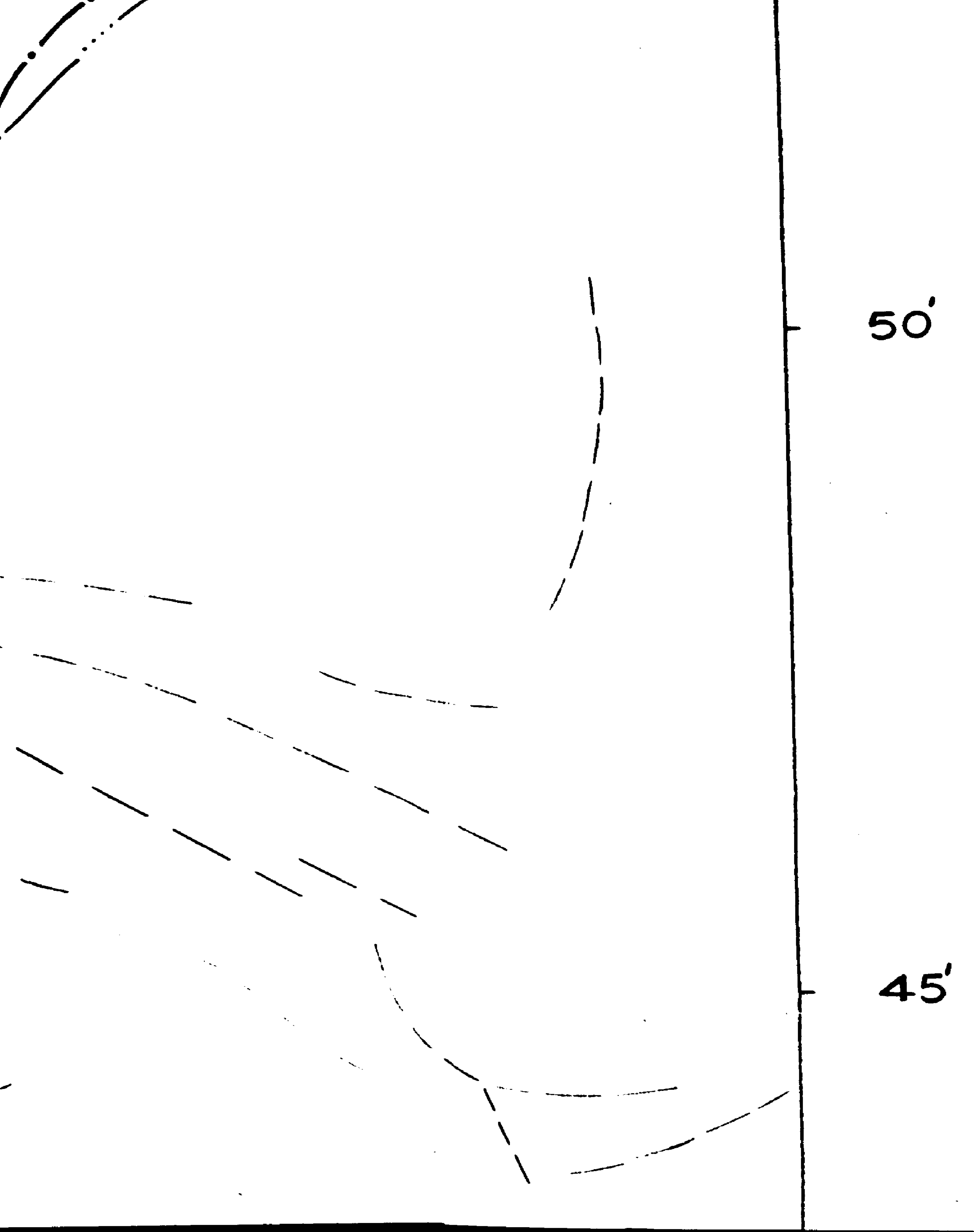
10'
88°07'30"
46°55
HURON BAY

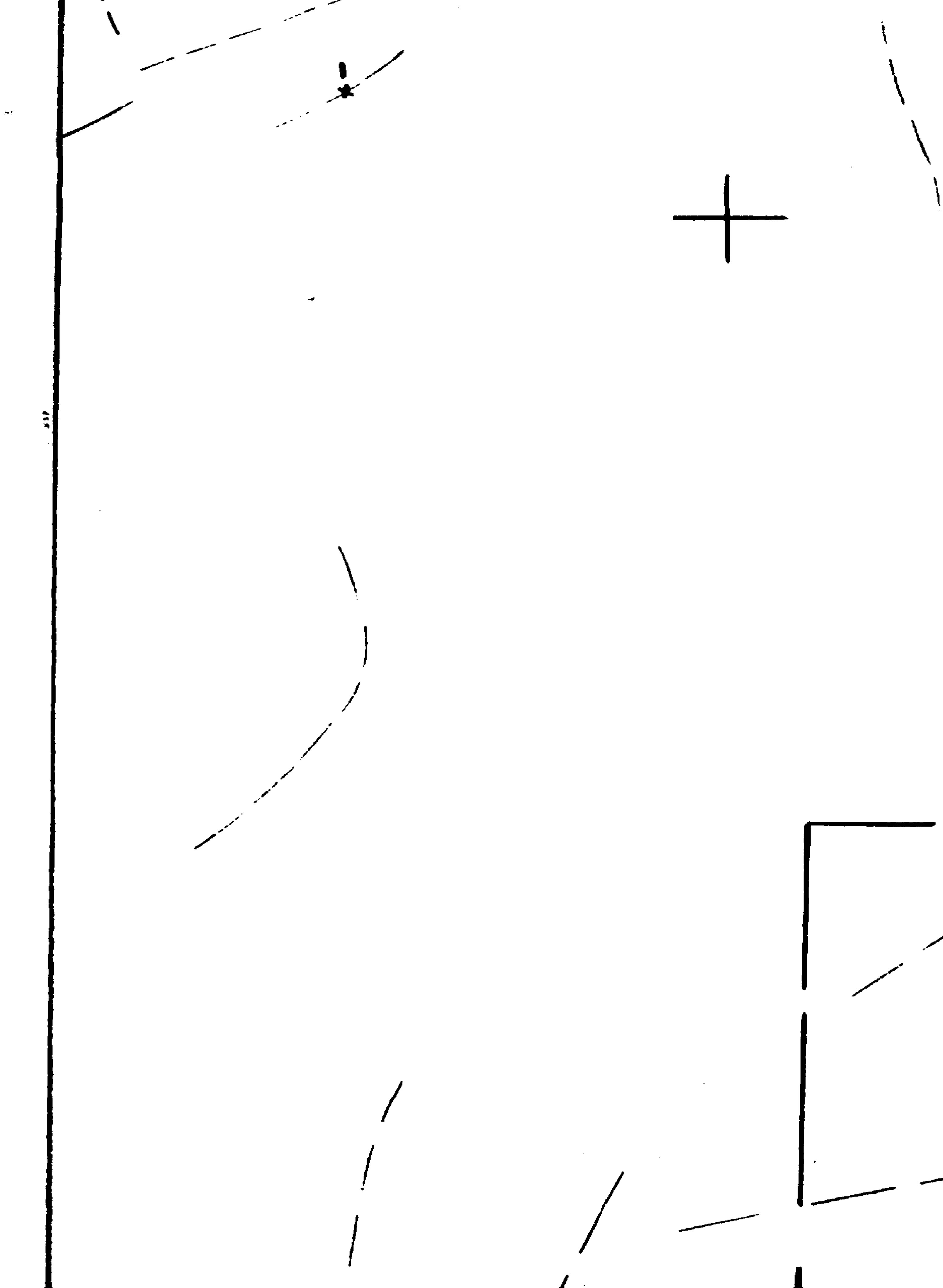


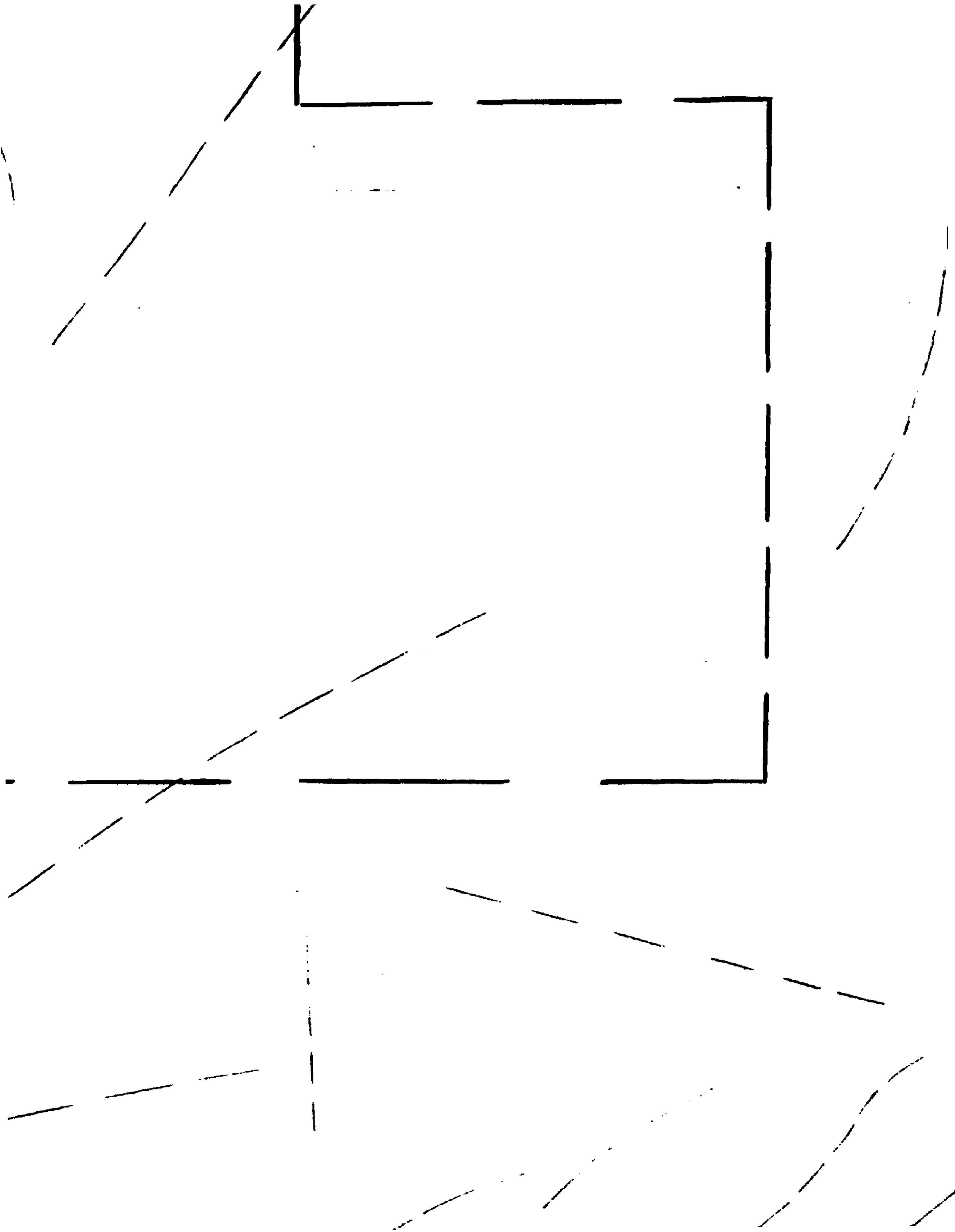

6
5


6

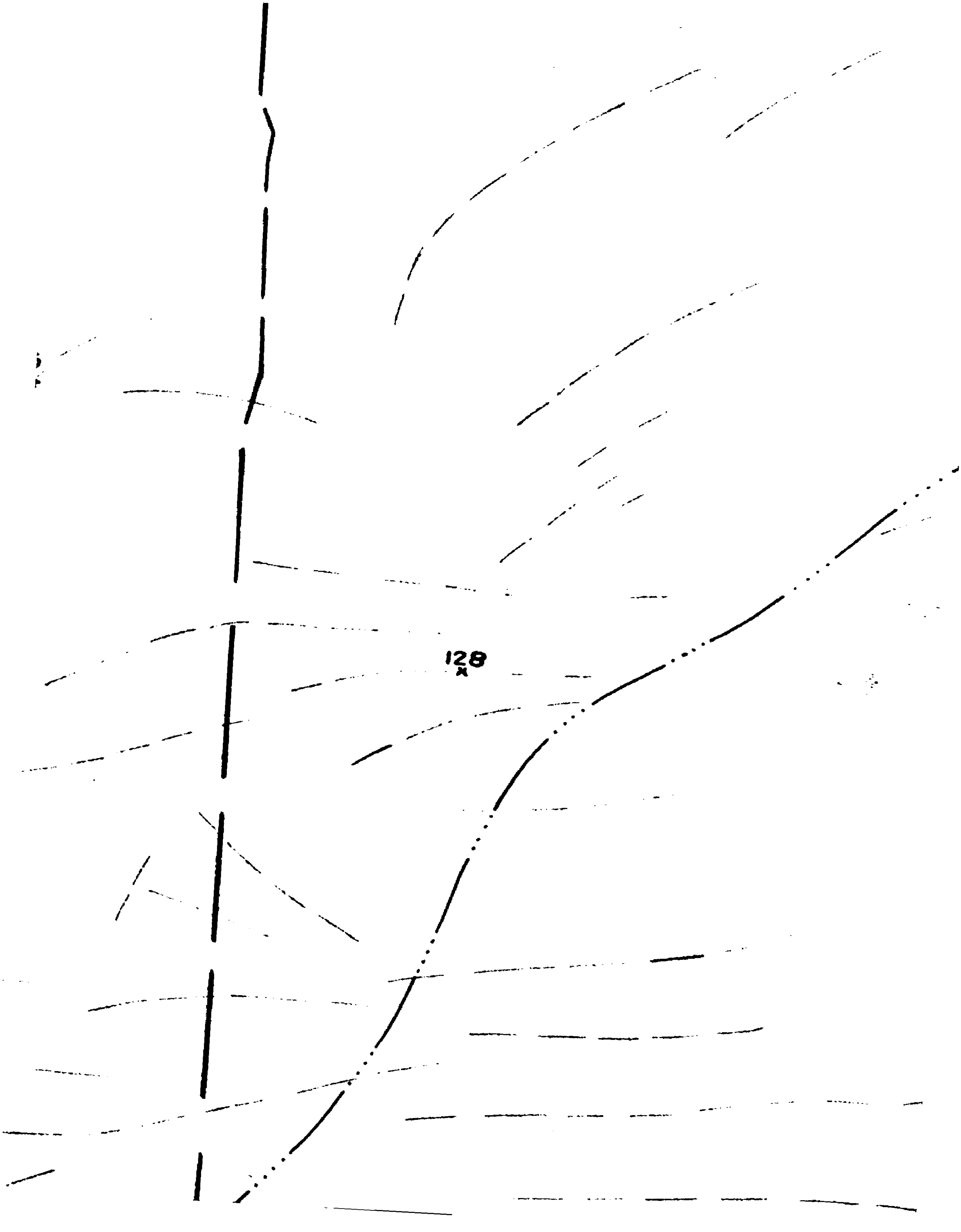

KEWEE

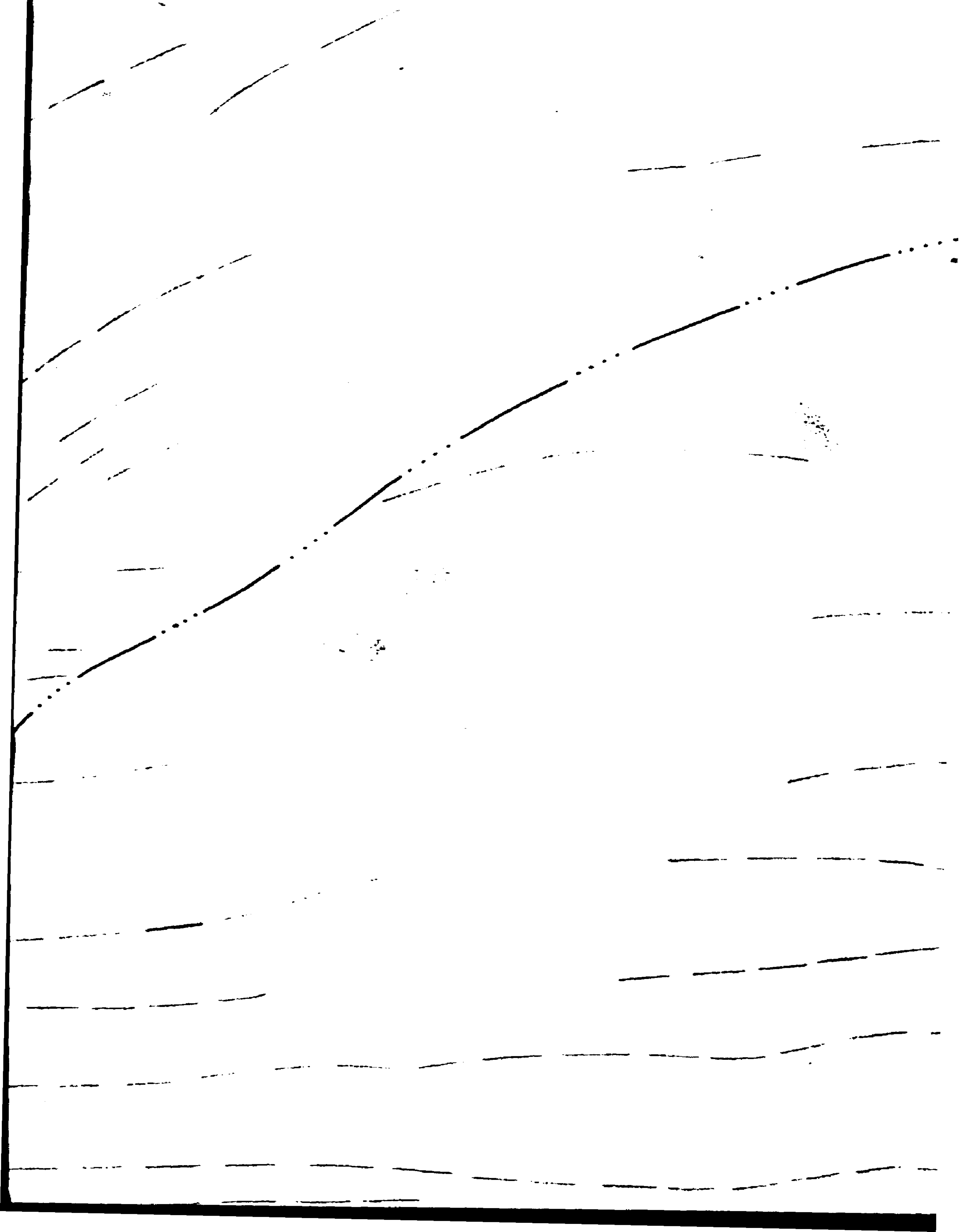

50′
45′

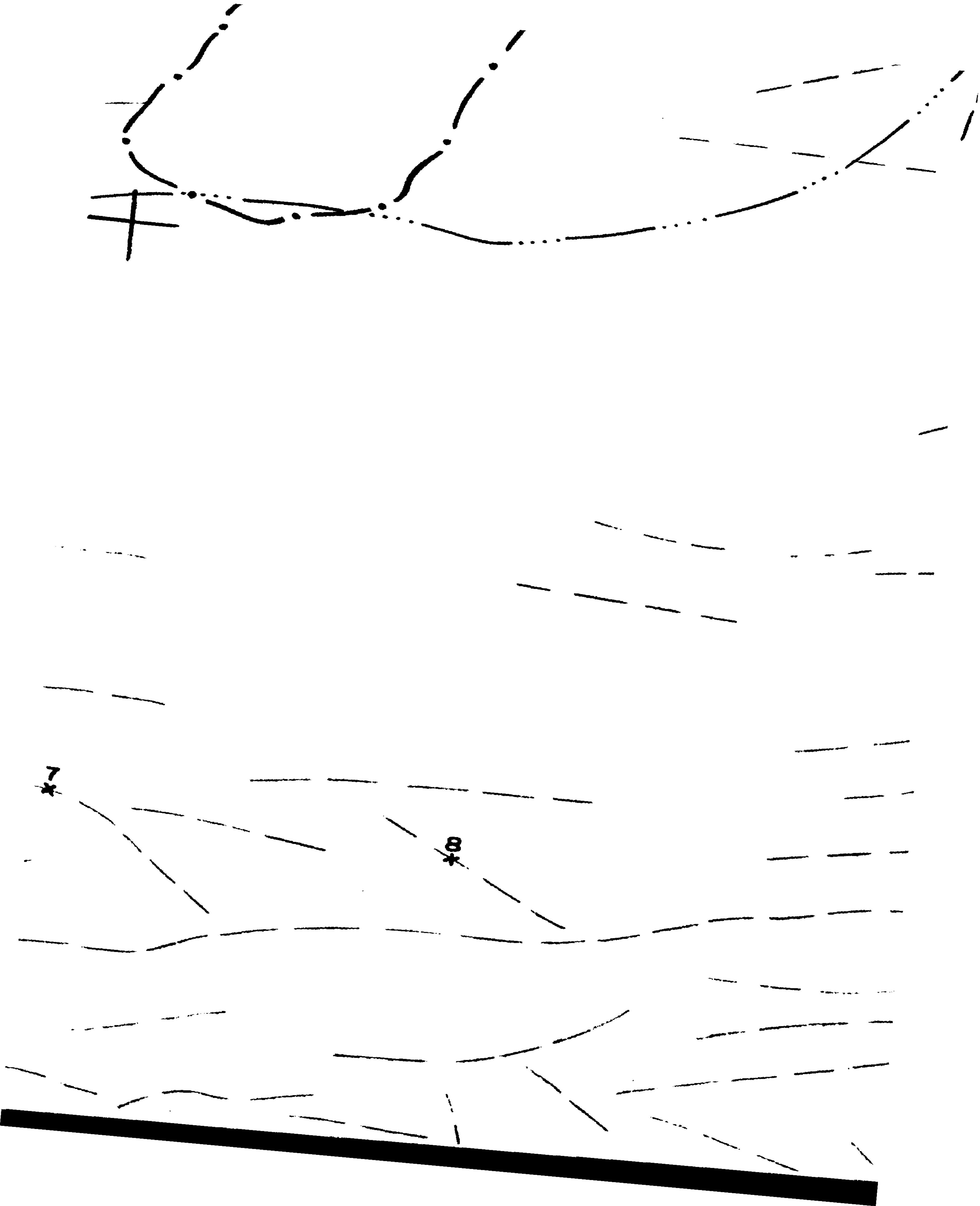


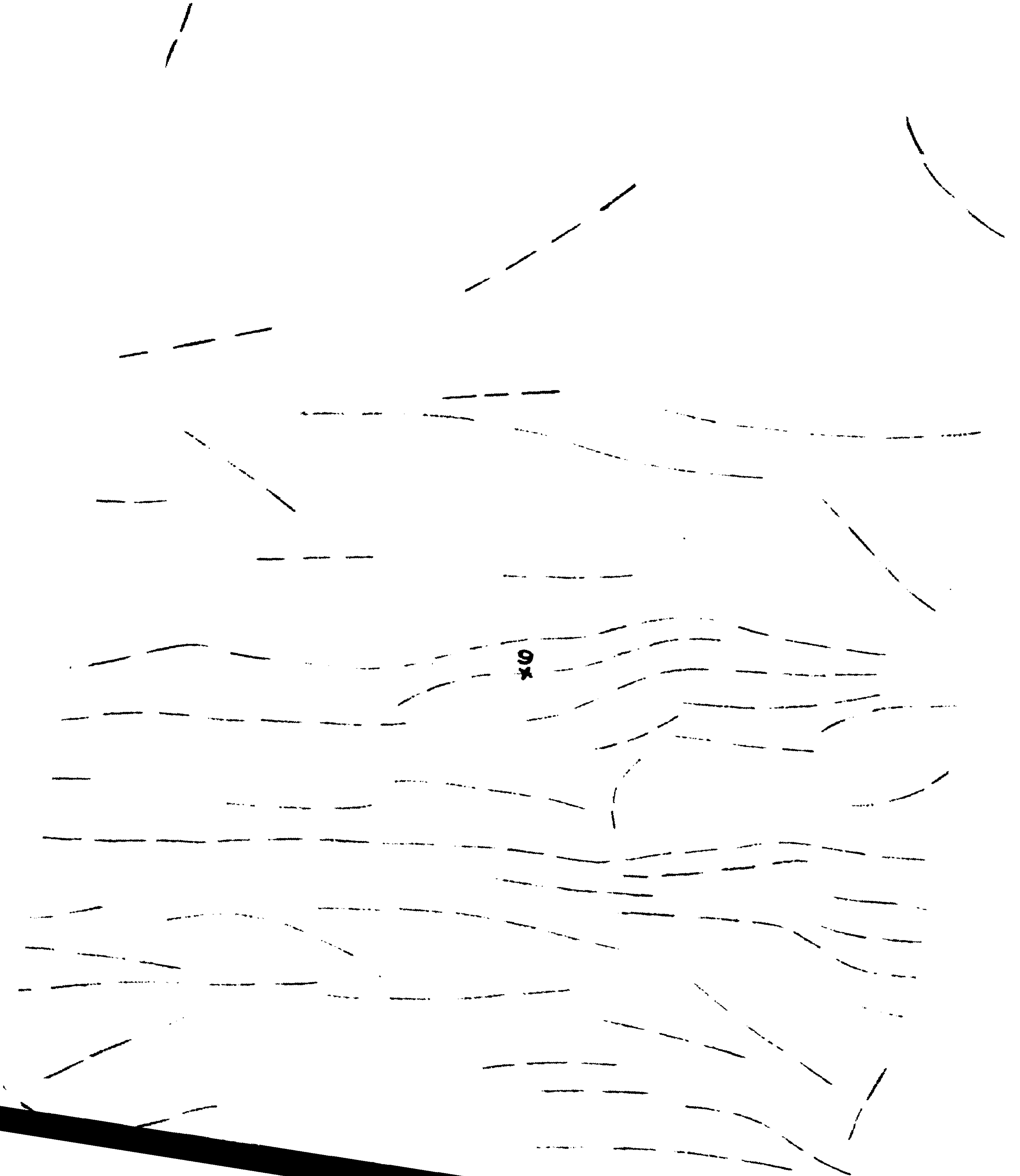


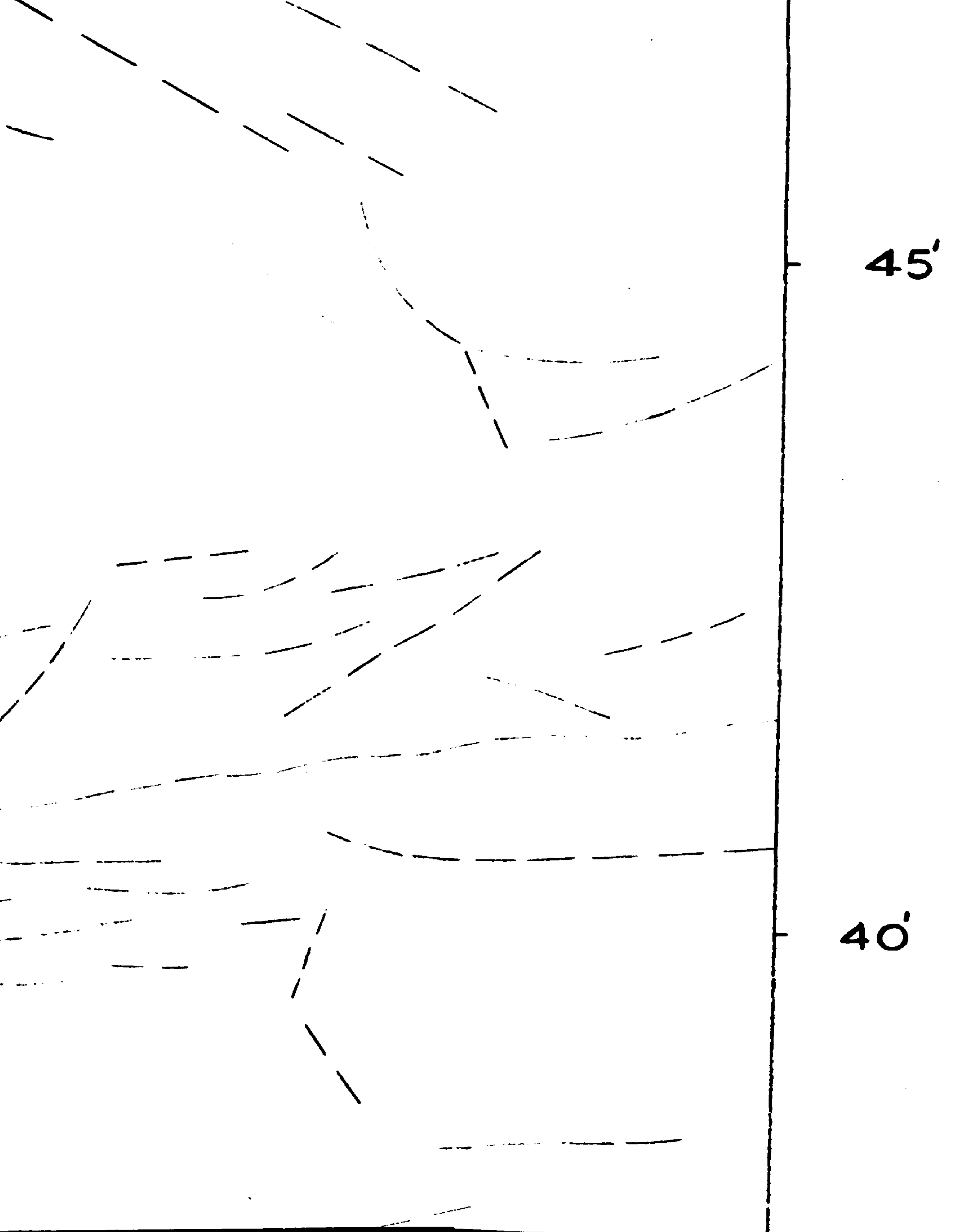

5
4

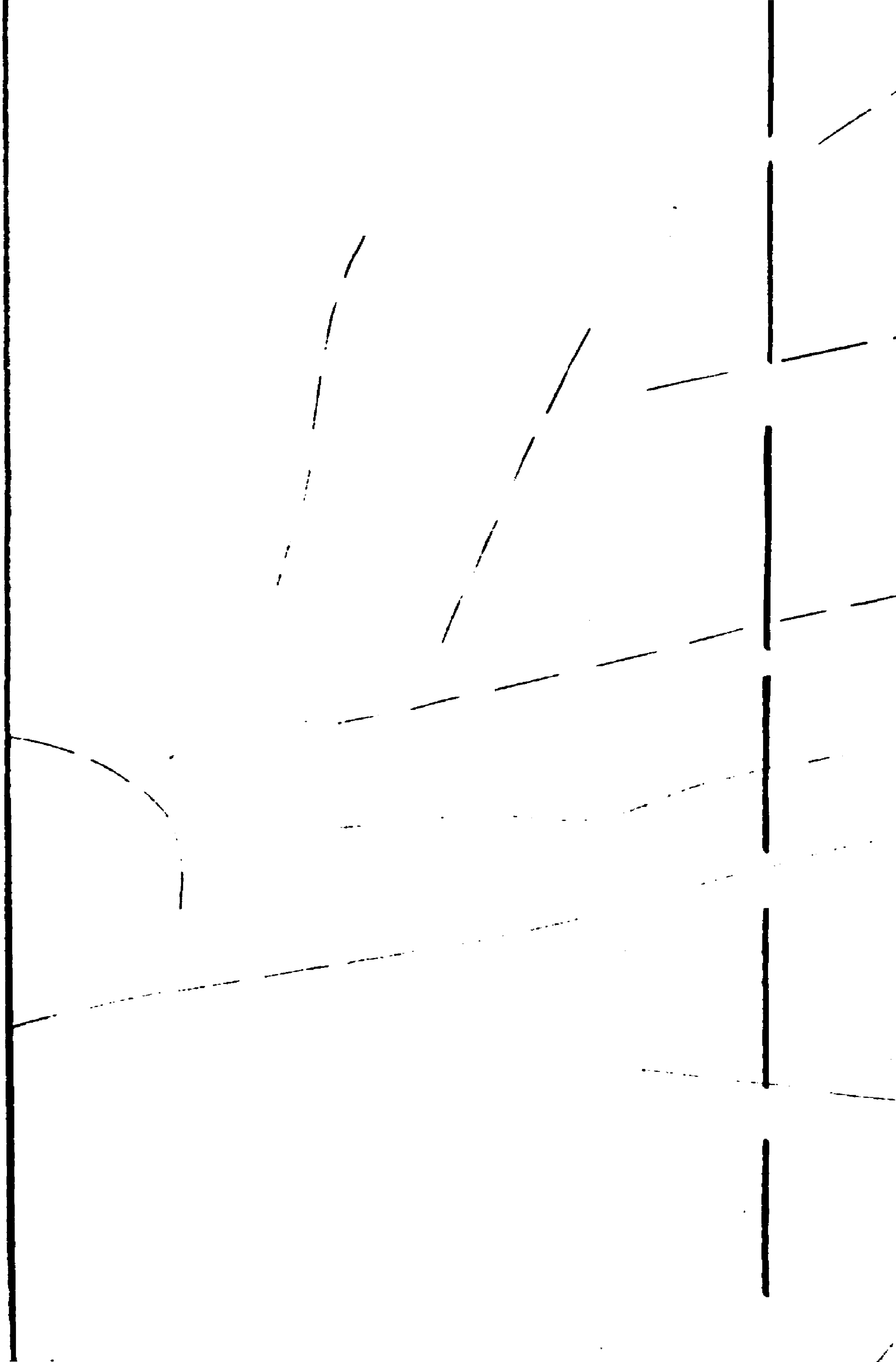

128

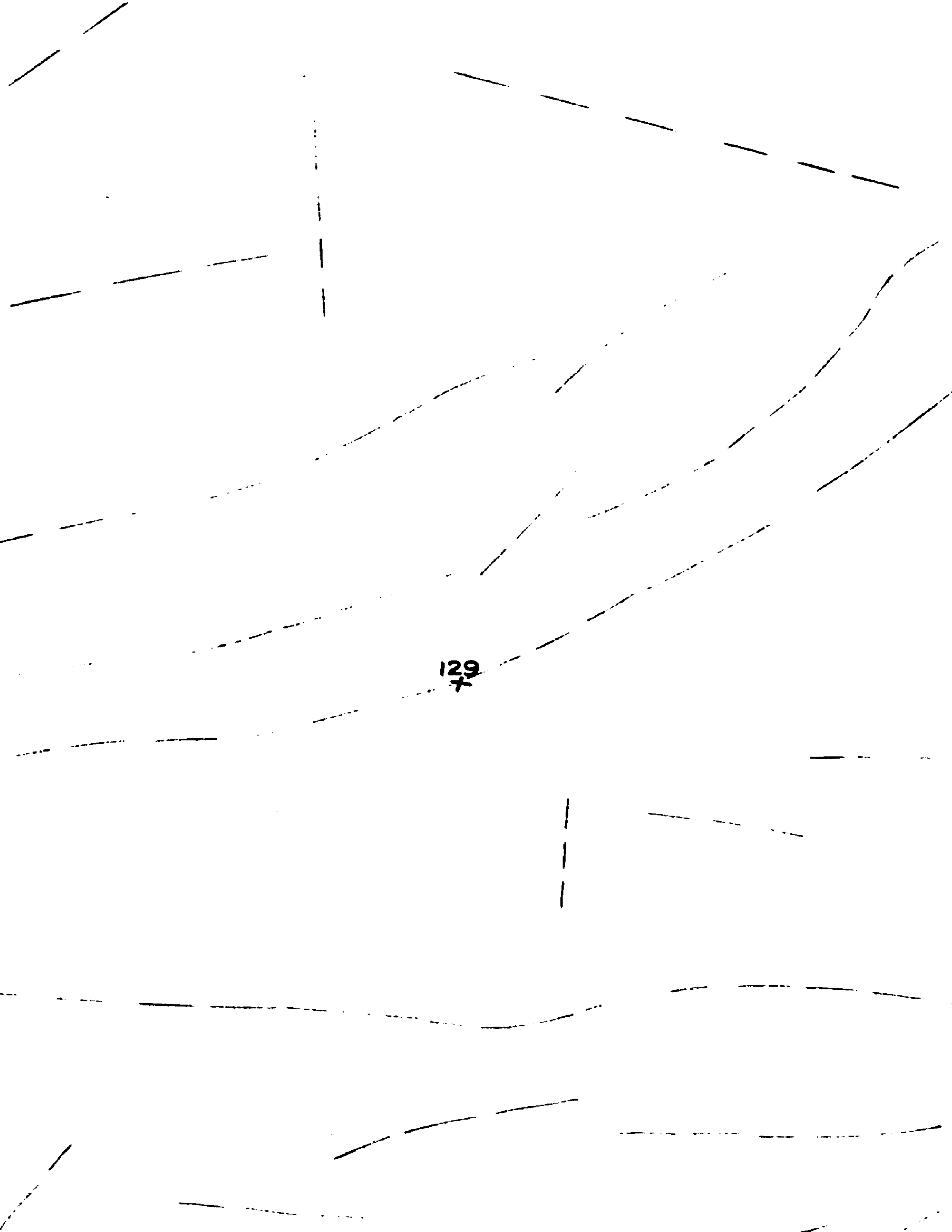


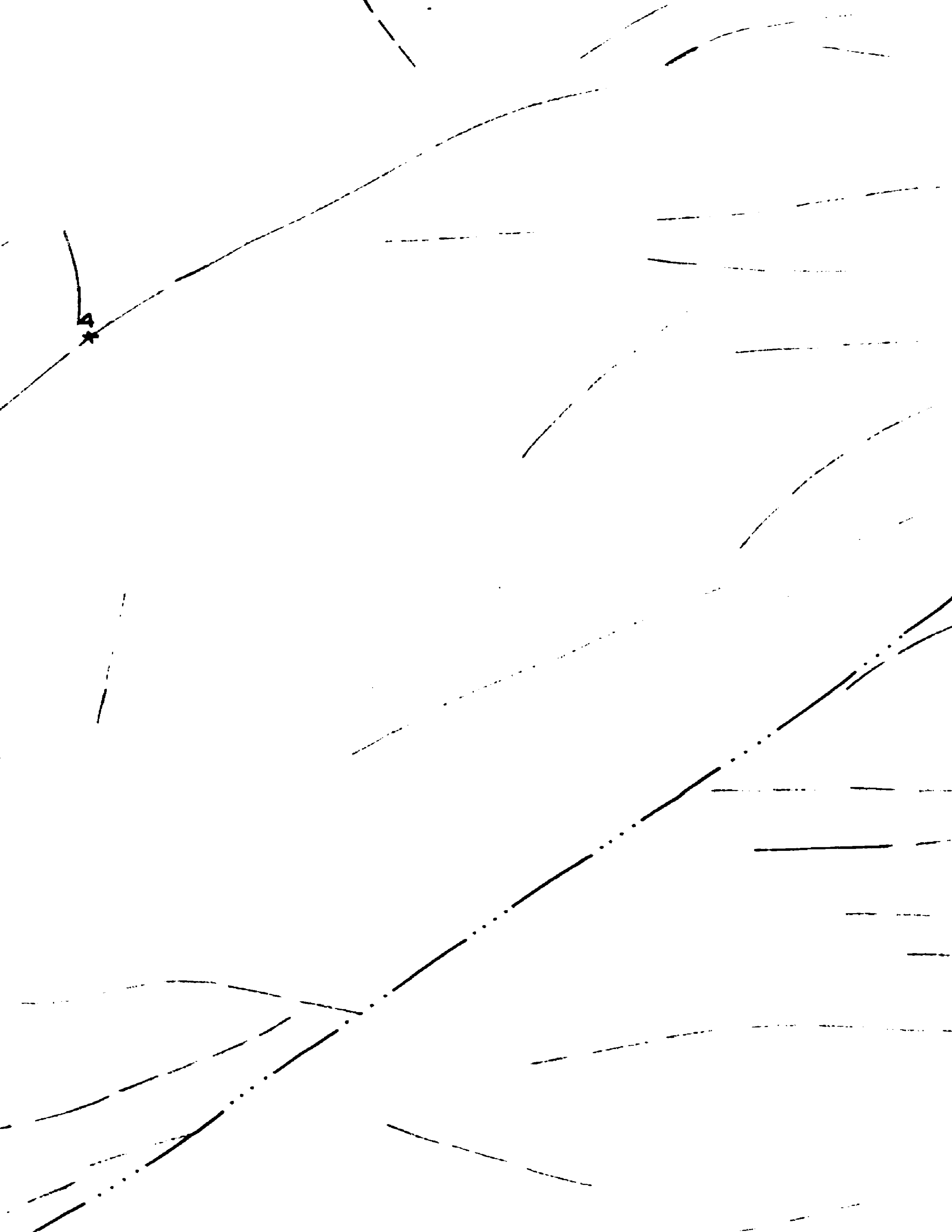

7
8


9


45'
40'




129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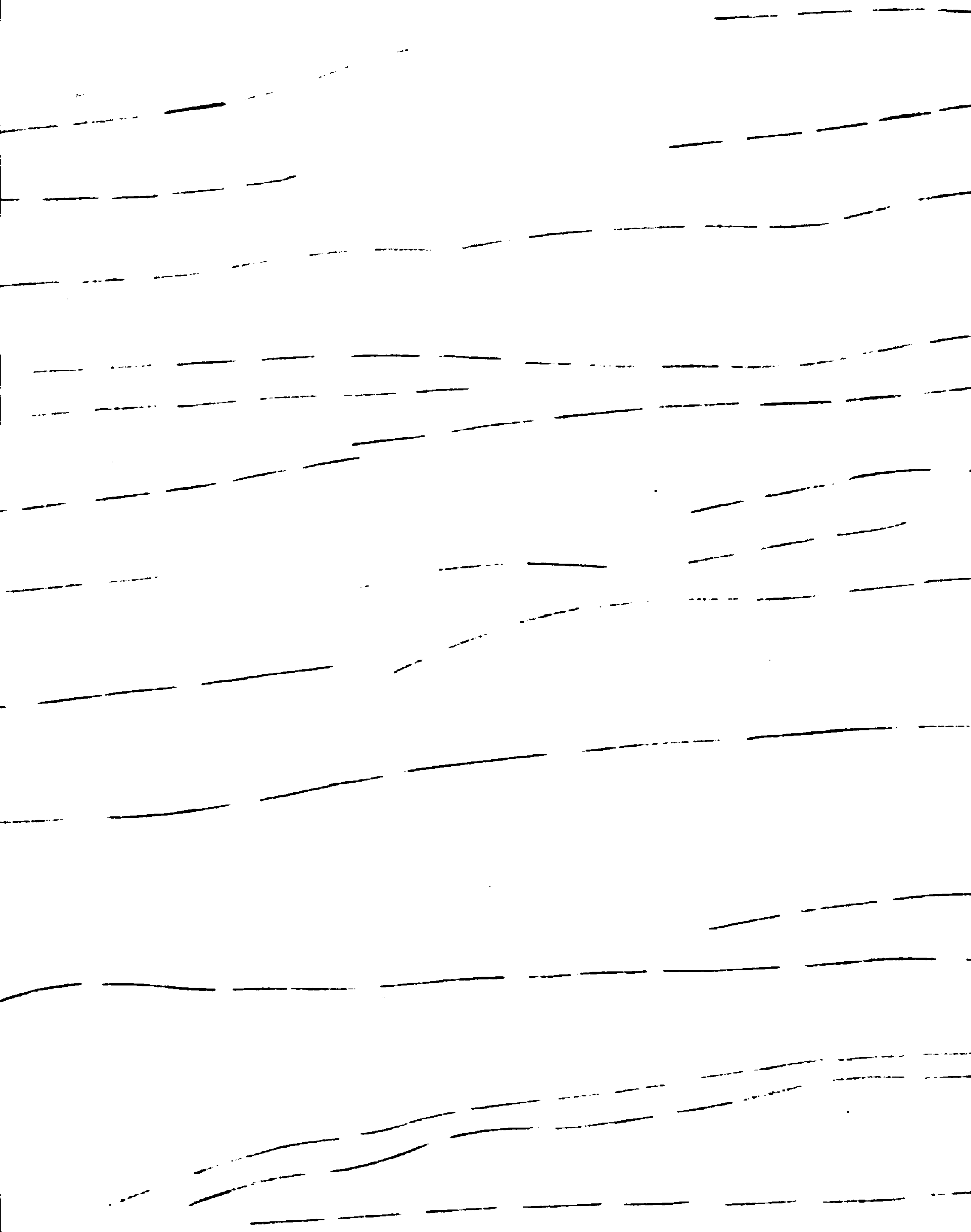
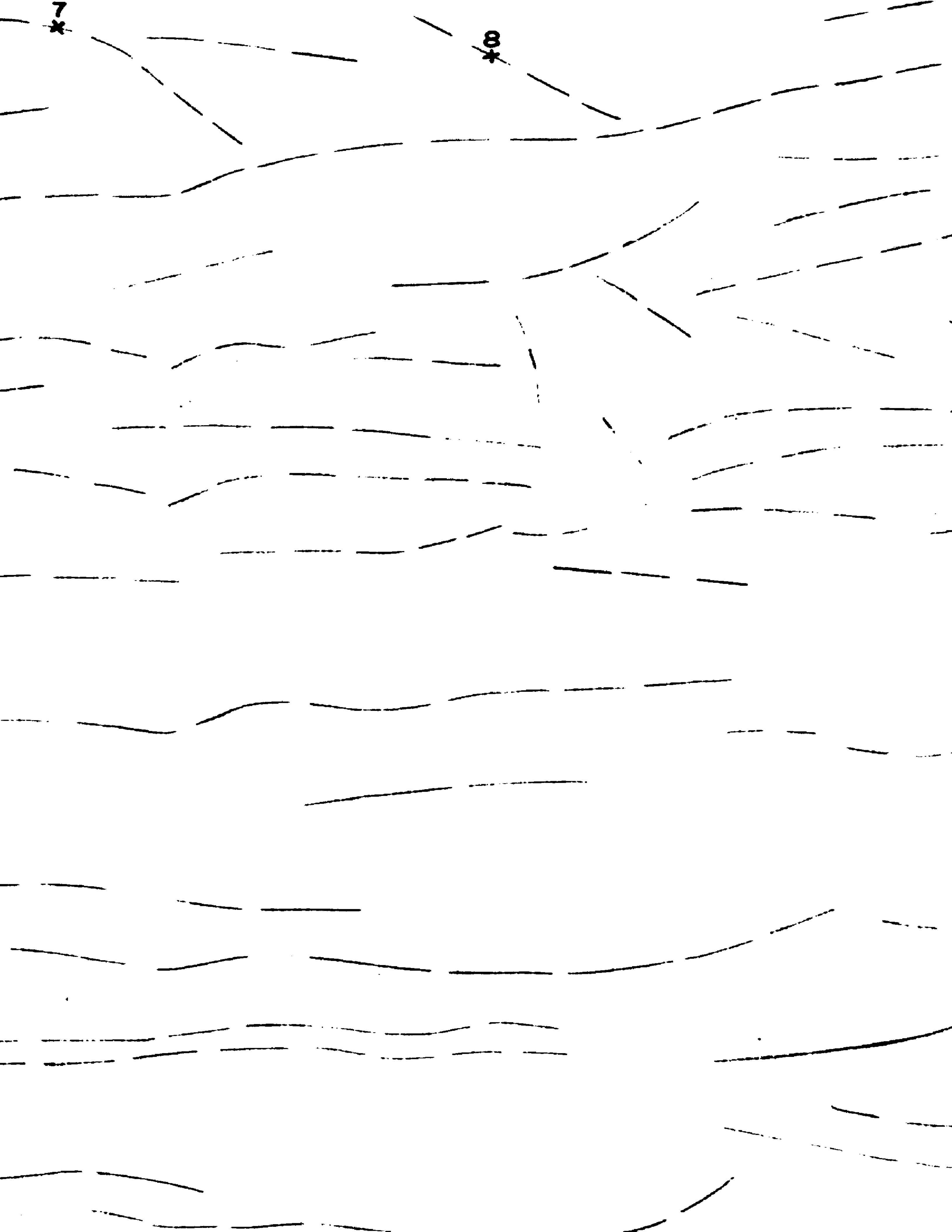
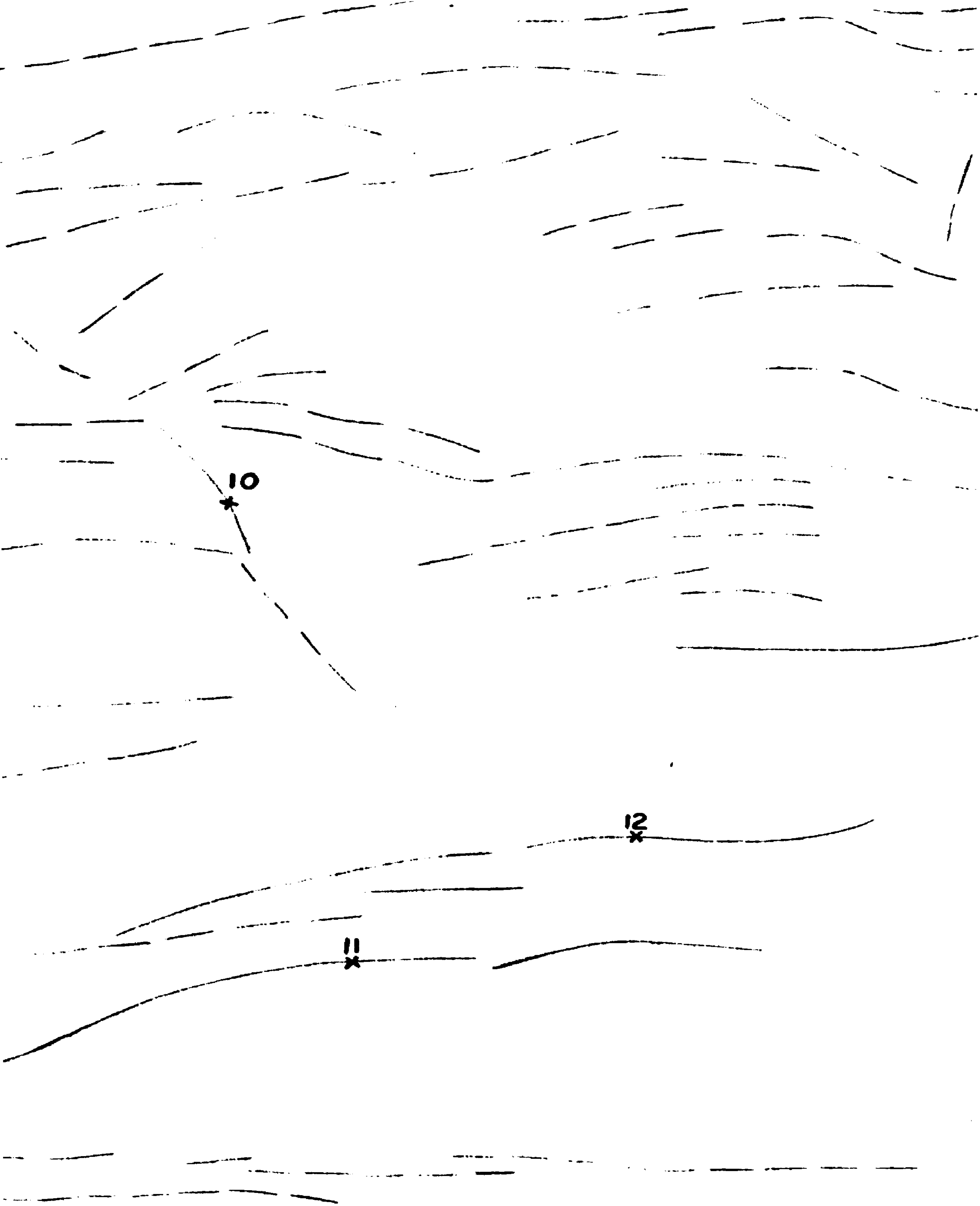
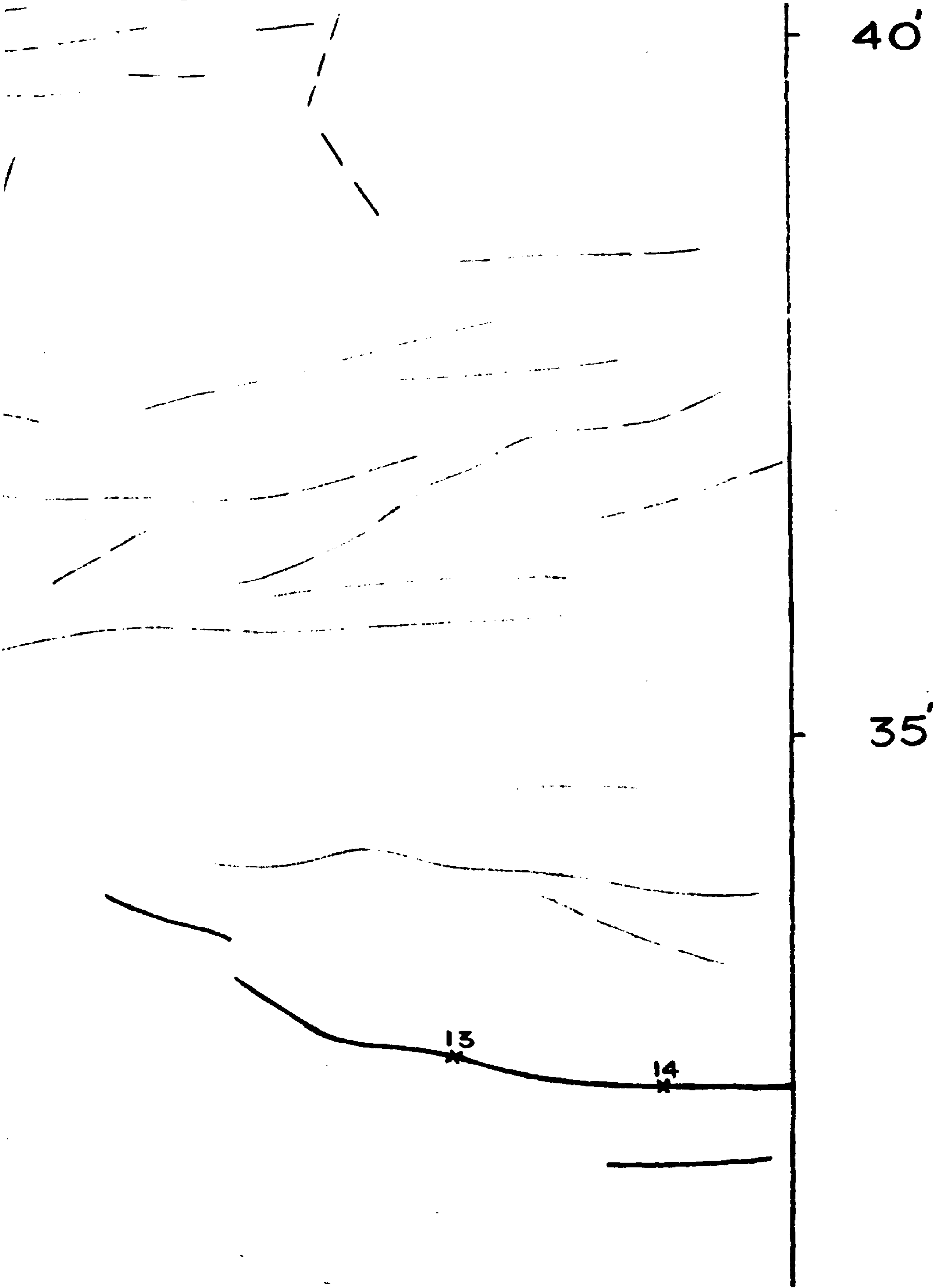
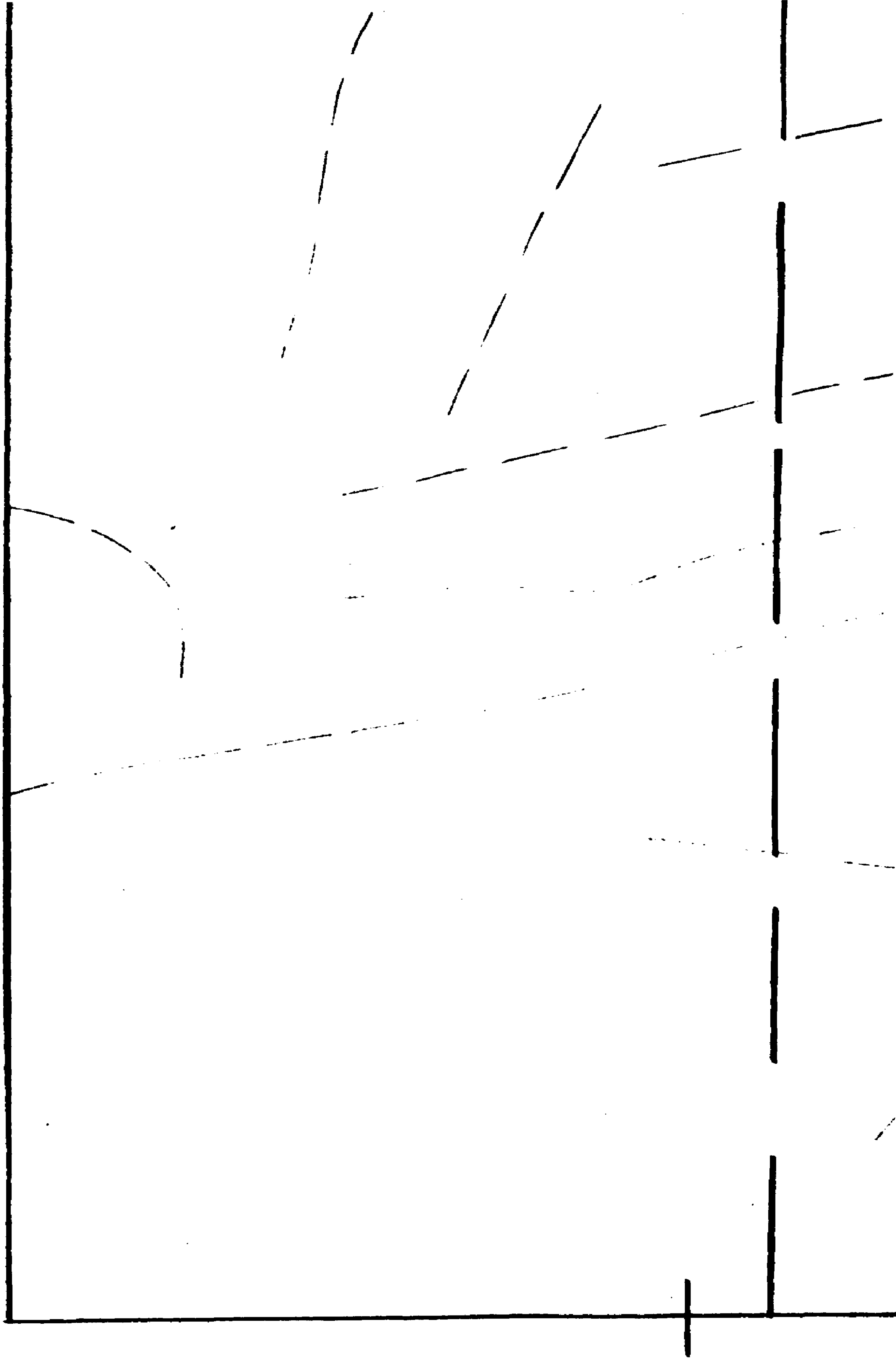


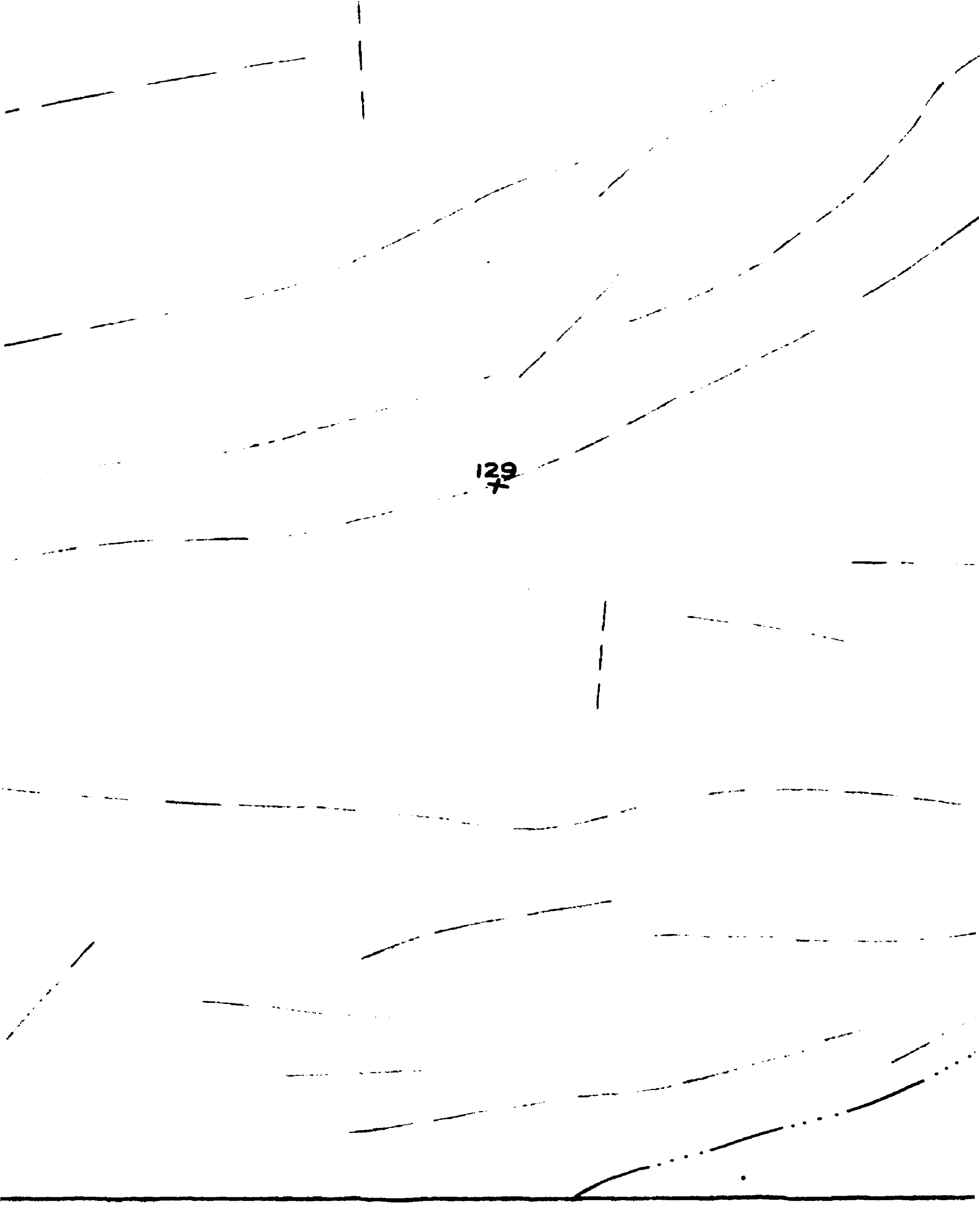

7
8


10
12
11



40'
35'
13
14

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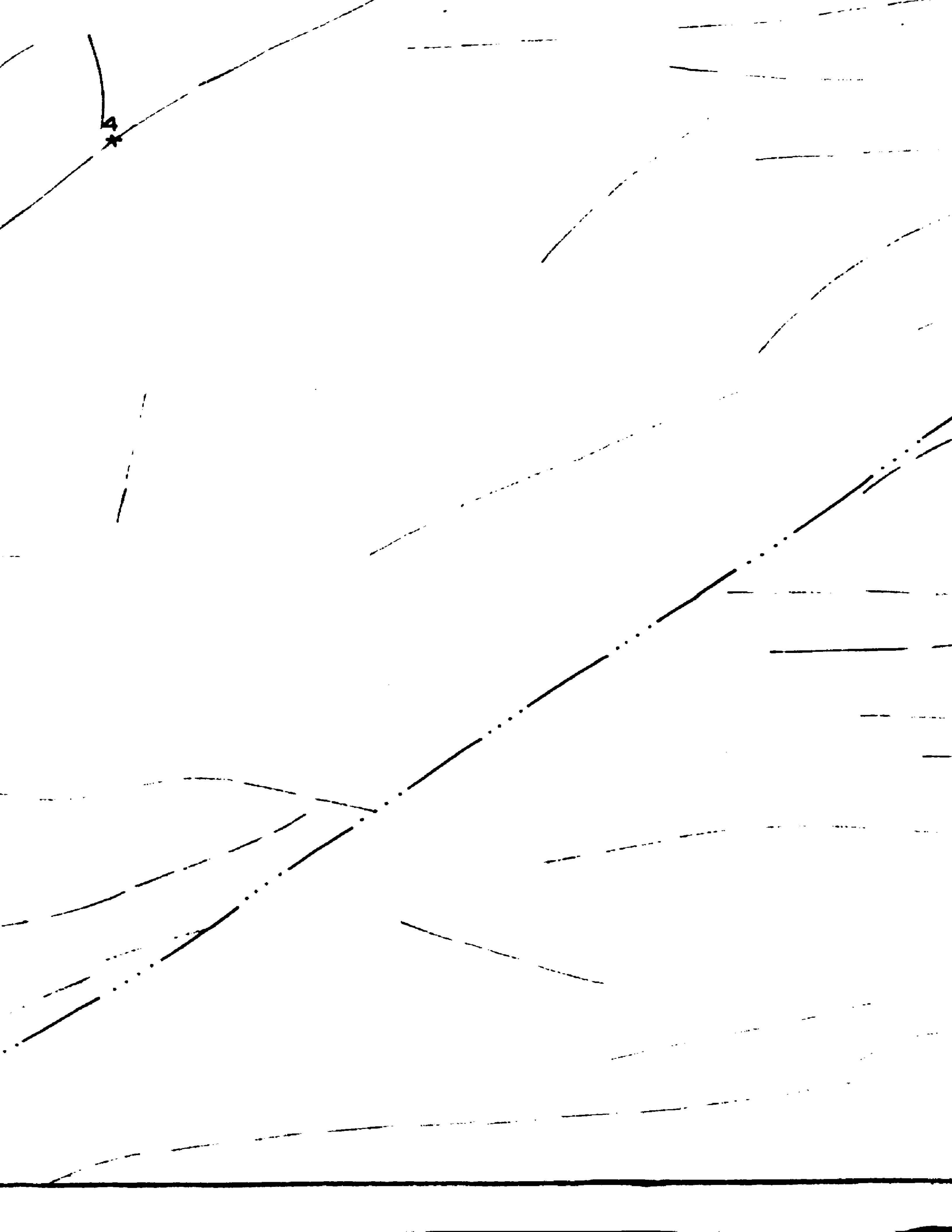
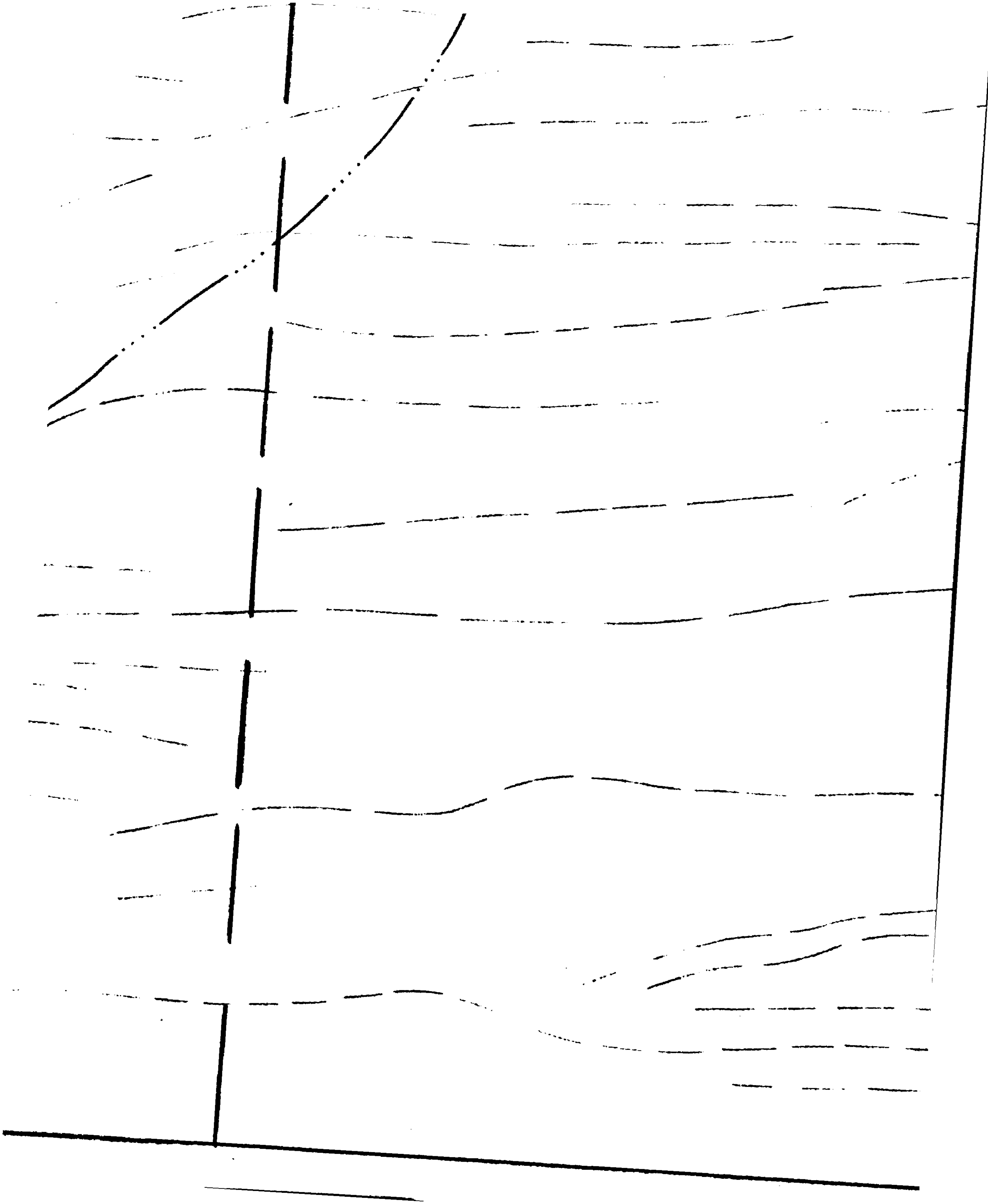
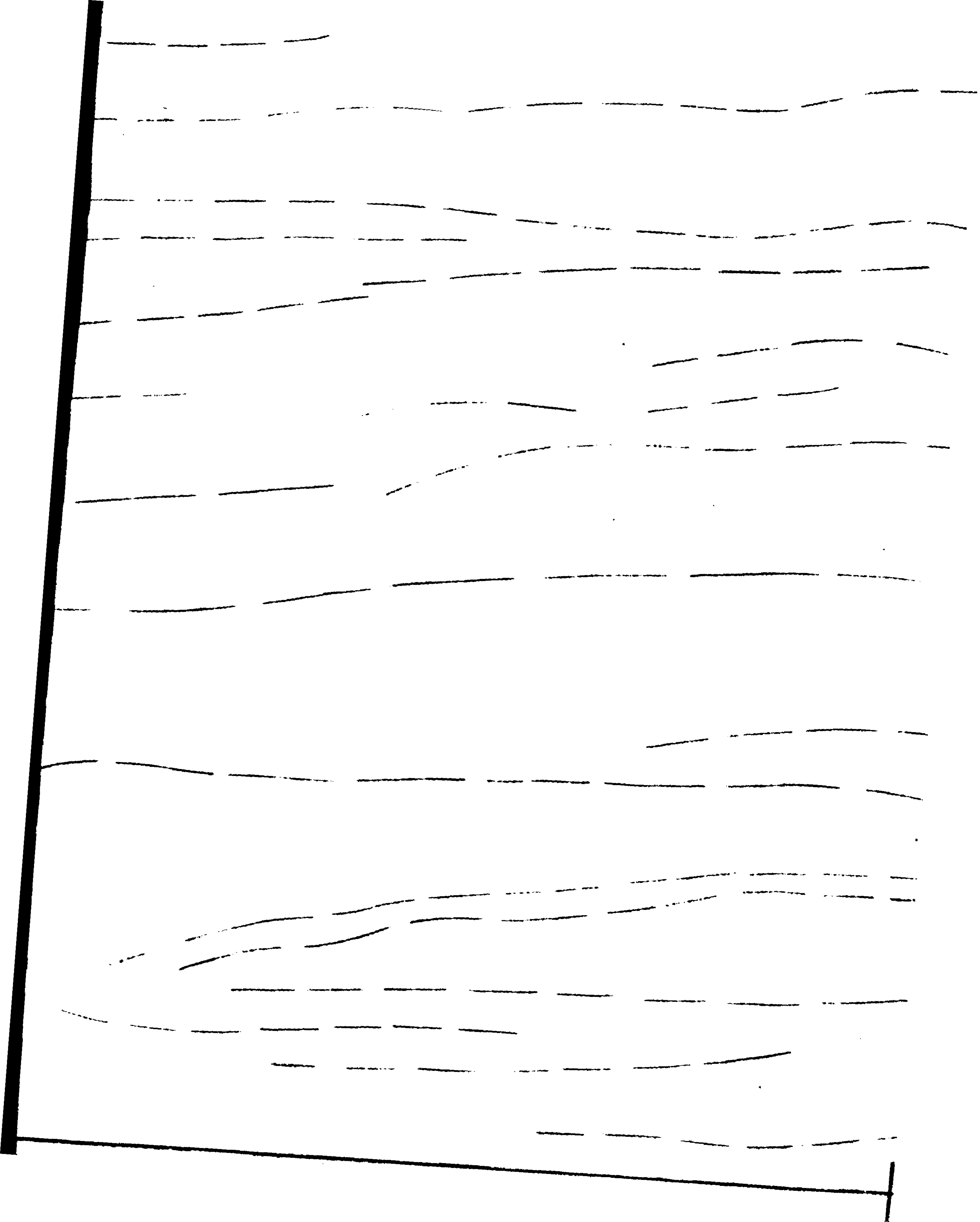
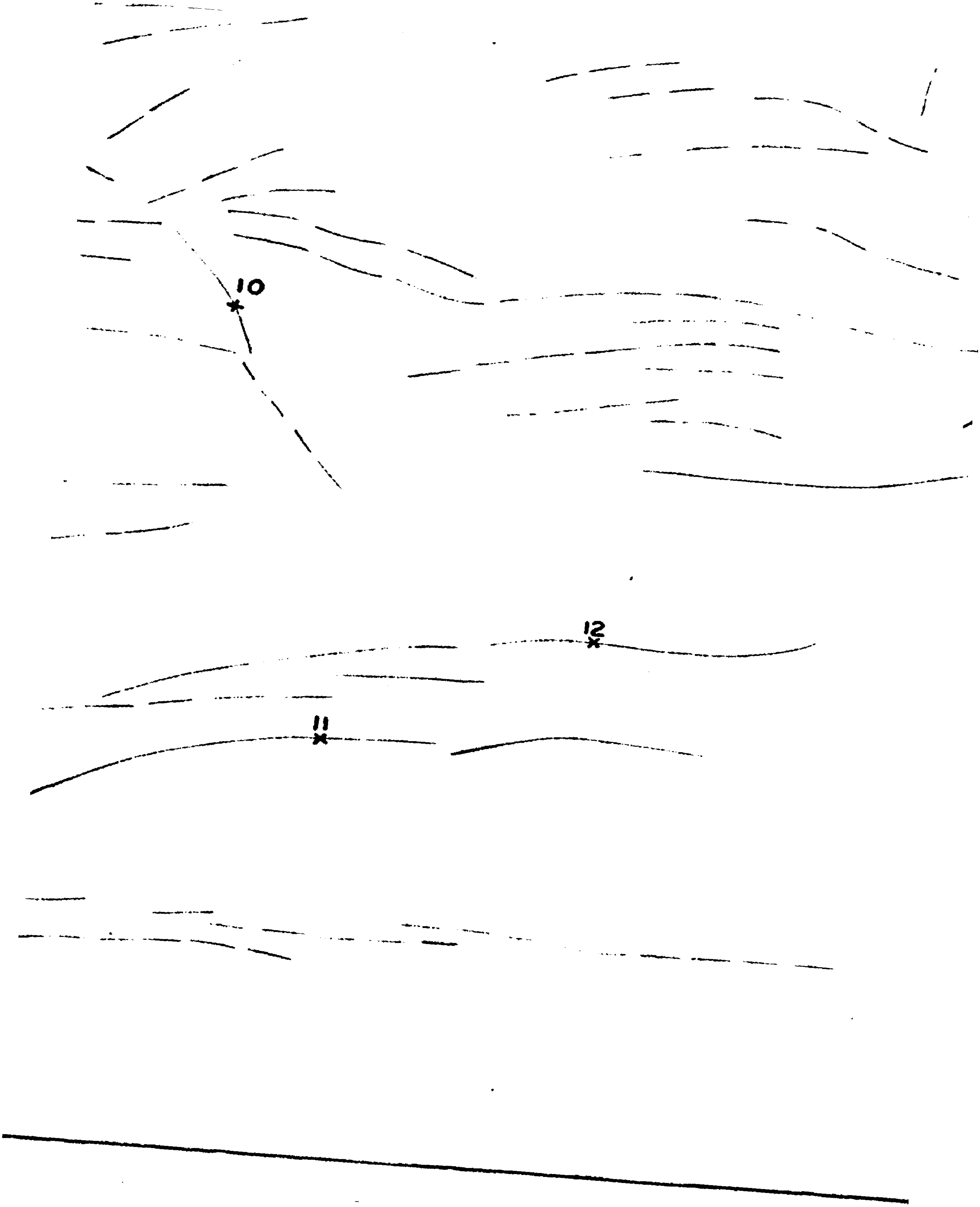
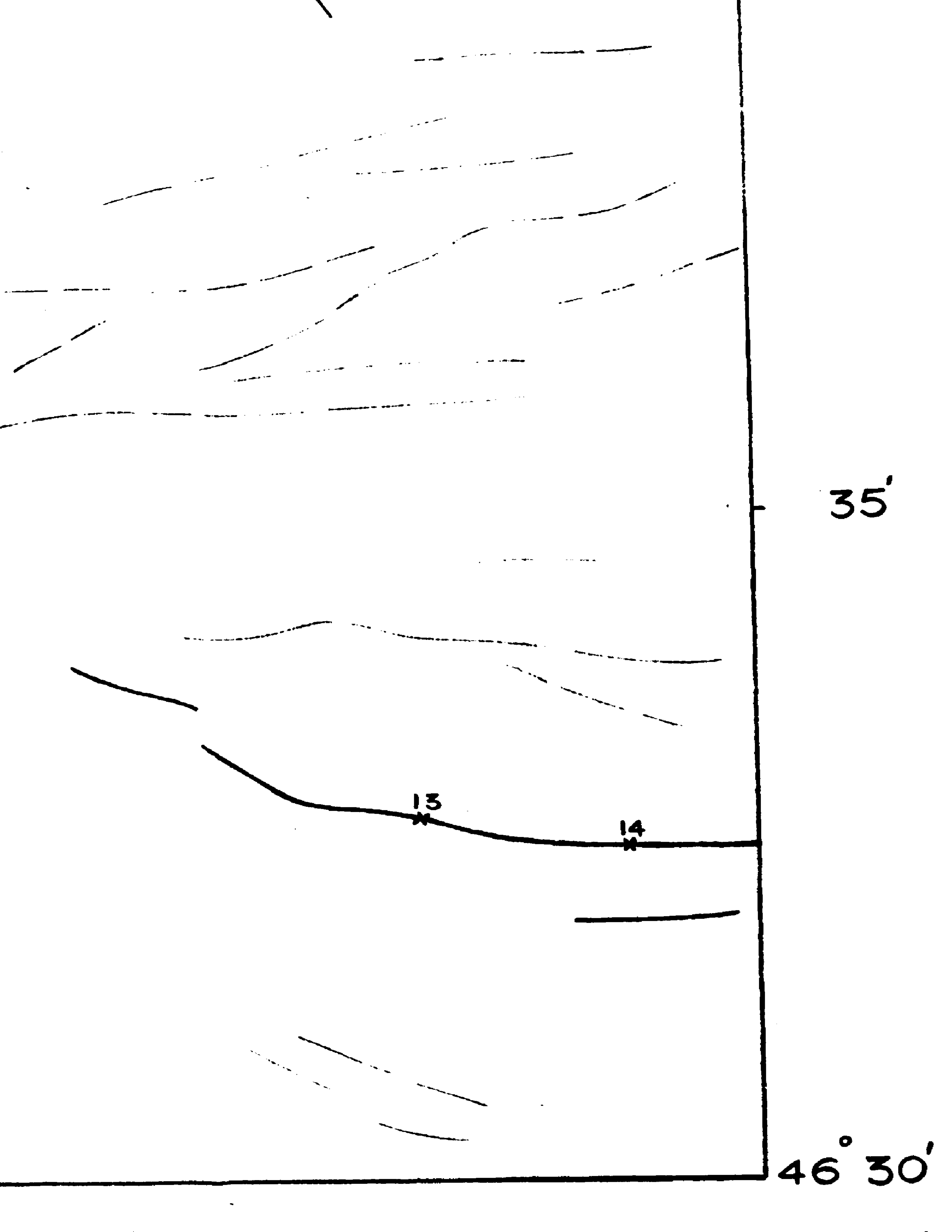
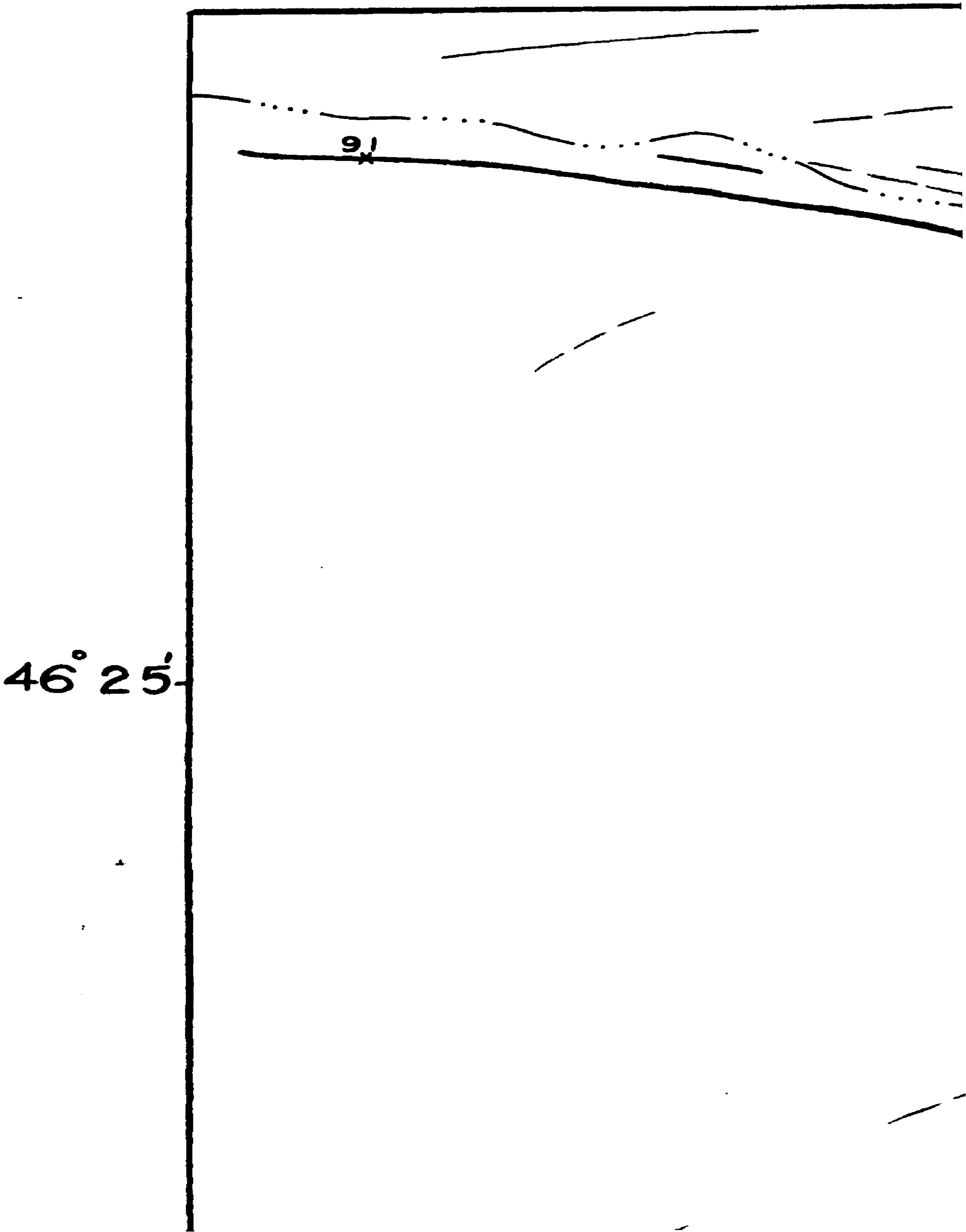

4

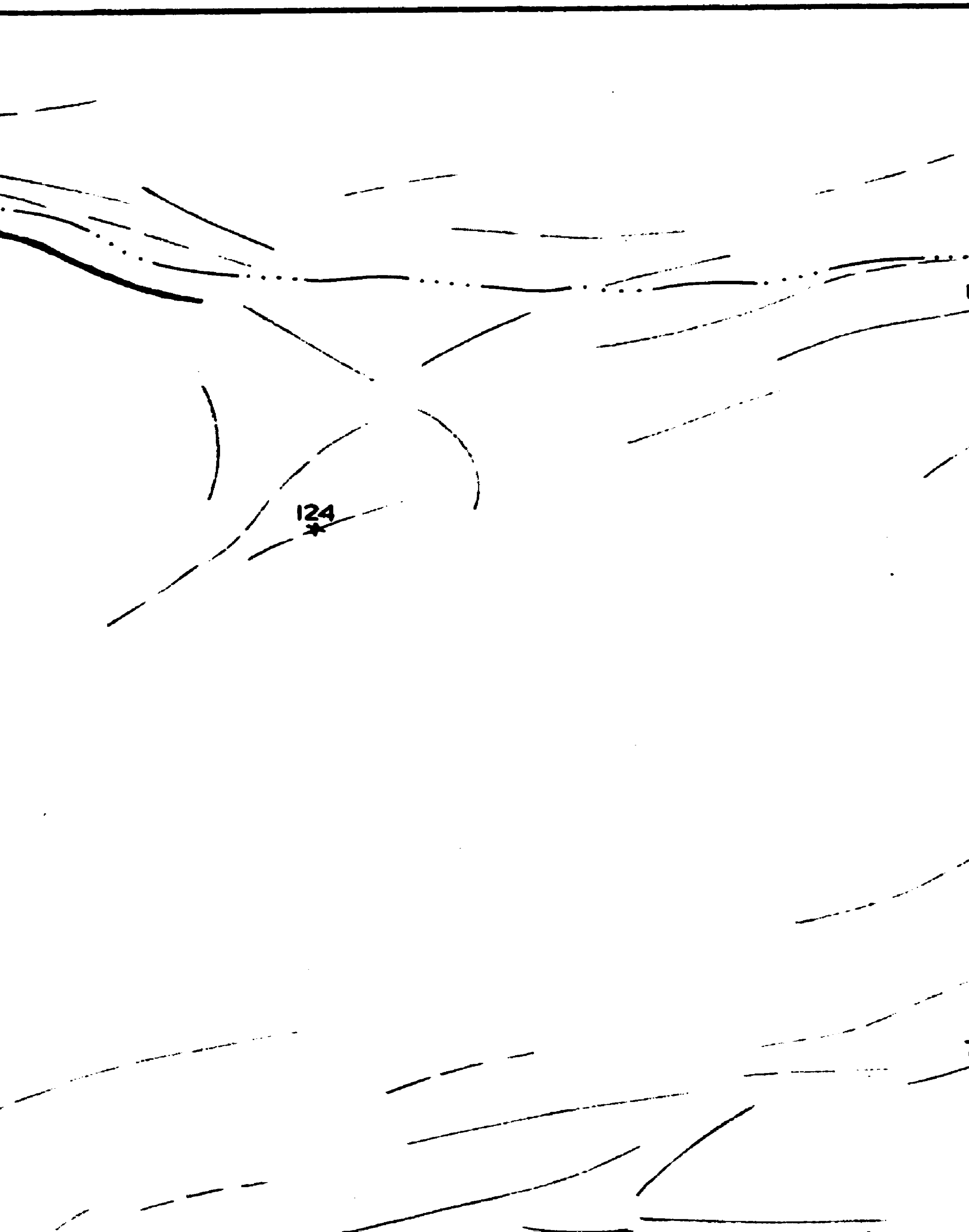




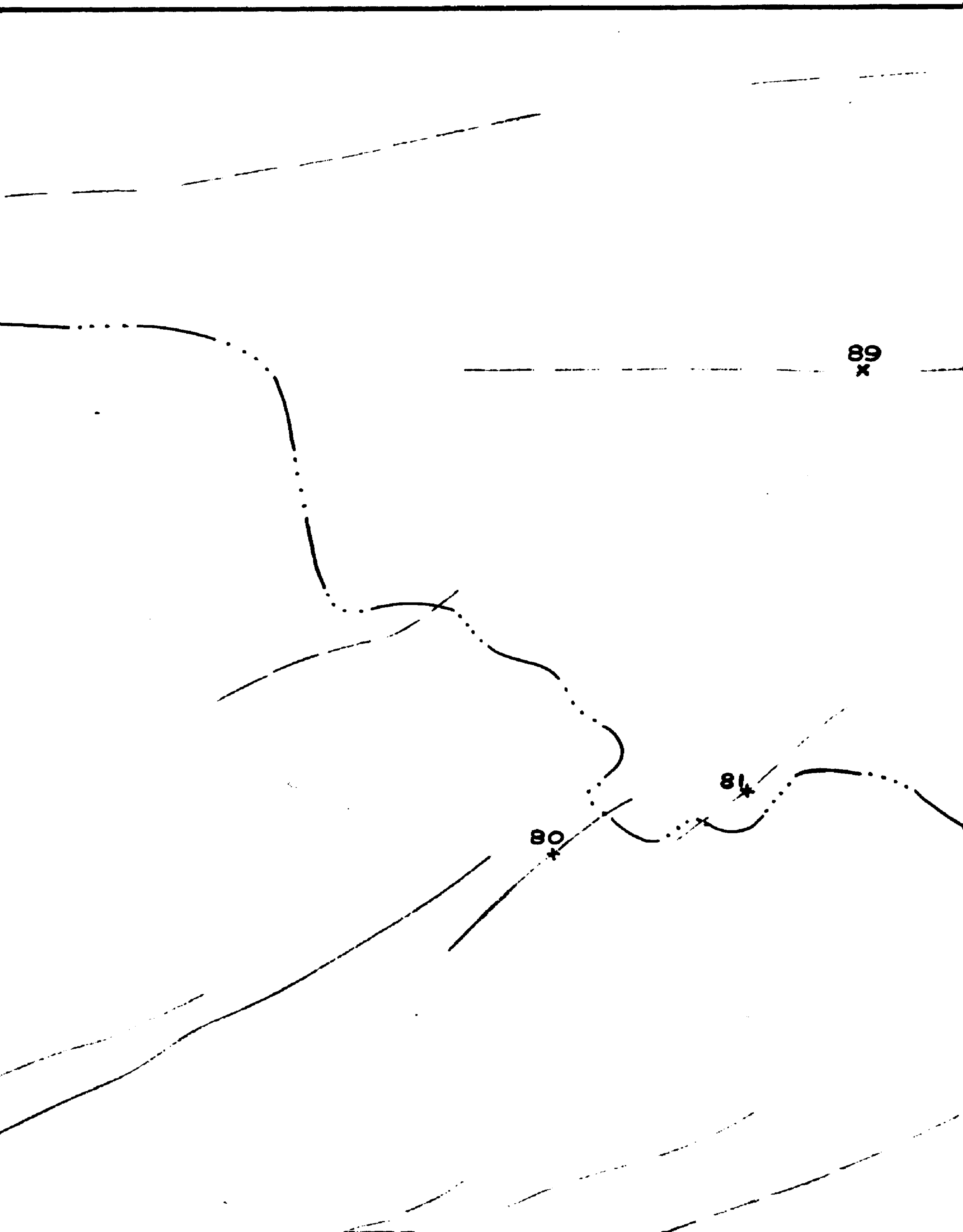

10
12
11


35'
13
14
46° 30'


46° 25'
91

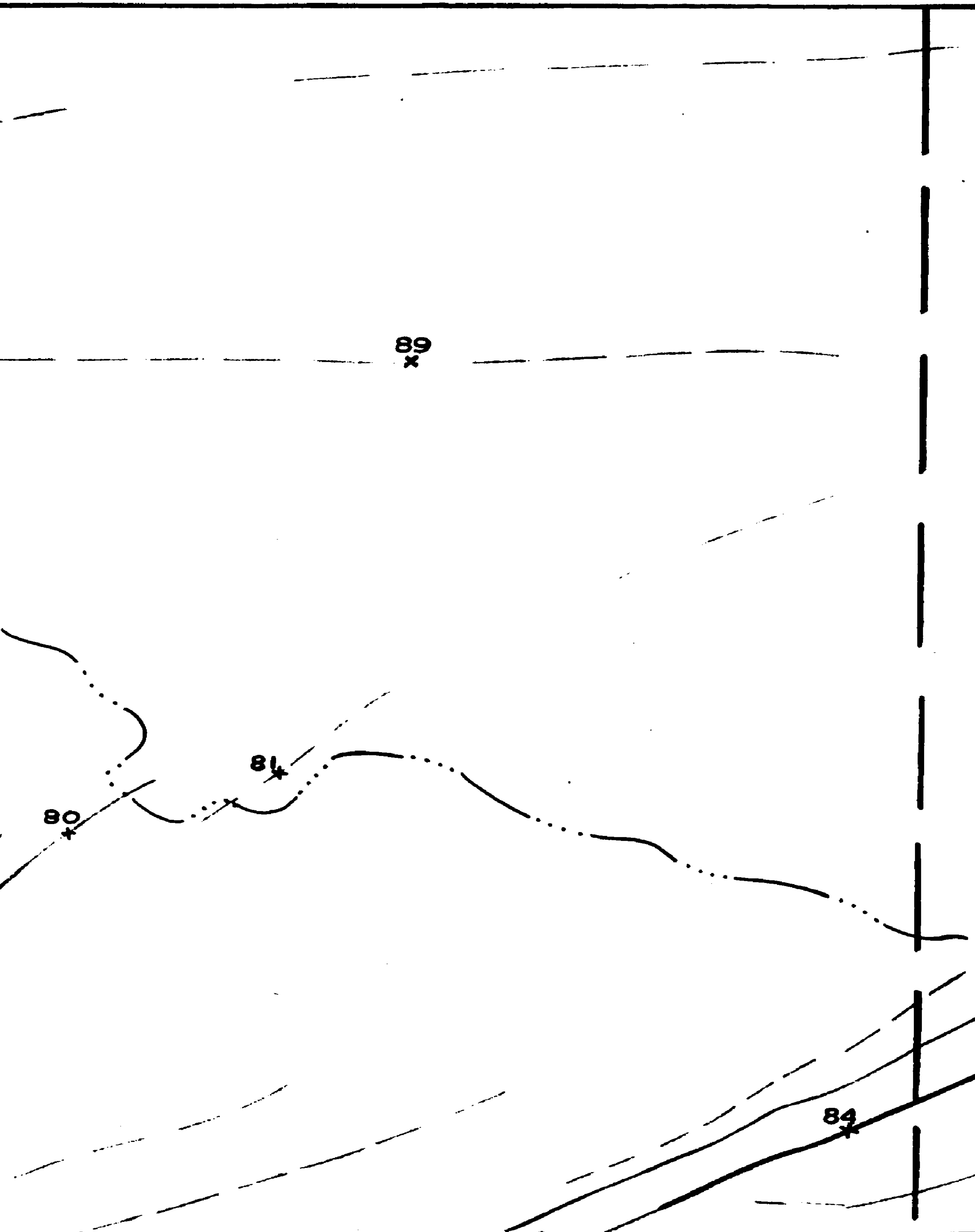

124

125
77
78
79



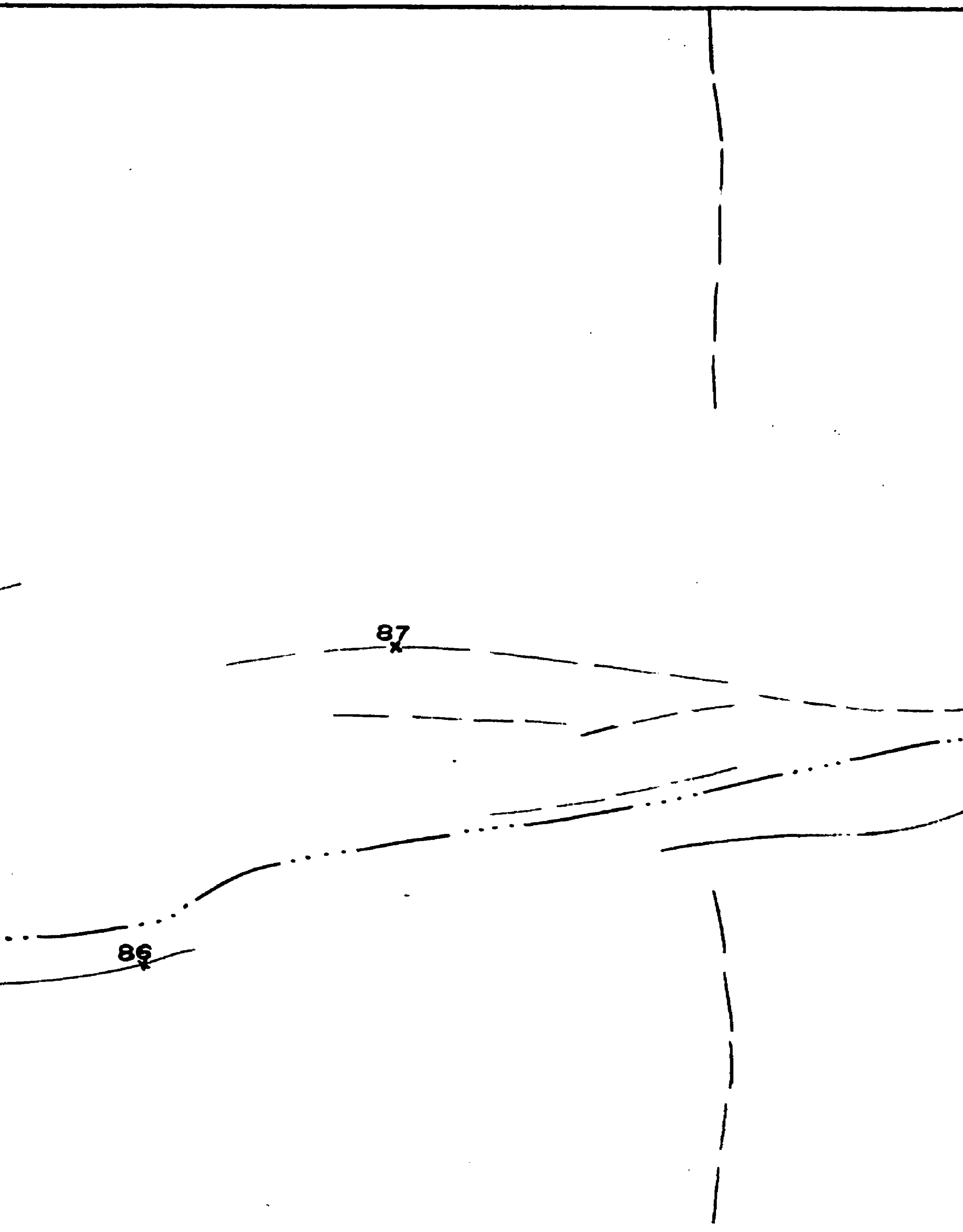
89
81
80

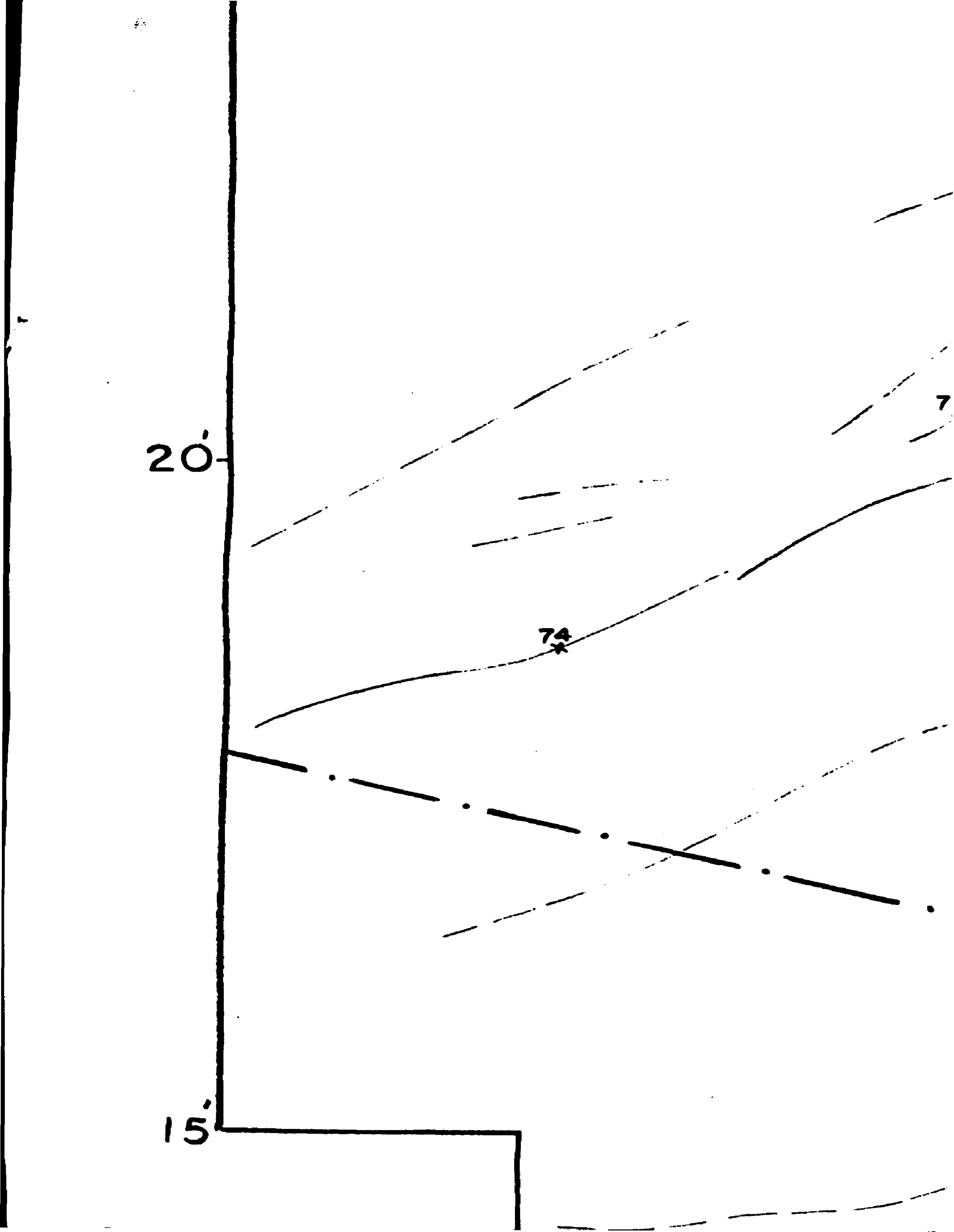

78
79

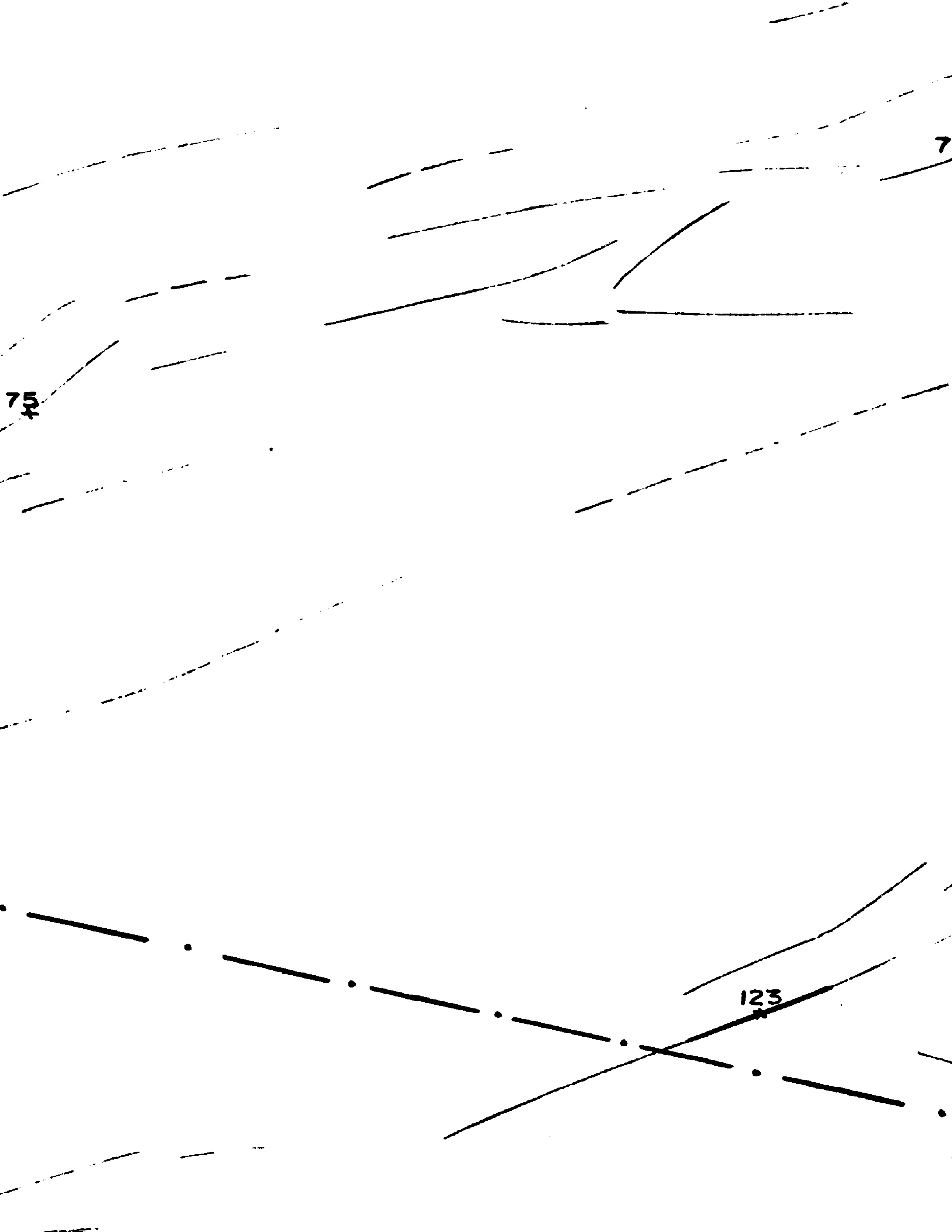


89
81
80
84

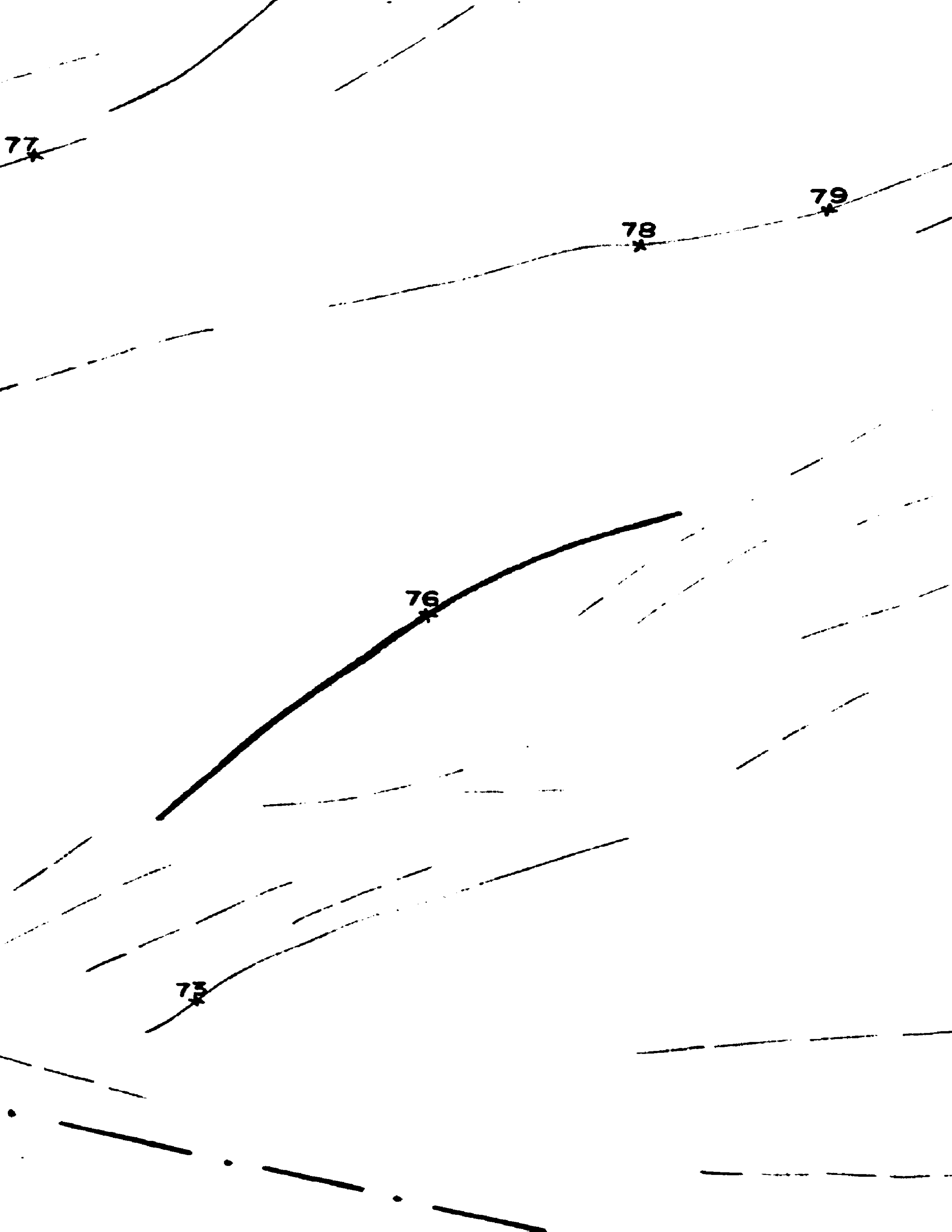

85


87
86

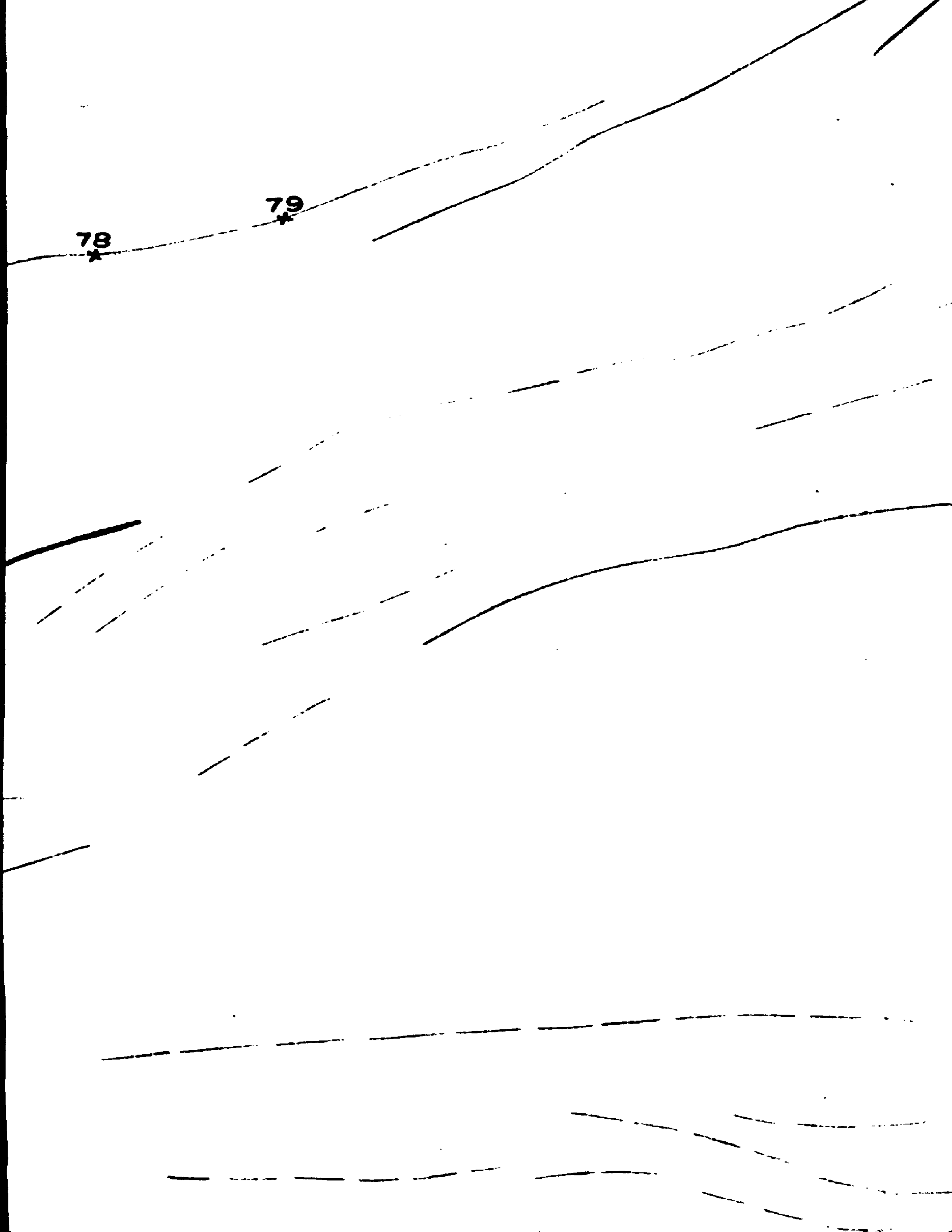

20'
74
15'

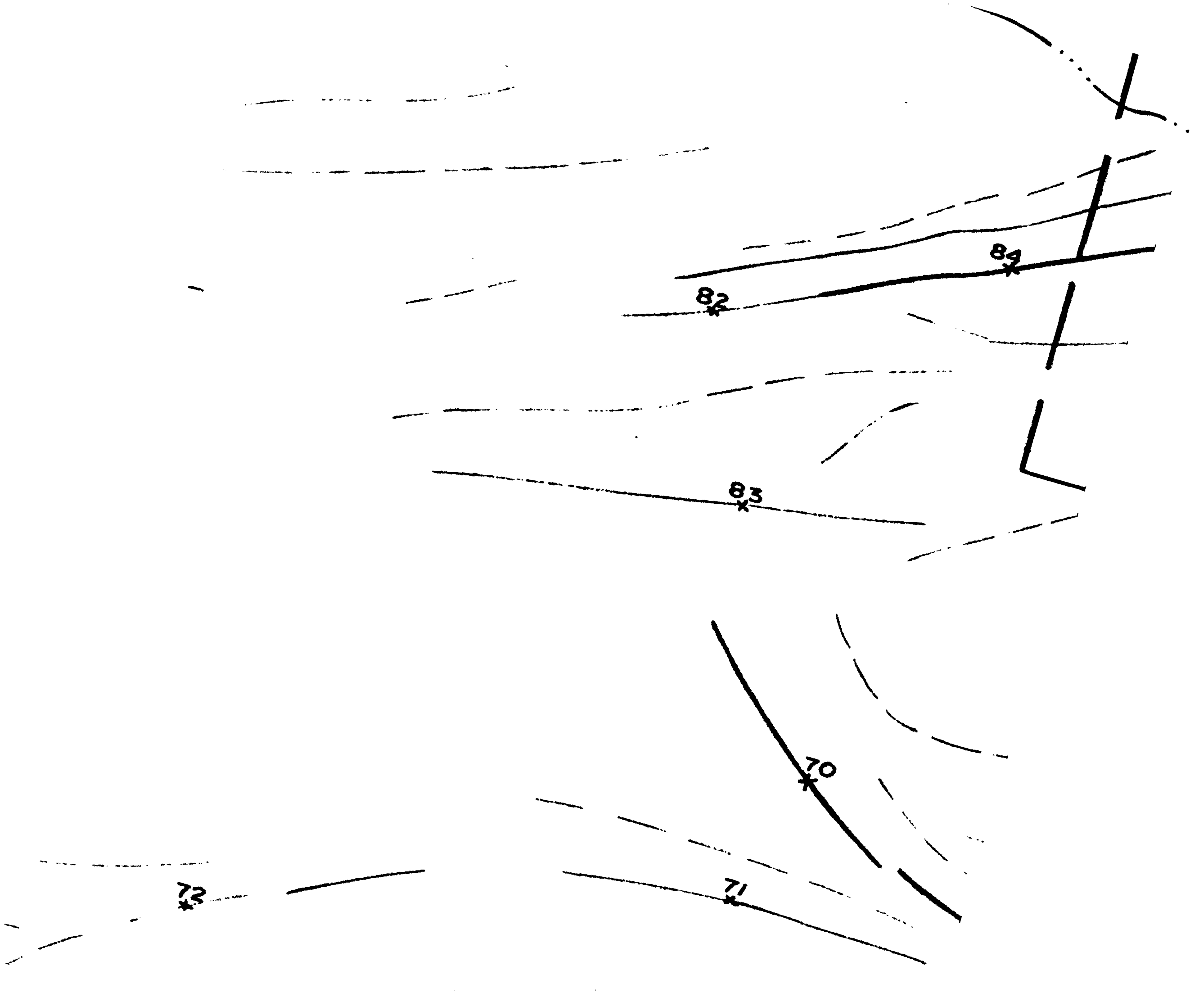


7
75
123

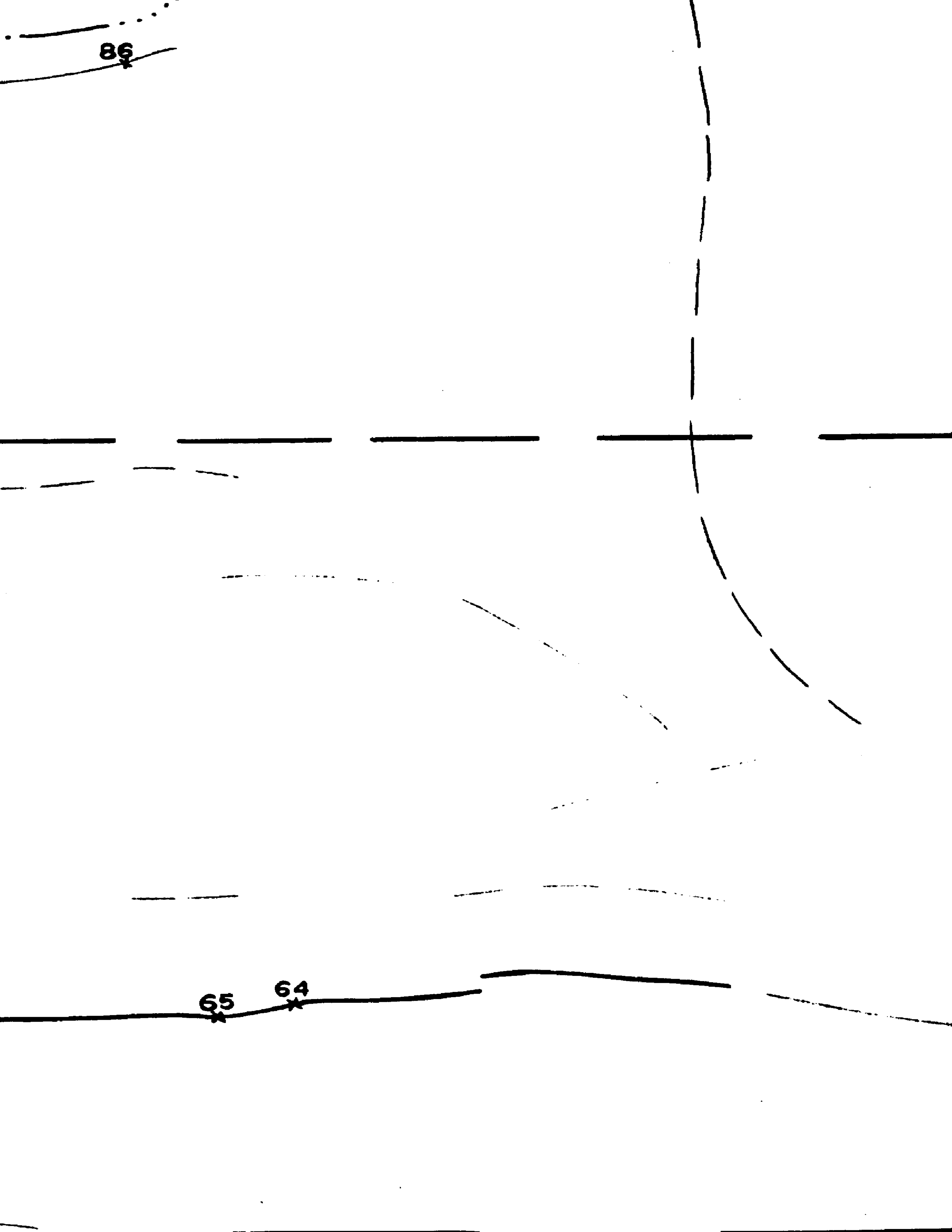

77
78
79
76
75

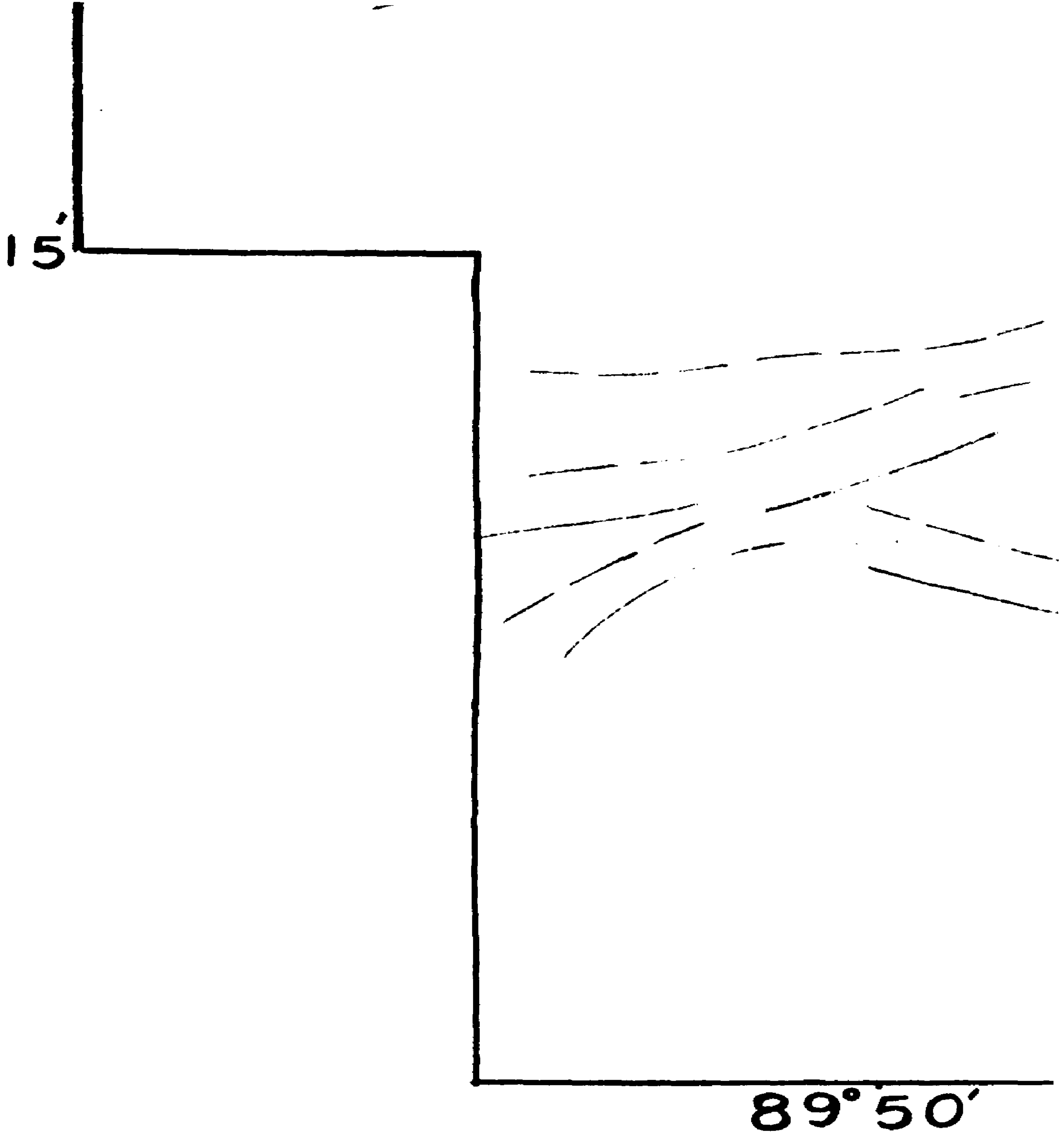

72

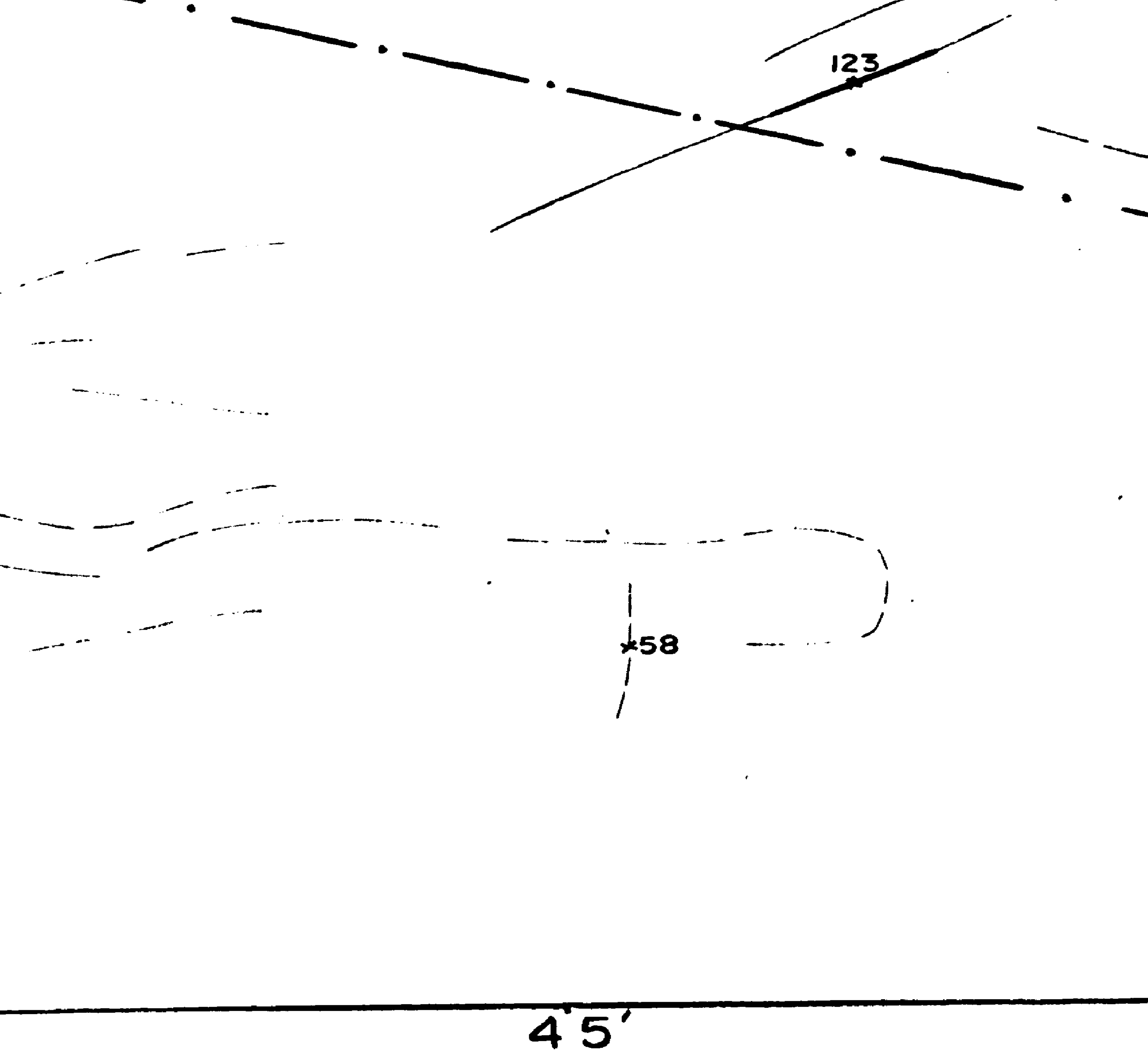

78
79

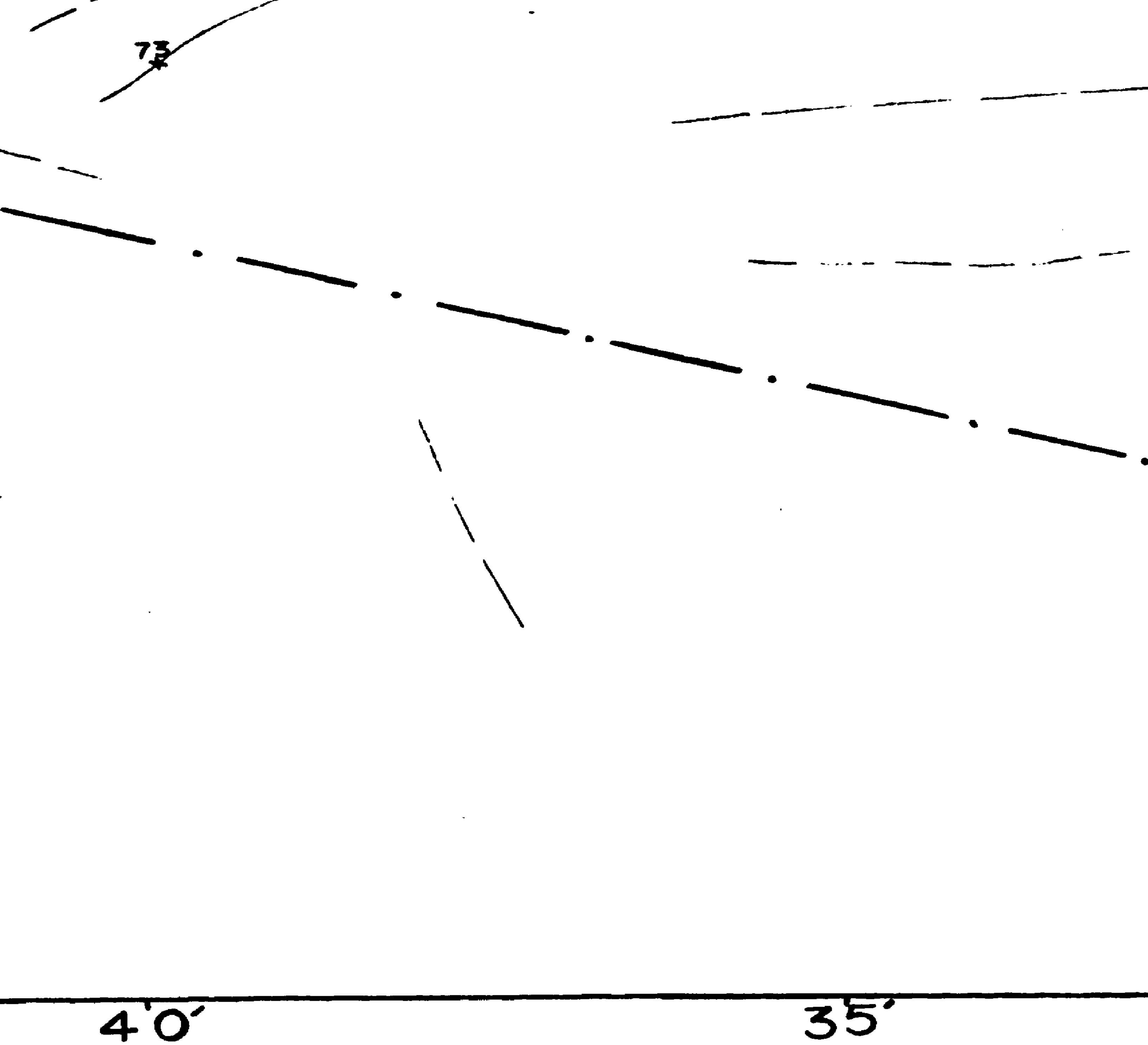

84
82
83
70
72
71


85
69
68
67
66

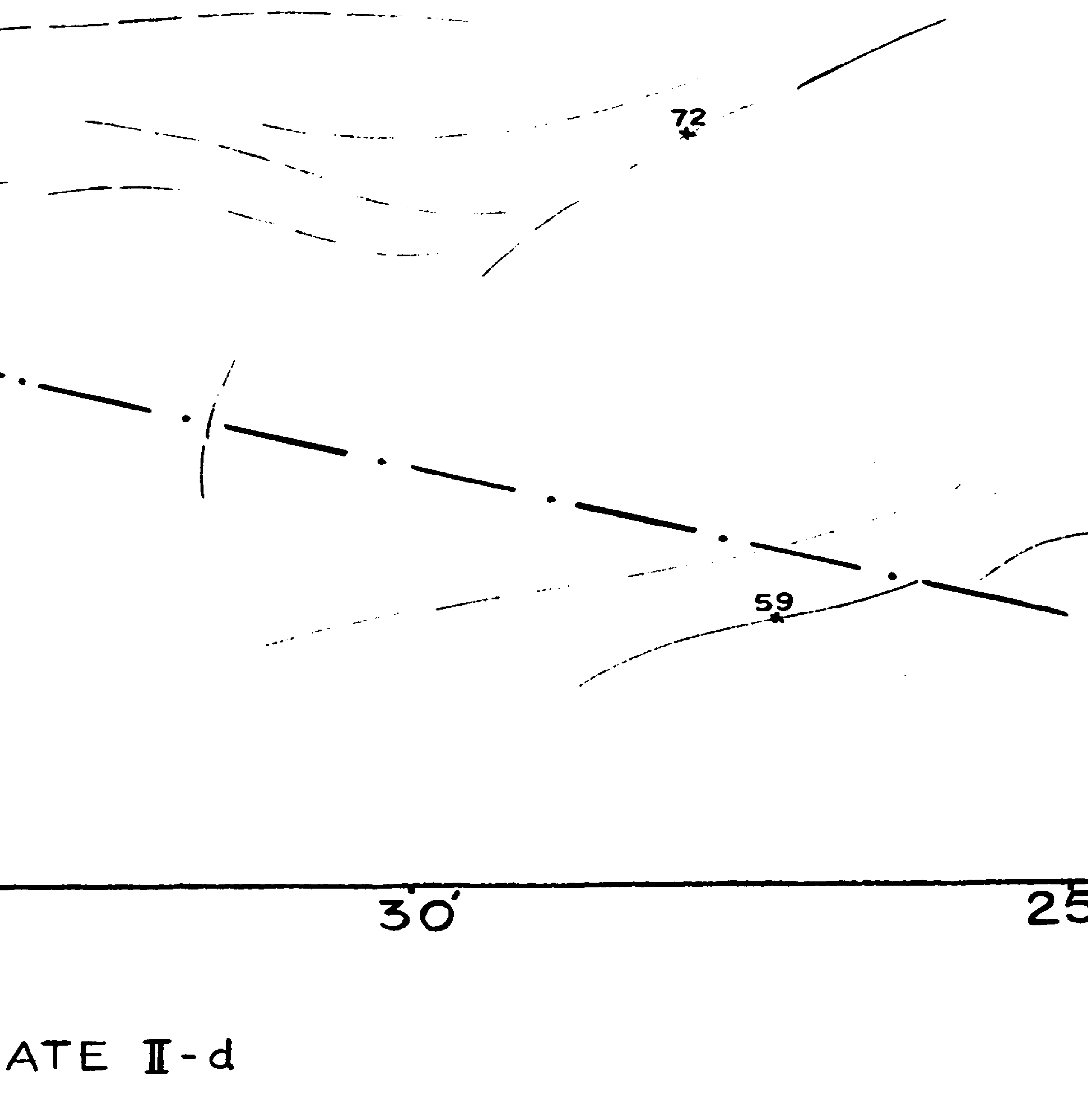

86
65
64


15'
89°50'


123
58
45′



PLA



ATE II-d

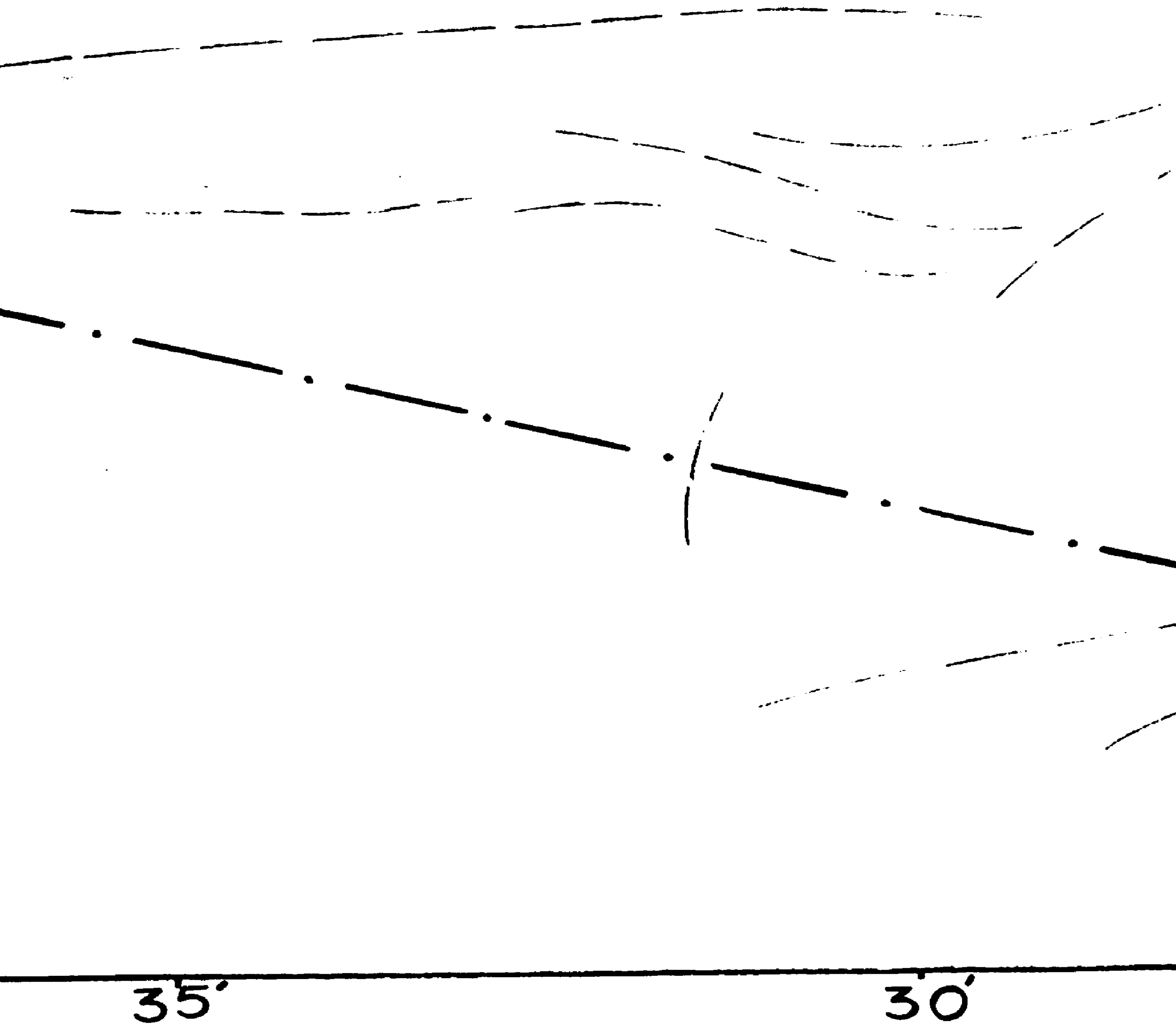
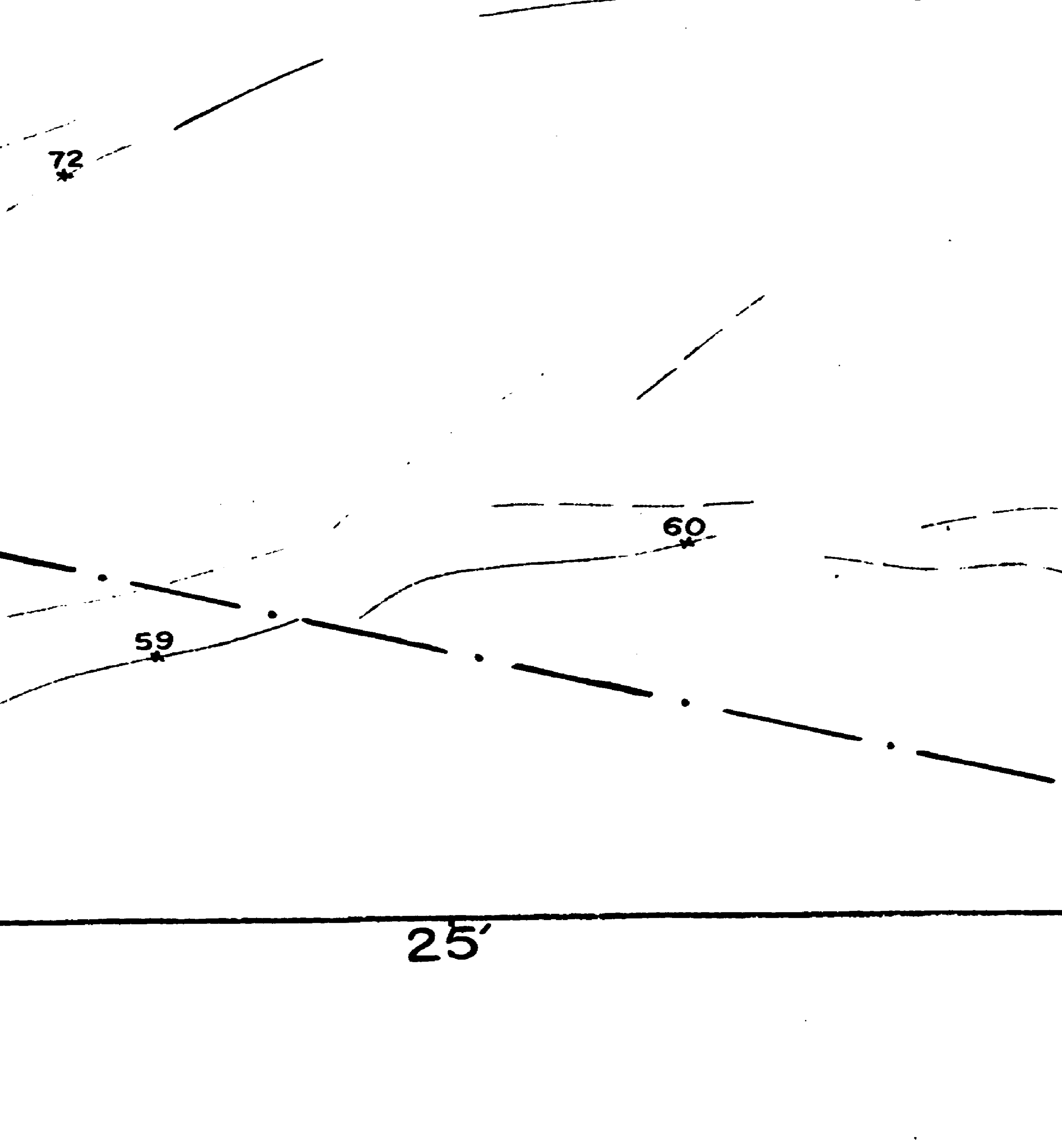
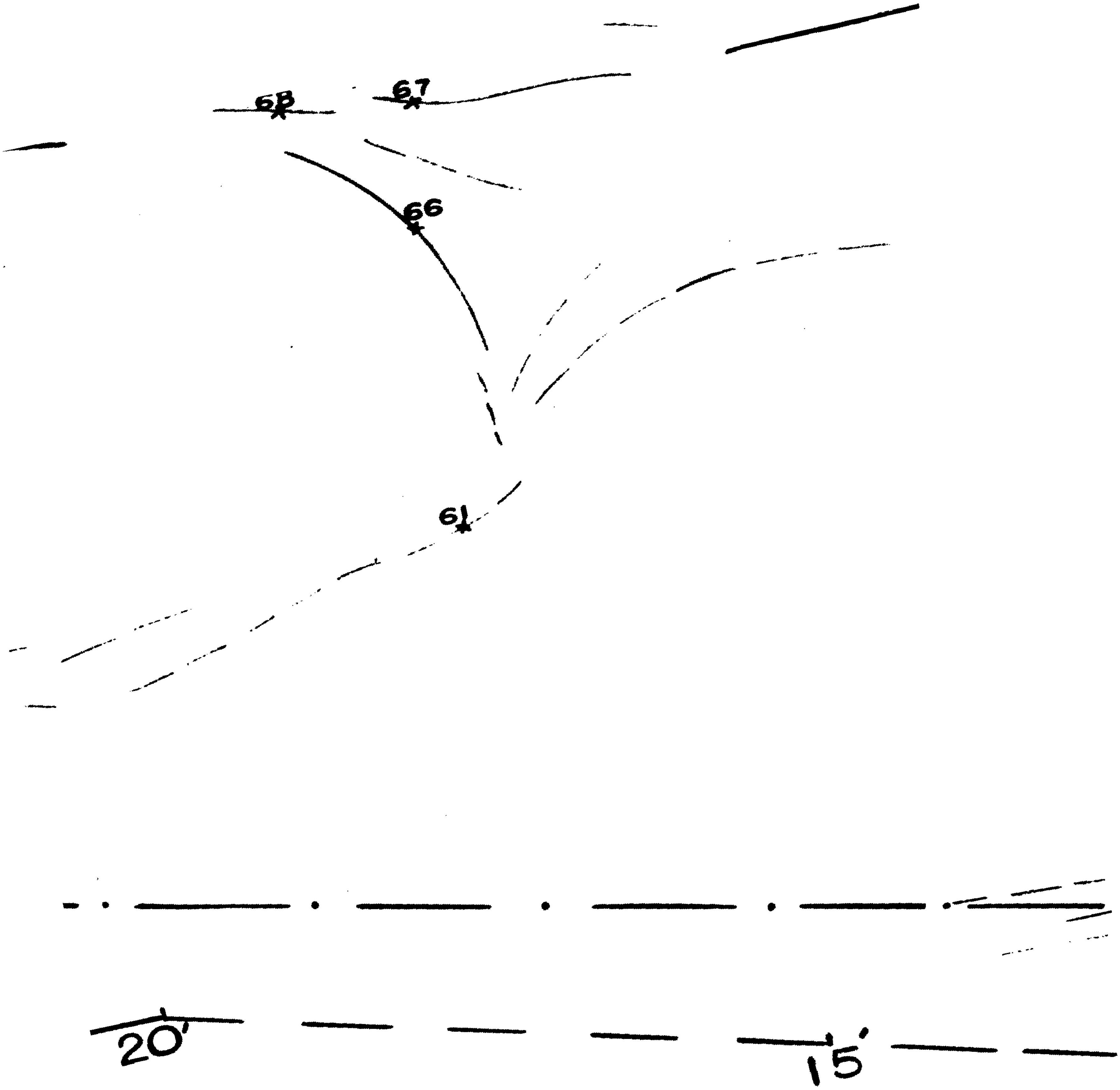
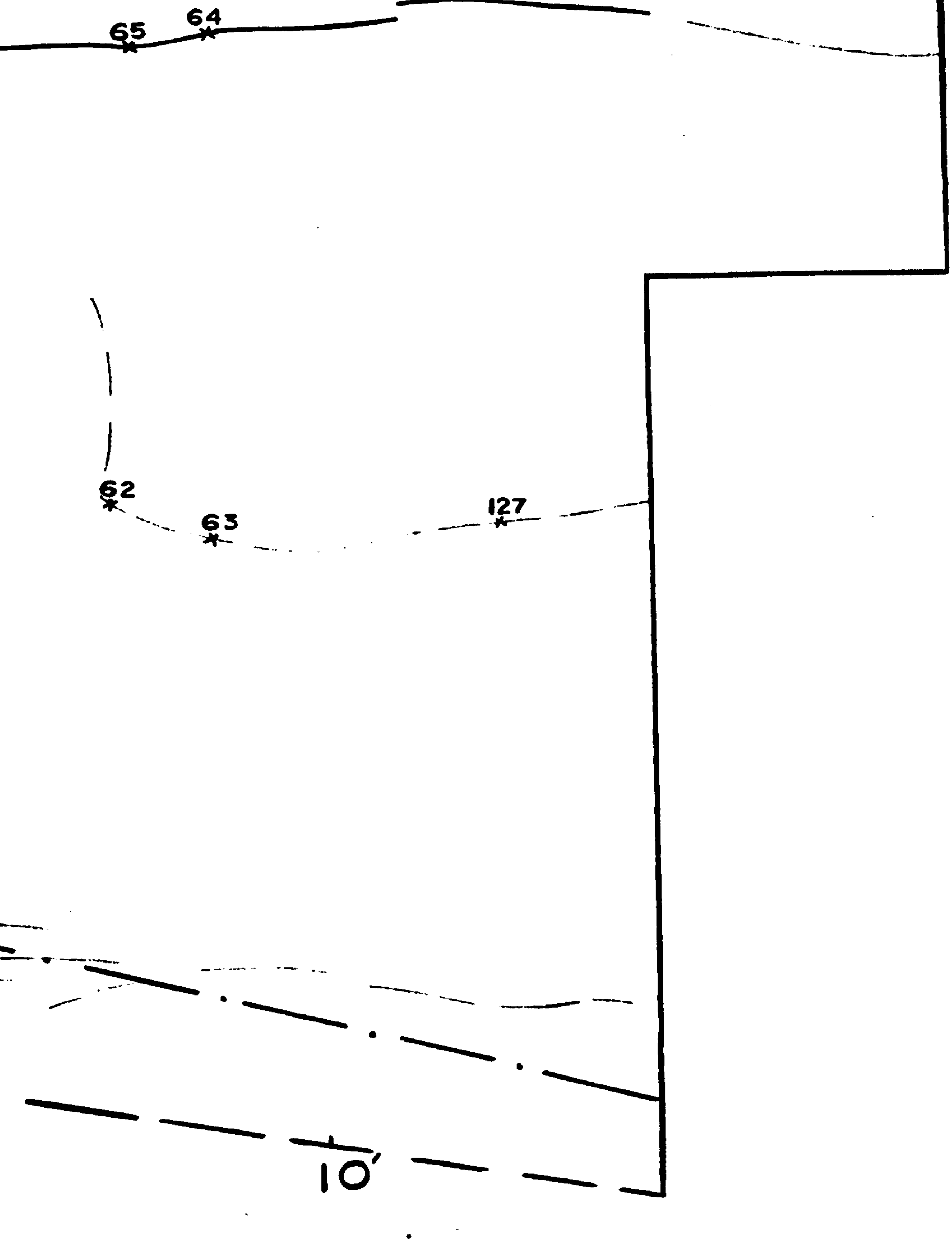
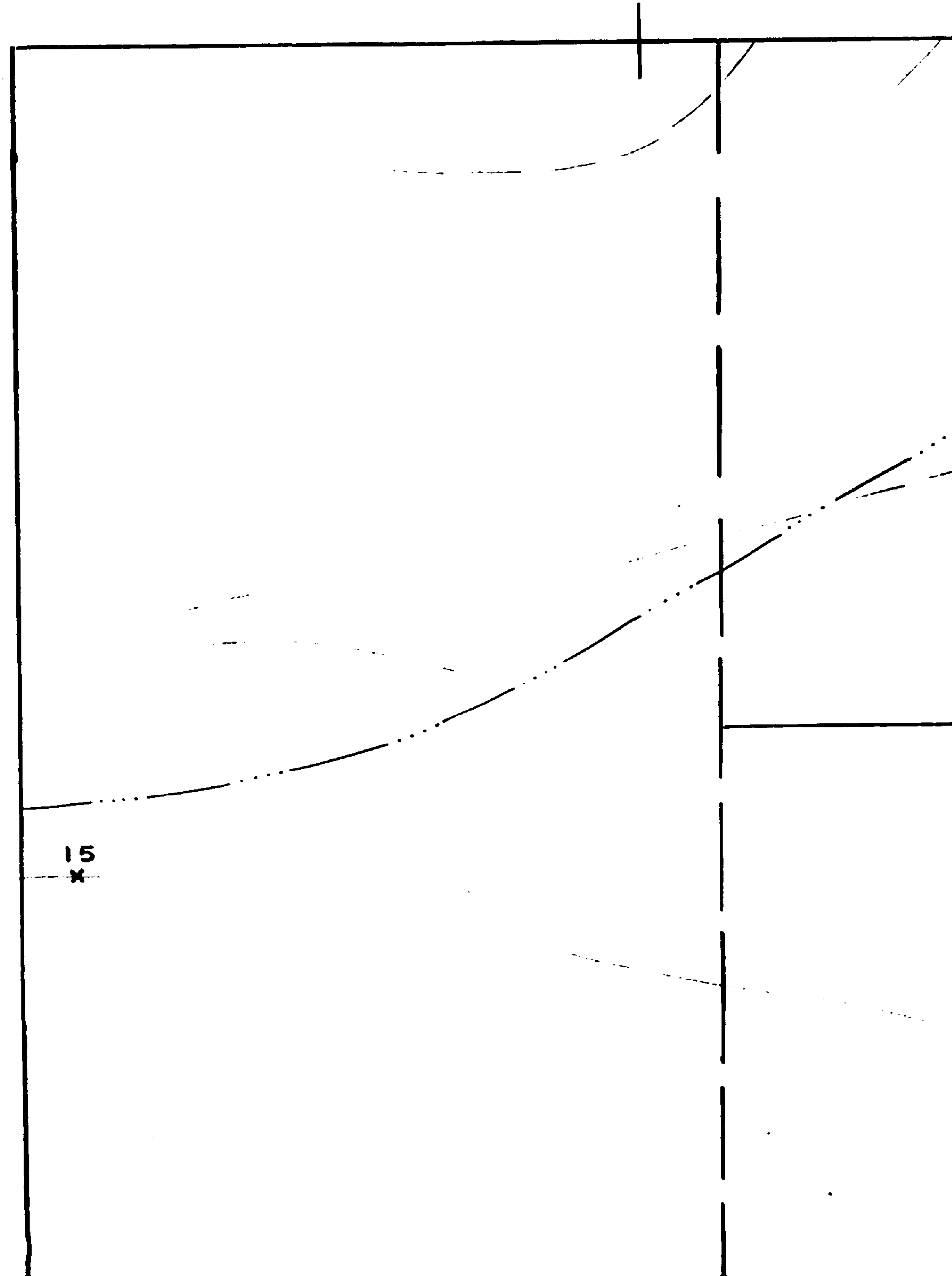


PLATE II-d


72
59
60
25′


68
67
66
61
20'
15'


65
64
62
63
127
10'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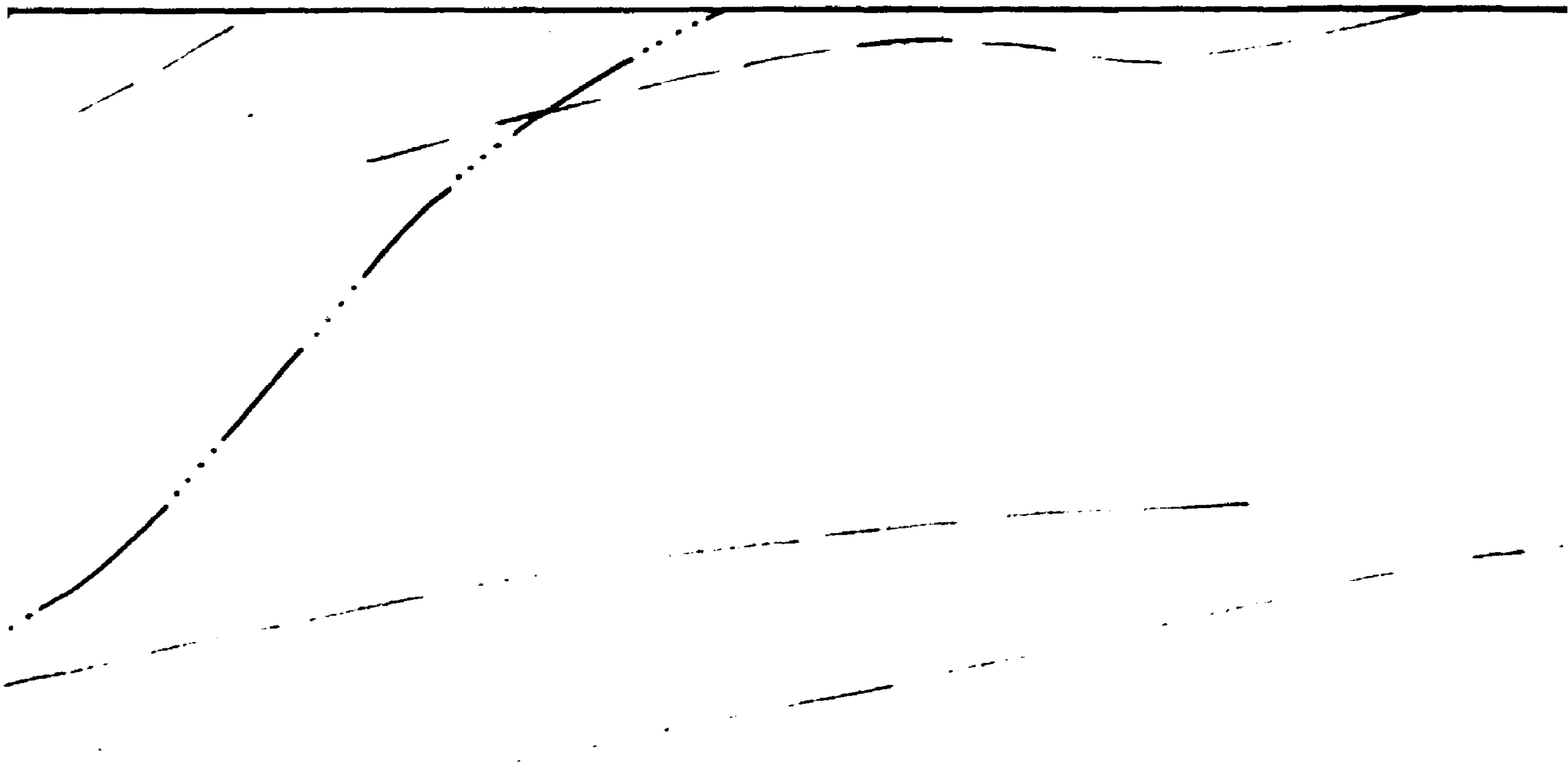

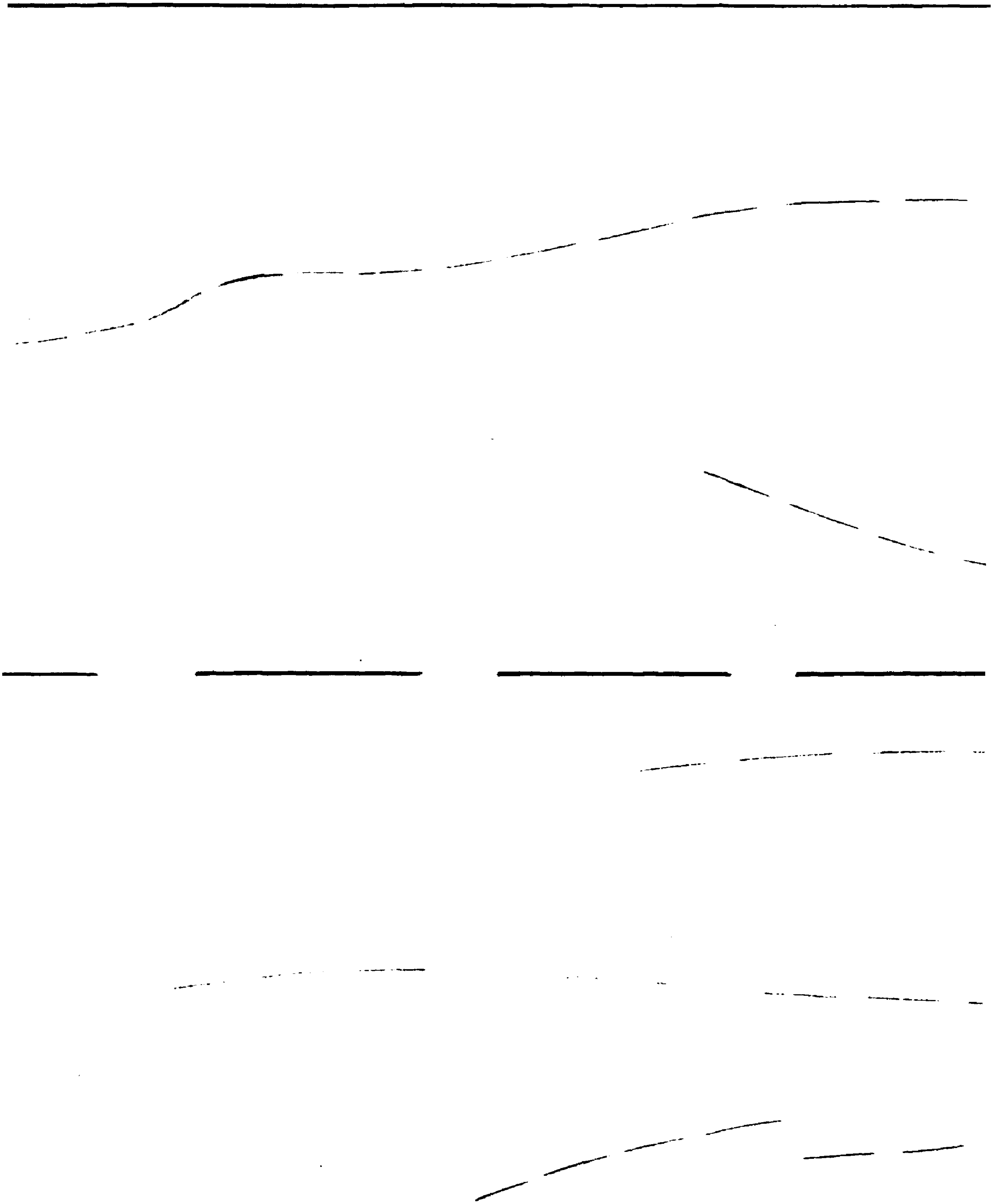

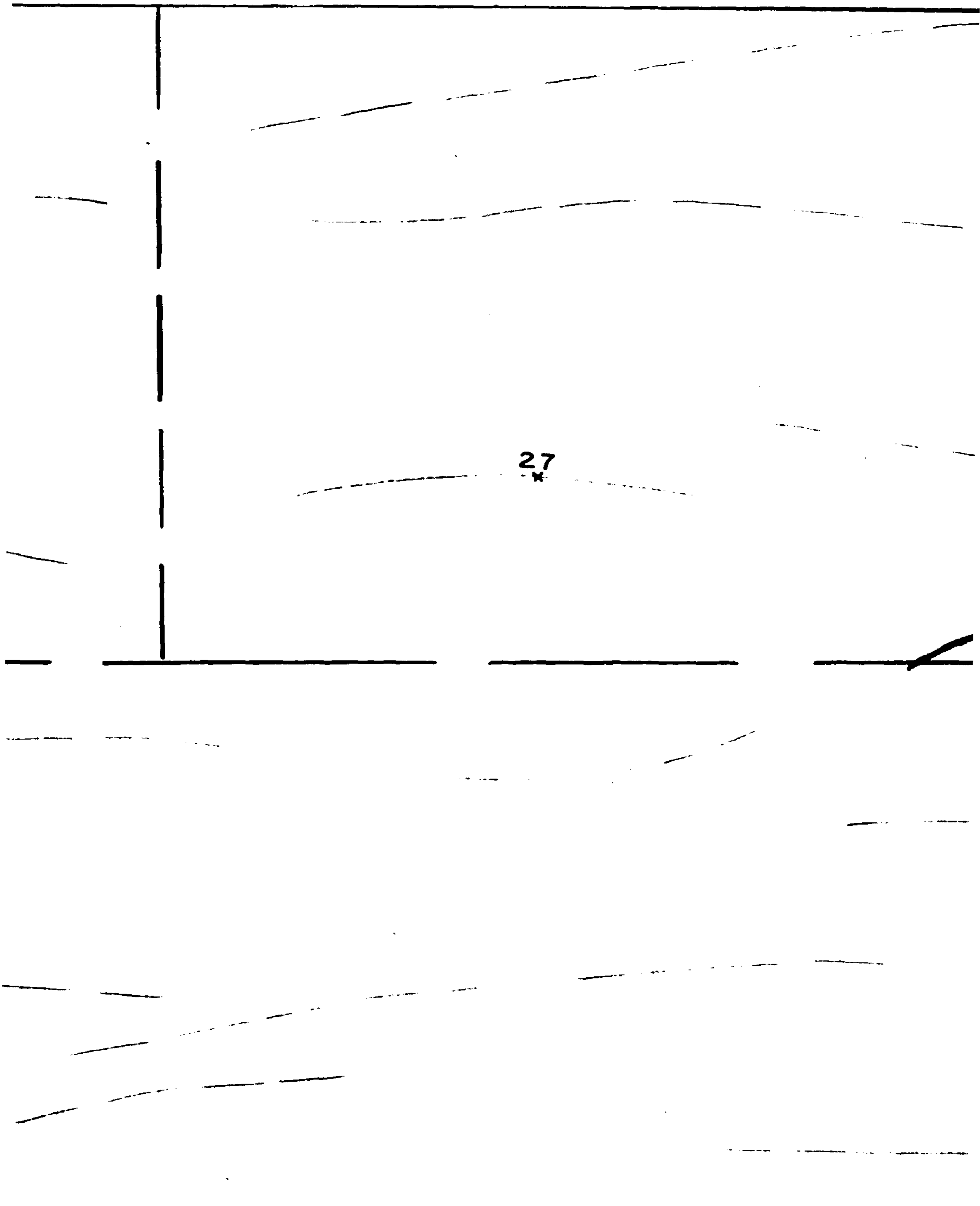
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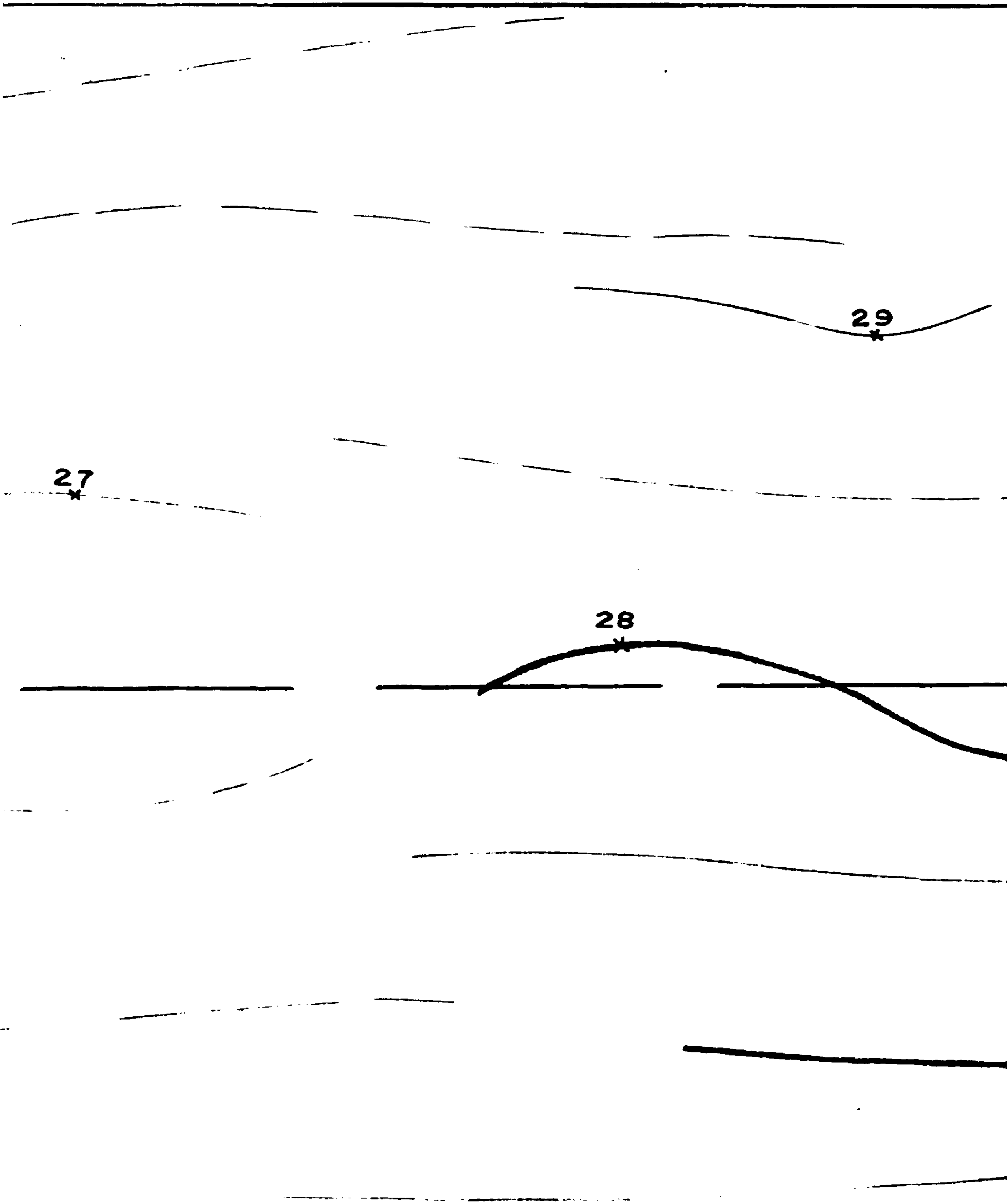
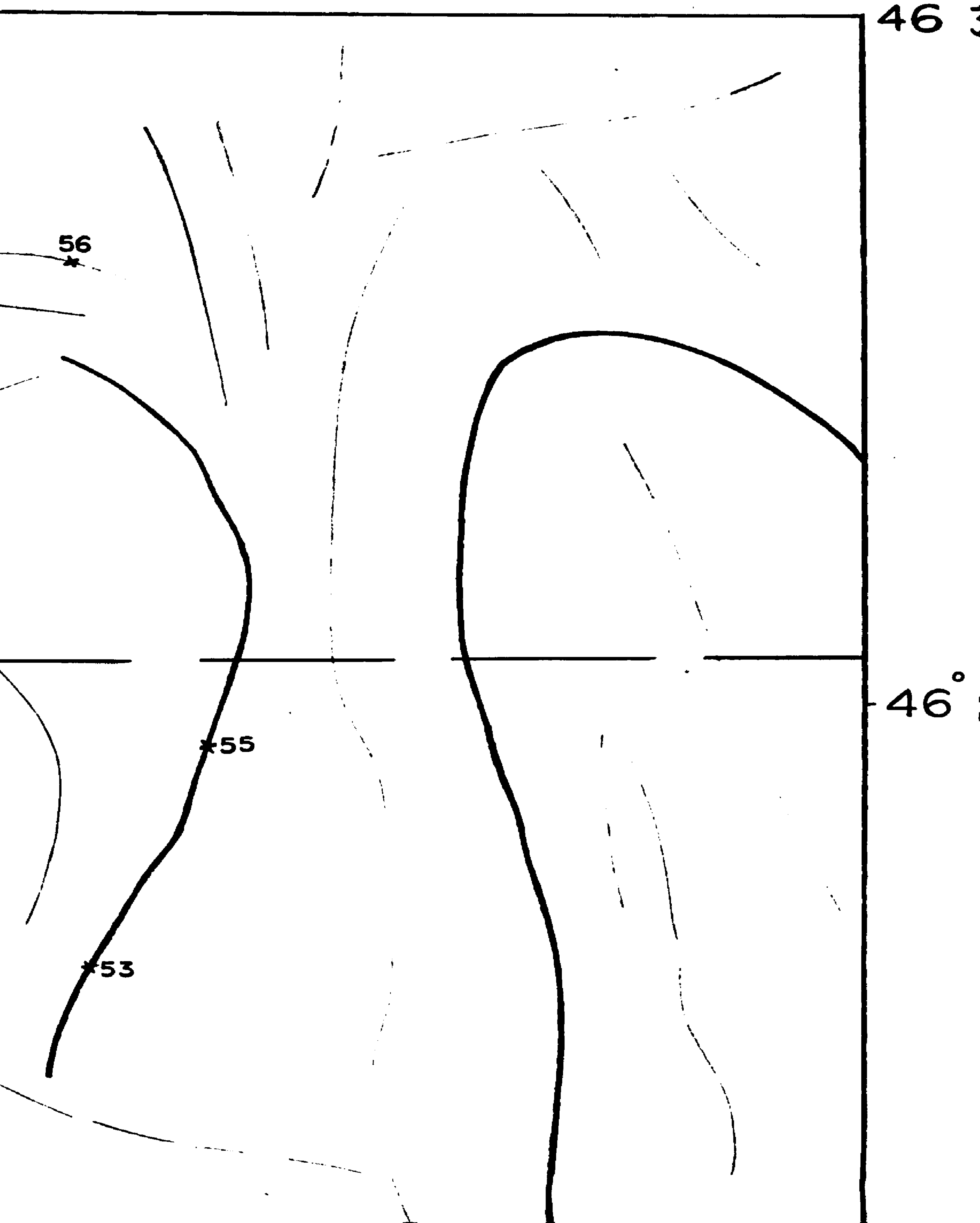
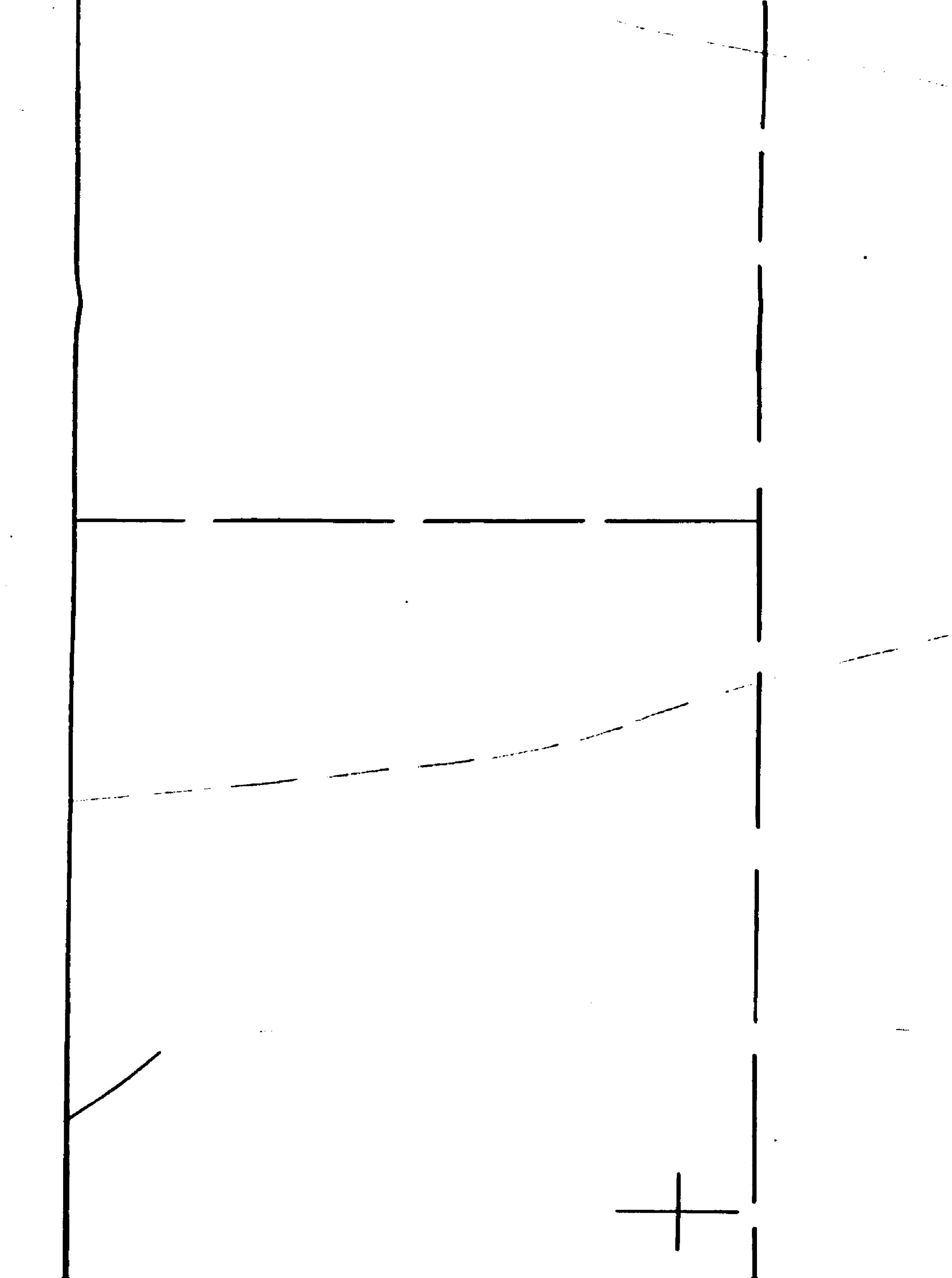

29
27
28

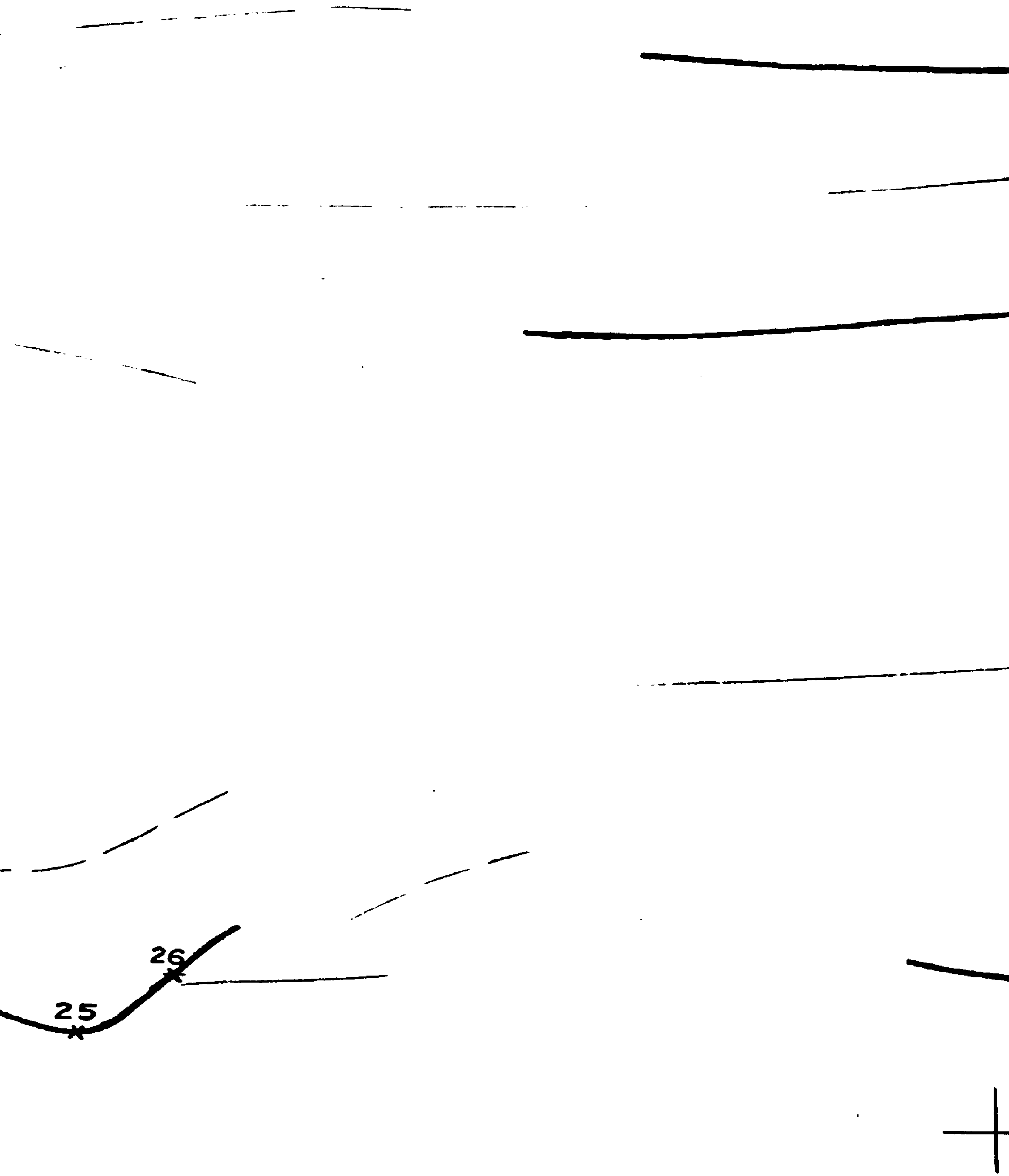

30

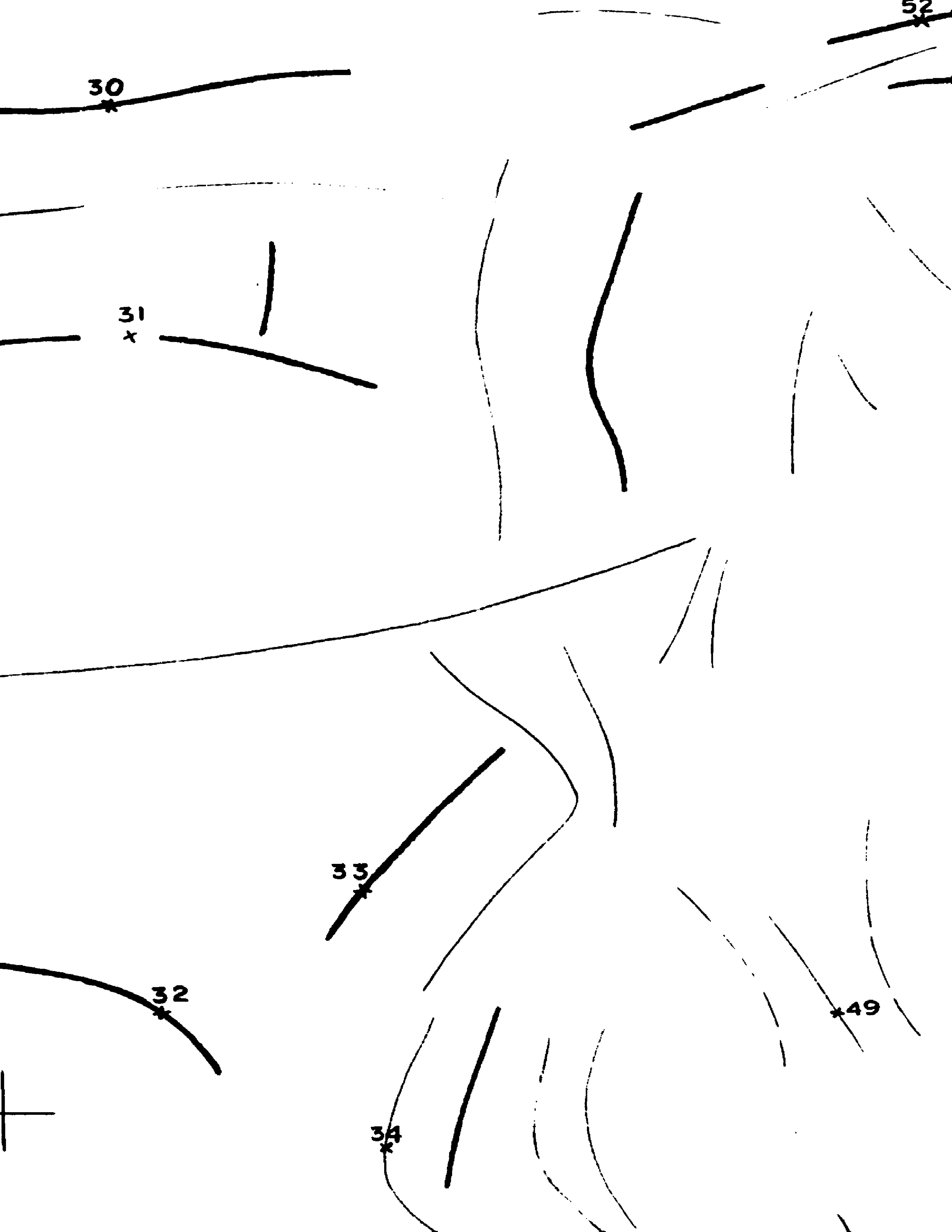
52
51
54


46°
46°
56
55
53

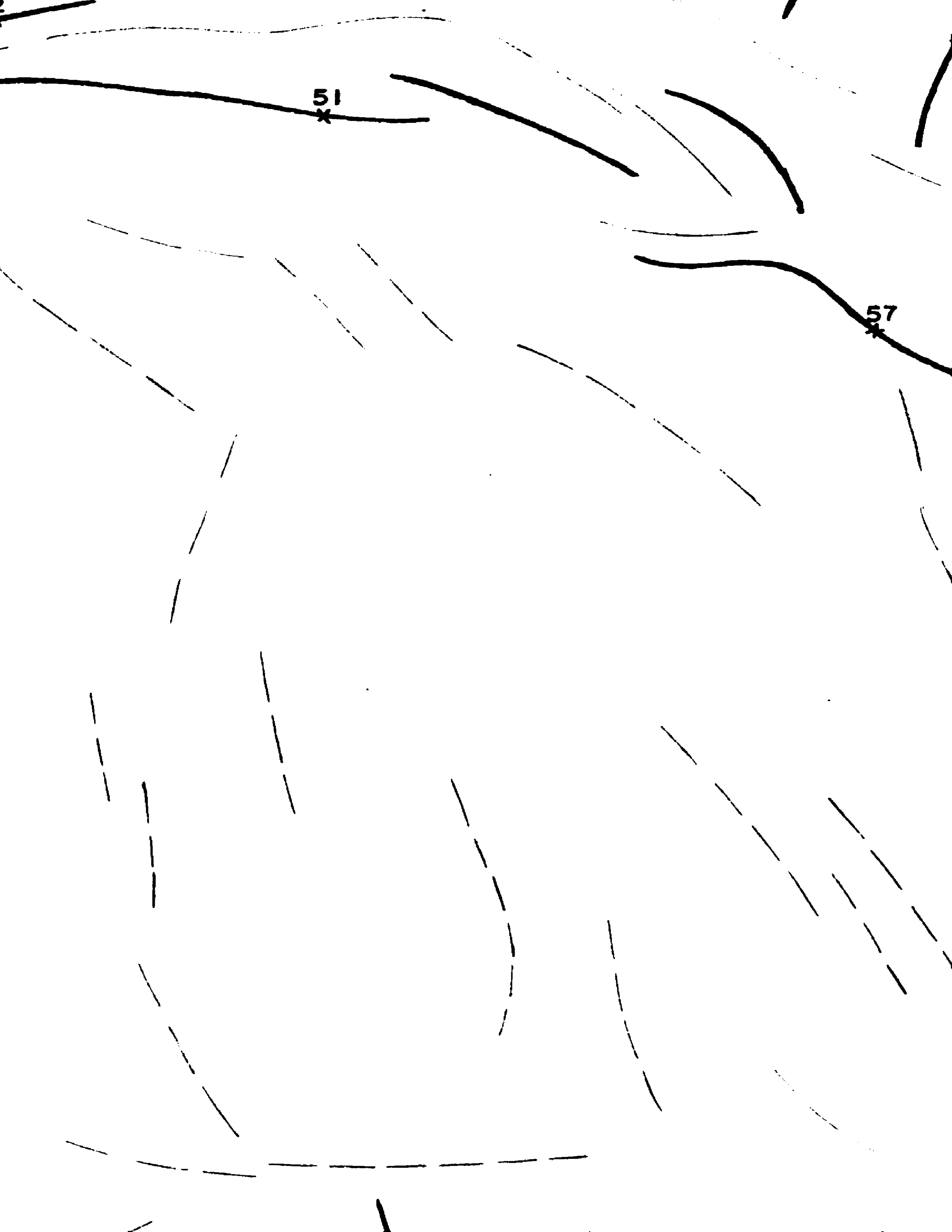


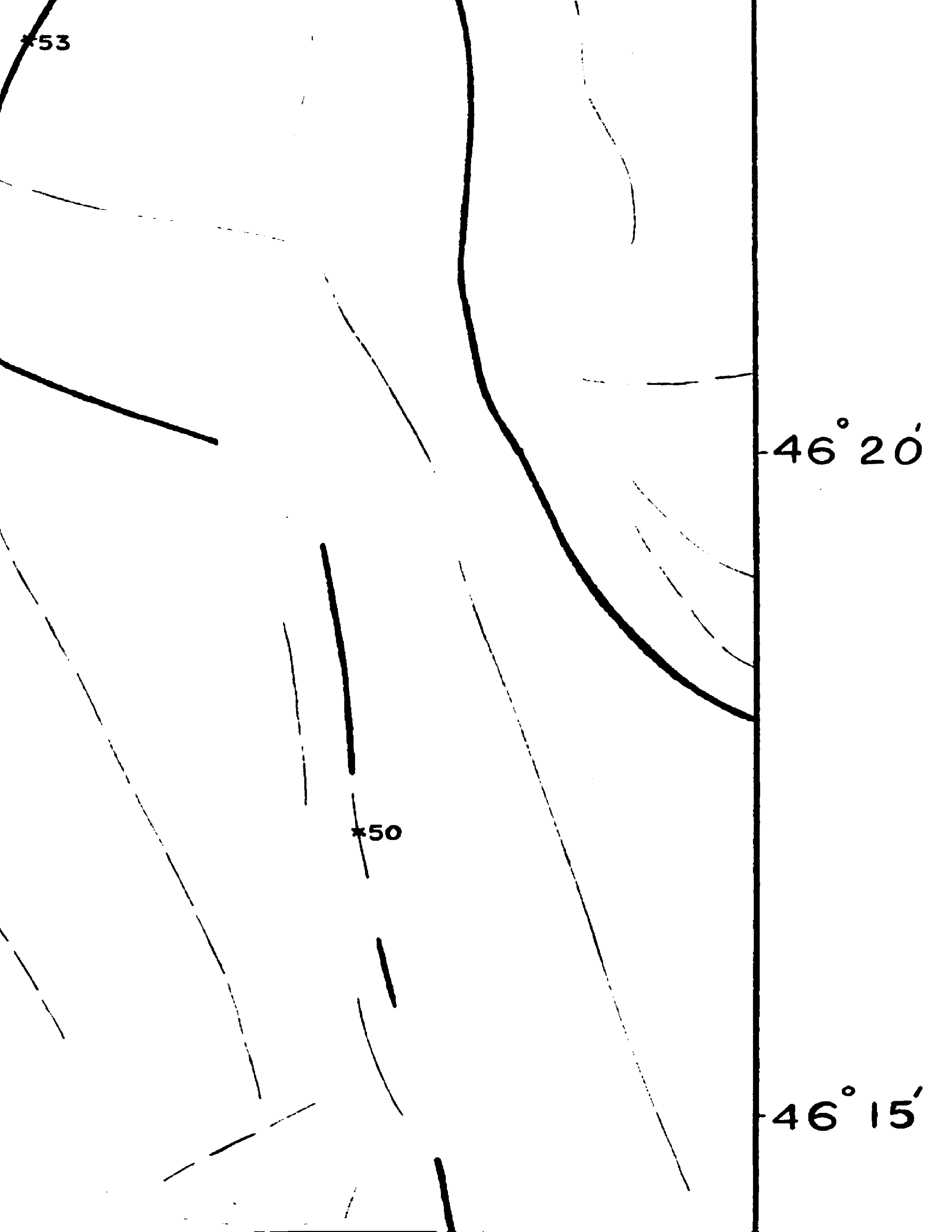

26
25


26
25

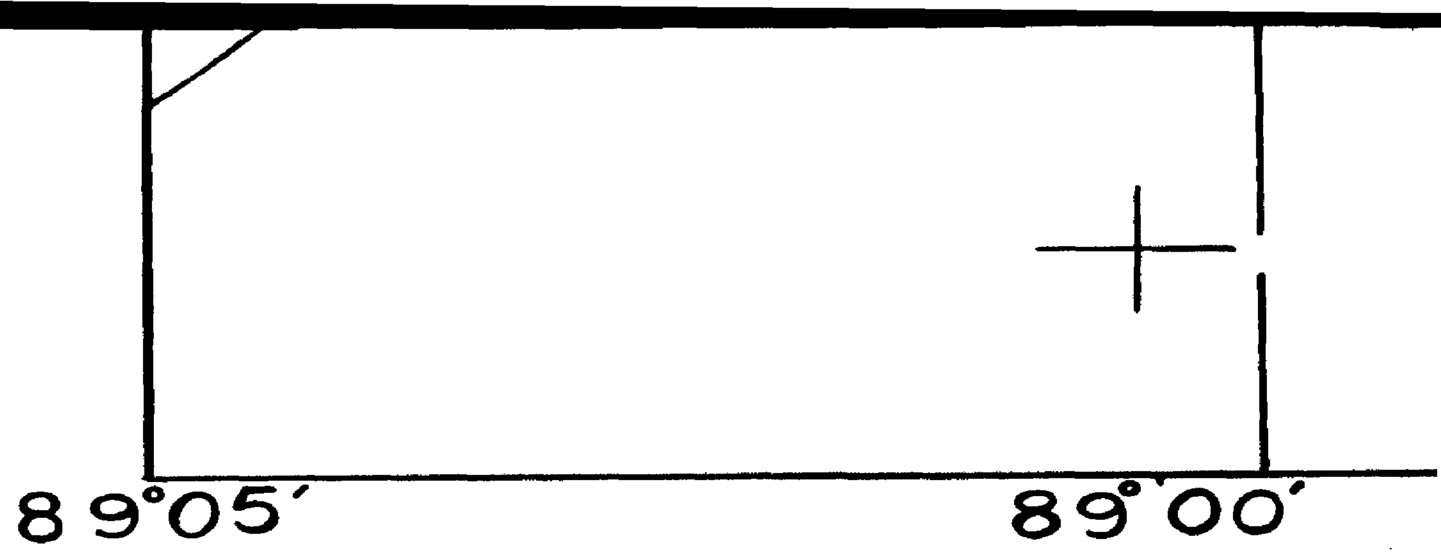


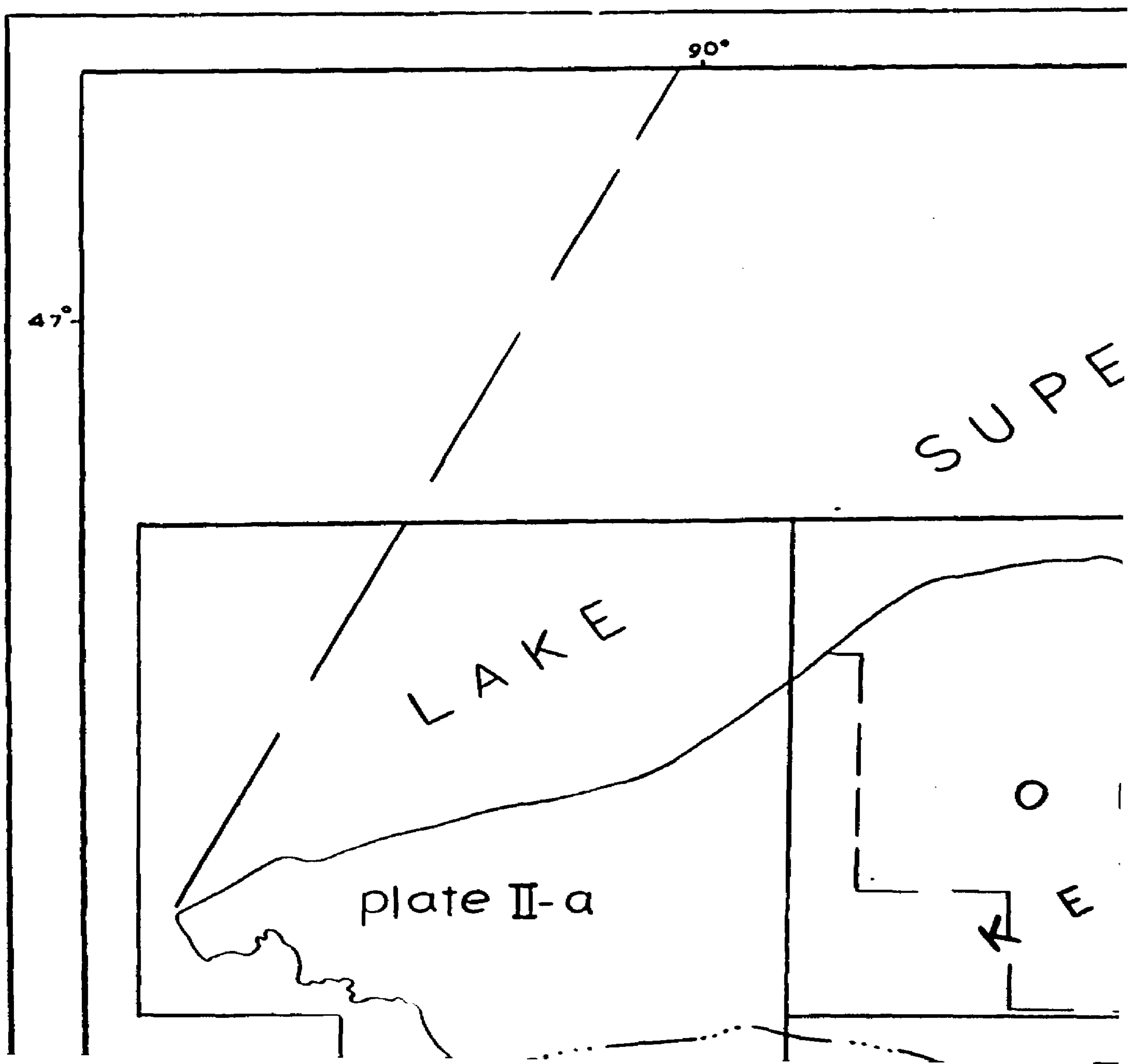
30
31
52
33
32
34
49

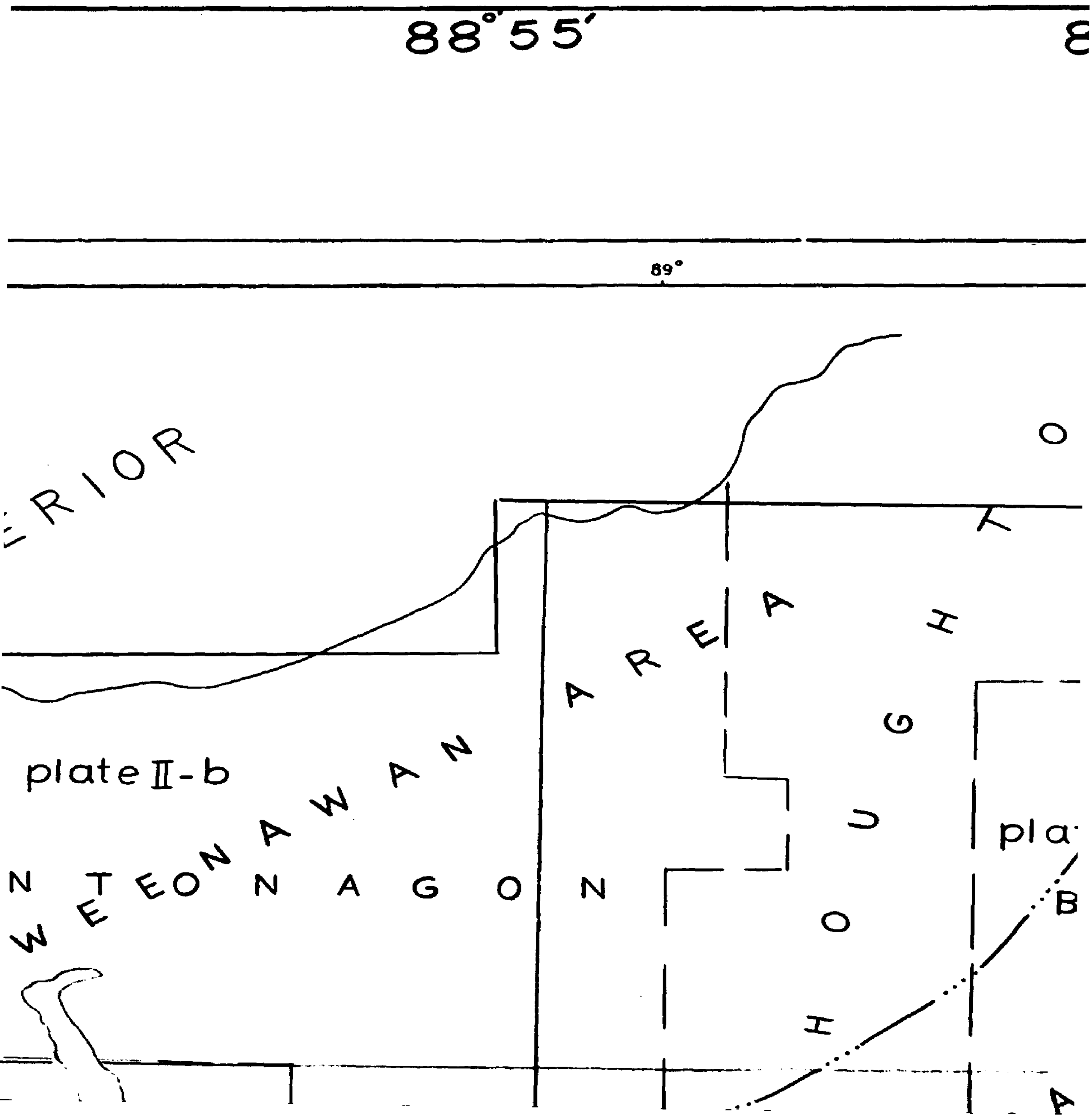

51
57



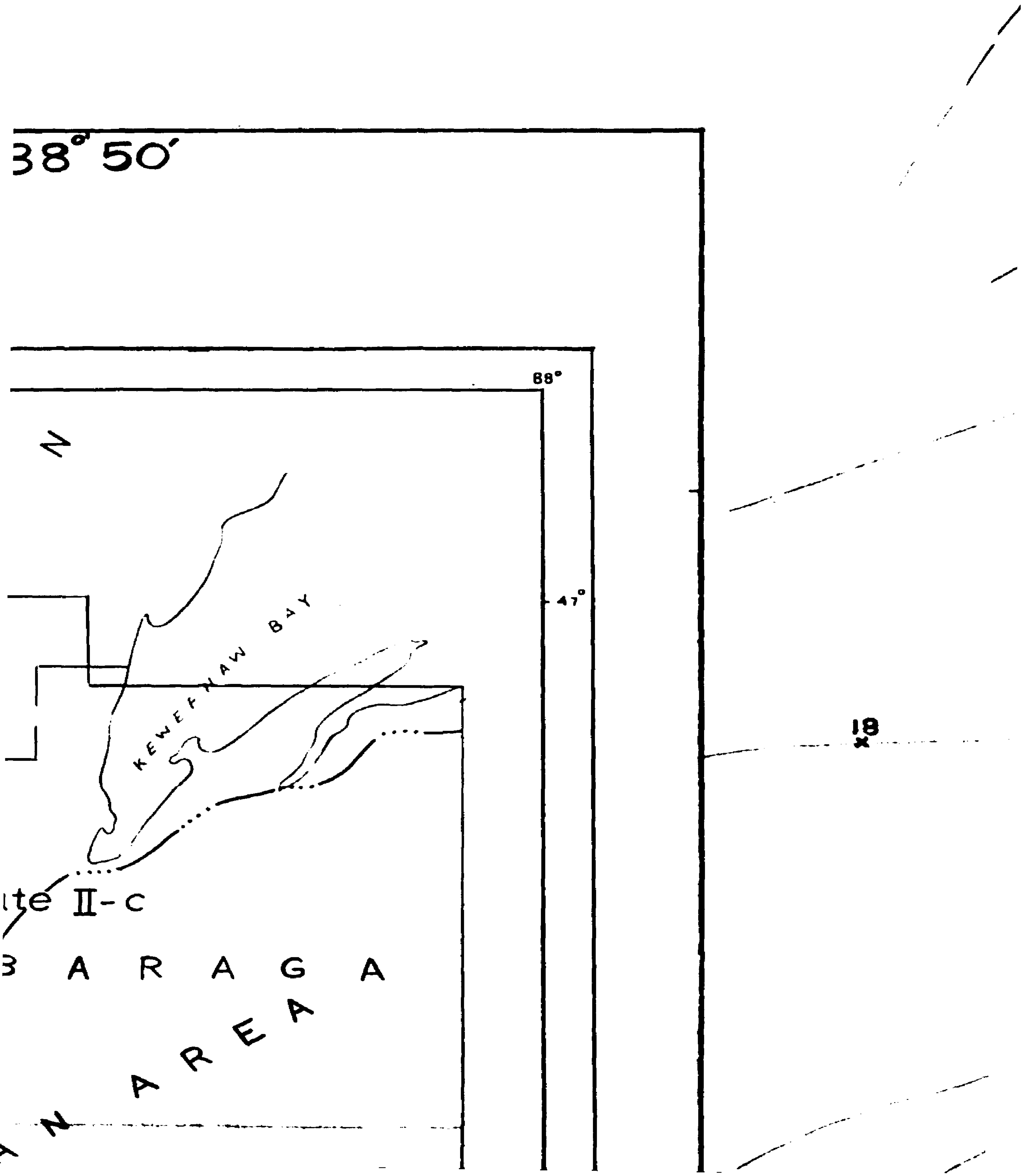
53
50
46°20′
46°15′

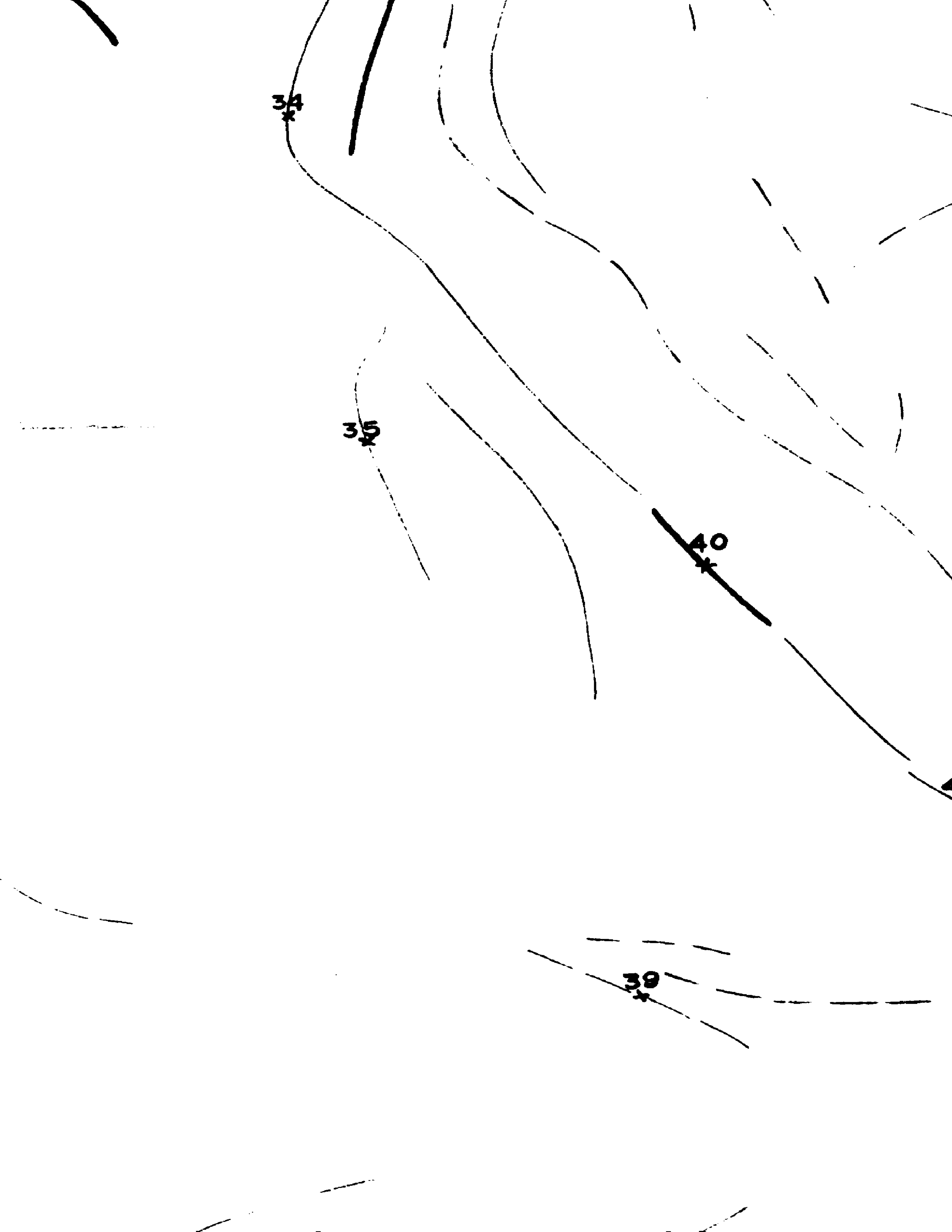

89°05′
89°00′

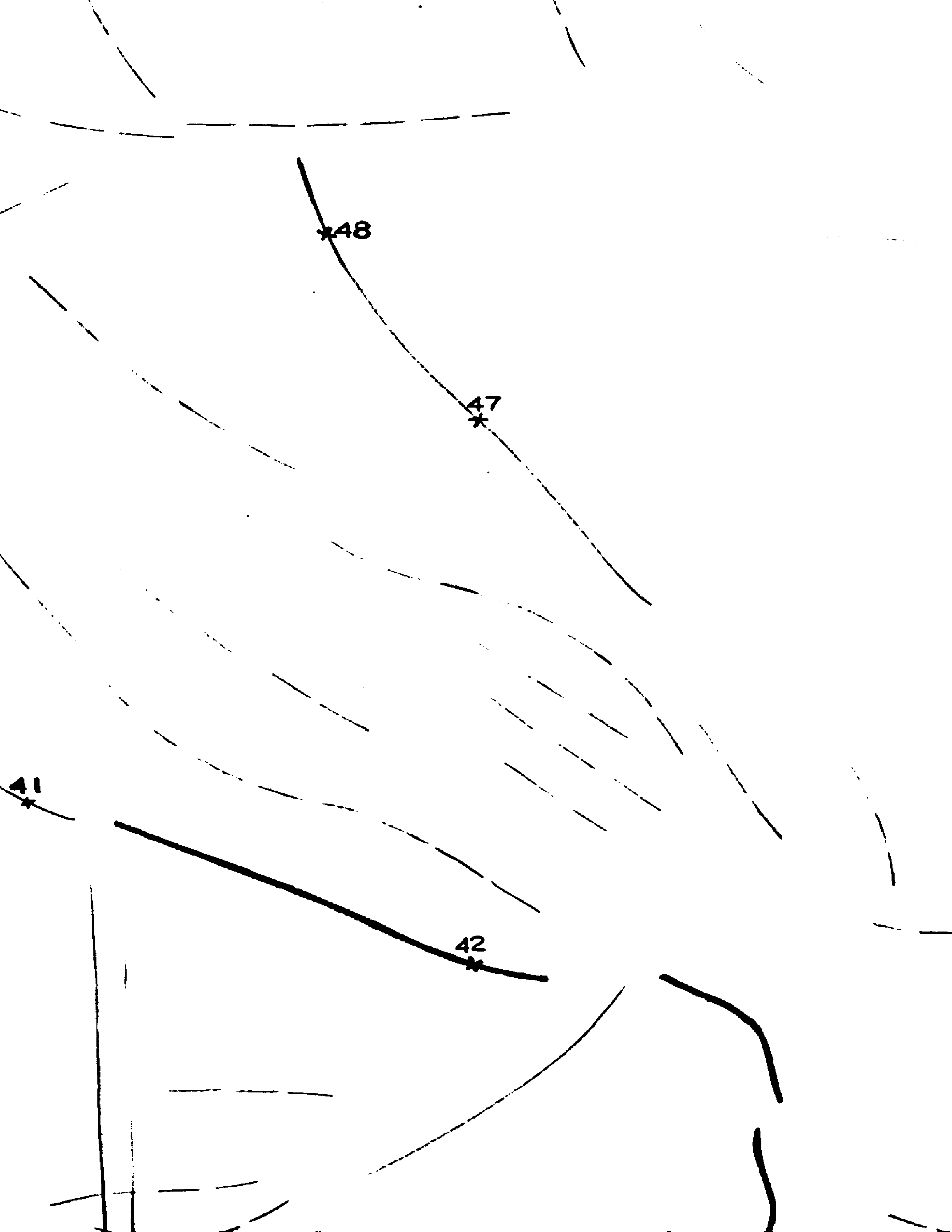

90°
47°
LAKE
plate II-a

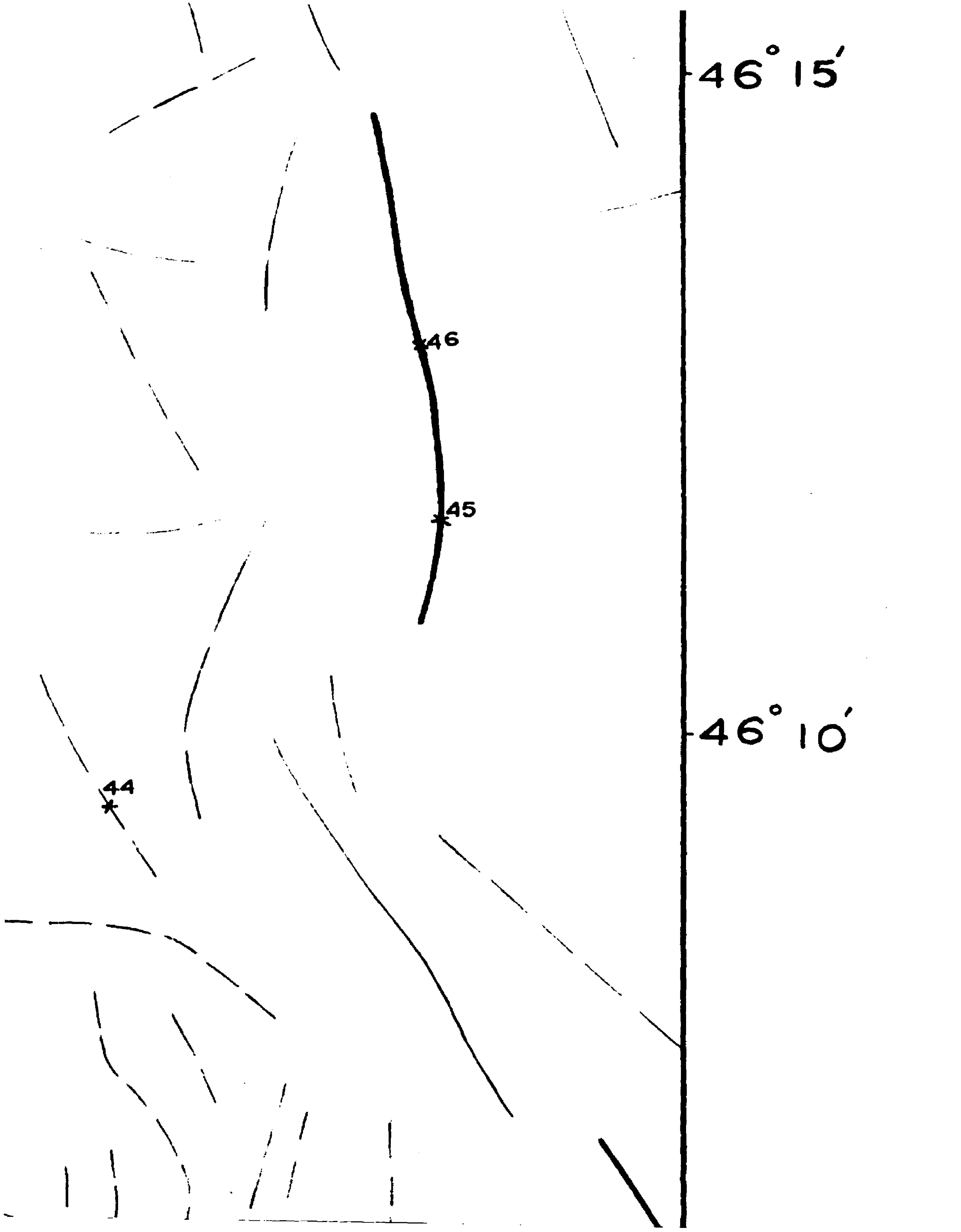


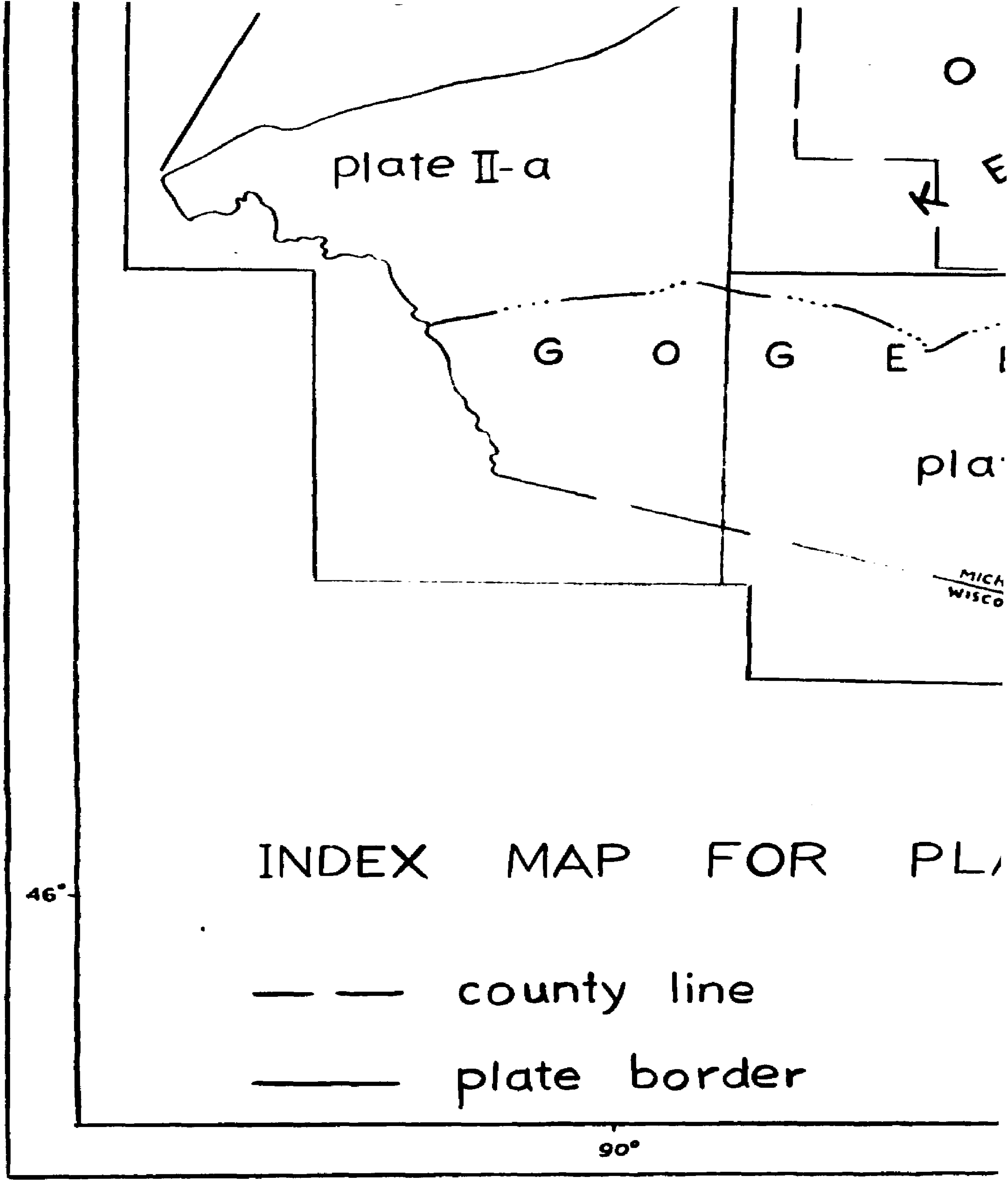
88°55′
89°
ERIOR
plate II-b
WEENAWAN
AREA
N T O N A G O N
H O U G H T O
pla
B
A


38° 50′
88°
47°
N
KEWEENAW BAY
18
te II-c
B A R A G A
N AREA

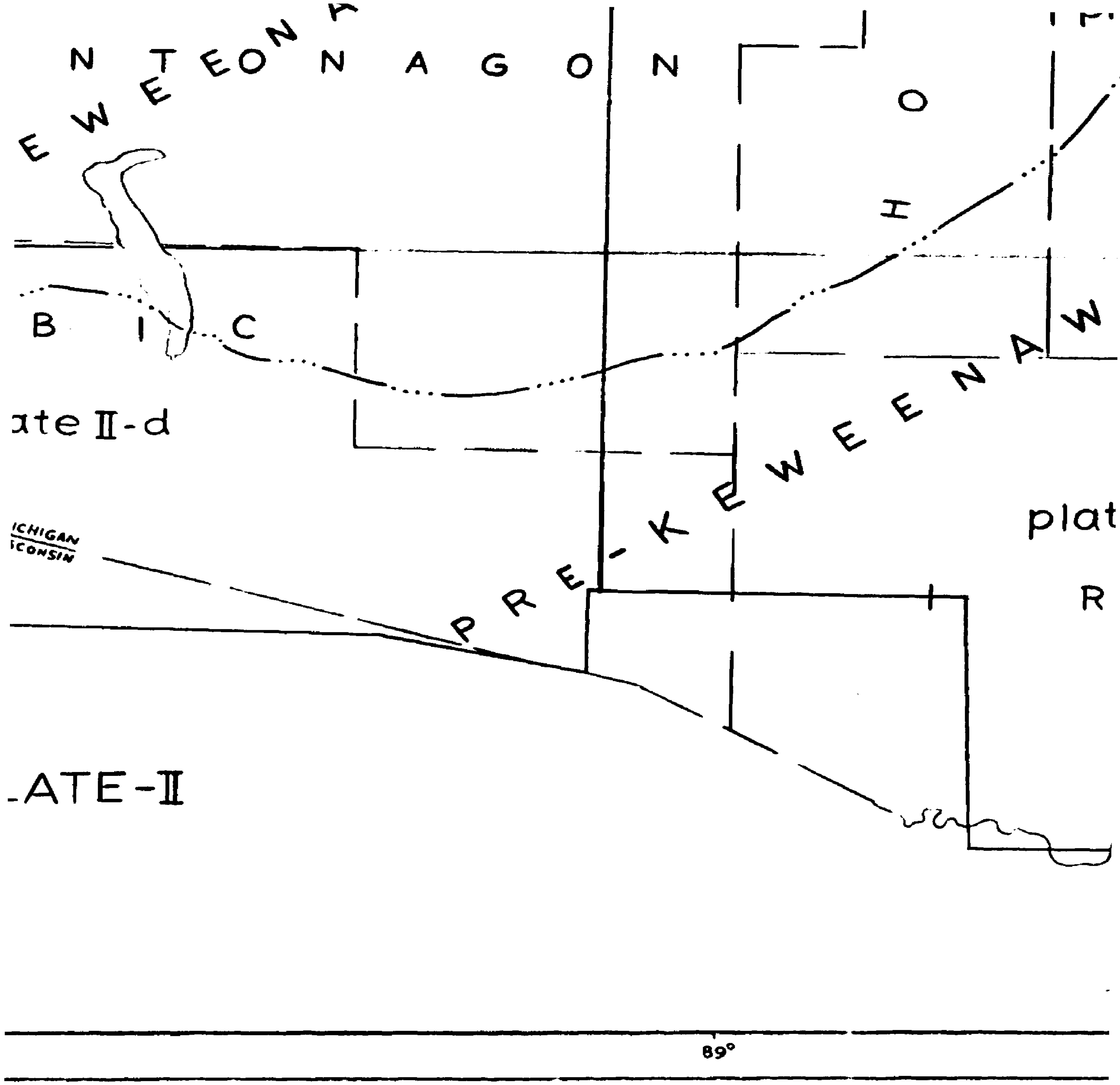

34
35
40
39


48
47
41
42

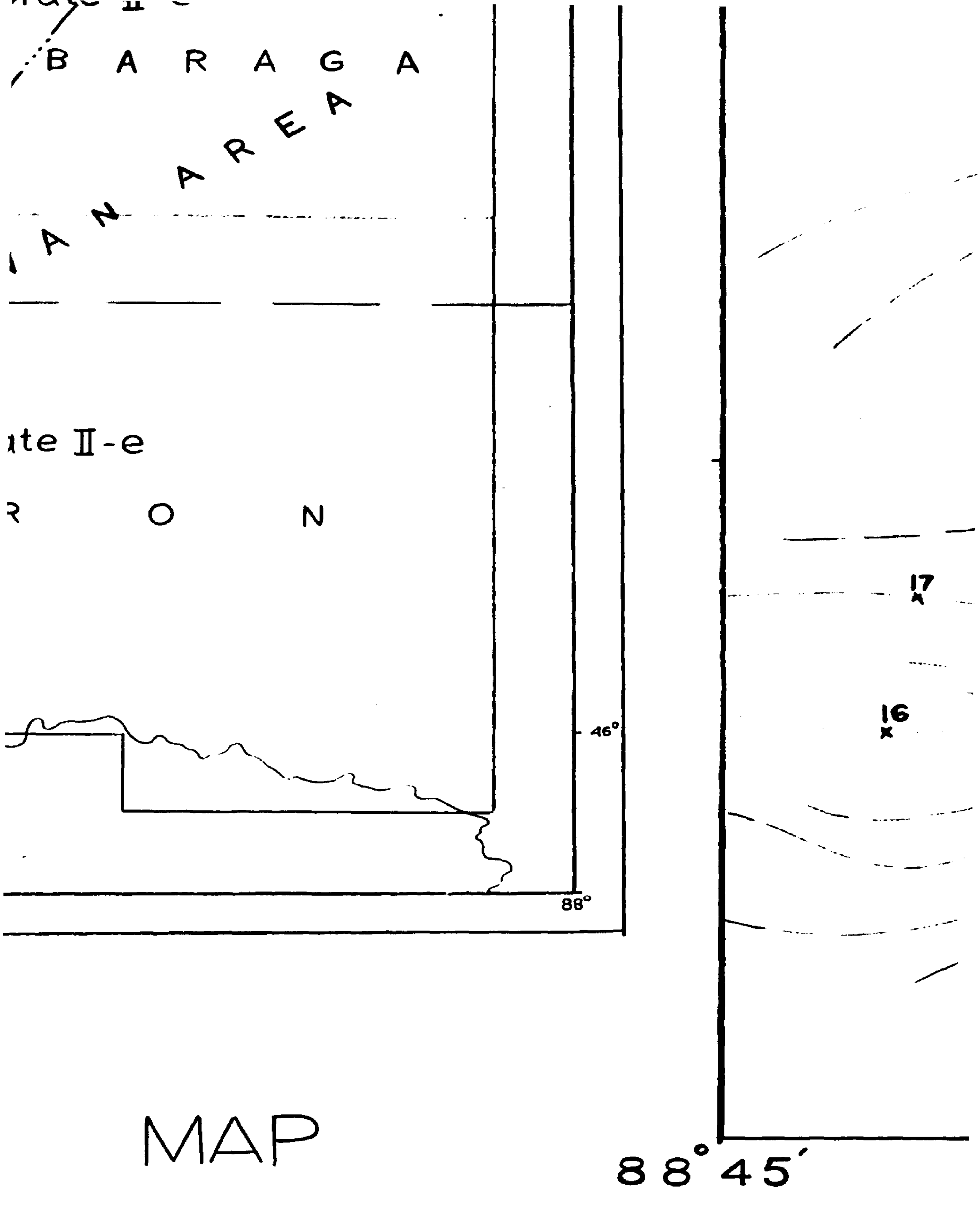

46°15′
46
45
46°10′
44



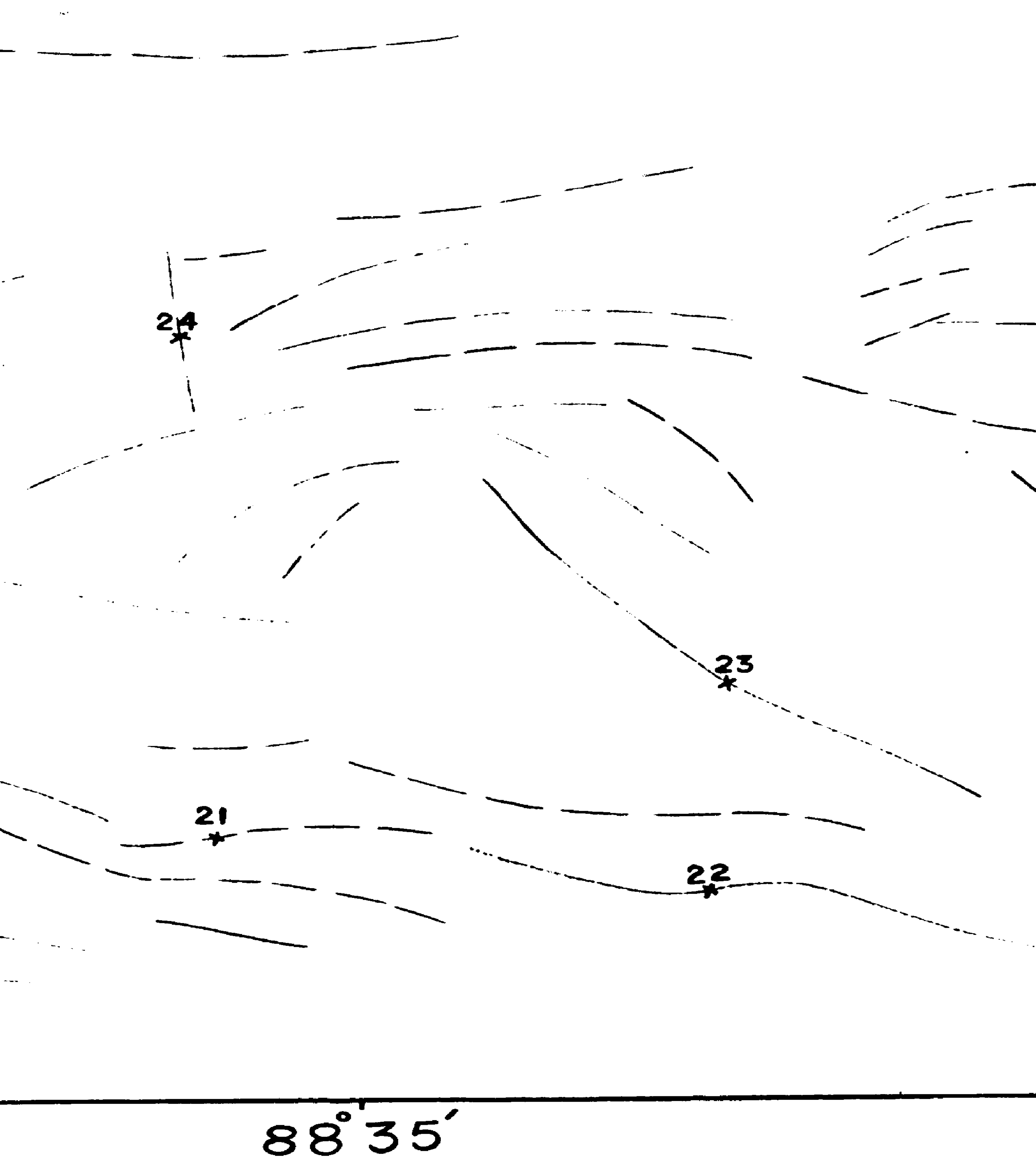
MAGNETIC

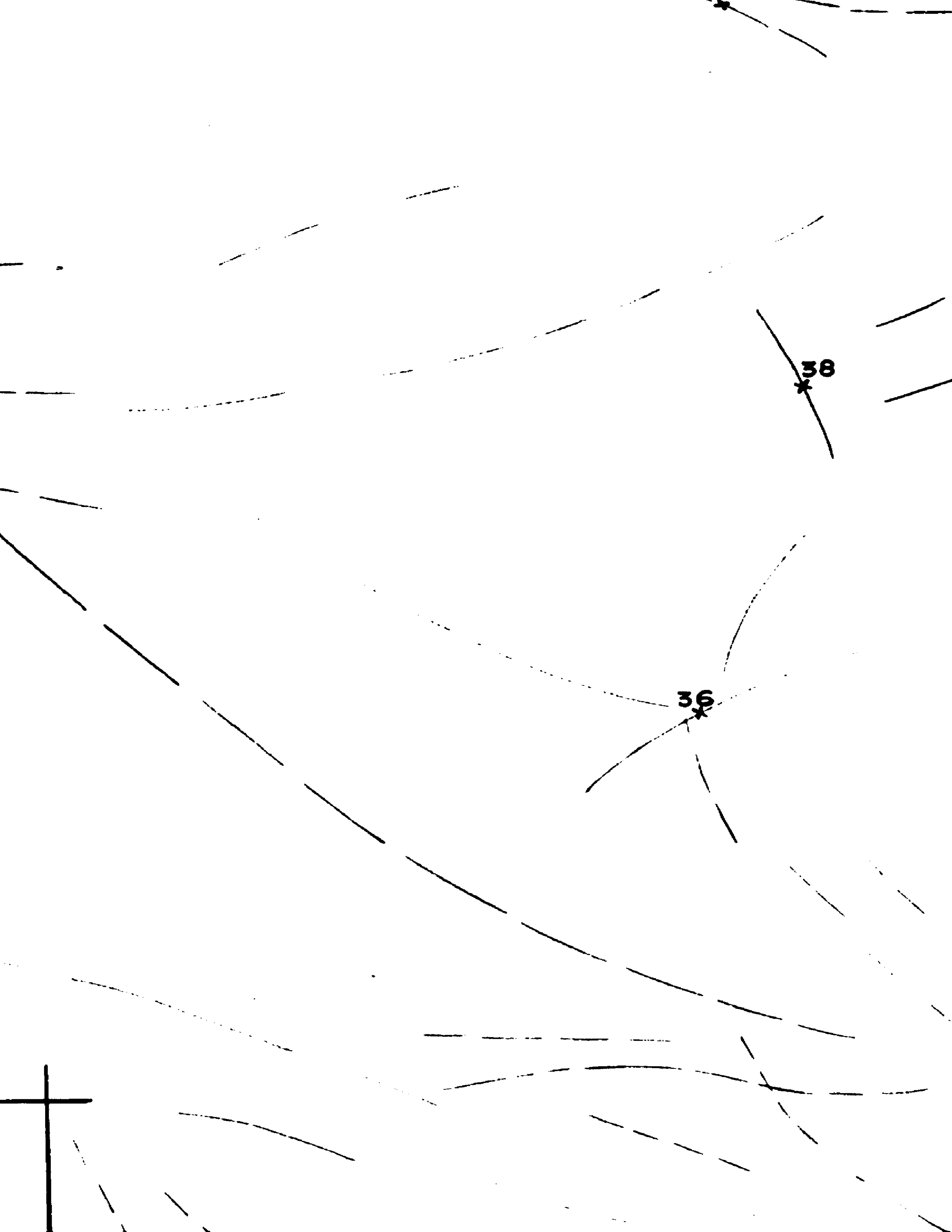


TREND ANALYSIS

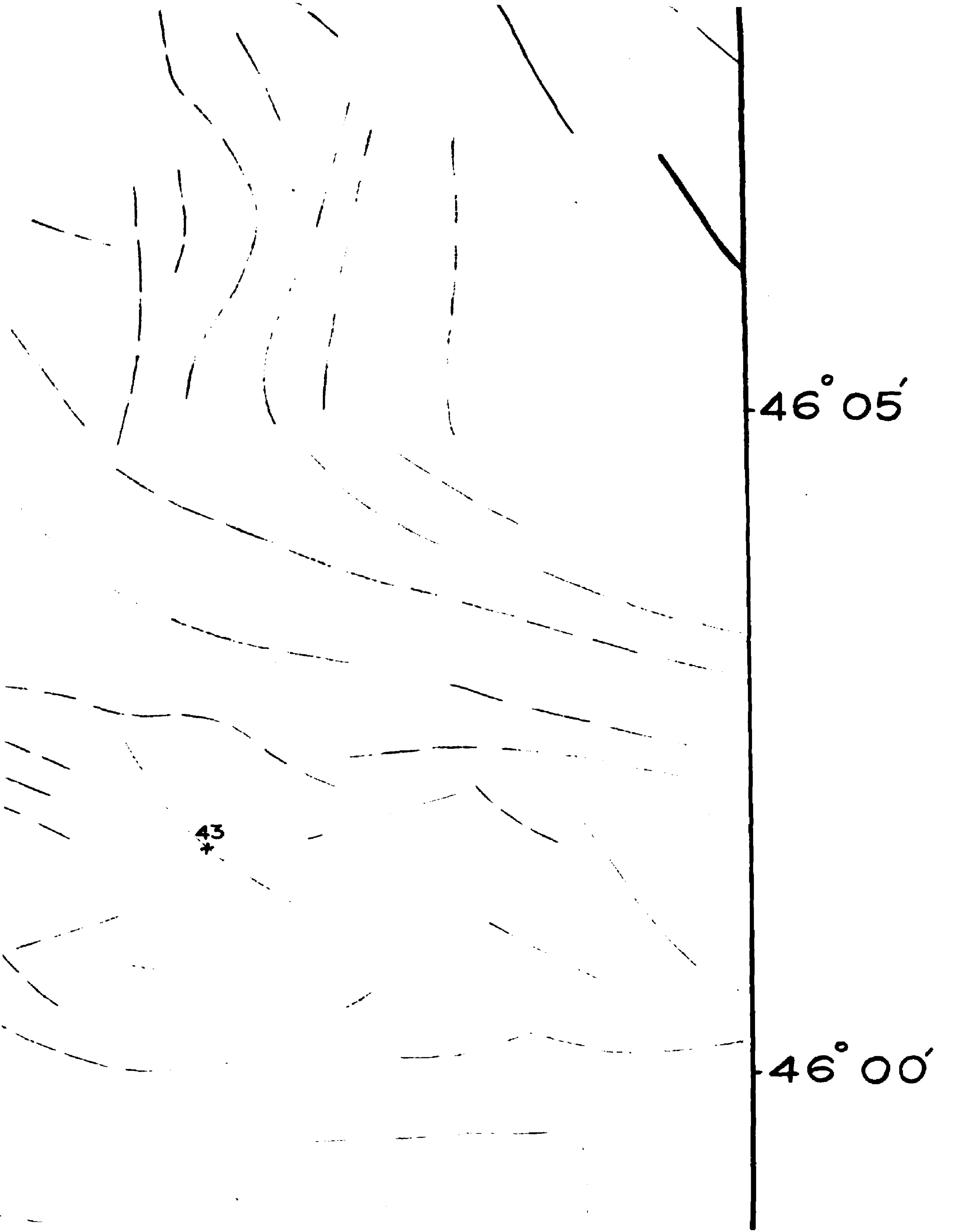

B A R A G A
AN AREA
ate II-e
R O N
46°
88°
17
16
MAP
88°45′


24
21
19
20
40′


24
23
21
22
88°35′


38
36


3.7



46°05′
43
46°00′

INDEX MAP FOR P

46°

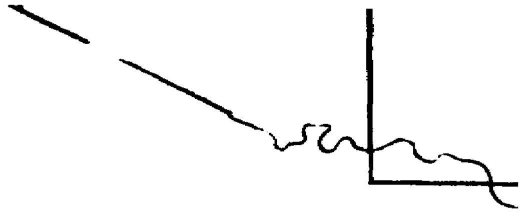
— — county line

—— plate border

90°

MAGNETIC

PLATE-II

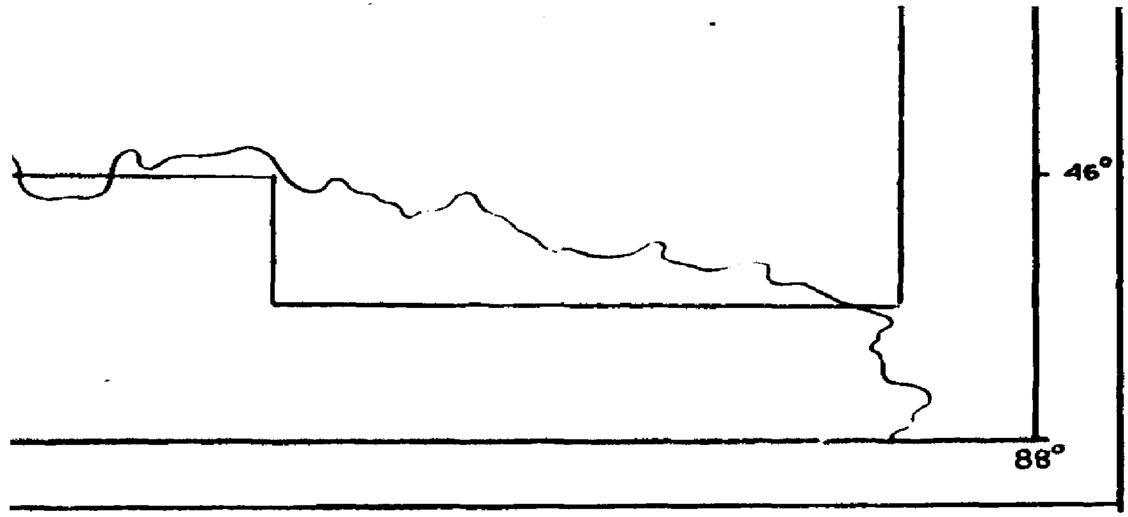


89°

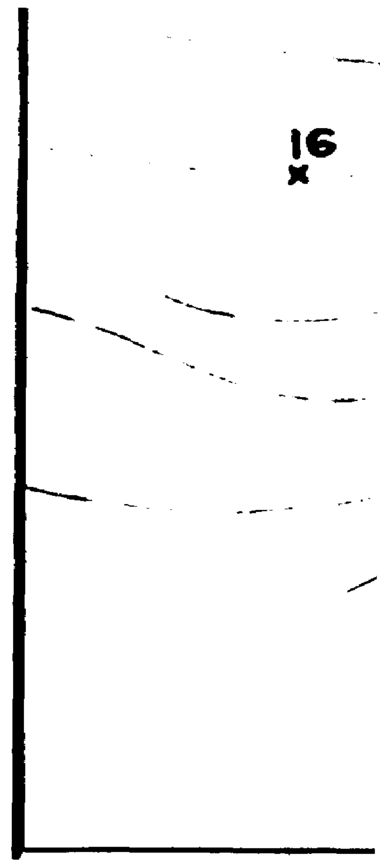
TREND ANALYSIS

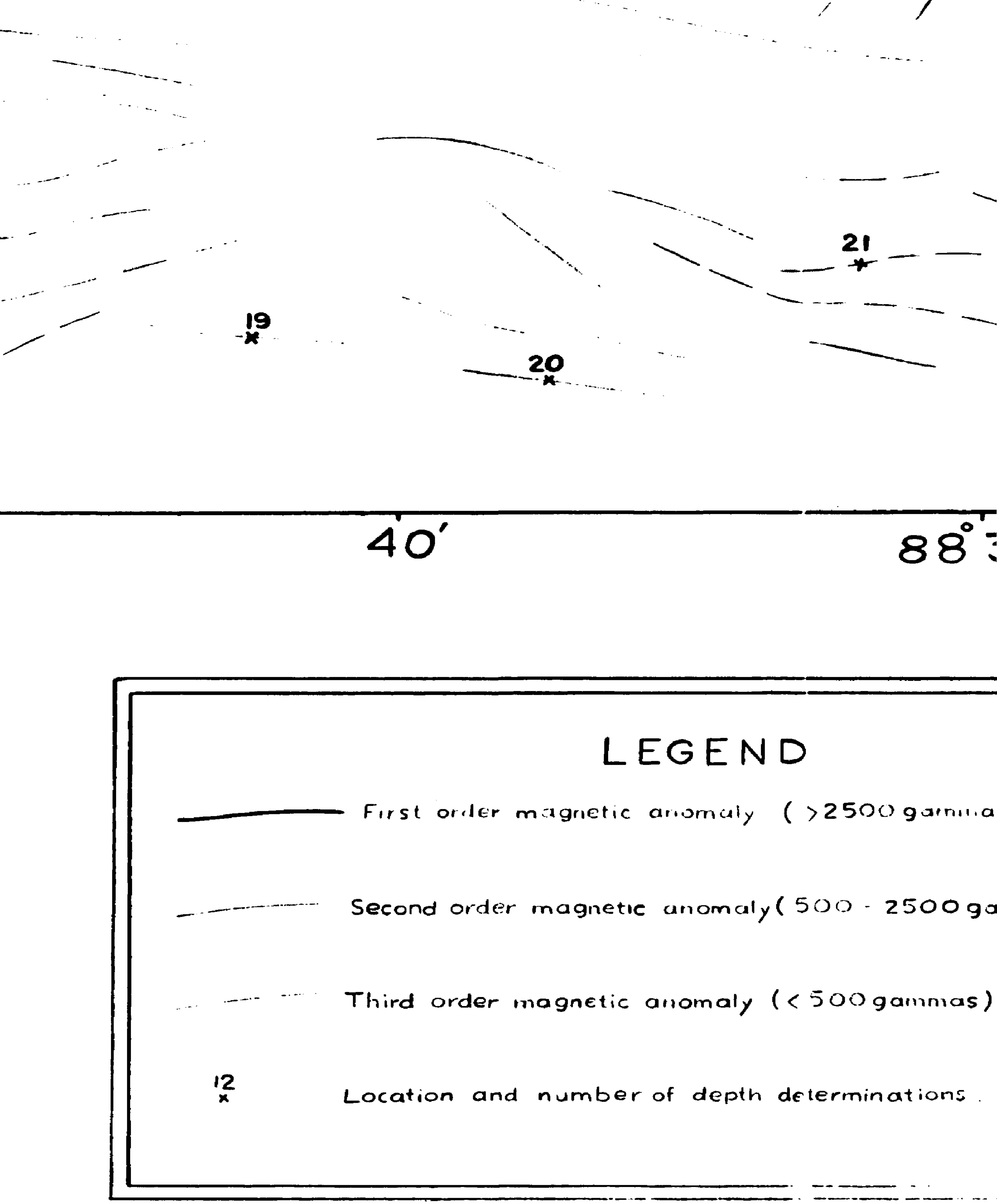
SCALE 1: 62500

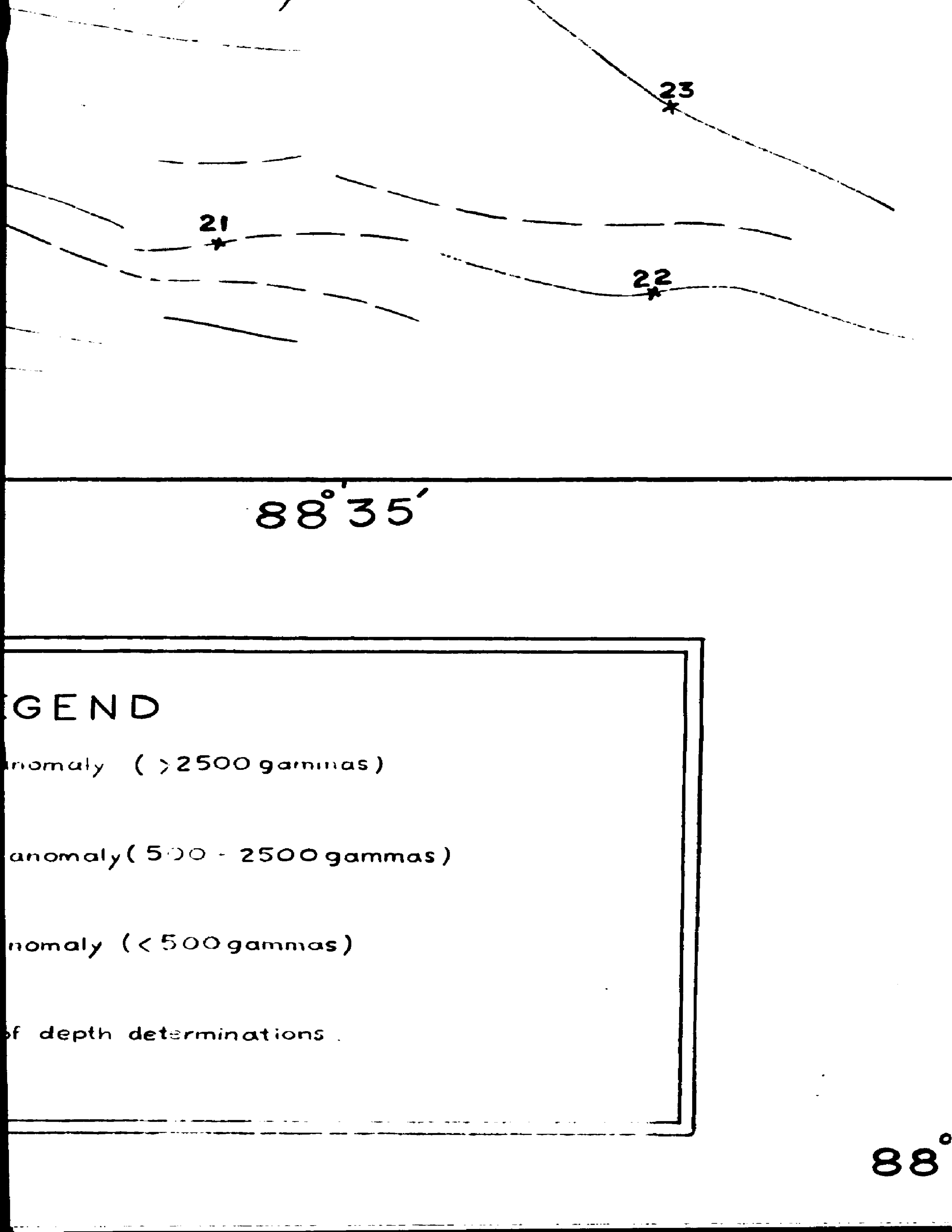
PLATE II-e



MAP

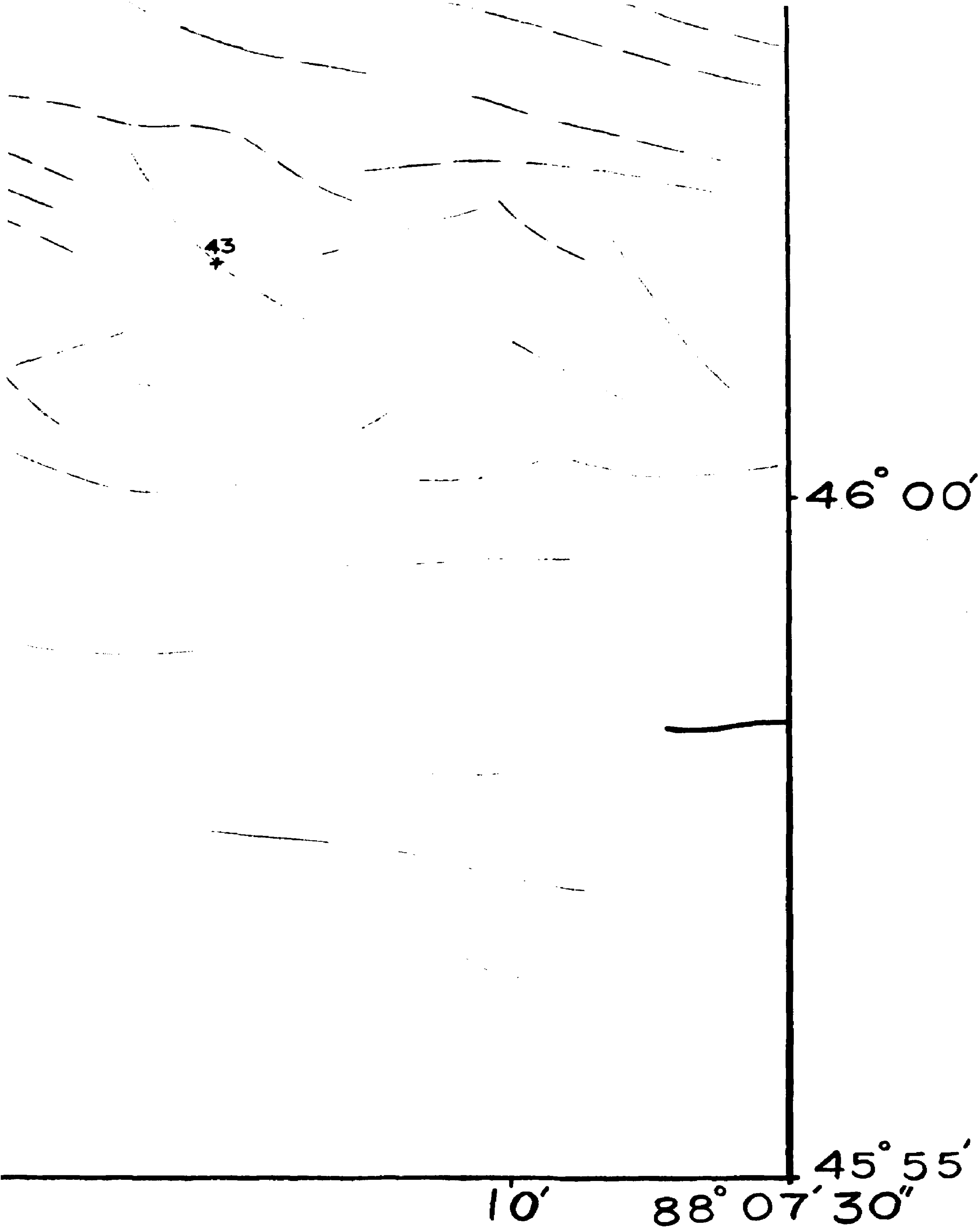



19
20
21
40′
88°
LEGEND
First order magnetic anomaly (>2500 gamma
Second order magnetic anomaly(500 - 2500 ga
Third order magnetic anomaly (< 500 gammas)
12
Location and number of depth determinations .


23
21
22
88°35′
GEND
nomaly (>2500 gammas)
anomaly (500 - 2500 gammas)
nomaly (< 500 gammas)
of depth determinations .
88°

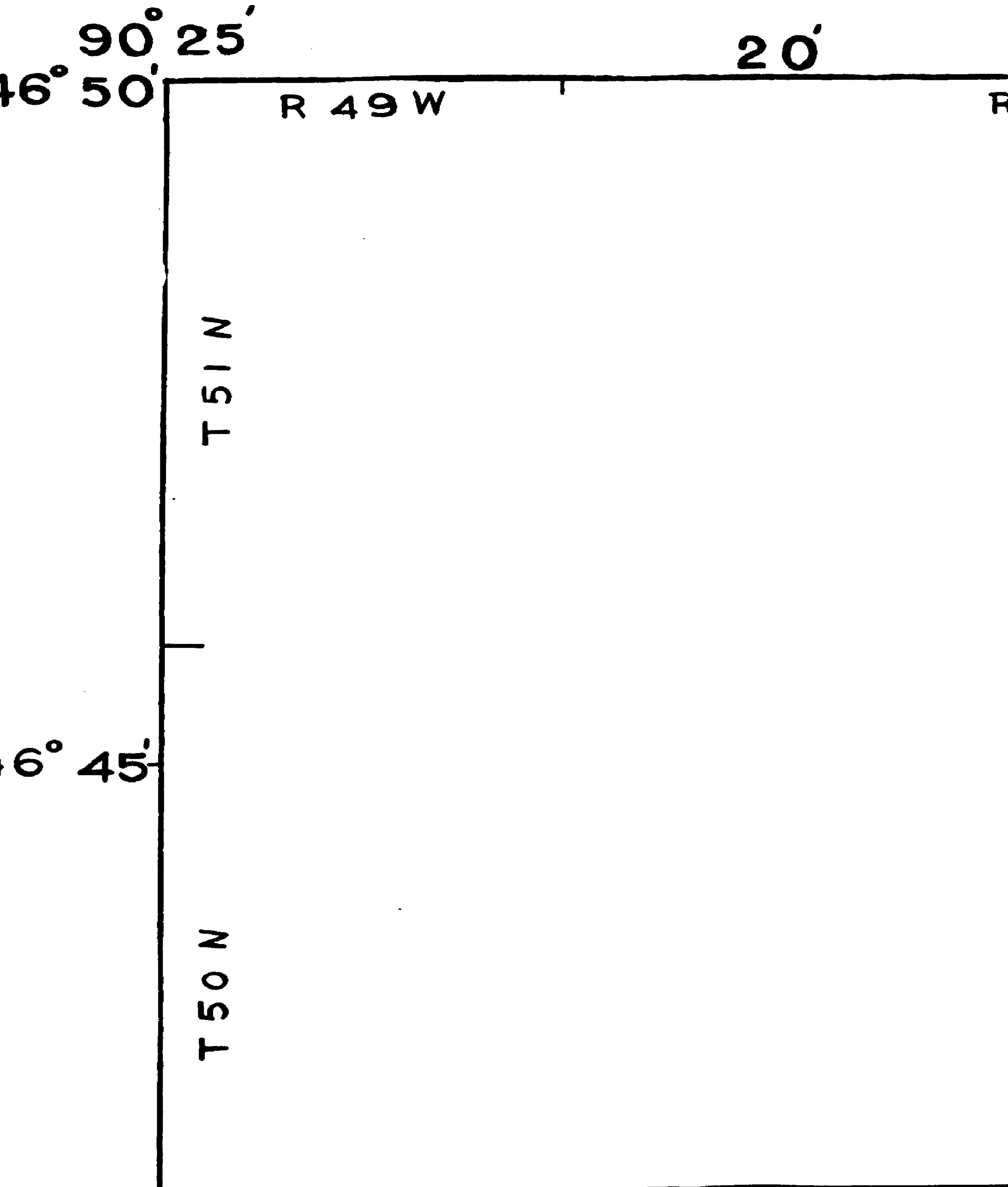

36
3° 30′
25′

20′
15′


43
46°00′
45°55′
10′
88°07′30″

4

4


90° 25'
46° 50'
20'
R 49 W
R
T 51 N
46° 45'
T 50 N

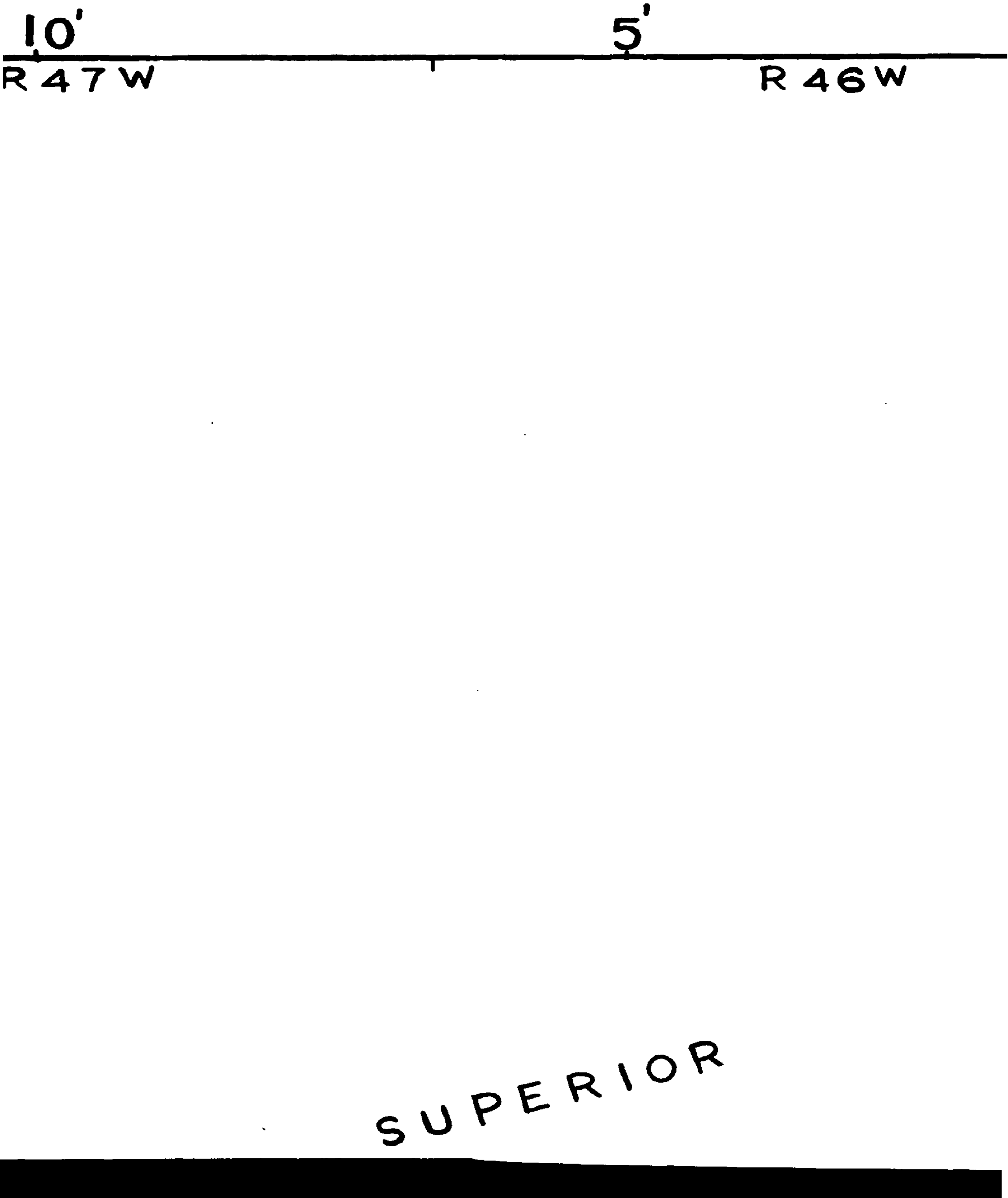
PLATE

15'

R 48 W

R

: III-a



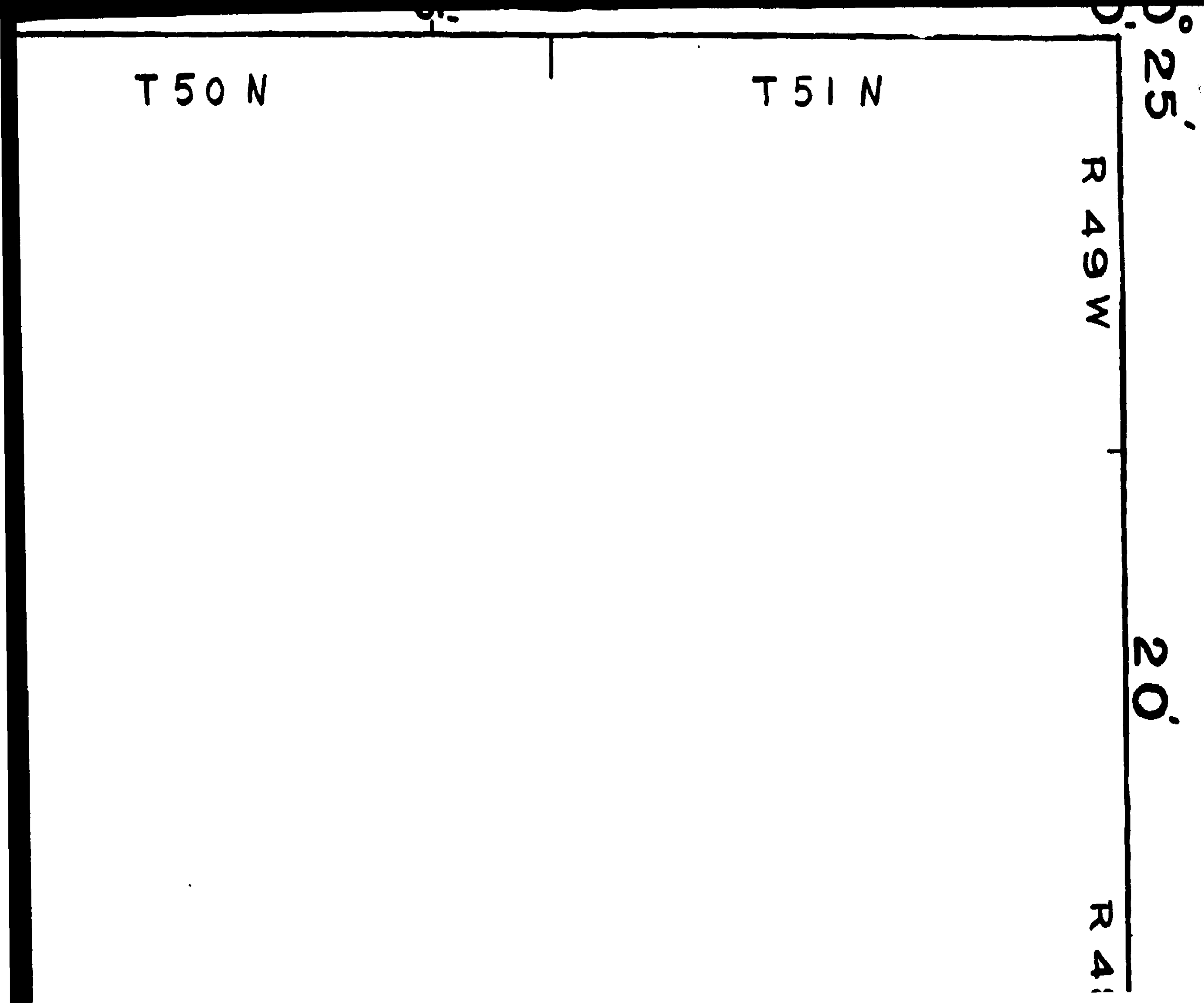

T50 N
T51 N
R 49 W
25'
20'

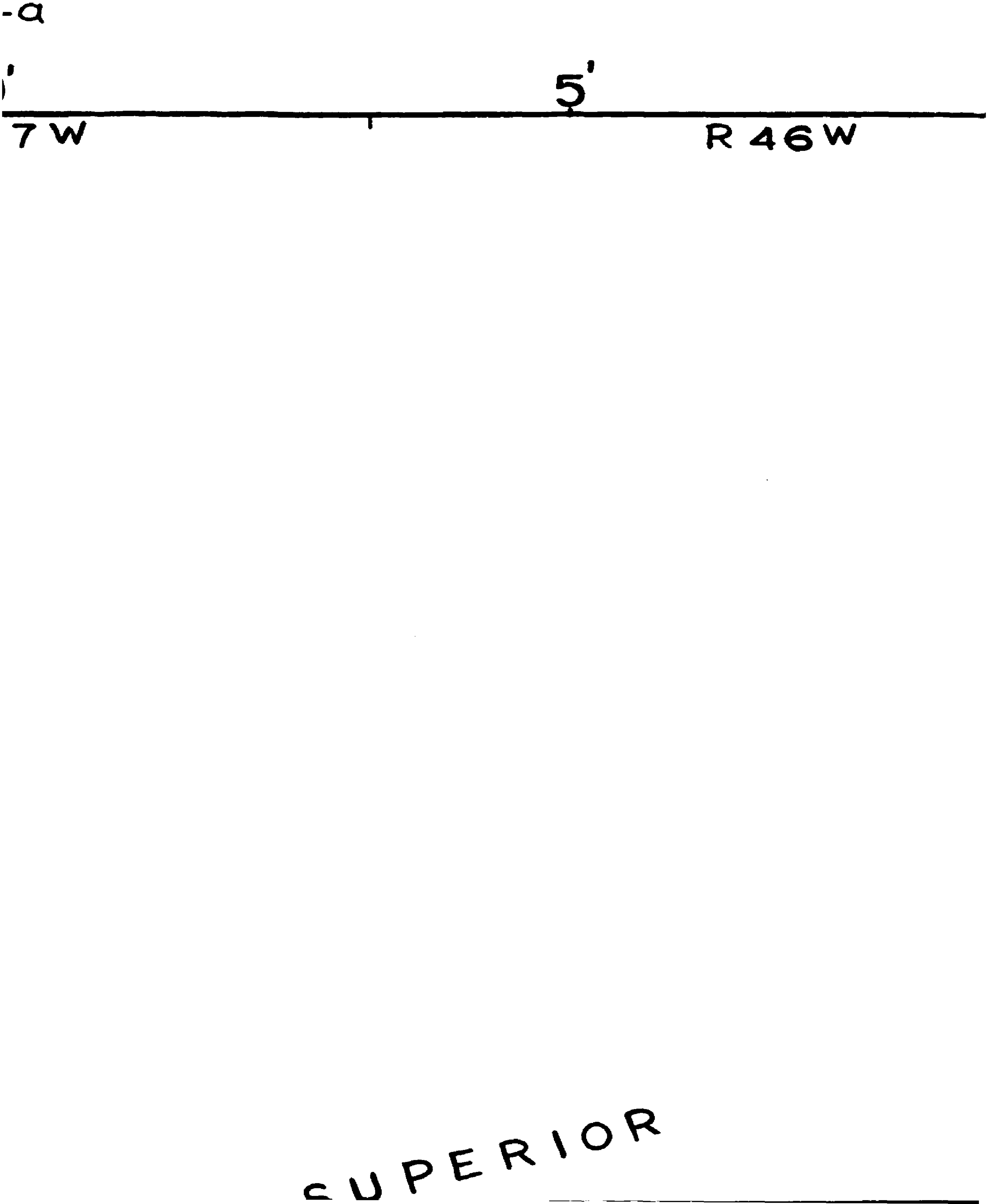
PLATE III-

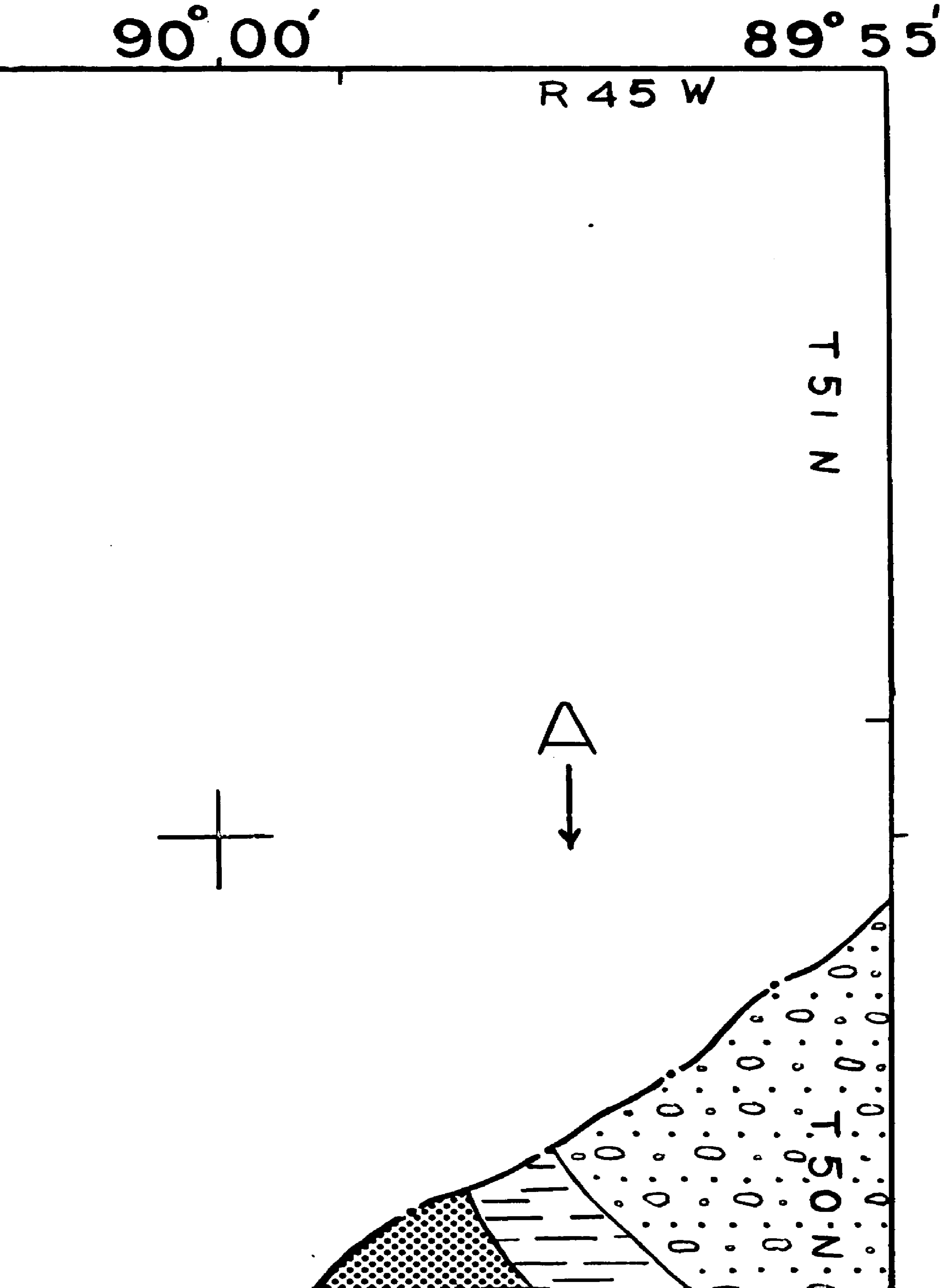
15'

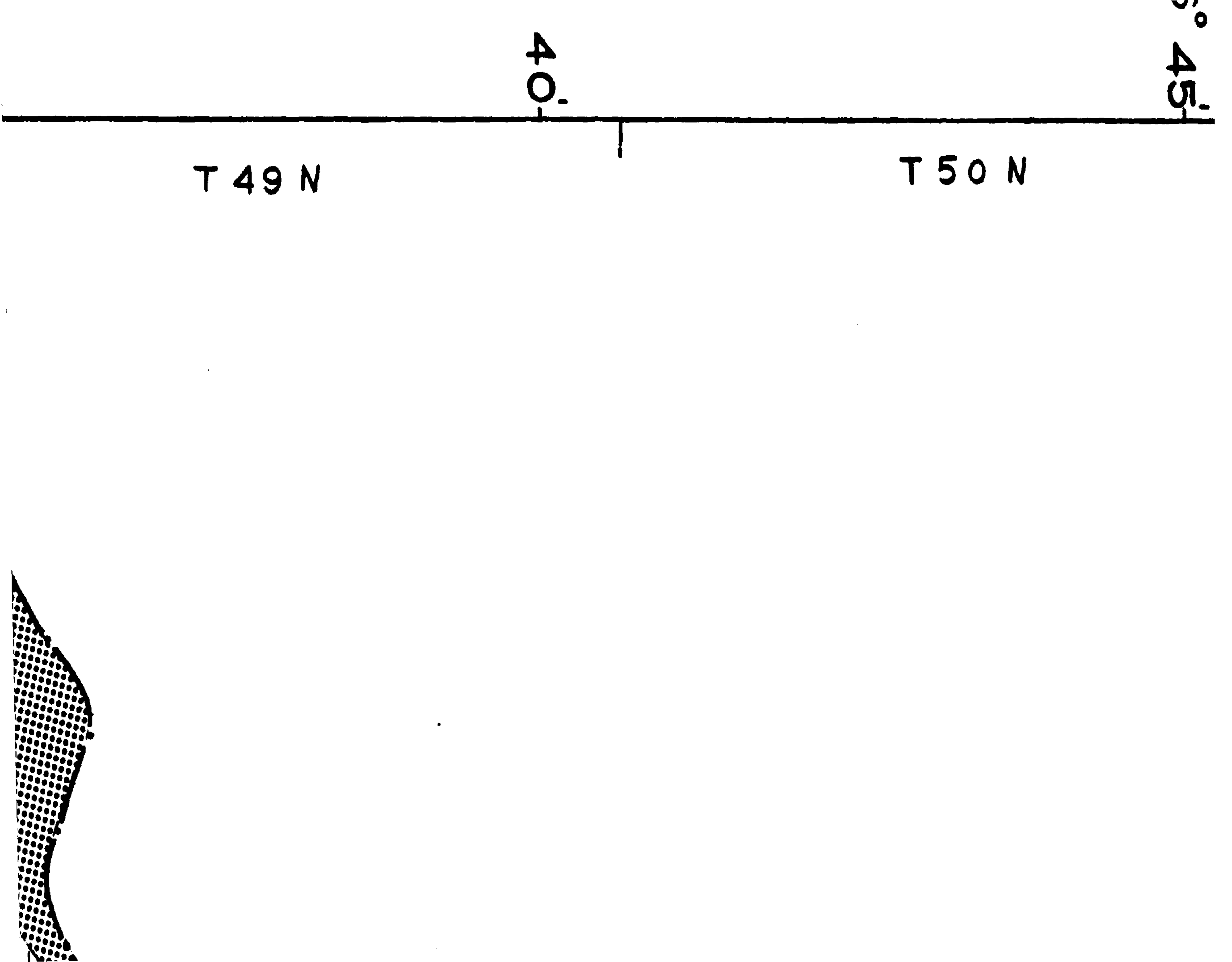
10'

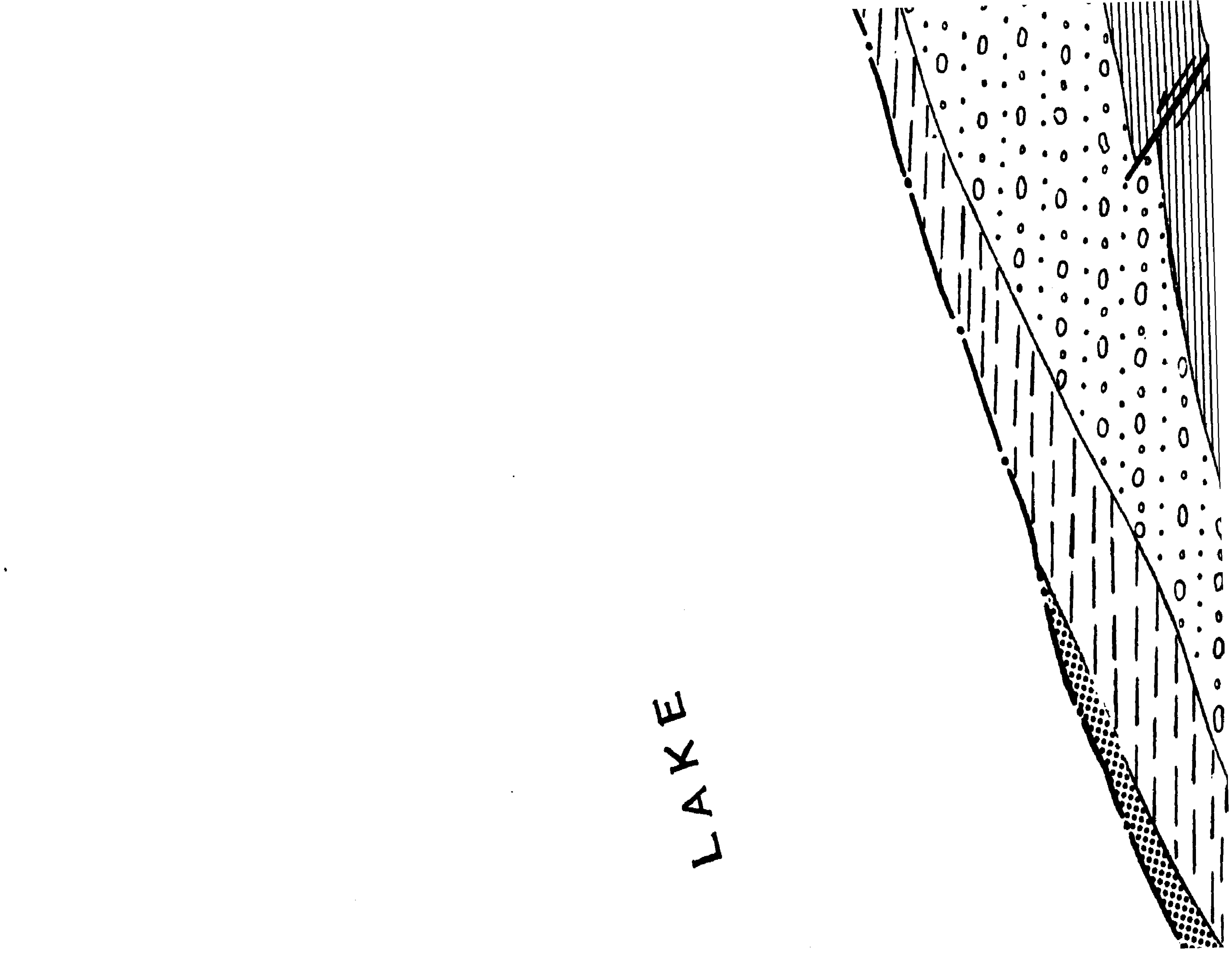
48 W

R 4

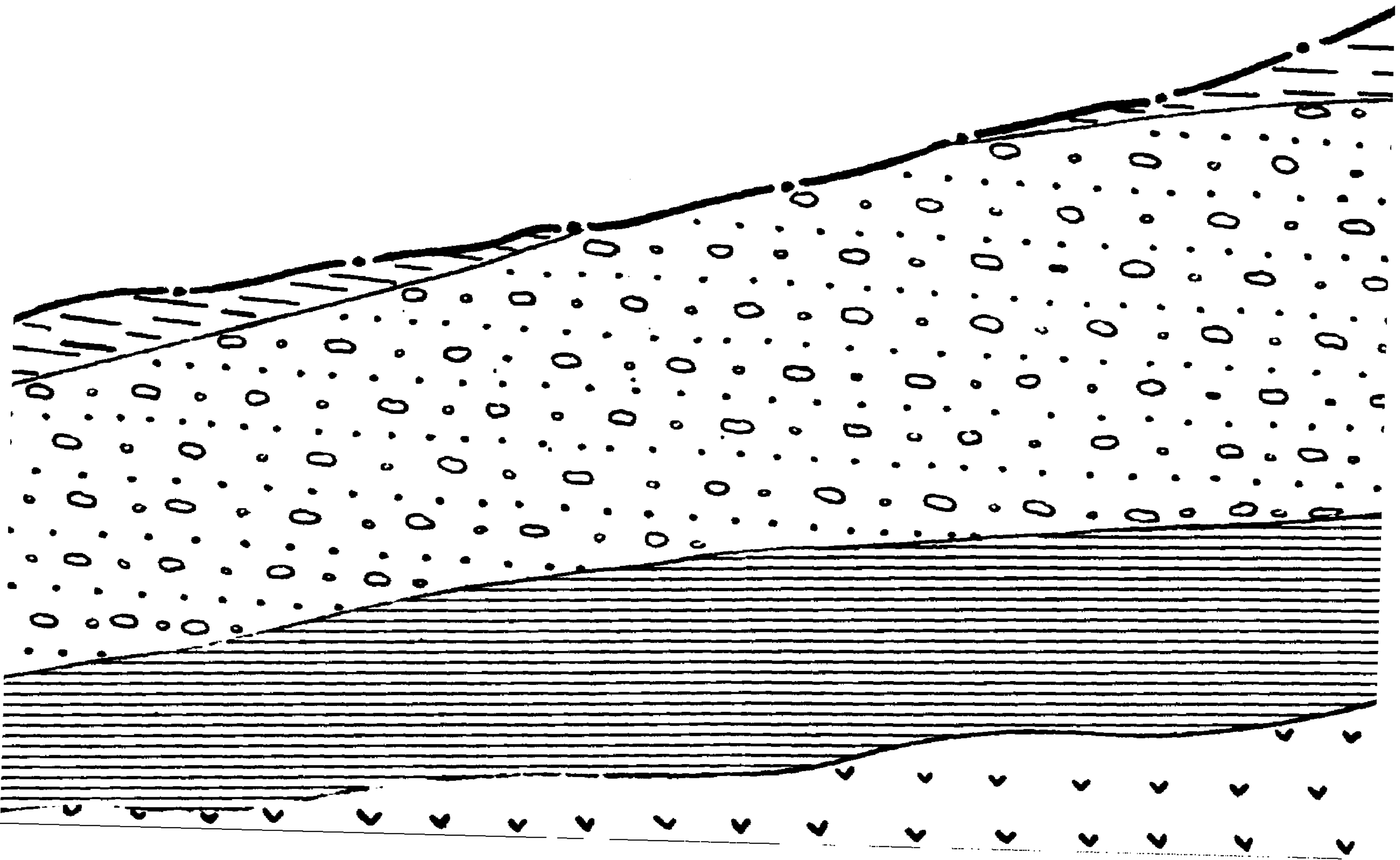

-a
5'
7 W
R 46 W
SUPERIOR

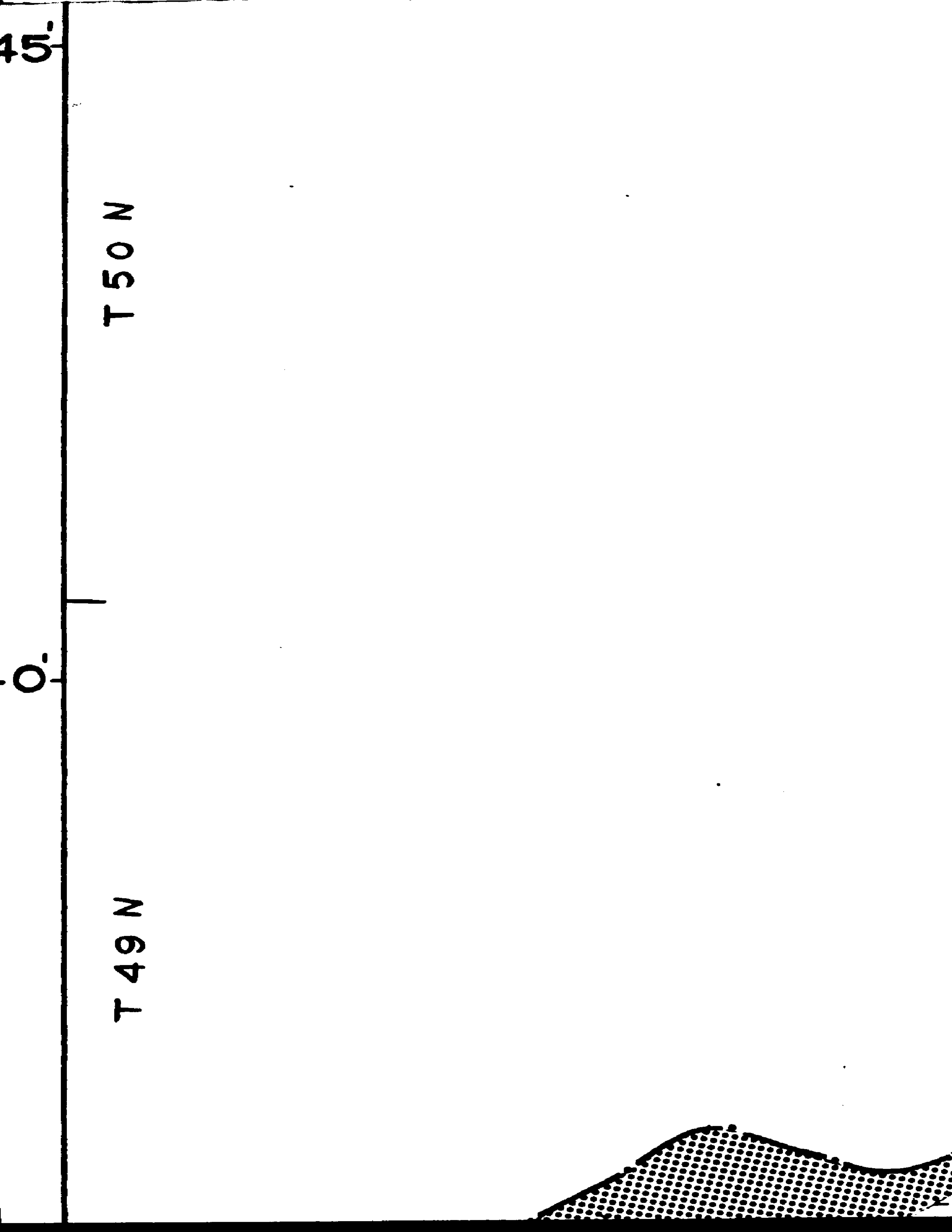

90°00′
89°55′
R 45 W
T 51 N
A
T 50 N

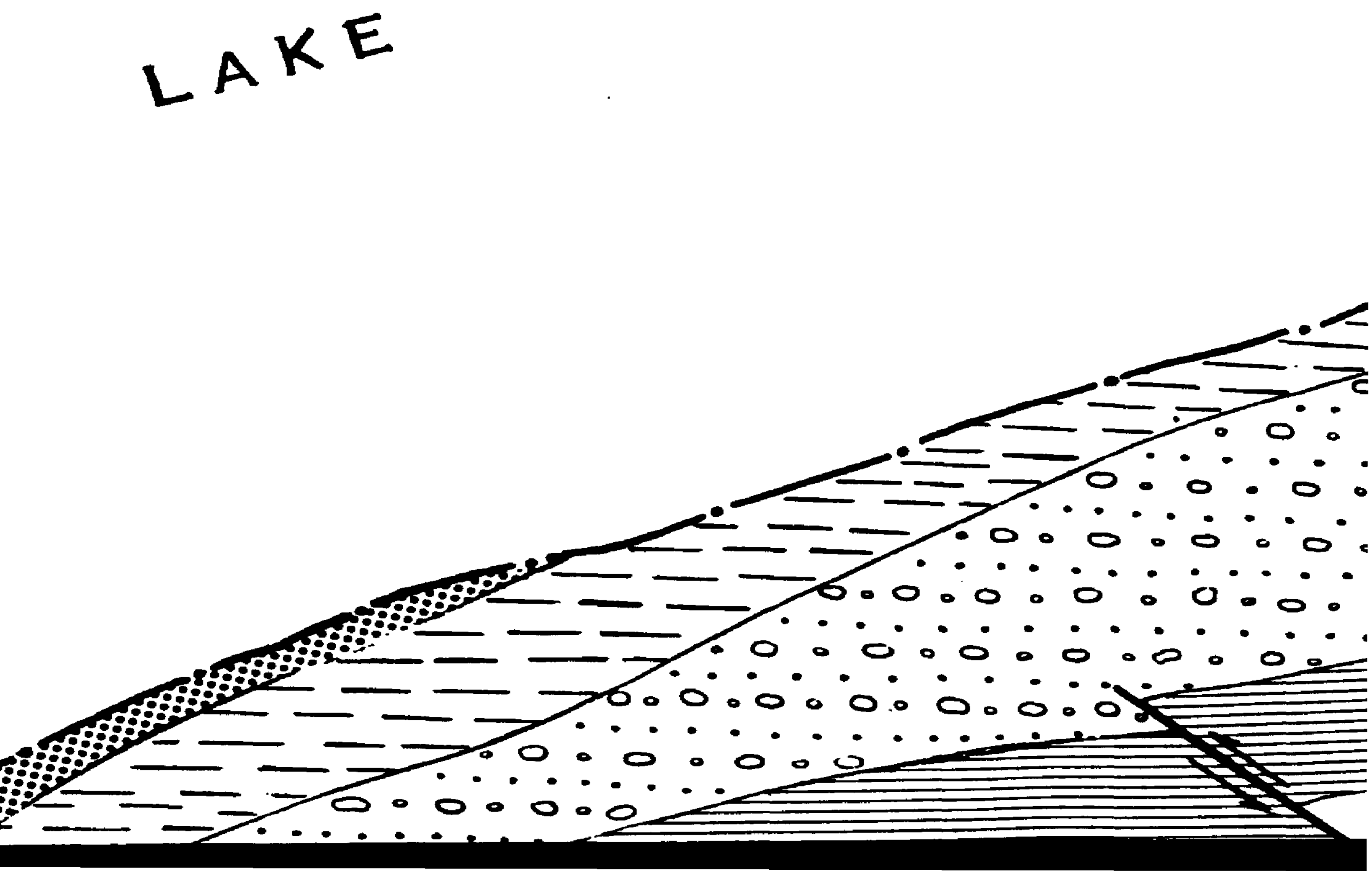

40'
45'
T 49 N
T 50 N


LAKE

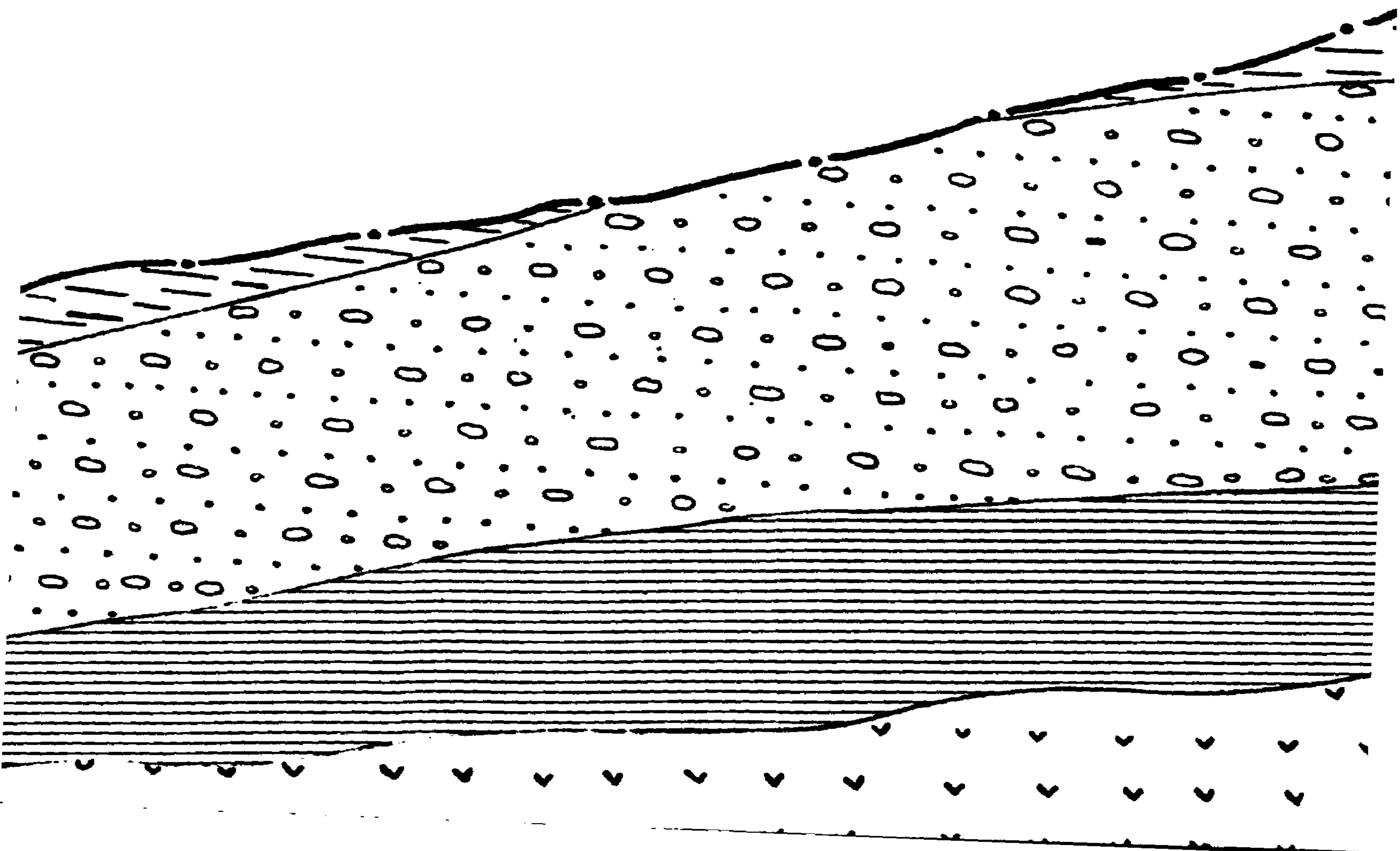
SUPERIOR

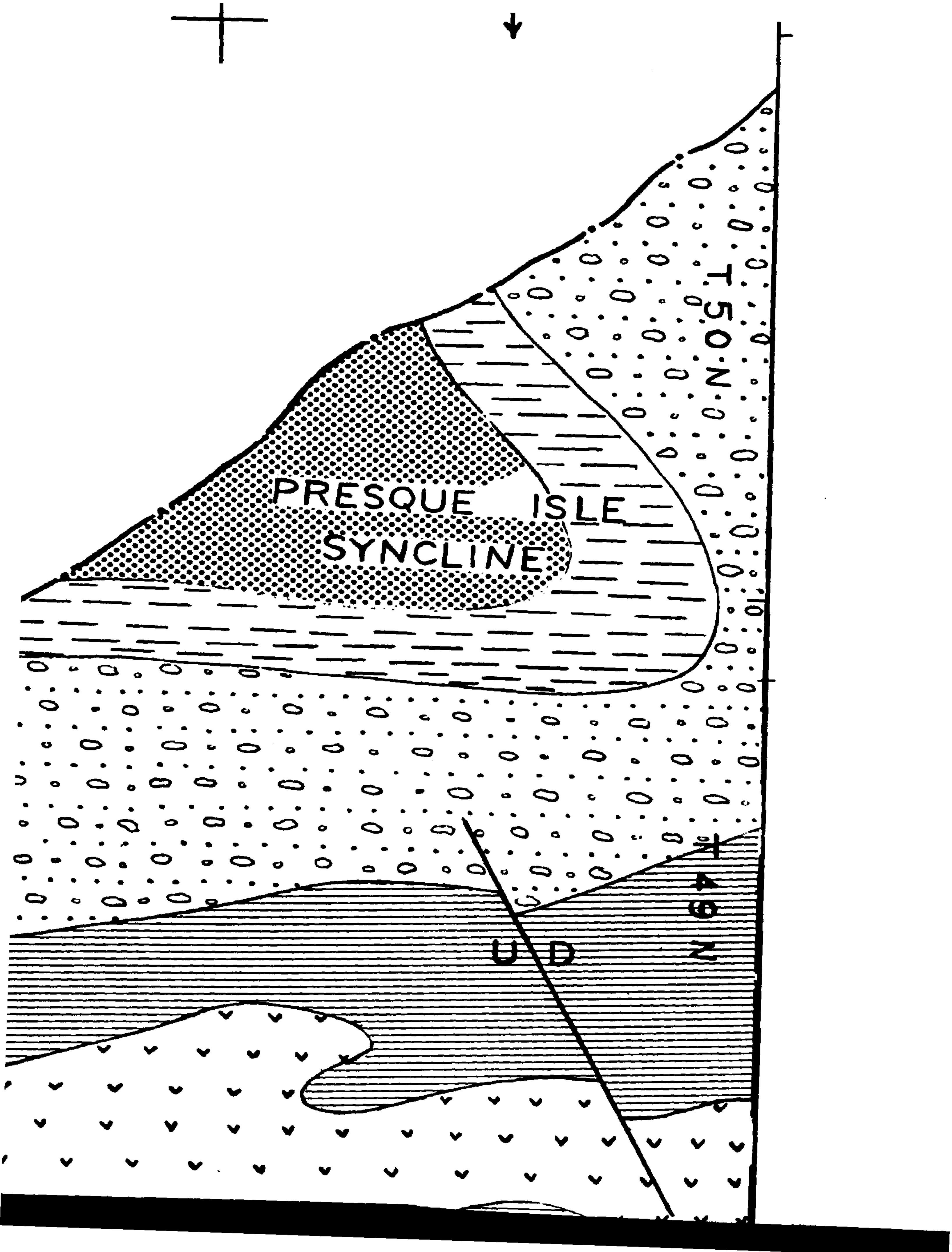



45'
T 50 N
0'
T 49 N


LAKE

SUPERIOR



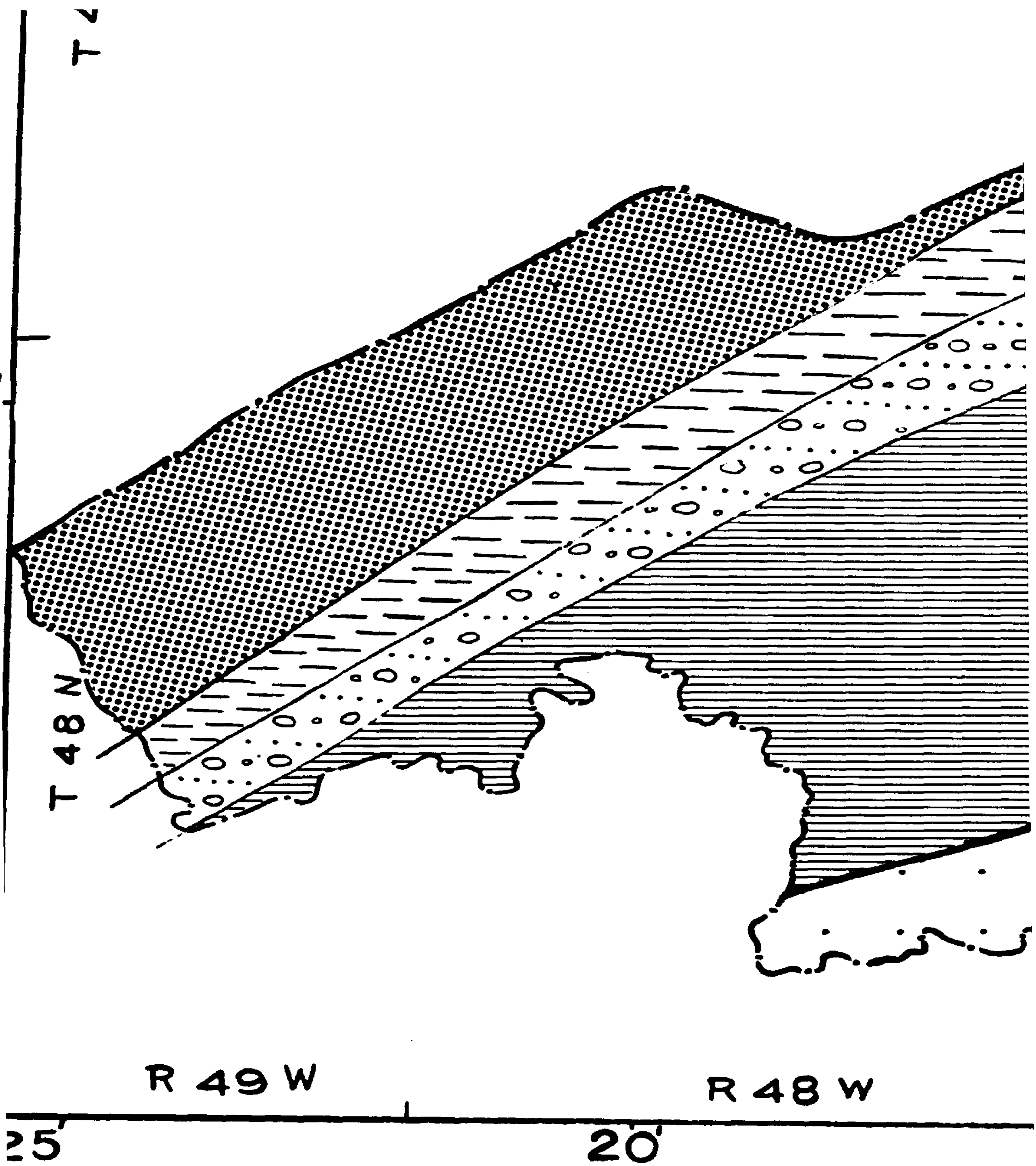


PRESQUE ISLE
SYNCLINE
T 50 N
T 49 N
U
D

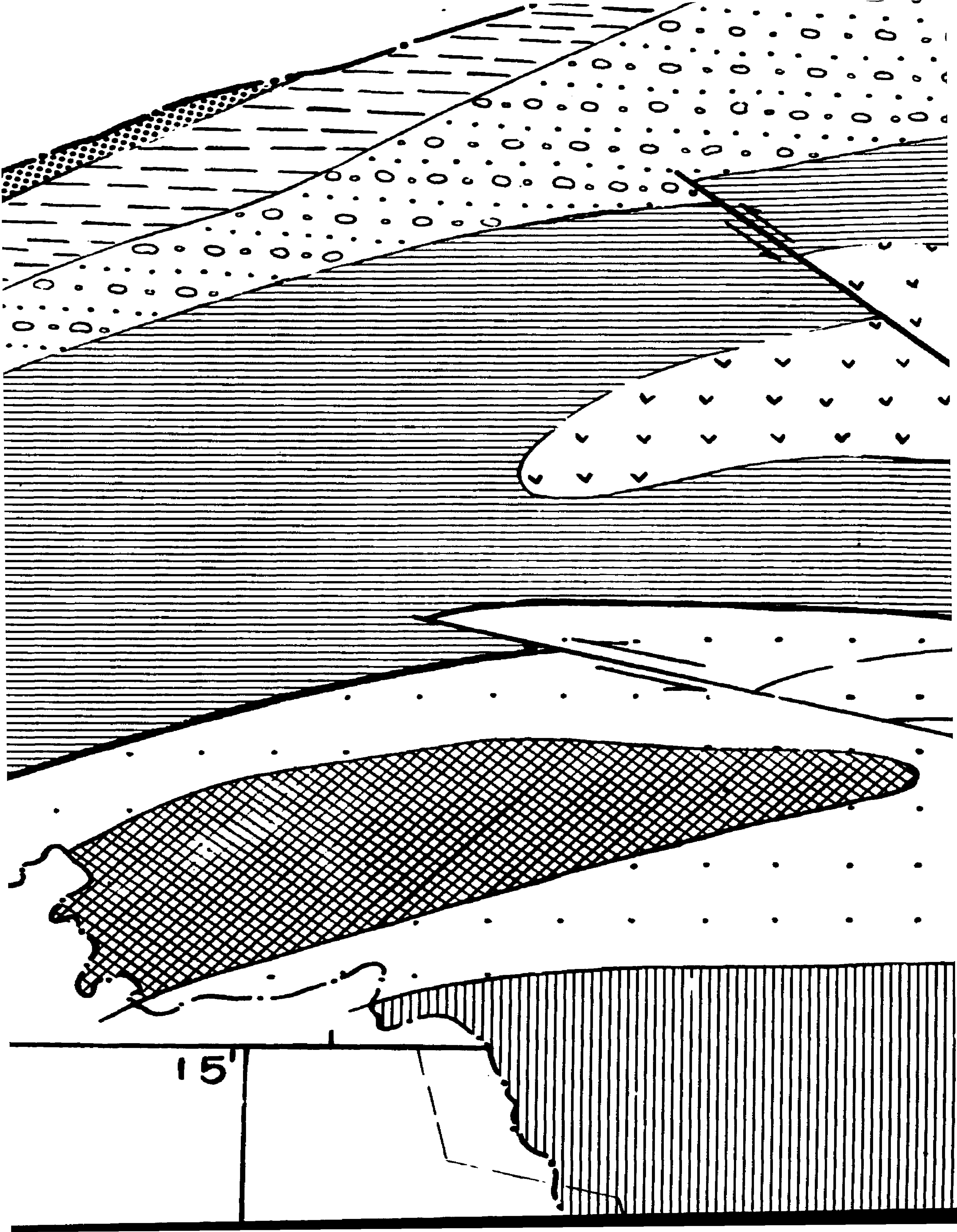
35'

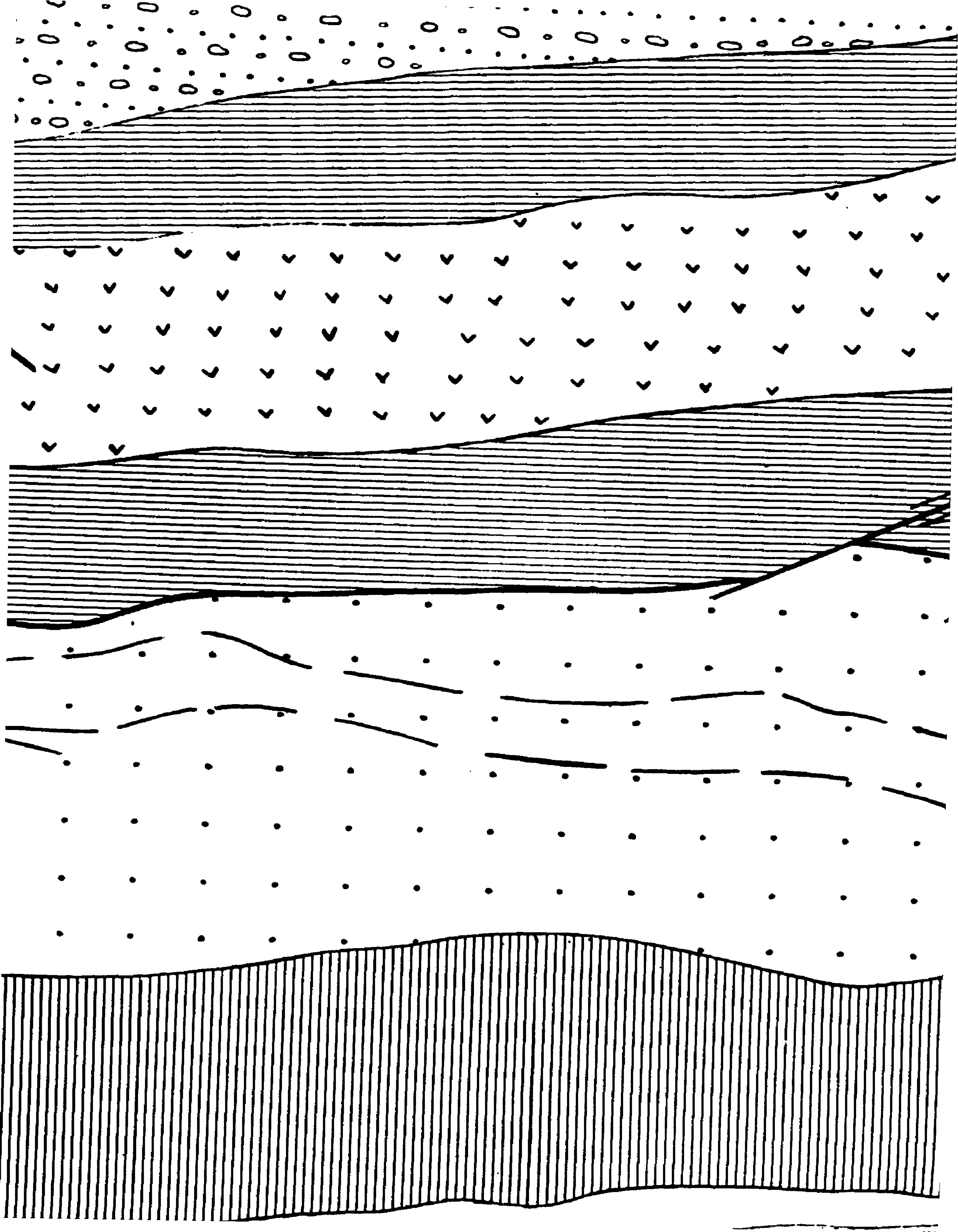
46°30'
90°2

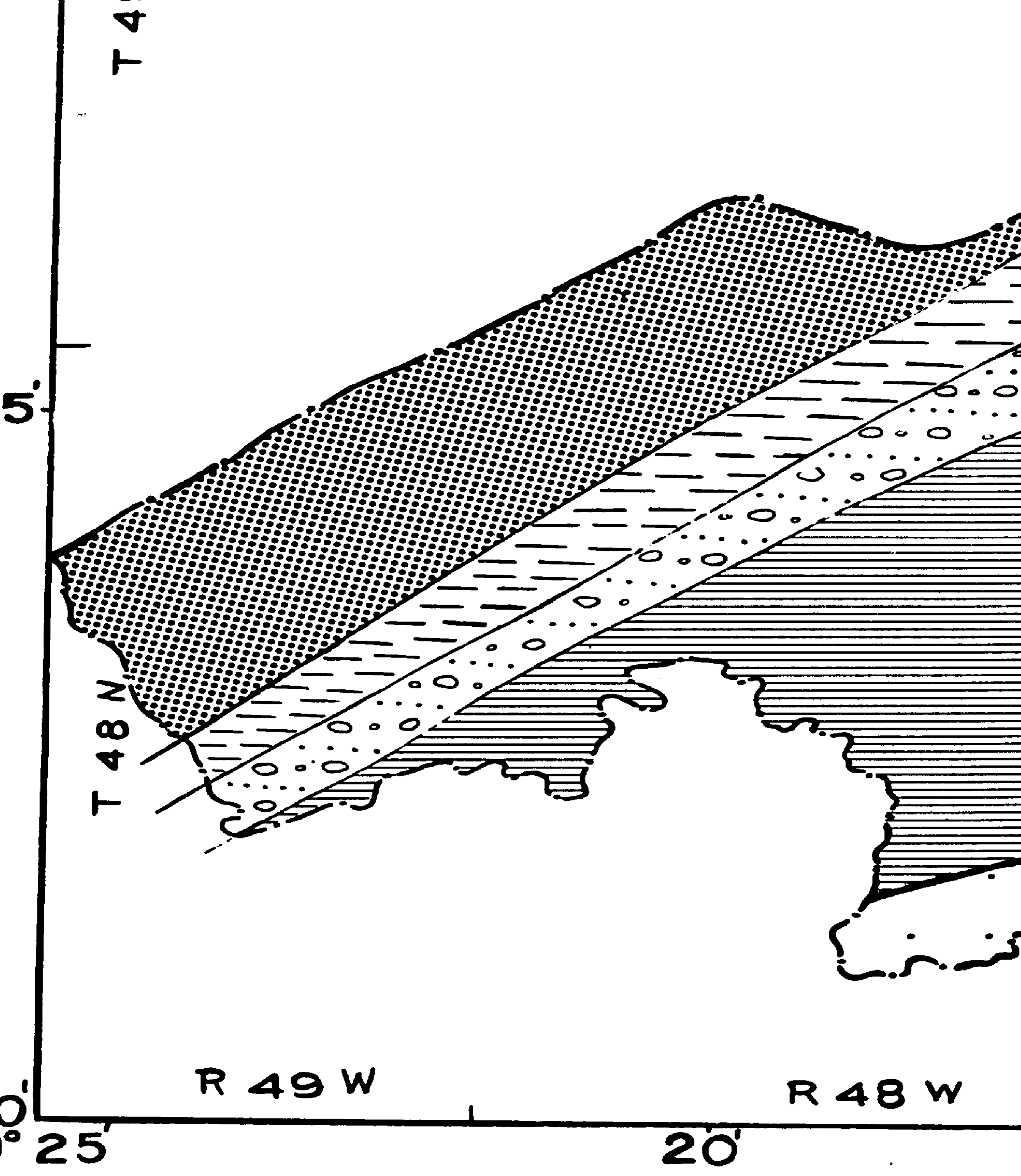
GE



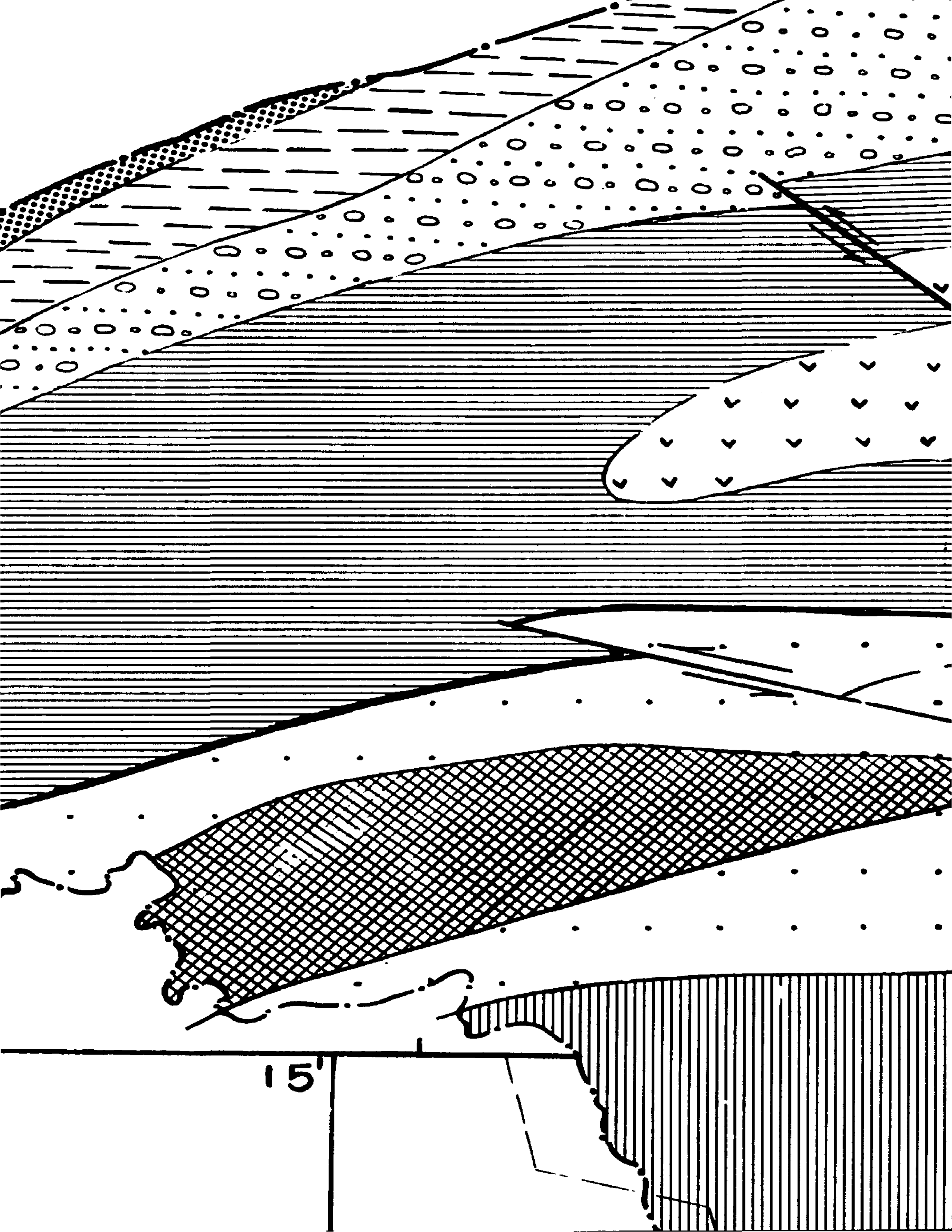
EOLOGIC COLUMN

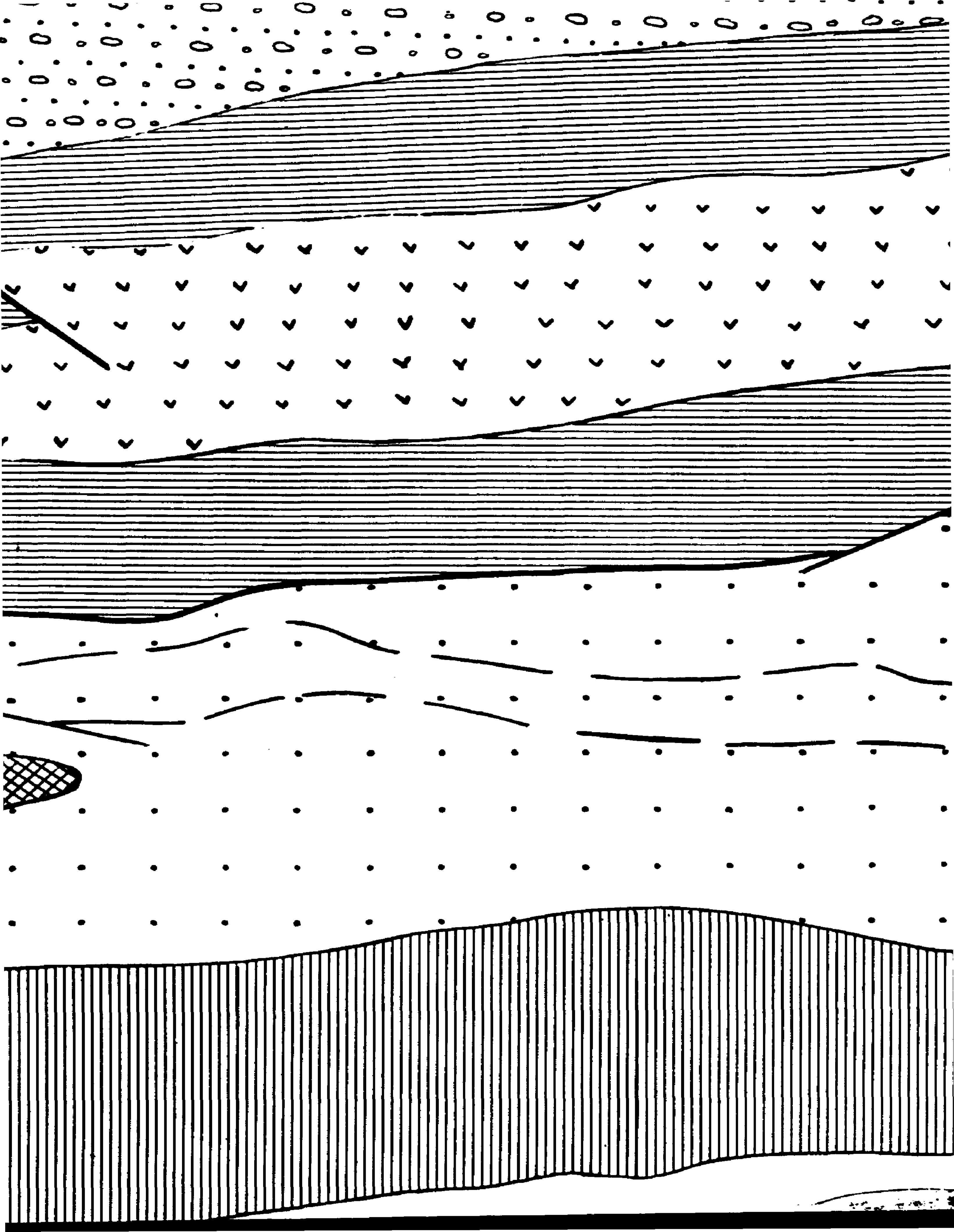

15'

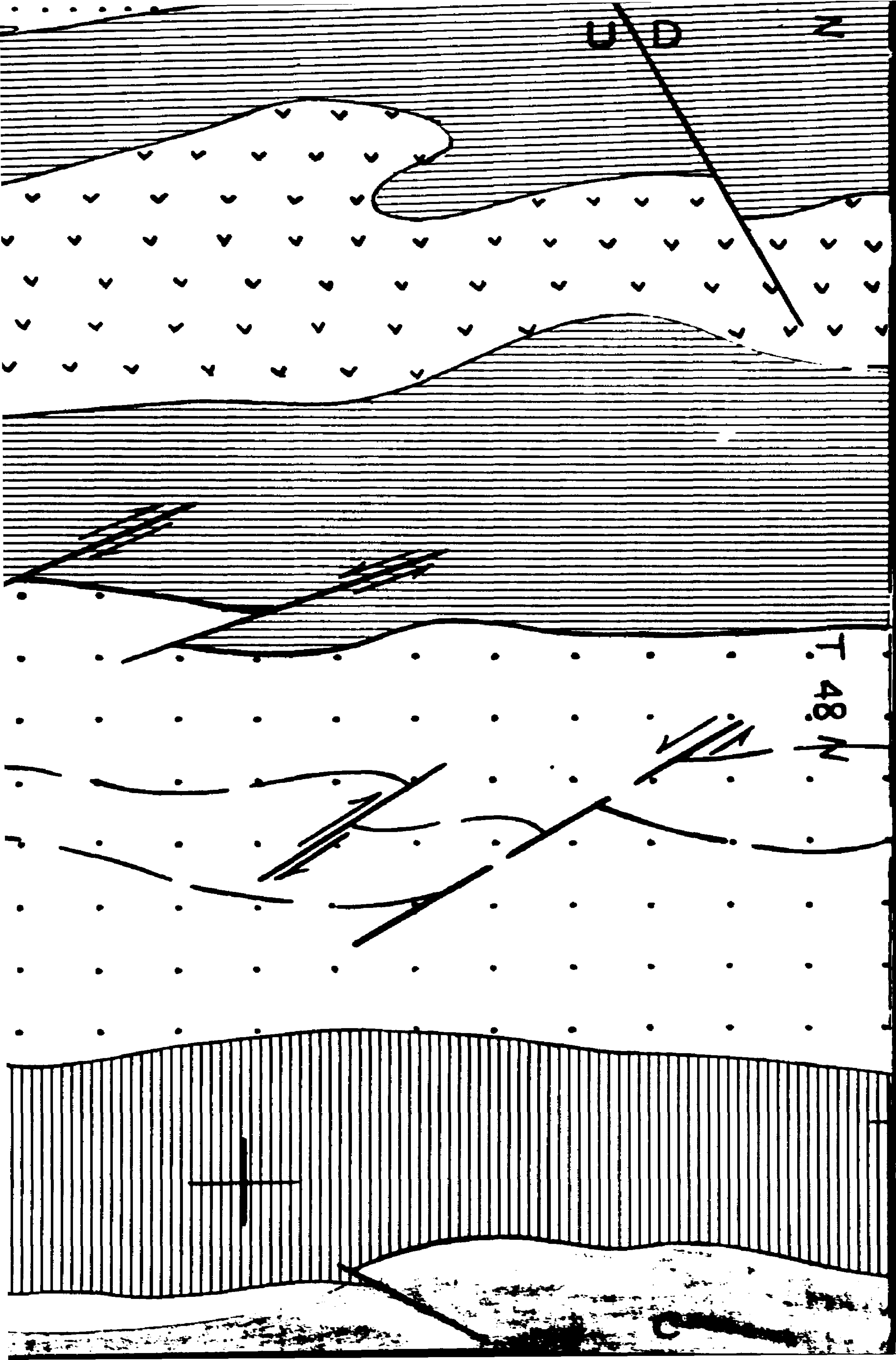


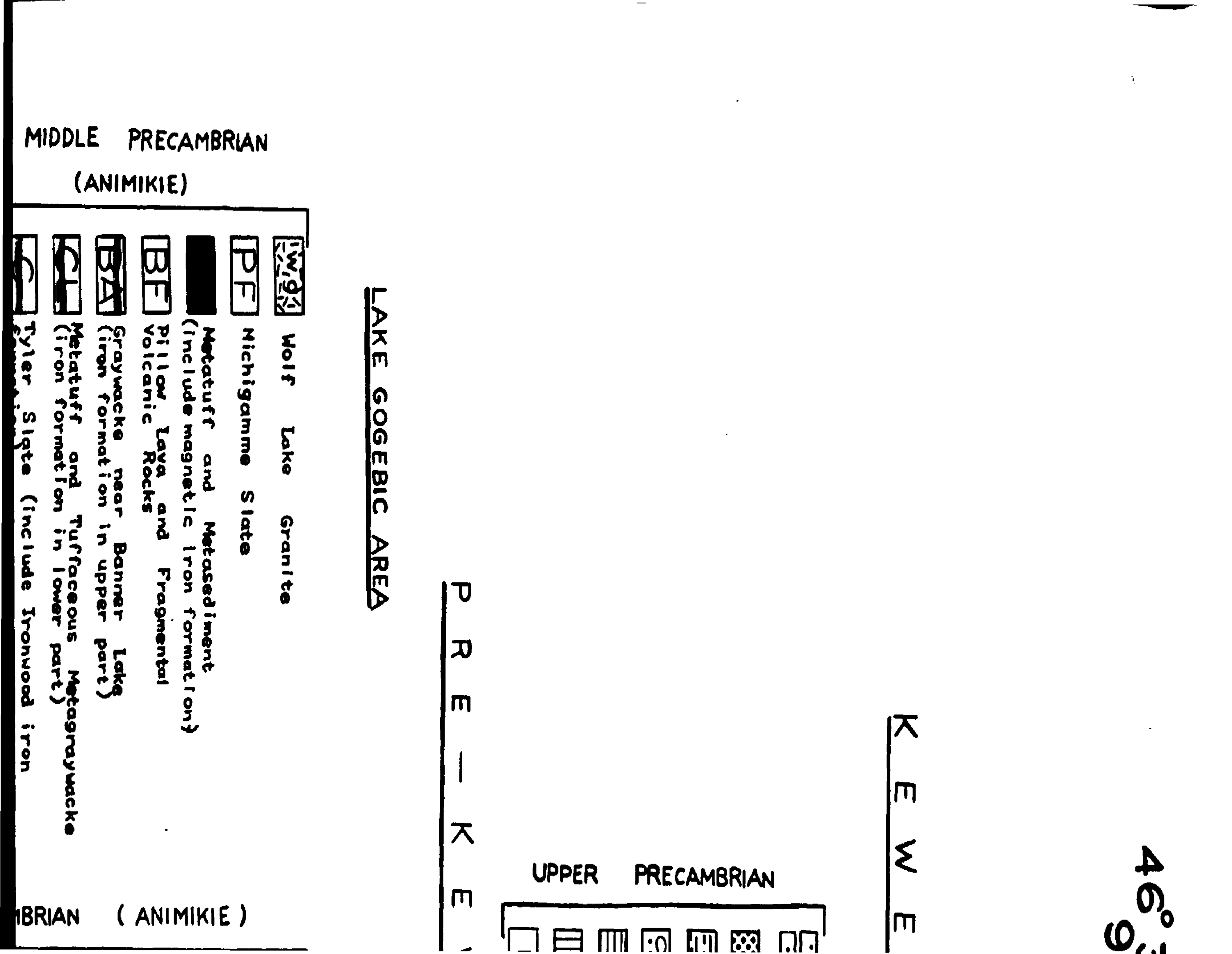


GEOLOGIC COLUMN


15'




U D
T 48 N


MIDDLE PRECAMBRIAN
(ANIMIKIE)
WG
Wolf Lake Granite
PF
Nichigamme Slate
Metatuff and Metasediment (include magnetic iron formation)
BF
Pillow Lava and Fragmental Volcanic Rocks
BA
Graywacke near Banner Lake (iron formation in upper part)
CL
Metatuff and Tuffaceous Metagraywacke (iron formation in lower part)
Tyler Slate (include Ironwood iron
LAKE GOGEBIC AREA
PRE-KE
KEWE
UPPER PRECAMBRIAN
BRIAN (ANIMIKIE)
46°

30' R 49 W R 48 W

90° 25' 20'

GEOLOGIC COLUMN

ENAWAN ROCKS

Jacobsville Sandstone

Freda Sandstone

Nonesuch Shale

Copper Harbor Sandstone and Conglomerate

Portage Lake Lava Series

South Trap Range Lavas

KS Quartzitic Sandstone

Rhyolite and Felsitic

Diabase Dikes

WEENAWAN ROCKS

IRON RIVER - CRYSTAL FALLS and AMASA OVAL AR

GD Fine-grained Greenstone

Metagabbro and Metadiabase

PAINT RIVER GROUP

FS Fortune Lake Slate

PS Stambaugh Formation

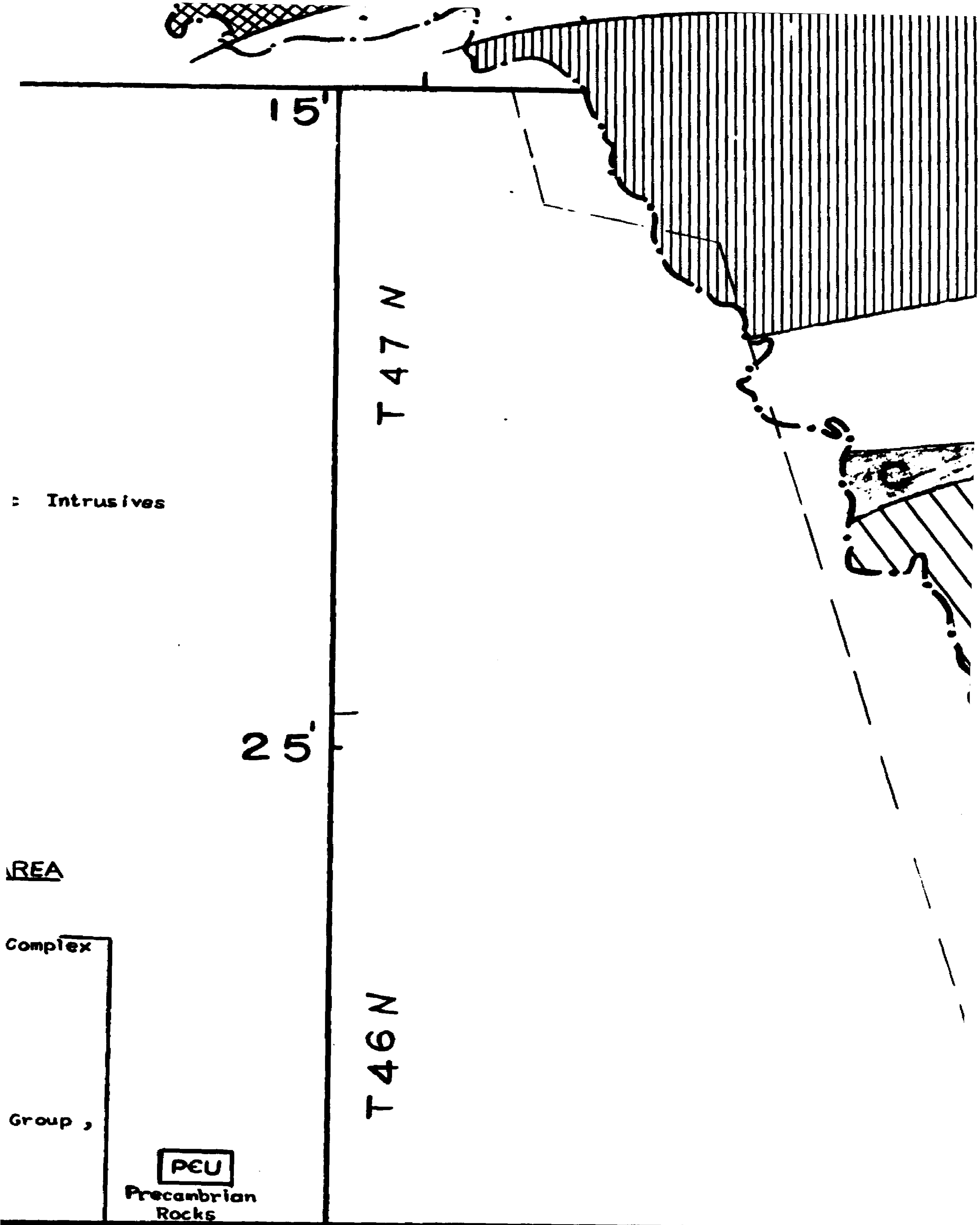
PH Hiawatha Graywacke

PR Riverton Iron Formation

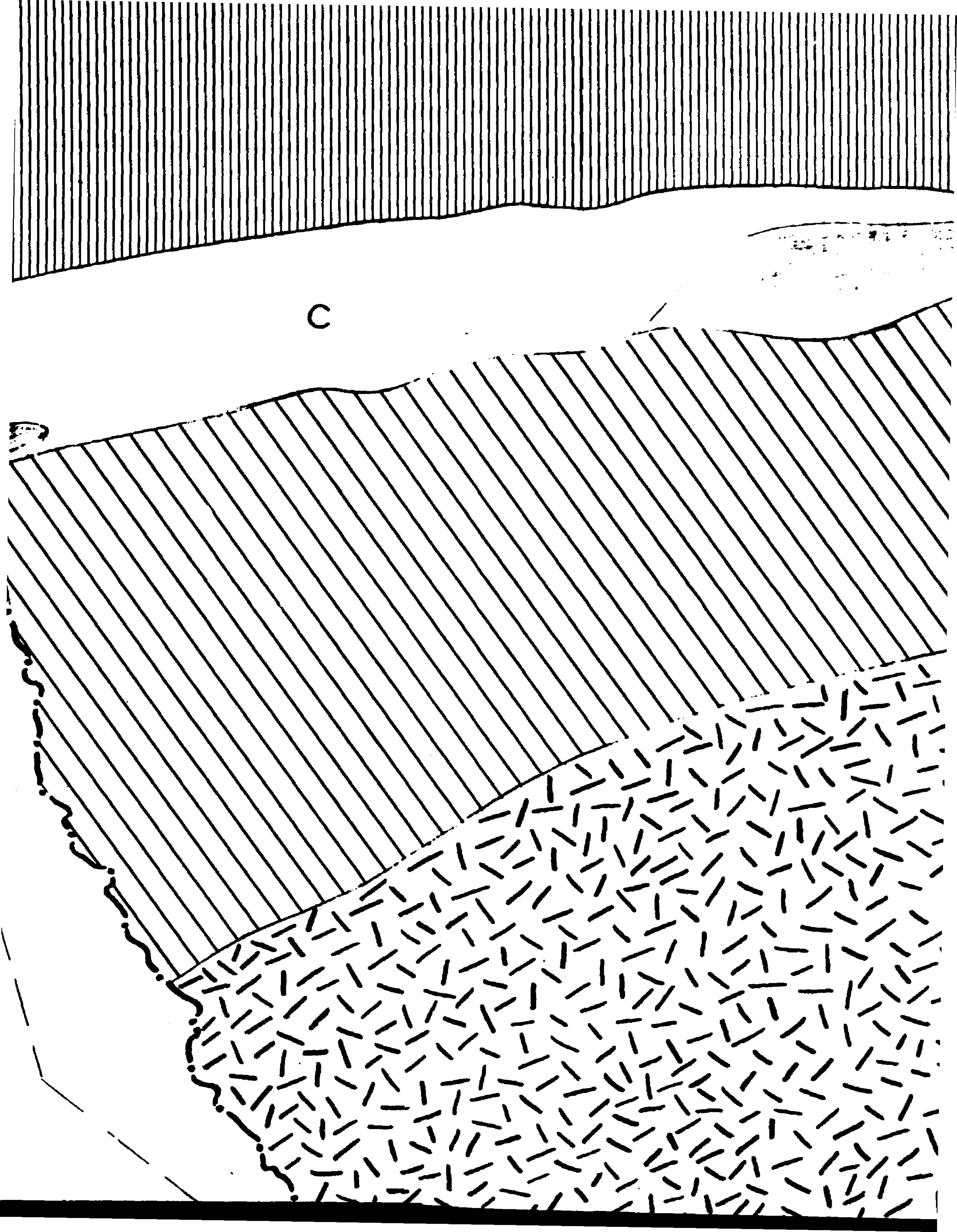
PD Dun Creek Slate

PPC Peavy Pond Co

PU Paint River G undivided



15'
T 47 N
: Intrusives
25'
REA
Complex
T 46 N
Group ,
PЄU
Precambrian
Rocks


C

R 49 W

R 4

46° 30'
90° 25'

20'

GEOLOGIC COLUMN

W E E N A W A N   R O C K S

UPPER PRECAMBRIAN

- Jacobsville Sandstone
- Freda Sandstone
- Nonesuch Shale
- Copper Harbor Sandstone and Conglomerate
- Portage Lake Lava Series
- South Trap Range Lavas
- KS Quartzitic Sandstone

- Rhyolite ar
- Diabase Dik

E W E E N A W A N   R O C K S

IRON RIVER - CRYSTAL FALLS and AMASA

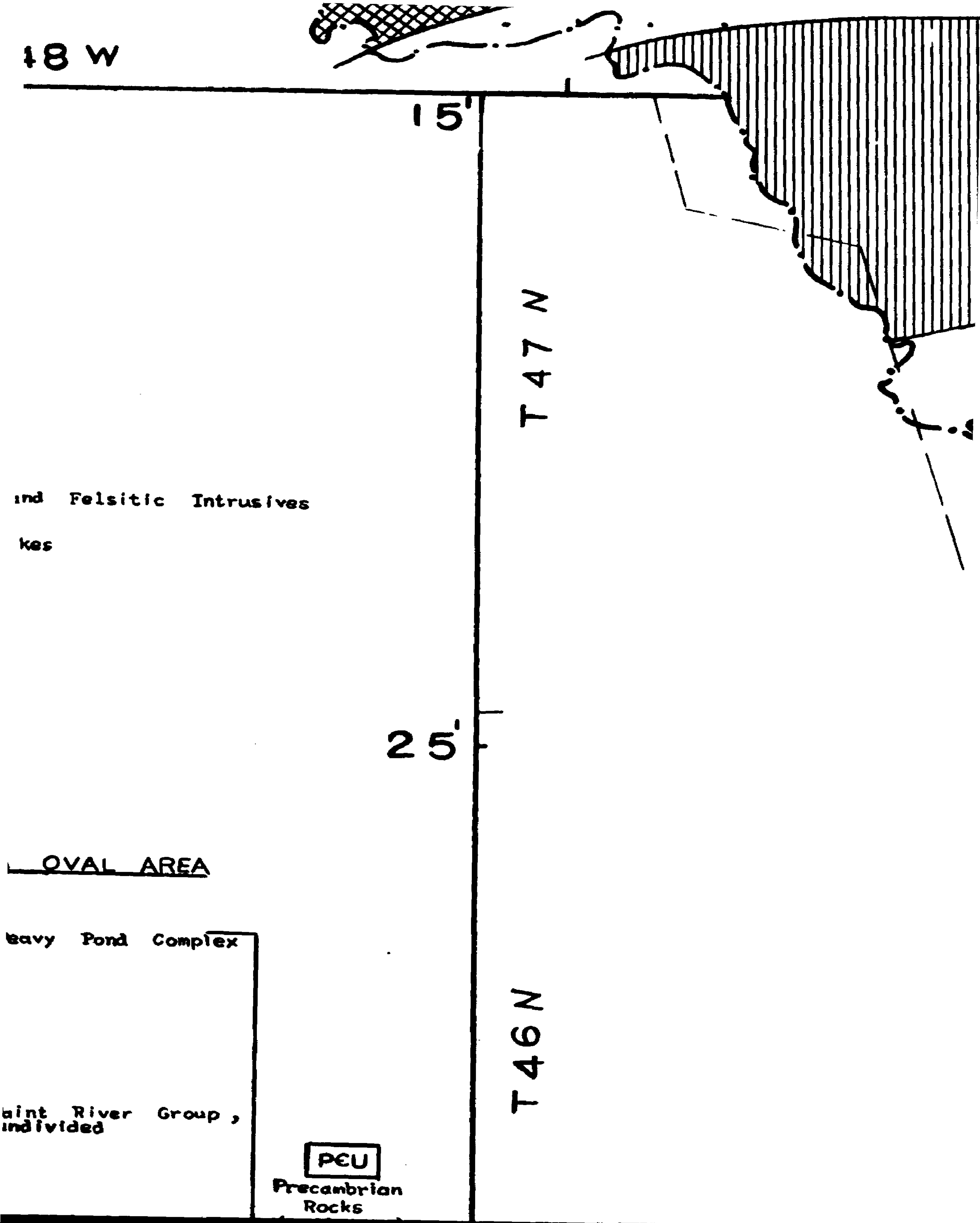
BRIAN (ANIMIKIE)

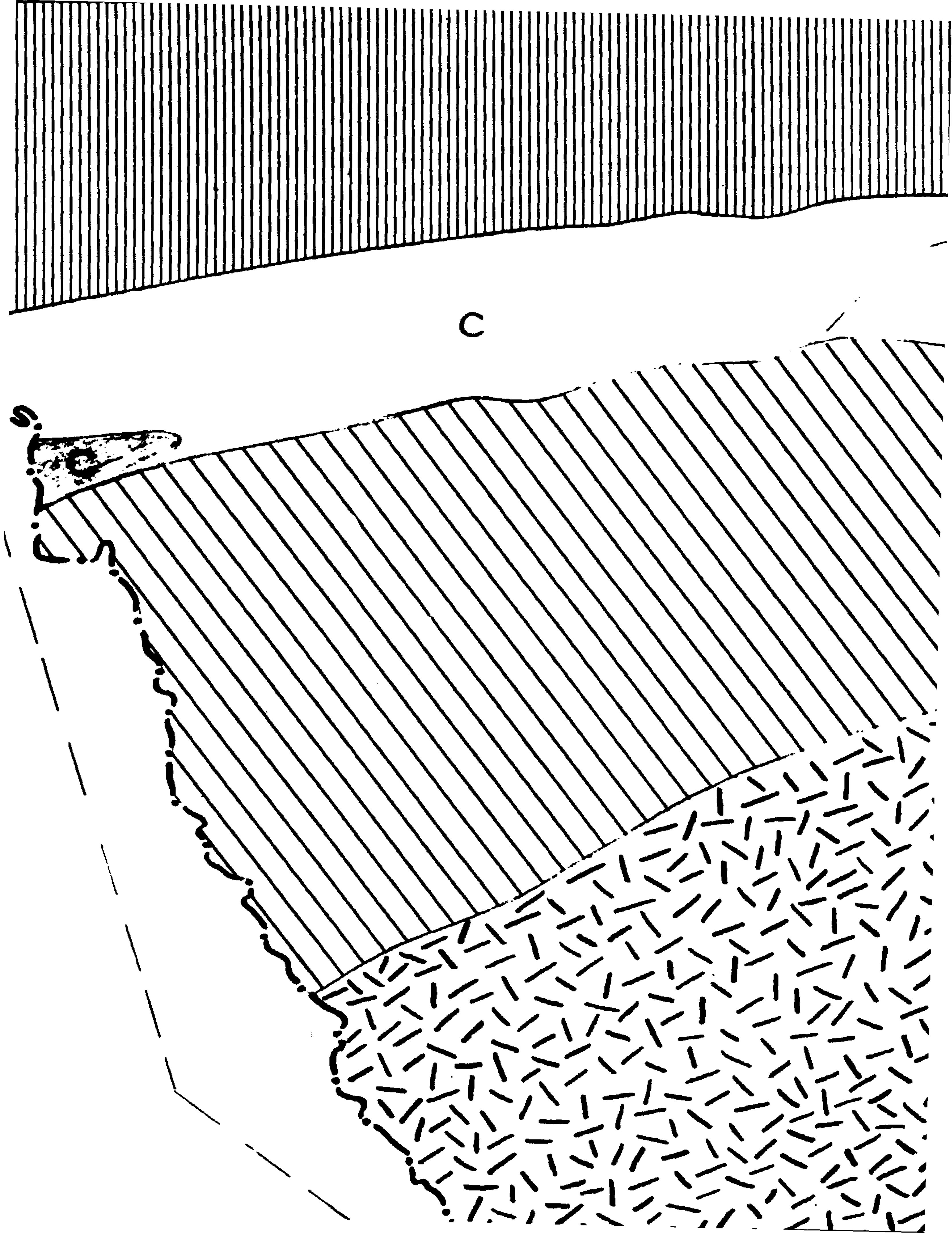
- GD Fine-grained Greenstone
- Metagabbro and Metadiabase

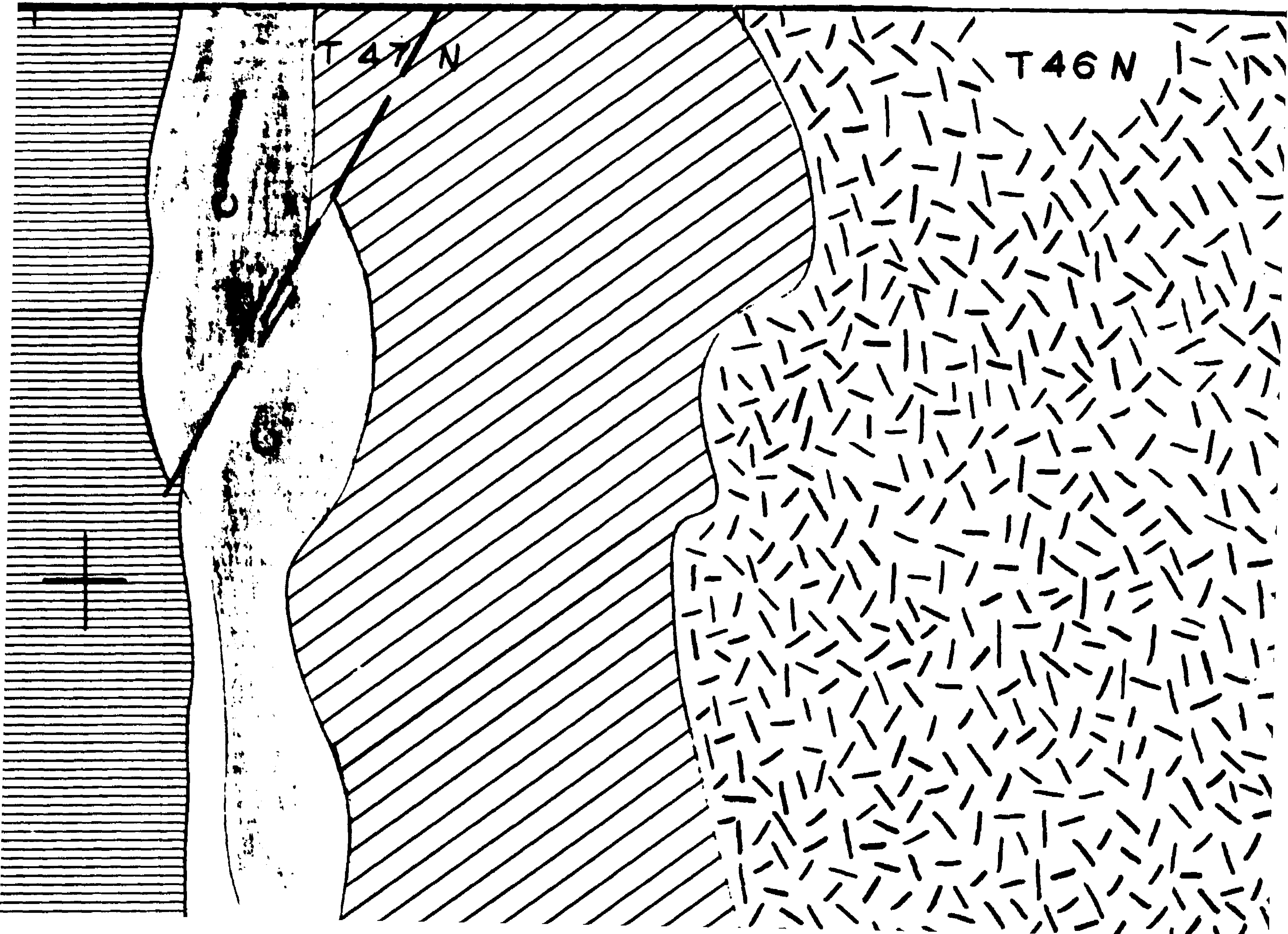
PAINT RIVER GROUP

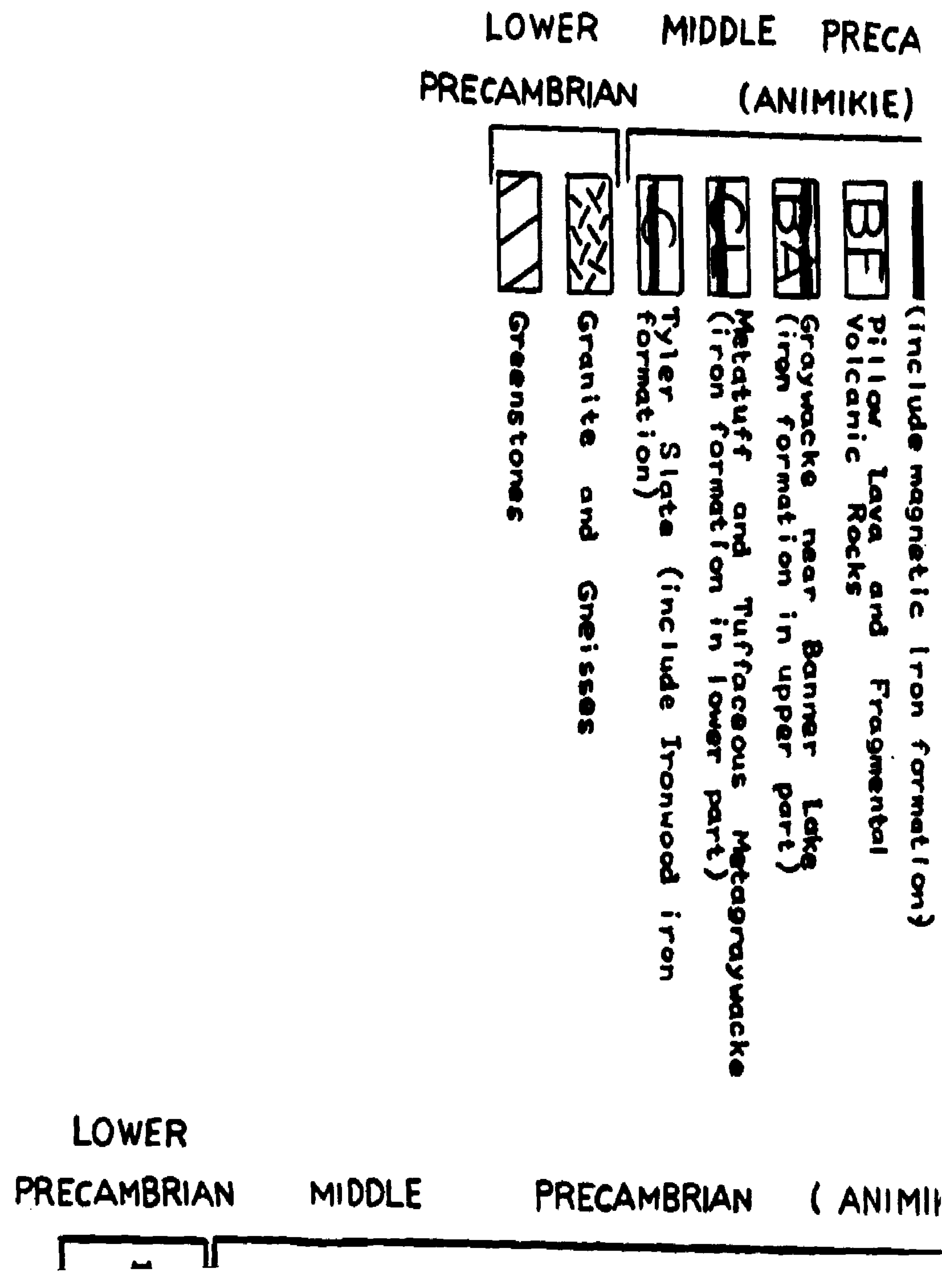
- FS Fortune Lake Slate
- PS Stambaugh Formation
- PH Hiawatha Graywacke
- PR Riverton Iron Formation
- PD Dun Creek Slate

- PPC Pe
- PU Pa un


48 W
15'
T 47 N
ınd Felsitic Intrusives
kes
25'
OVAL AREA
eavy Pond Complex
aint River Group ,
ındivided
T46N
PЄU
Precambrian
Rocks


C
S
C


T 47 N
T 46 N


LOWER PRECAMBRIAN
MIDDLE PRECA
(ANIMIKIE)
Greenstones
Granite and Gneisses
Tyler Slate (include Ironwood iron formation)
Metatuff and Tuffaceous Metagraywacke (iron formation in lower part)
BA
Graywacke near Banner Lake (iron formation in upper part)
BF
Pillow Lava and Fragmental Volcanic Rocks
(include magnetic iron formation)
LOWER PRECAMBRIAN
MIDDLE PRECAMBRIAN
(ANIMIK

PAINT RIVER GROUP

- FS Fortune Lake Slate
- PS Stambaugh Formation
- PH Hiawatha Graywacke
- PR Riverton Iron Formation
- PD Dun Creek Slate

PU Paint River undivided

BARAGA GROUP

- BB Badwater Greenstone
- PF Michigamme Slate
- B Amasa Formation
- BH Hemlock Formation
- BG Goodrich Quartzite`

FR Fence River F

CHOCOLAY GROUP

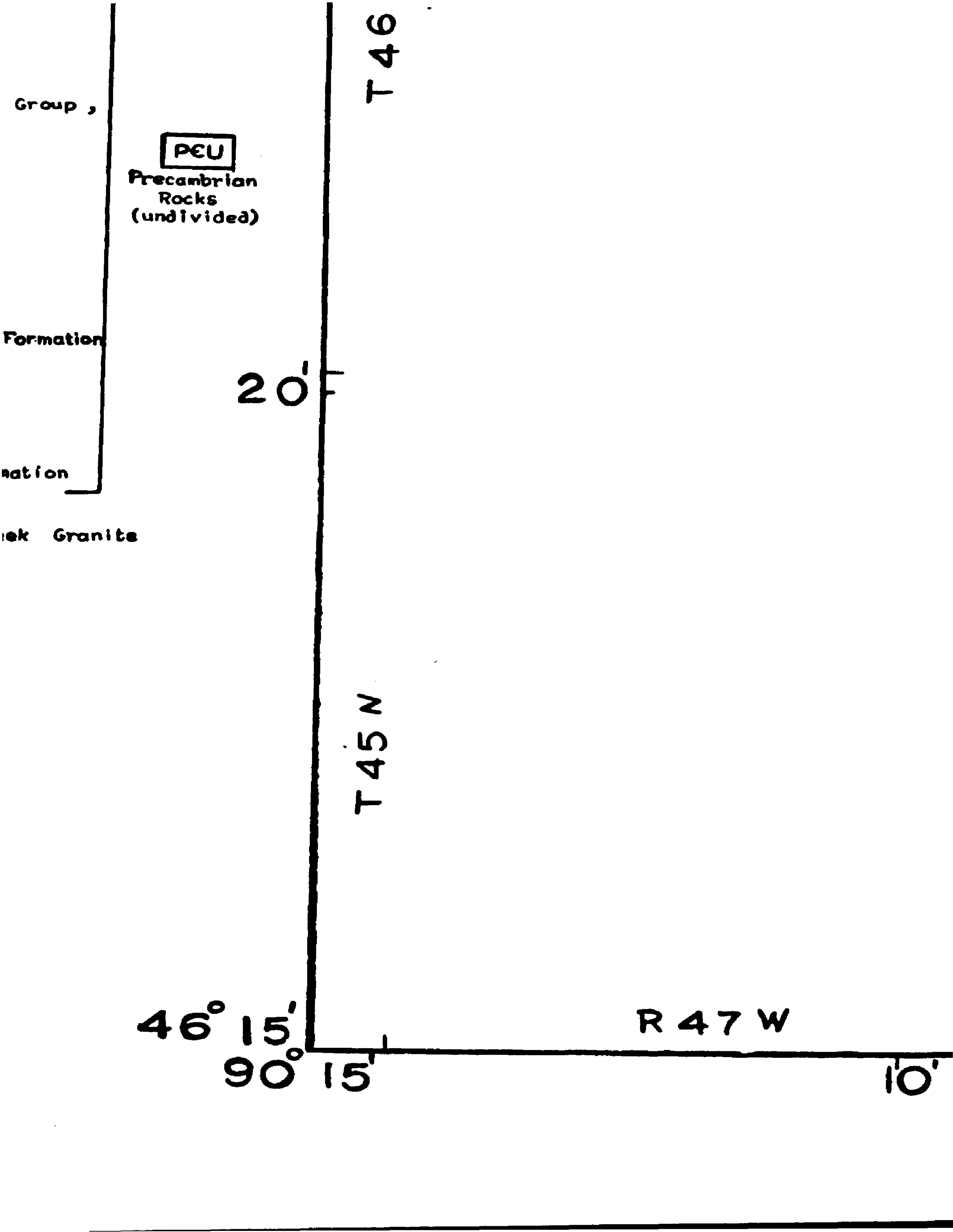
- CR Randville Dolomite

CSA Saunders Forma

DICKINSON GROUP

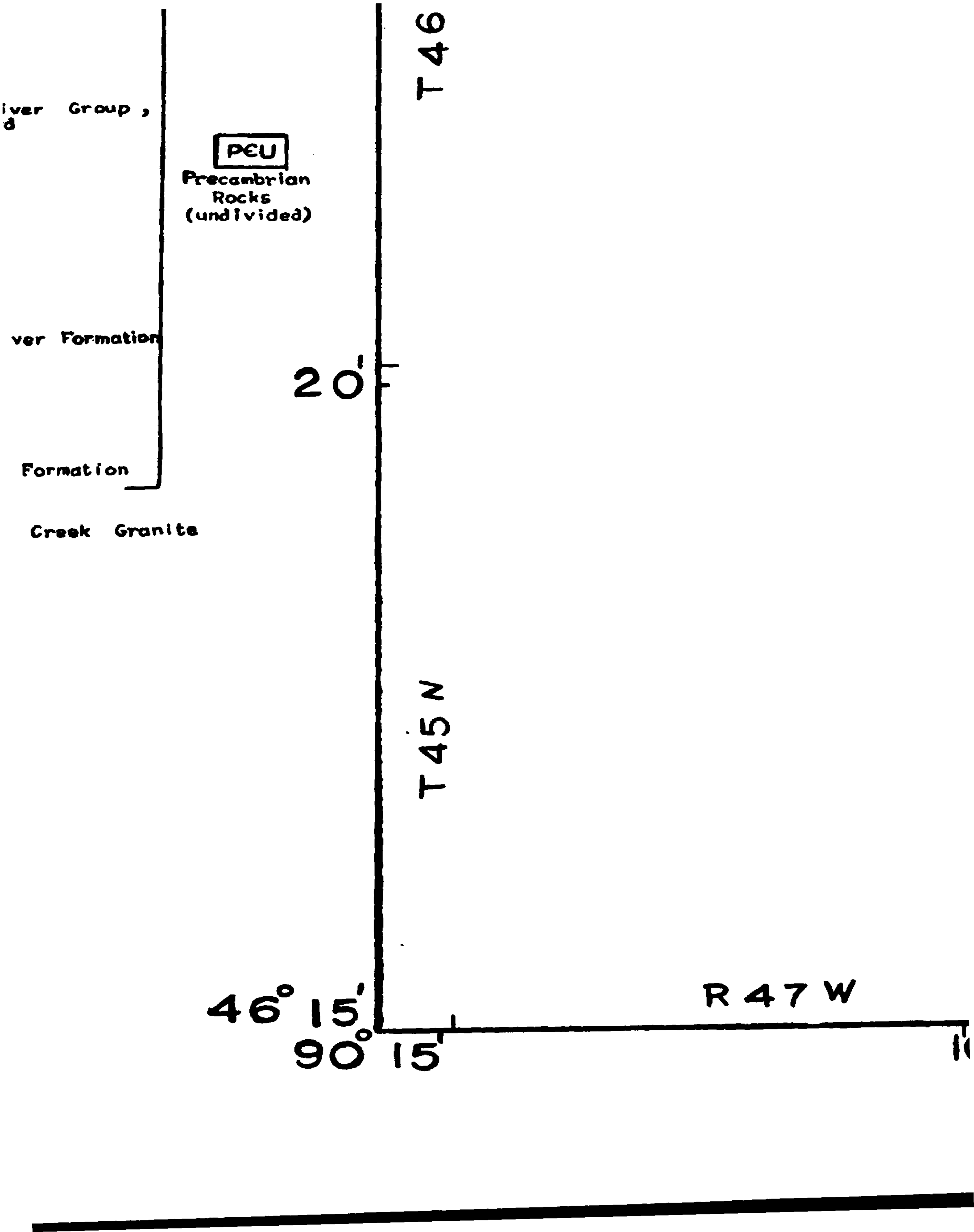
- DU Dickinson Group , undivided
- GS Greenstone along Brule River

Margenson Cree


Group ,
PЄU
Precambrian Rocks (undivided)
Formation
Granite
T 46
20'
T 45 N
46° 15'
90° 15'
R 47 W
10'

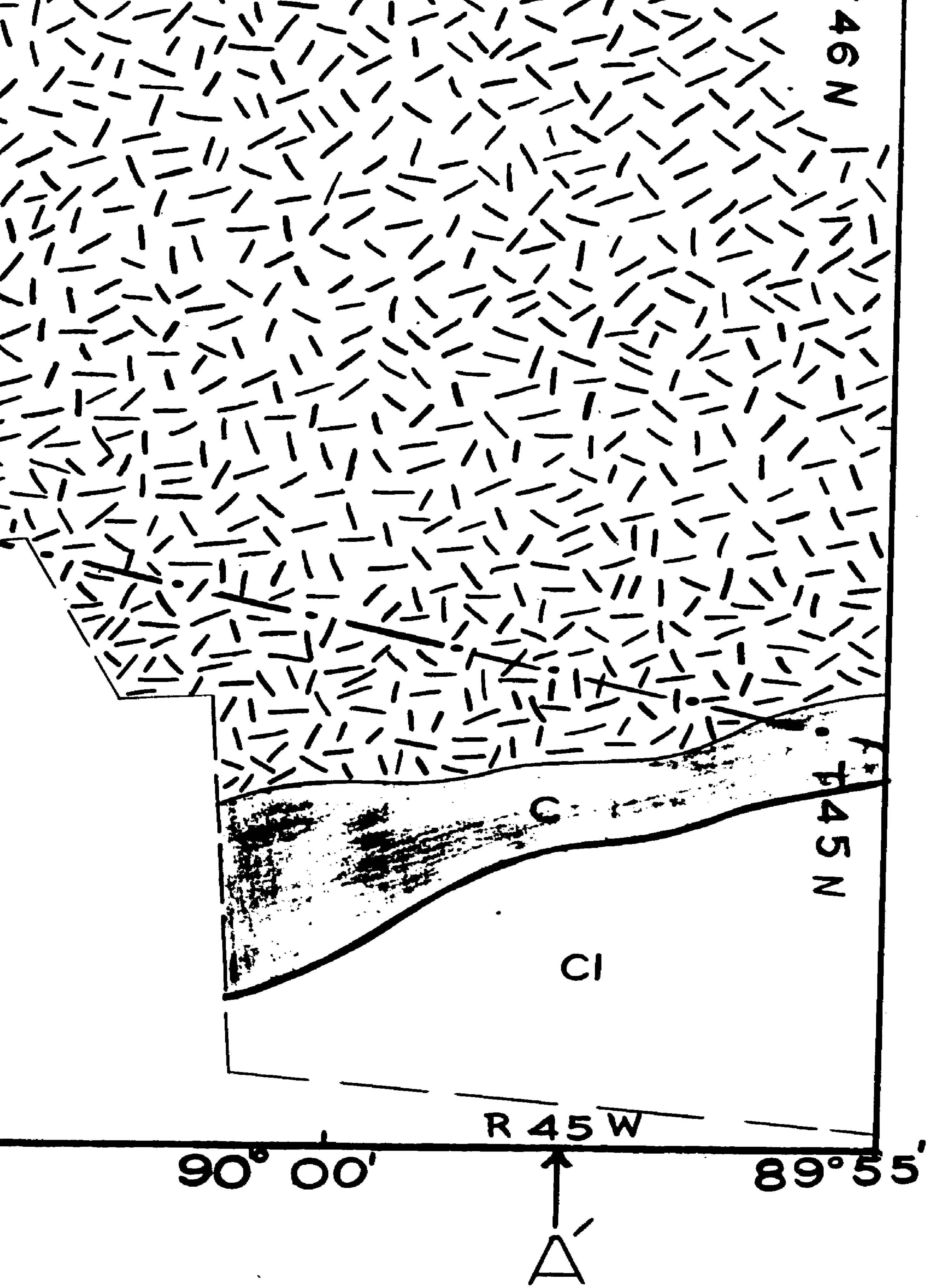

R 46 W
5'

PAINT RIVER GROUP	FS	Fortune Lake Slate		
	PS	Stambaugh Formation		
	PH	Hiawatha Graywacke	PU	Paint Riv undivided
	PR	Riverton Iron Formation		
	PD	Dun Creek Slate		
BARAGA GROUP	BB	Badwater Greenstone		
	PF	Michigamme Slate		
	B	Amasa Formation	FR	Fence Riv
	BH	Hemlock Formation		
	BG	Goodrich Quartzite		
CHOCOLAY GROUP	CR	Randville Dolomite	CSA	Saunders F
DICKINSON GROUP	DU	Dickinson Group, undivided		Margenson
	GS	Greenstone along Brule River		



iver Group ,
d
PЄU
Precambrian
Rocks
(undivided)
ver Formation
Formation
Creek Granite
T 46
20'
T 45 N
46° 15'
90° 15'
R 47 W

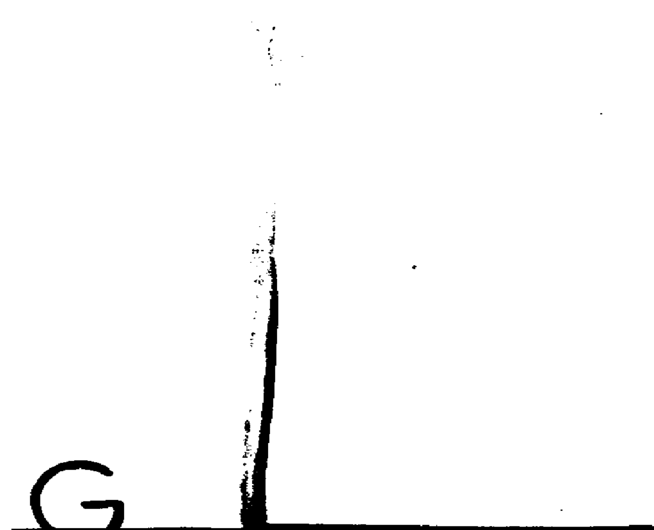
R 46 W
O'
5'

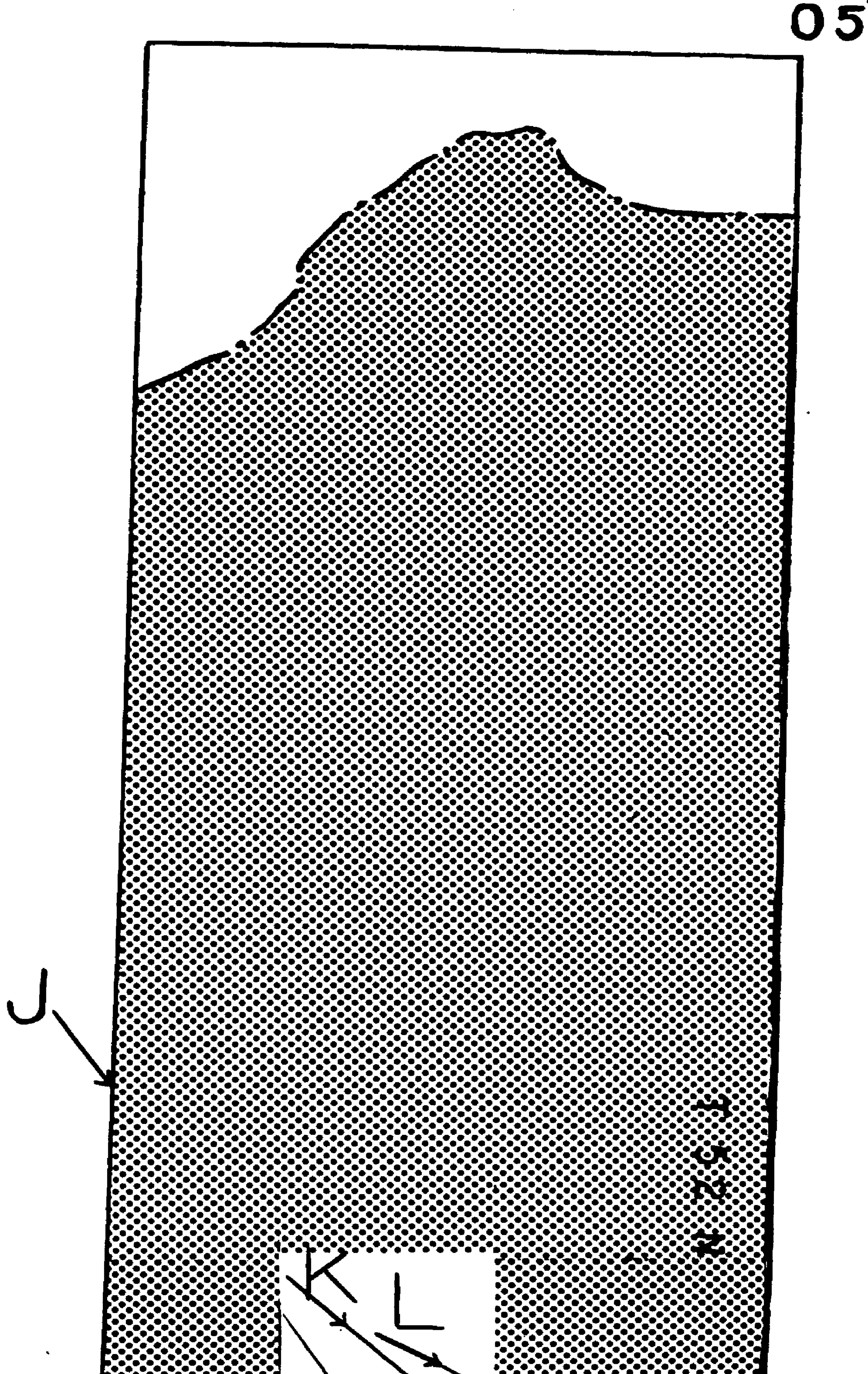


T 46 N
C
T 45 N
Cl
R 45 W
90° 00'
89°55'
A'

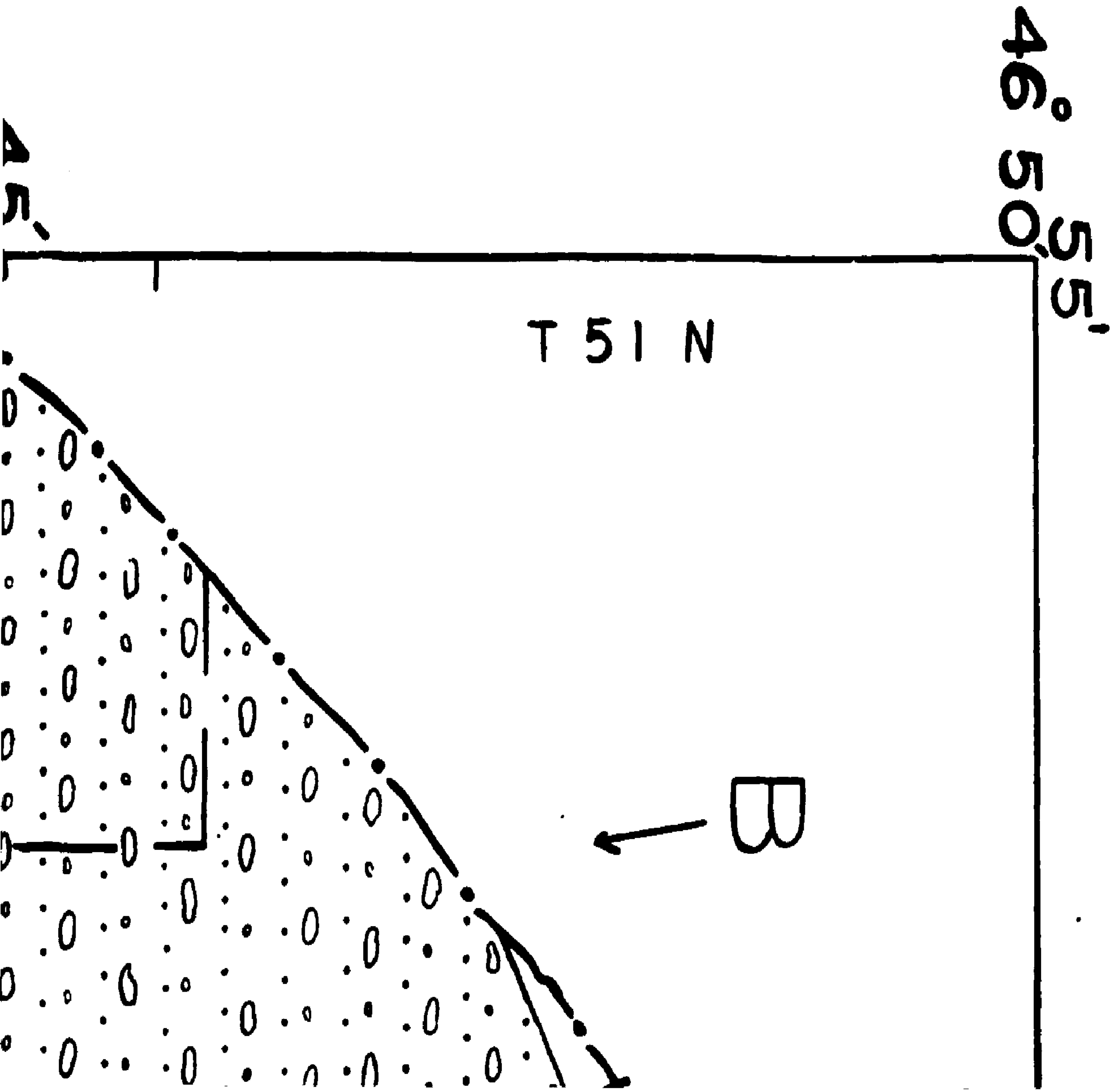
PLATE III-b

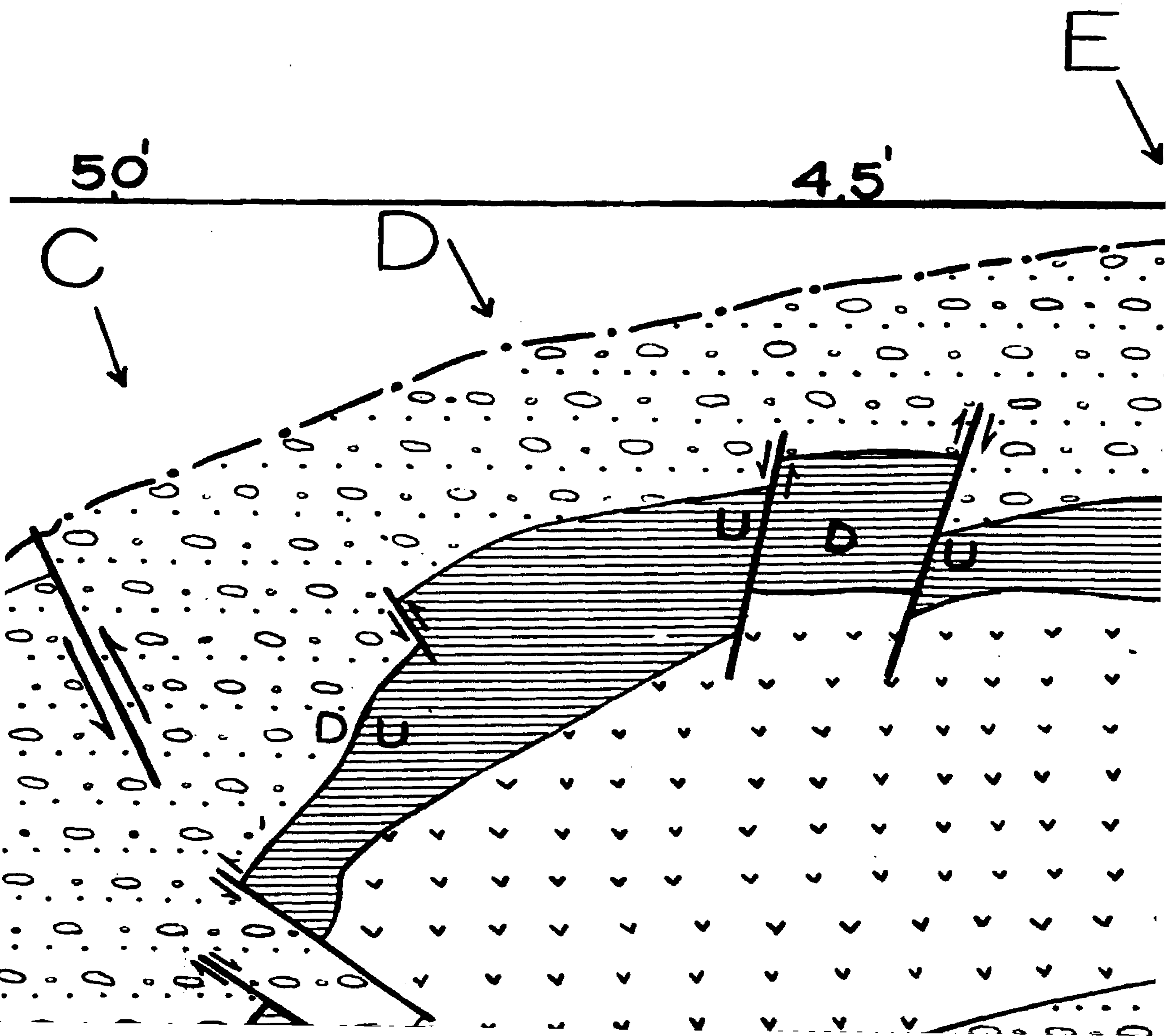
PLATE III-b



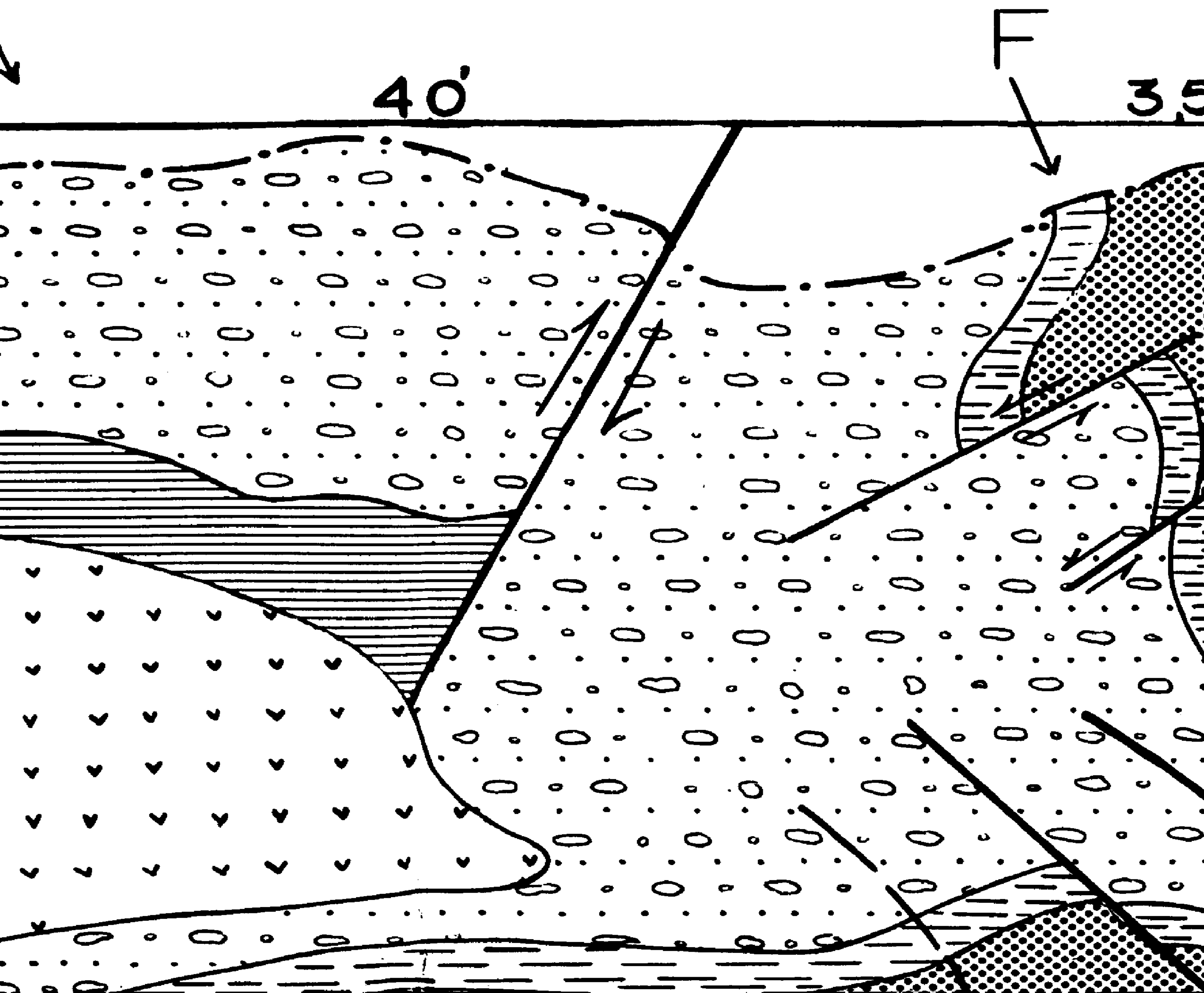


05'
J
K
L
T 52 N


46° 50' 55'
T 51 N
B



E
50'
4.5'
C
D
U
D
U
D
U



F
40'
3,5

PLATE III-b

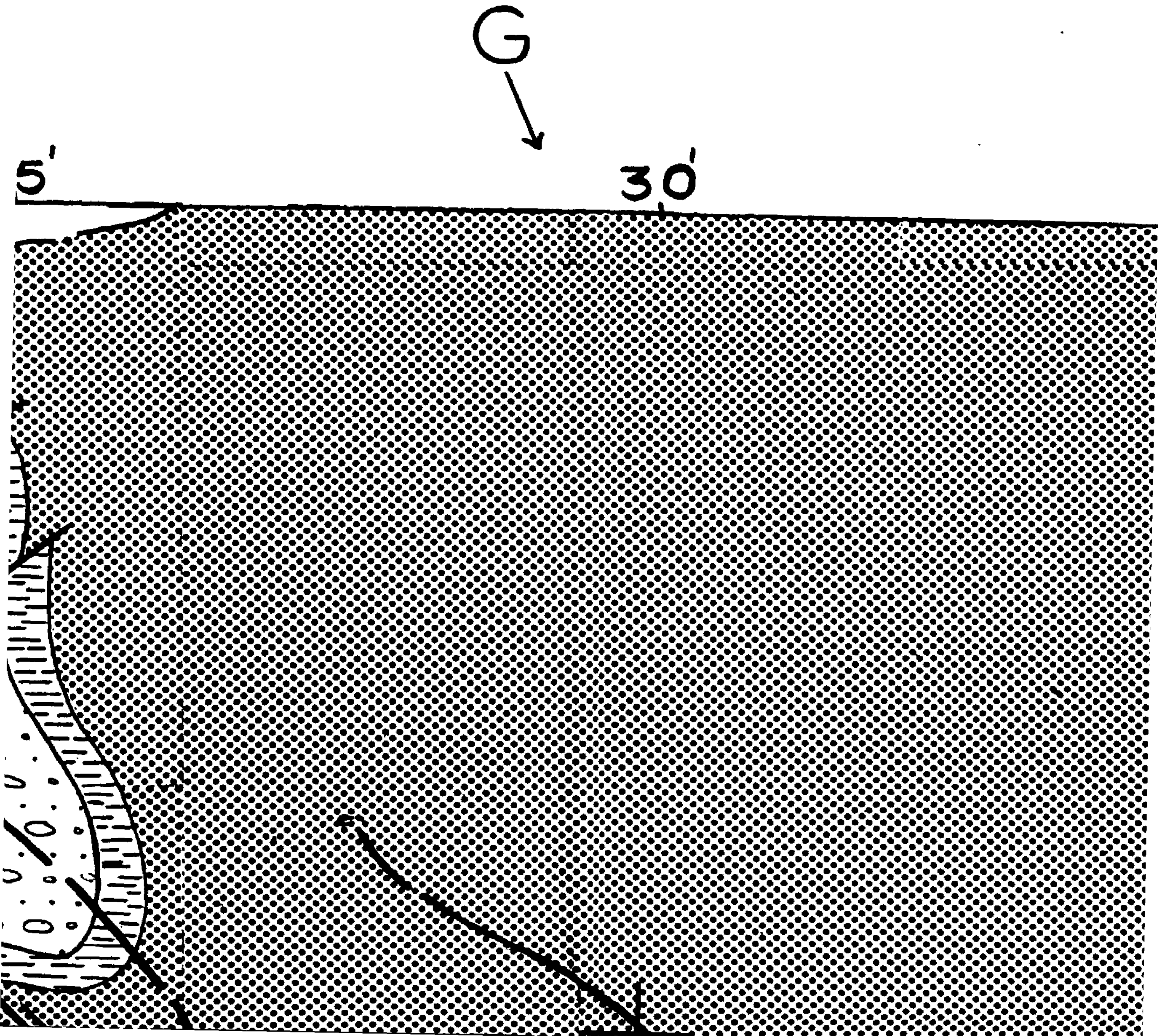
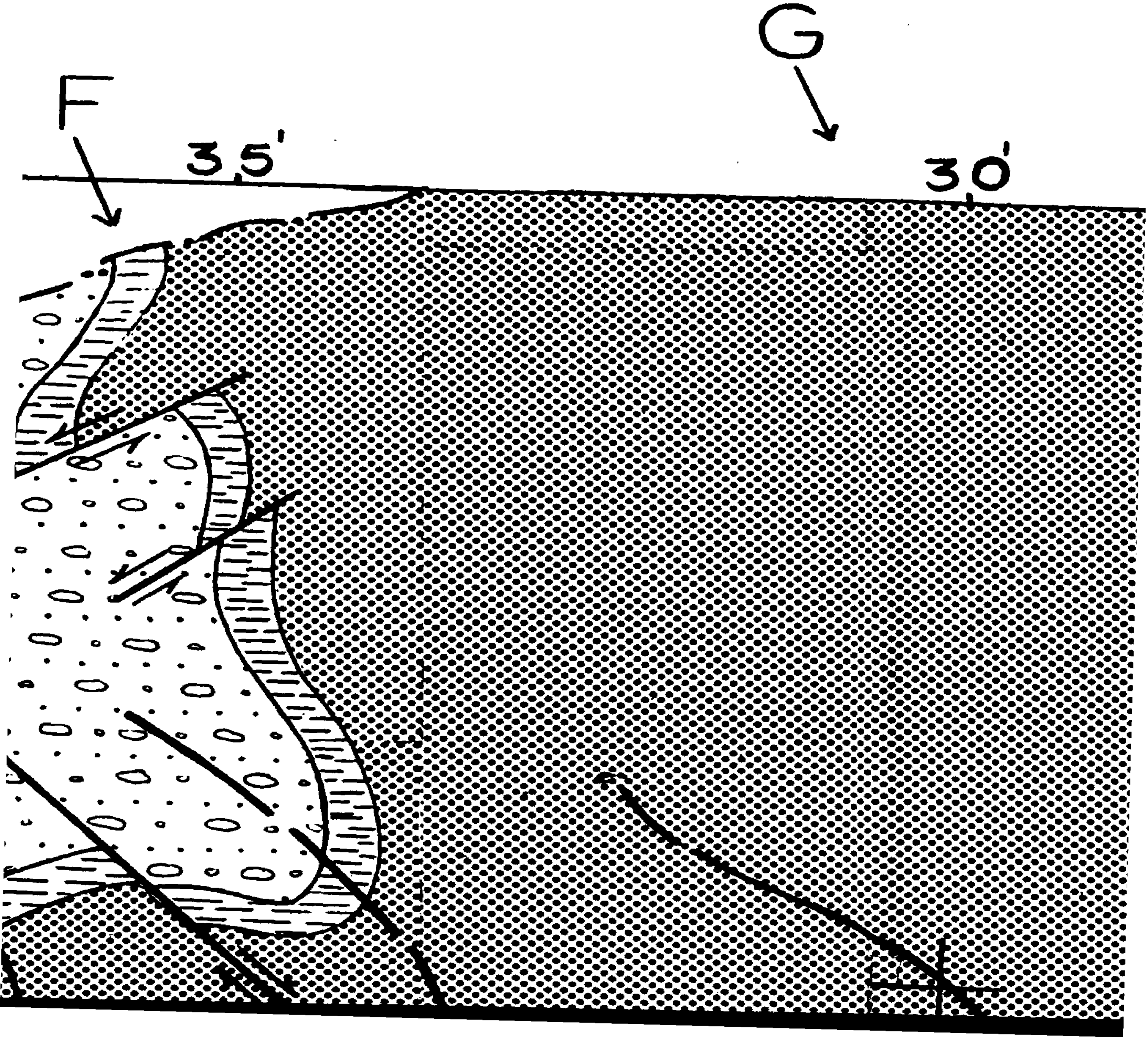
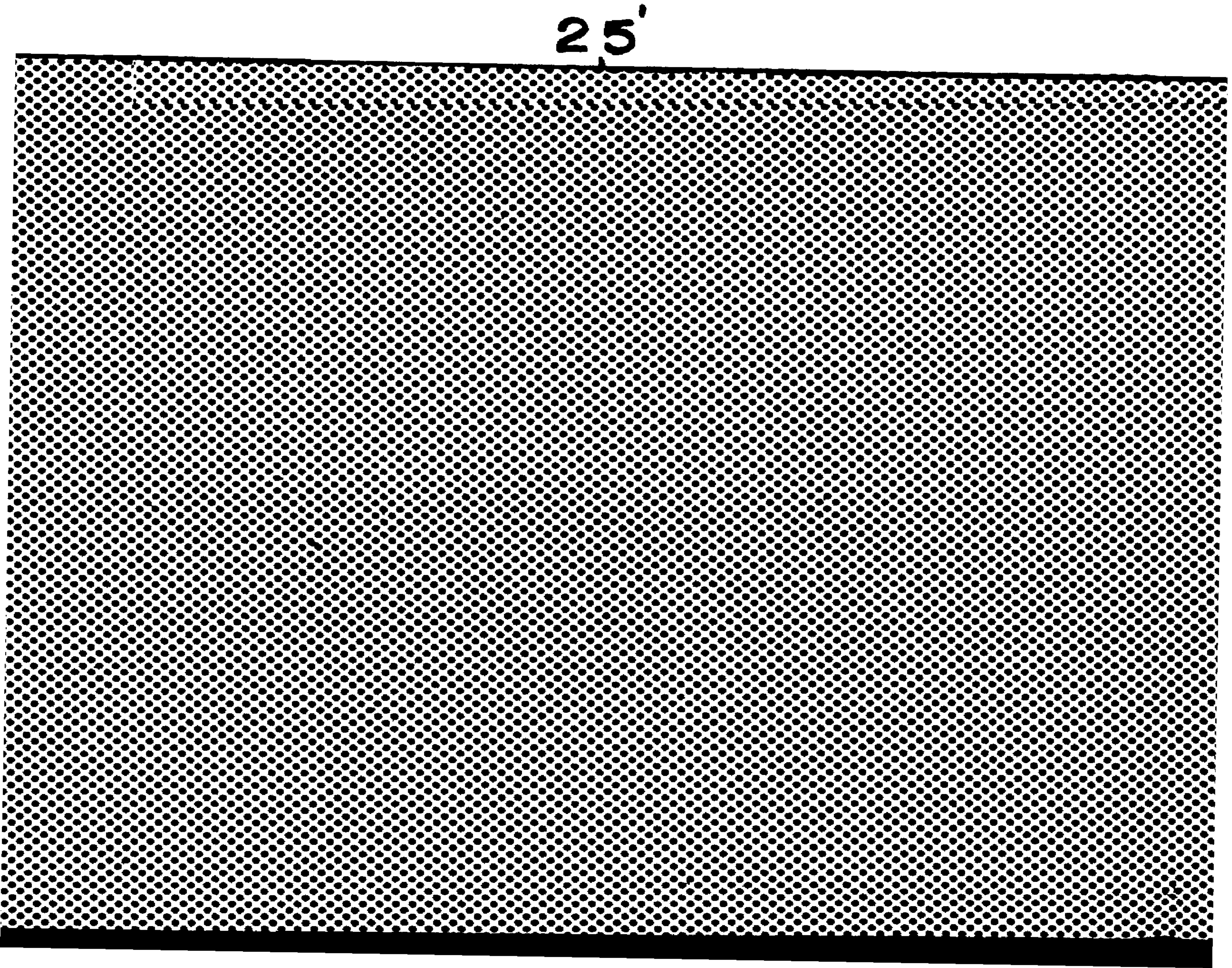
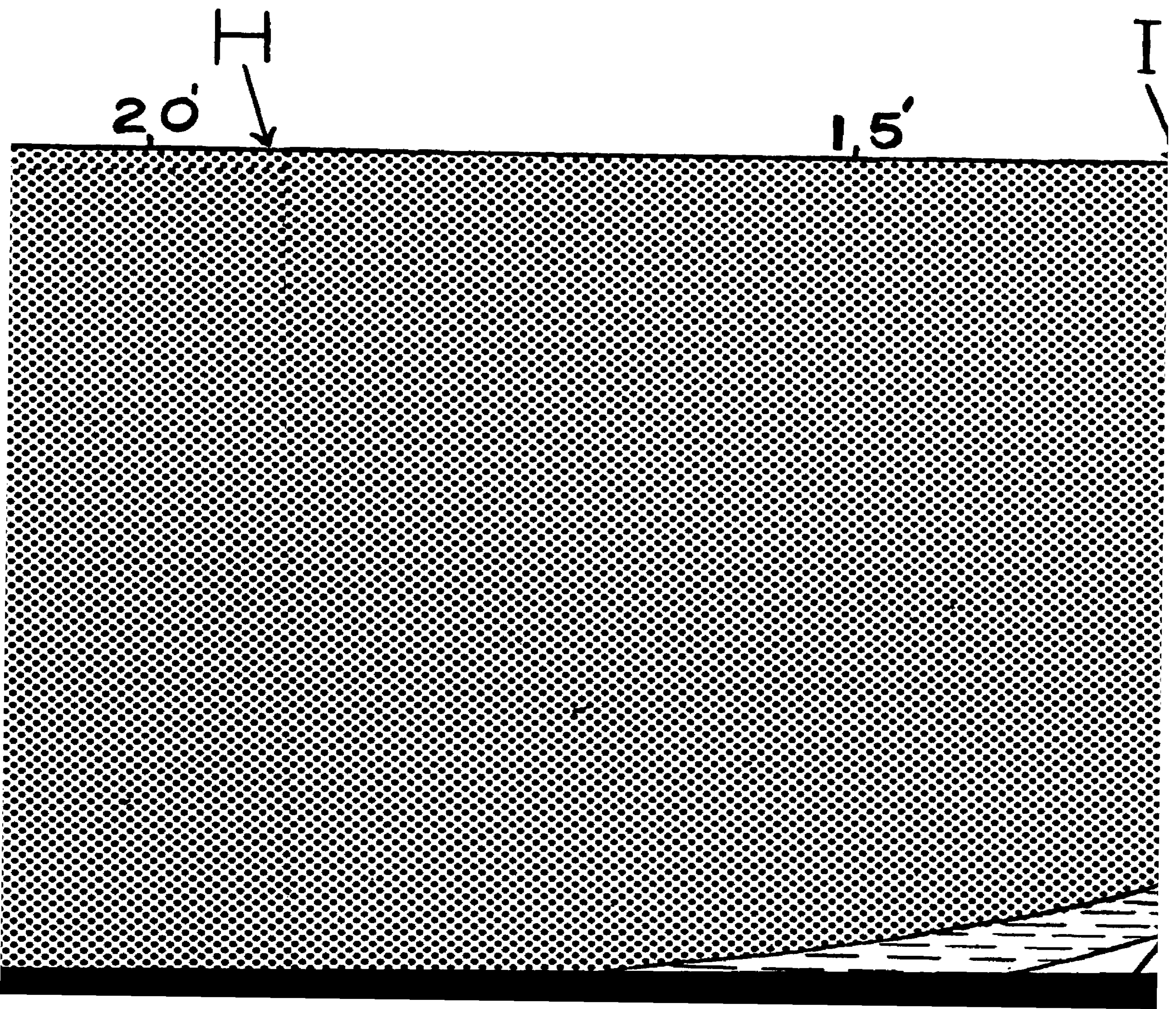


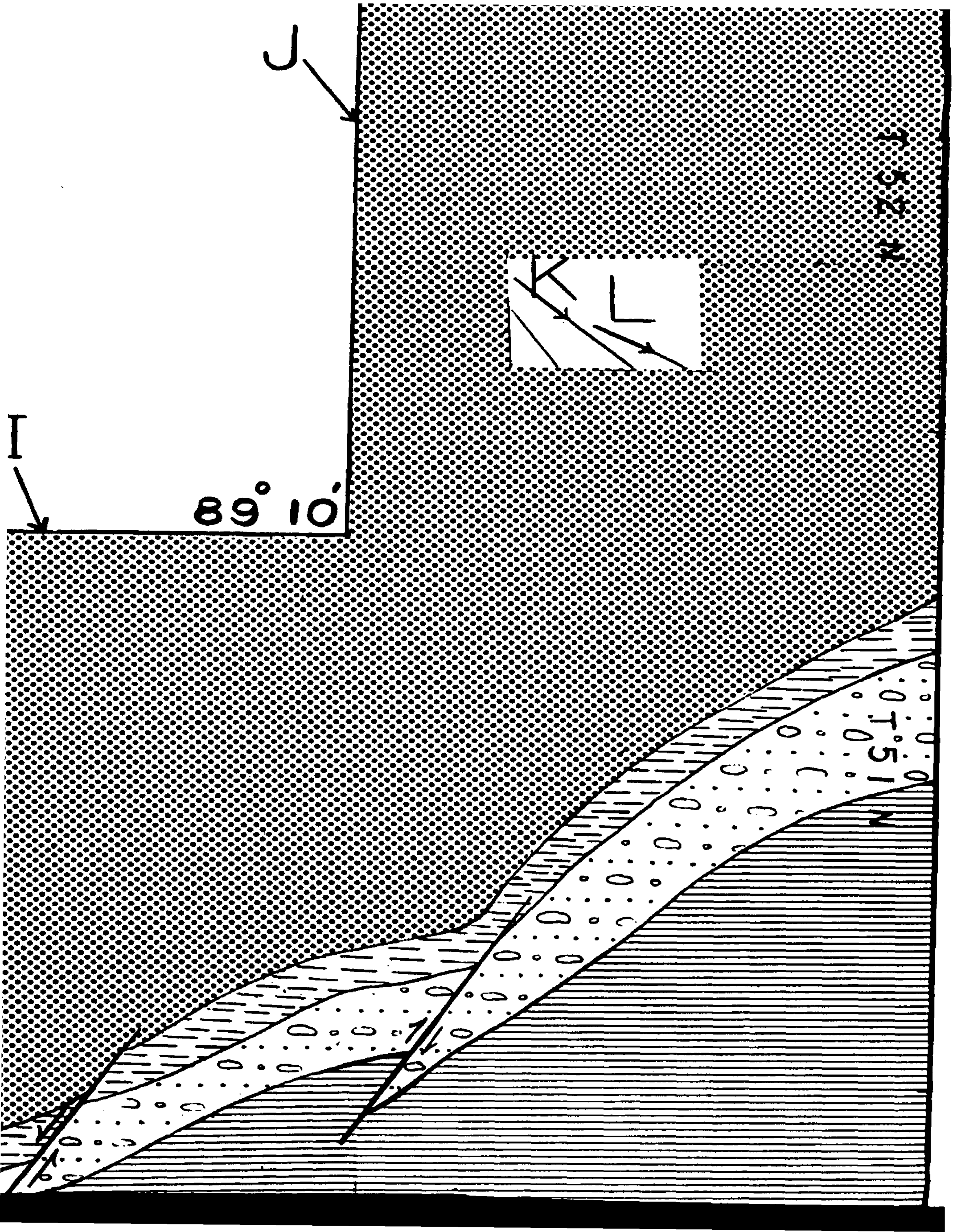
PLATE III-b

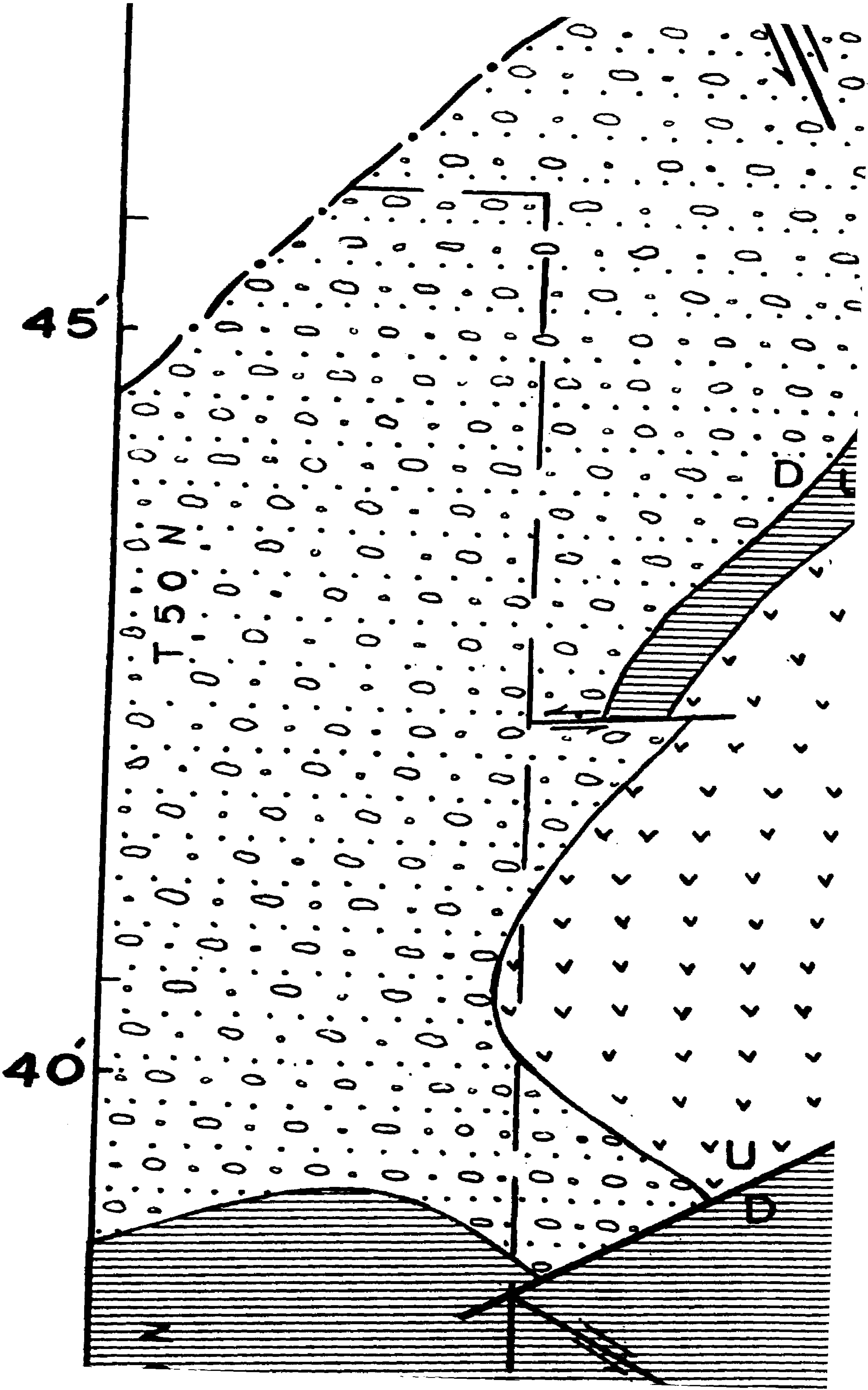


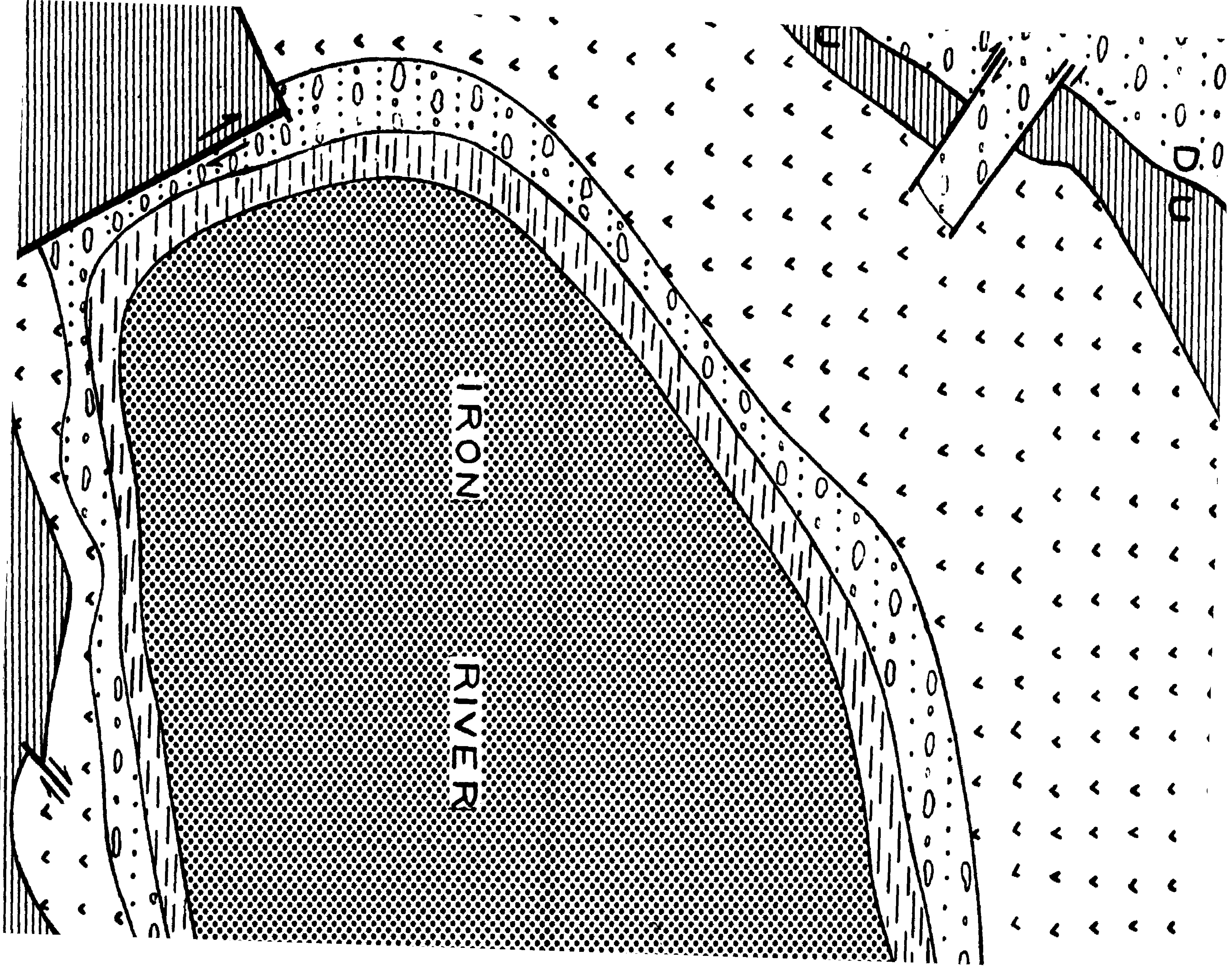

25'

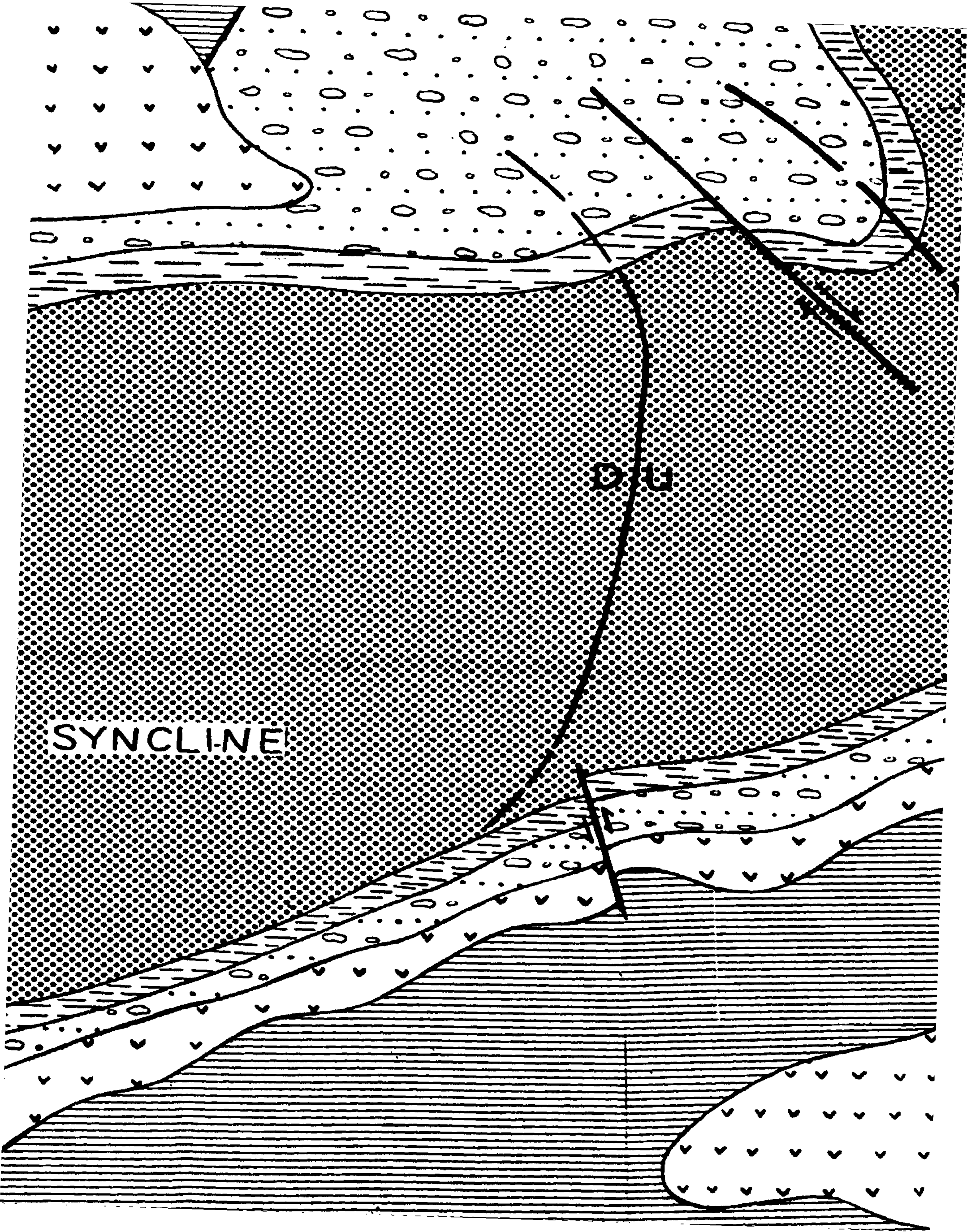


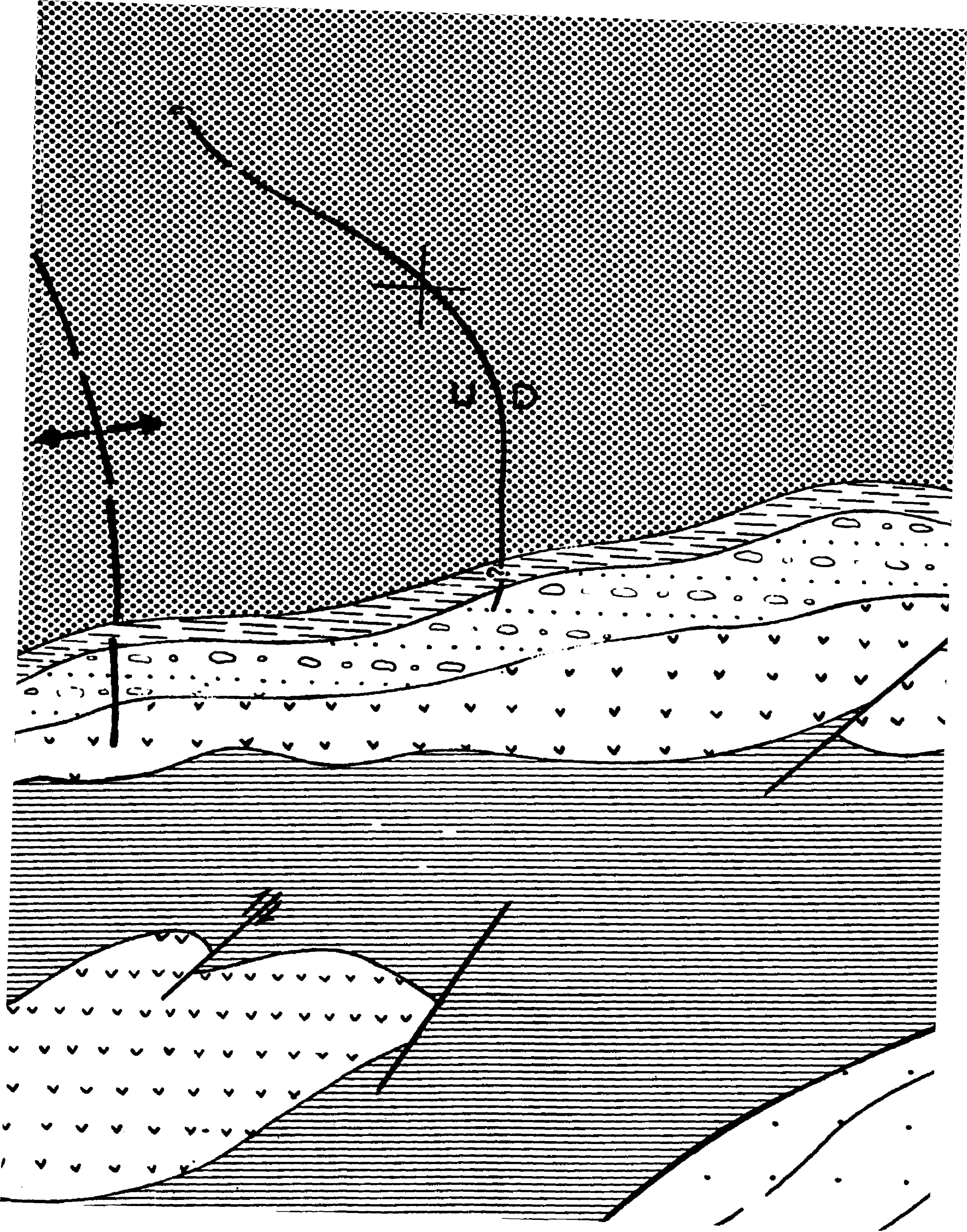
H
20'
1.5'
I


J
K
L
I
89° 10′
T 52 N
T 51 N

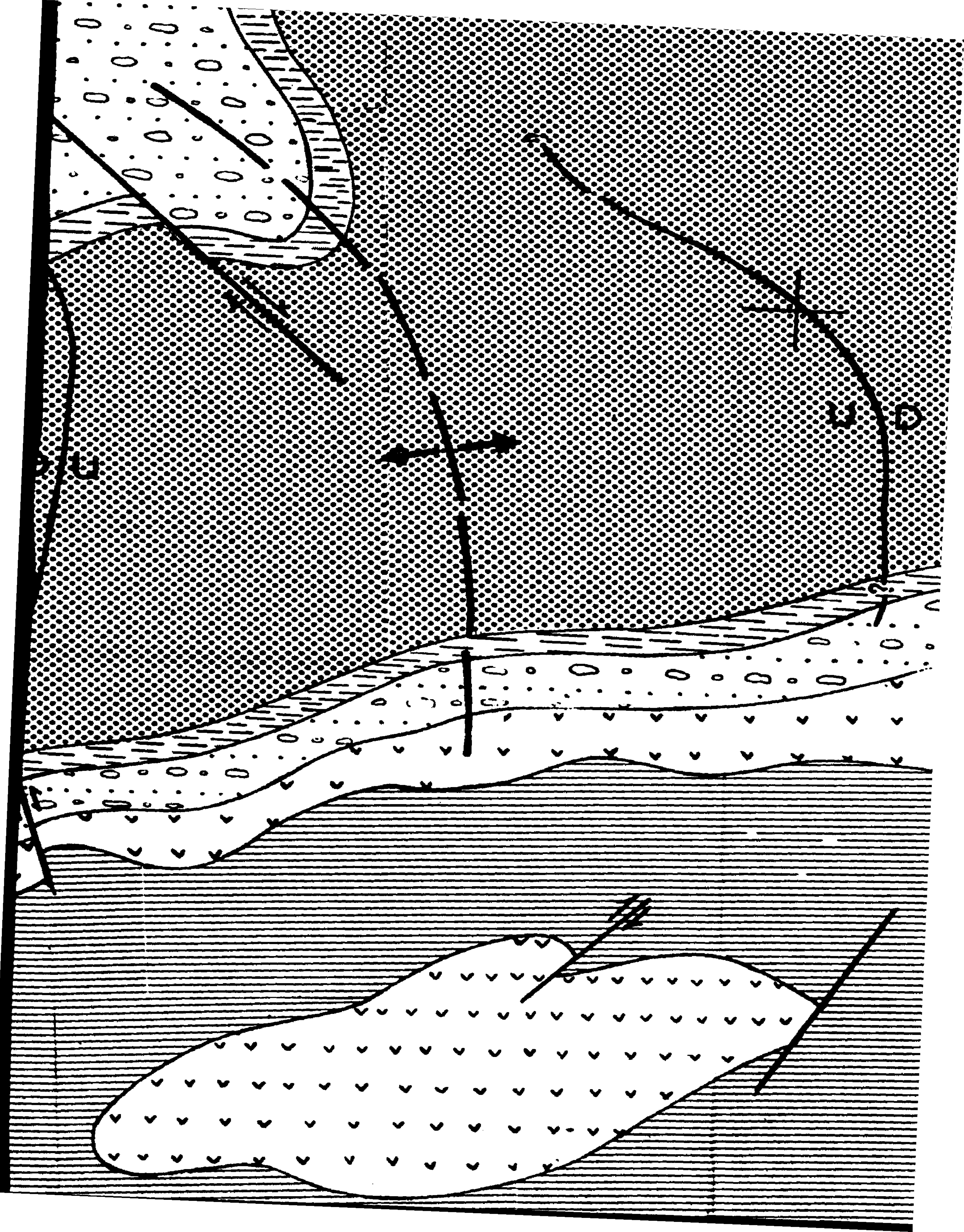

45'
40'
T 50 N
D
U
D

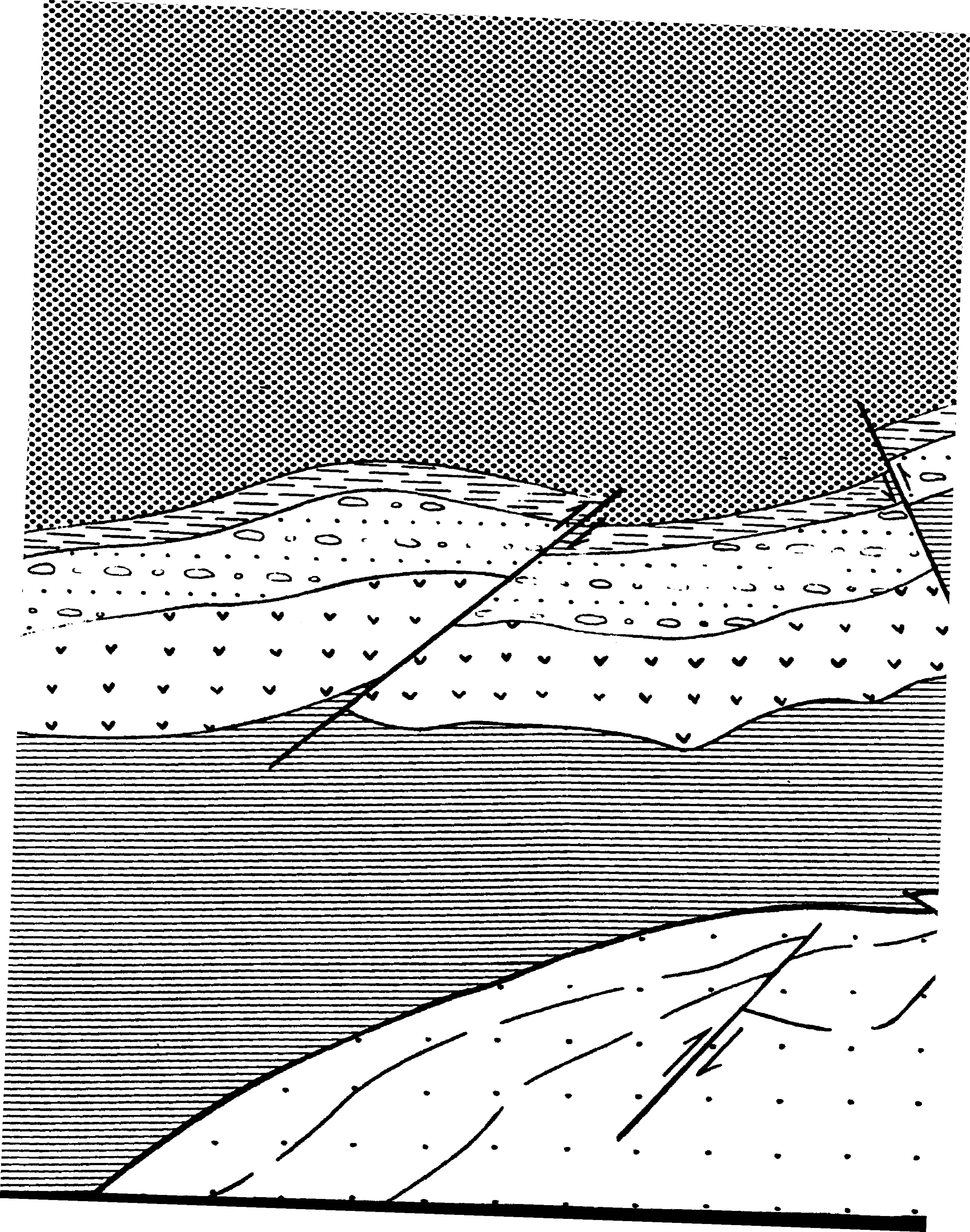

IRON RIVER
D
U

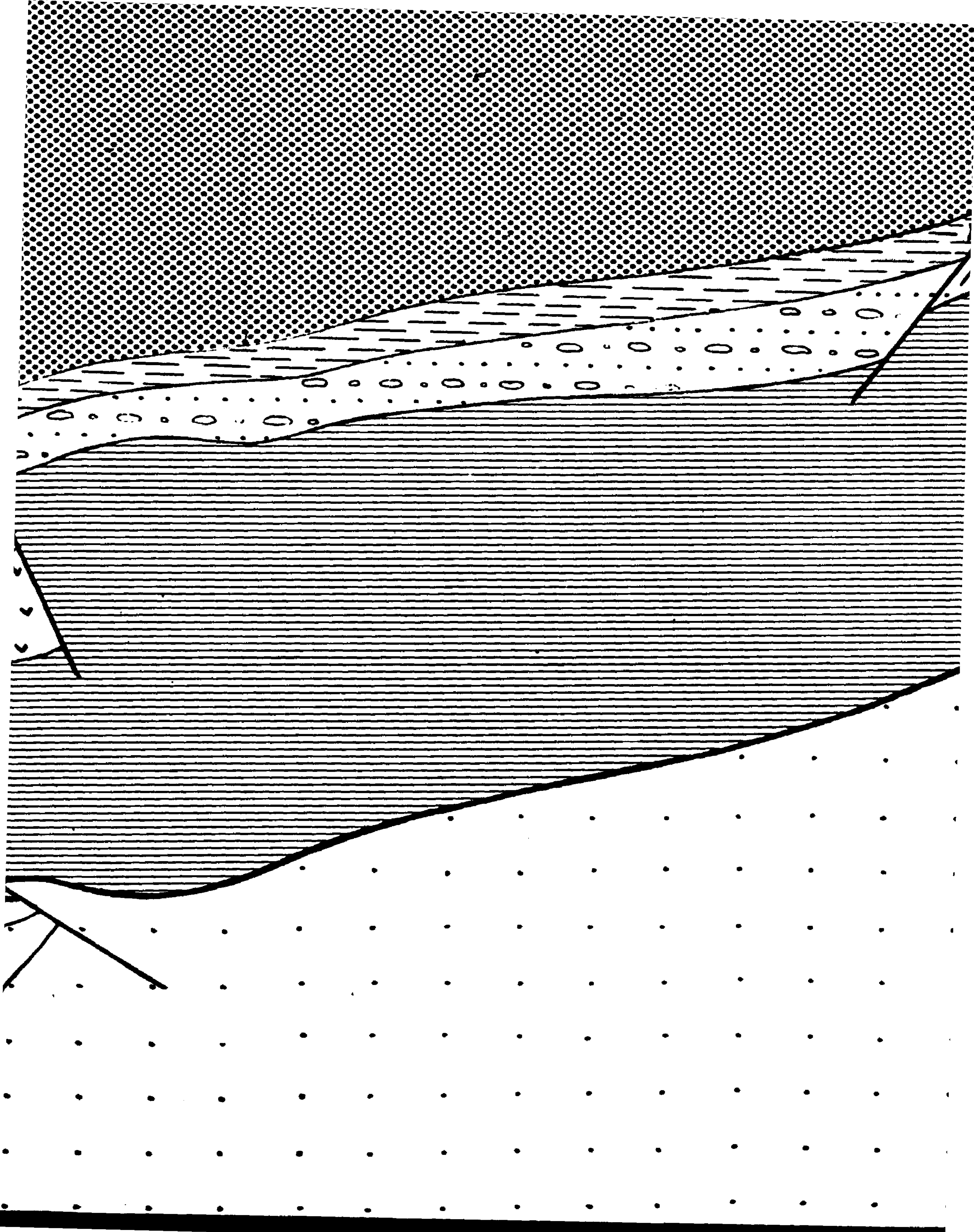

D U
SYNCLINE

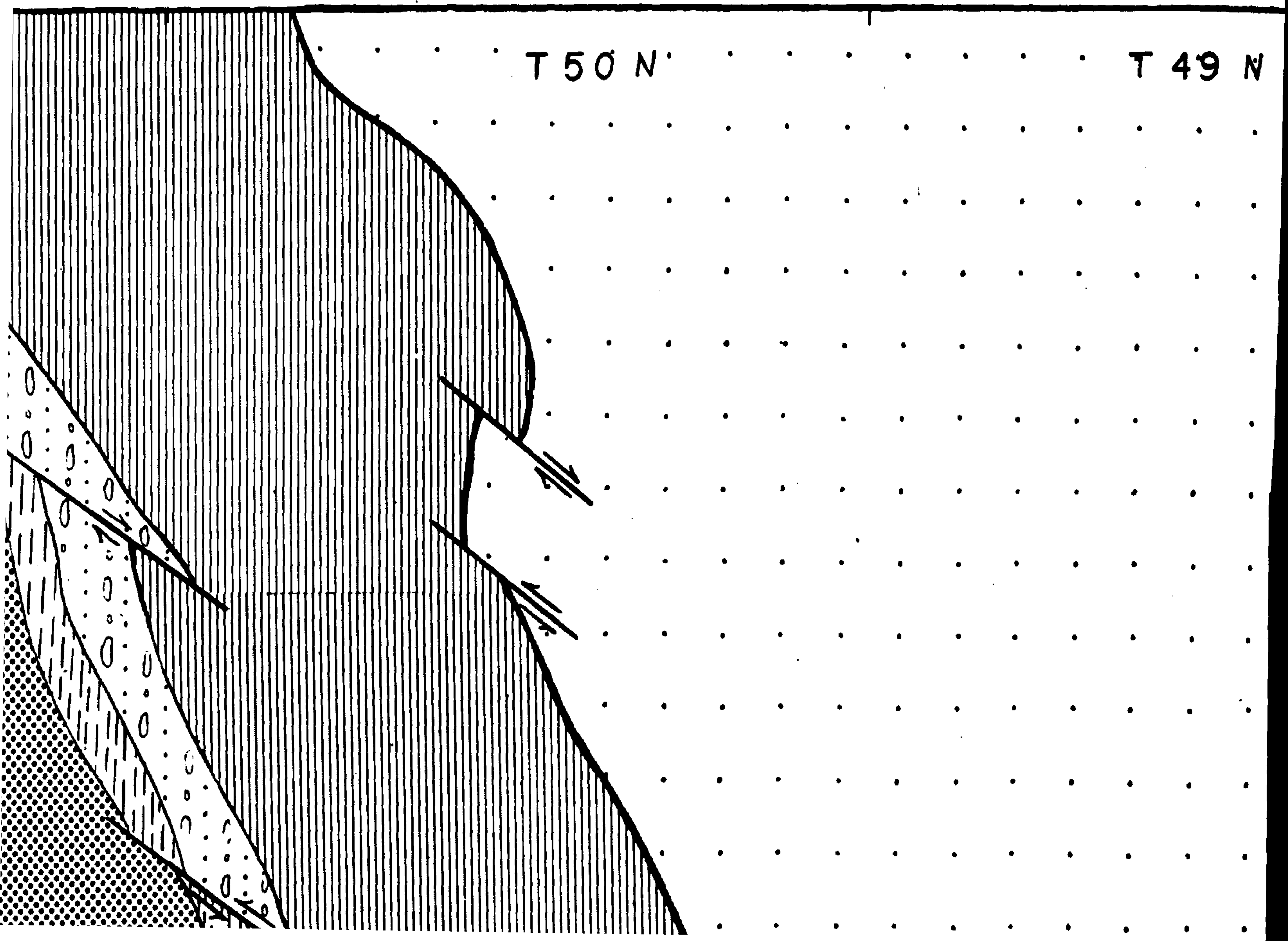


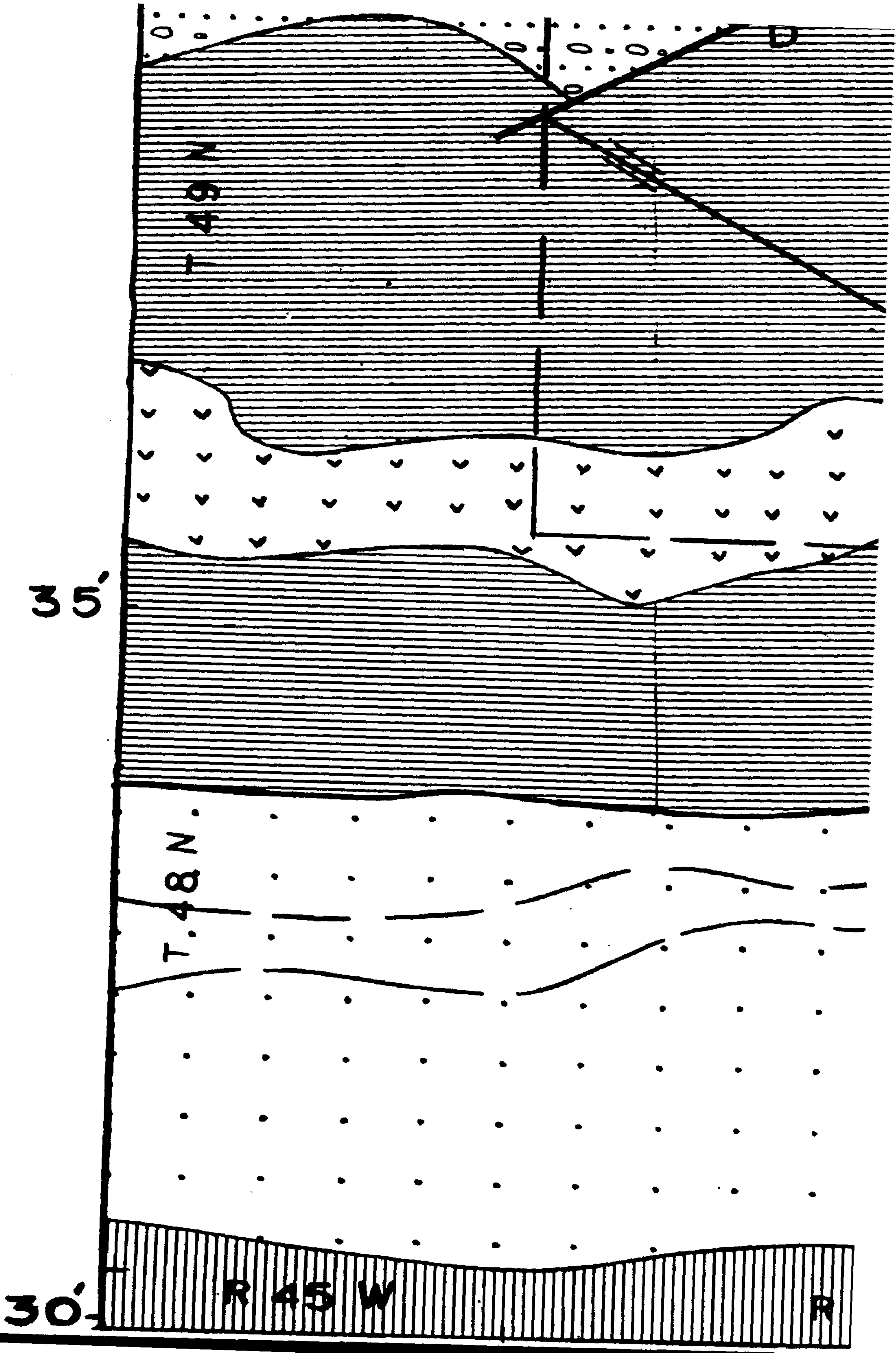
U
D


U D
U

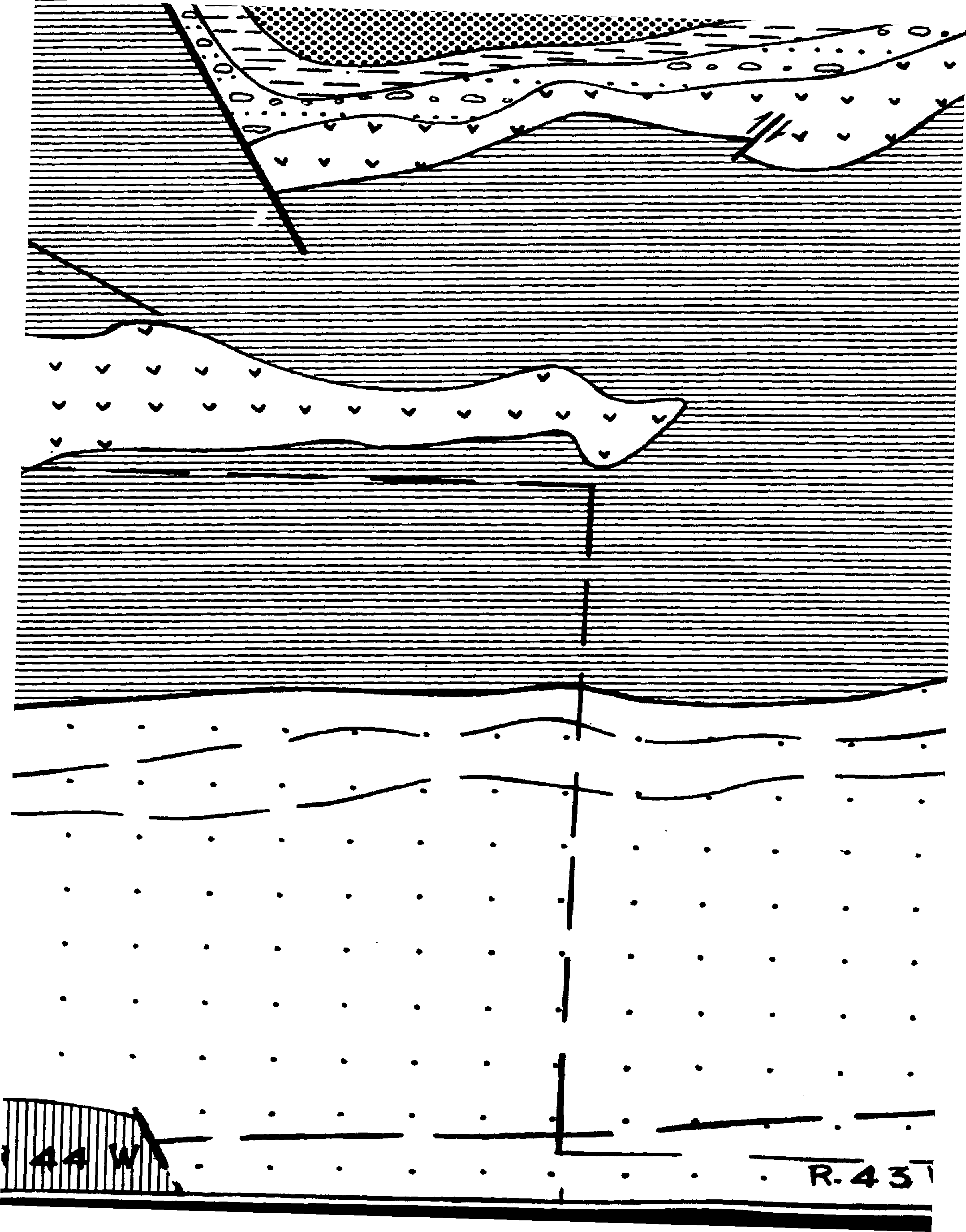




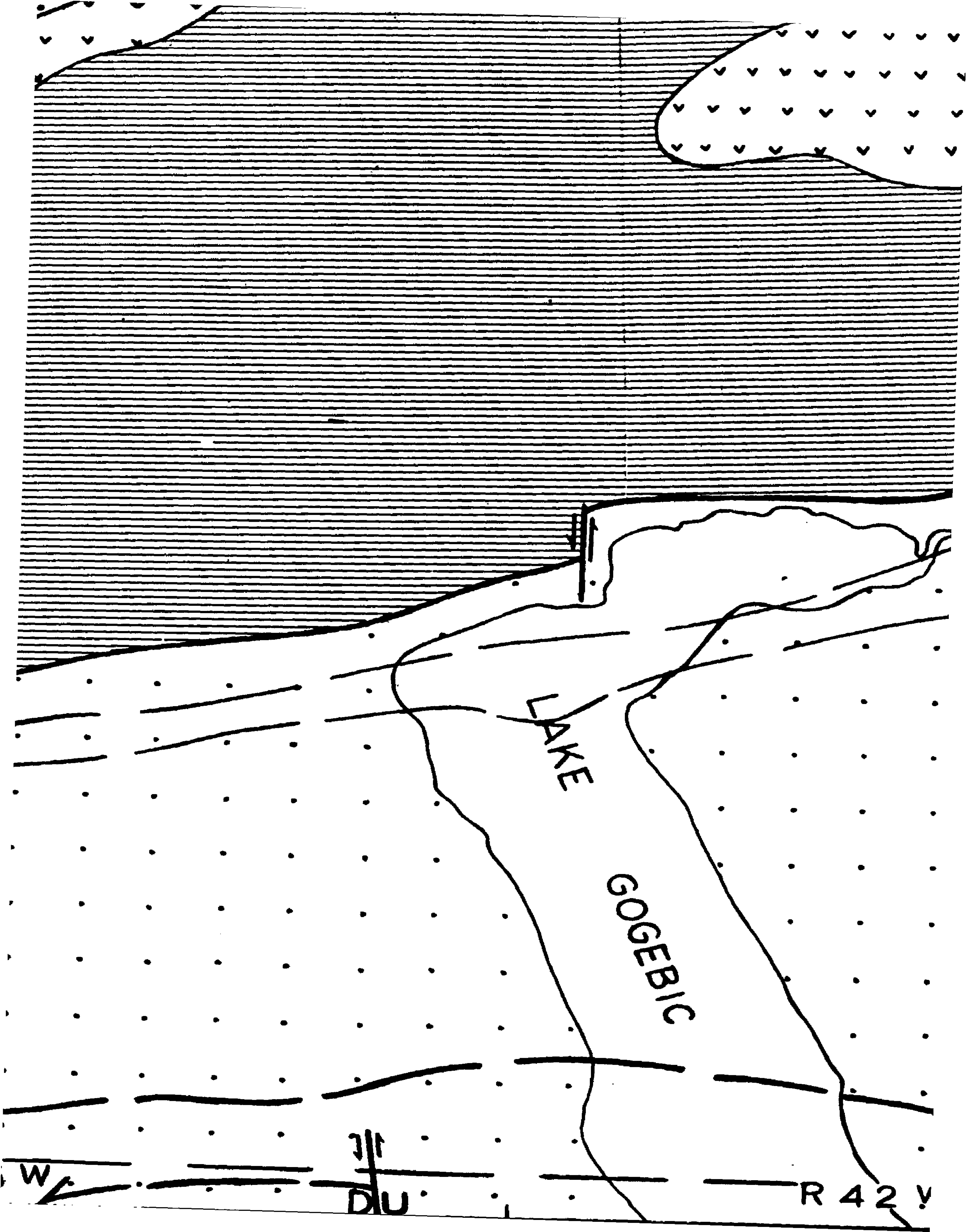

T 50 N
T 49 N



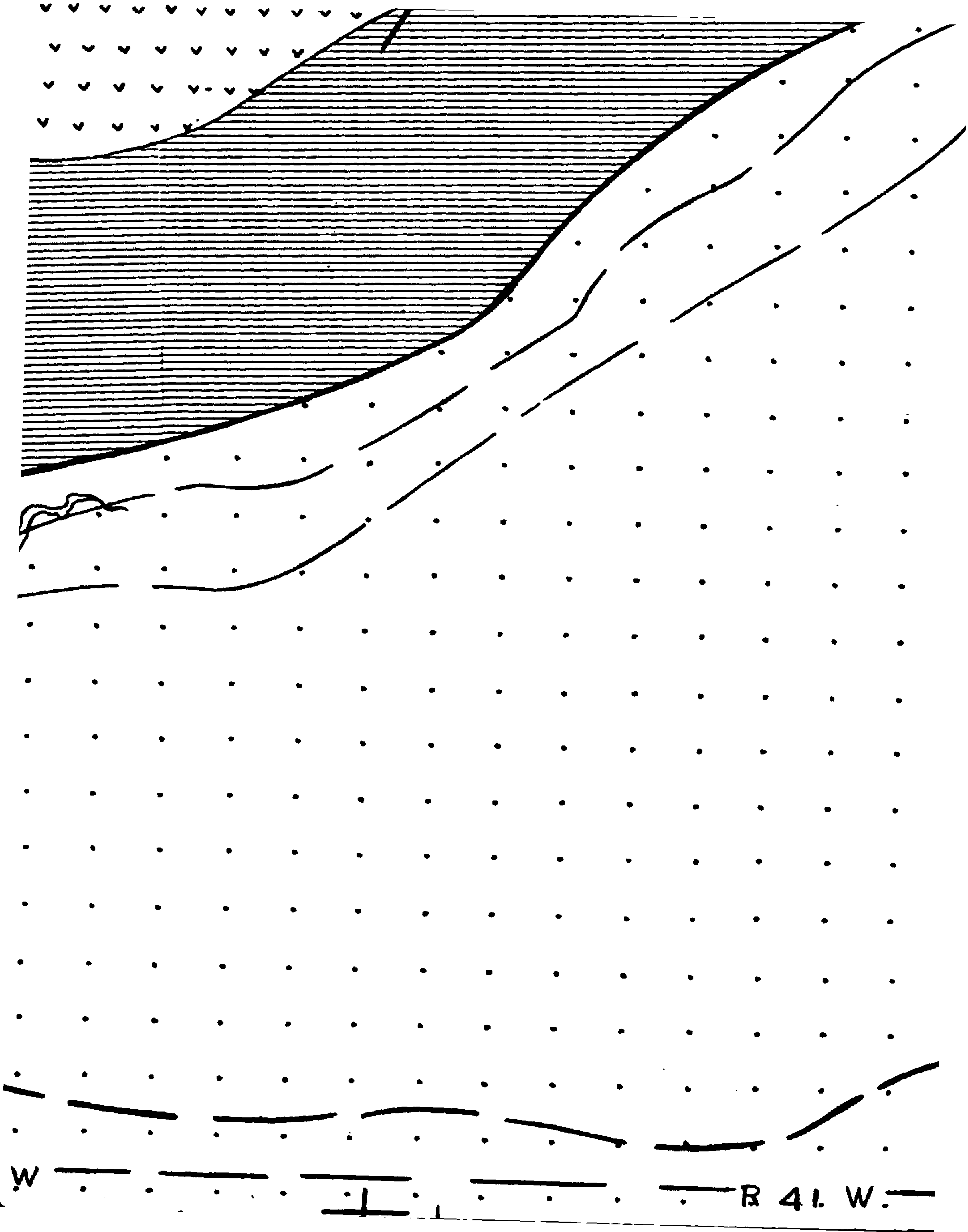
D
T 49 N
35′
T. 48 N.
30′
R 45 W
R

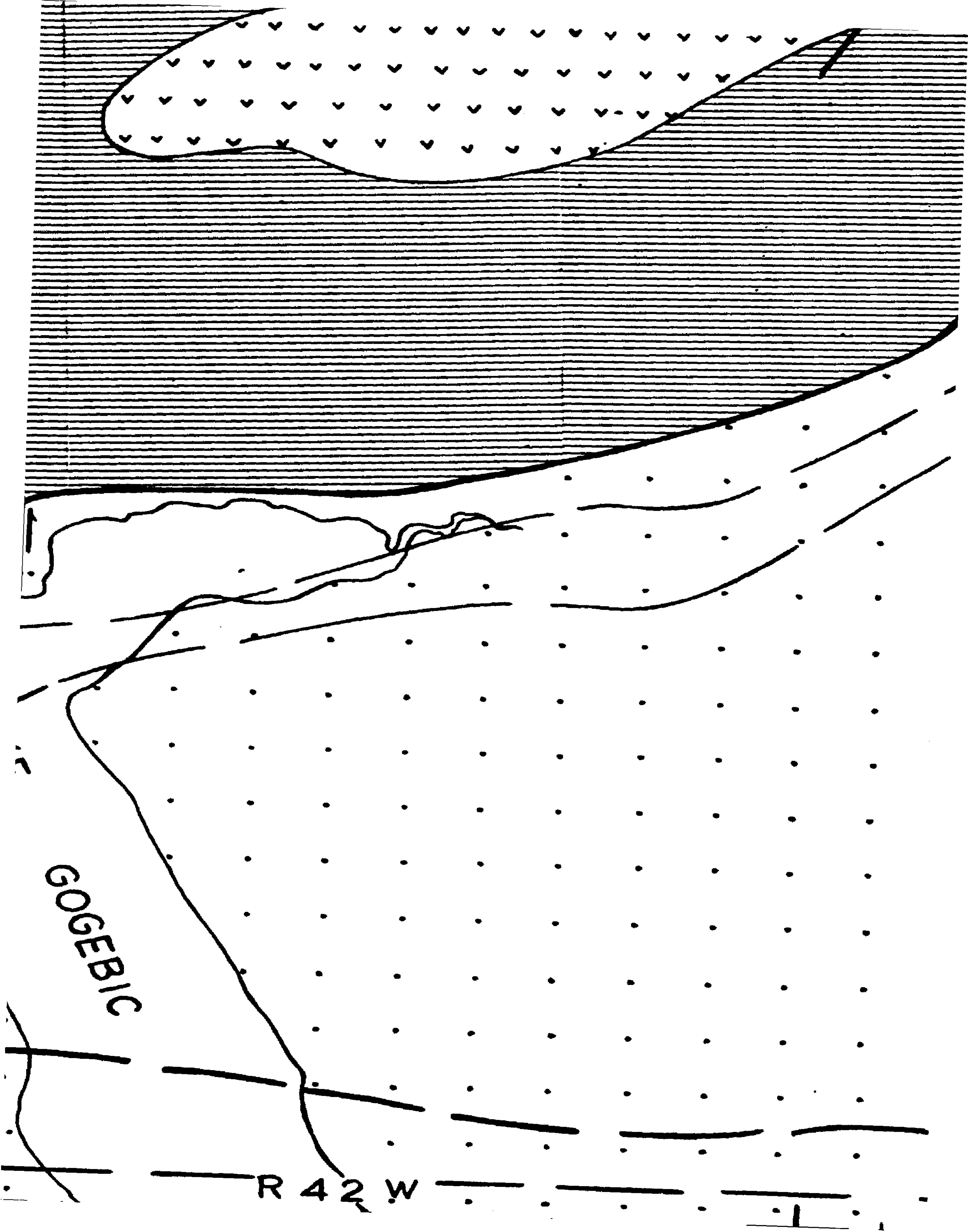


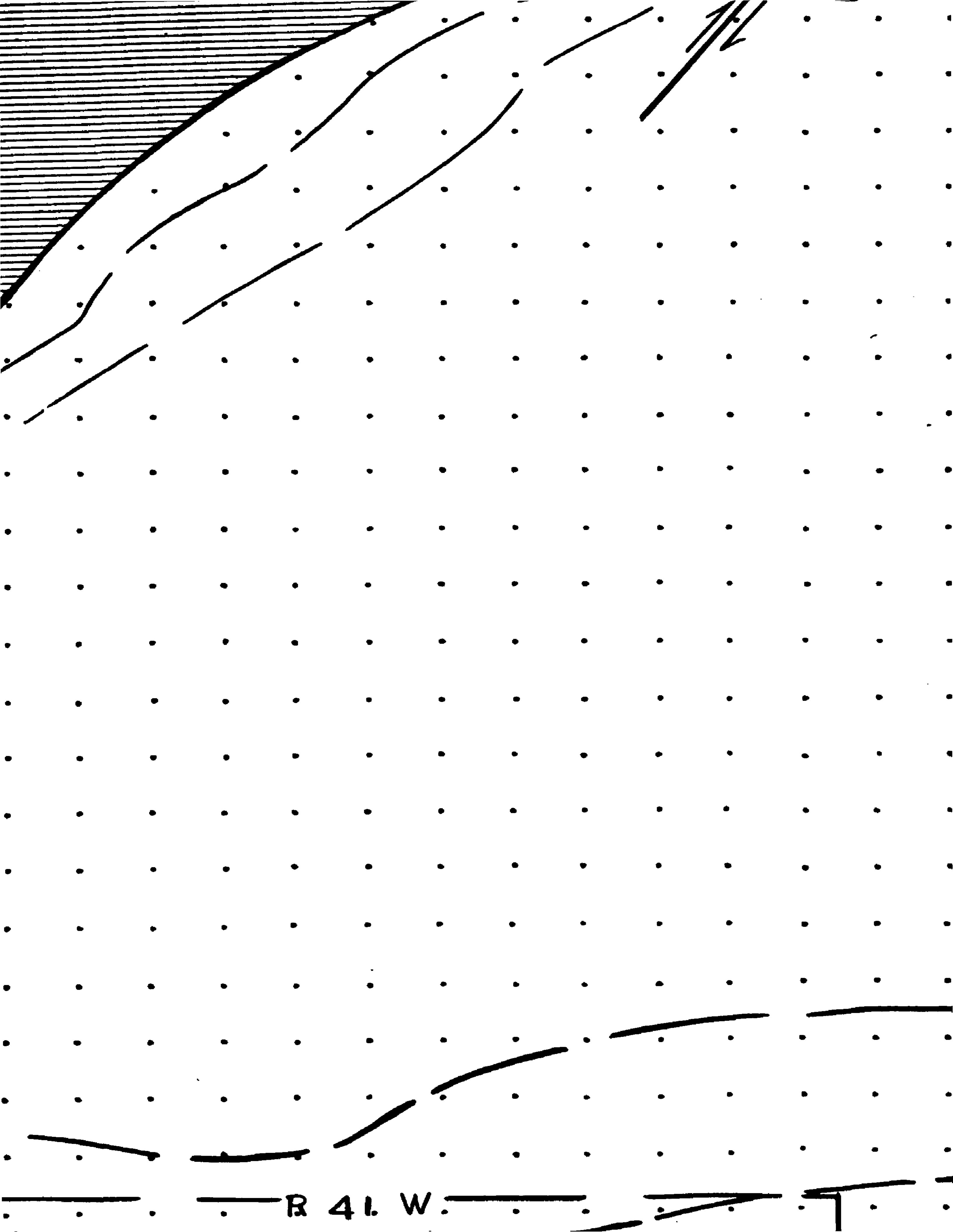
44 W
R.43

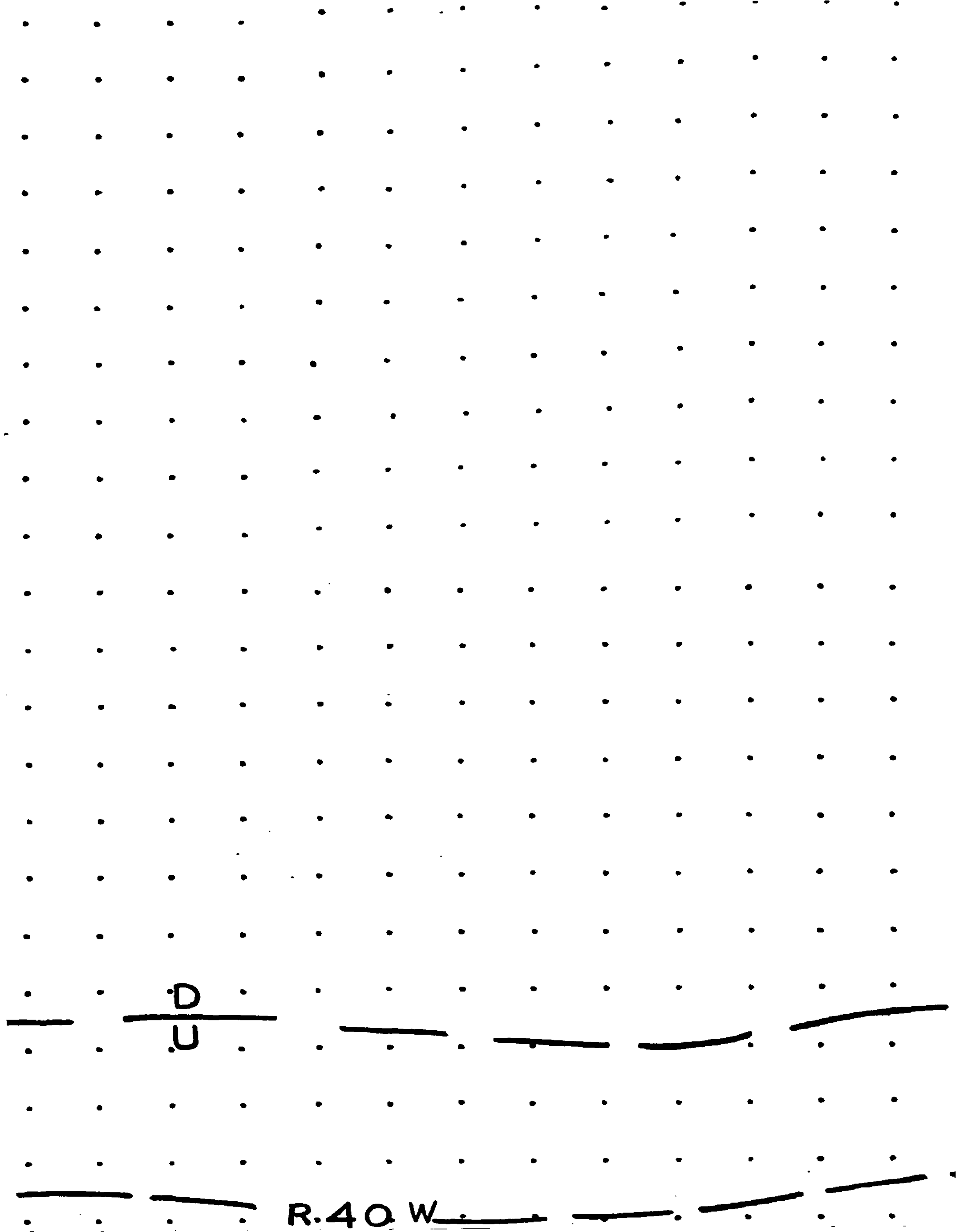


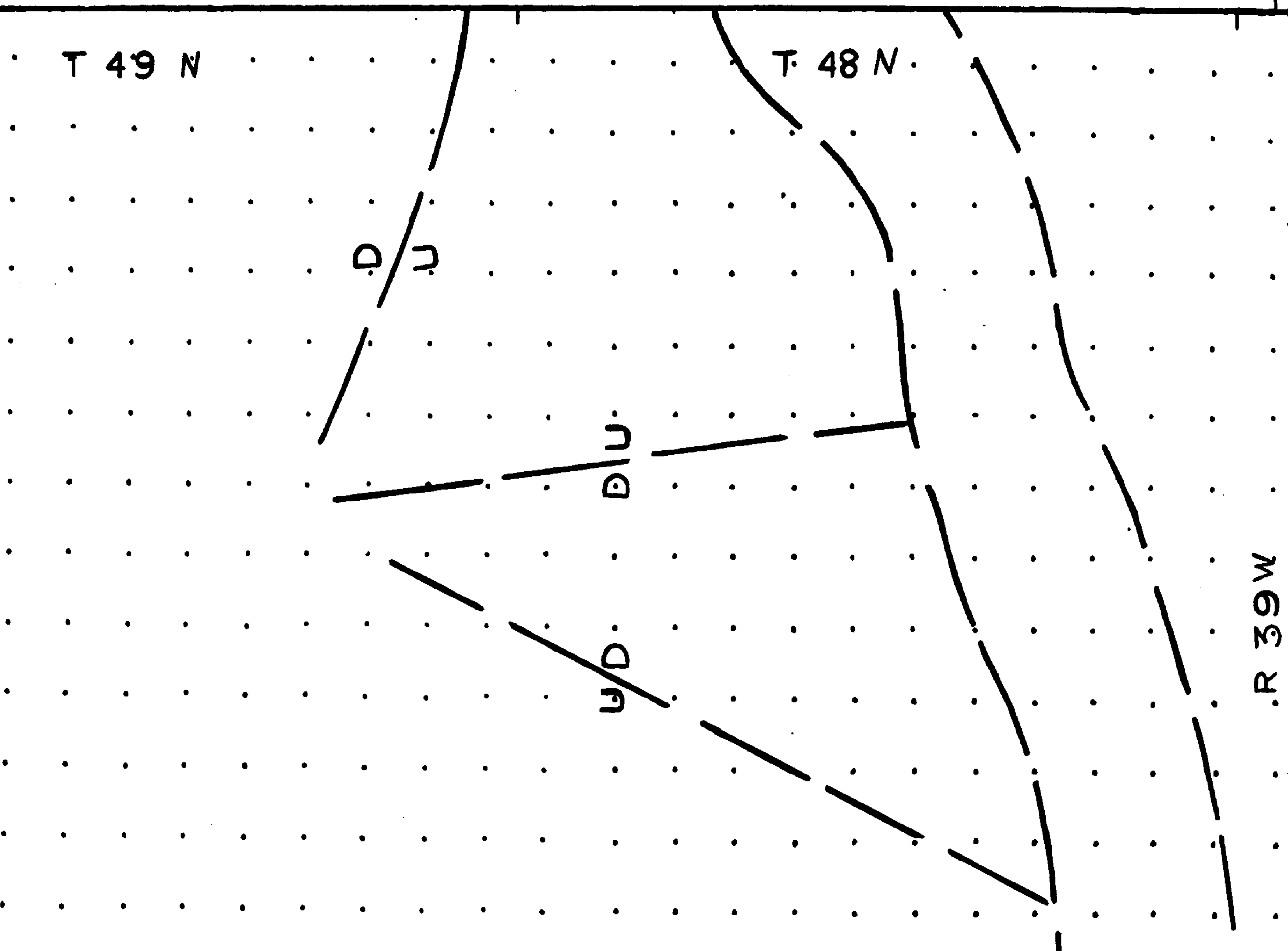
LAKE
GOGEBIC
W
D
U
R 42 W

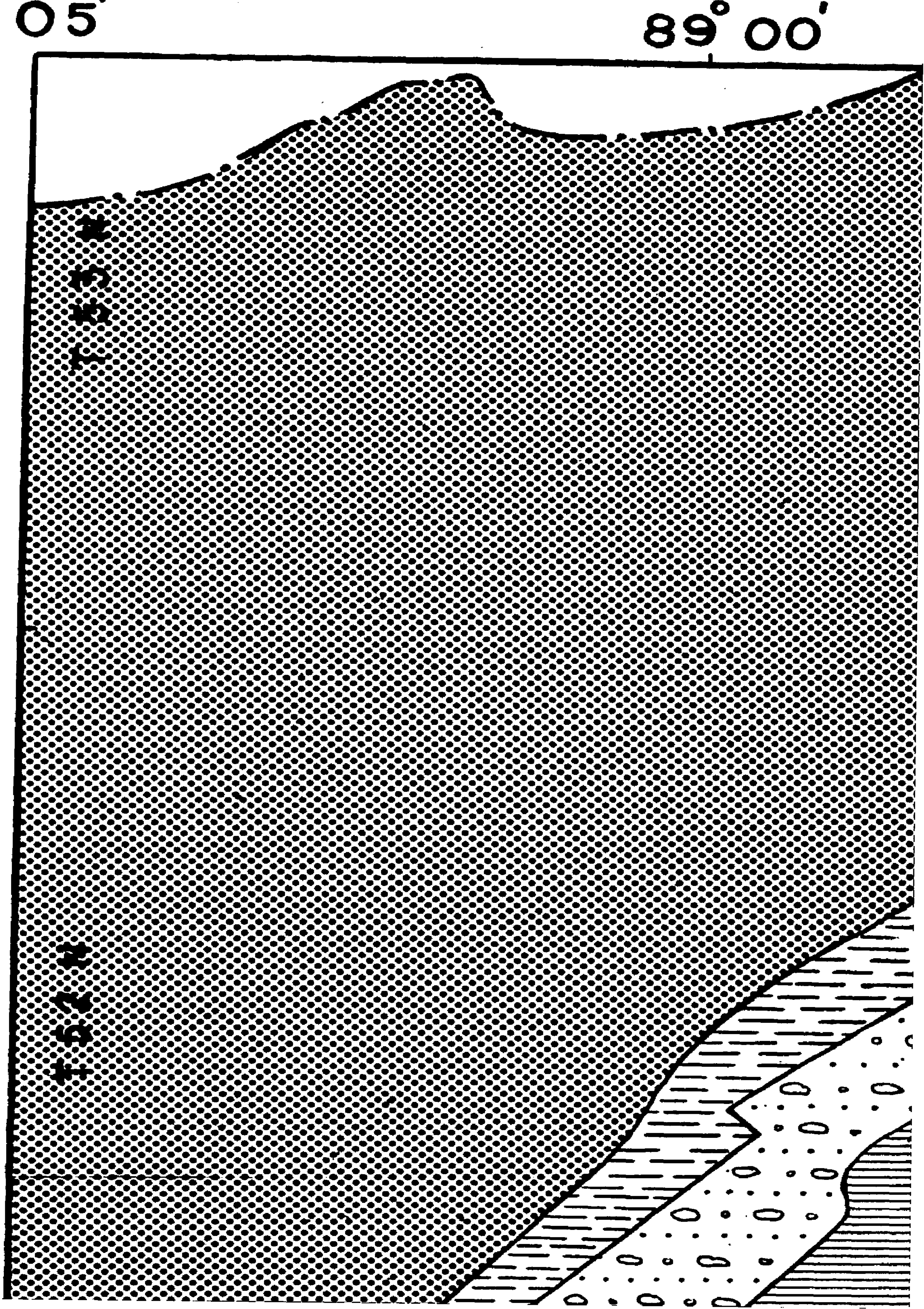

W
R 41. W.


GOGEBIC
R 42 W

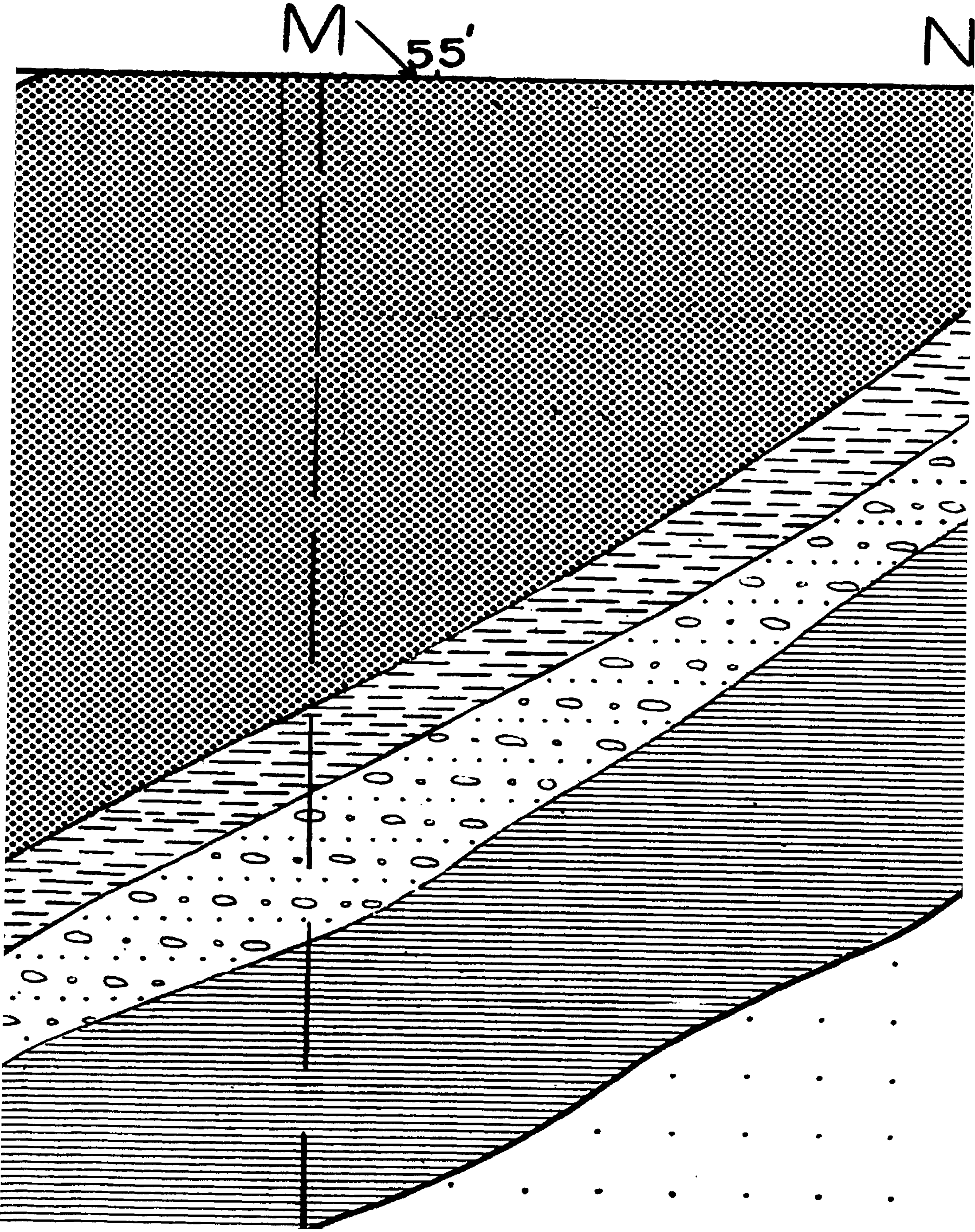

R 41 W

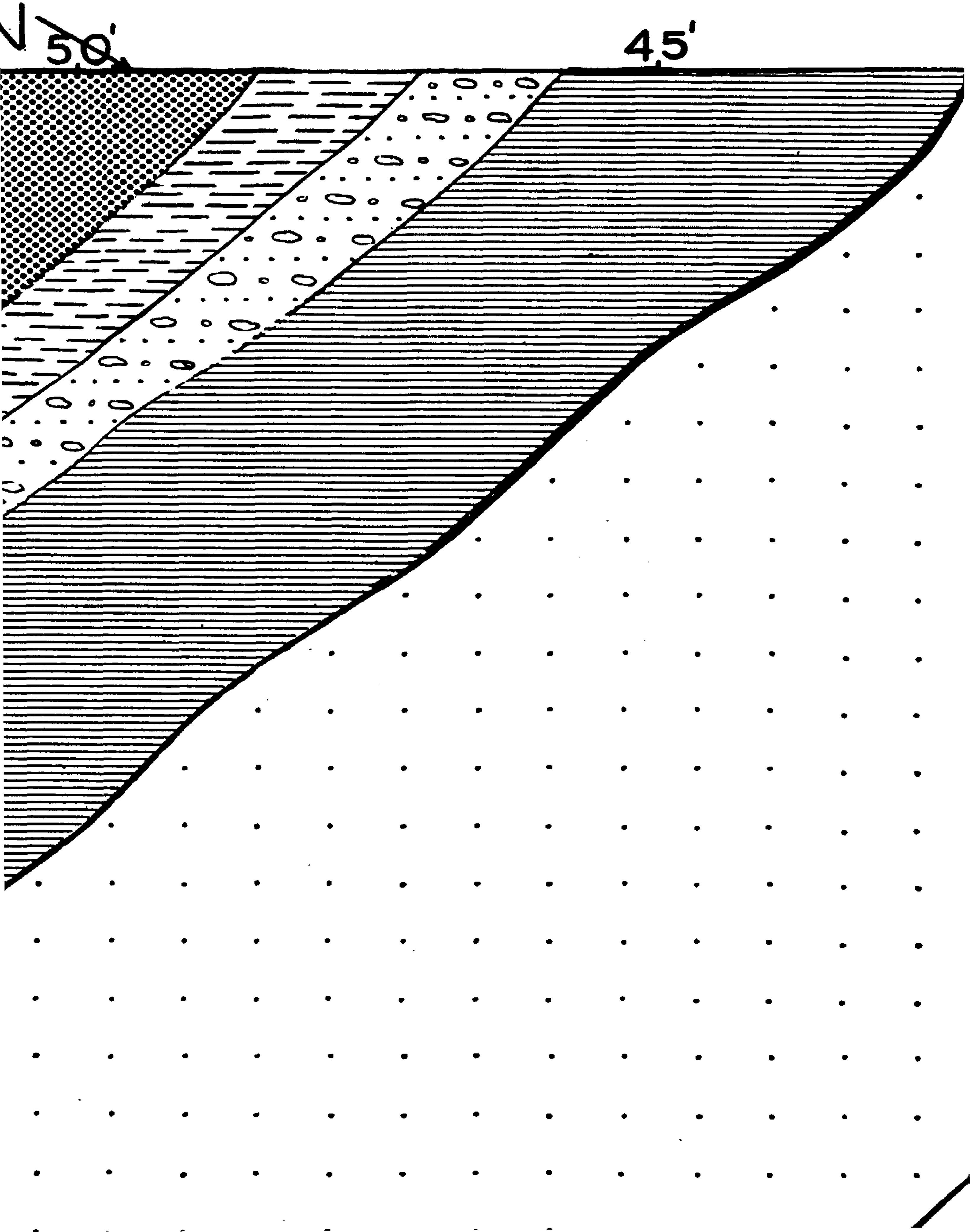

D
U
R.40 W


T 49 N
T 48 N
R 39 W
D U
D U
U D

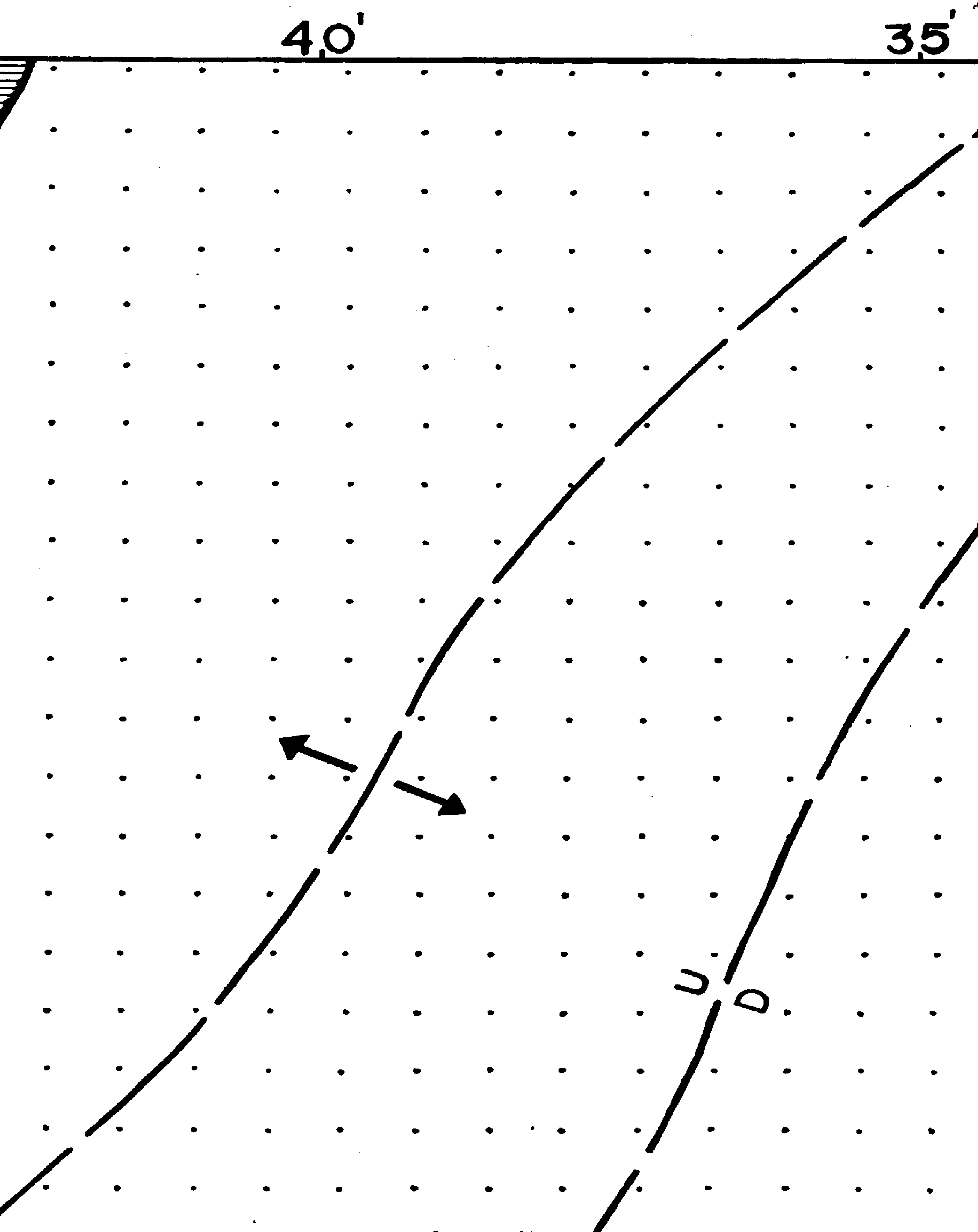


05'
89°00'
T53N
T52N

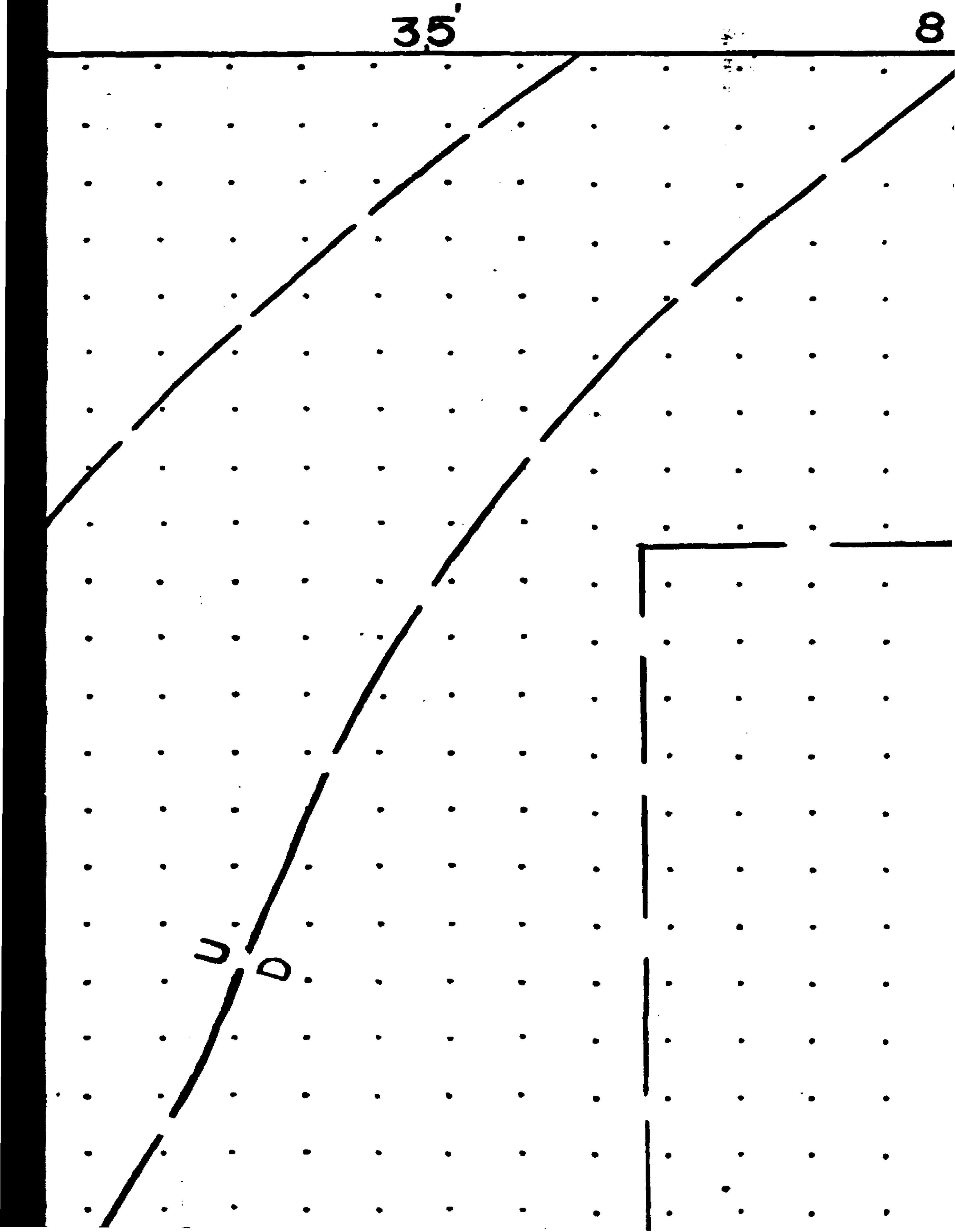

M
55′
N

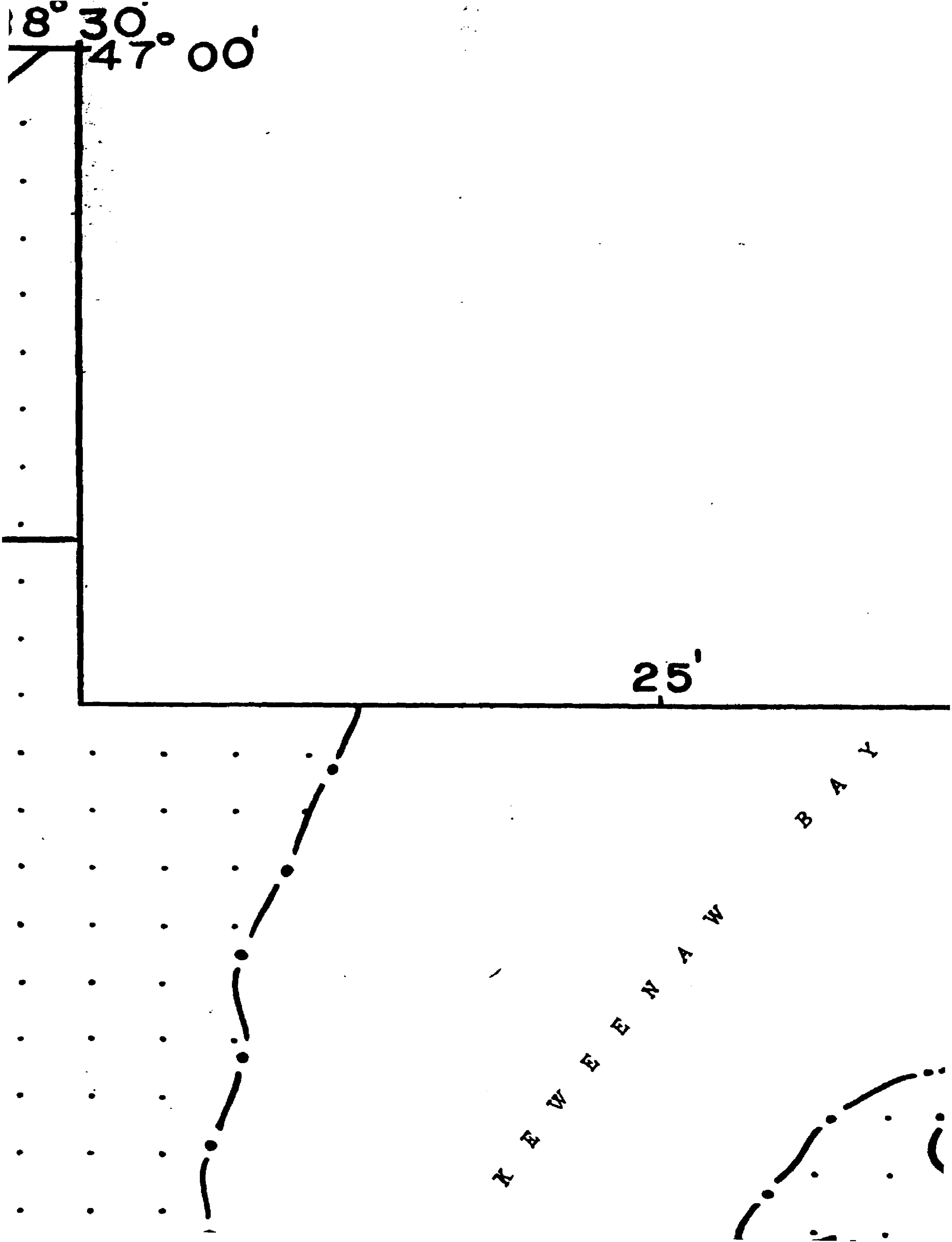


50'
45'



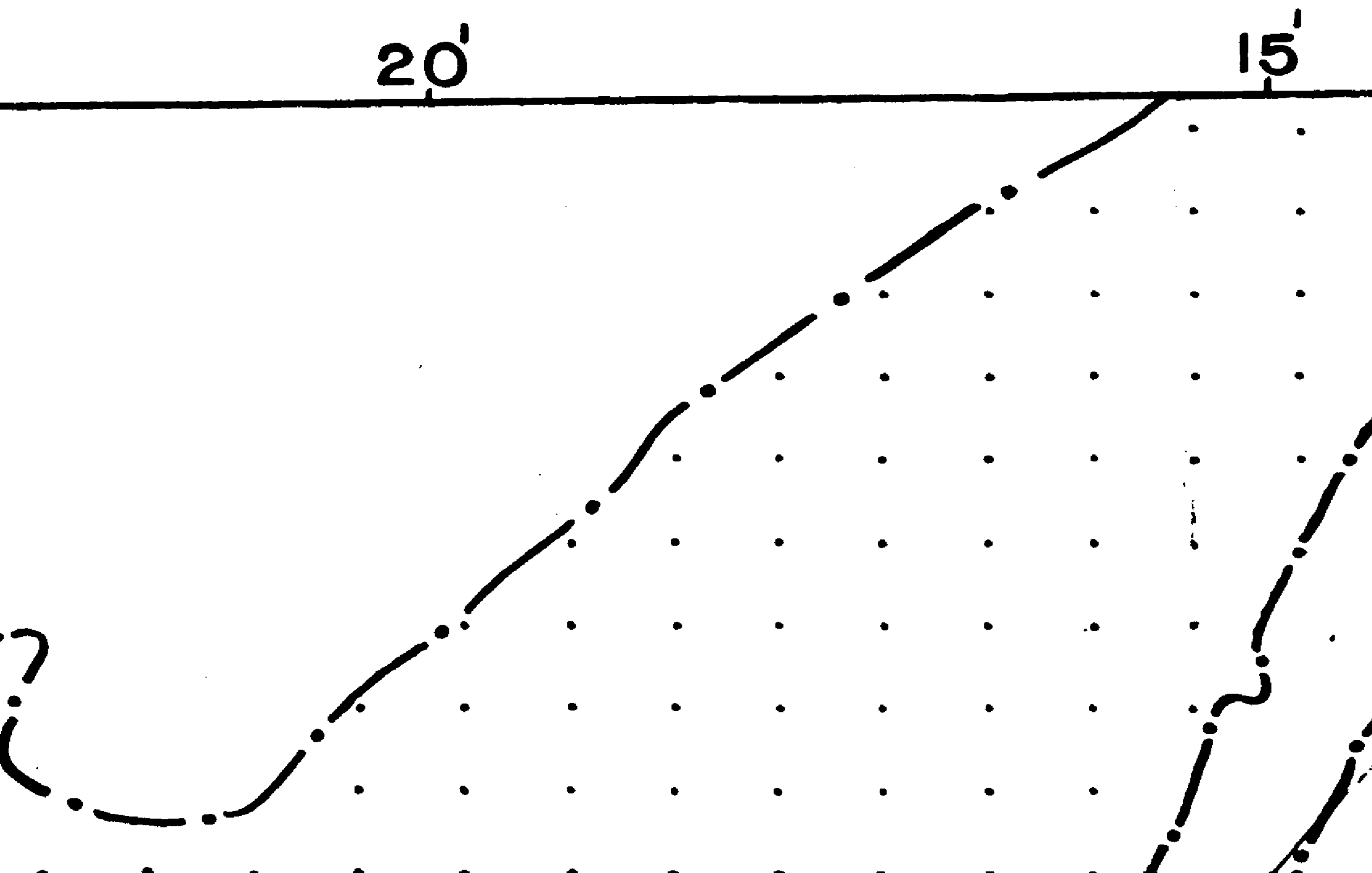
40'
35'
U
D

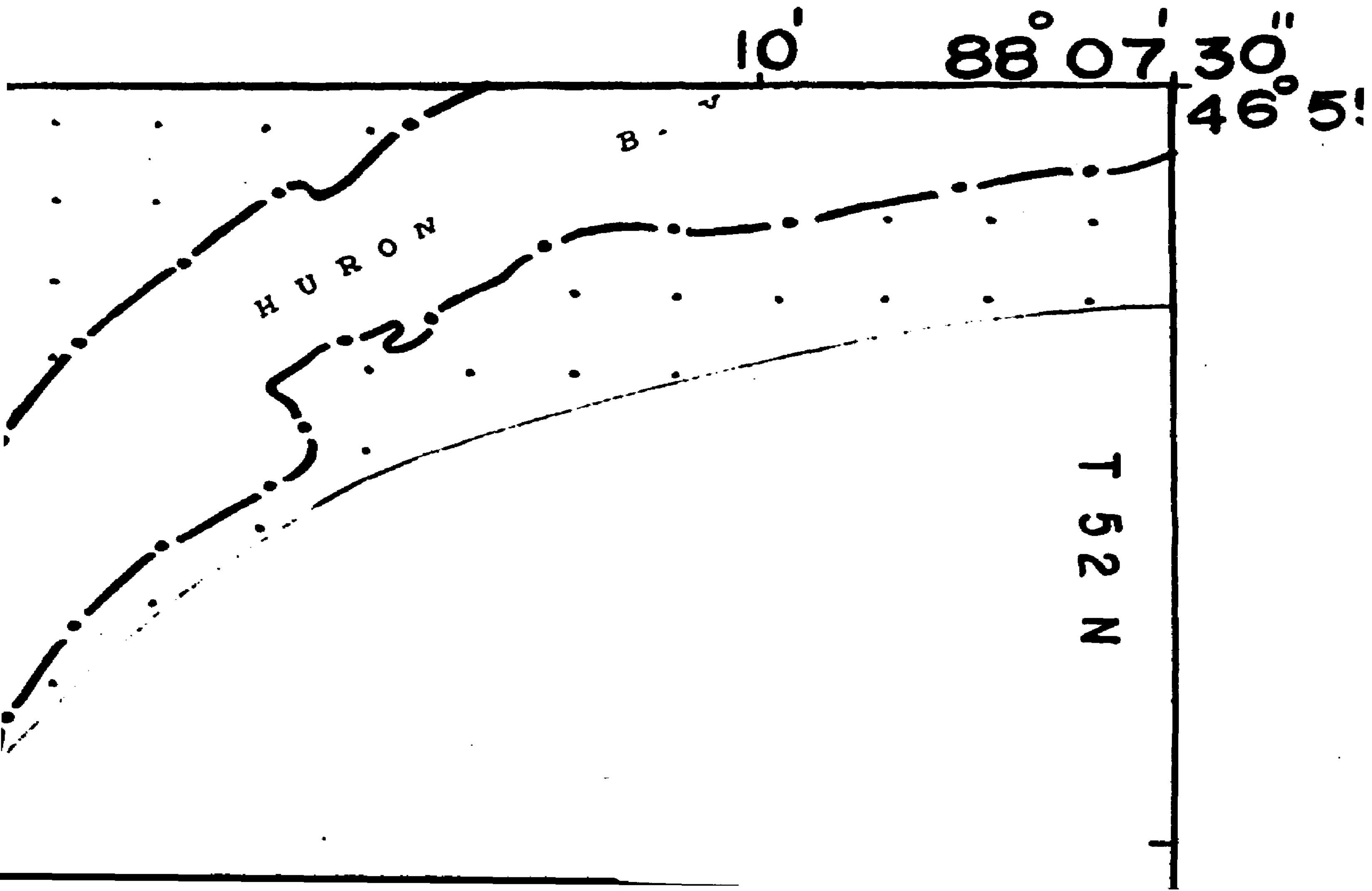

35'
8
U
D

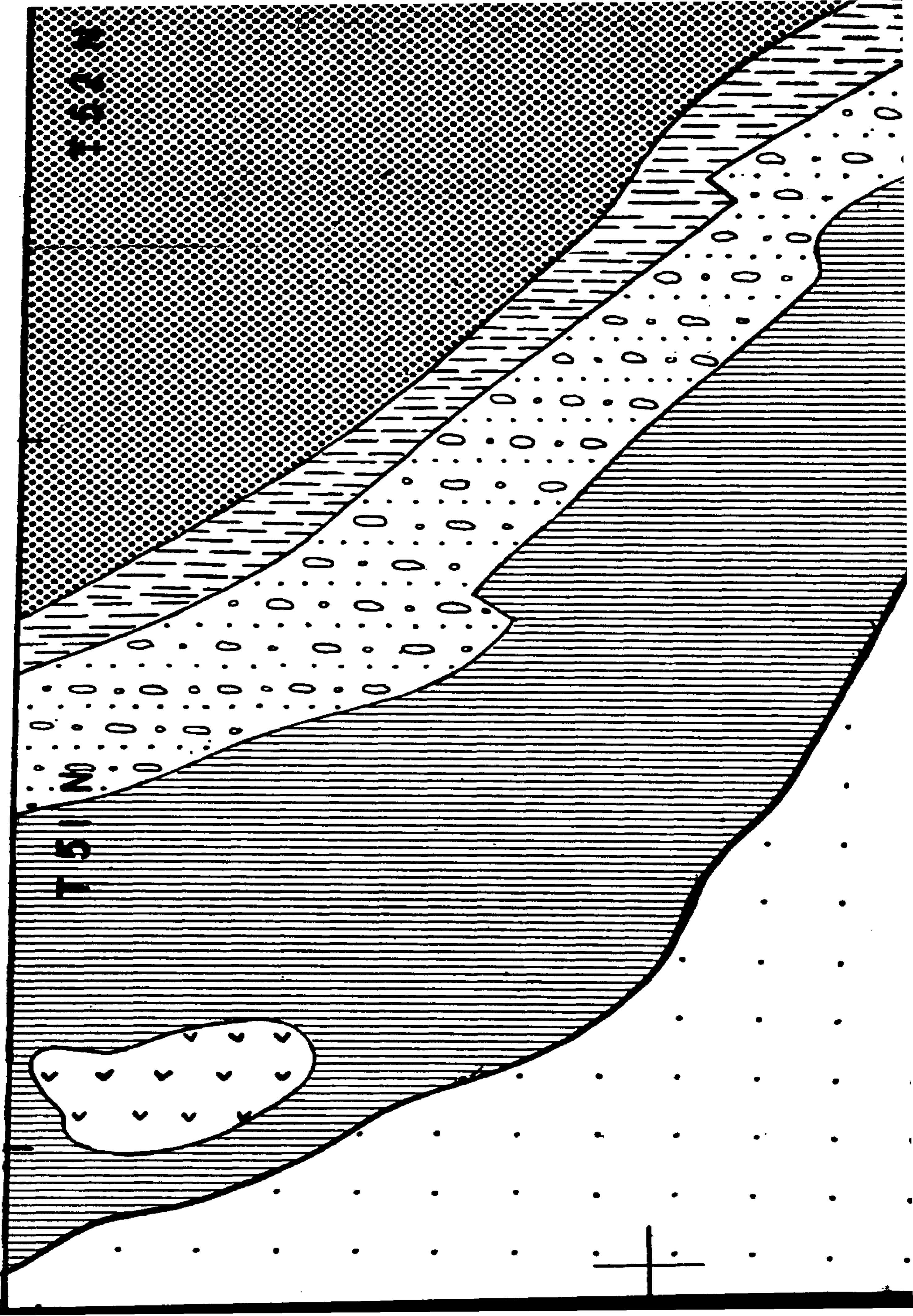


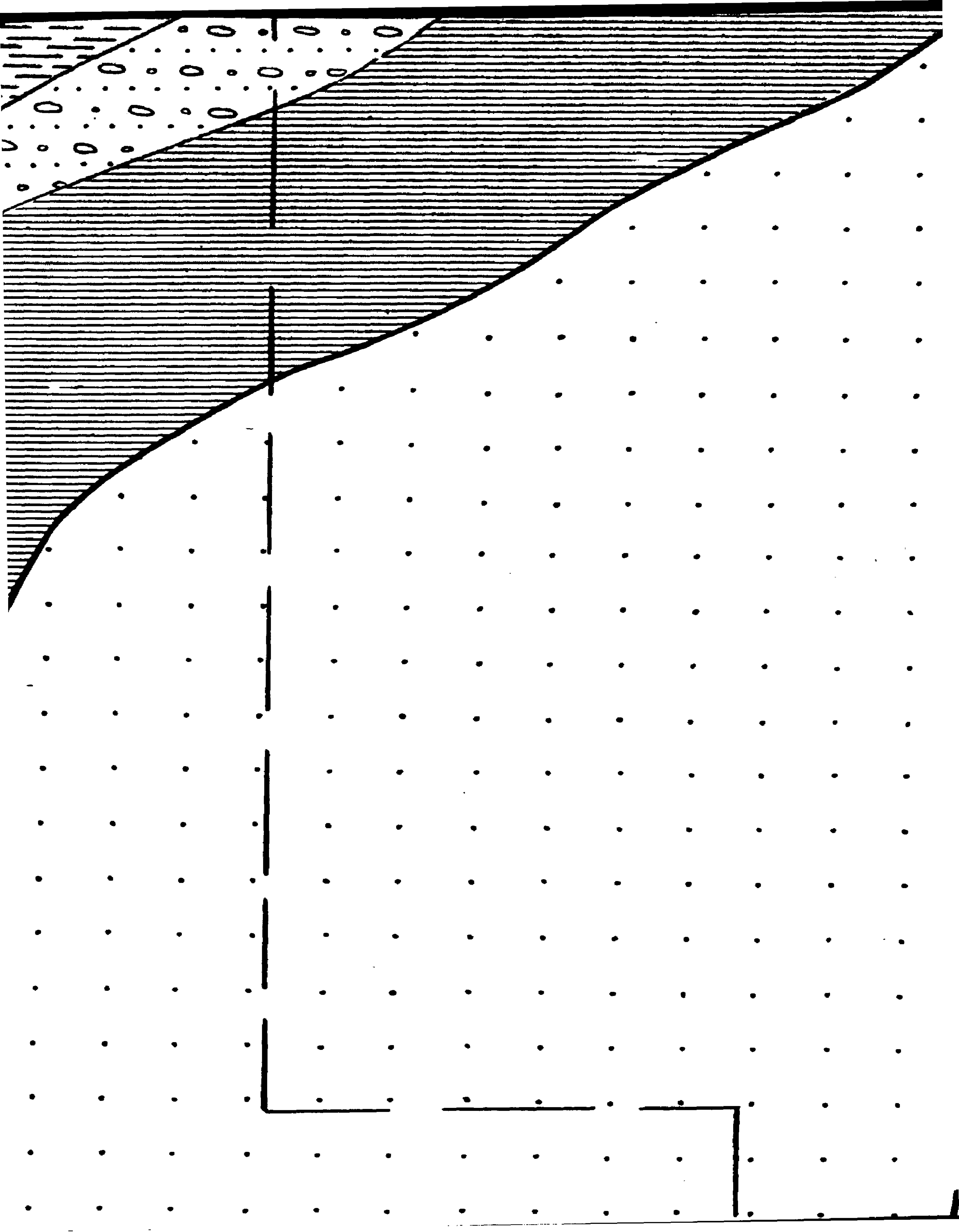
8° 30'
47° 00'
25'
KEWEENAW BAY

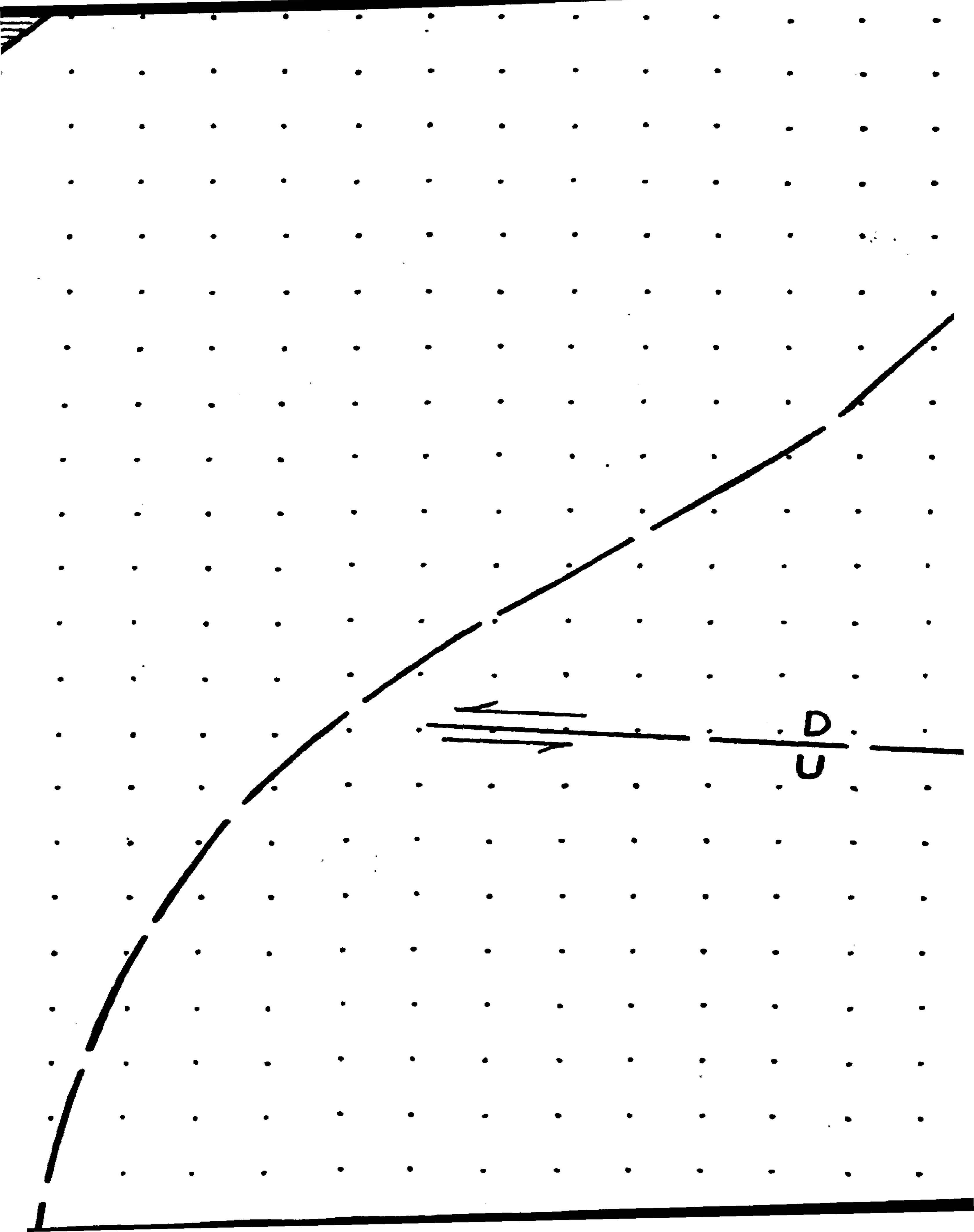
PLATE III-c

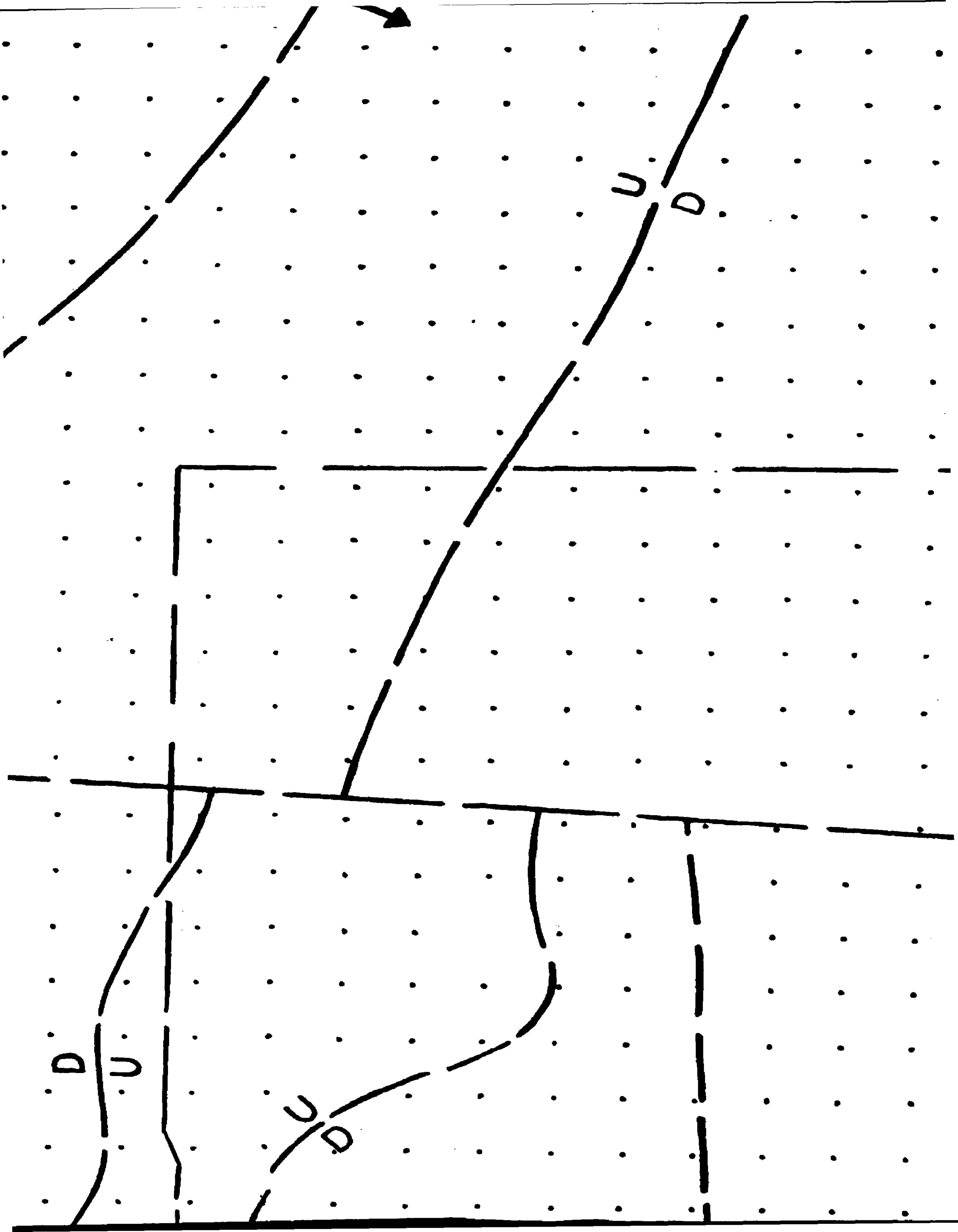


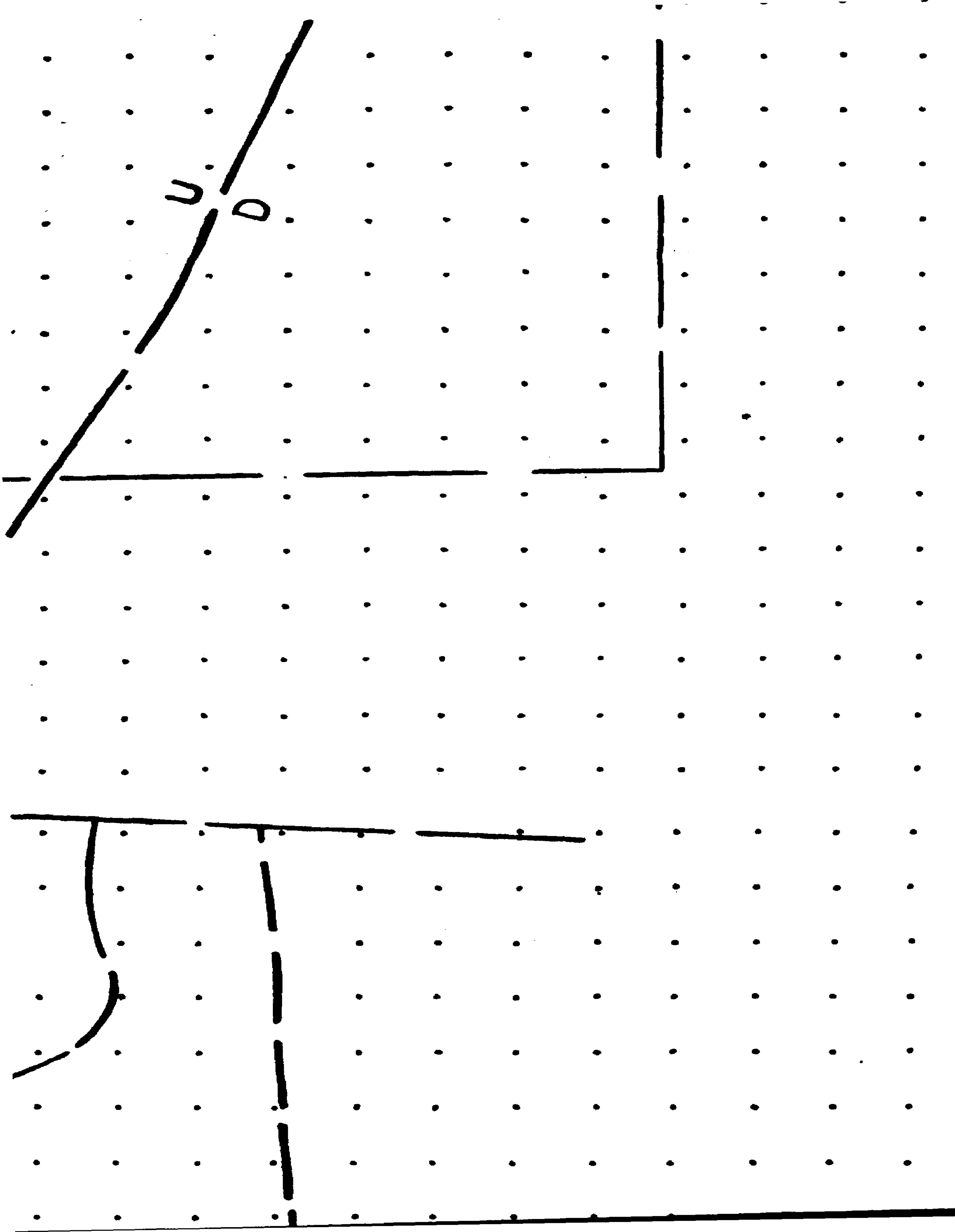

10'
88°07'30"
46°5
HURON
B
T 52 N

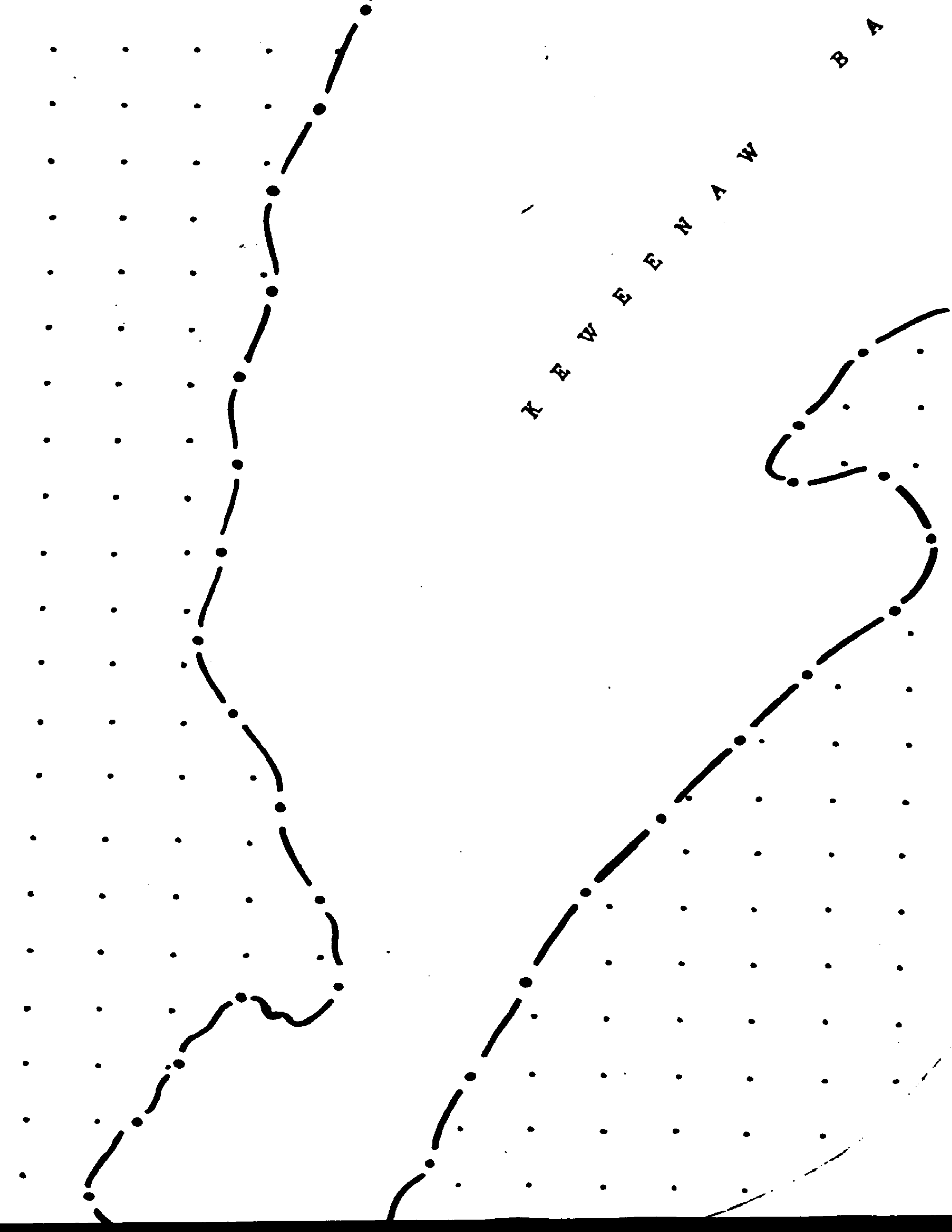

T 52 N
T 51 N

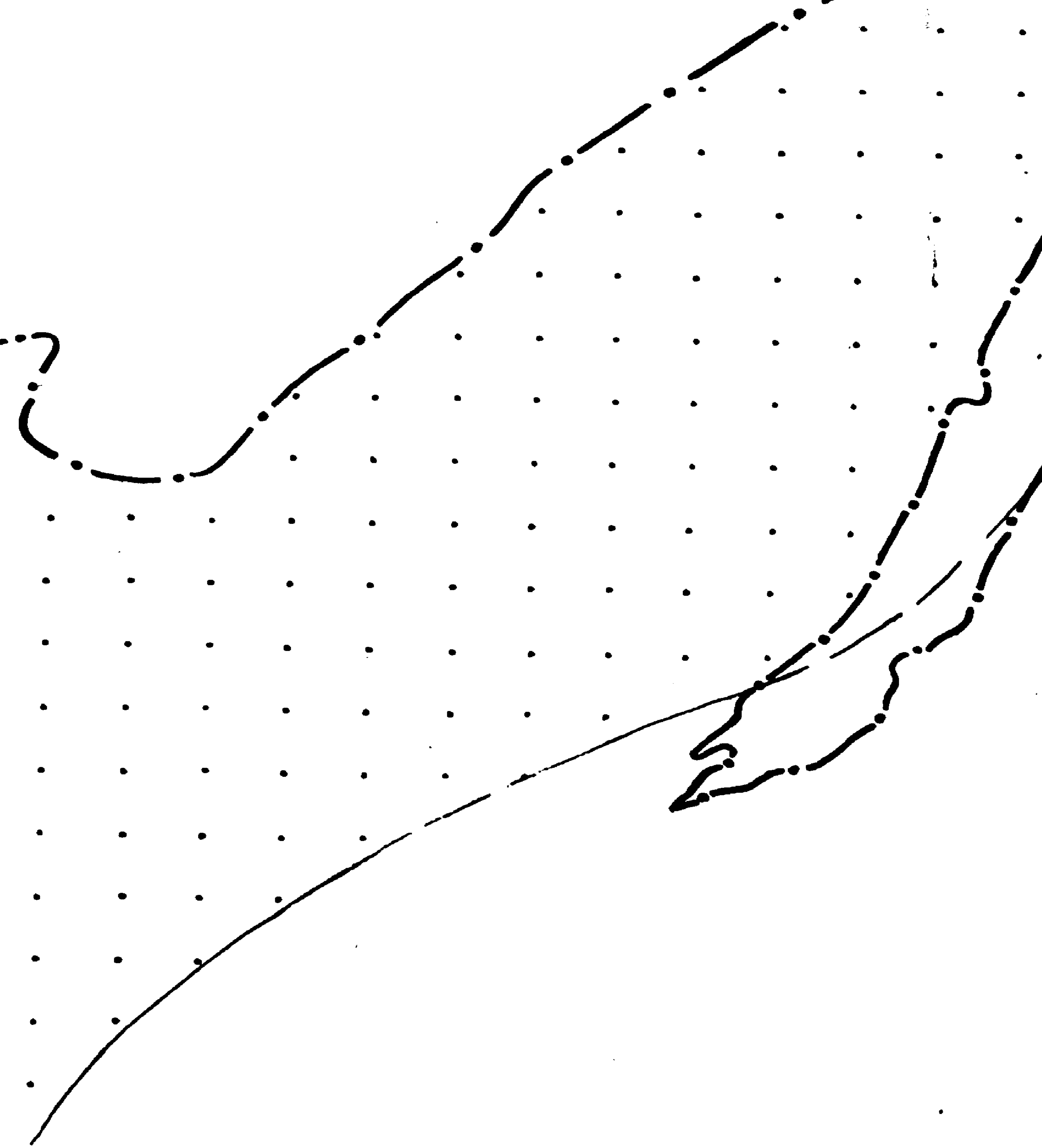


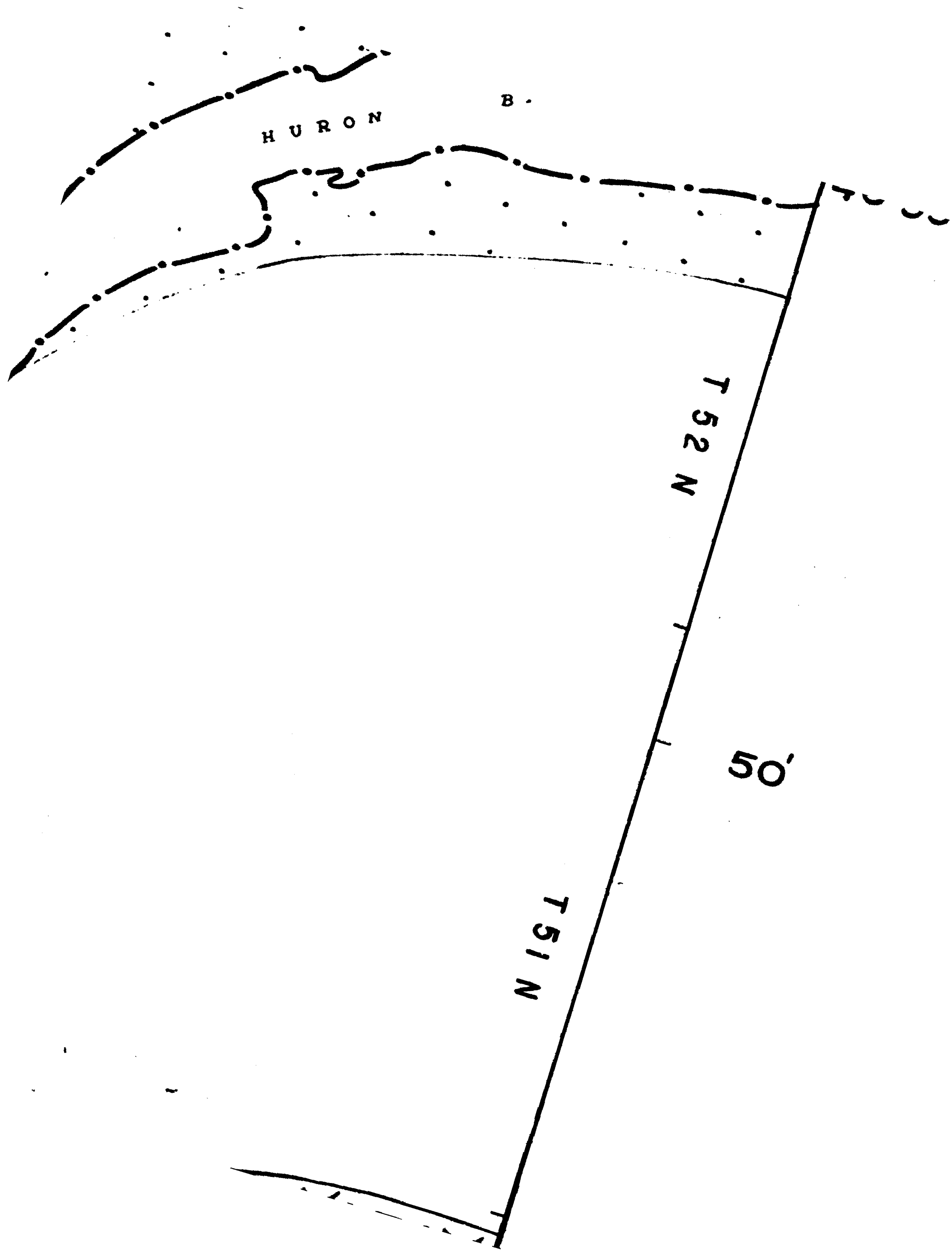

D
U


U
D
D
U
U
D

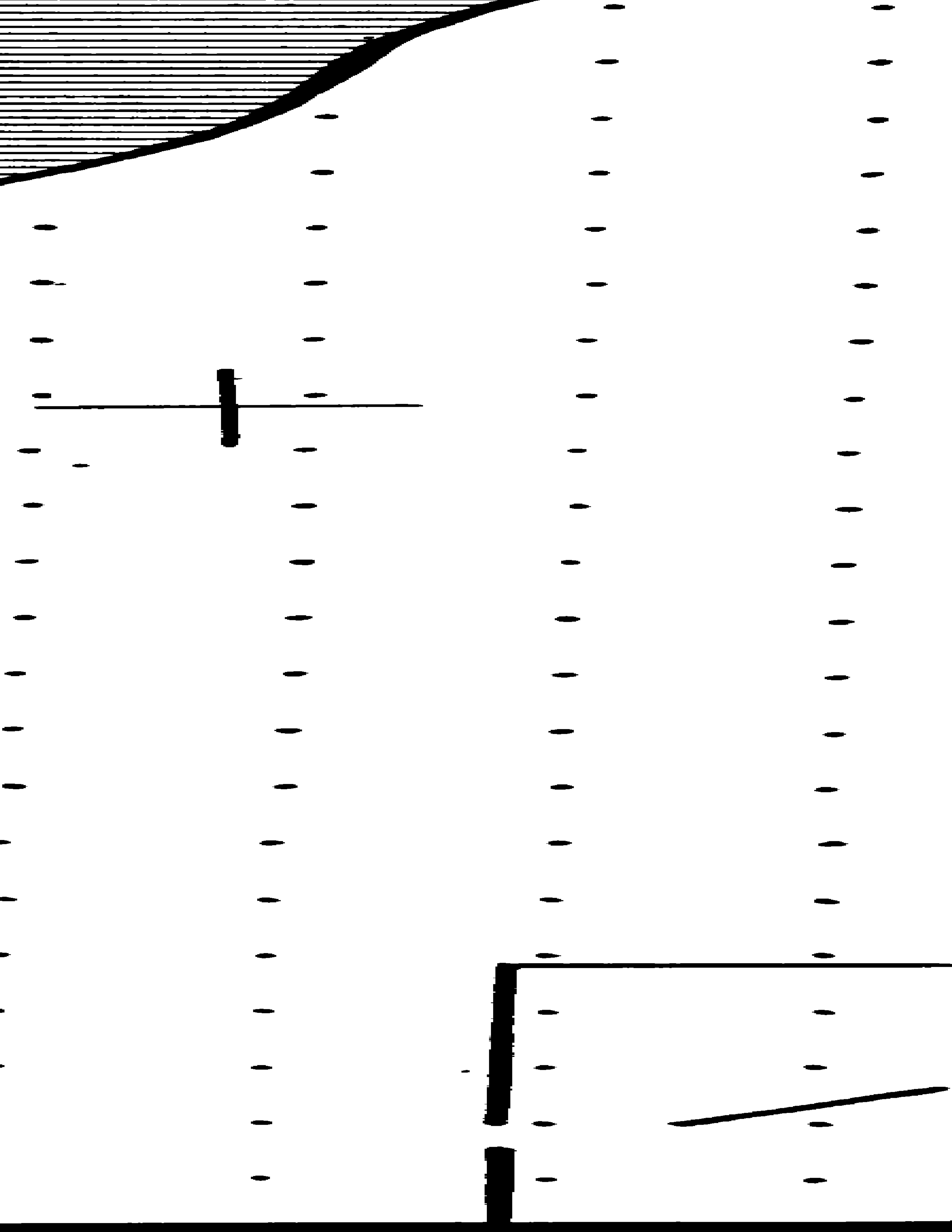


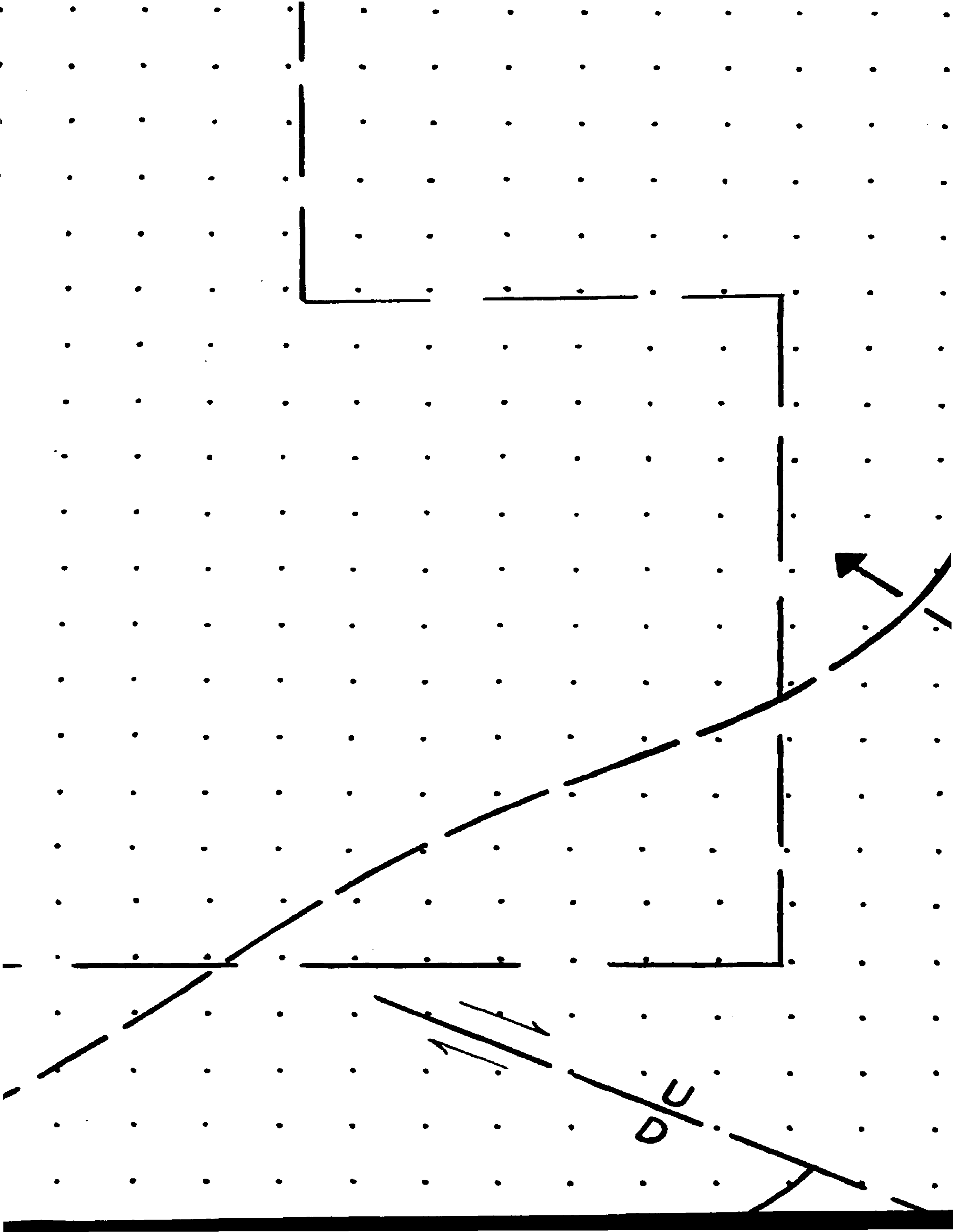

K E W E E N A W B A

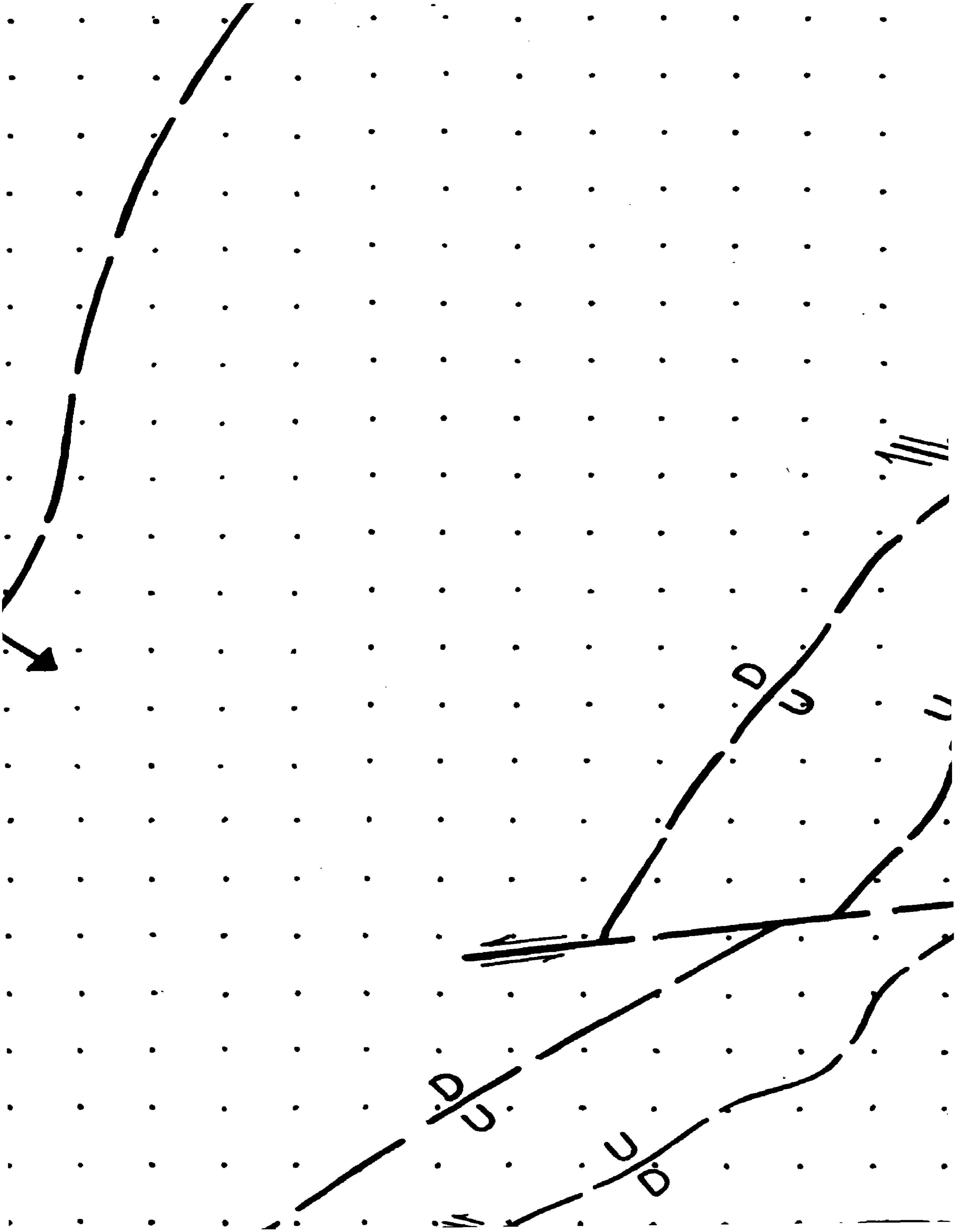


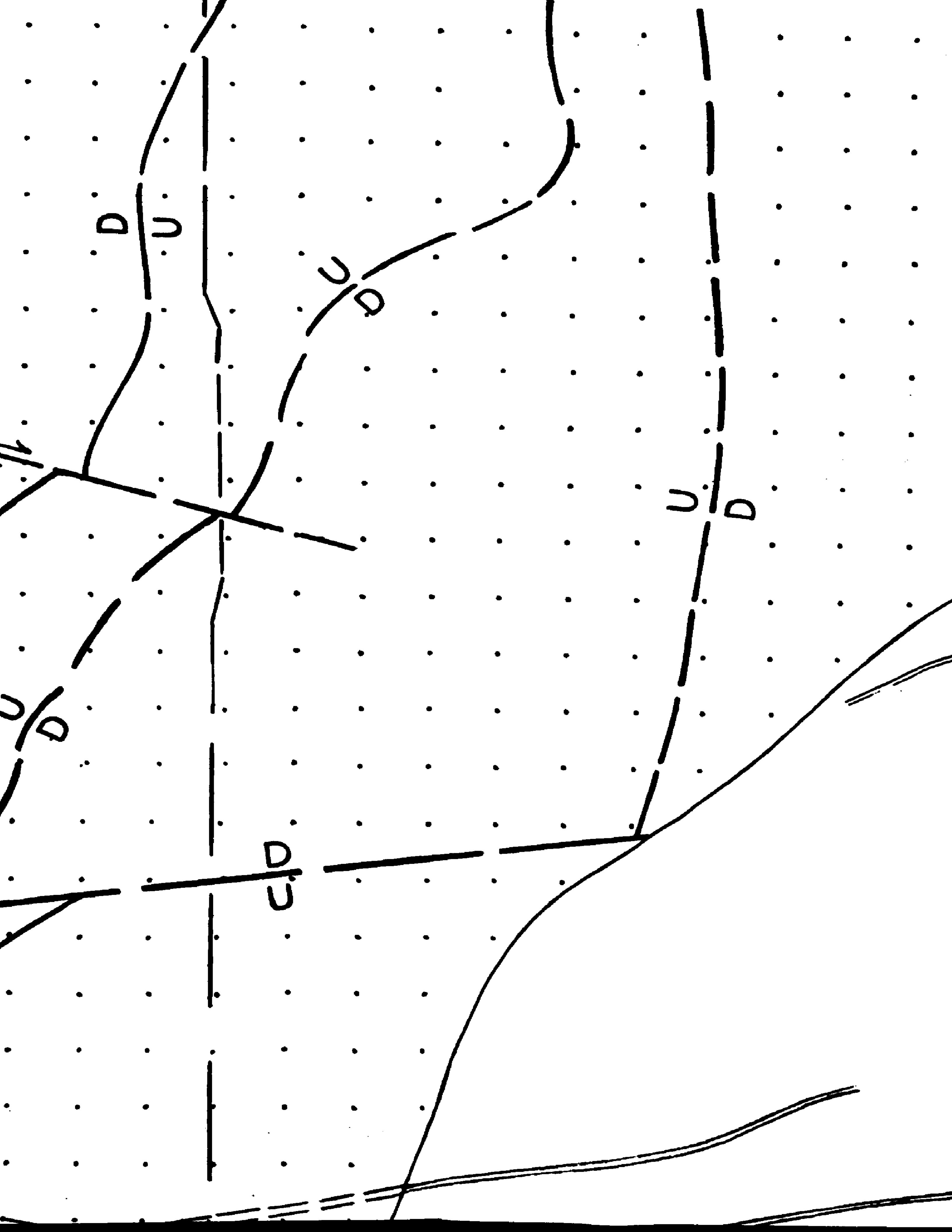


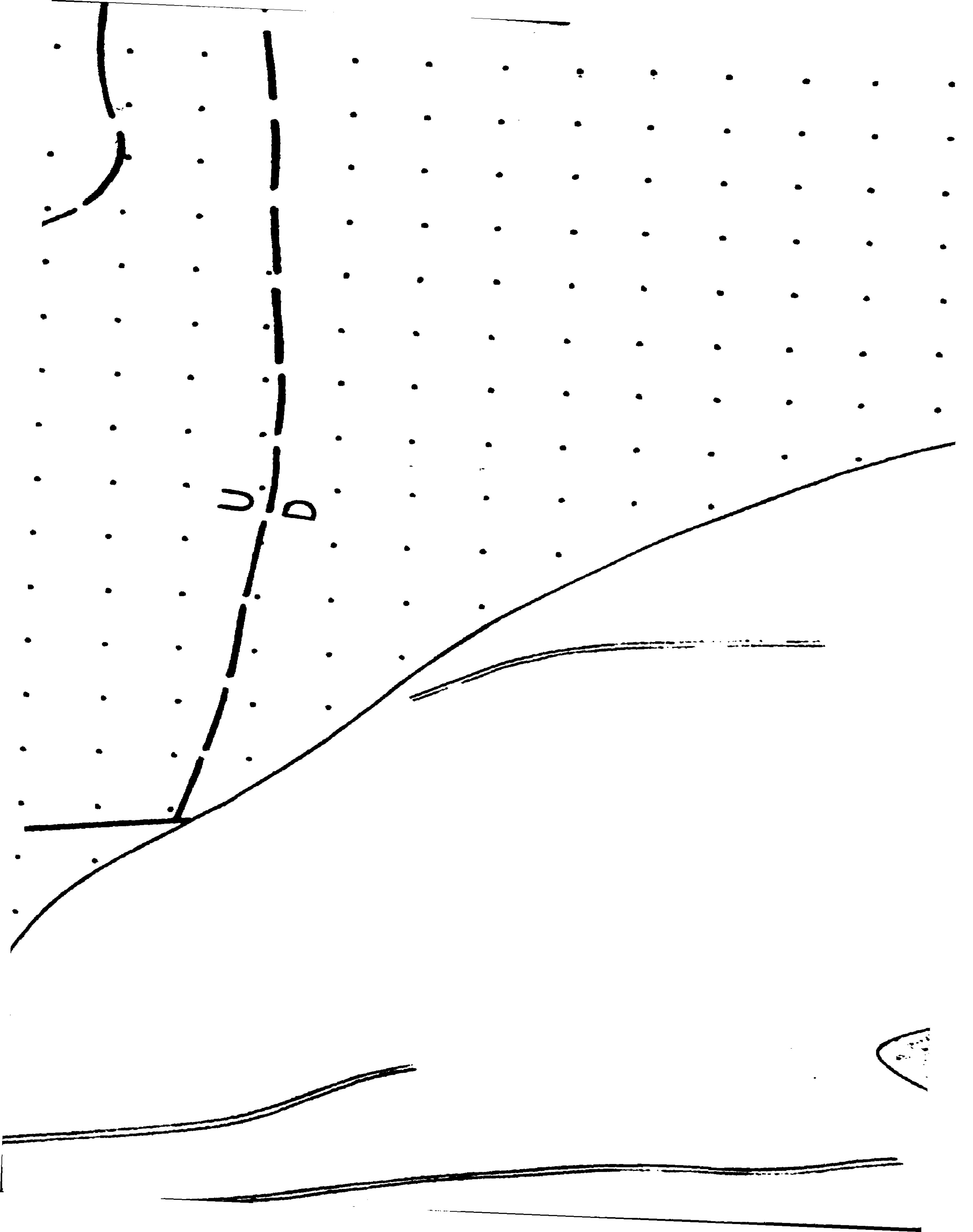
HURON B
T 52 N
50'
T 51 N

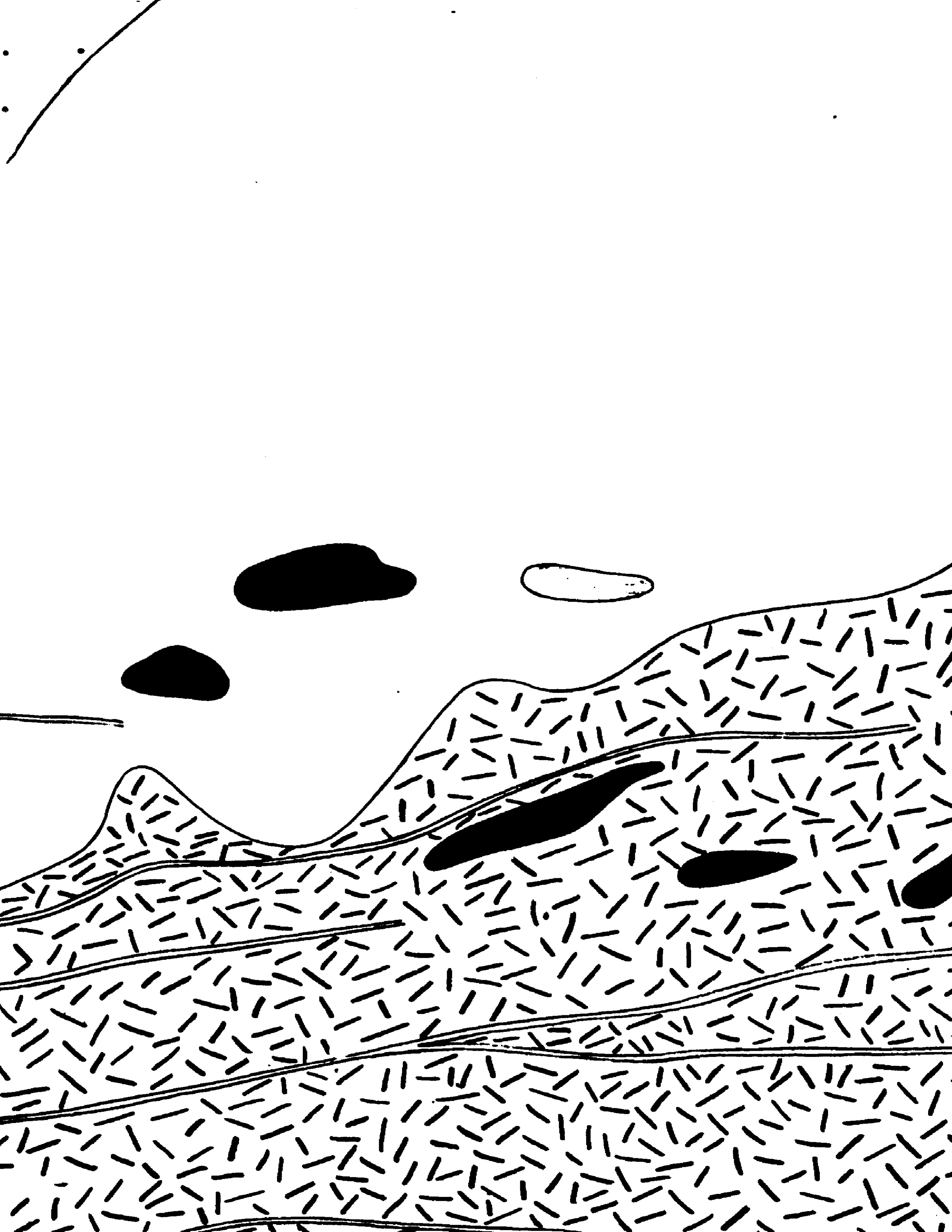


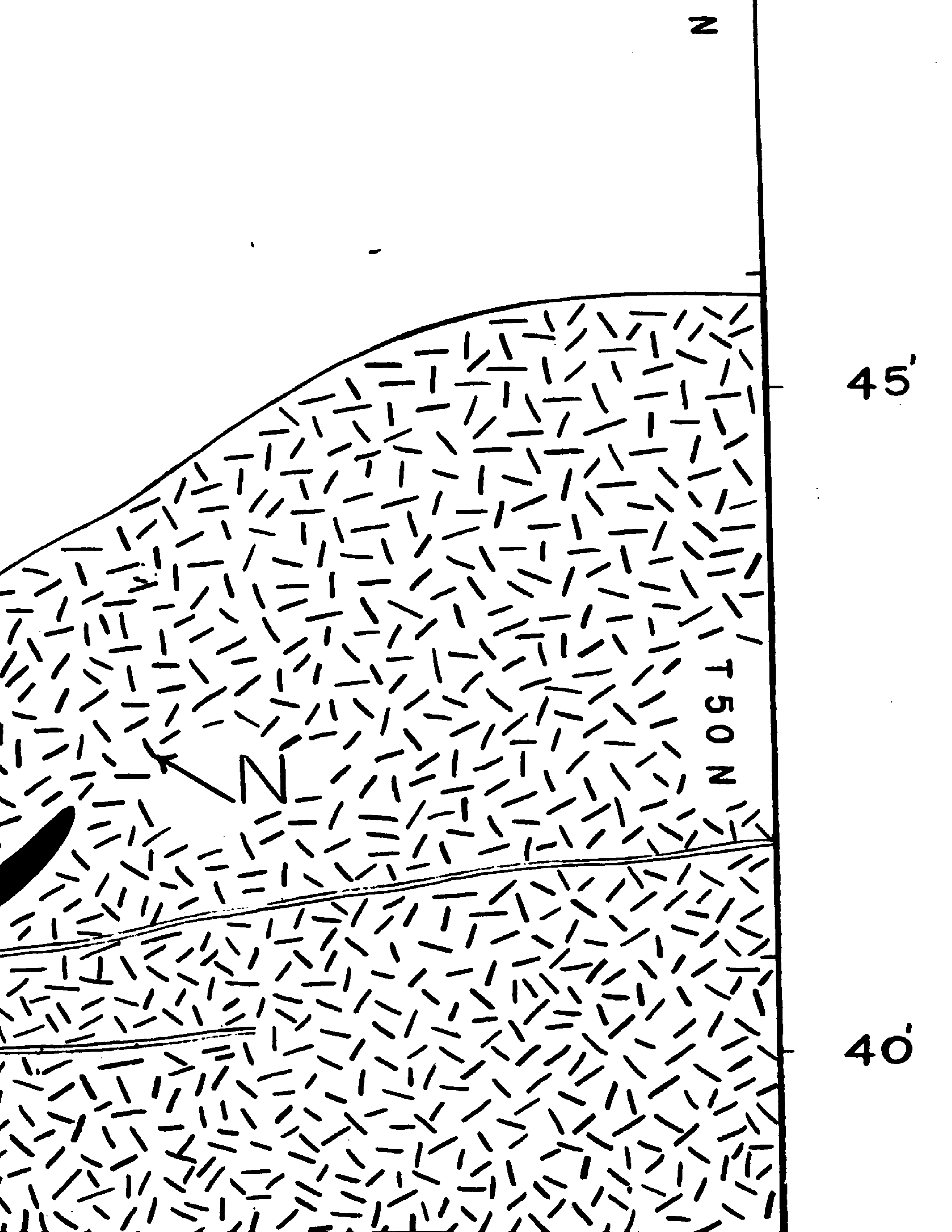

U
D


D
U
U
D
U
U
D

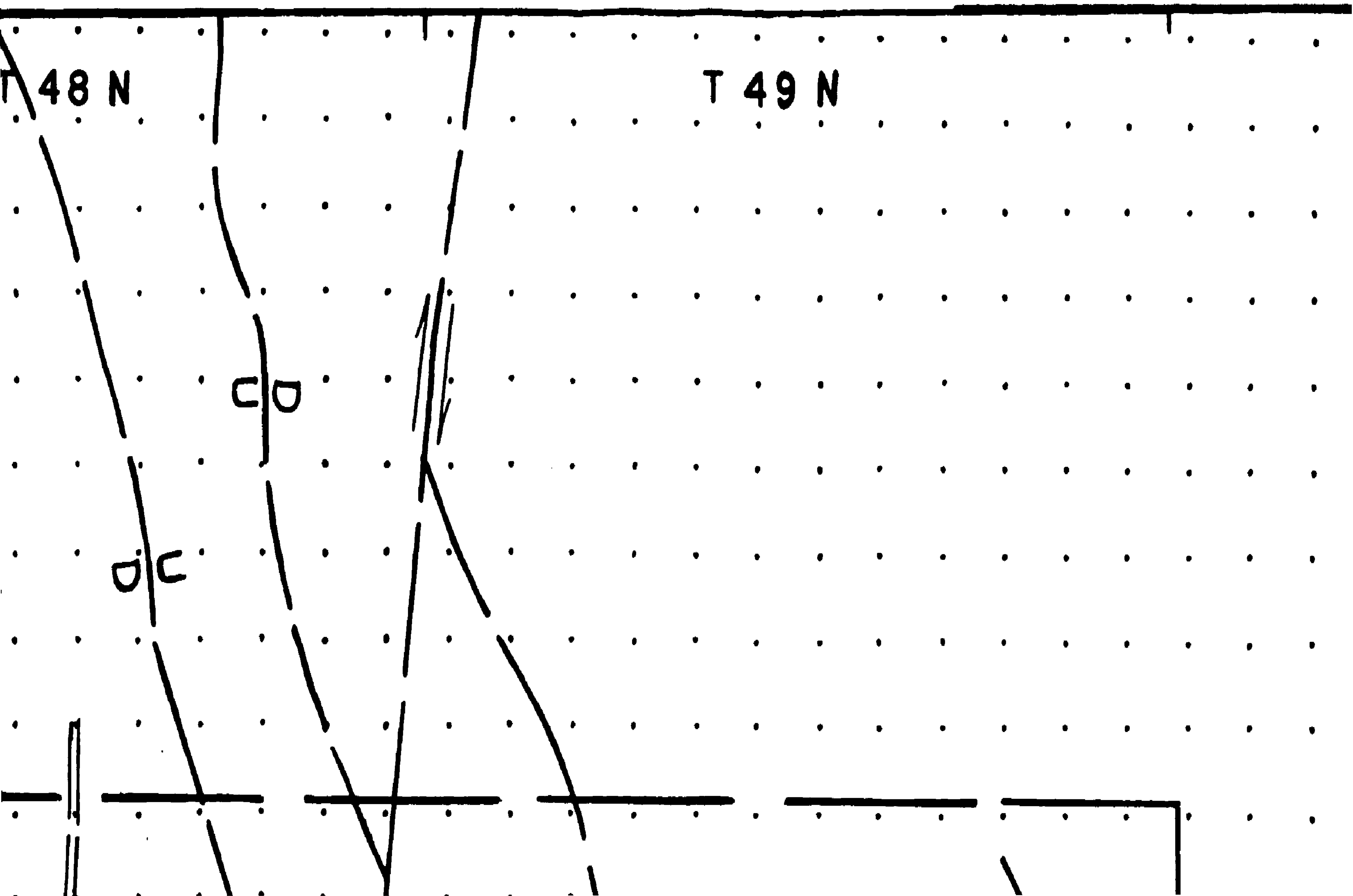

D
U
U
D
U
D
U
D
D
U

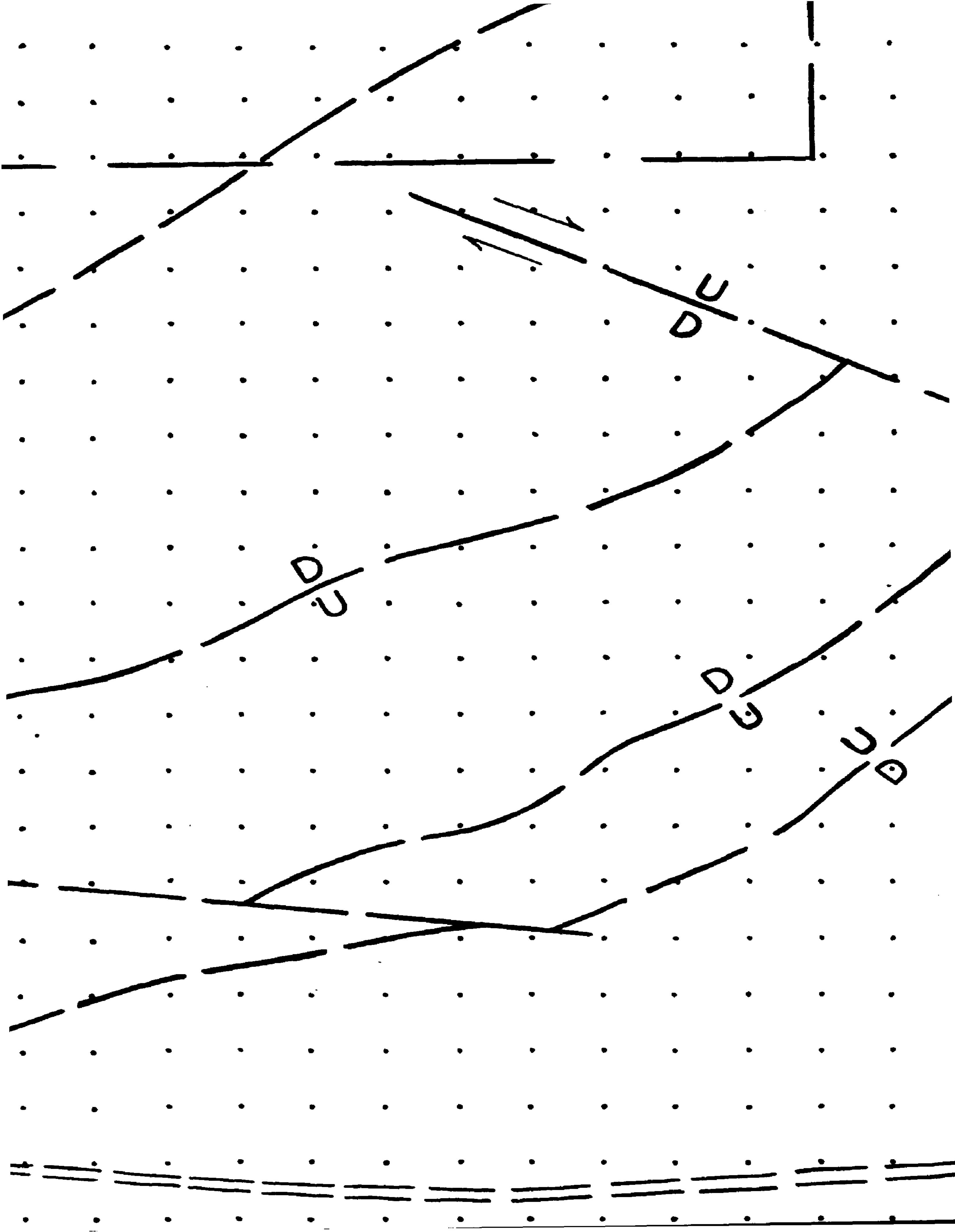

U
D

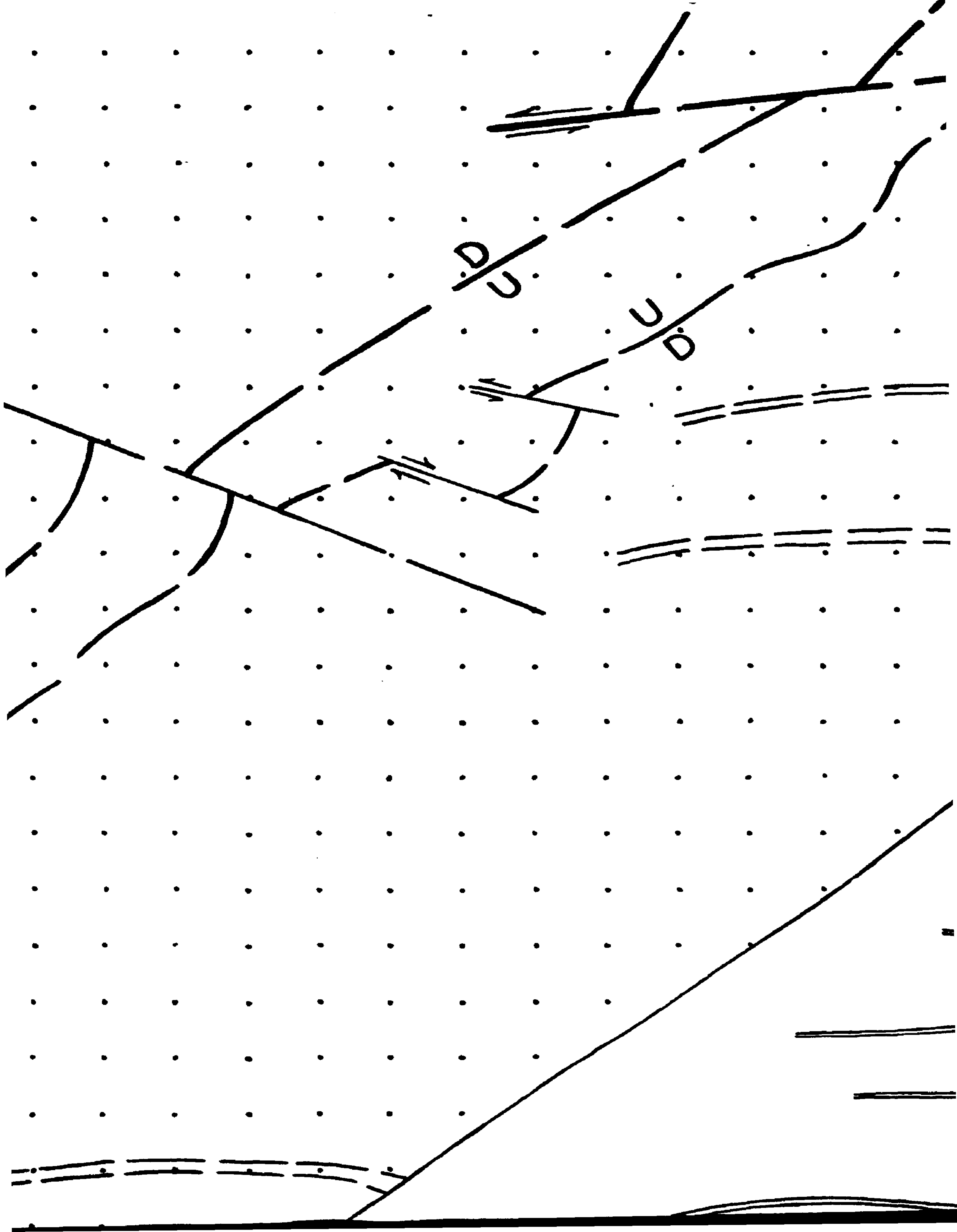


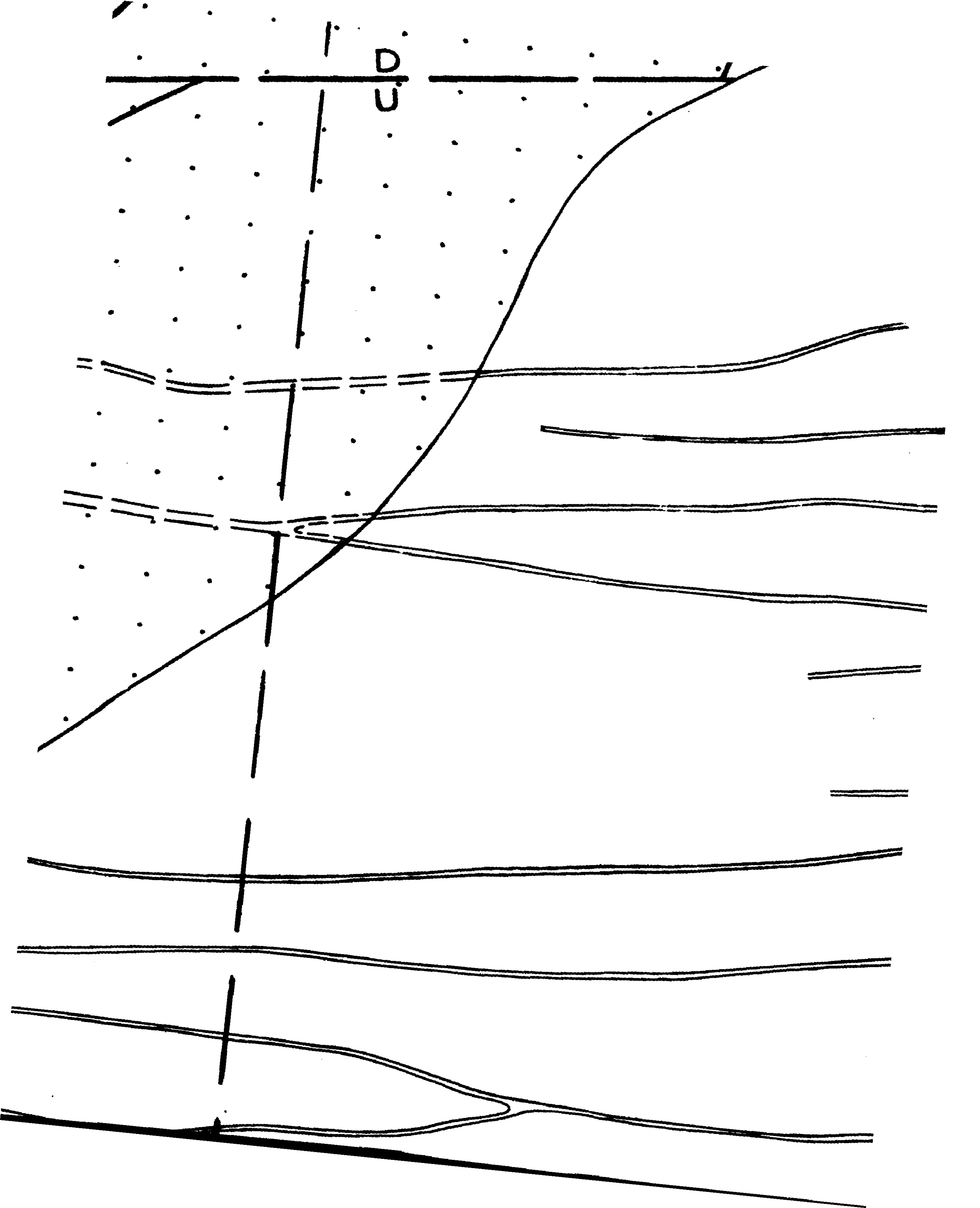


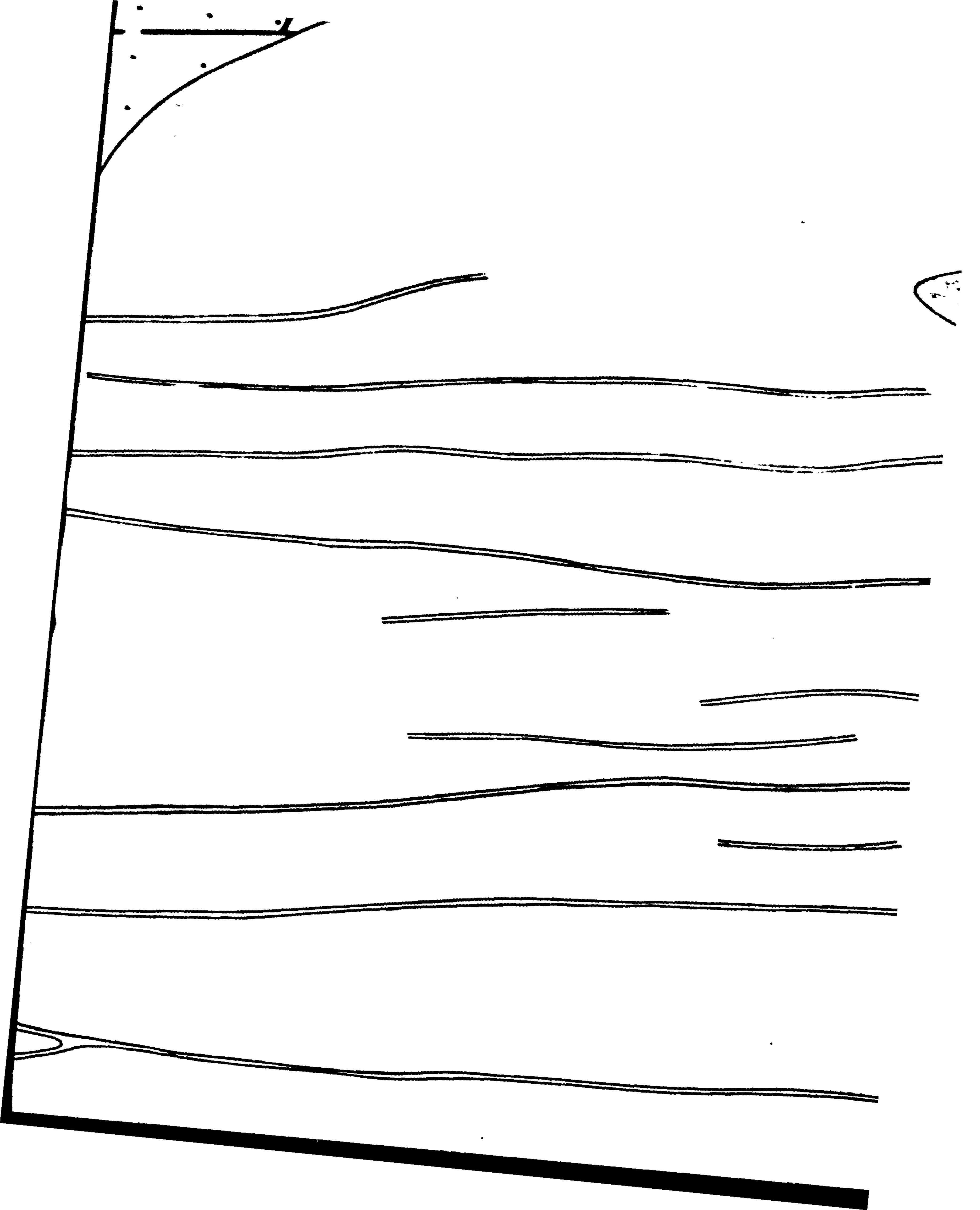
N
45′
40′
T 50 N
N

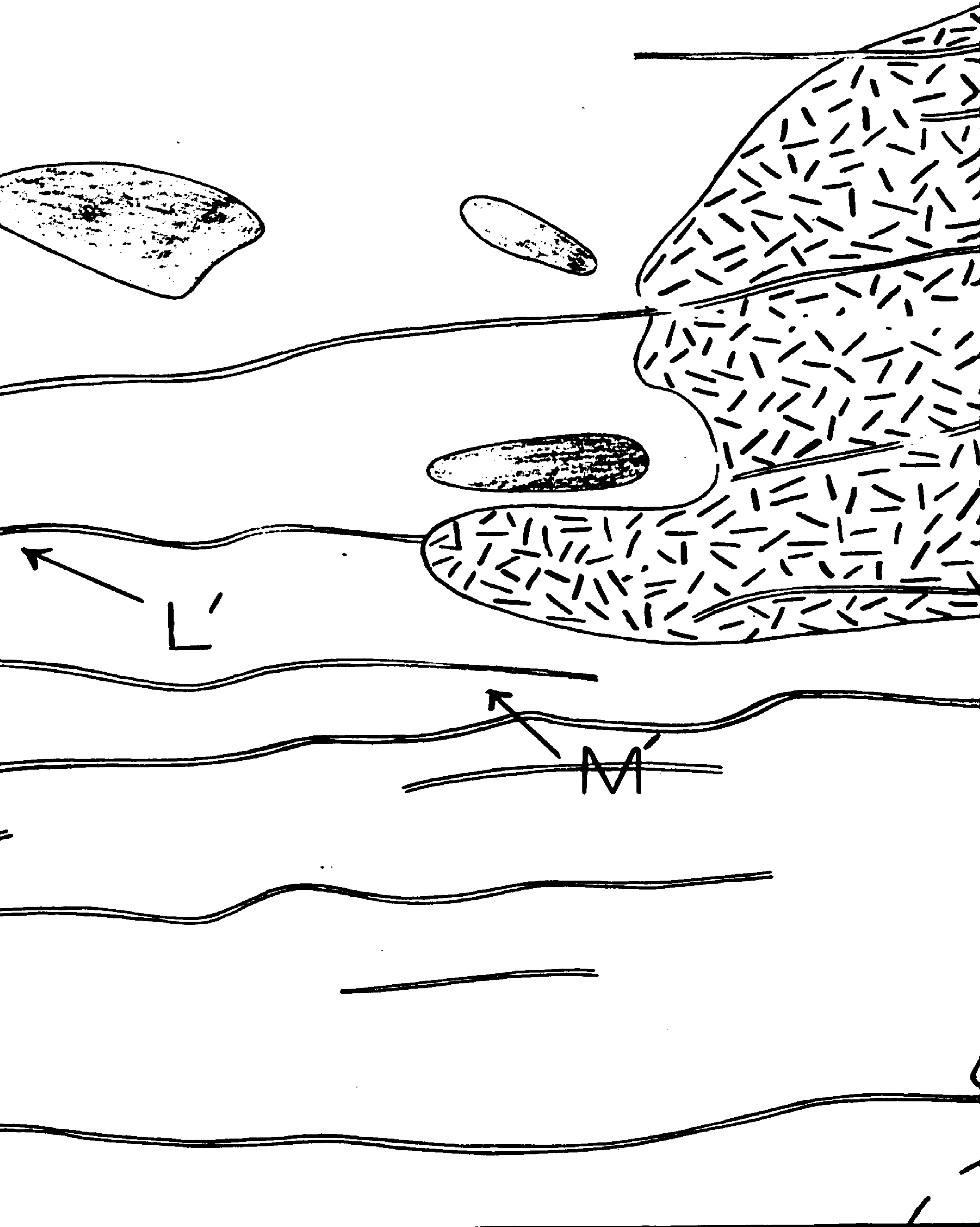

T 48 N
T 49 N
D
U
D
U


U
D
D
U
D
U
U
D

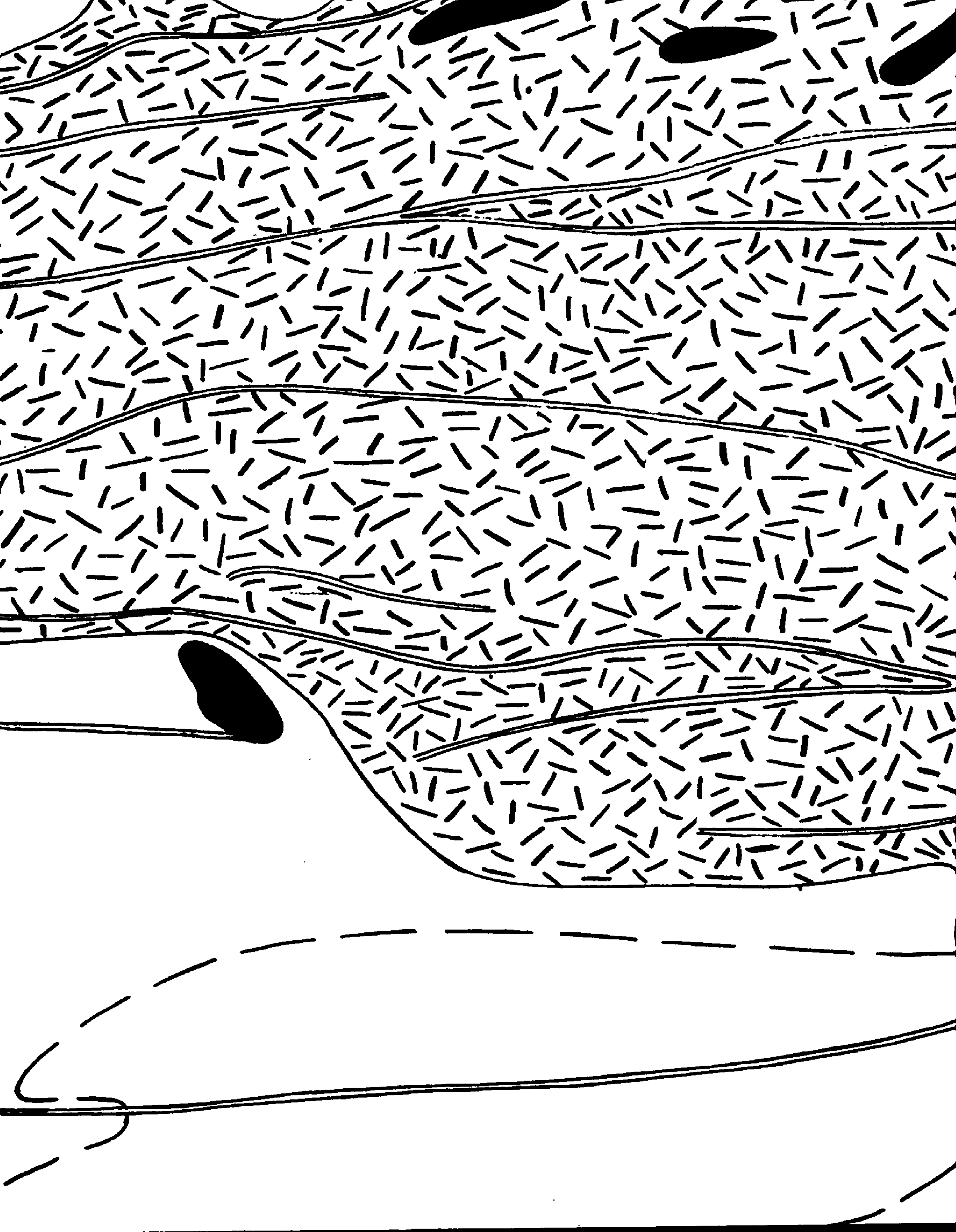

D
U
U
D

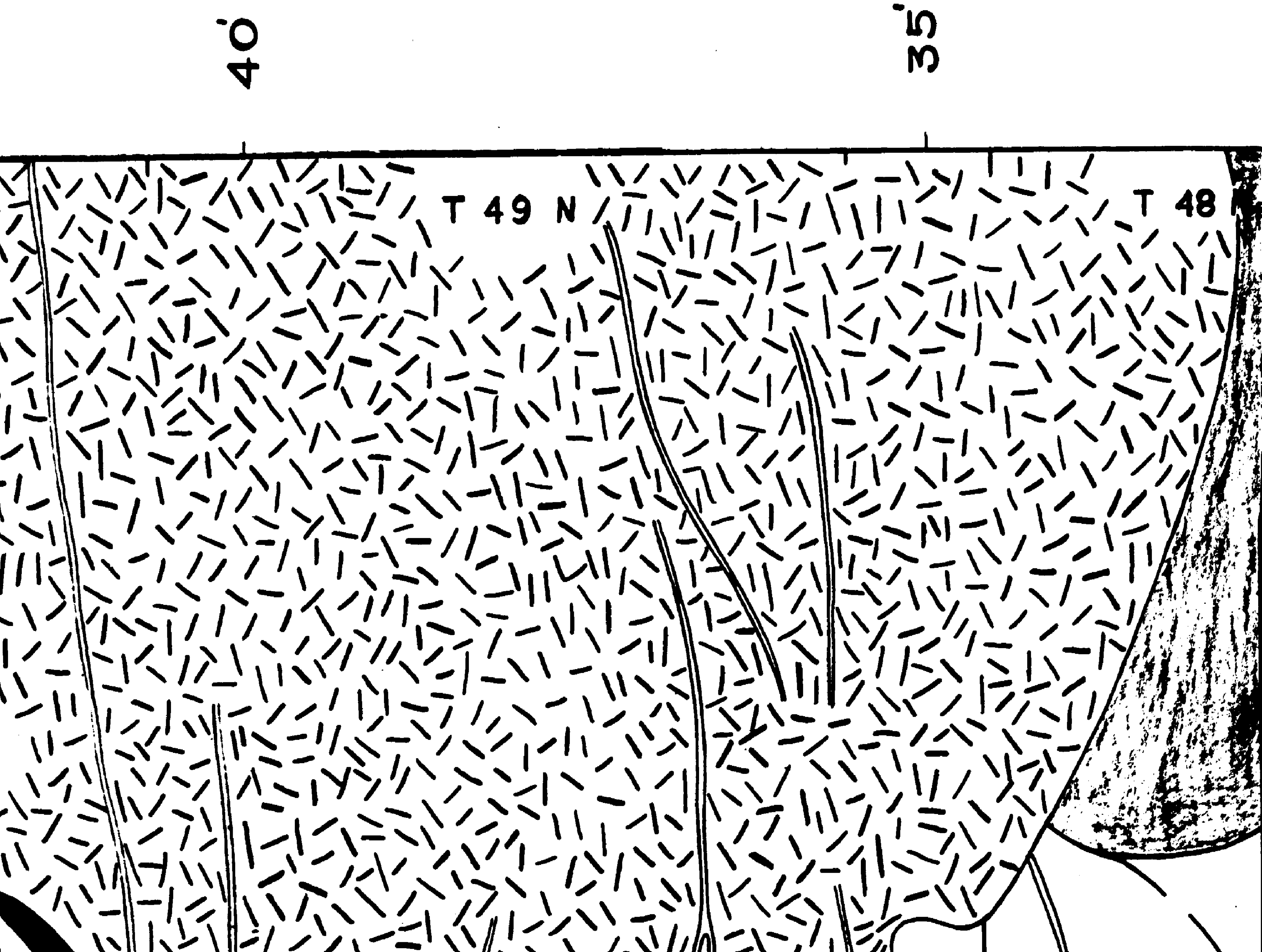

D
U

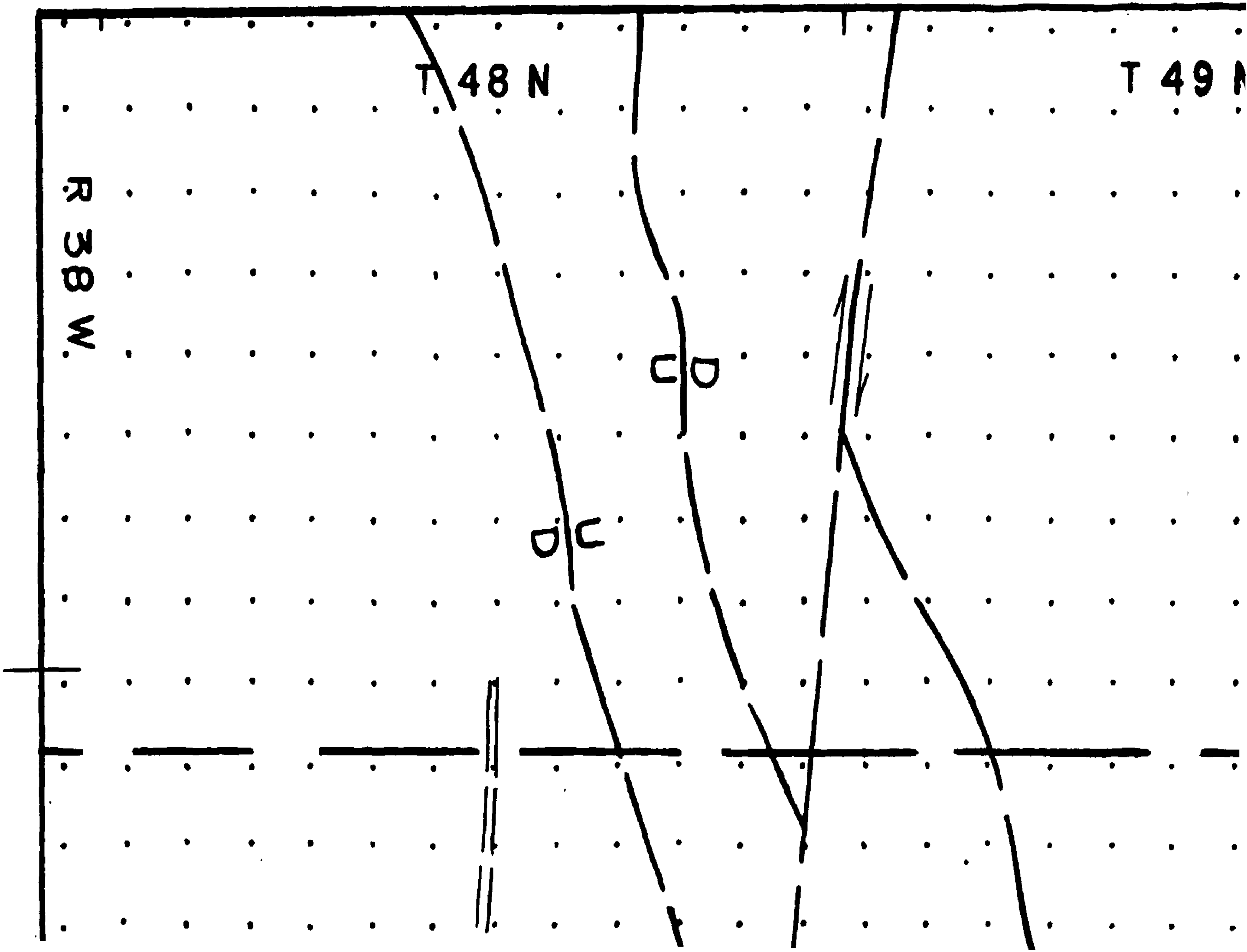


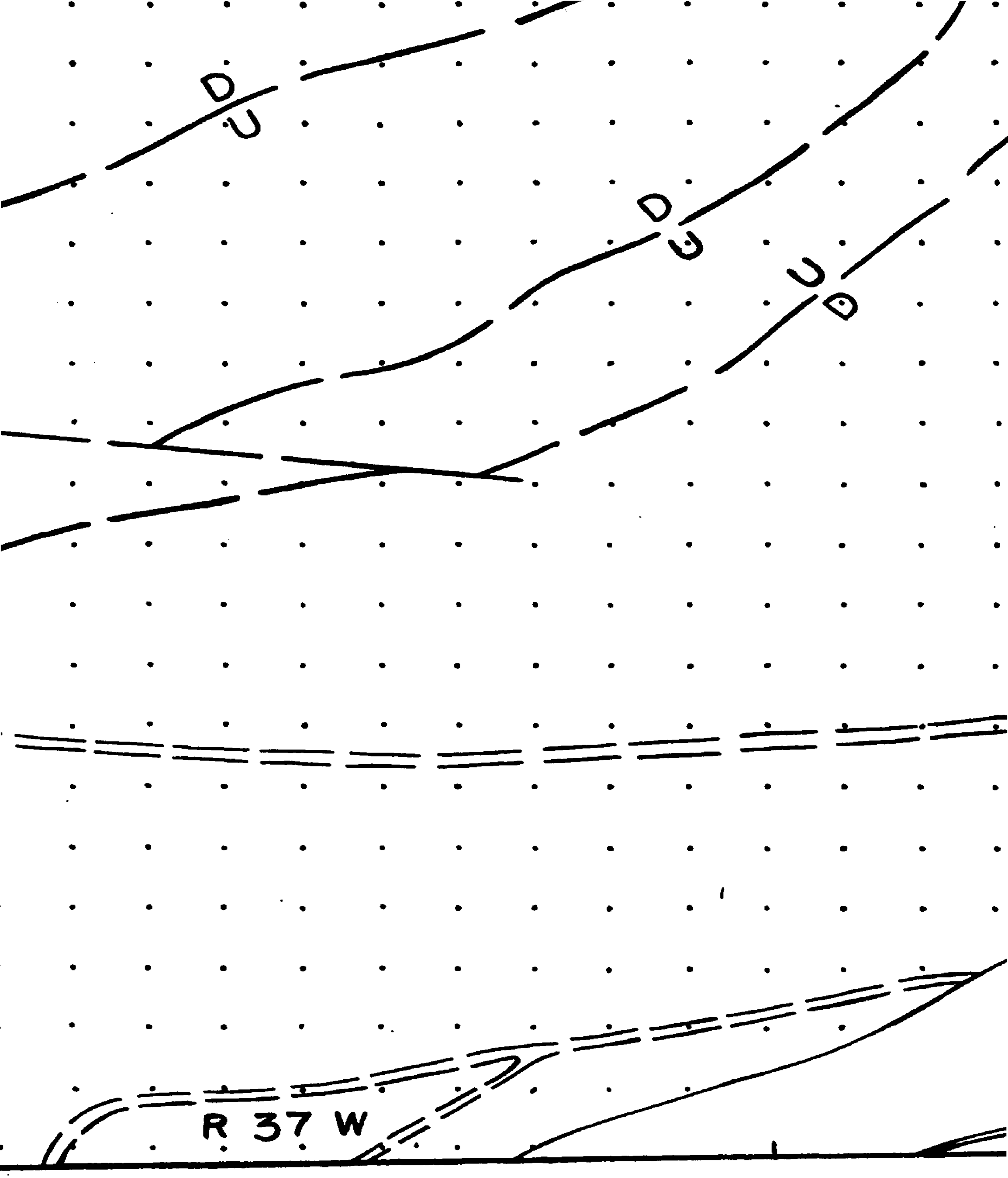


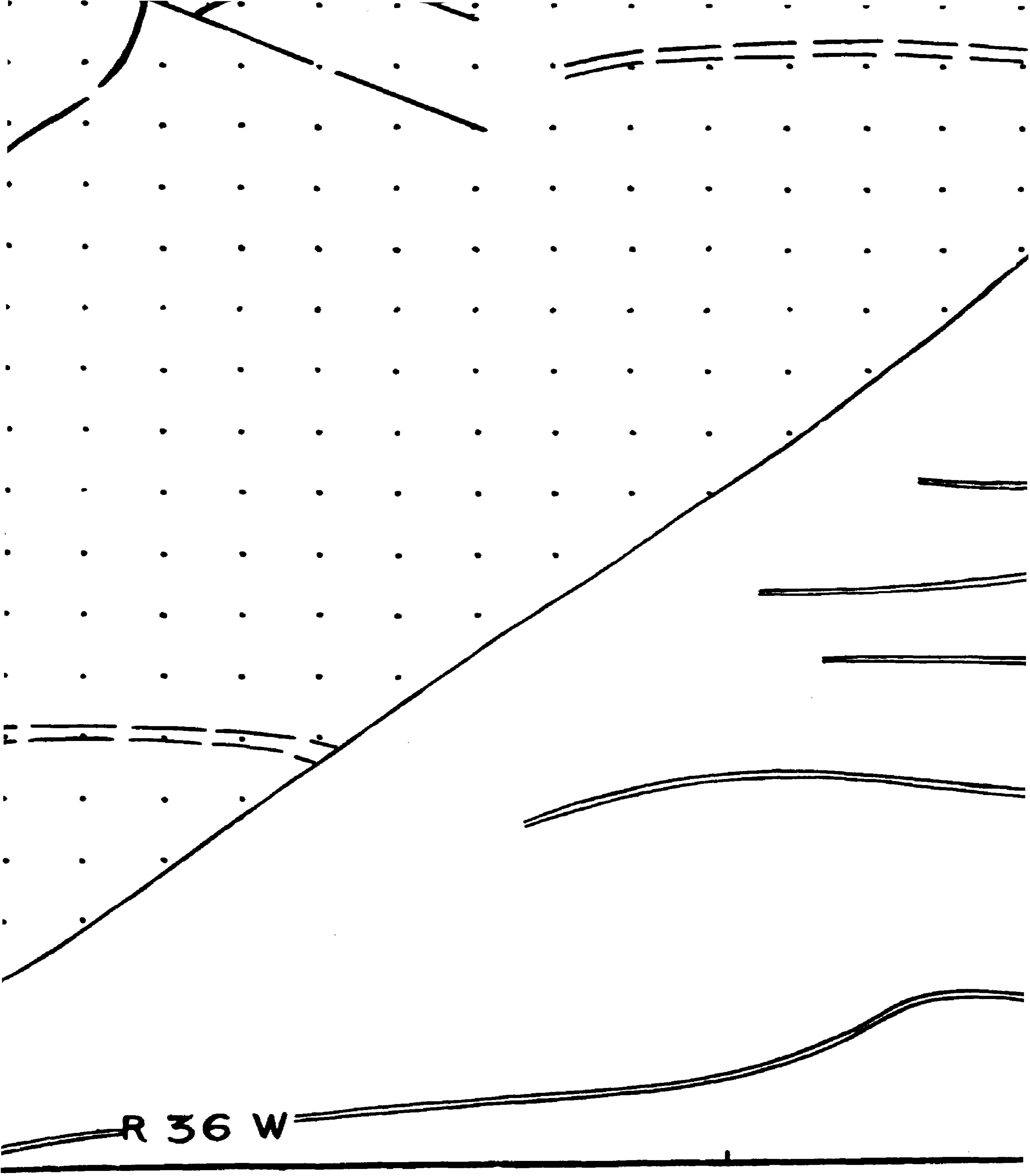
L′
M′

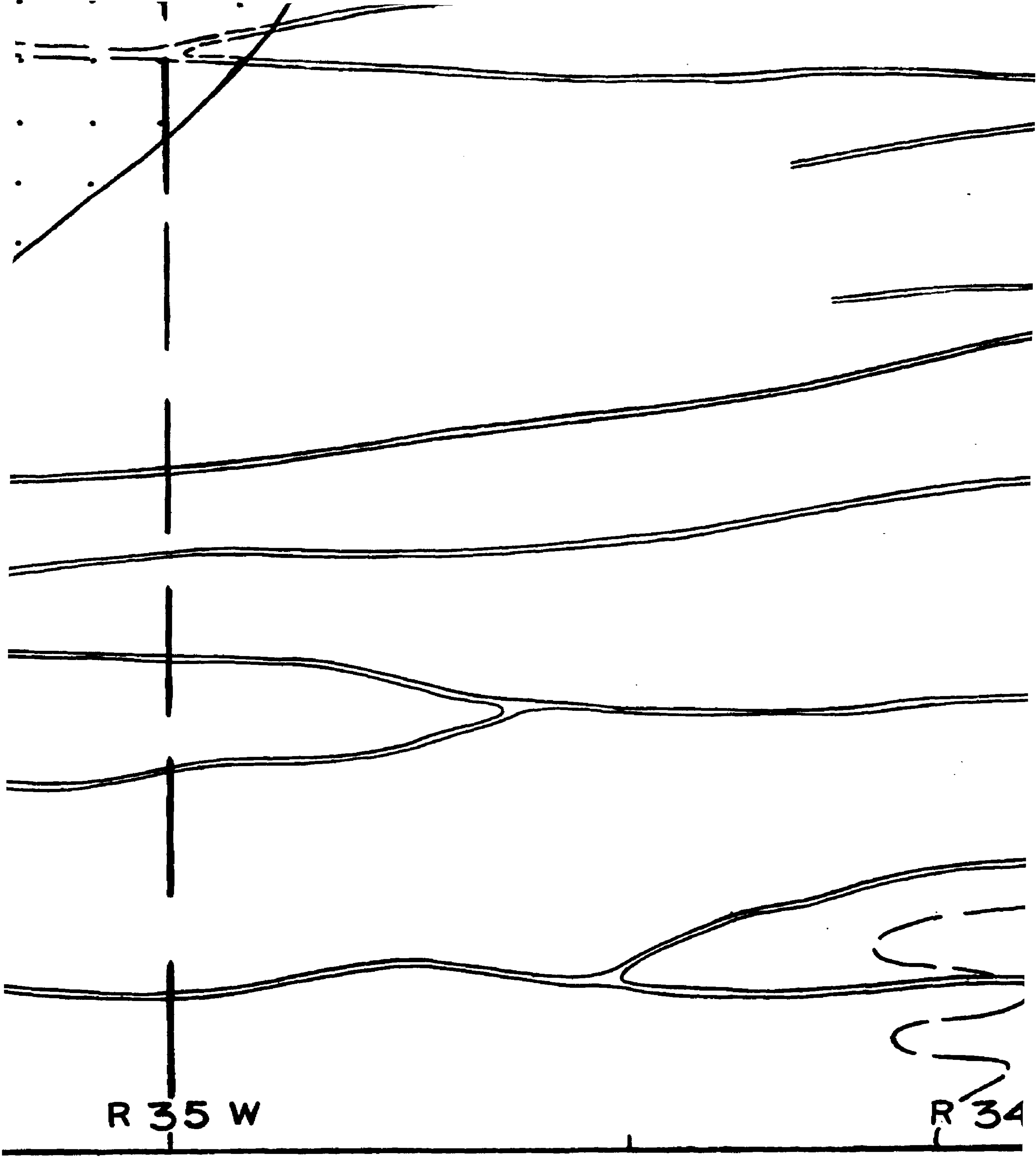


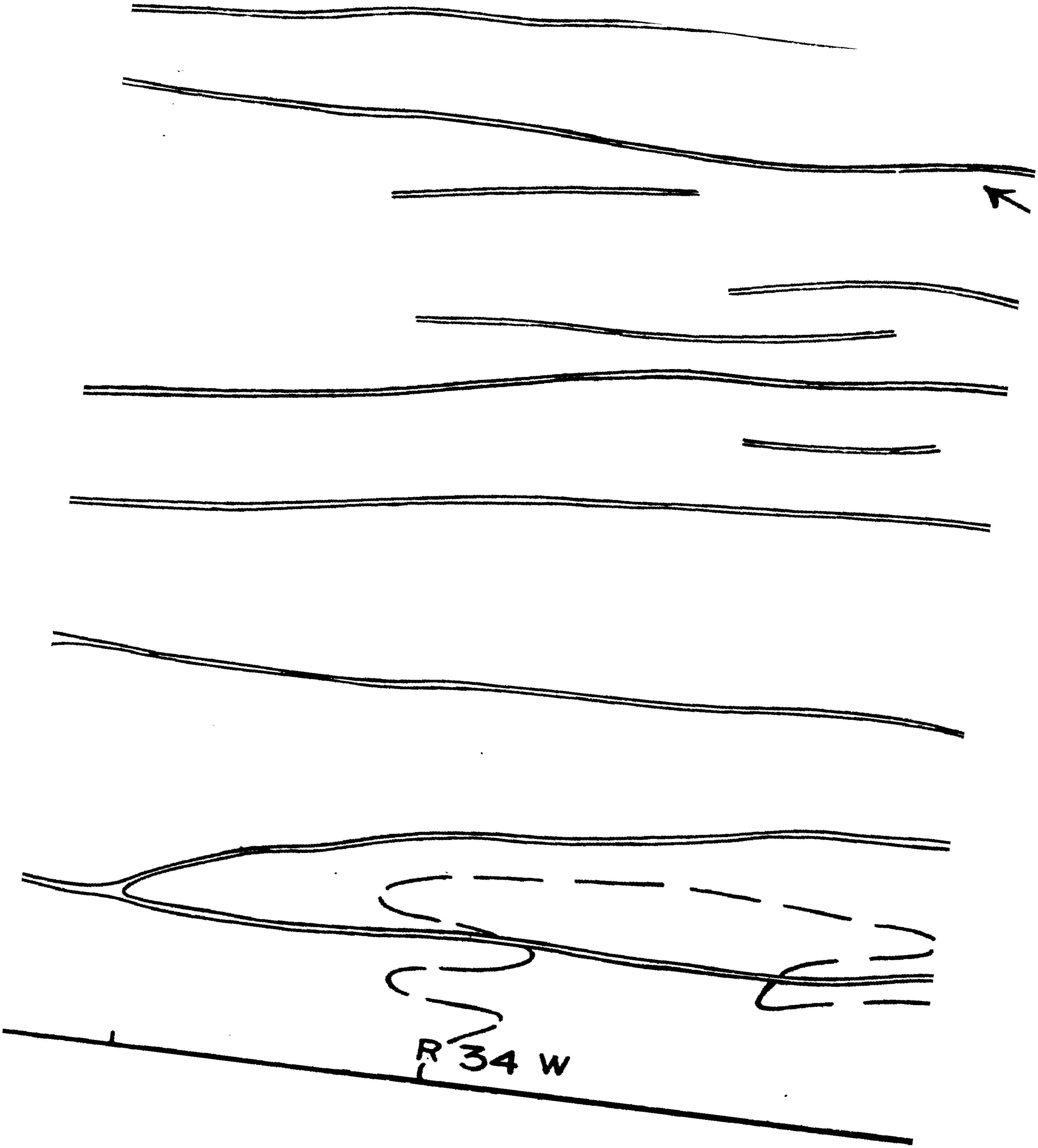

40'
35'
T 49 N
T 48

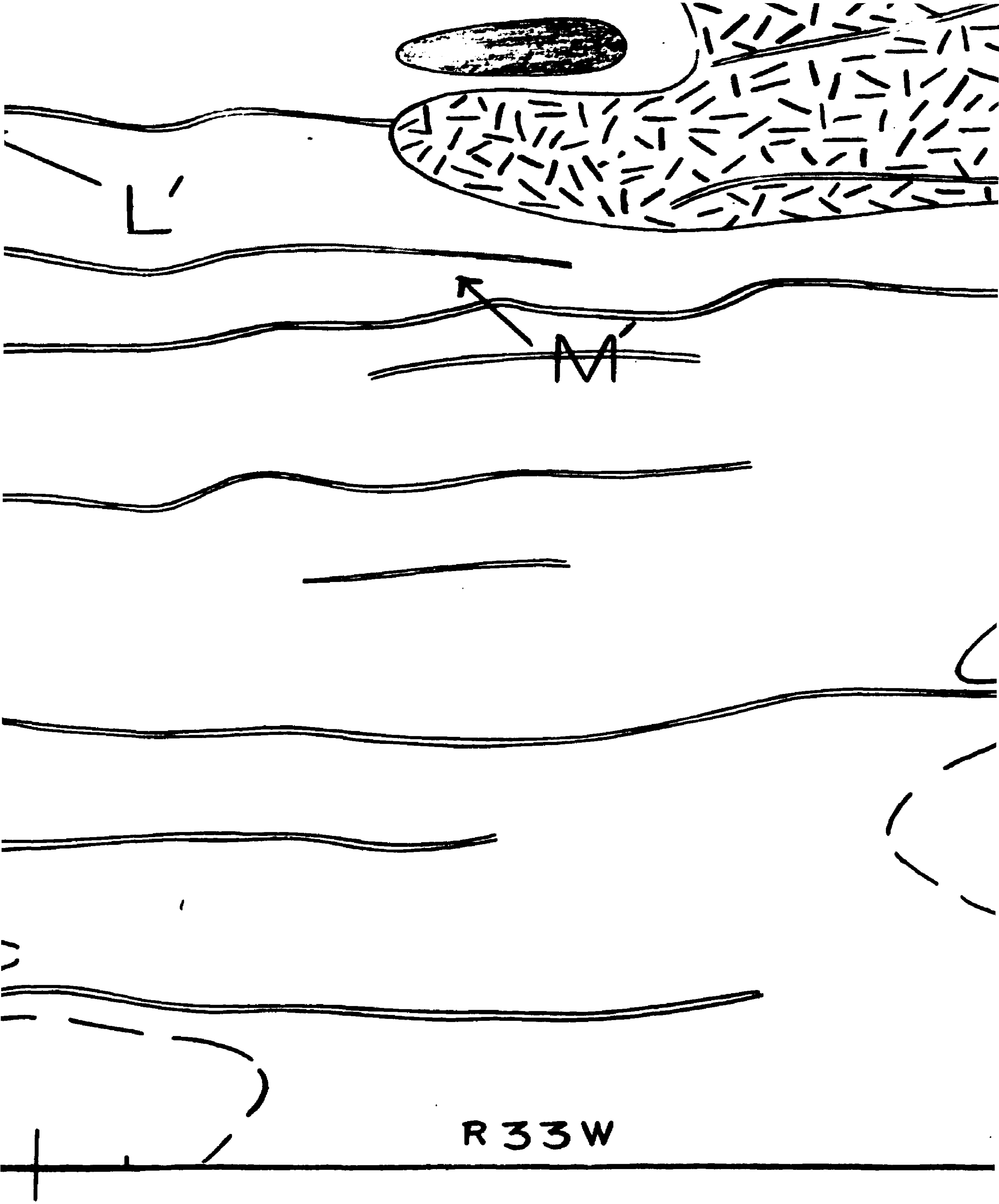

T 48 N
T 49 N
R 38 W
U
D
D
U

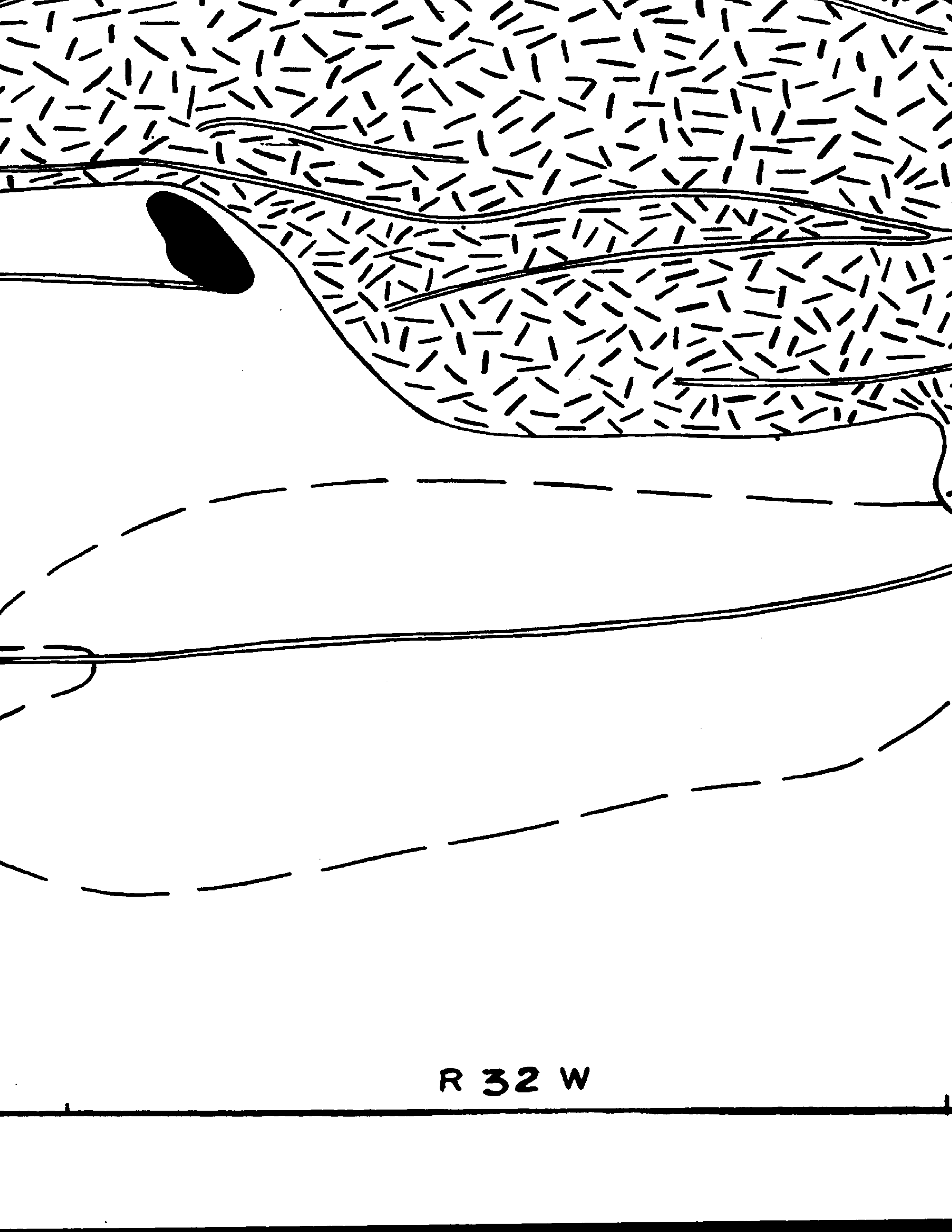

D
U
D
U
U
D
R 37 W

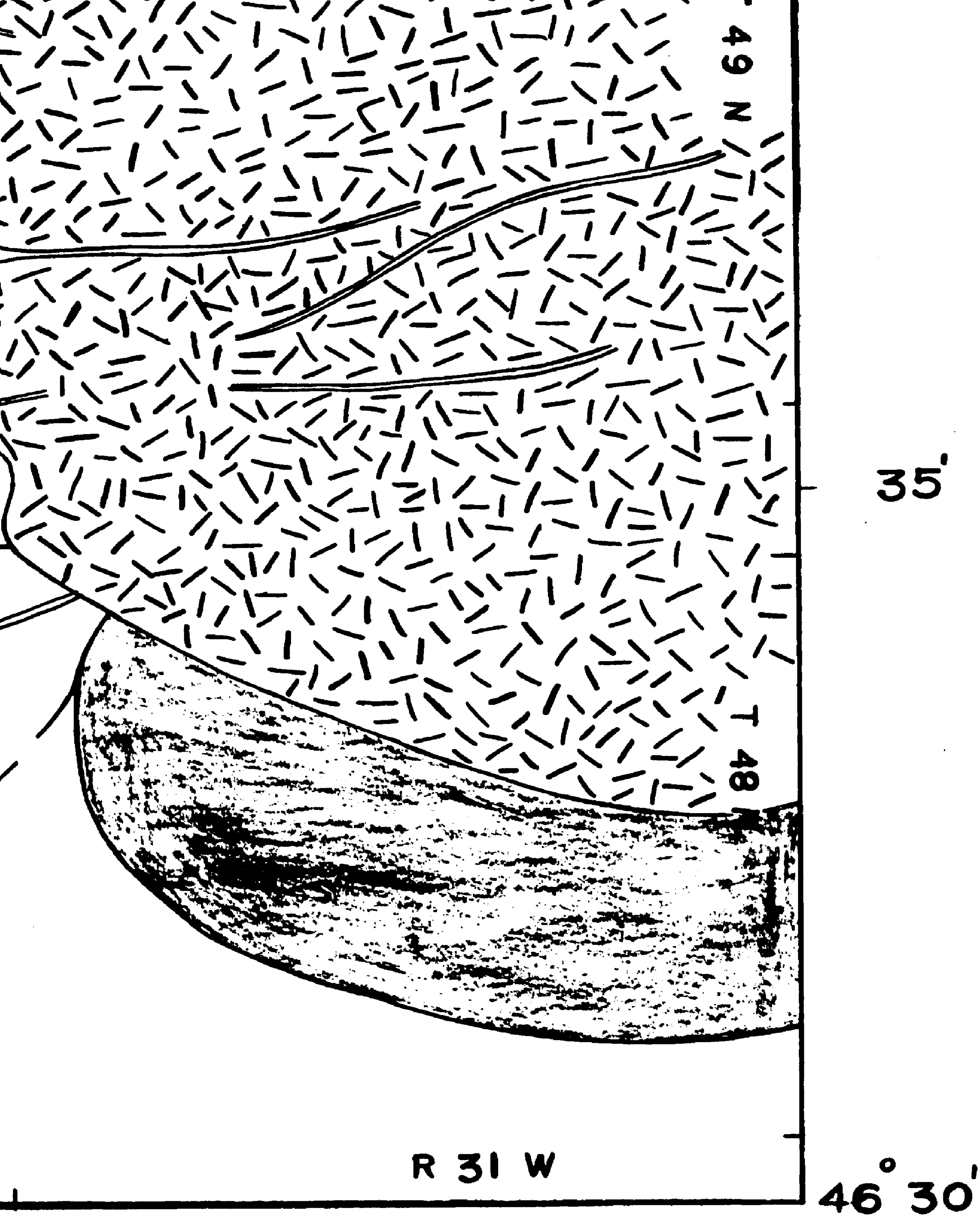

R 36 W


R 35 W
R 34

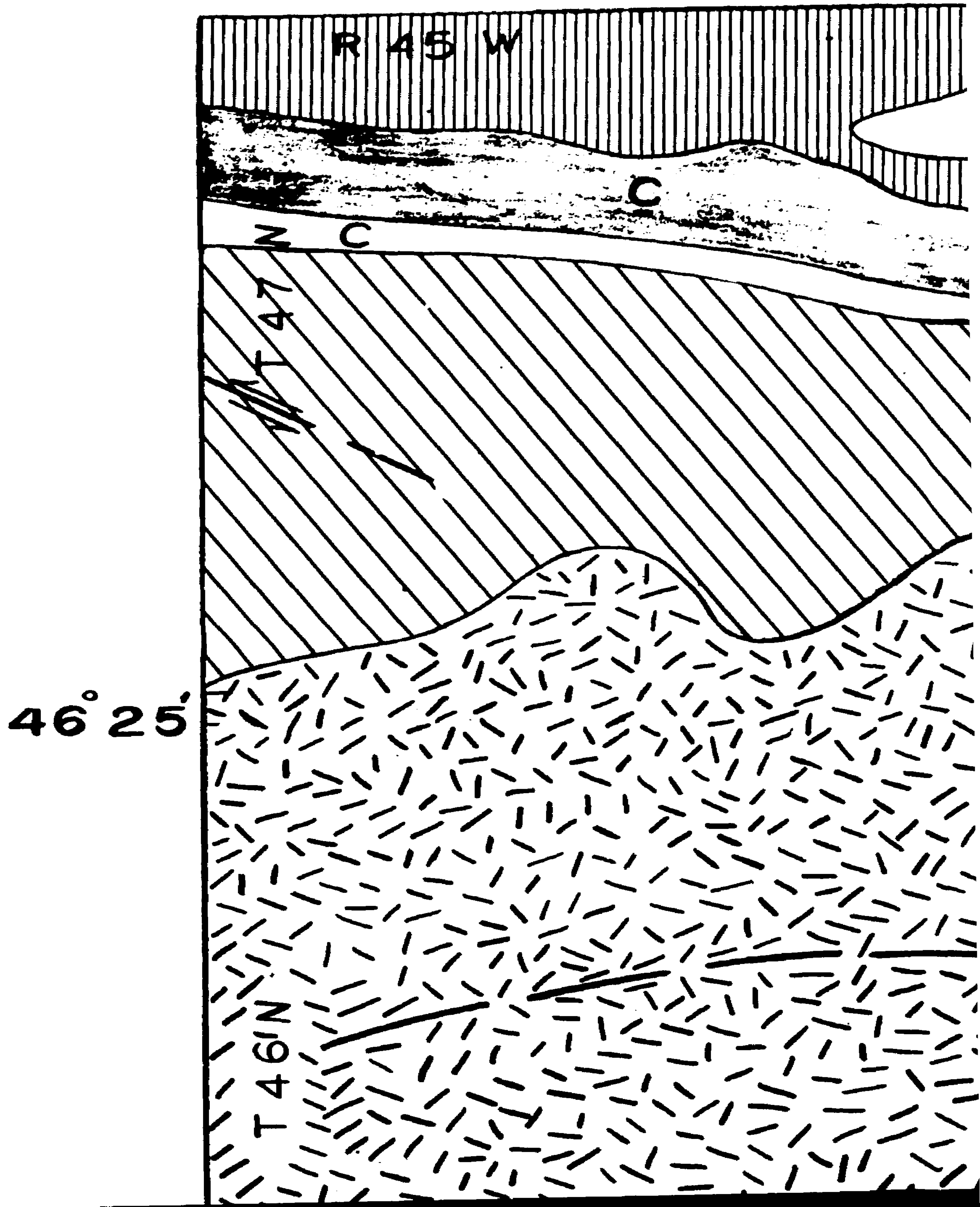

R 34 W


L'
M'
R 33 W

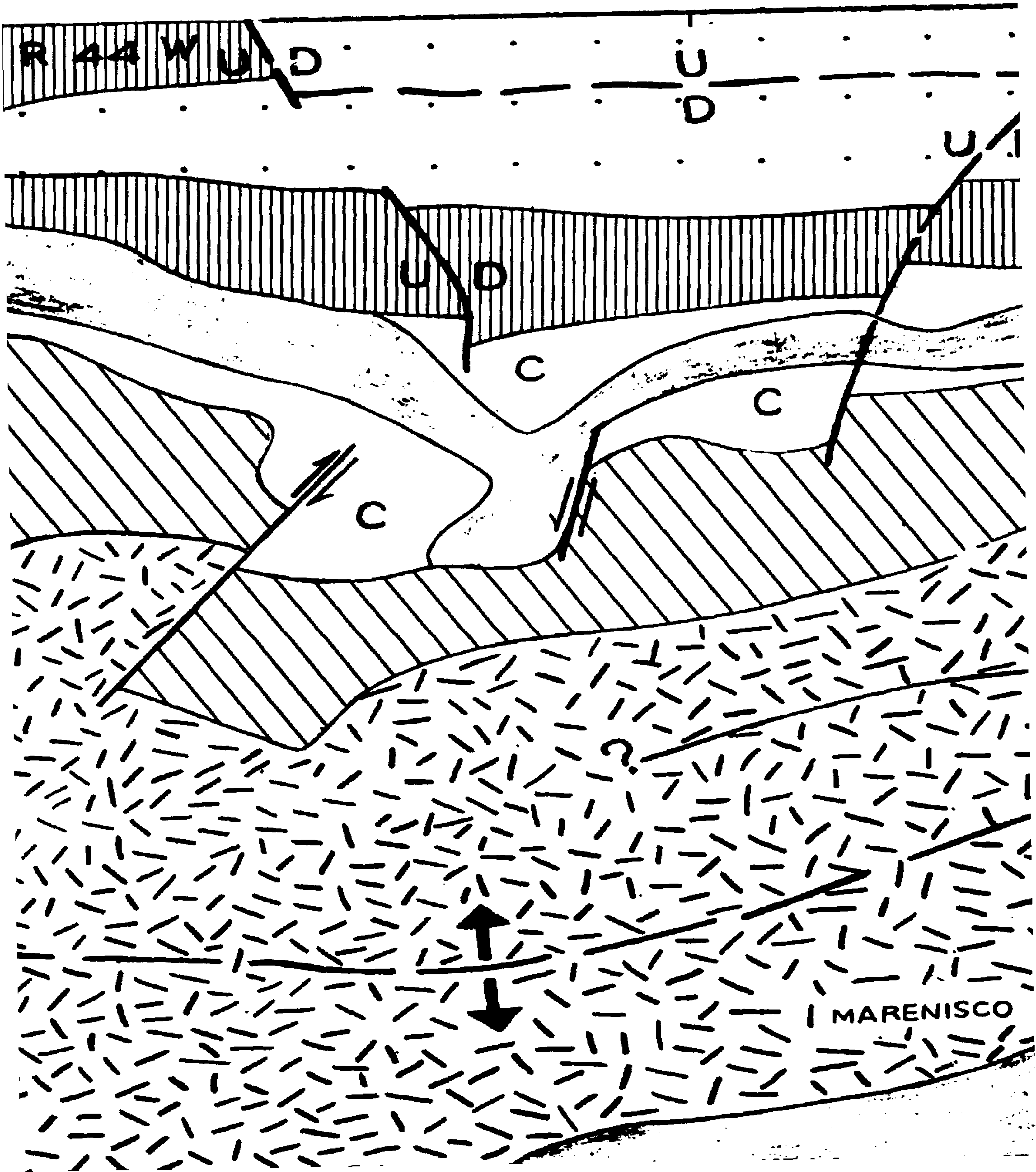

R 32 W

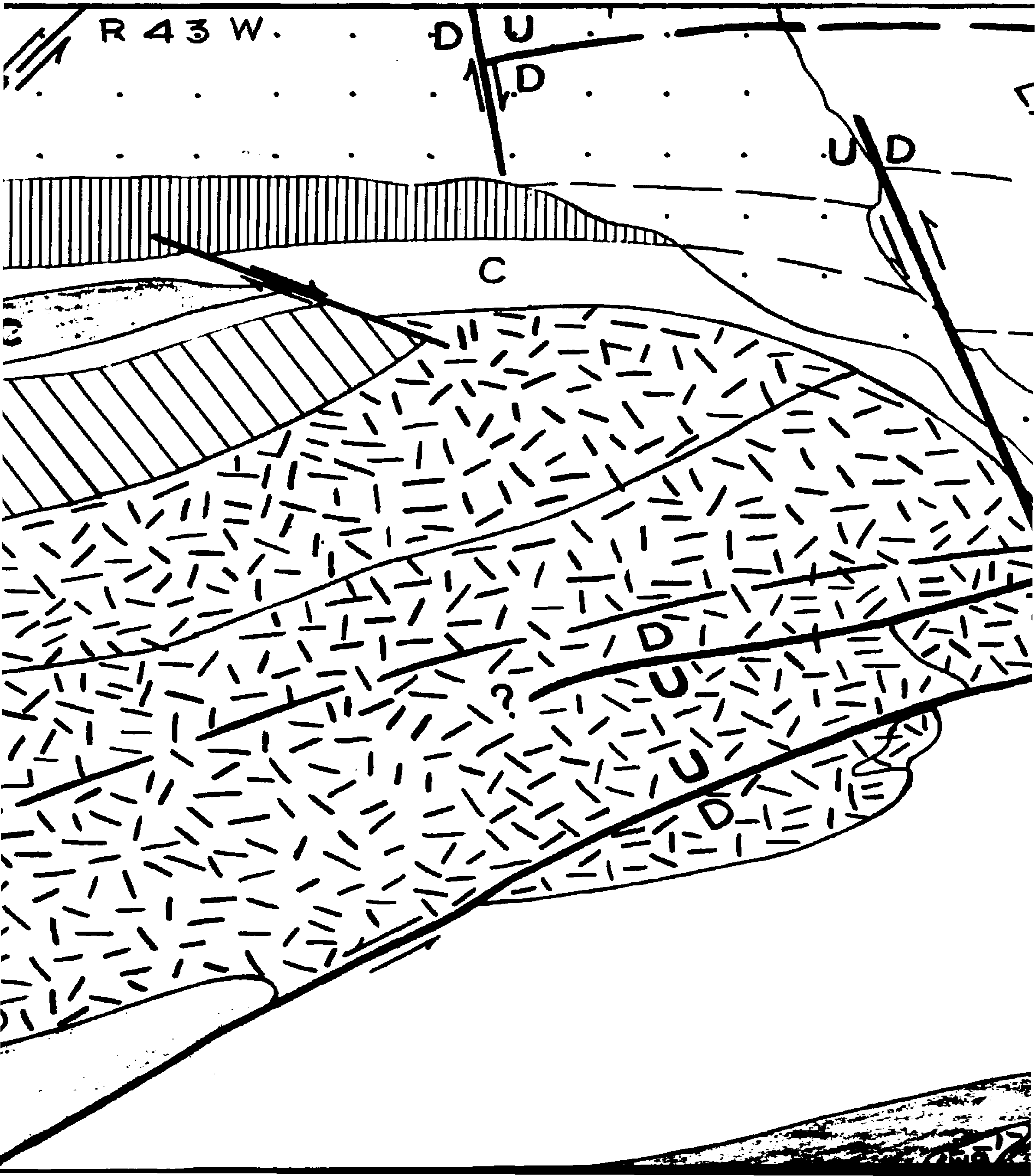


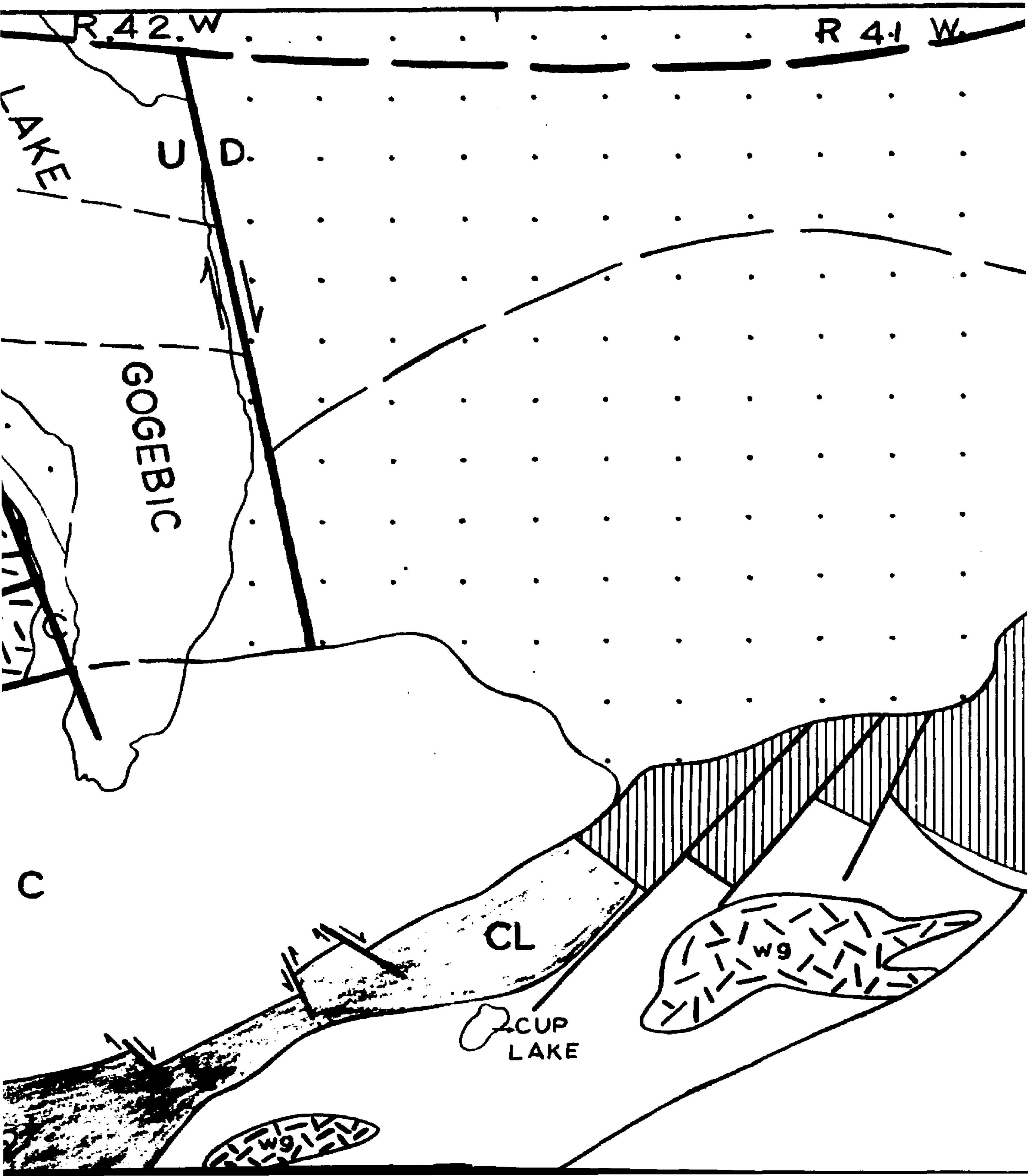
T 49 N
35'
T 48
R 31 W
46° 30'



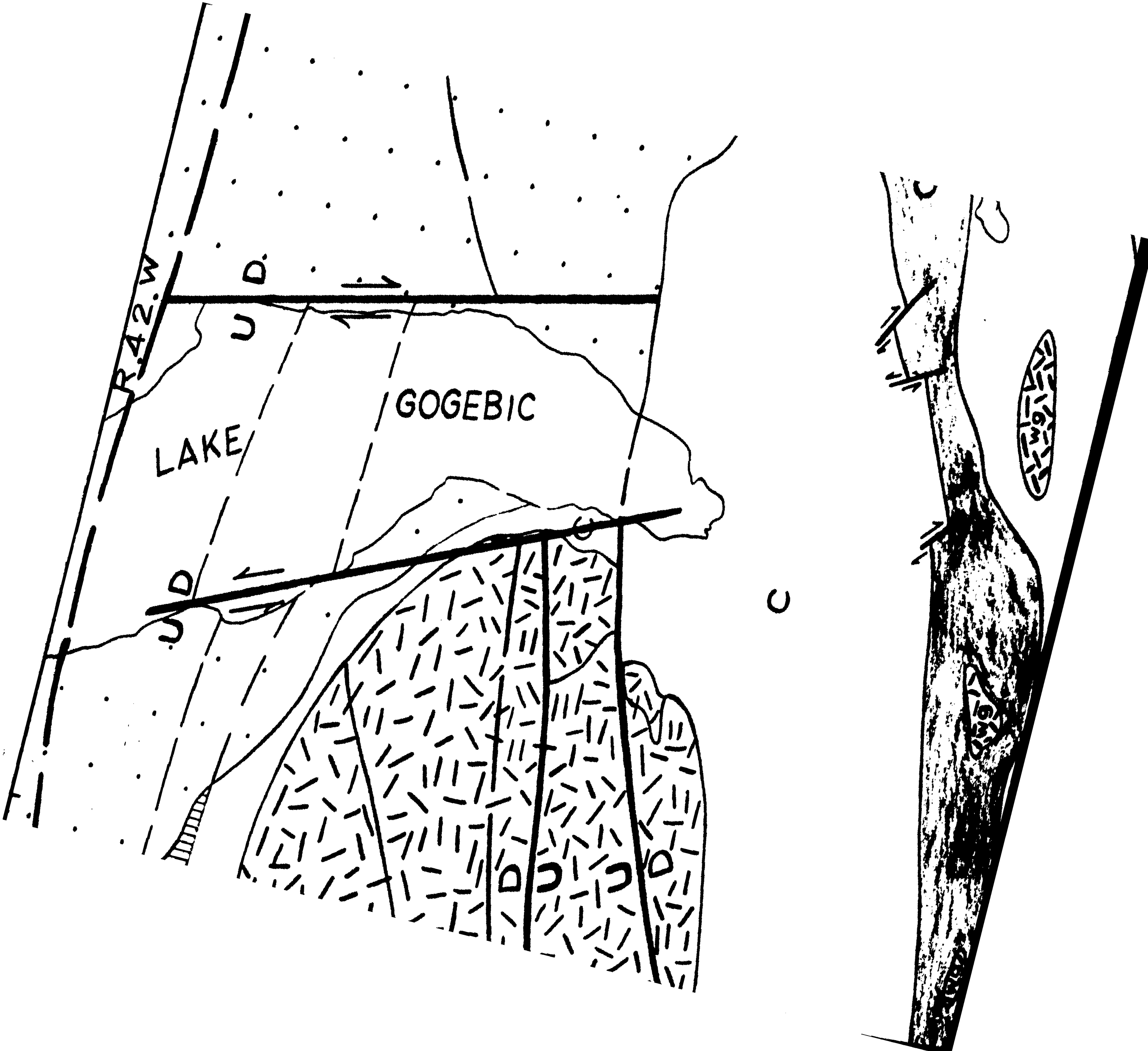
R 45 W
C
C
T 47 N
46° 25'
T 46 N

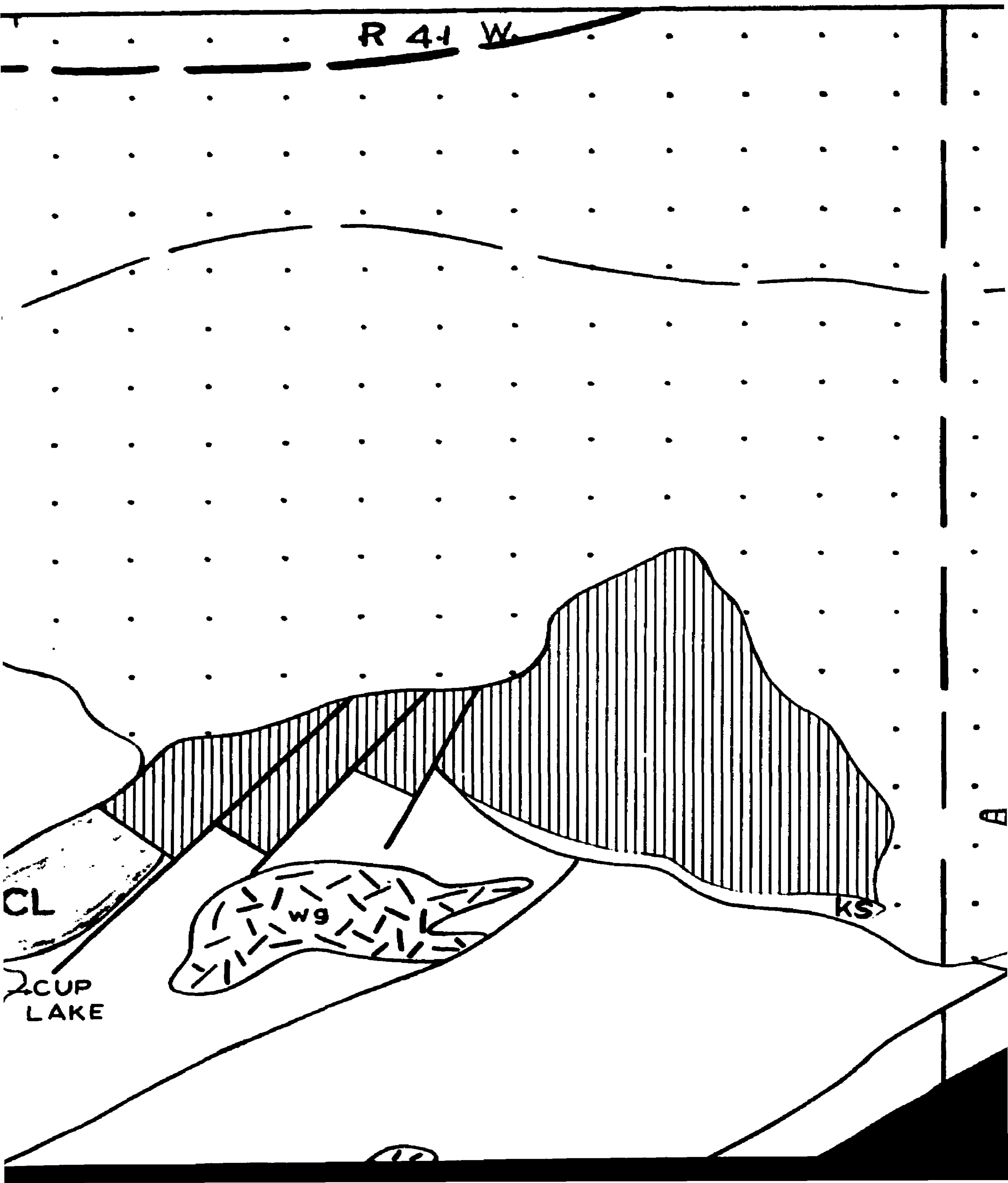

R 44 W
U
D
U
D
U
U
D
C
C
C
?
MARENISCO


R 43 W.
D
U
D
U
D
C
D
U
?
U
D

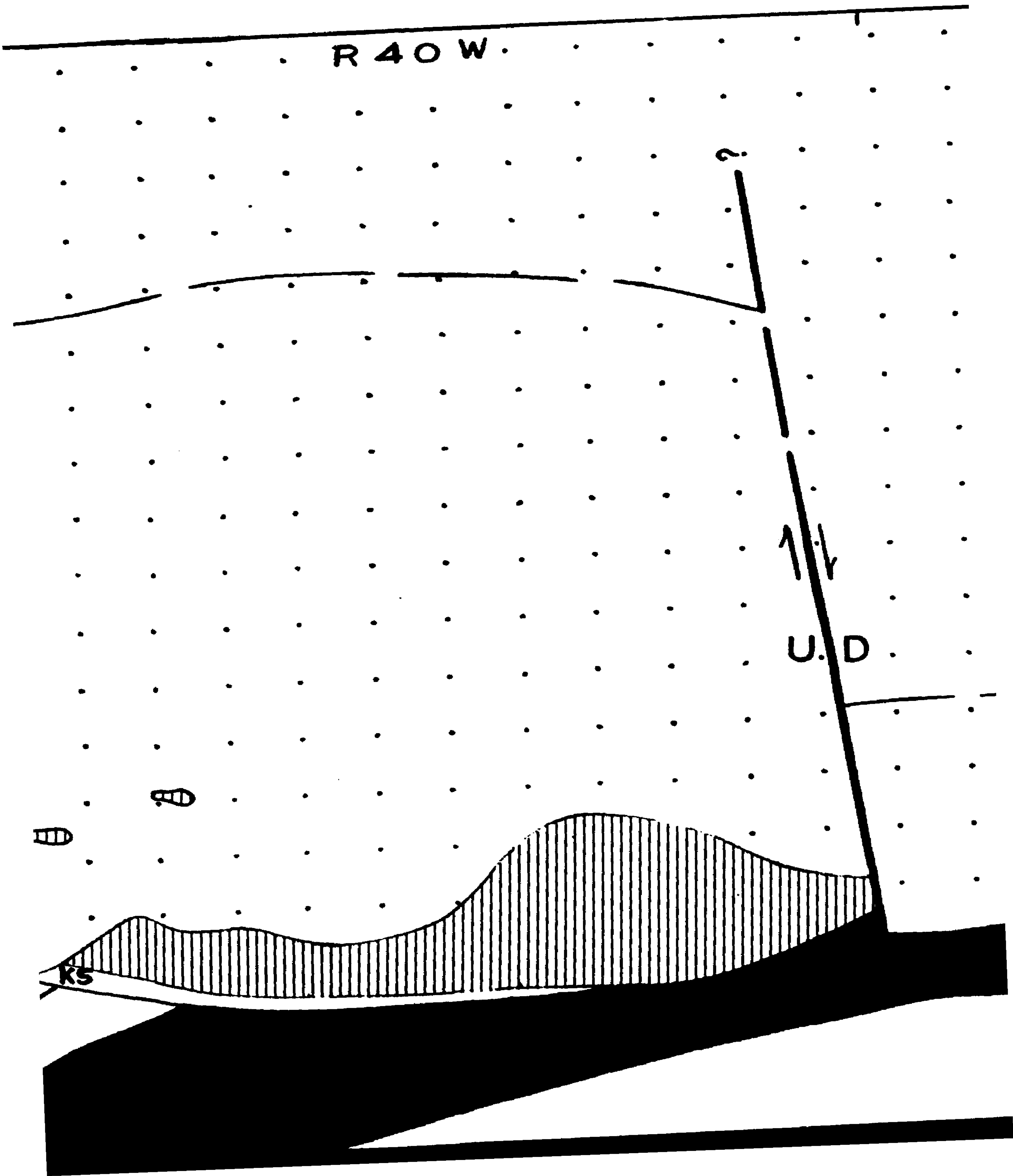


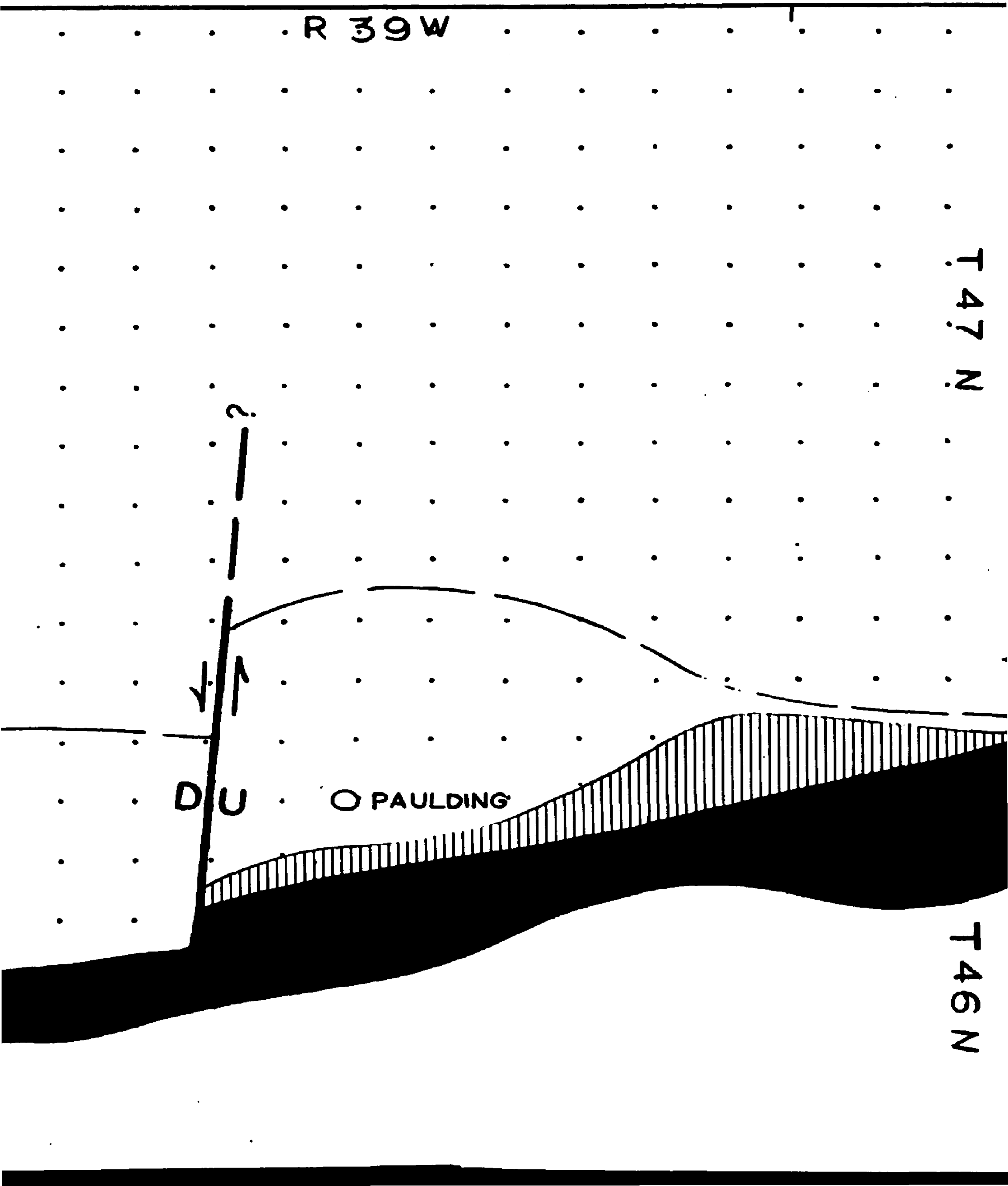
R.42.W
R 41 W.
LAKE
GOGEBIC
U
D.
C
CL
CUP
LAKE
wg
wg

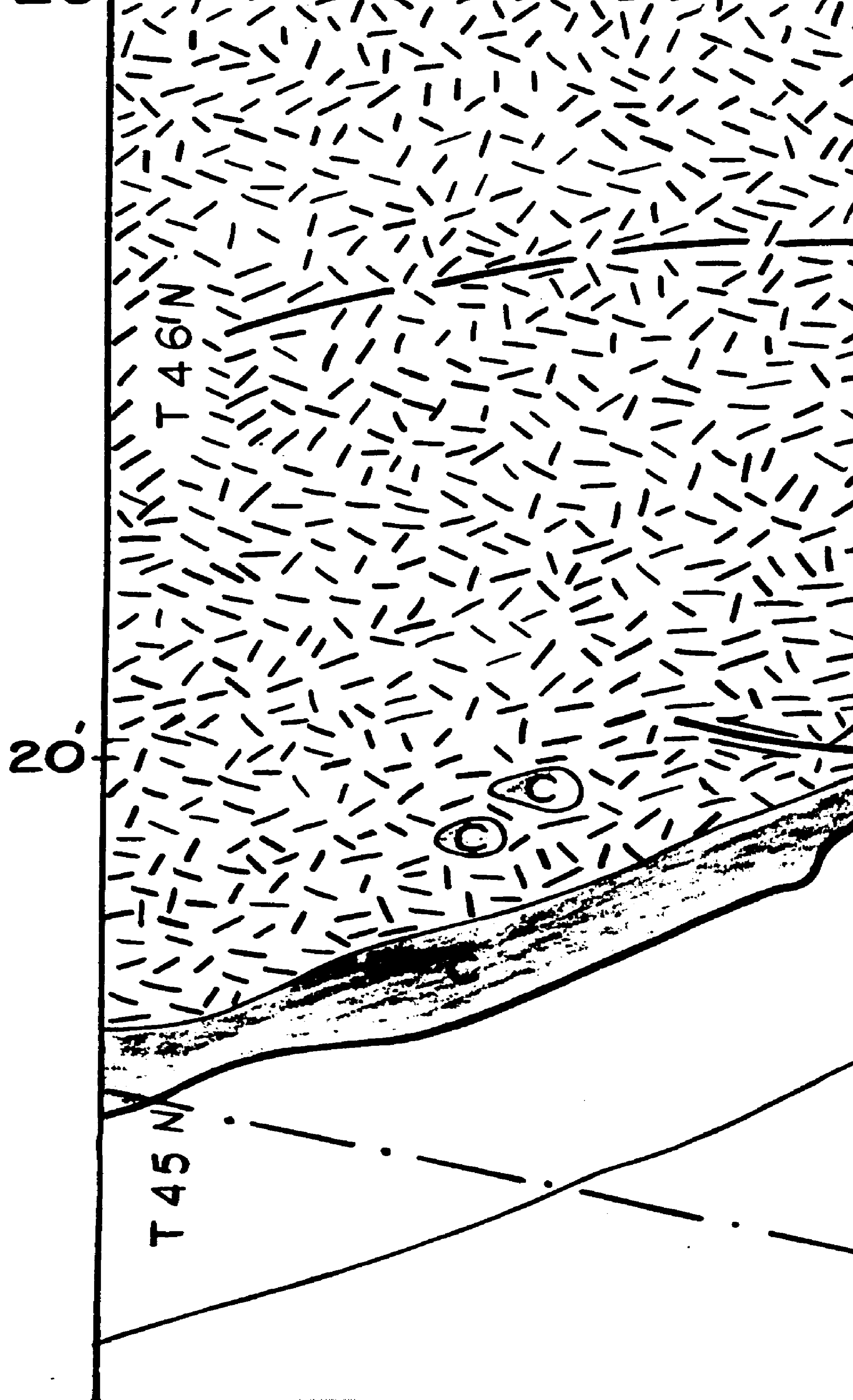

R.42 W.
U D
U D
LAKE
GOGEBIC
U D
U D
D U U D
C

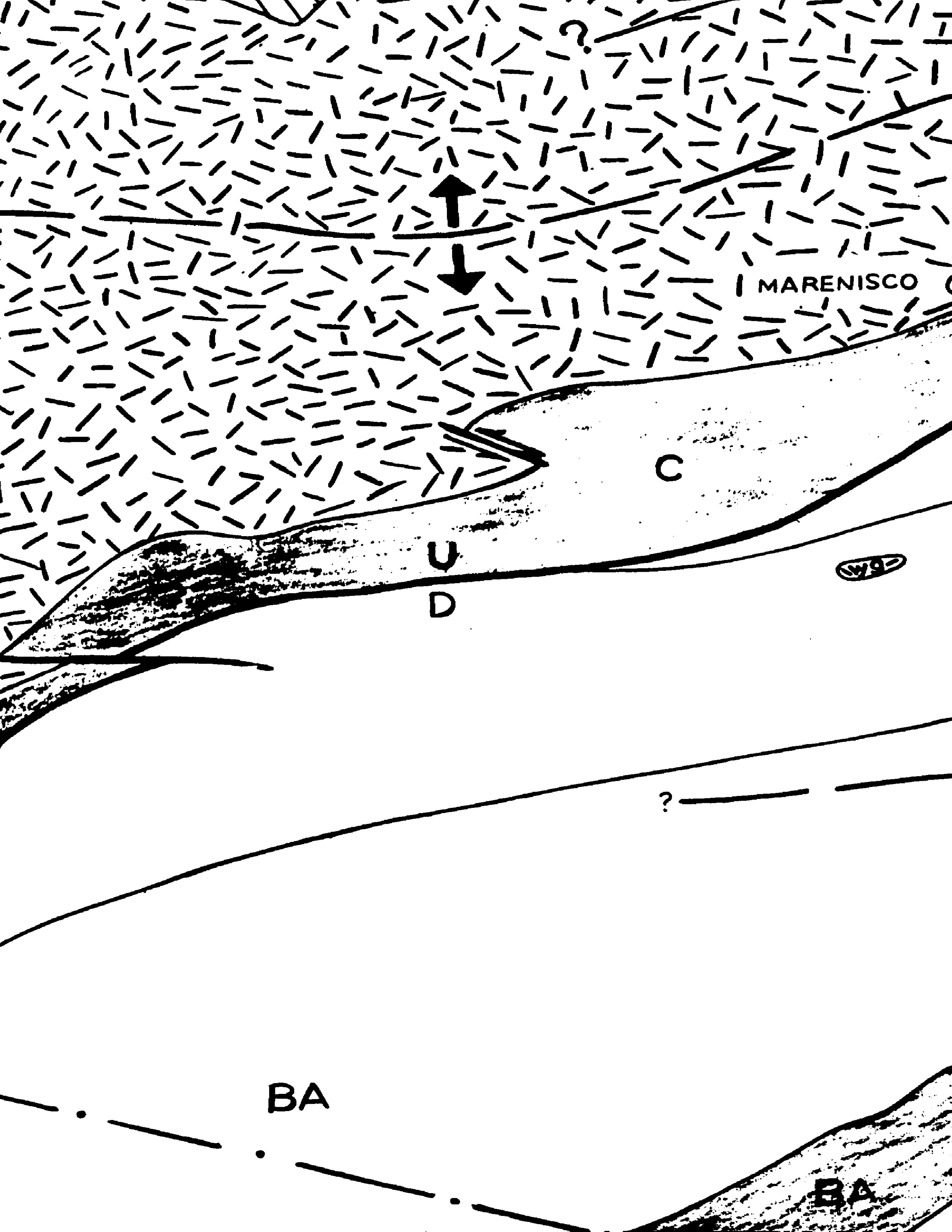


R 41 W.
CL
CUP
LAKE
wg
KS

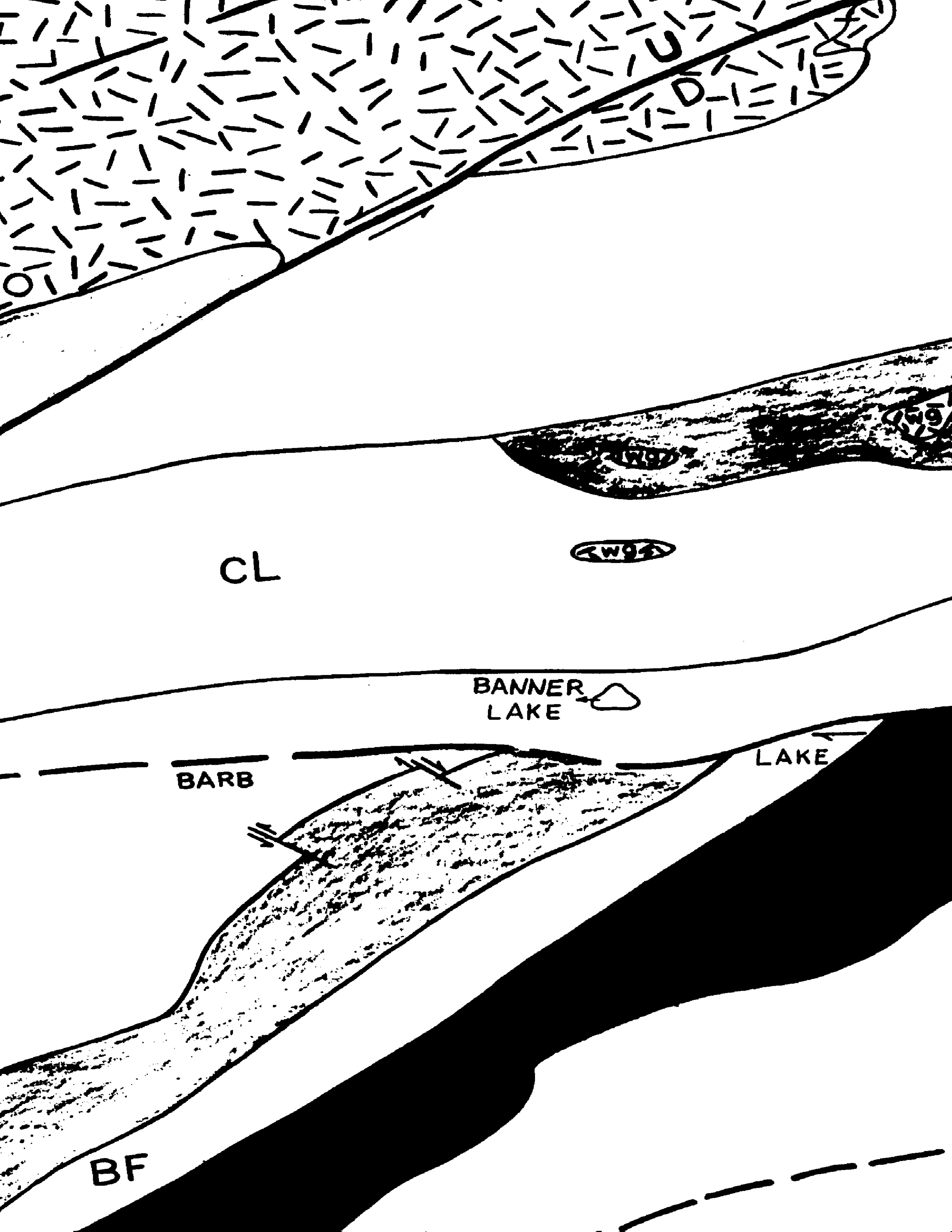

R 40 W
U D
KS

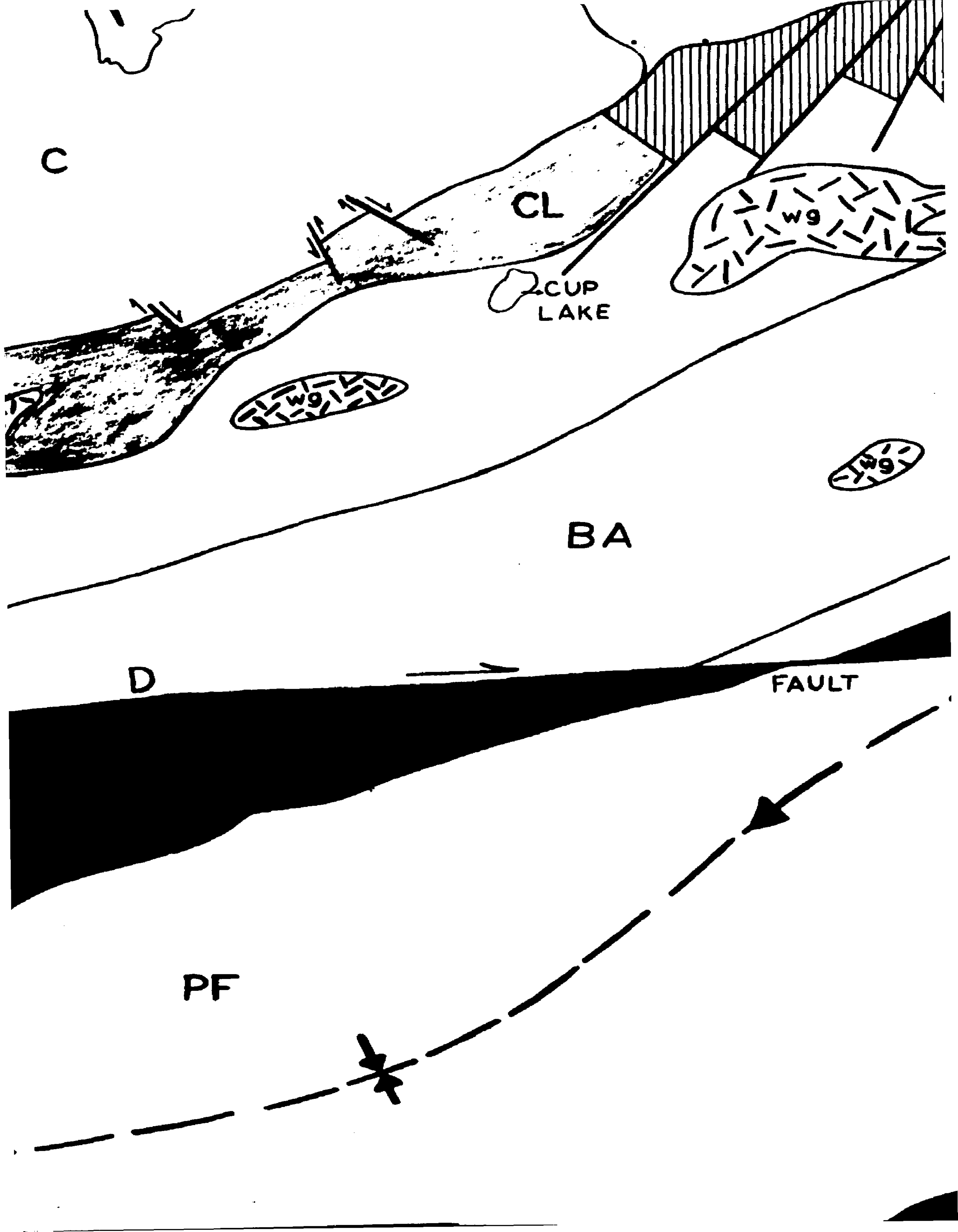

R 39W
T 47 N
?
D
U
PAULDING
T 46 N


T 46 N
20'
C
C
T 45 N

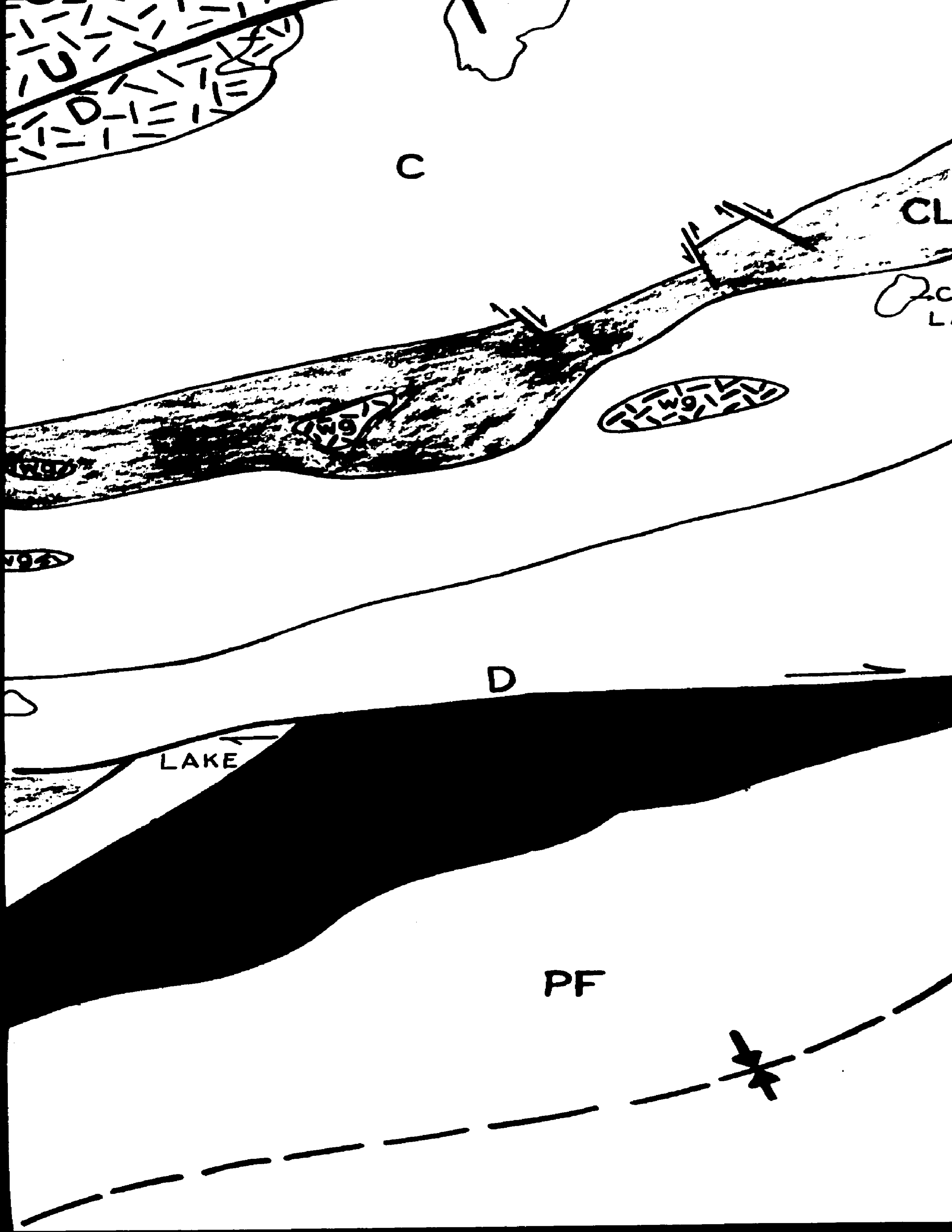


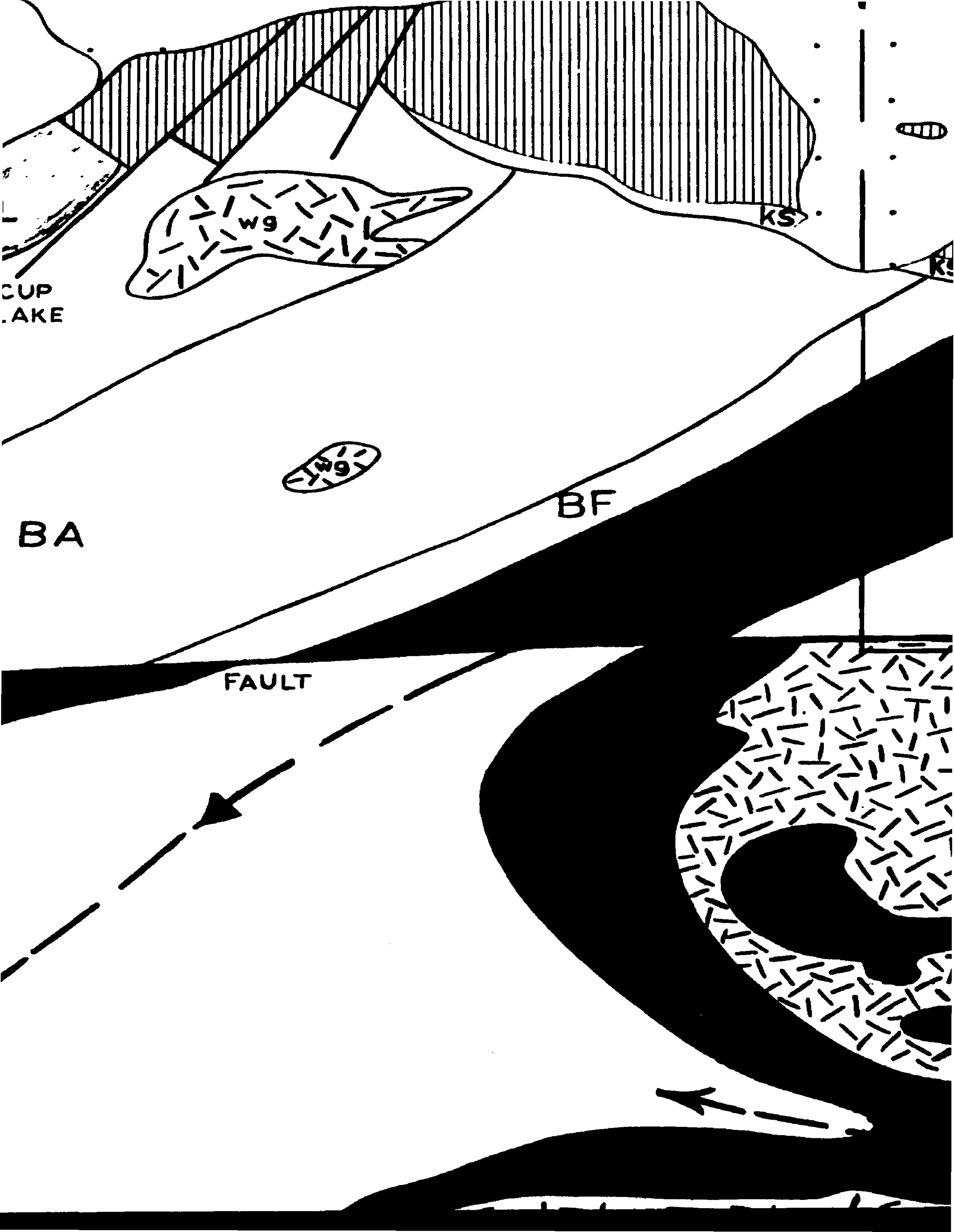
MARENISCO
C
U
D
BA
BA


U
D
CL
BANNER
LAKE
BARB
LAKE
BF

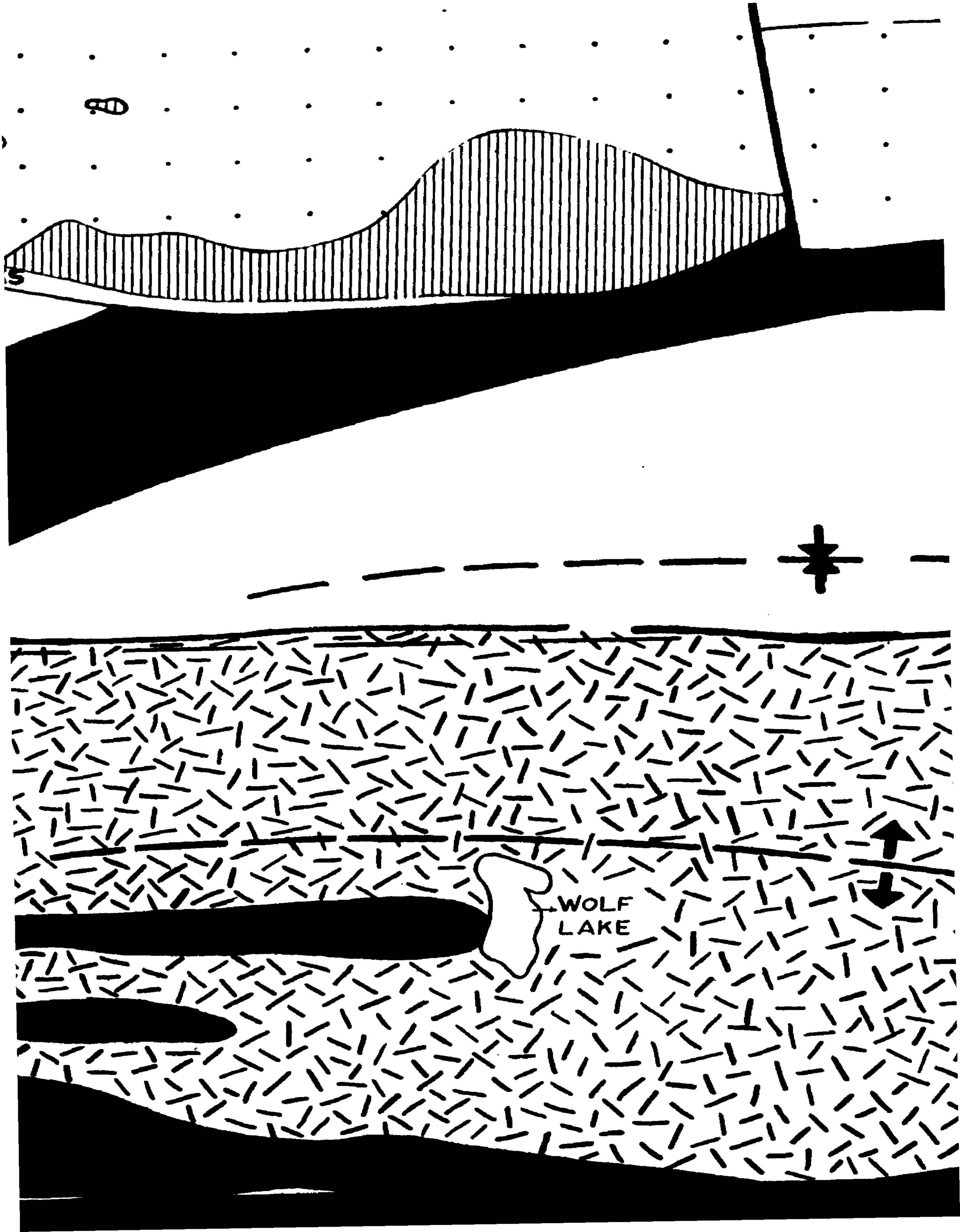


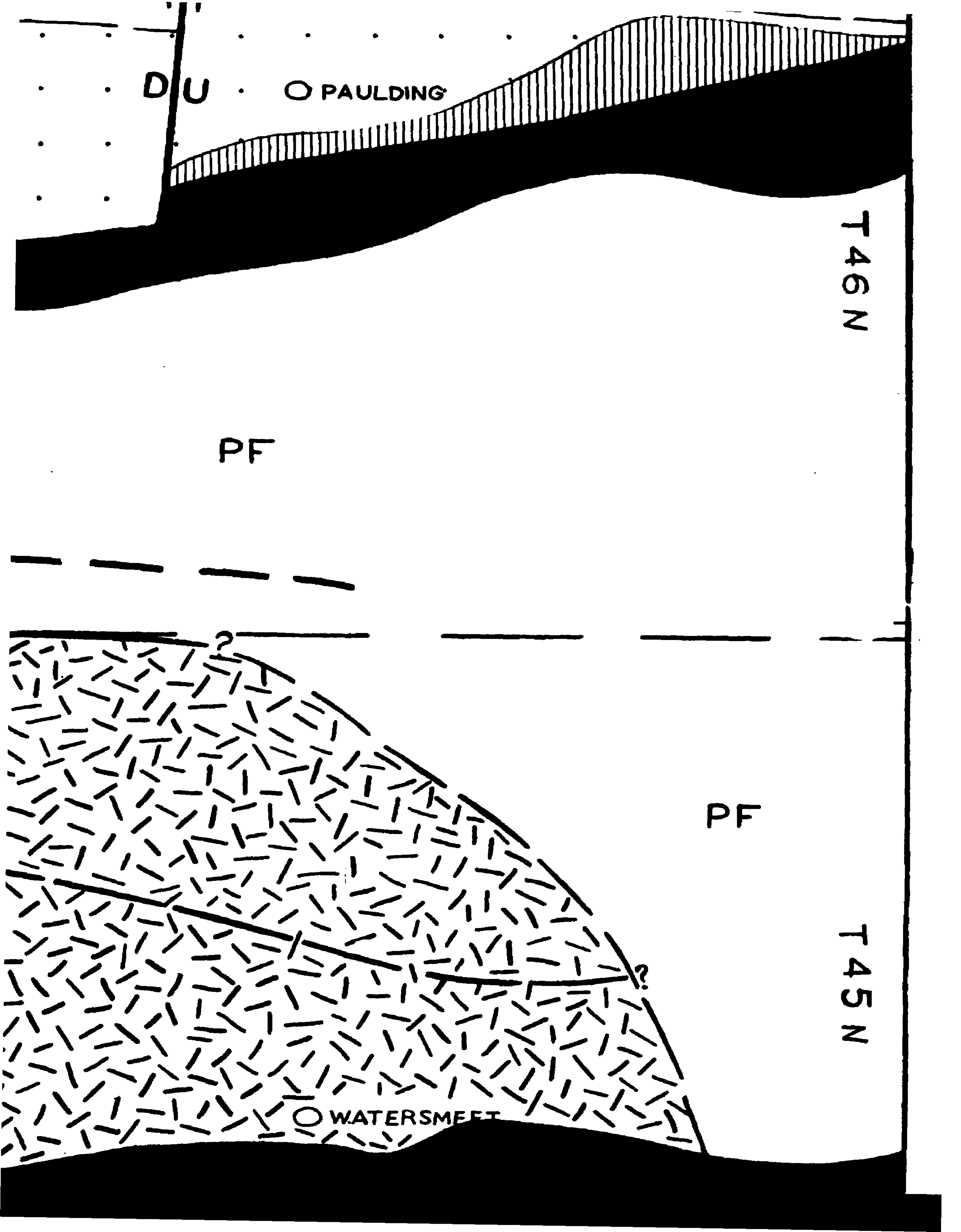
C
CL
CUP
LAKE
wg
wg
wg
BA
D
FAULT
PF

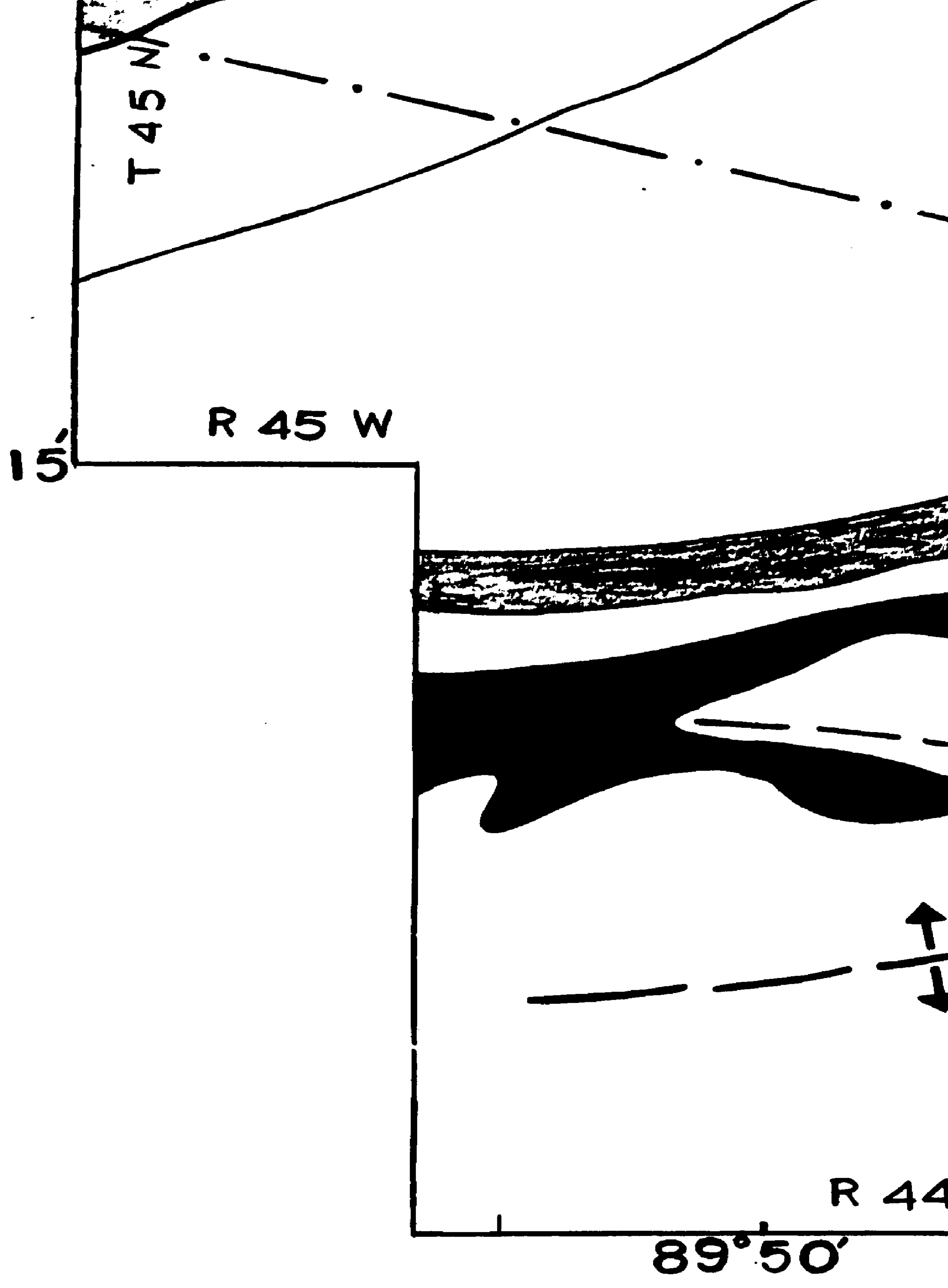

U
D
C
CL
W9
W9
W9
W9
D
LAKE
PF



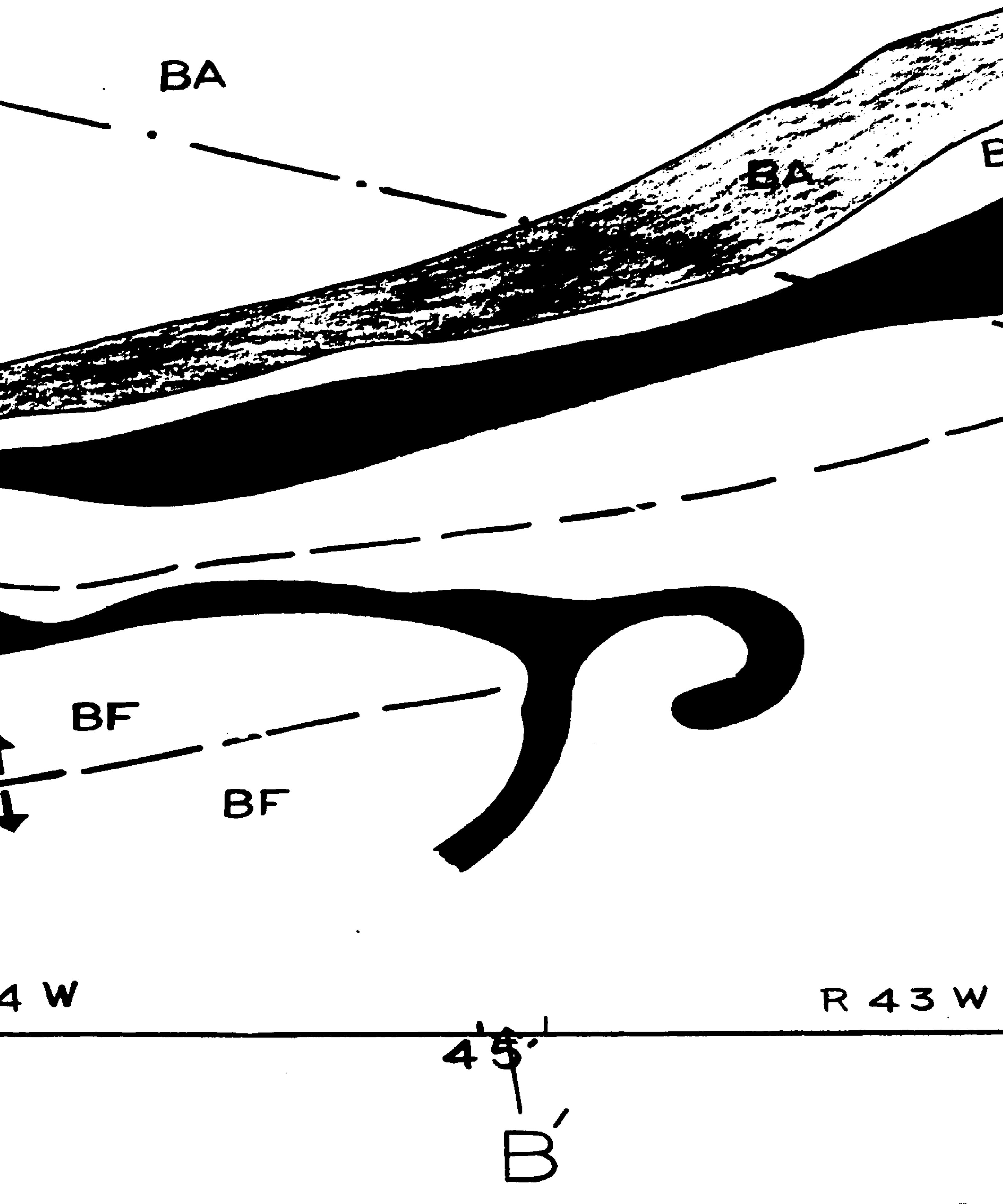
CUP
LAKE
wg
wg
KS
KS
BA
BF
FAULT

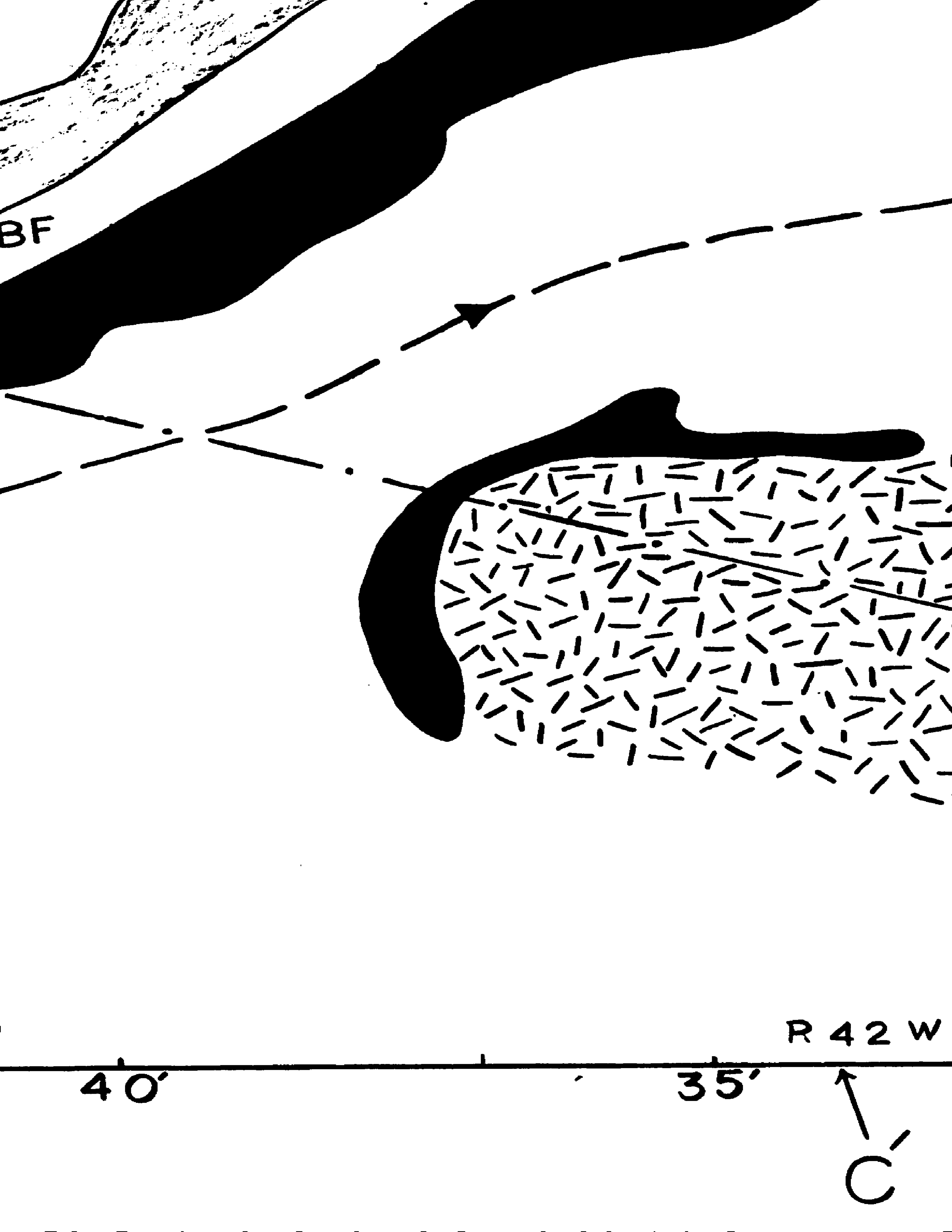

WOLF
LAKE

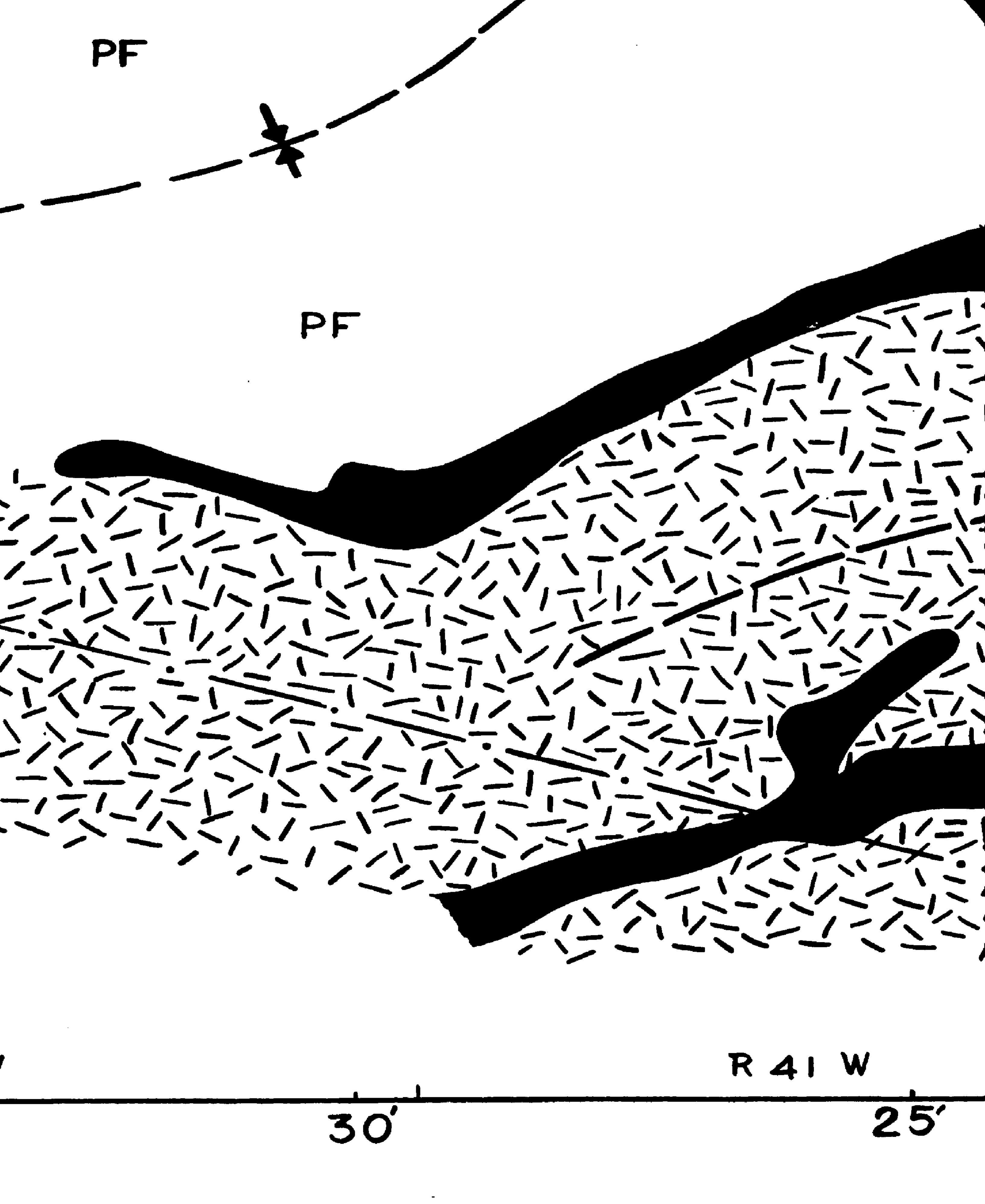

D
U
PAULDING
T46N
PF
PF
T45N
WATERSMEET

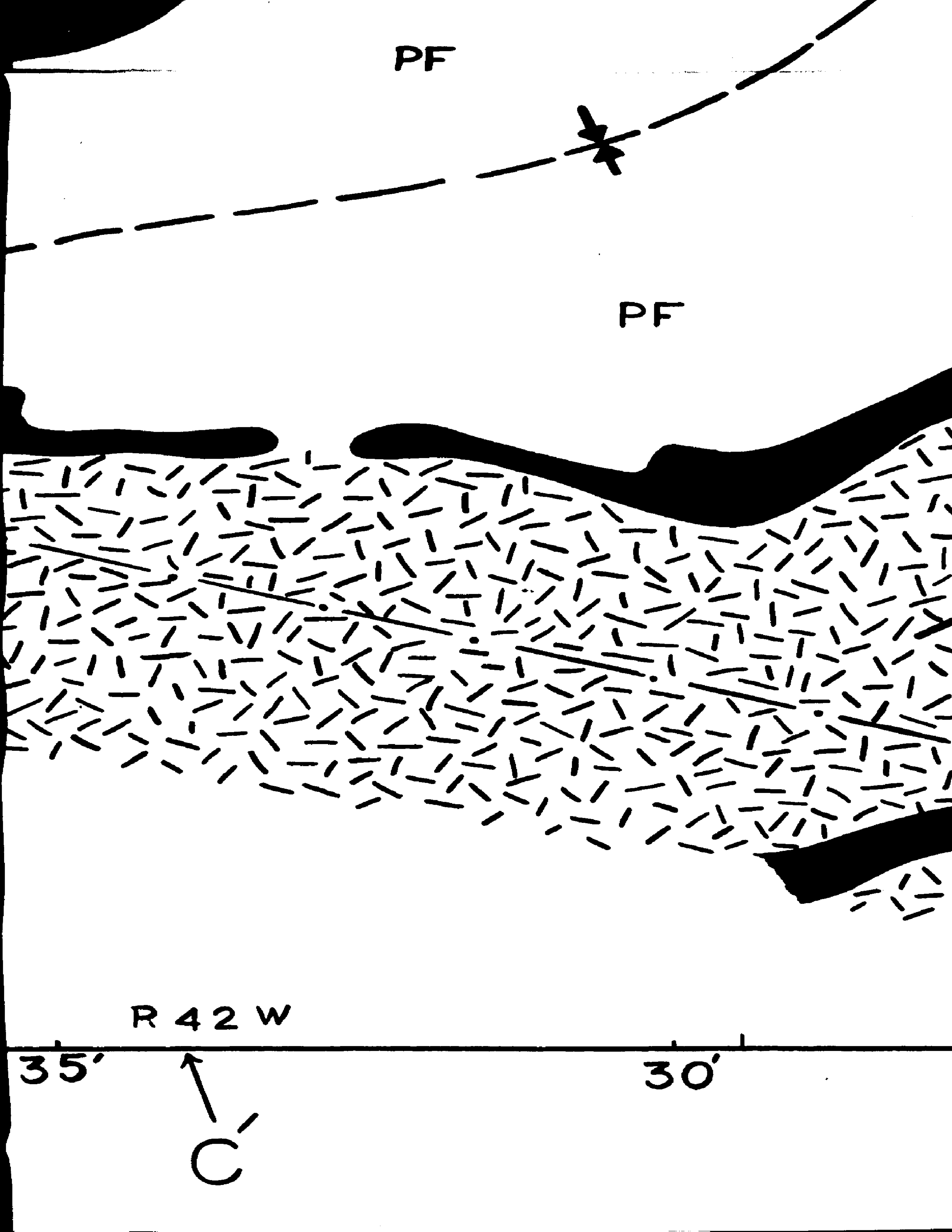


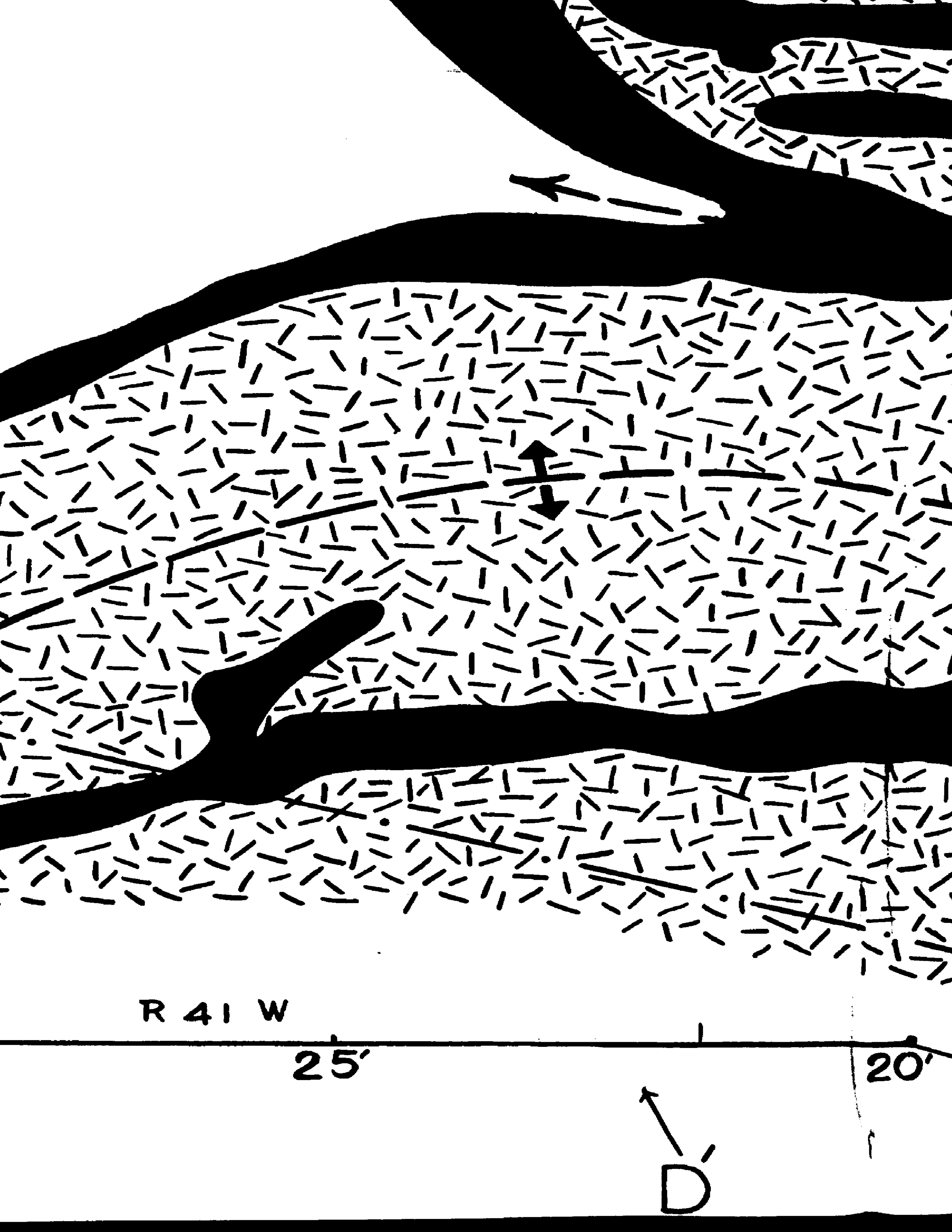
T 45 N
R 45 W
15′
R 44
89°50′


BA
BA
B
BF
BF
4 W
R 43 W
45'
B'

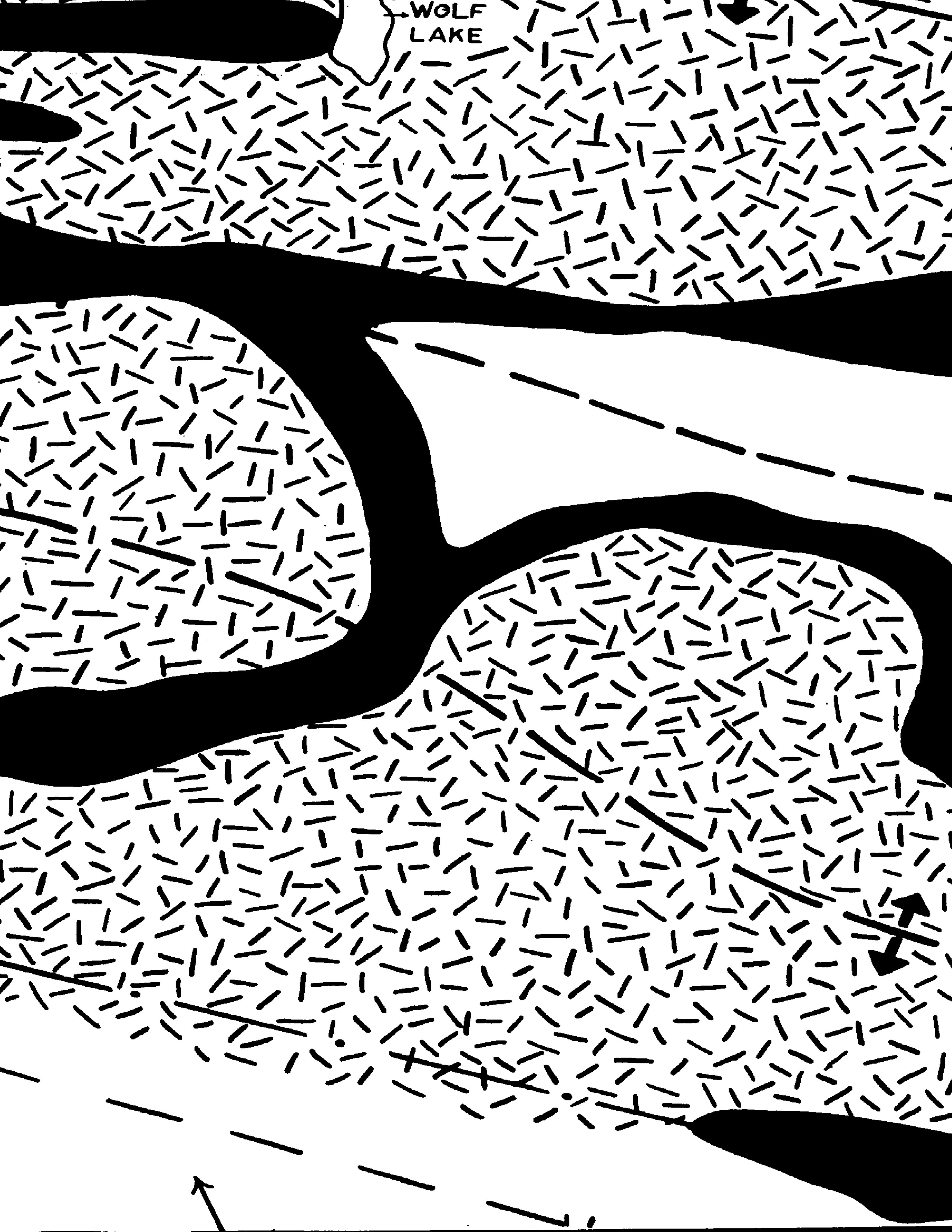

BF
R 42 W
40′
35′
C′

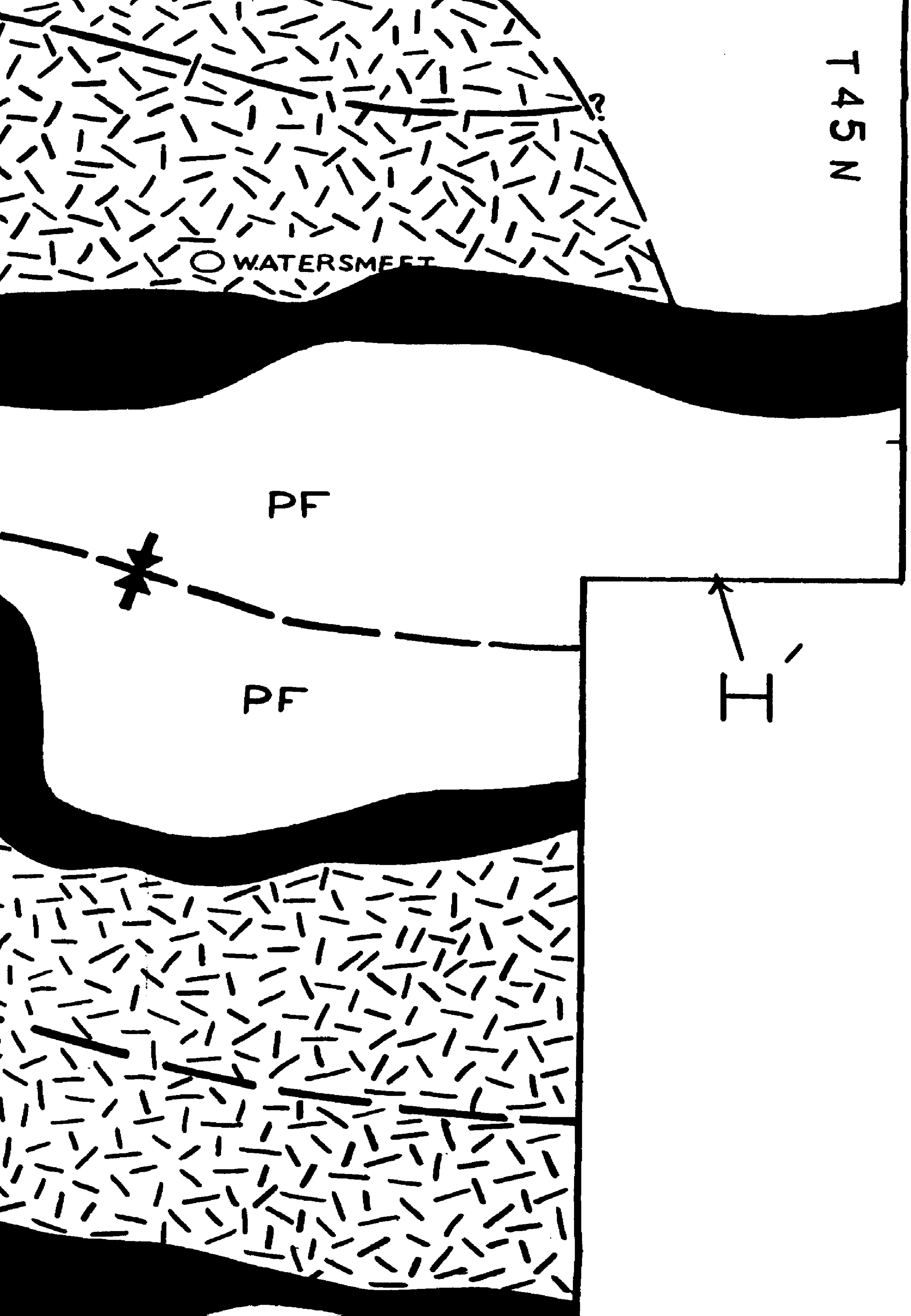

PF
PF
R 41 W
30′
25′

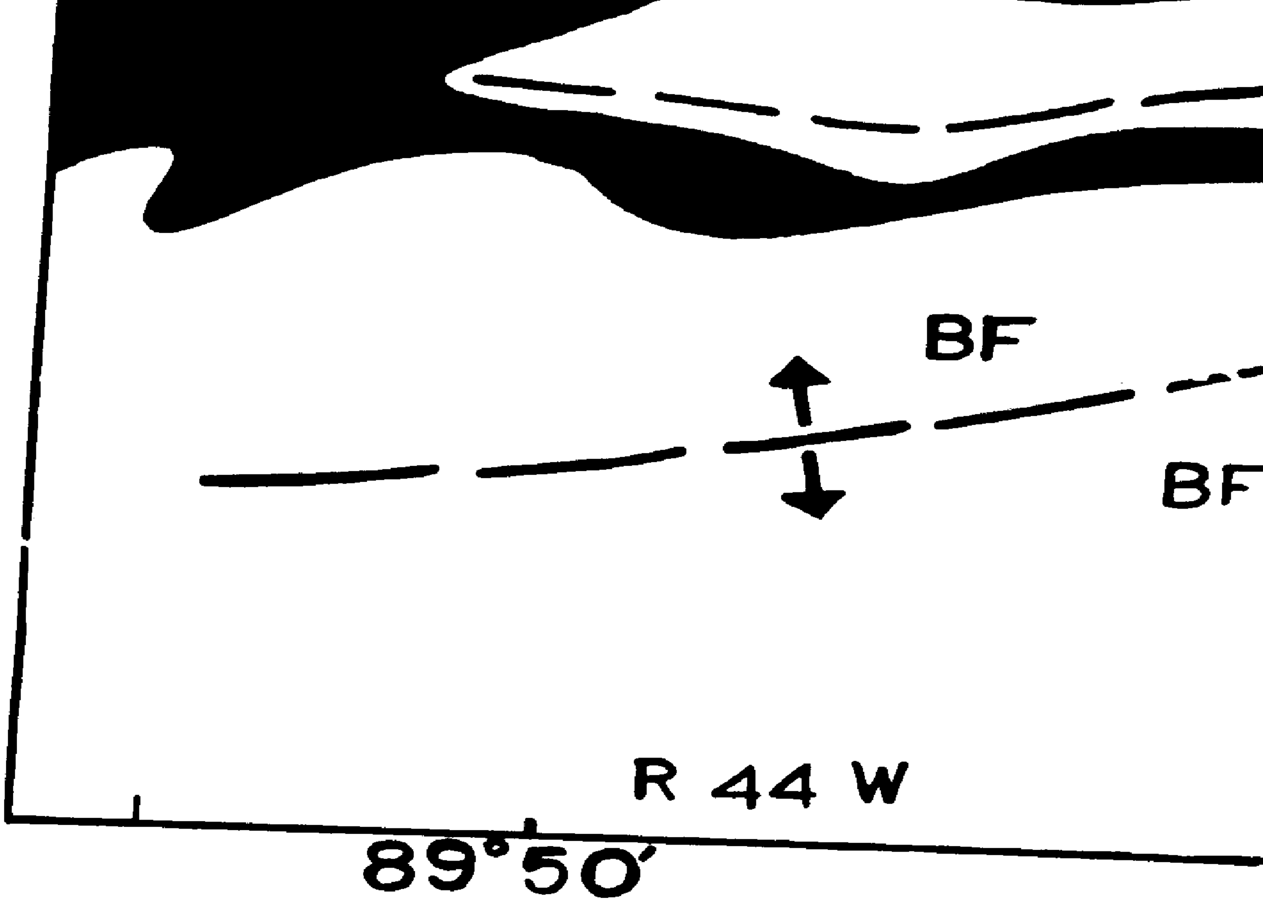

PF
PF
R 42 W
35'
30'
C

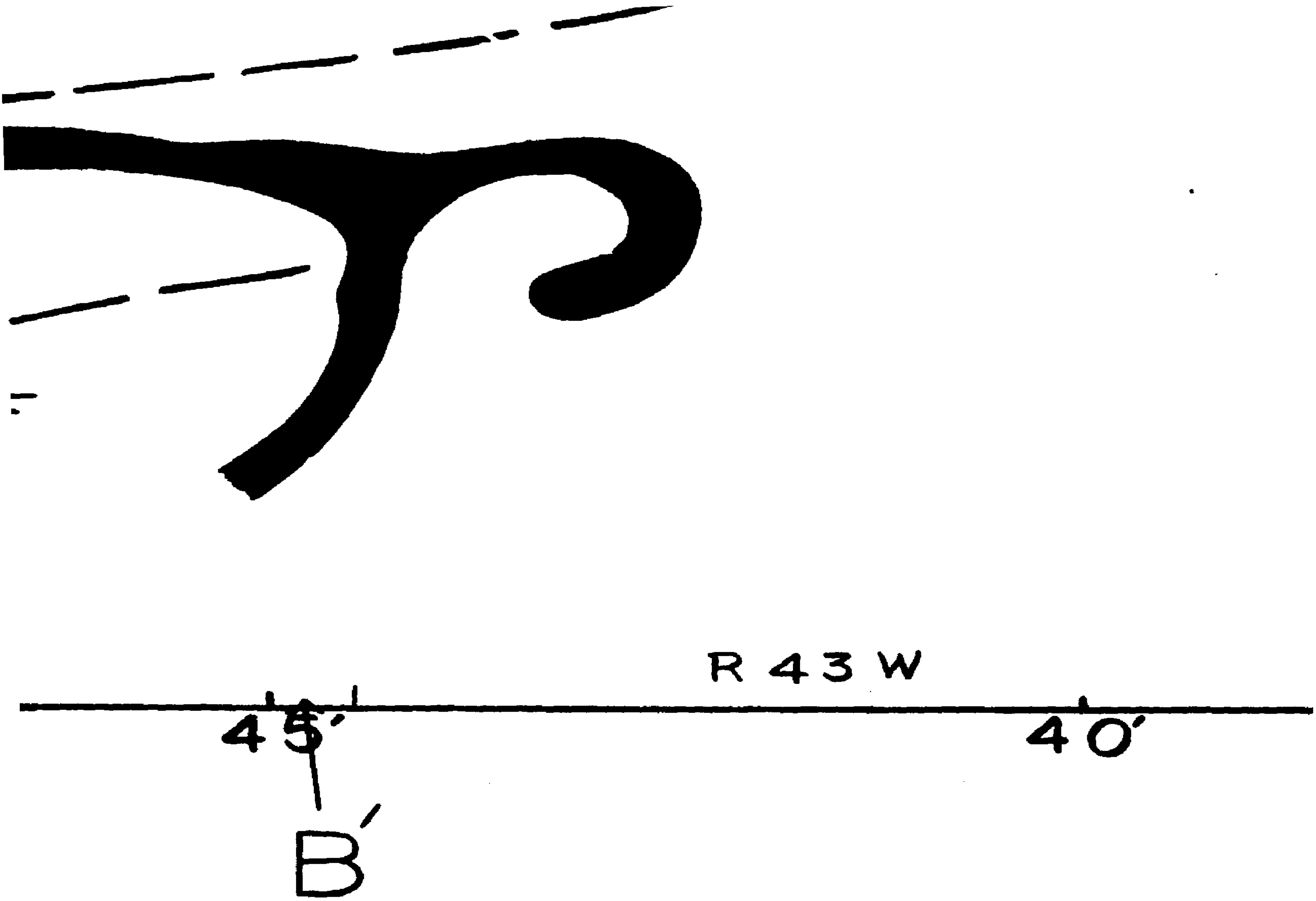


R 41 W
25'
20'
D'


WOLF
LAKE


WATERSMEET
?
T45N
PF
PF
H'


BF
BF
R 44 W
89°50′


R 43 W
45′
40′
B′

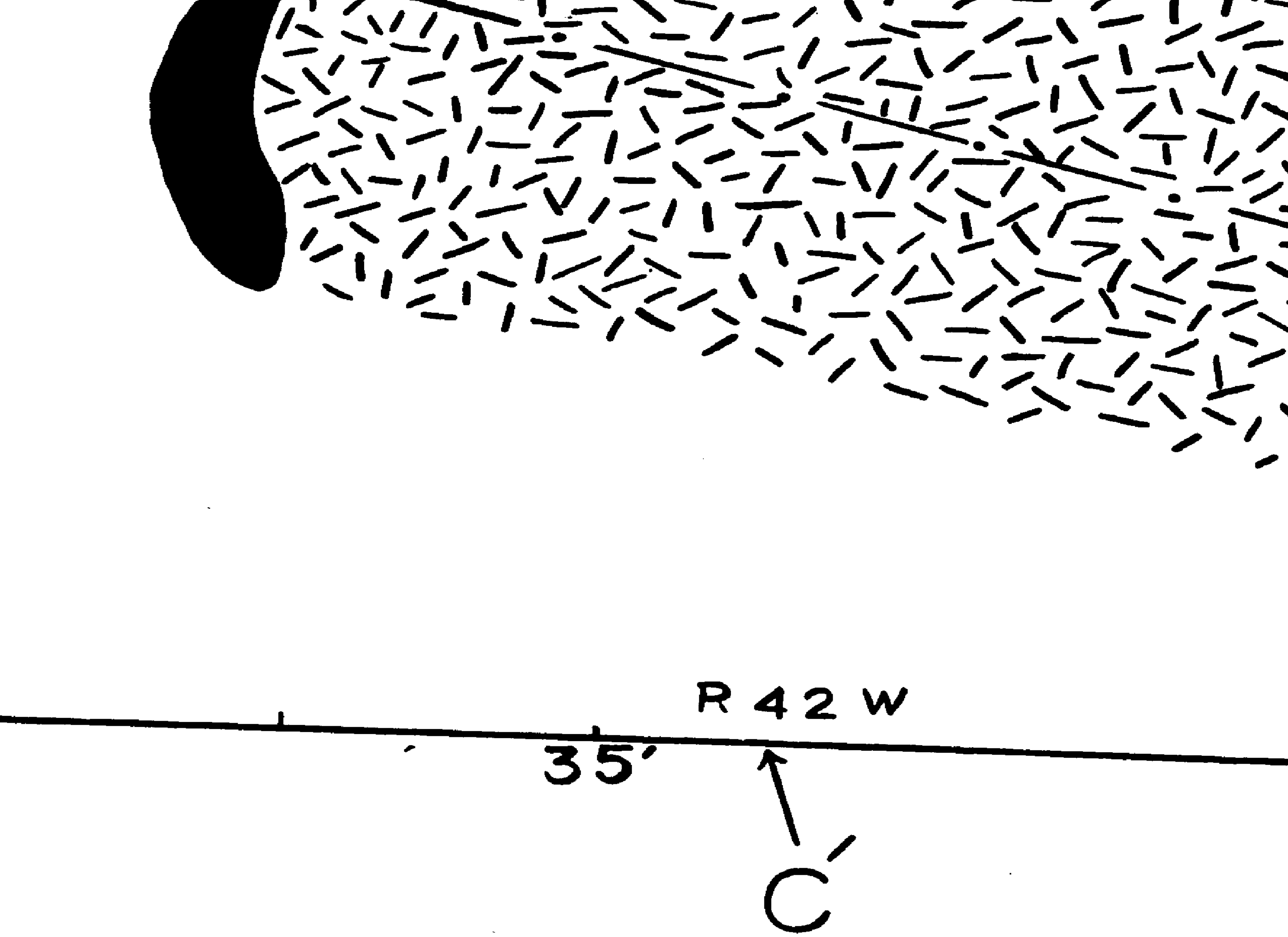
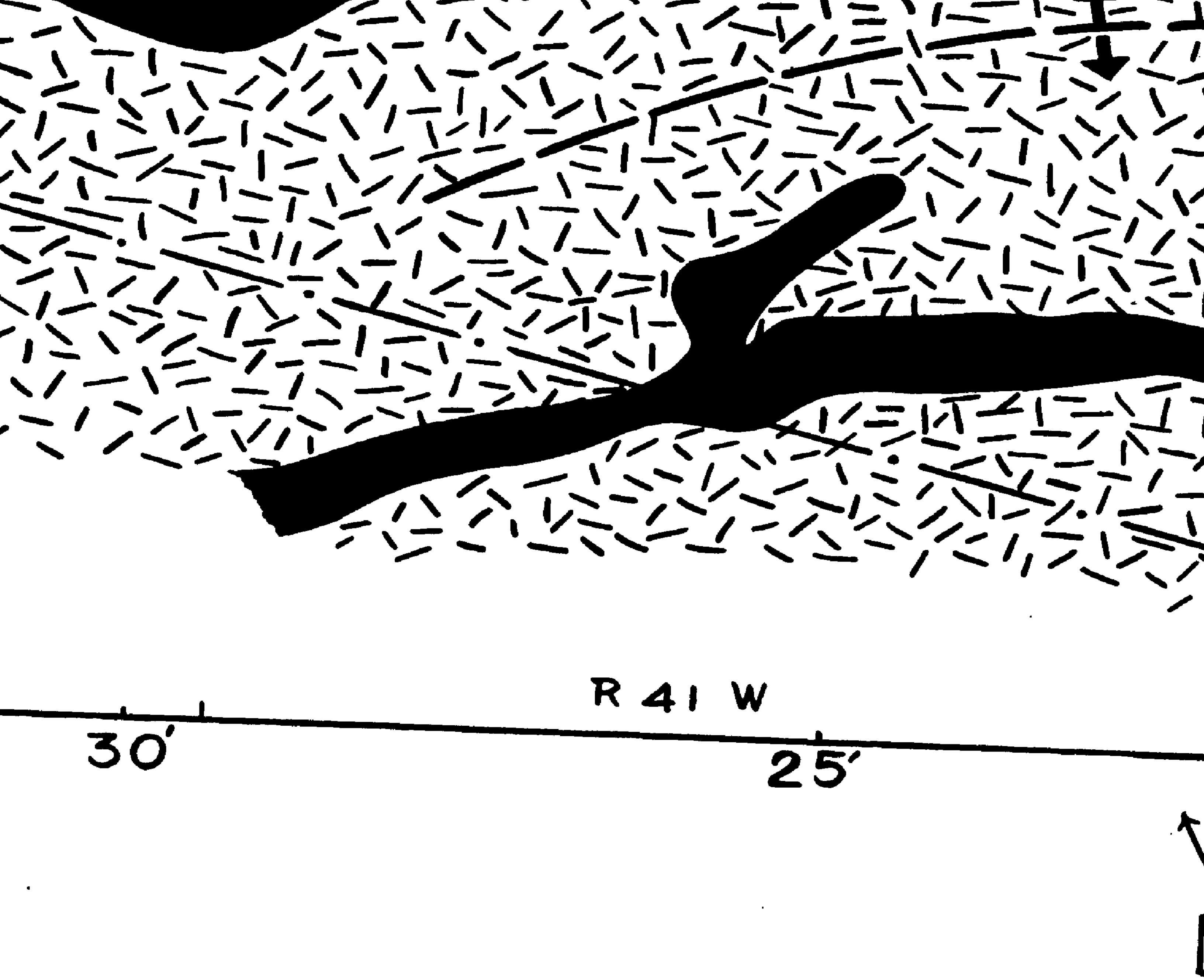


PLATE III-d


R 41 W
30'
25'

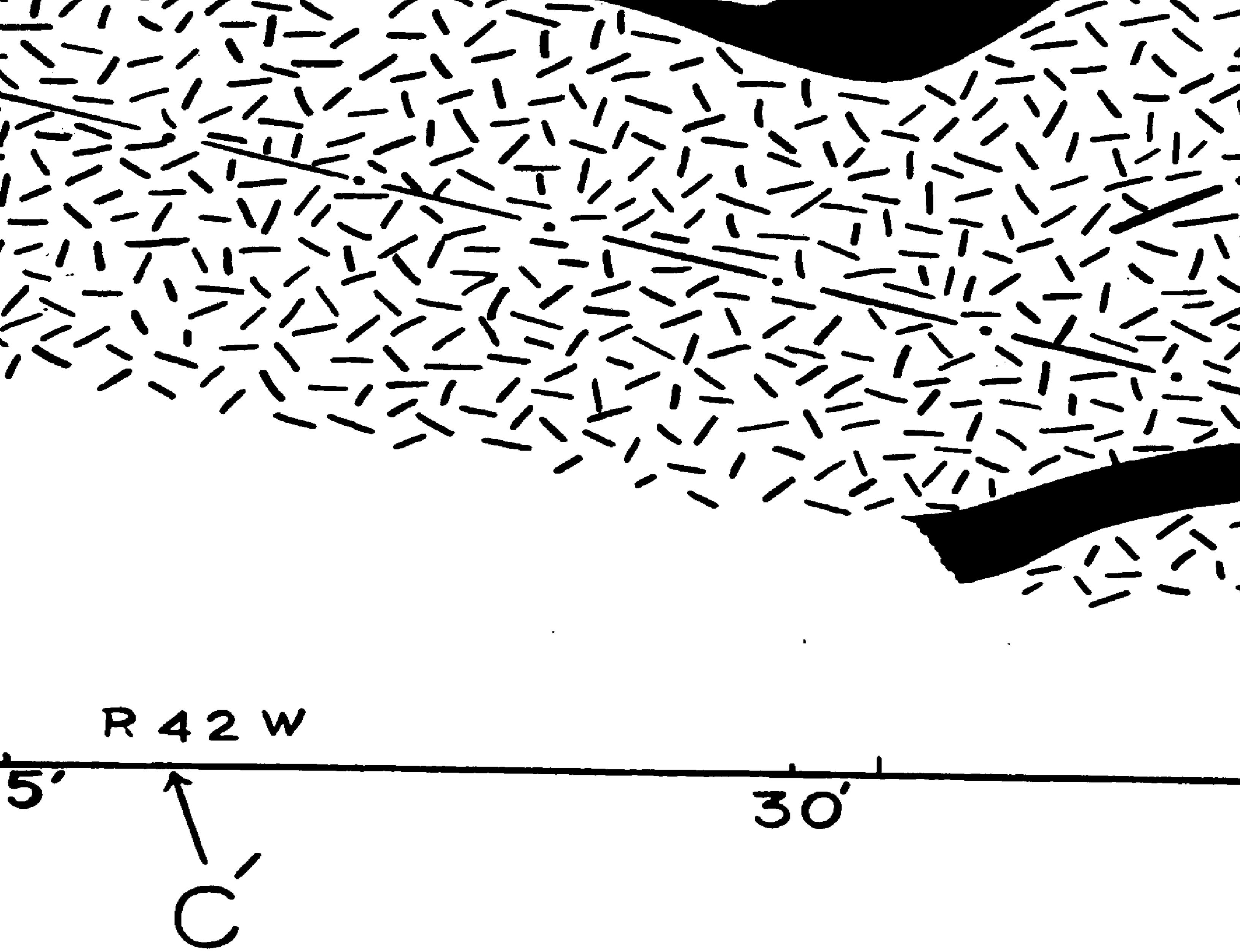
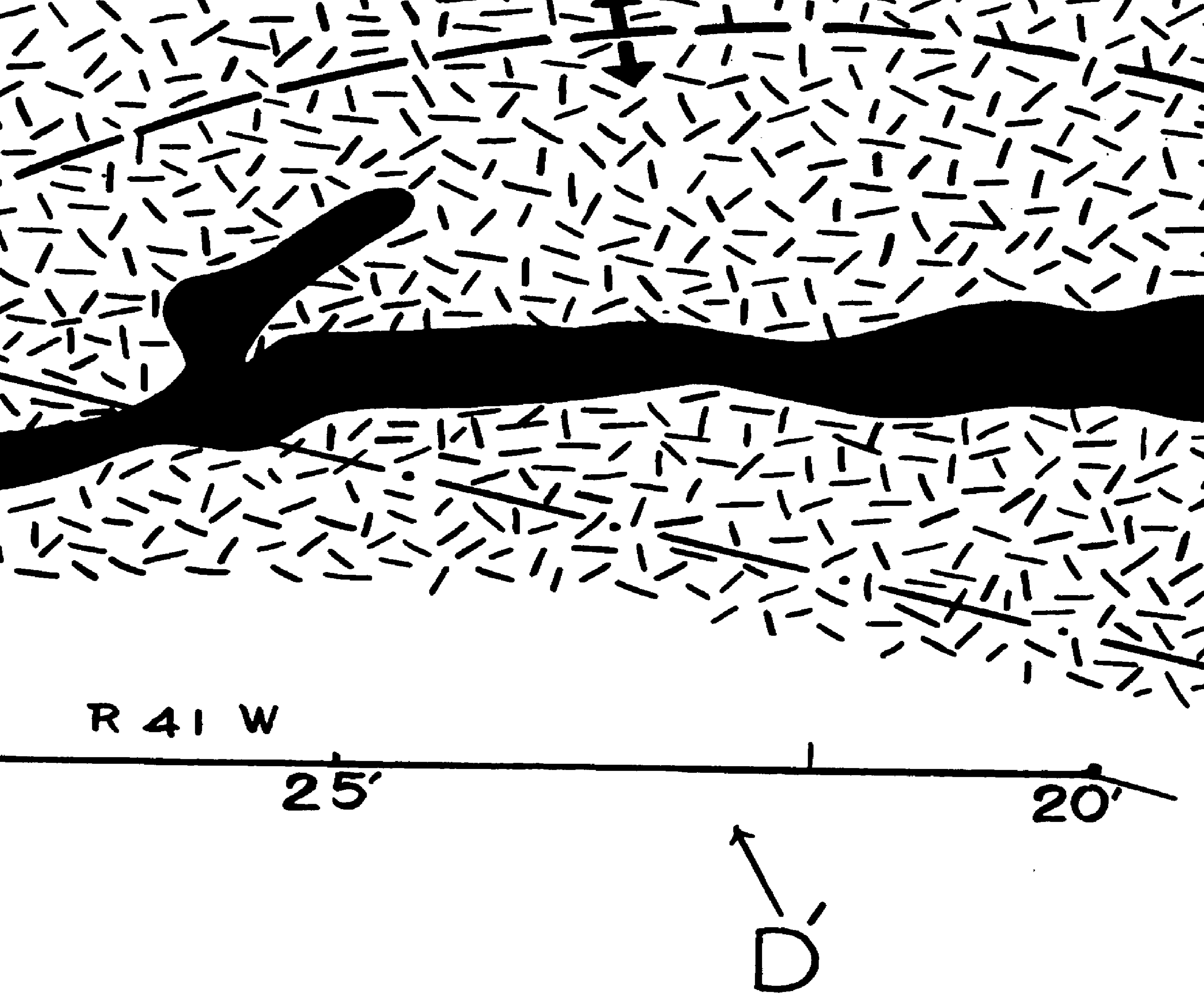
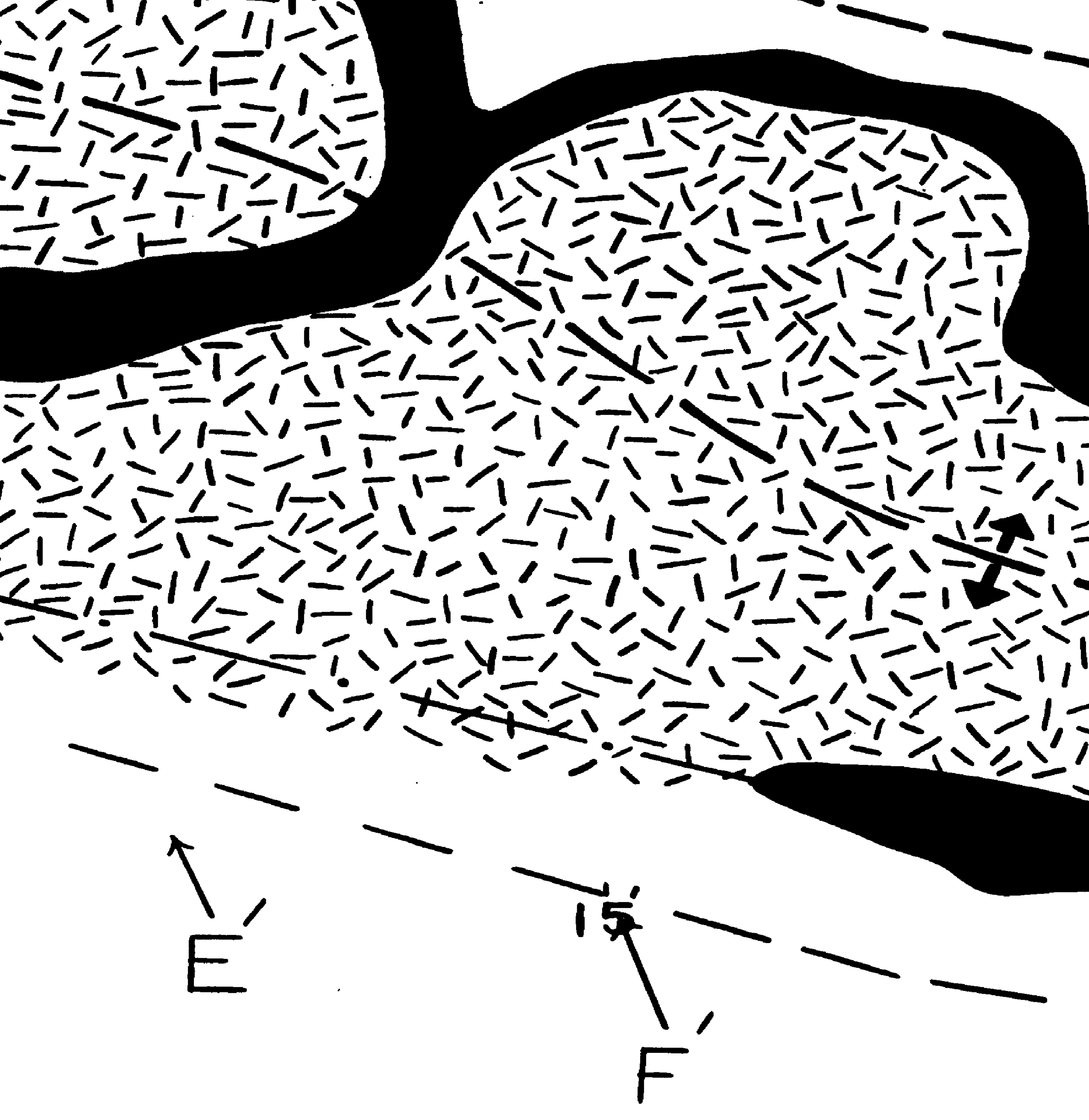
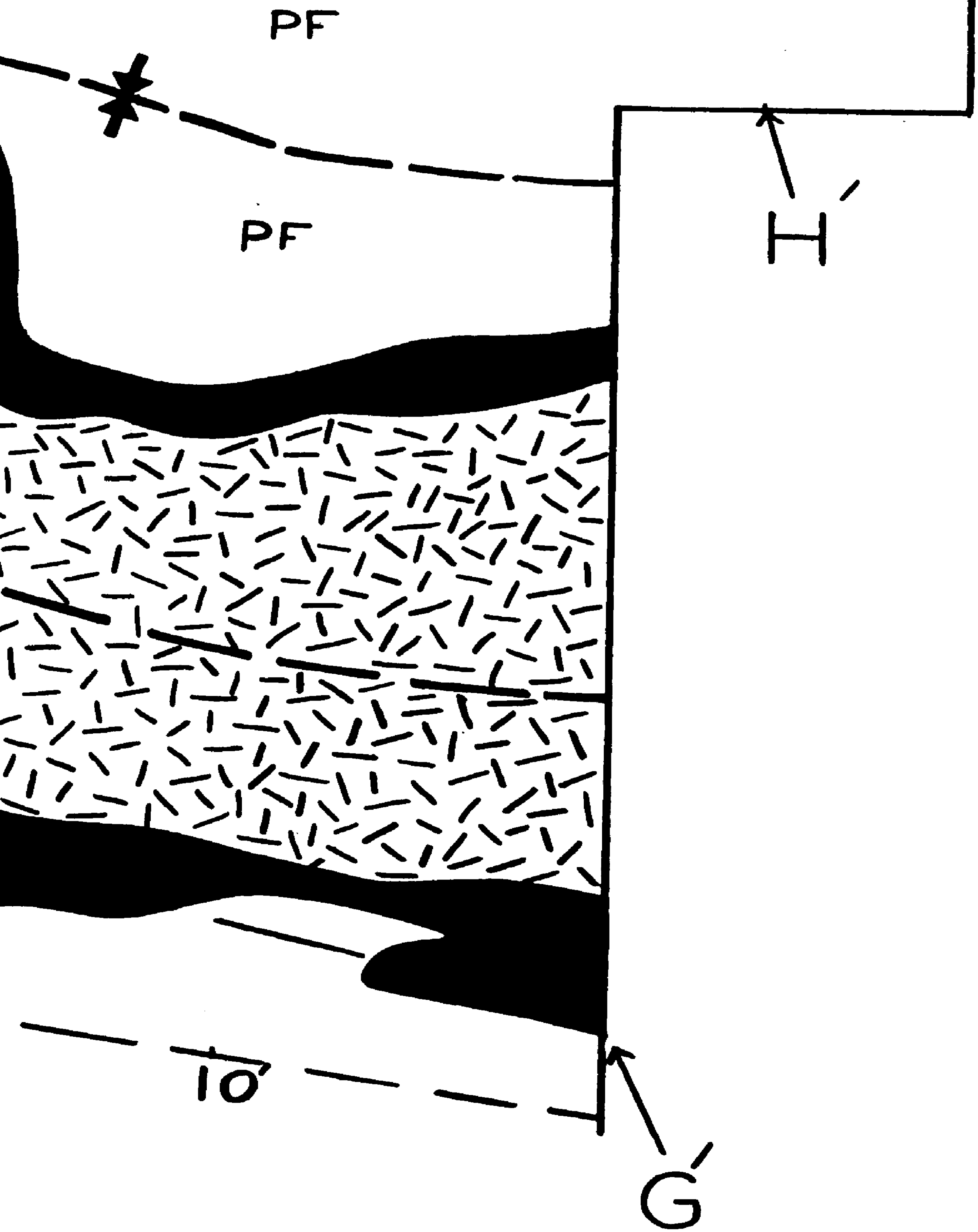


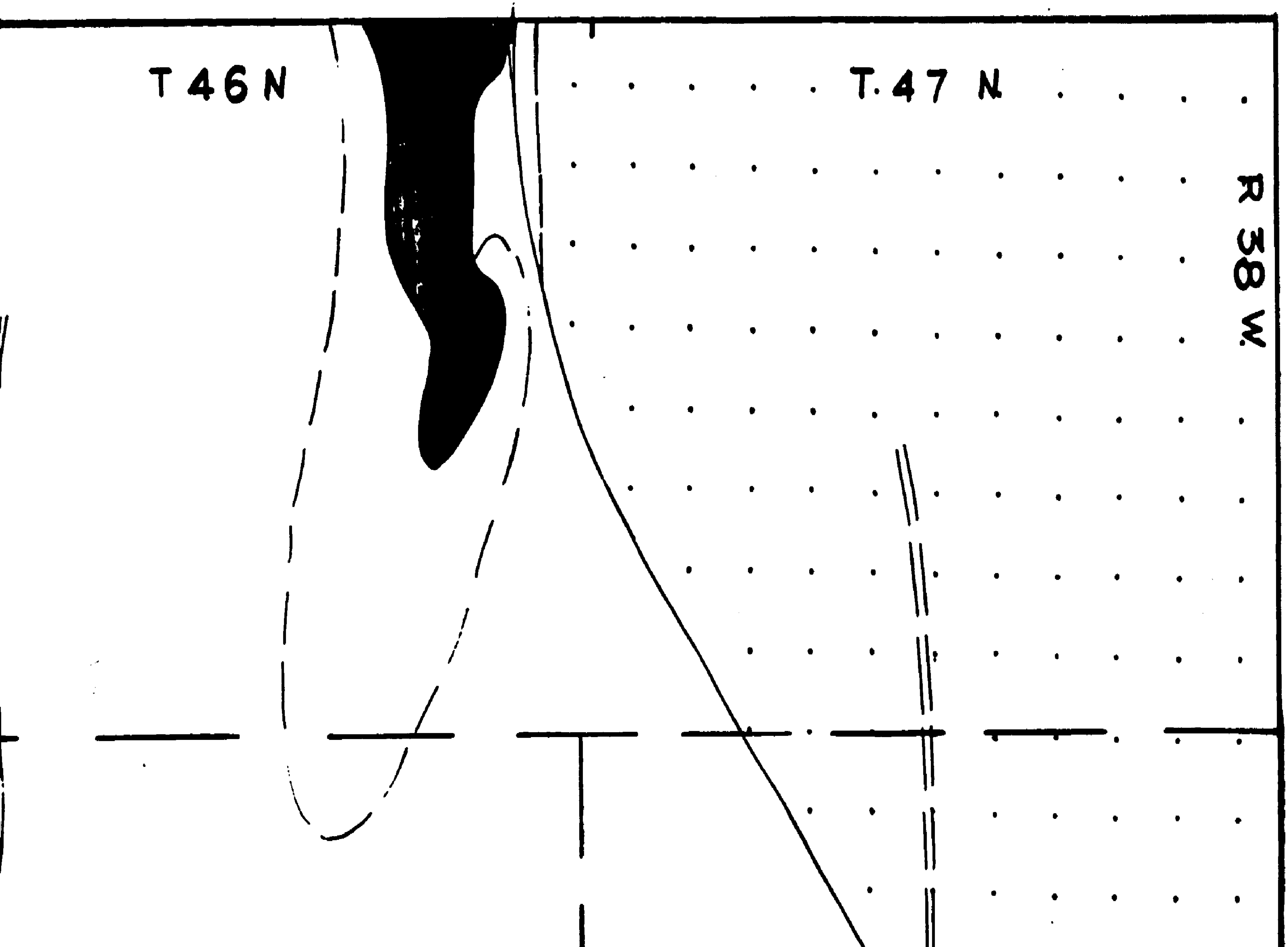
PLATE III-d

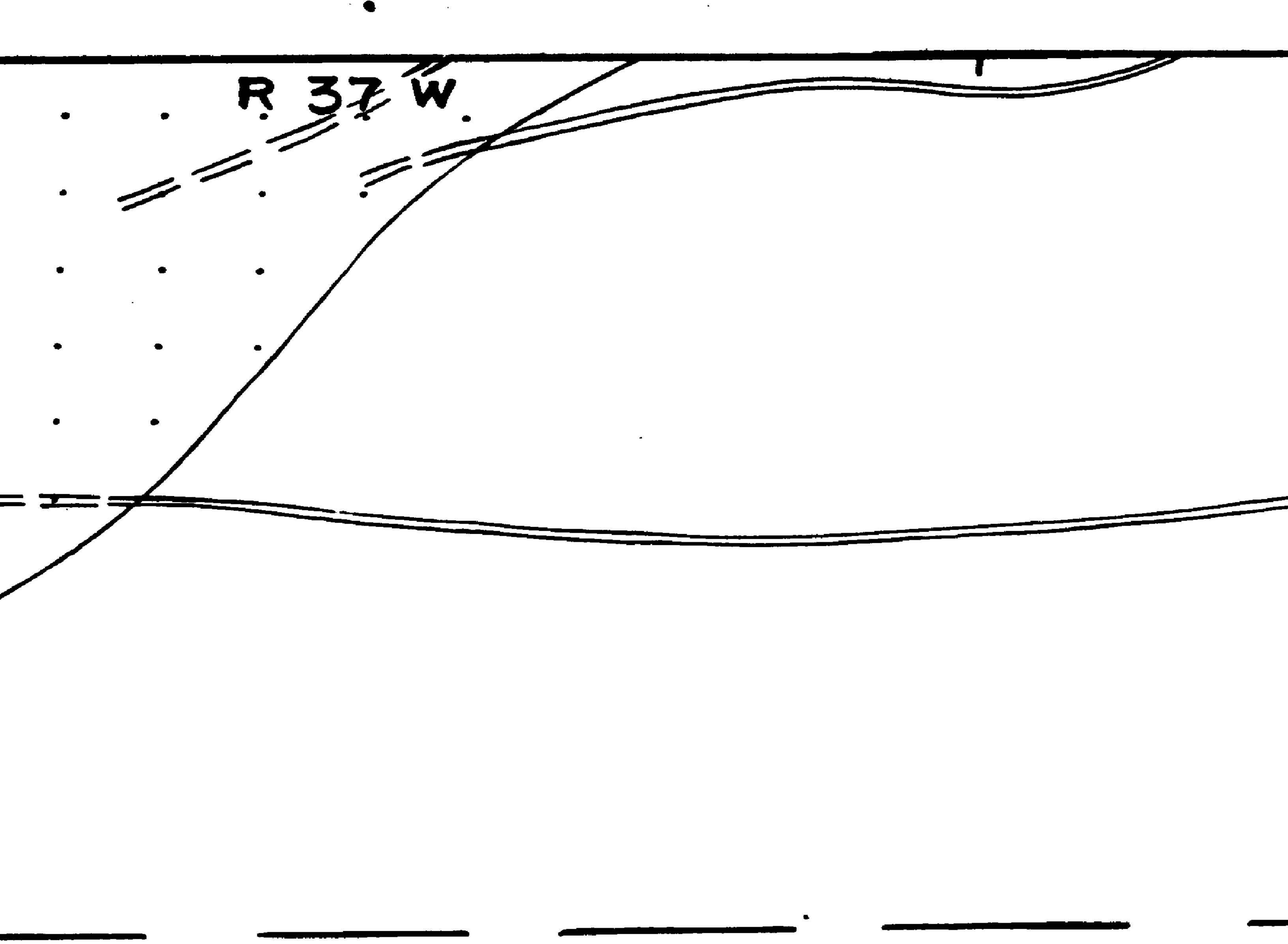

R 41 W
25'
20'
D

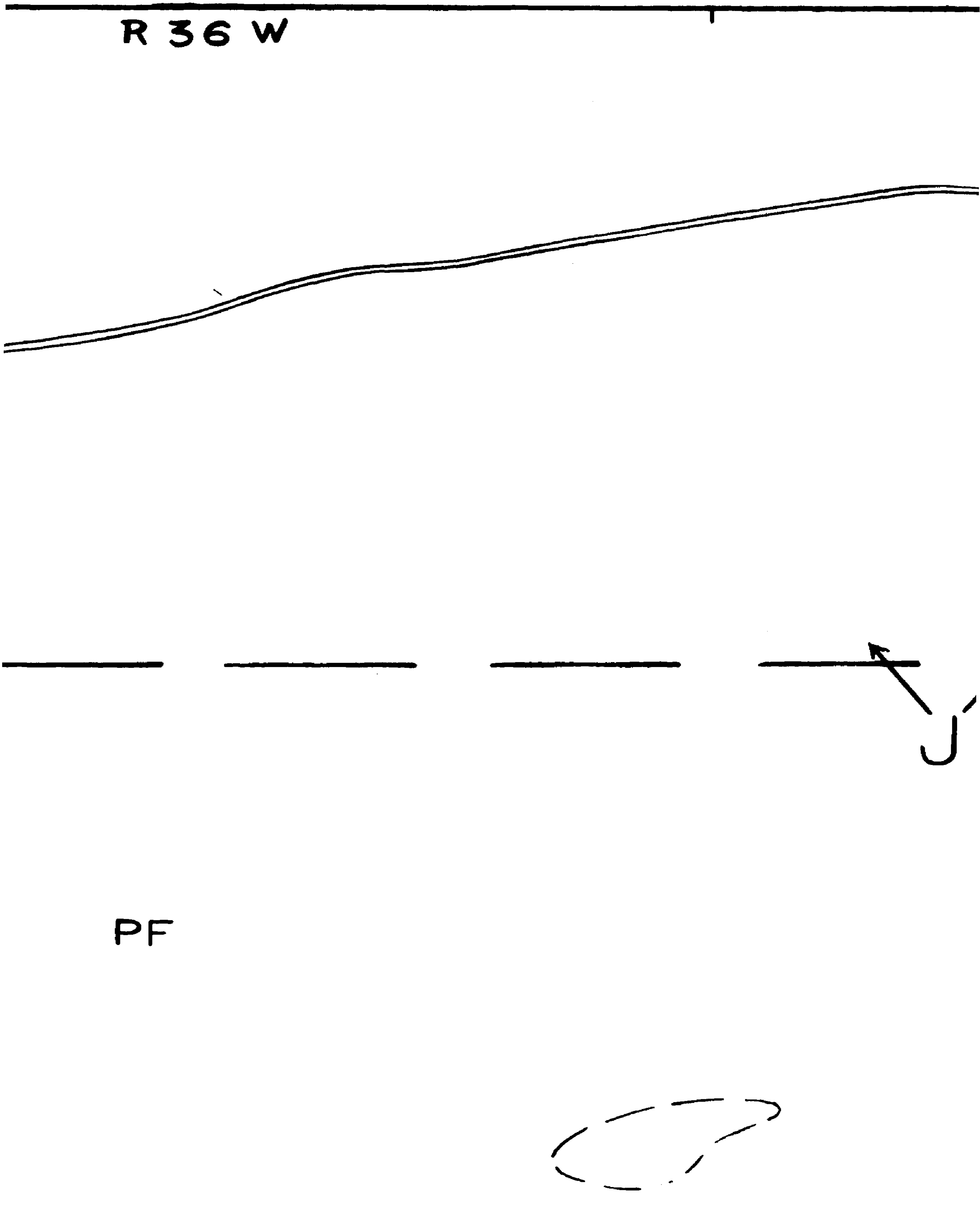

15
E
F



PF
PF
H'
10'
G'

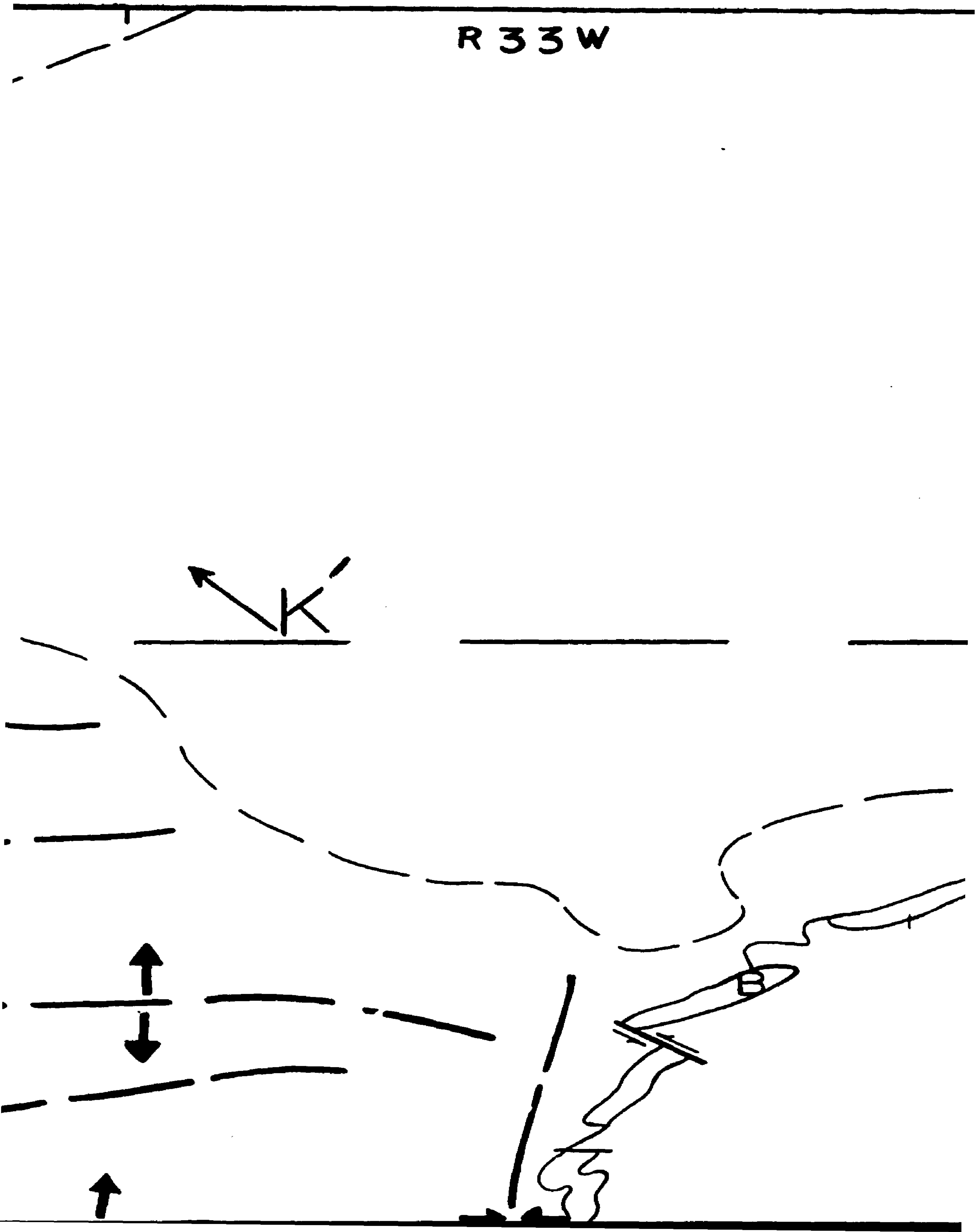

T 46 N
T. 47 N.
R 38 W.

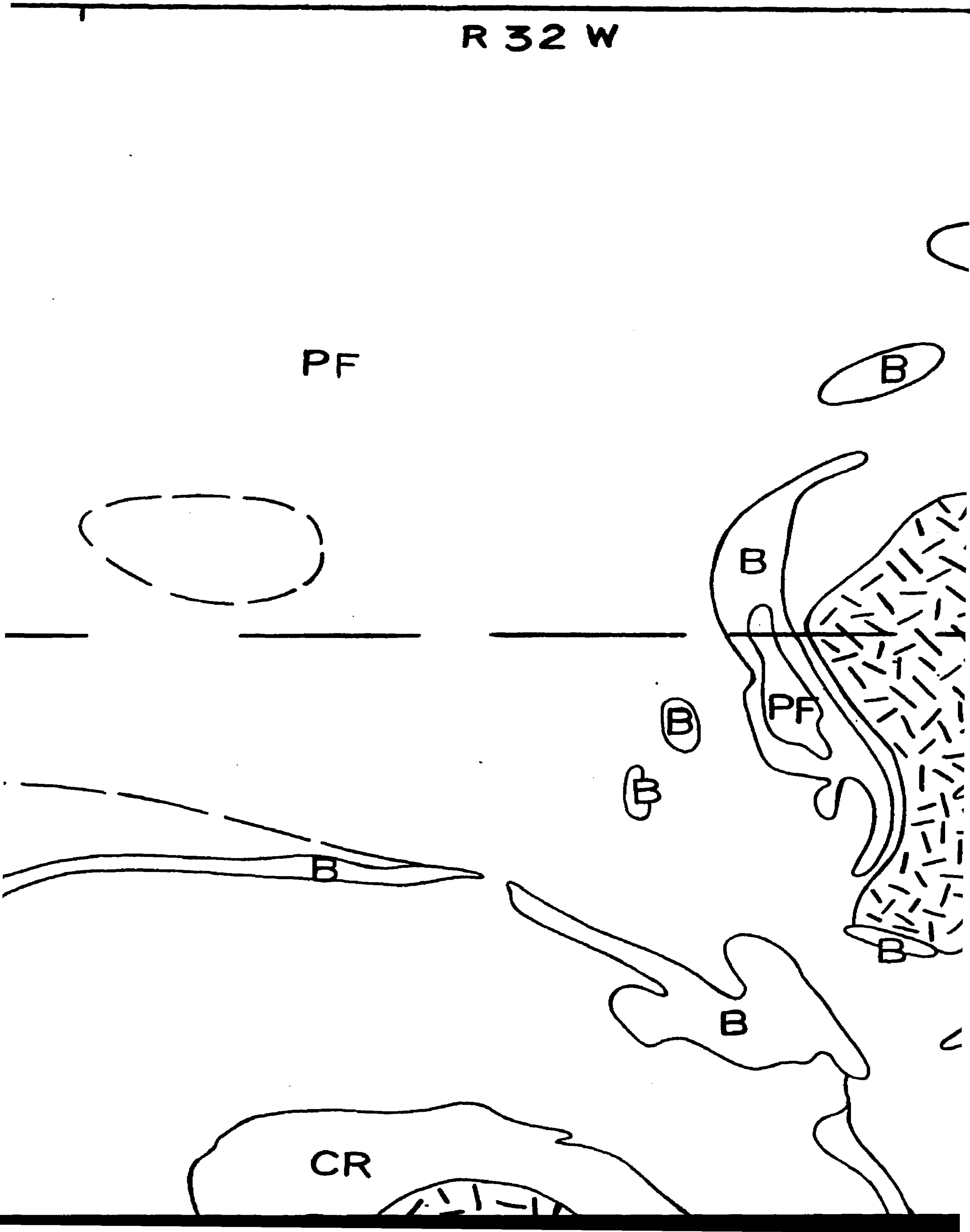

R 37 W

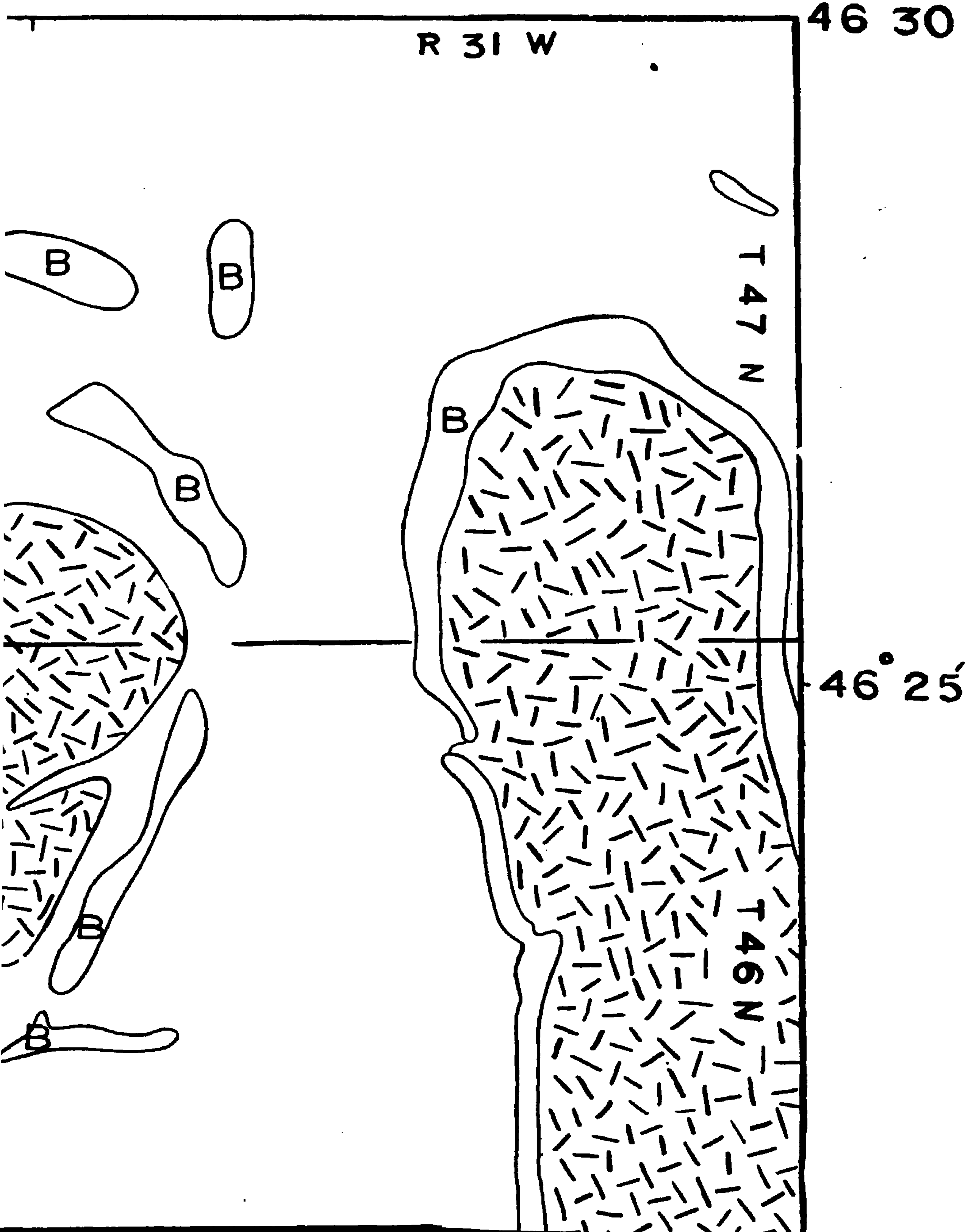

R 36 W
J
PF

R 35 W
R 34

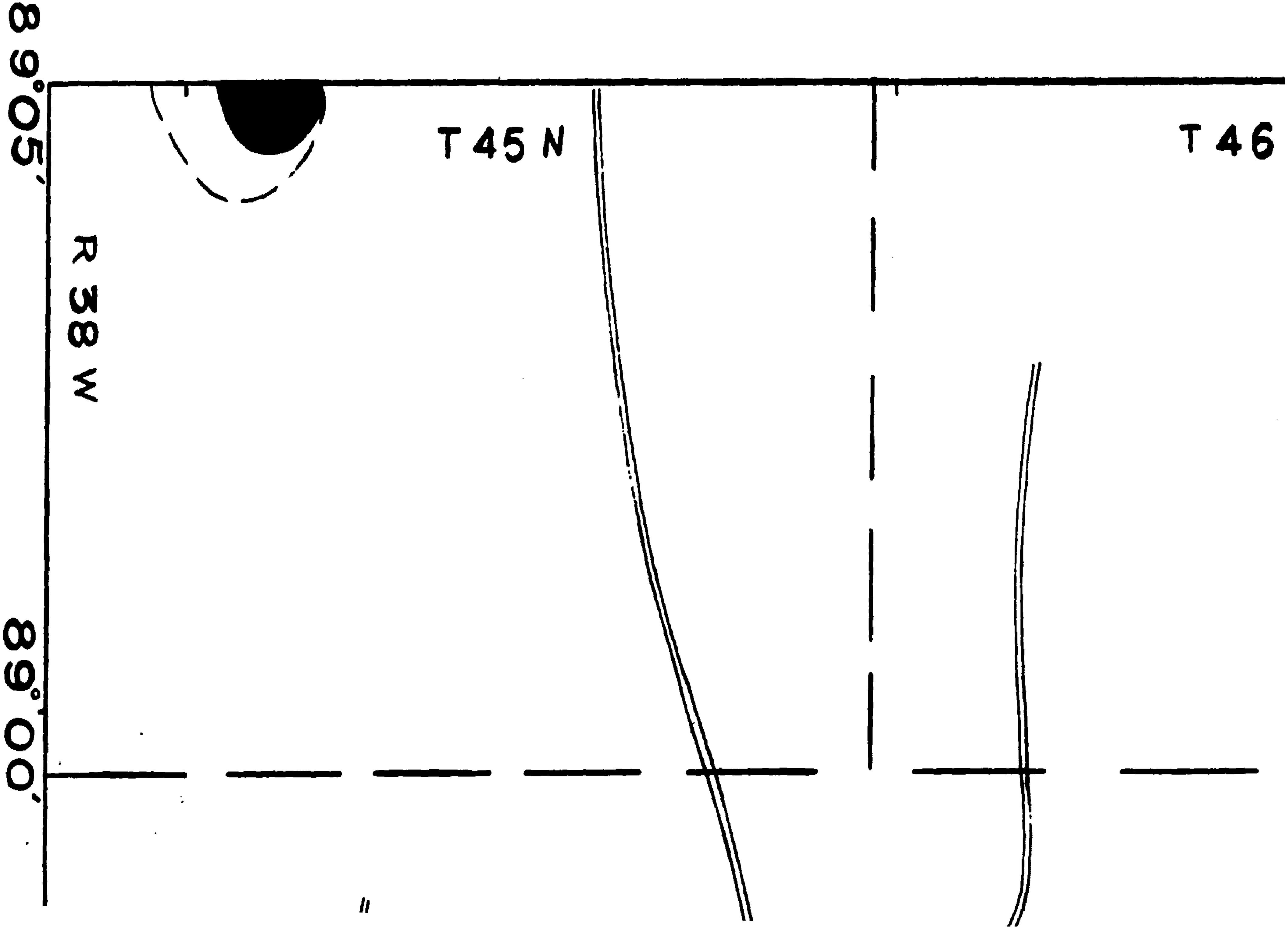

R 34 W


R 33 W
K'
B

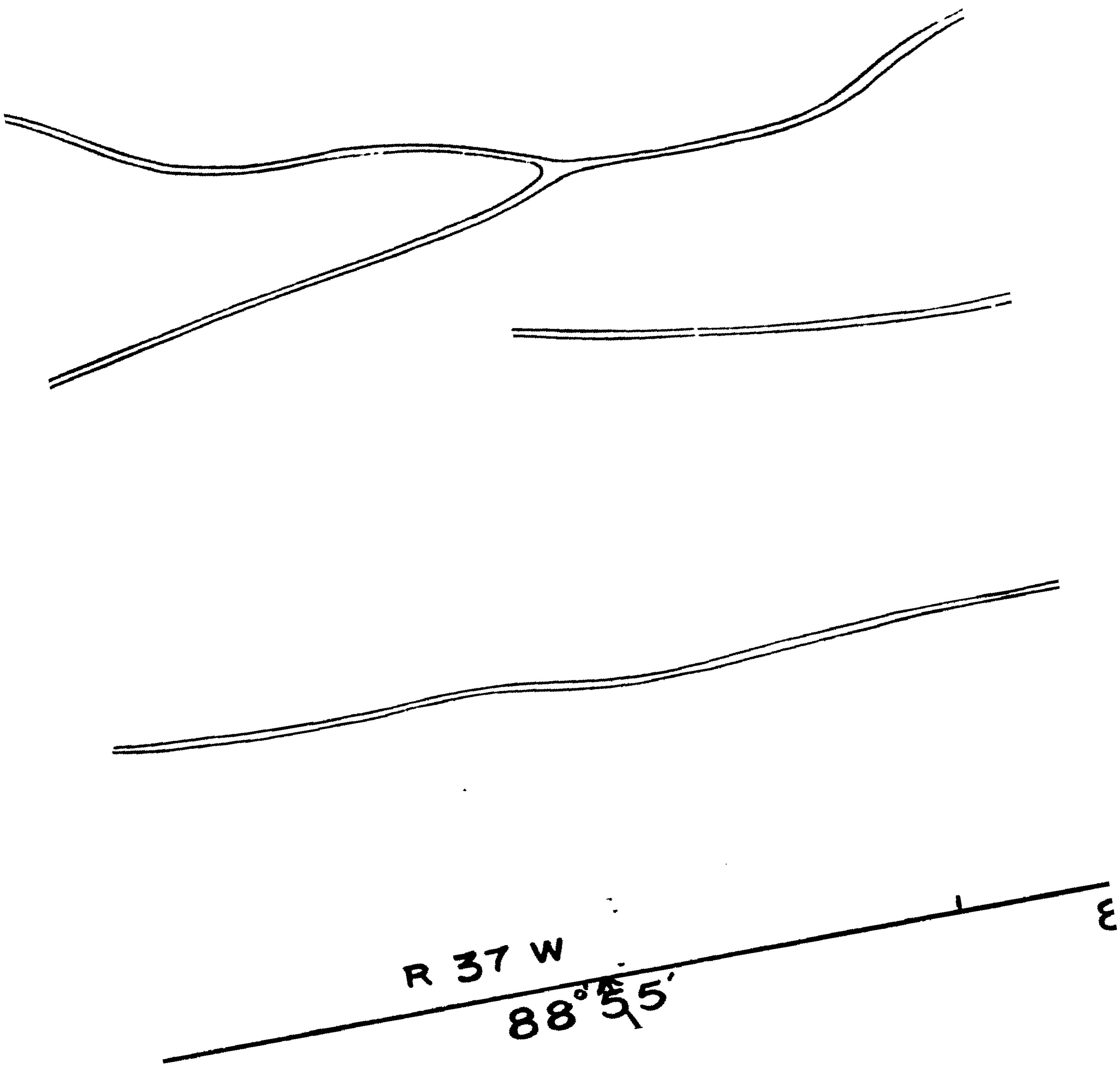

R 32 W
PF
B
B
PF
B
B
B
B
B
CR

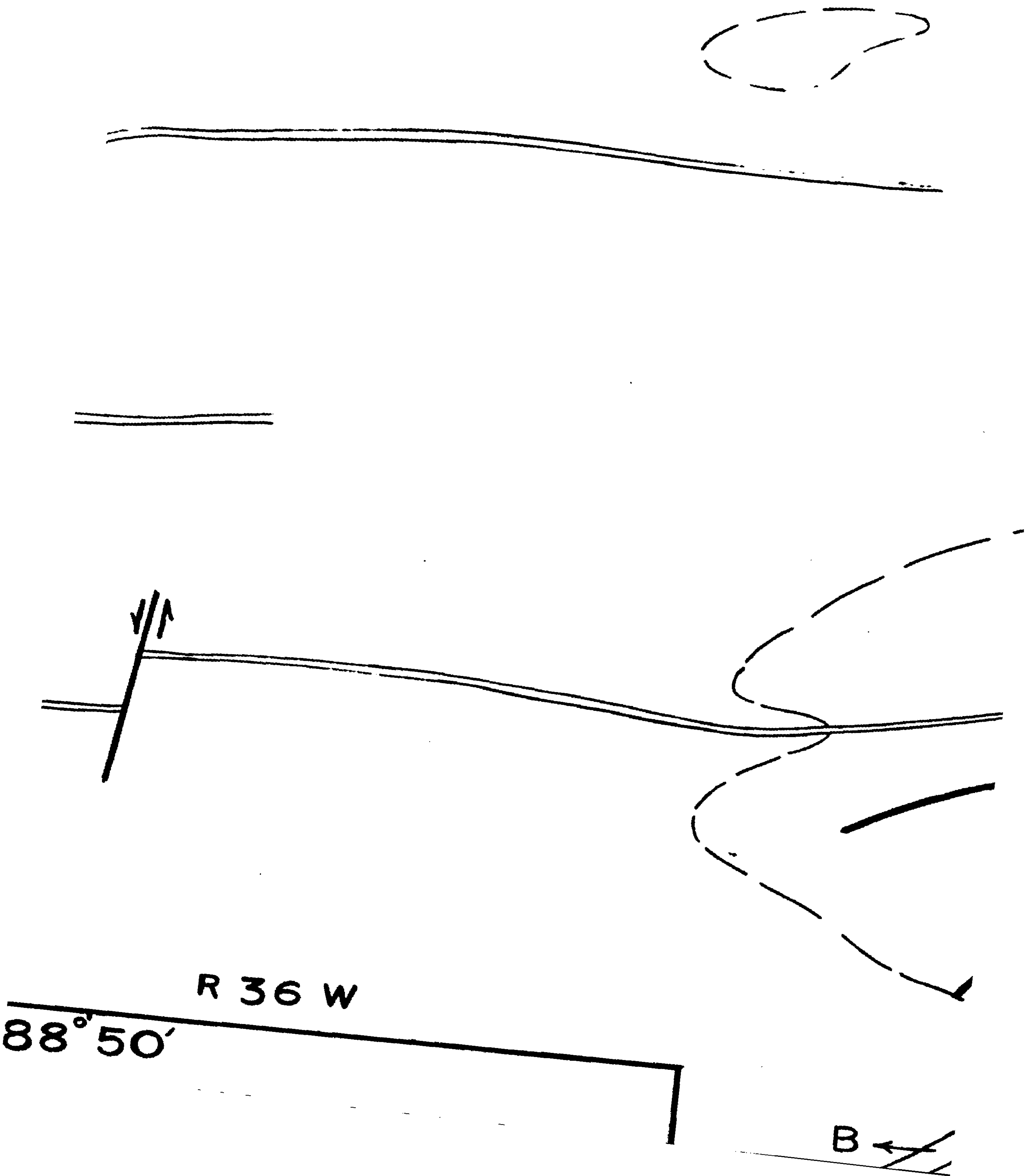


46 30
R 31 W
T 47 N
B
B
B
B
46°25′
B
B
T 46 N

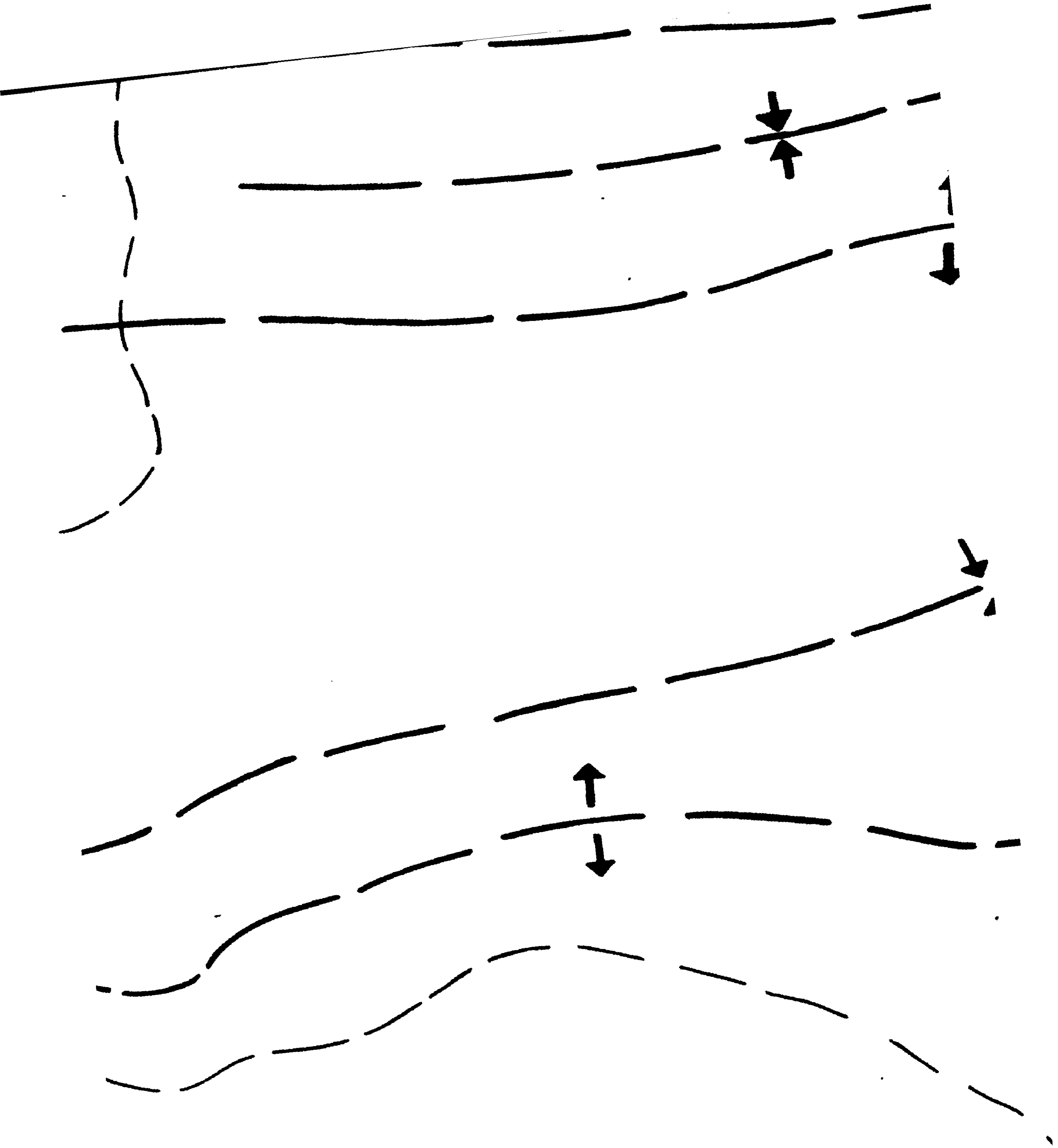


T 45 N
T 46
R 38 W
89°05'
89°00'

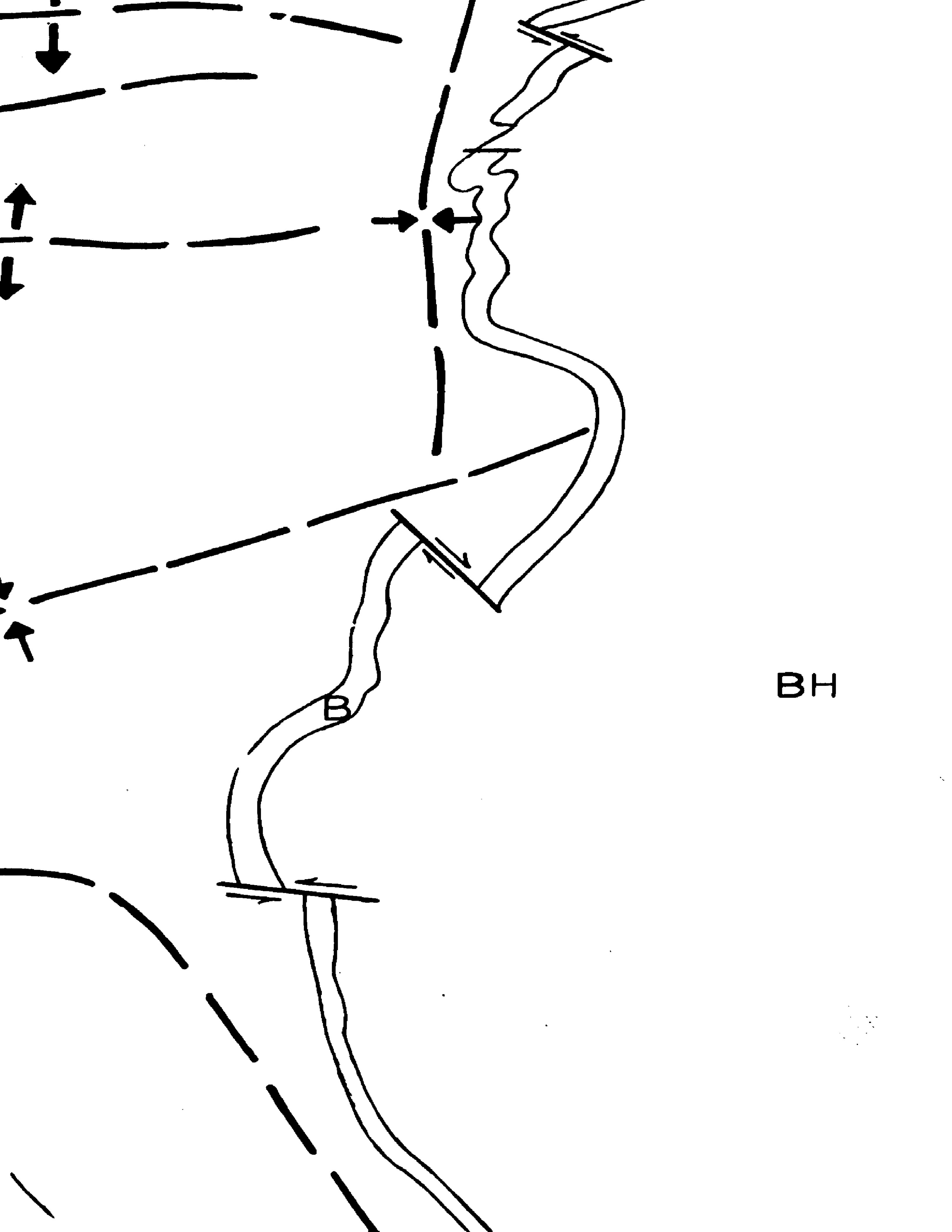

R 37 W
88°55'

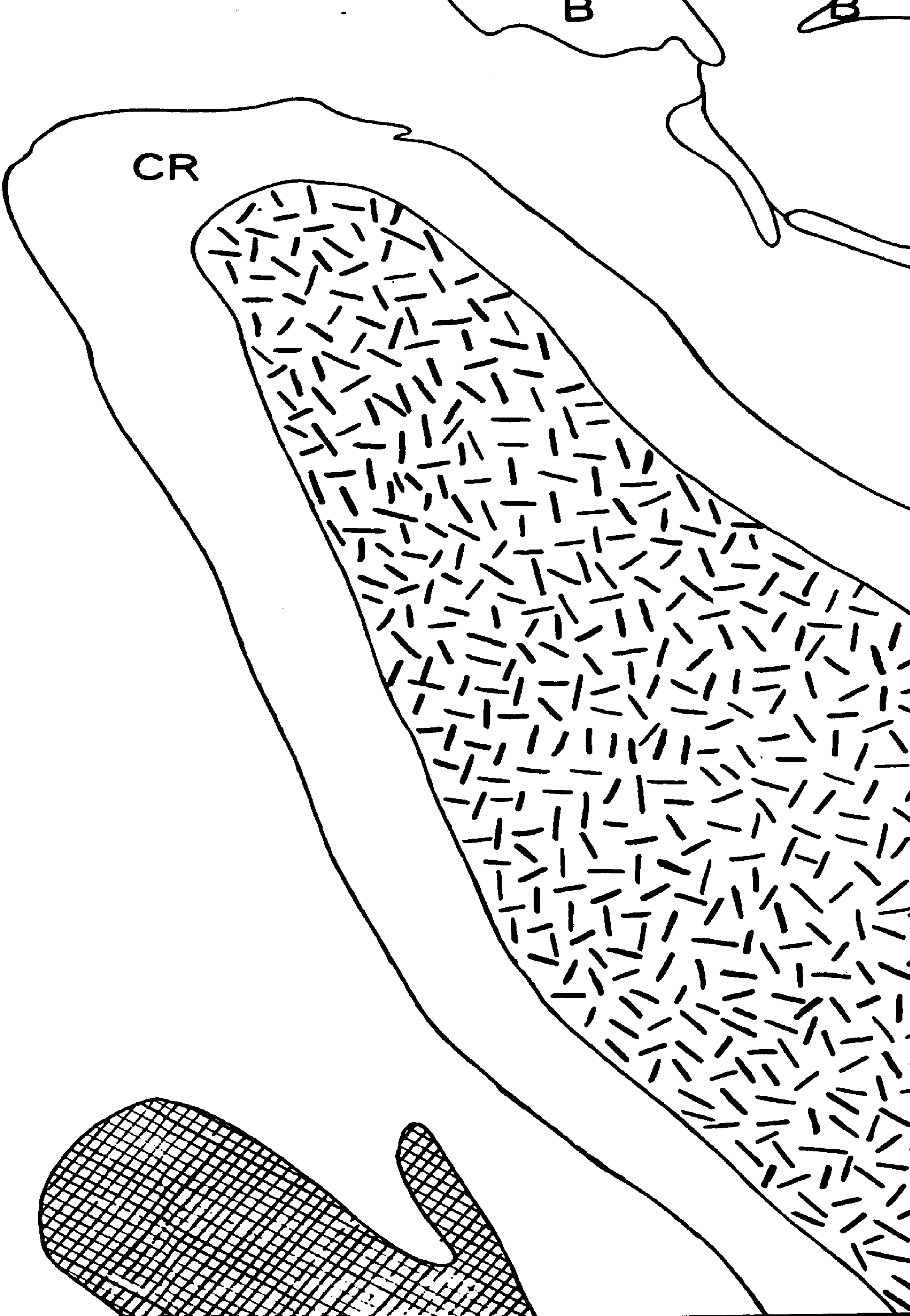

R 36 W
88°50′
B

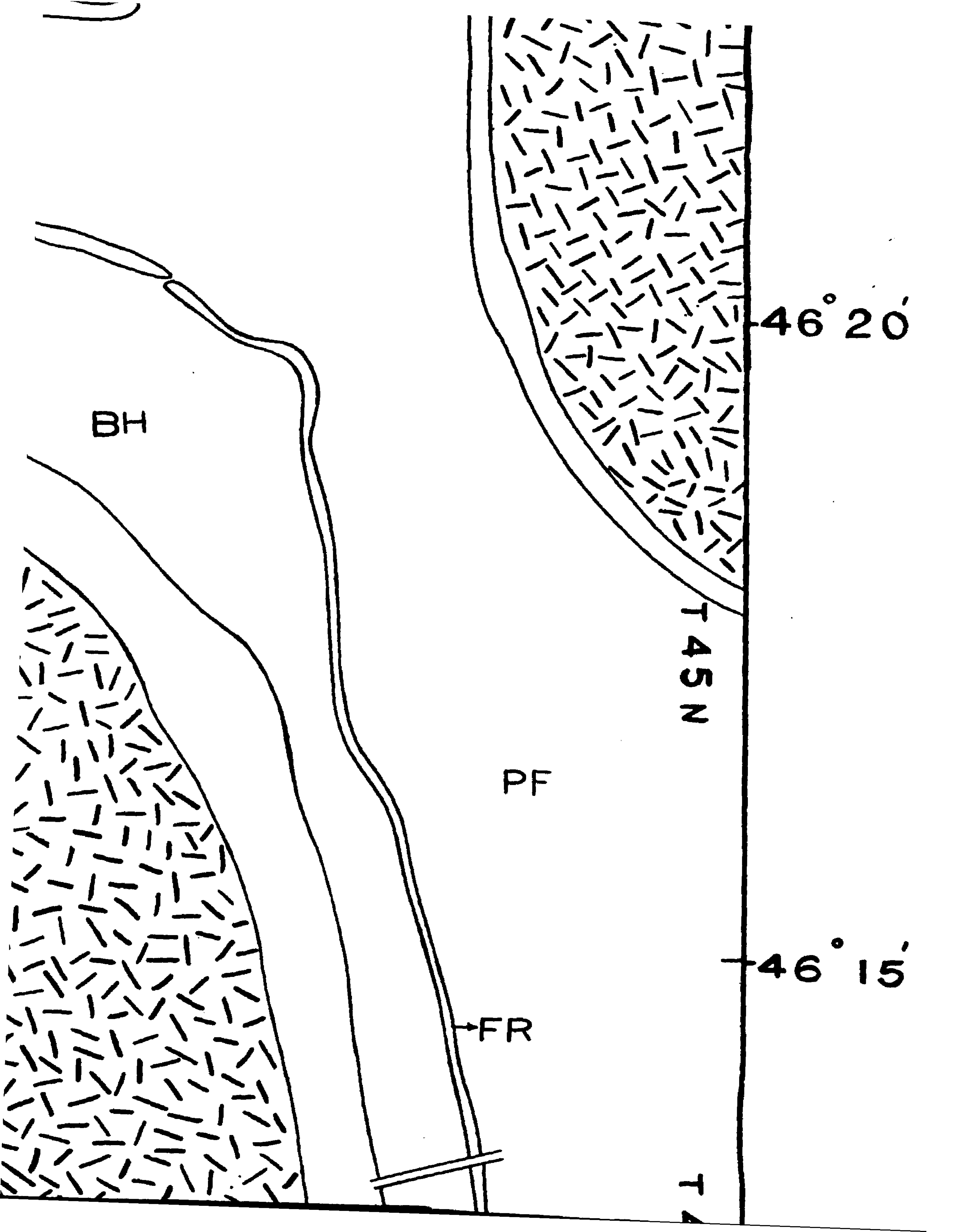

BH



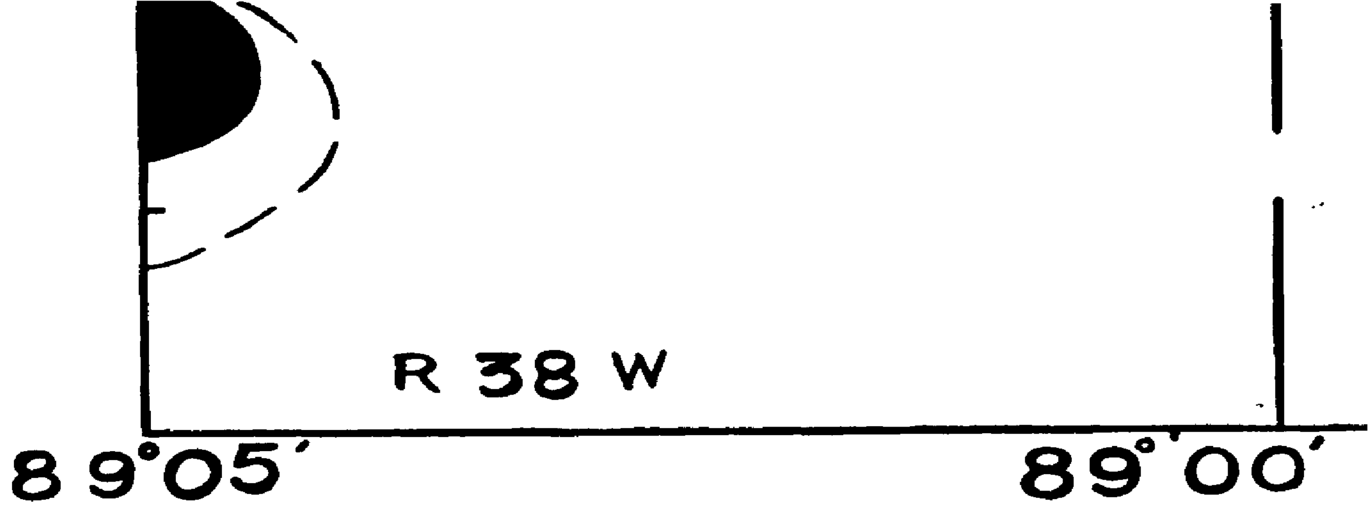
PF

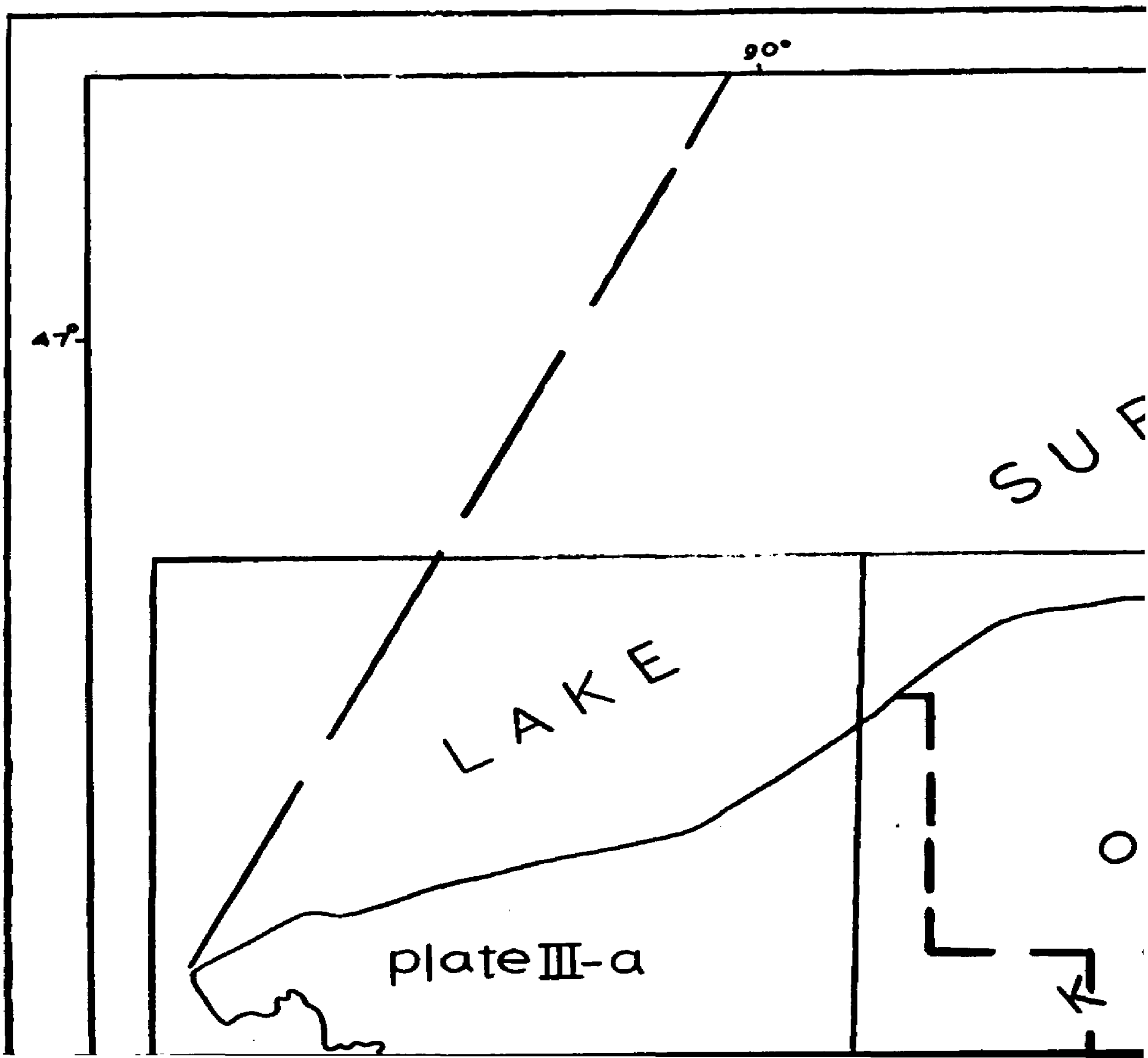

B
BH

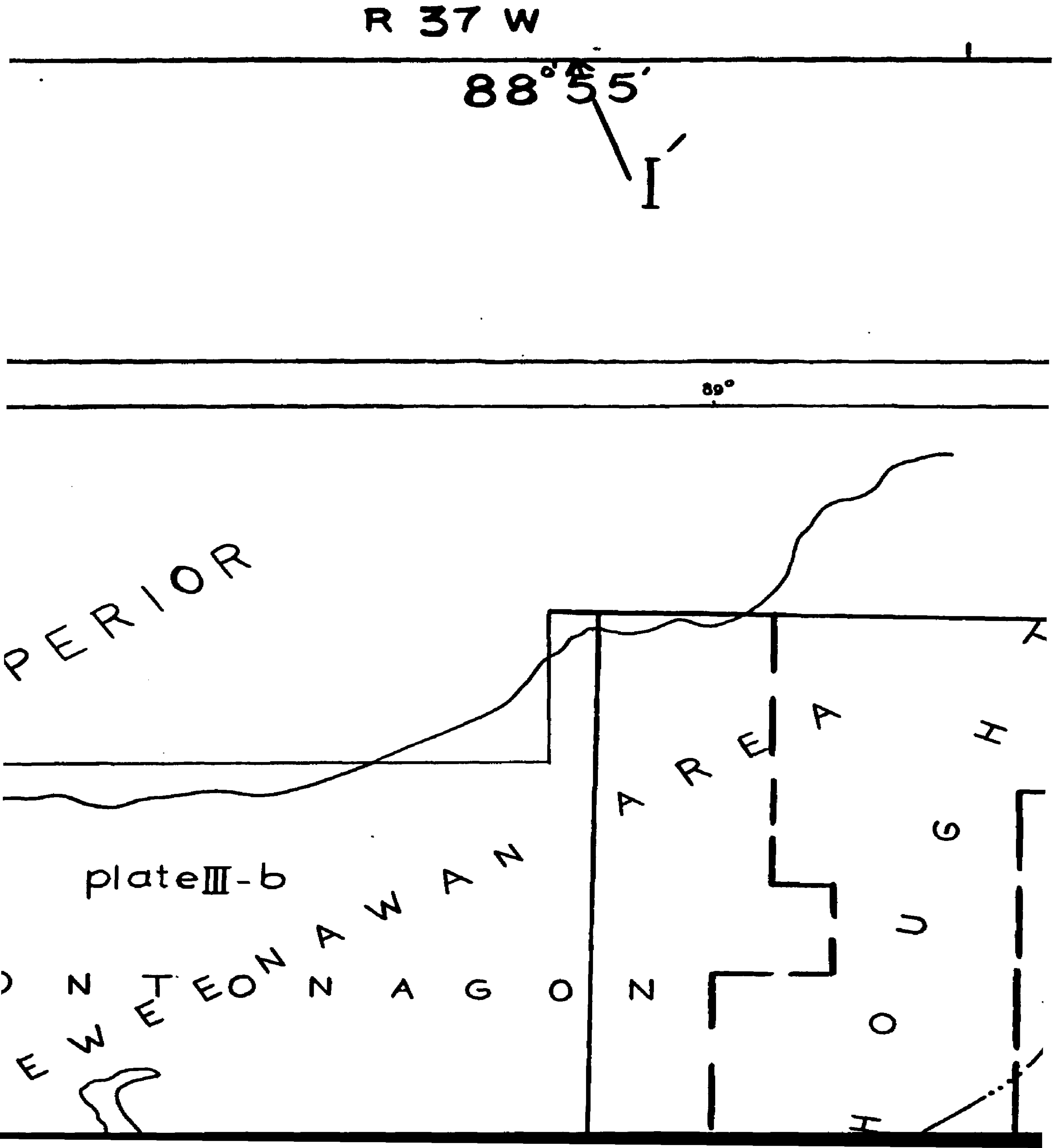

B
B
CR

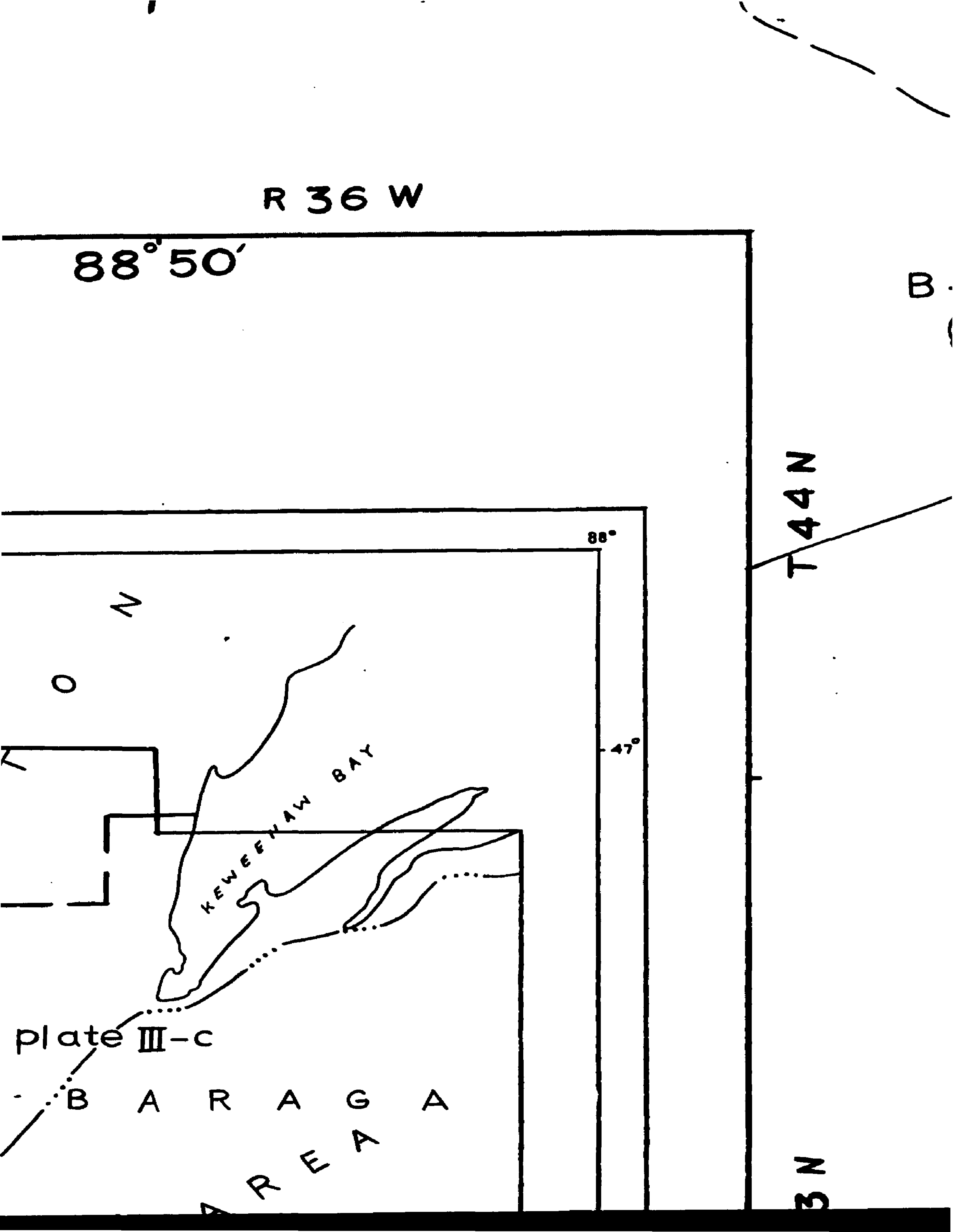


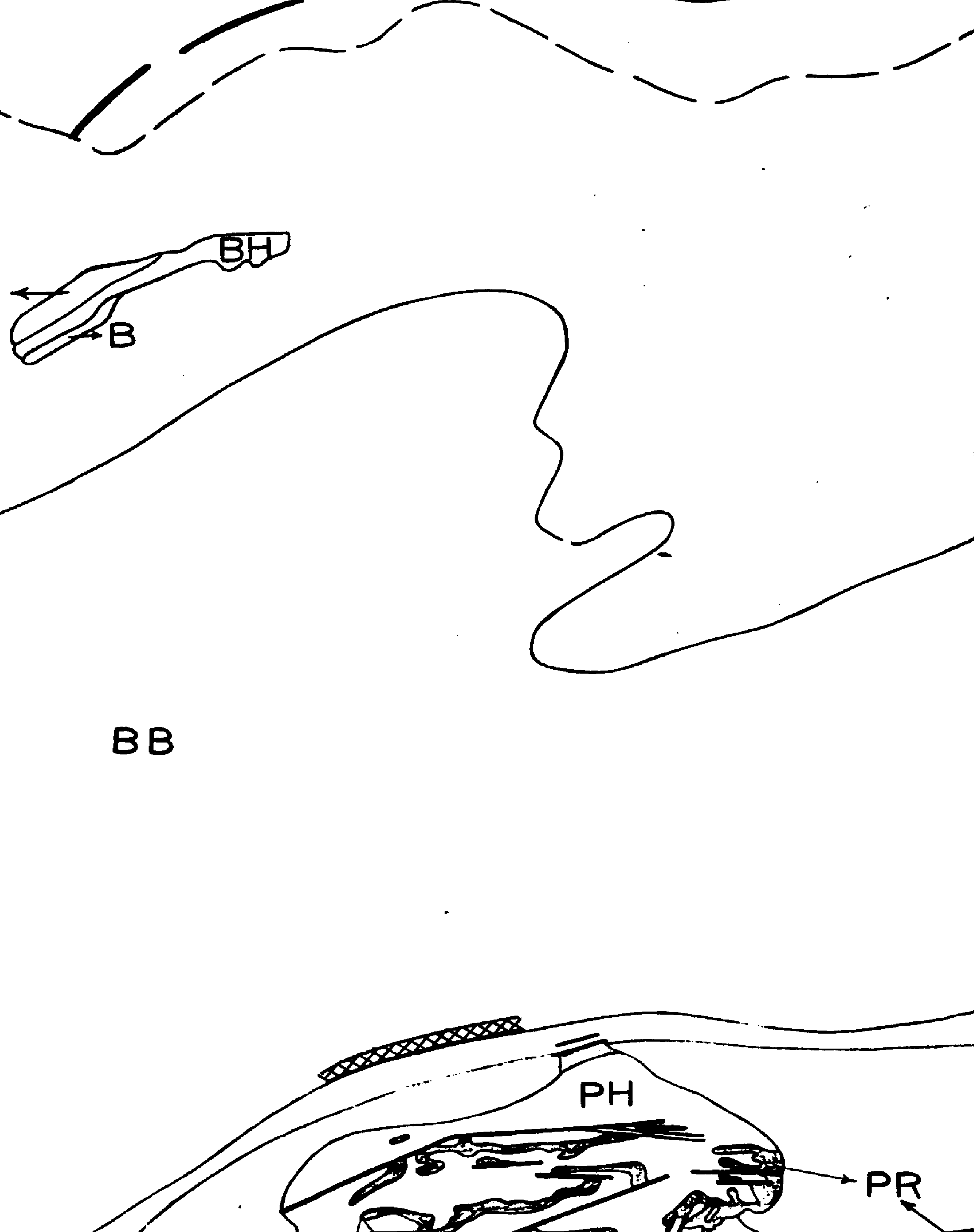
BH
PF
FR
46°20'
46°15'
T 45 N

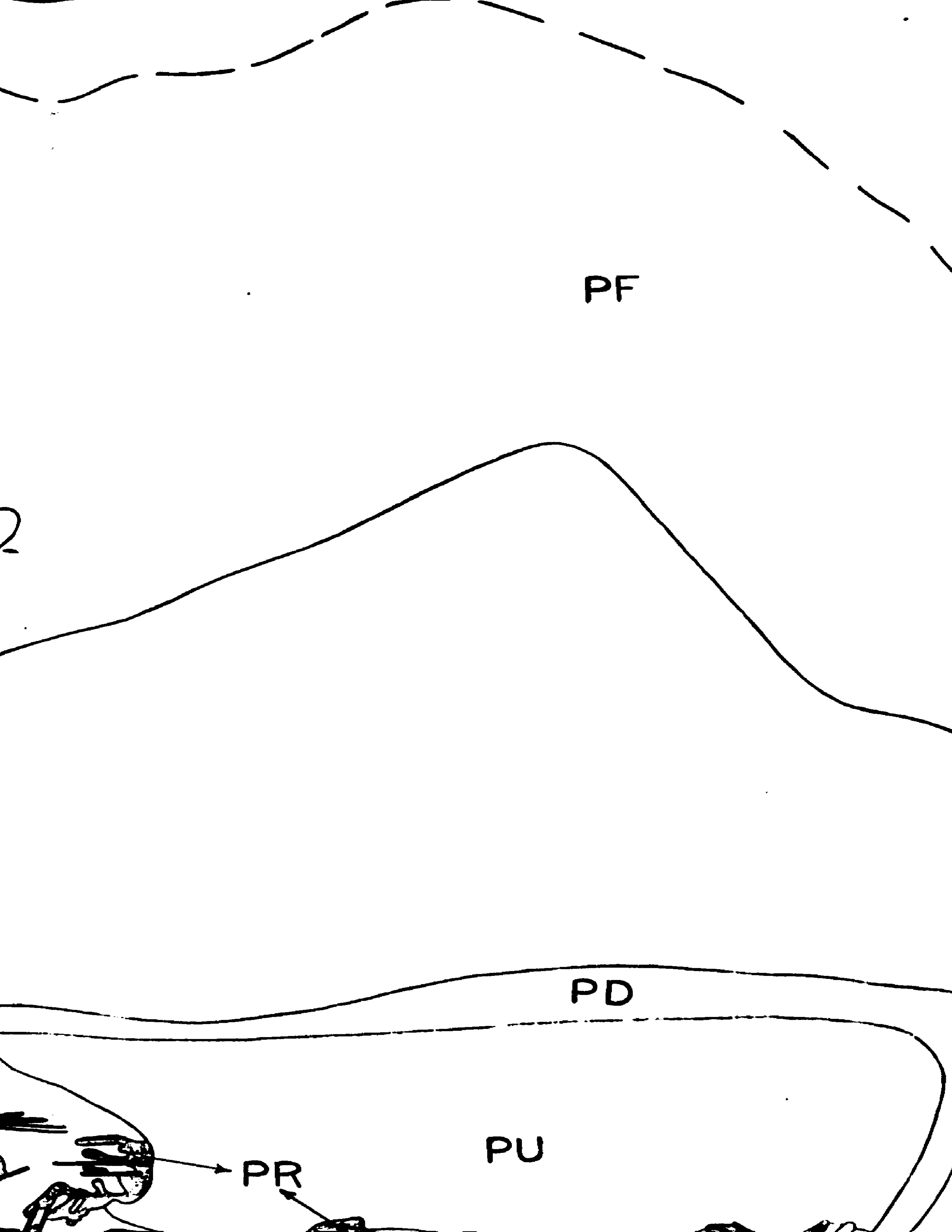

R 38 W
89°05′
89°00′

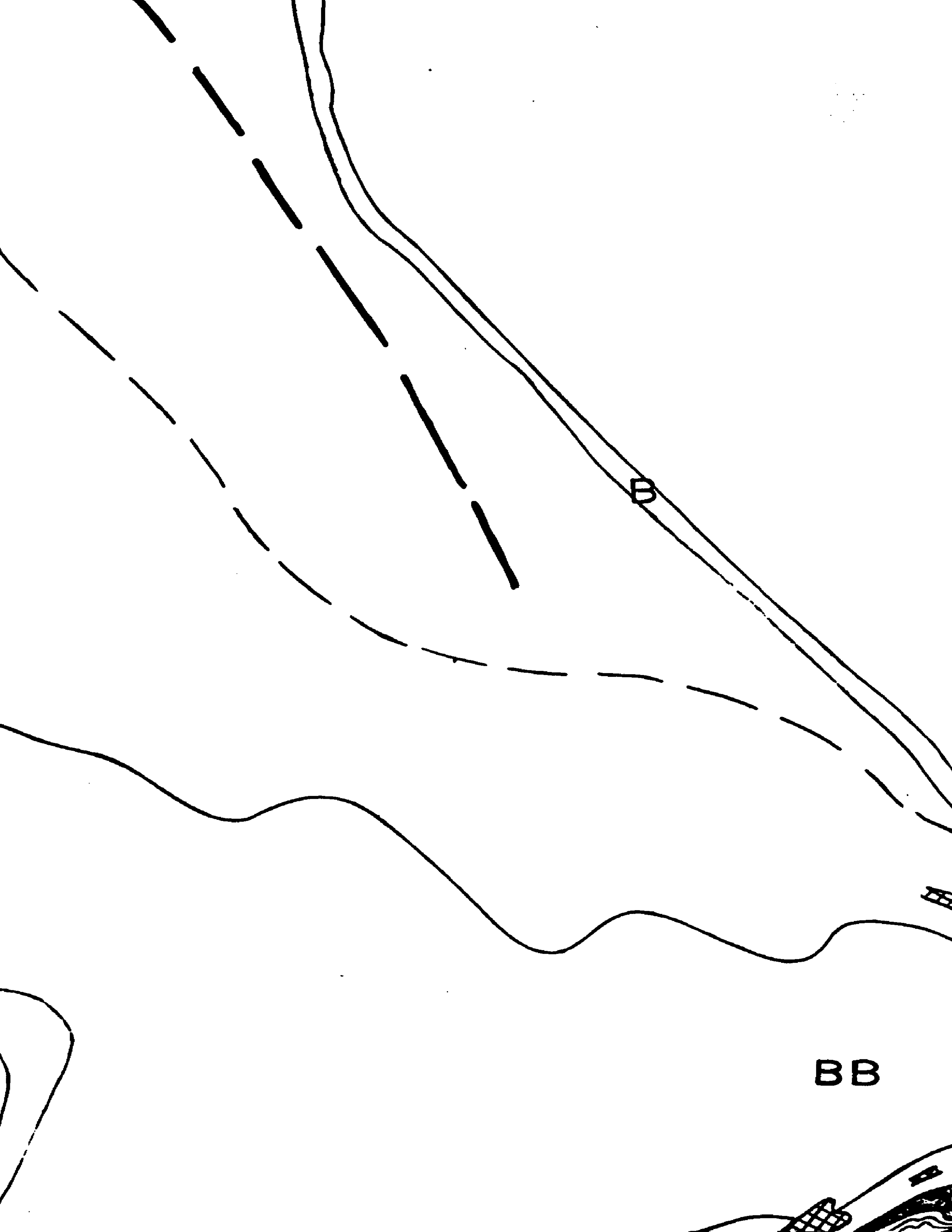

90°
47°
SU
LAKE
plate III-a
O
K

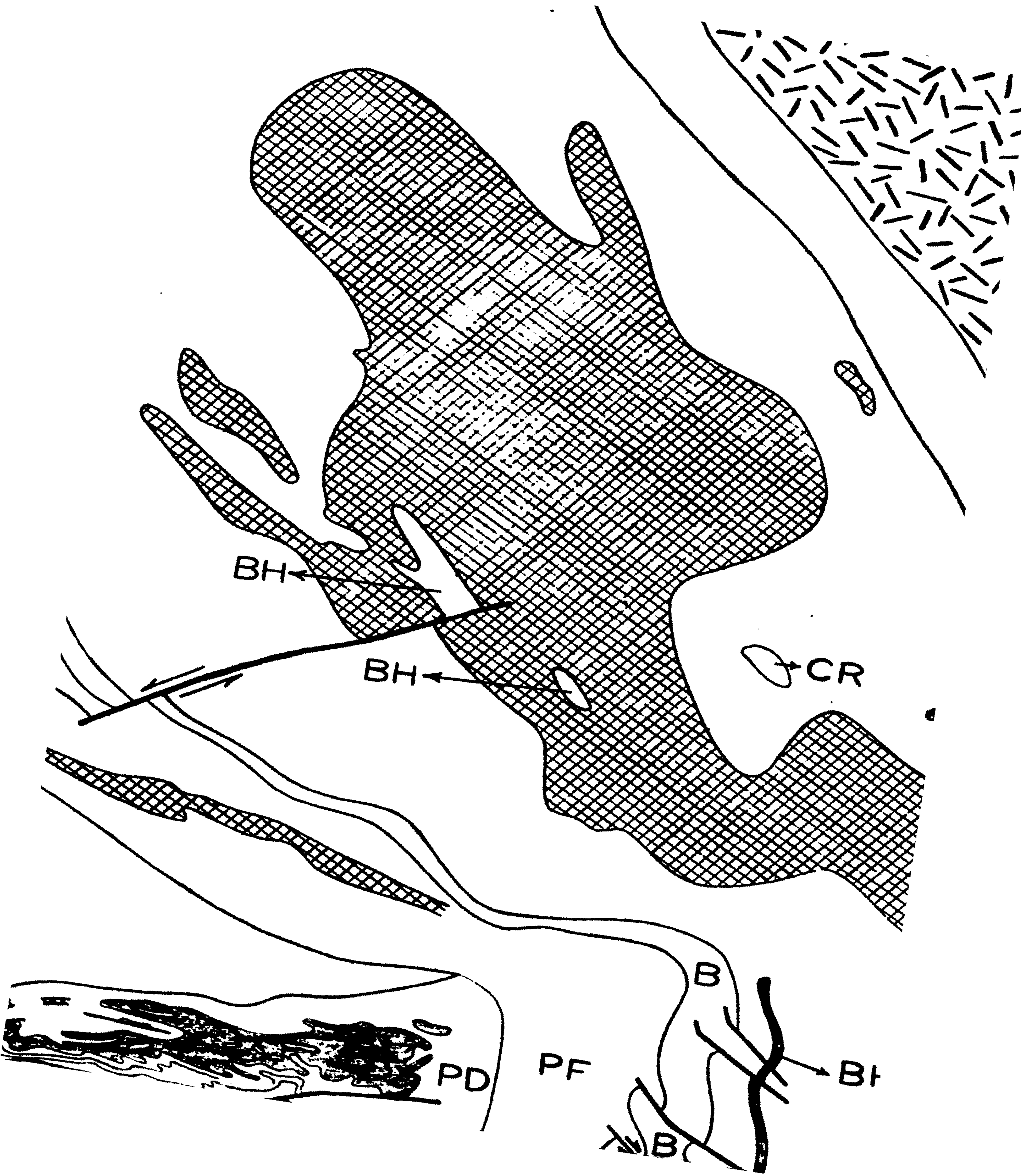

R 37 W
88°55'
I'
89°
PERIOR
plate III-b
EWEENAWAN AREA
NTONAGON
HOUGH

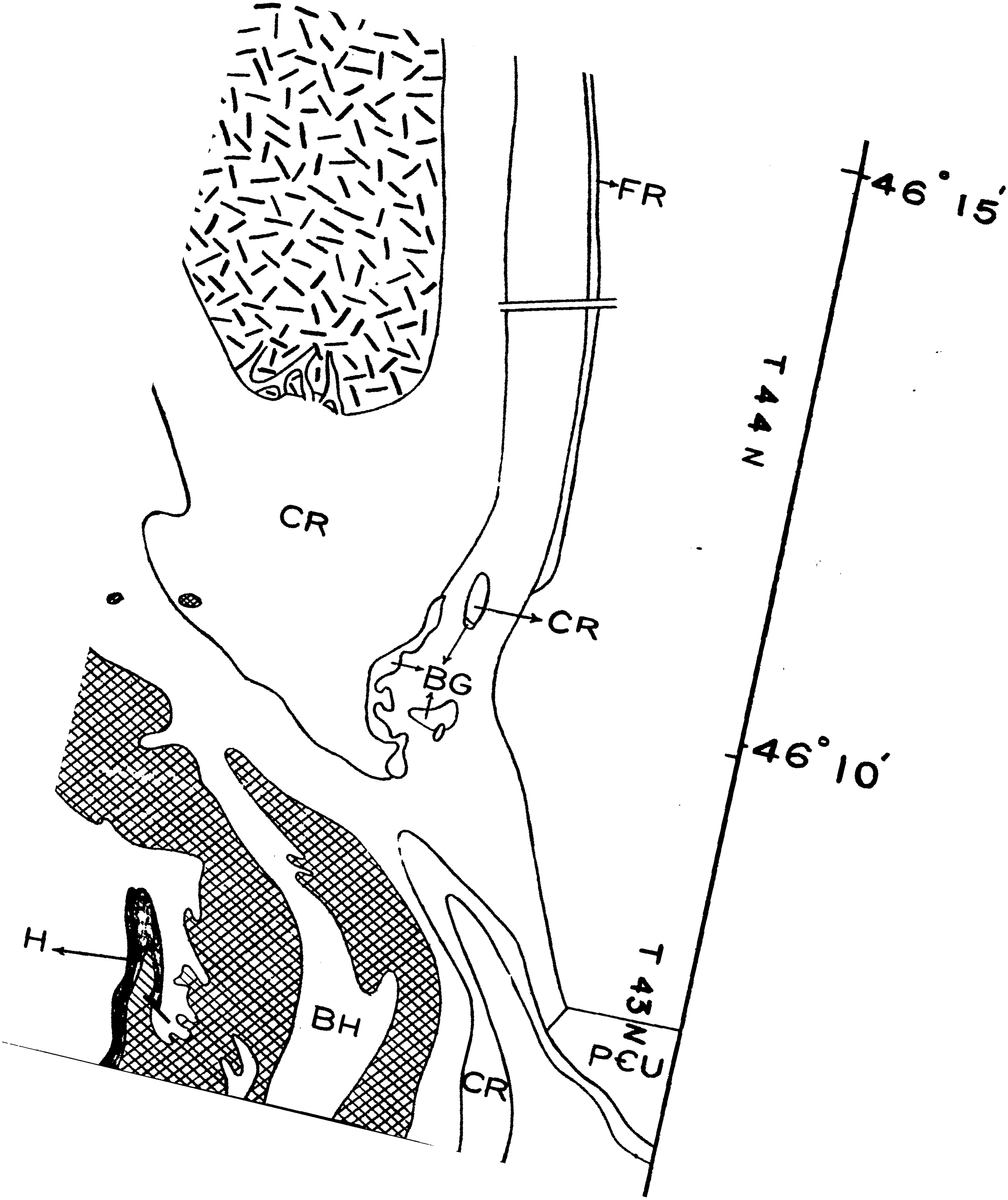

R 36 W
88°50′
B
T 44 N
88°
47°
N
O
KEWEENAW BAY
plate III-c
B A R A G A
A R E A
3 N


BH
B
BB
PH
PR


PF
PD
PU
PR


B
BB


BH
BH
CR
B
PD
PF
BH
B



FR
46° 15′
T 44 N
CR
CR
BG
46° 10′
H
BH
T 43 N
P€U
CR

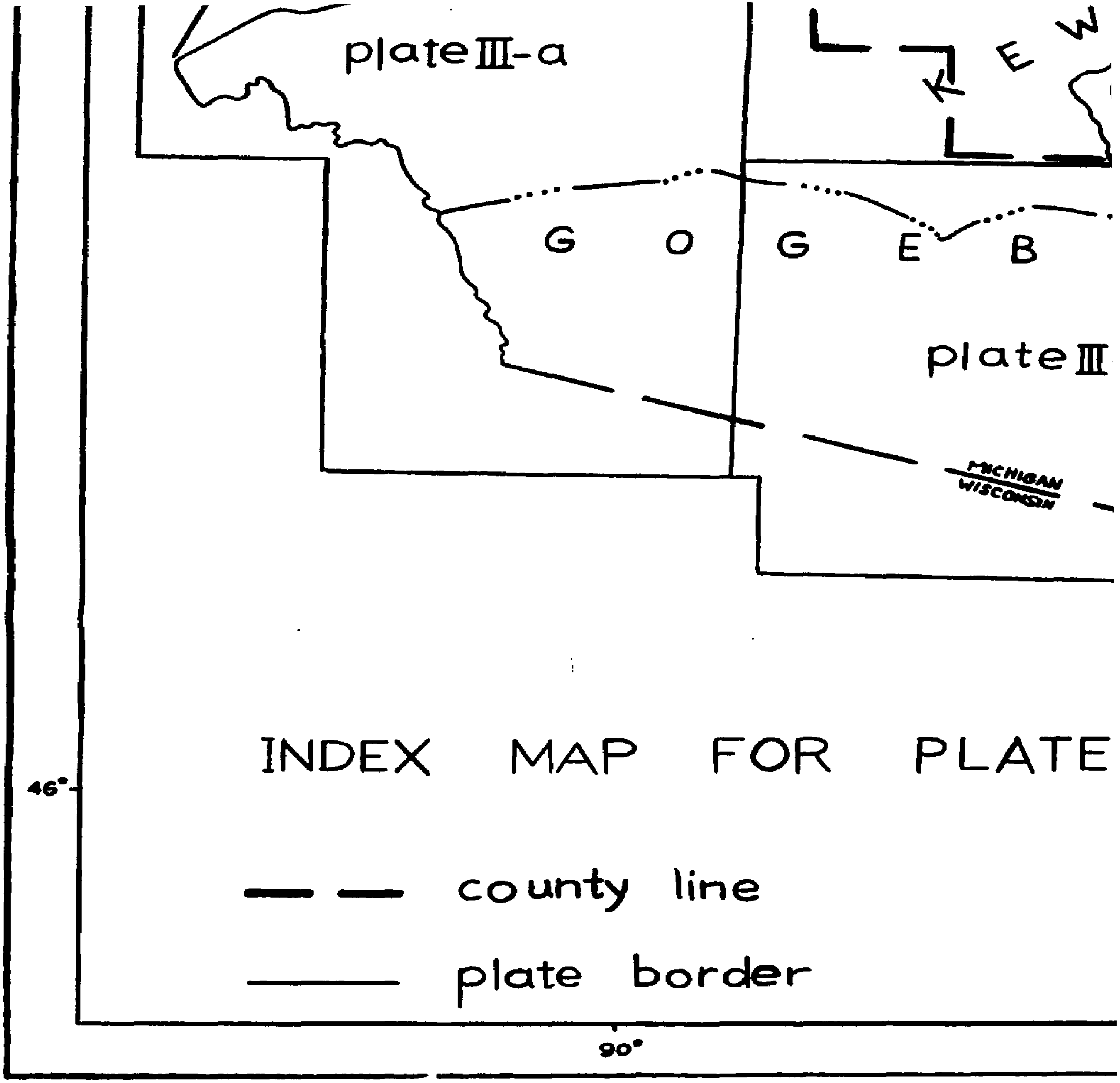
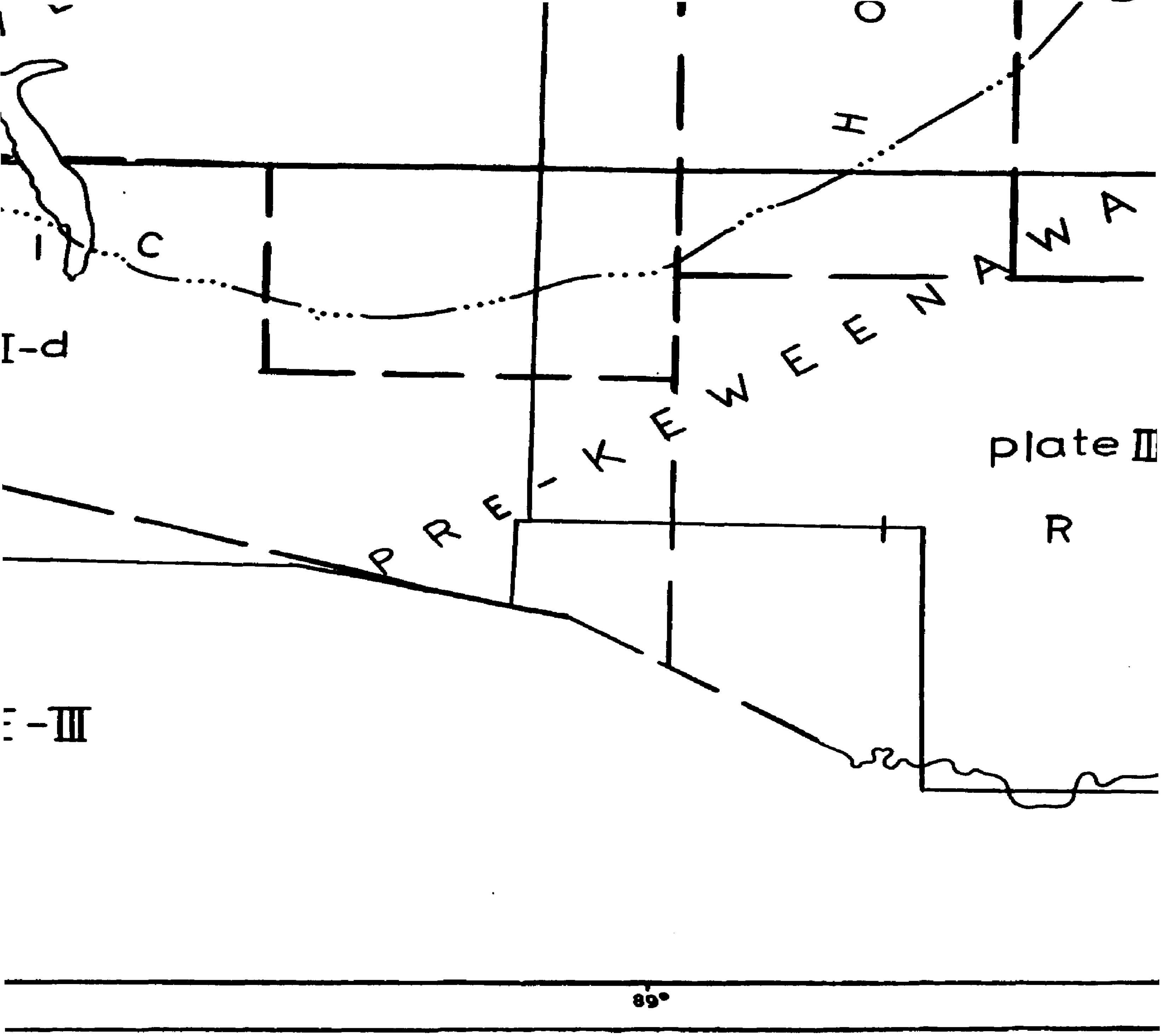
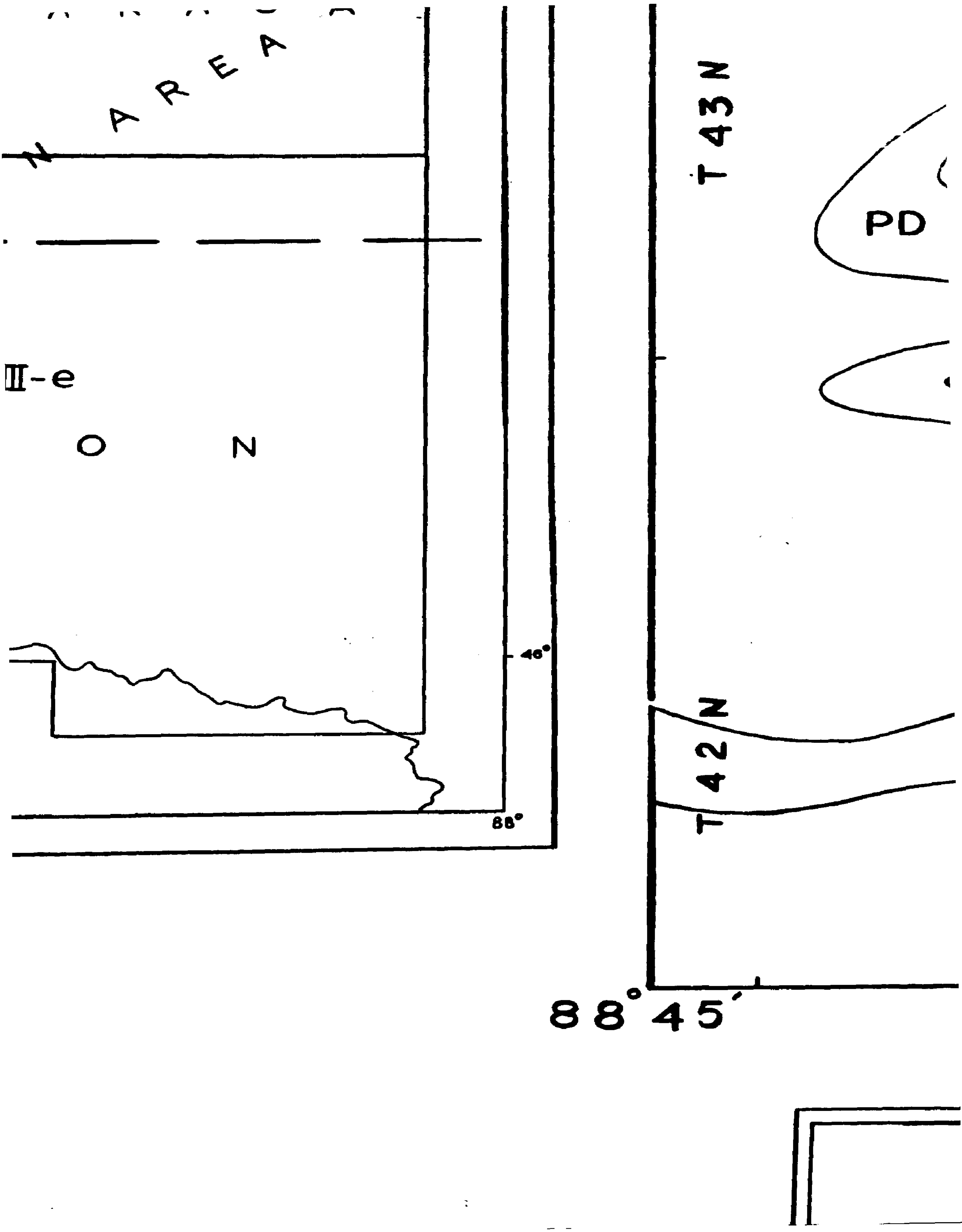


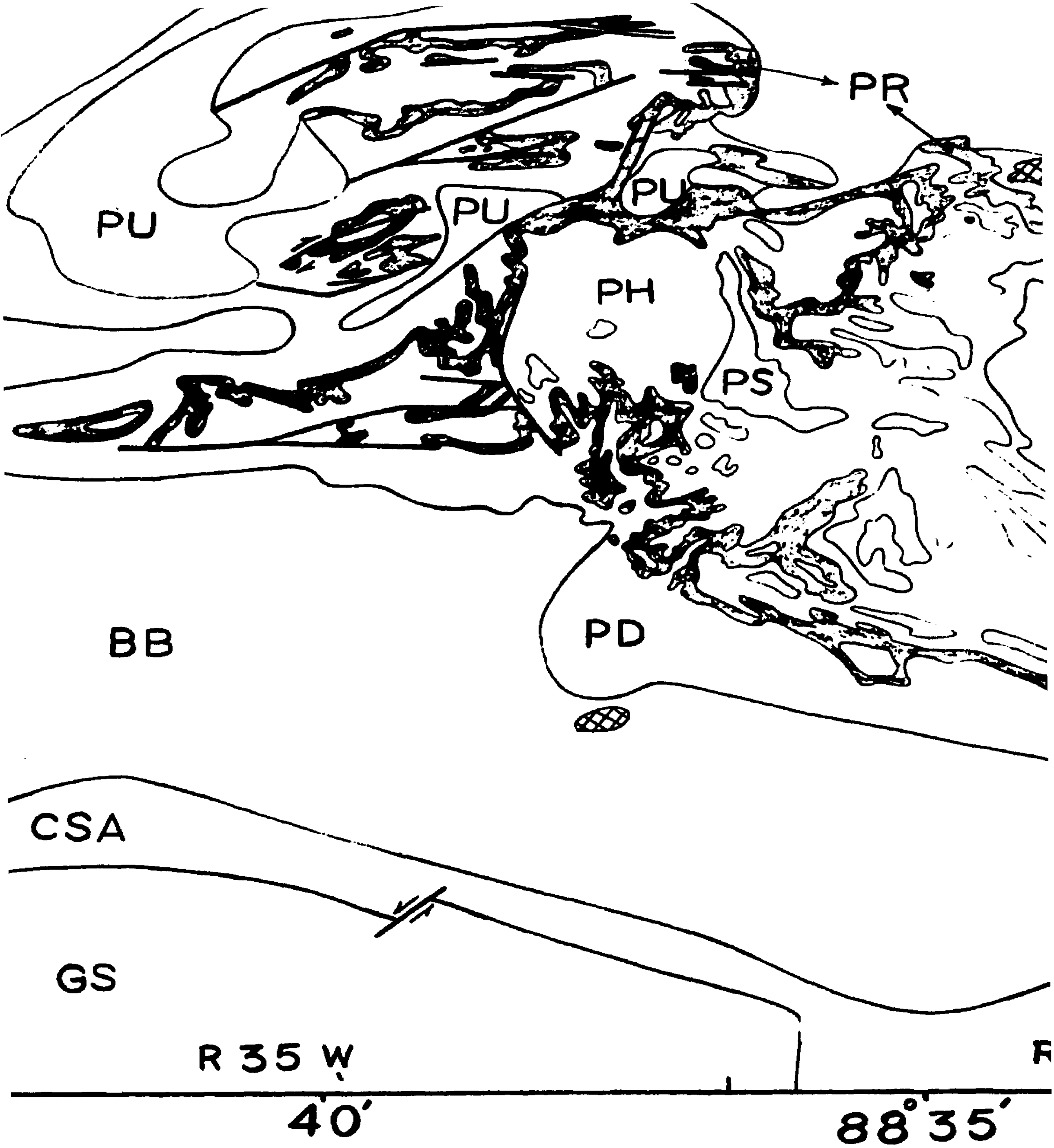
plate III-a
K E W
G O G E B
plate III
MICHIGAN
WISCONSIN
INDEX MAP FOR PLATE
county line
plate border
46°
90°

BEDROCK

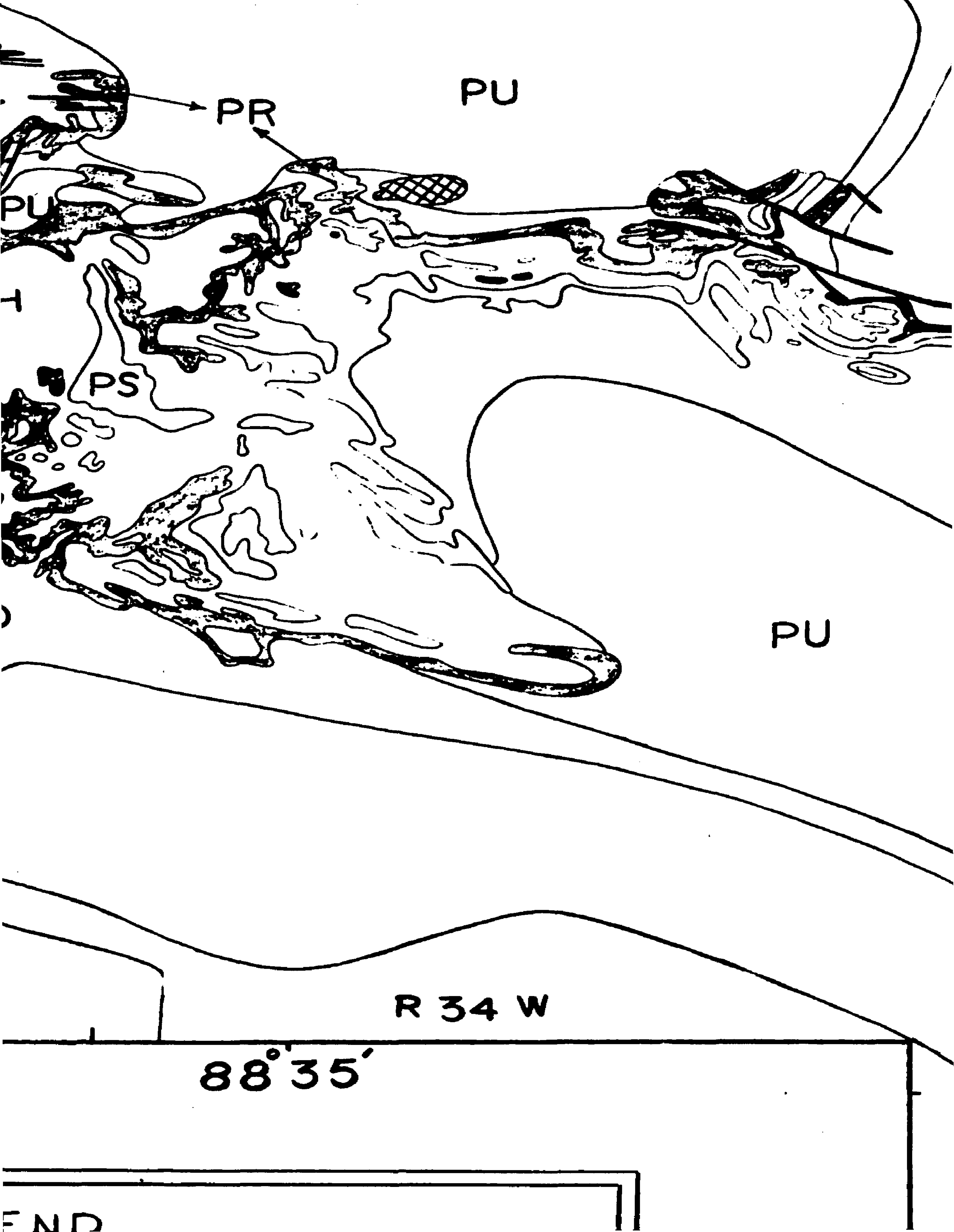


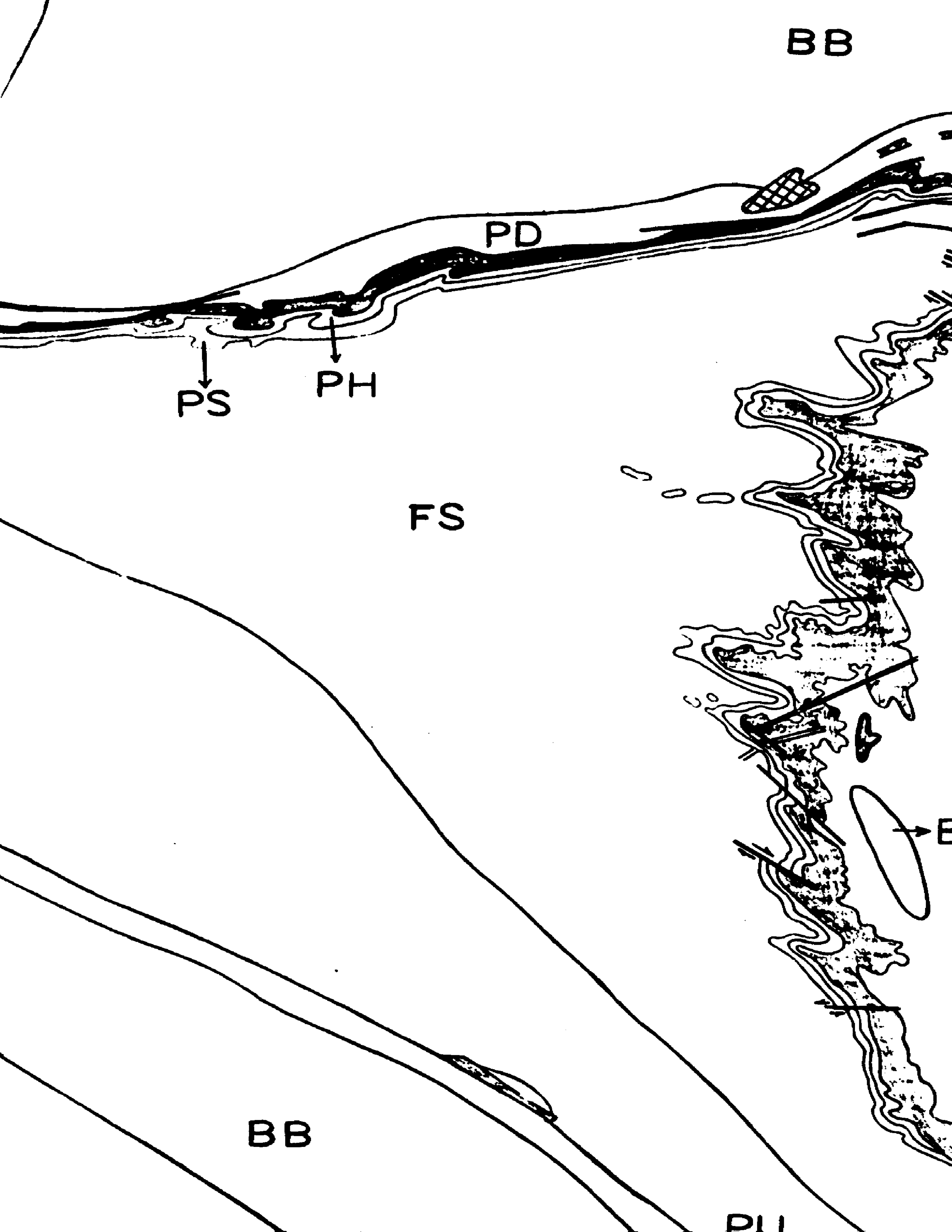
GEOLOGY MAP

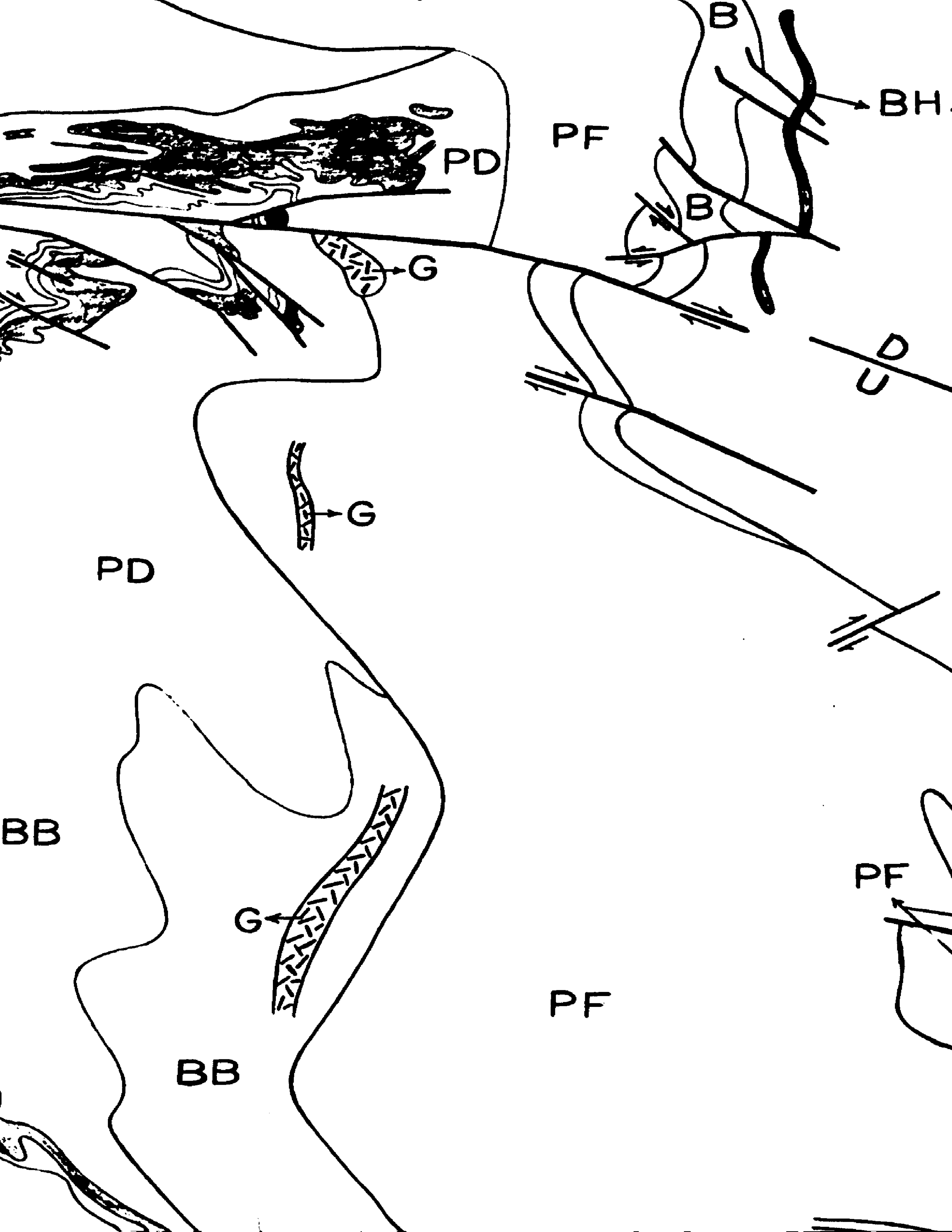

N AREA
III-e
O N
46°
88°
T 43 N
PD
T 42 N
88°45′

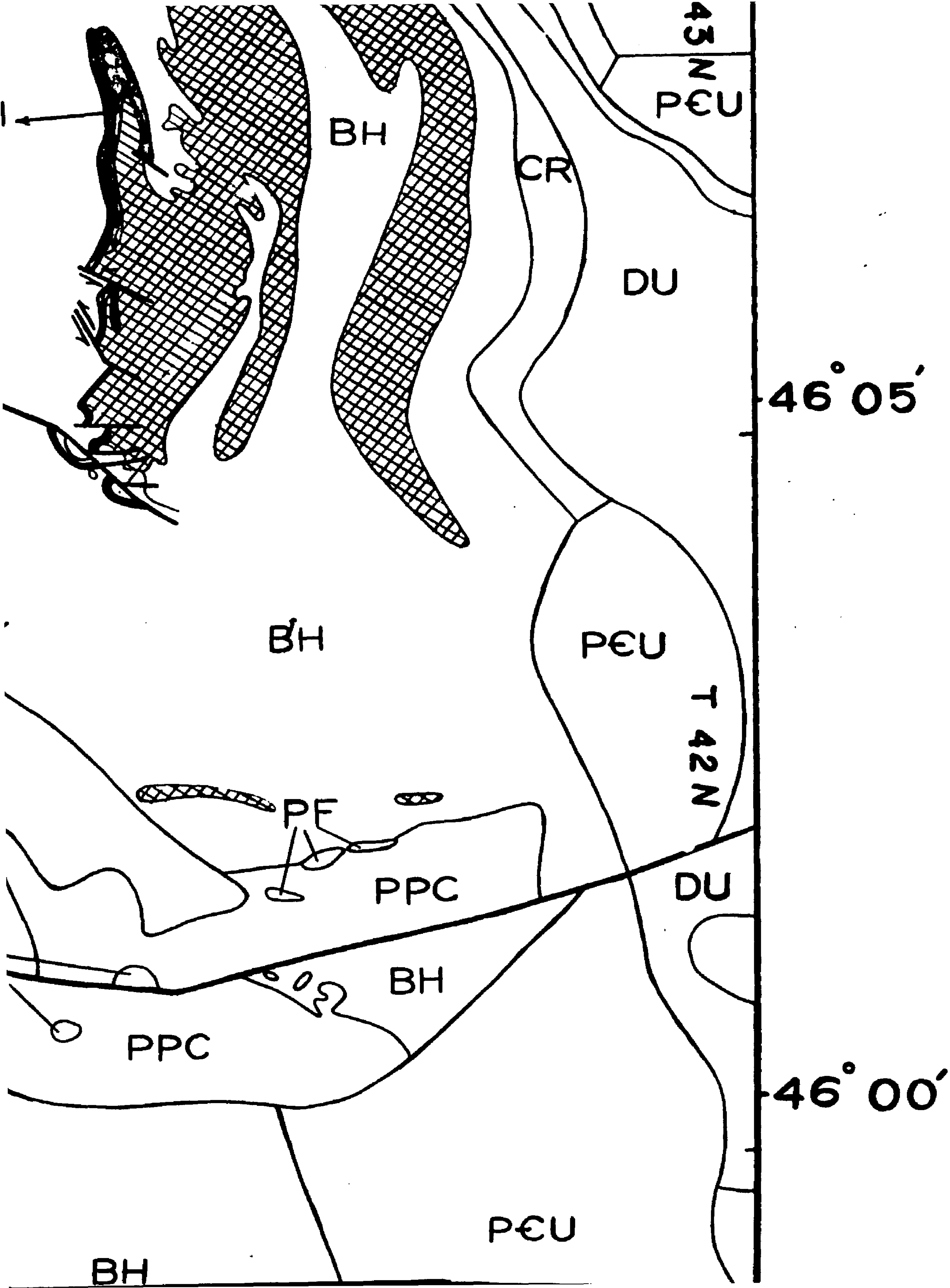


LEGEND

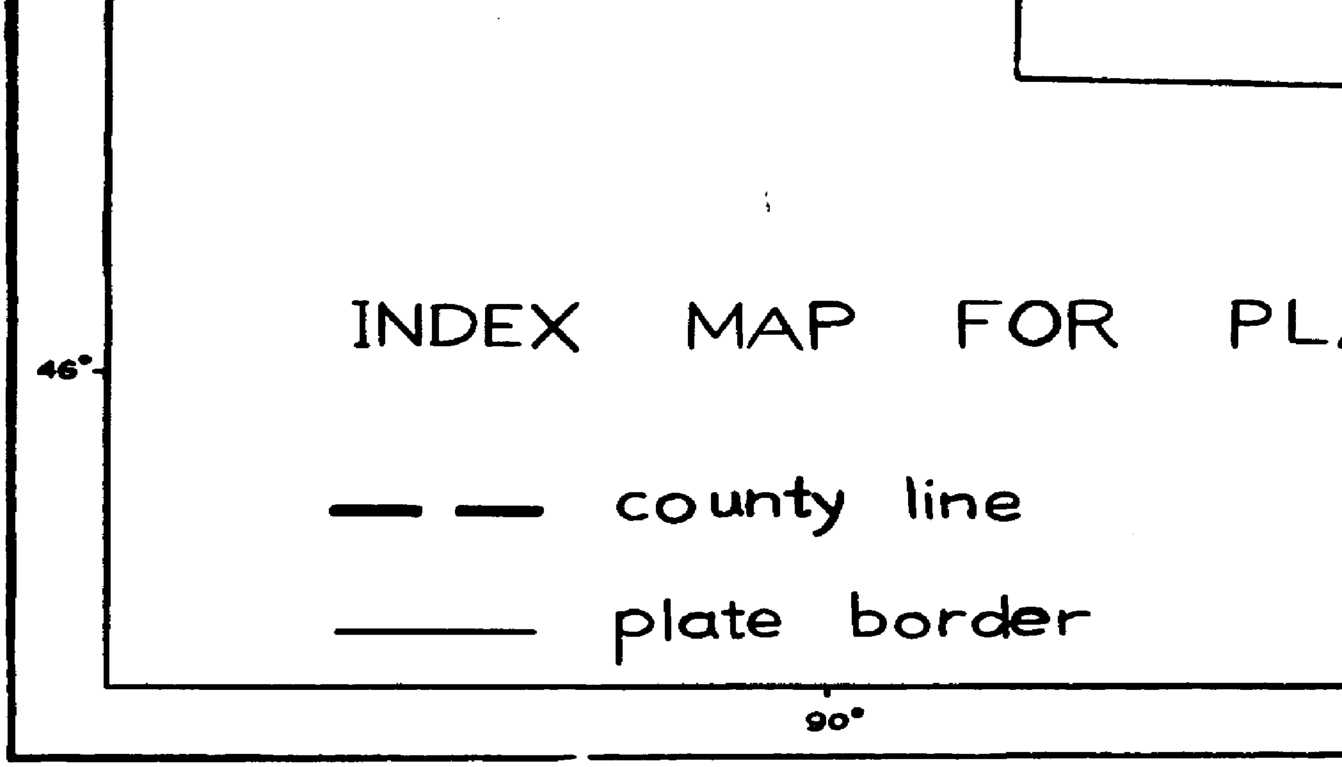

PU
PR
PU
PS
PU
R 34 W
88°35′
END


BB
PD
PS
PH
FS
E
BB
PU

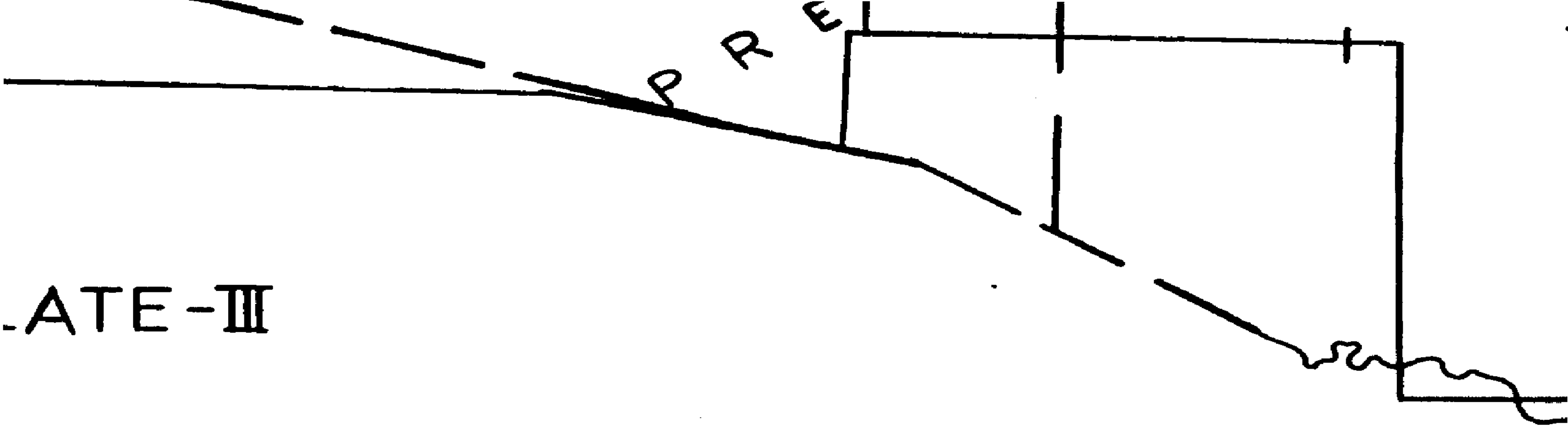

B
BH
PF
PD
B
G
D
U
G
PD
BB
PF
G
PF
BB



43N
PЄU
BH
CR
DU
46°05′
BH
PЄU
T 42N
PF
PPC
DU
BH
PPC
46°00′
PЄU
BH



BEDROC



-ATE-III

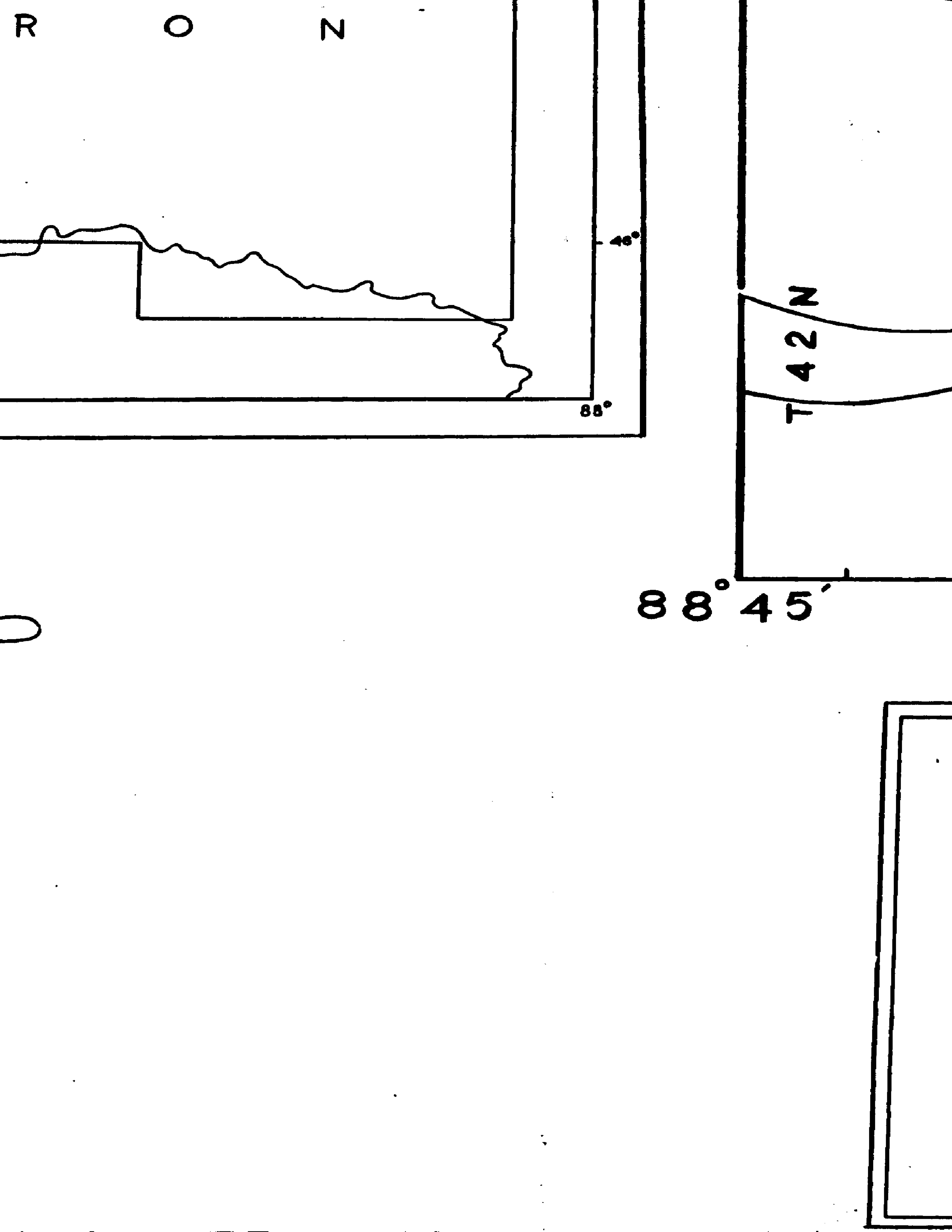
89°

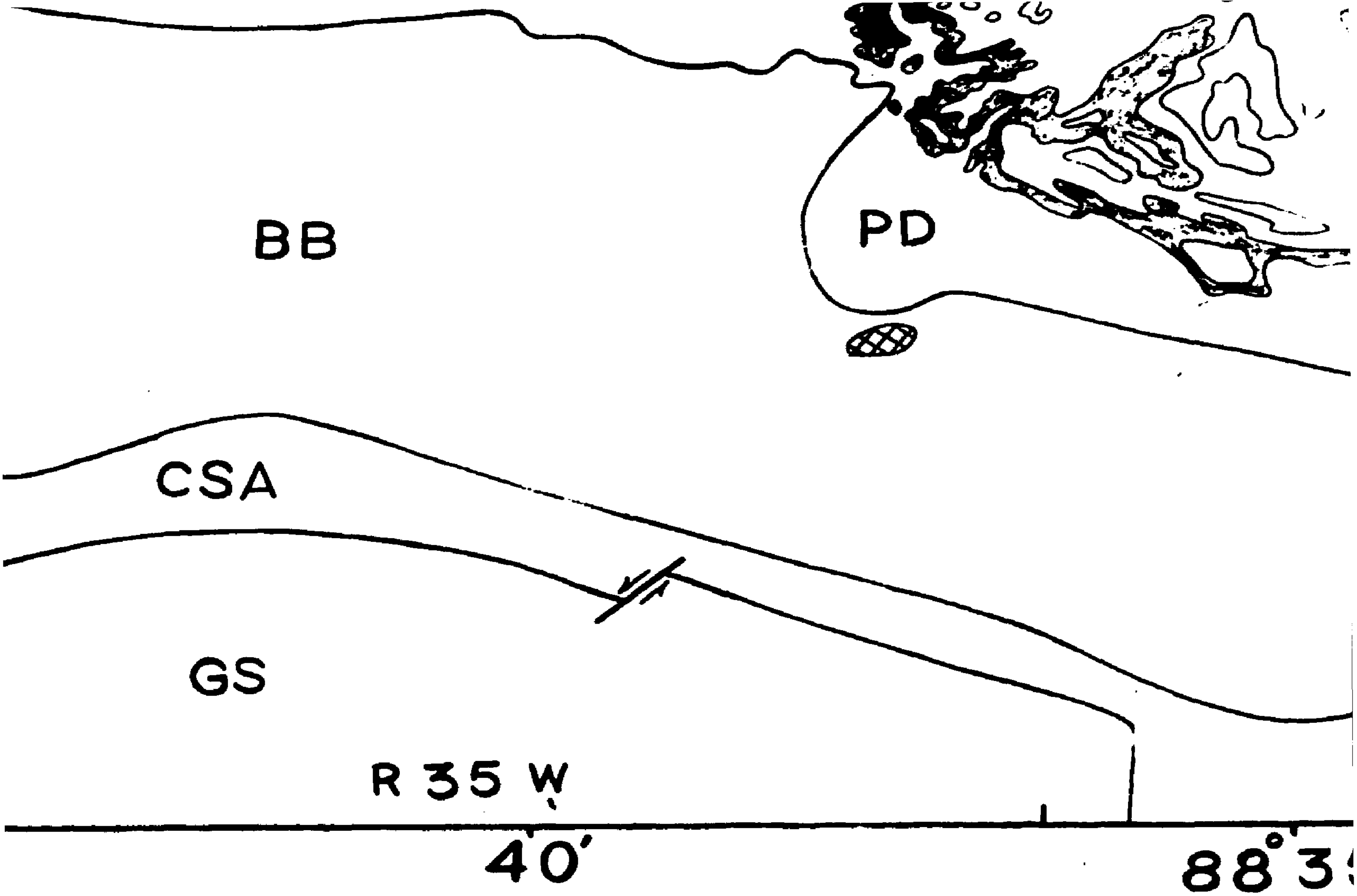
CK GEOLOGY MAP

SCALE 1: 62500

1 2 3 4 MILES

PLATE III-e


R O N
46°
88°
T 42 N
88°45′



LEGEND

Anticlinal axis

Synclinal

Fault

Probable fa

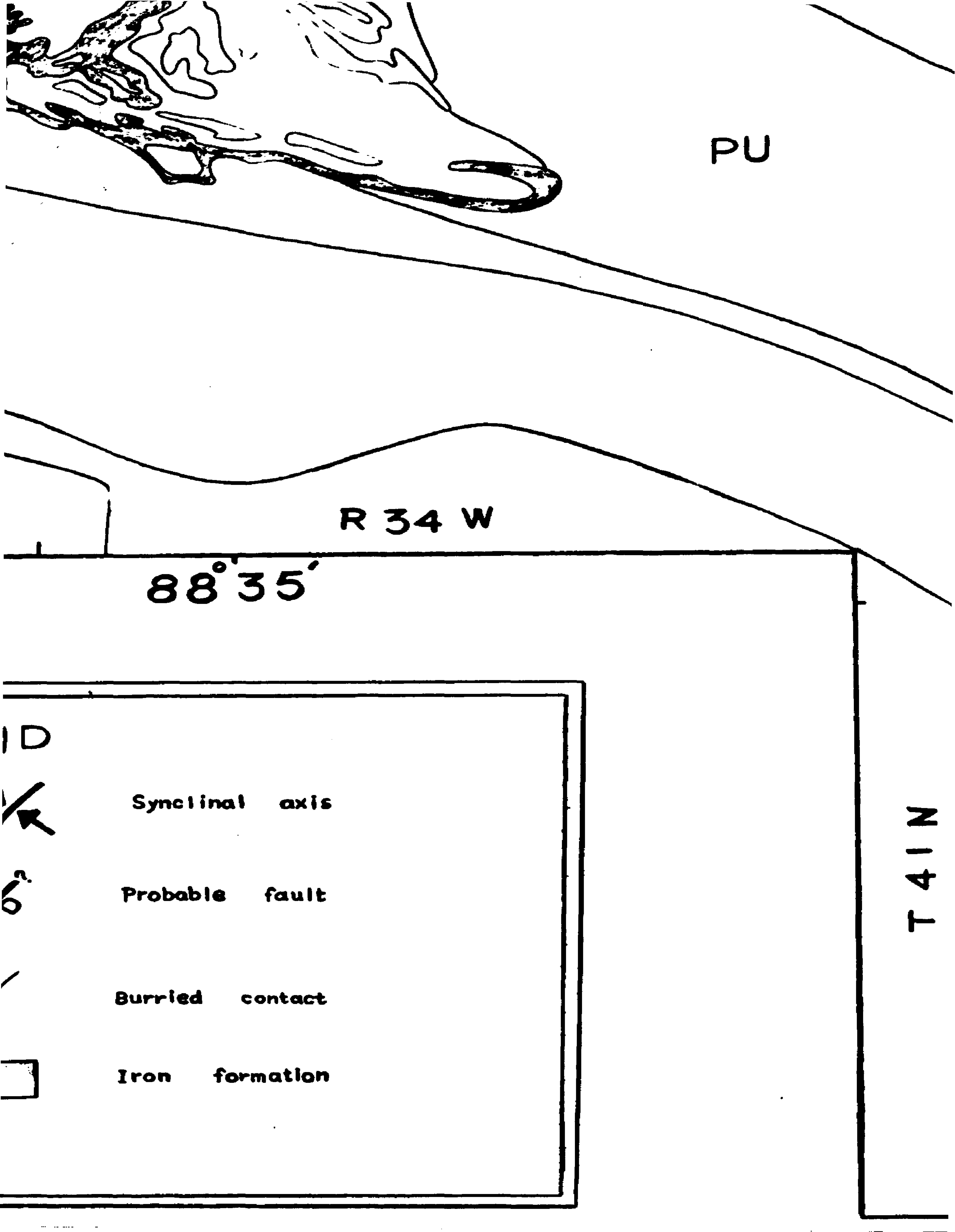
Burried fault

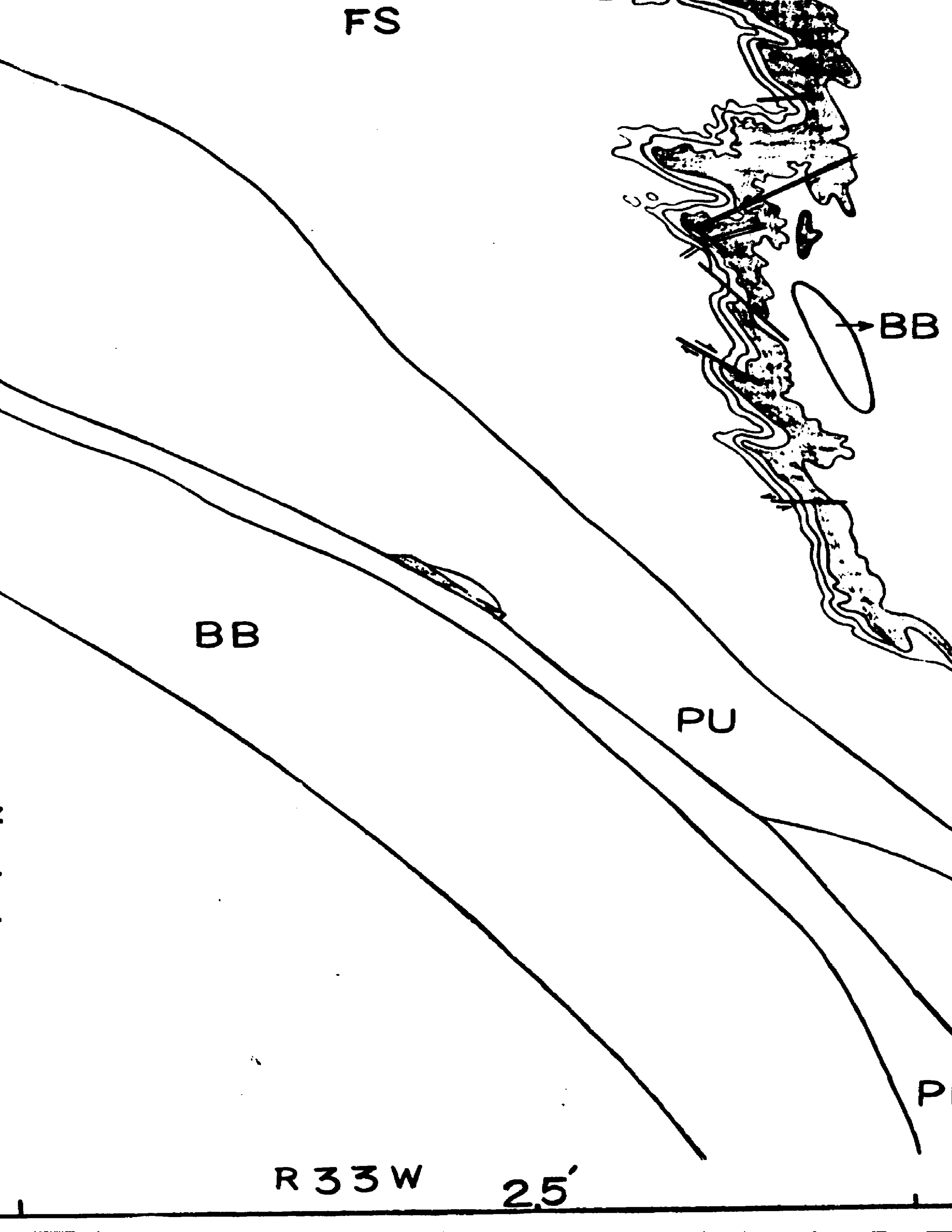
Burried cont

Diabase dike

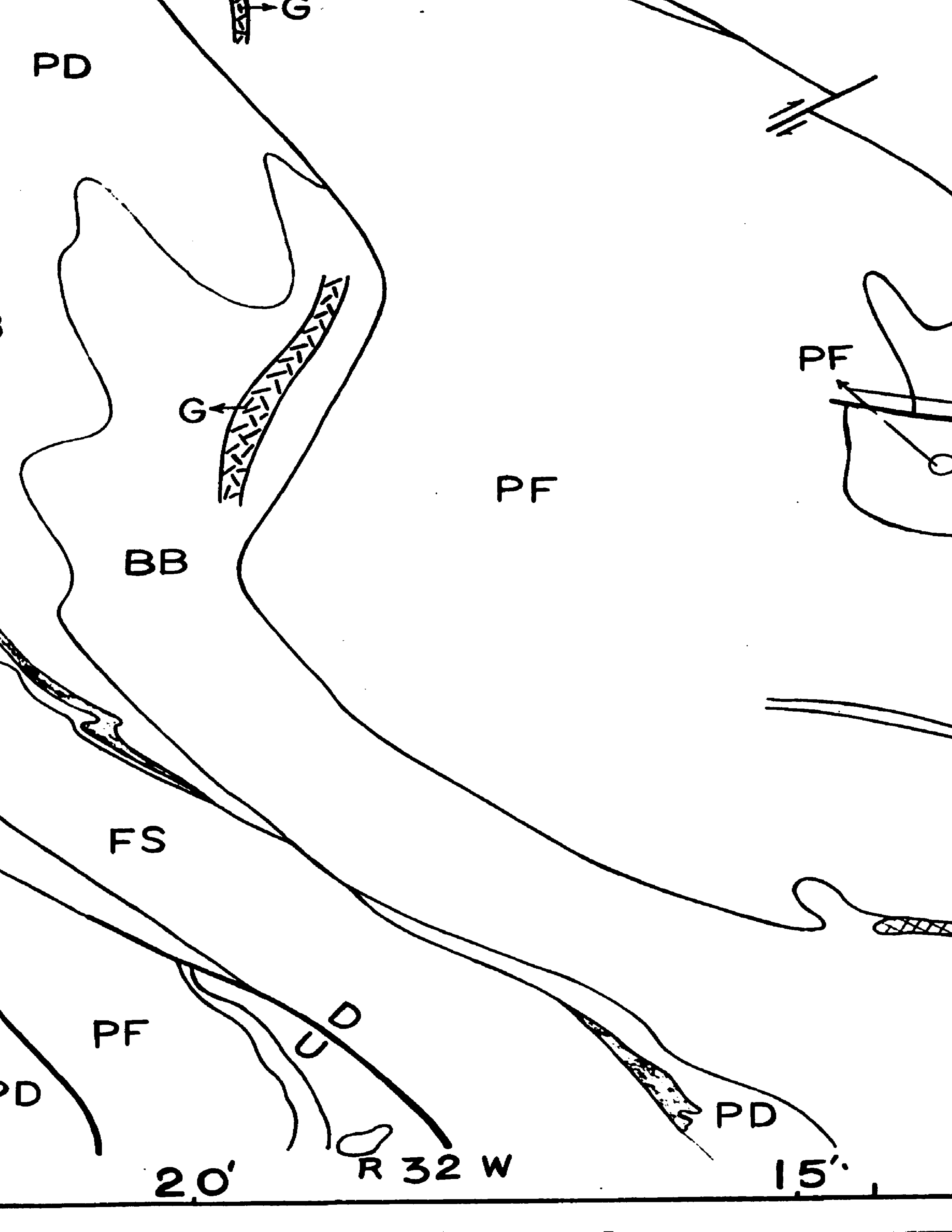
Iron format

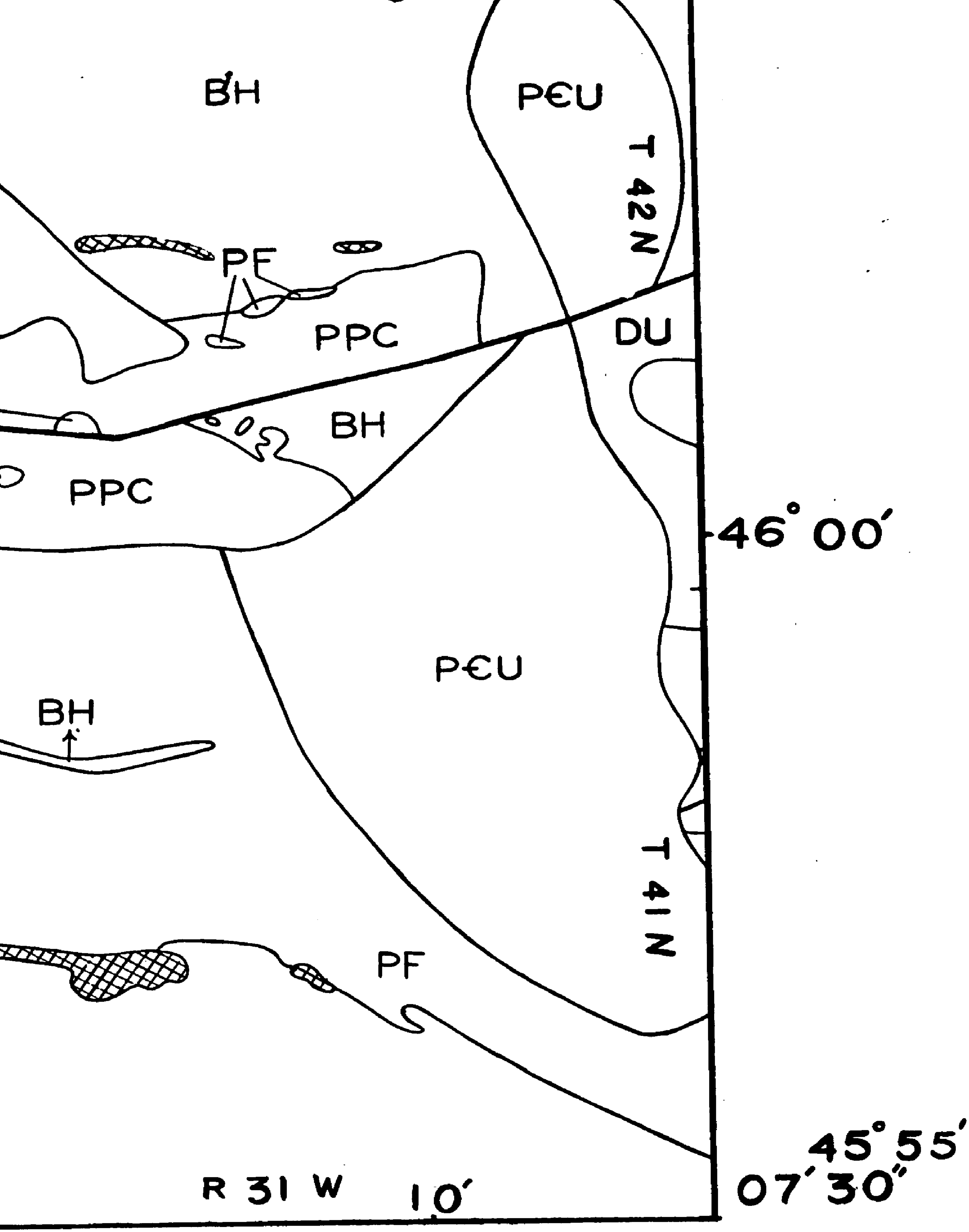
A A′ Location of profiles


PU
R 34 W
88°35′
T 41 N
ID
Synclinal axis
Probable fault
Burried contact
Iron formation

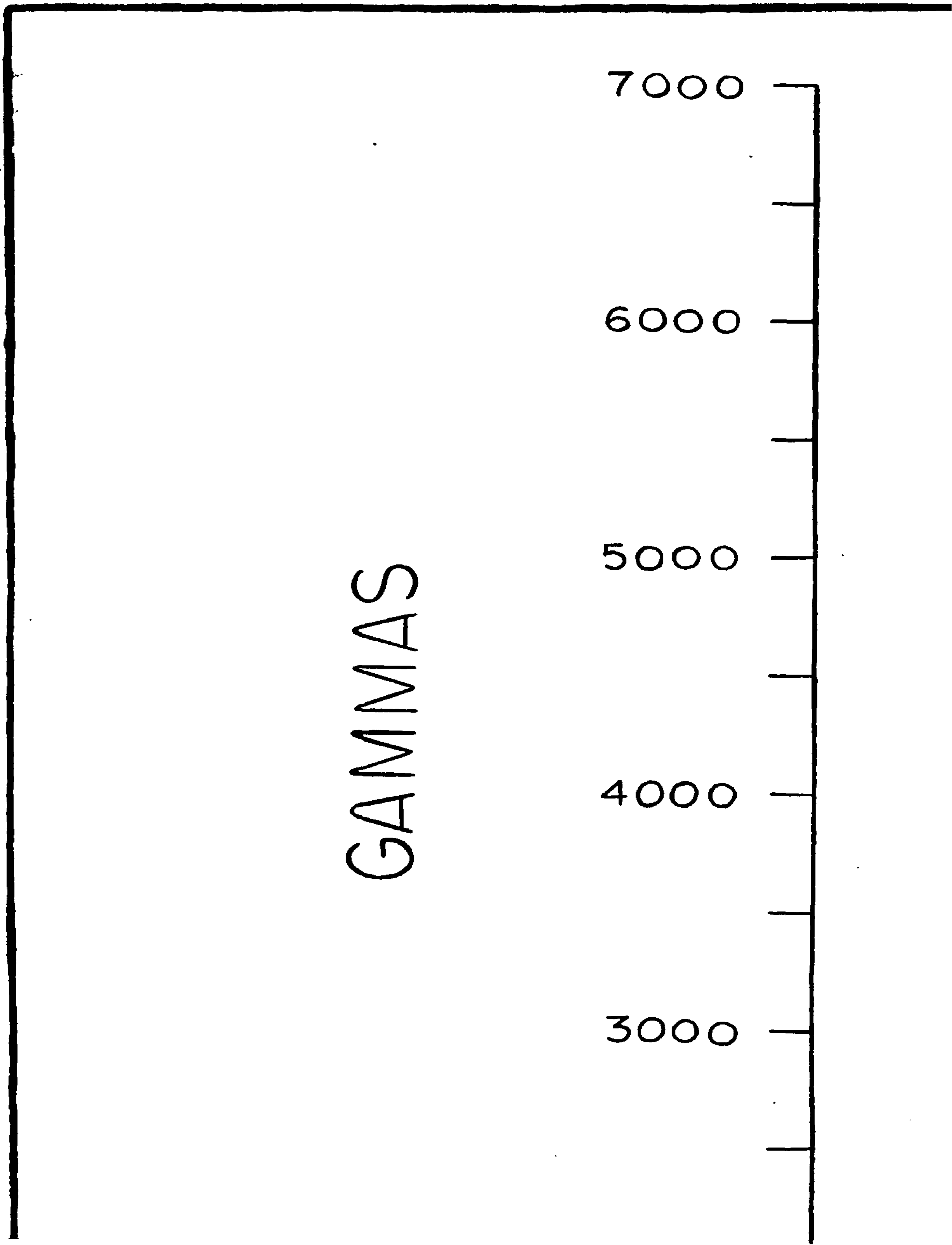


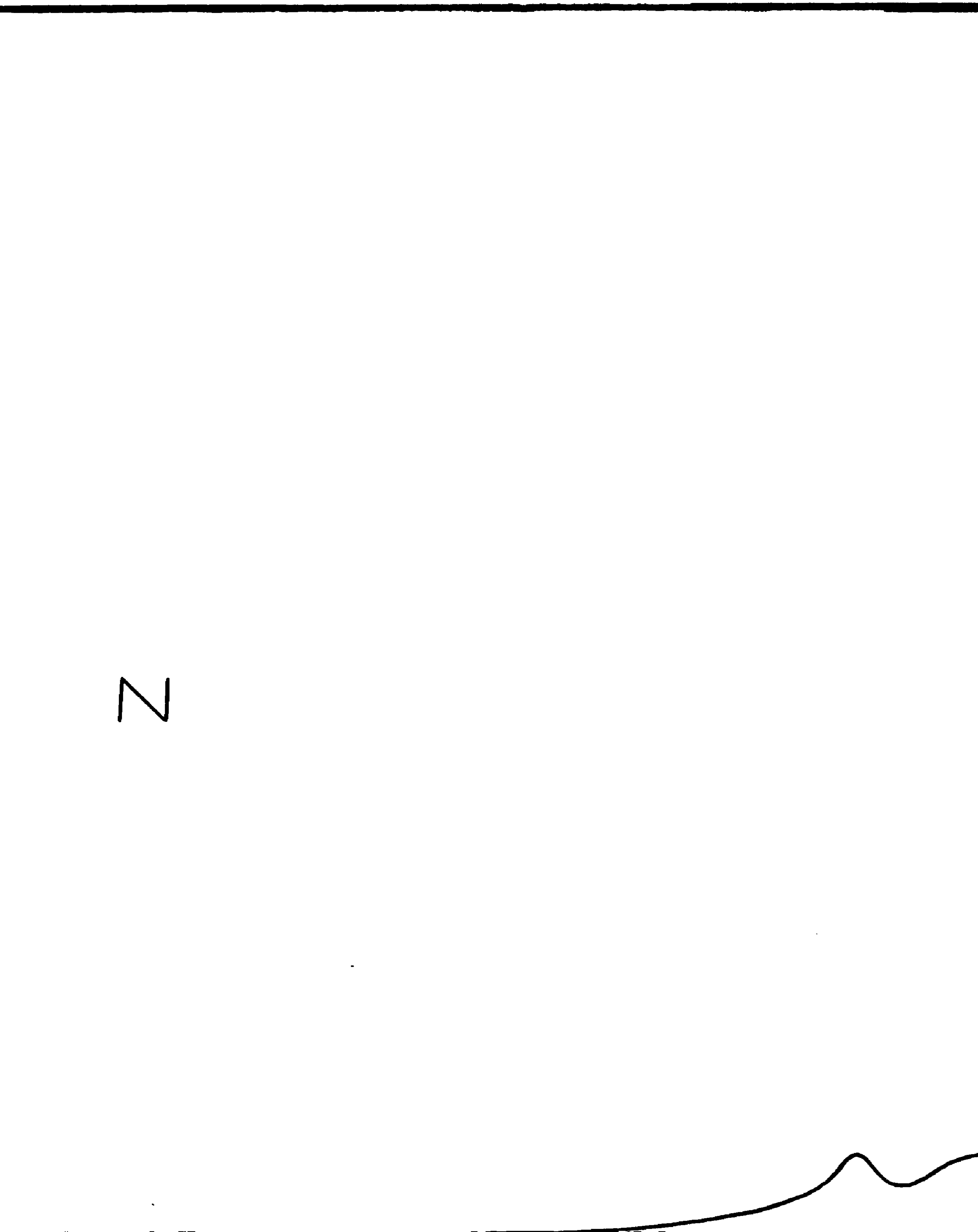
FS
BB
BB
PU
R 33 W
25′


G
PD
G
PF
PF
BB
FS
D
U
PF
PD
PD
R 32 W
20'
15'



BH
PЄU
T 42 N
PF
PPC
DU
BH
PPC
46° 00′
PЄU
BH
T 41 N
PF
45° 55′
R 31 W
10′
07′ 30″


7000
6000
5000
4000
3000
GAMMAS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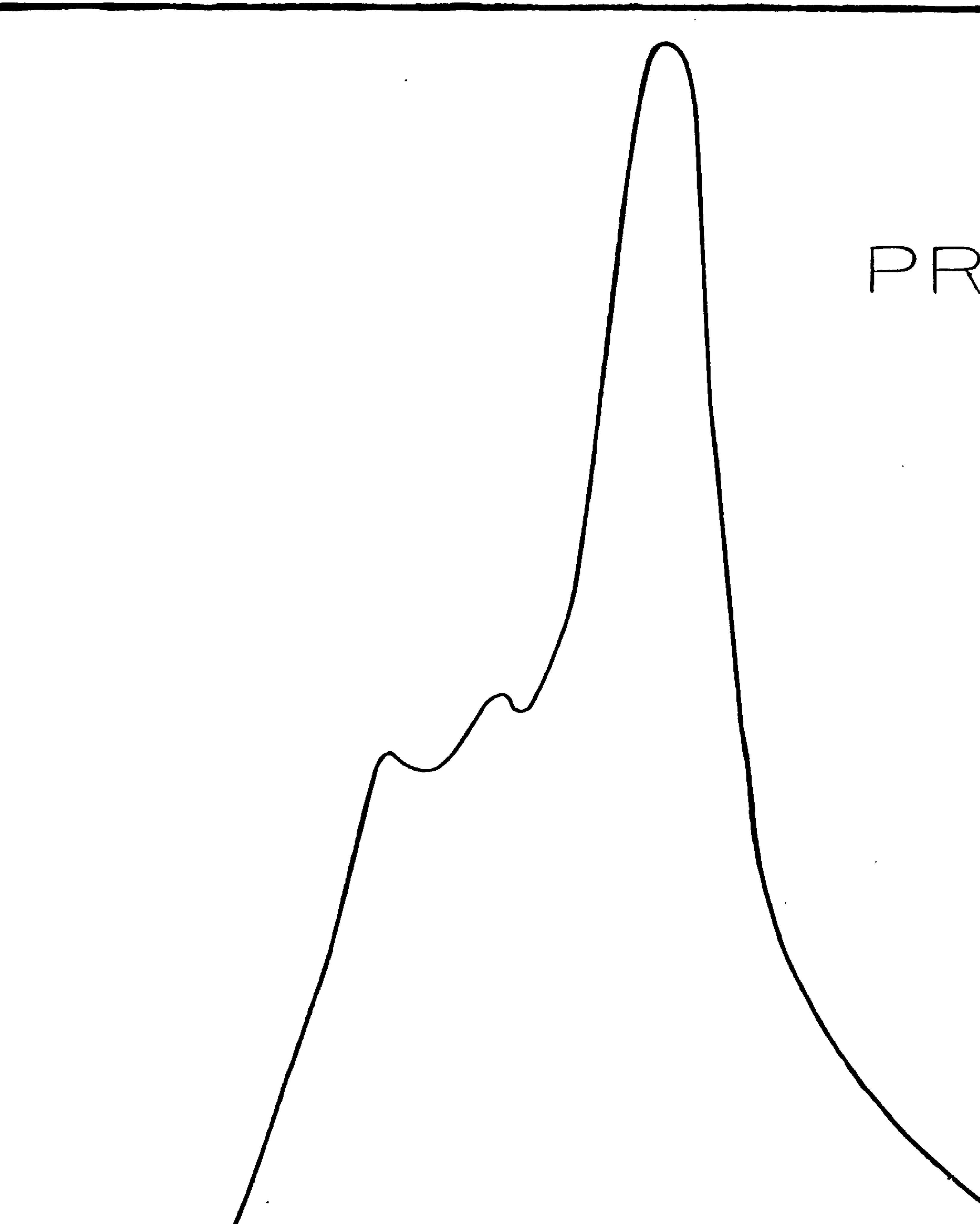
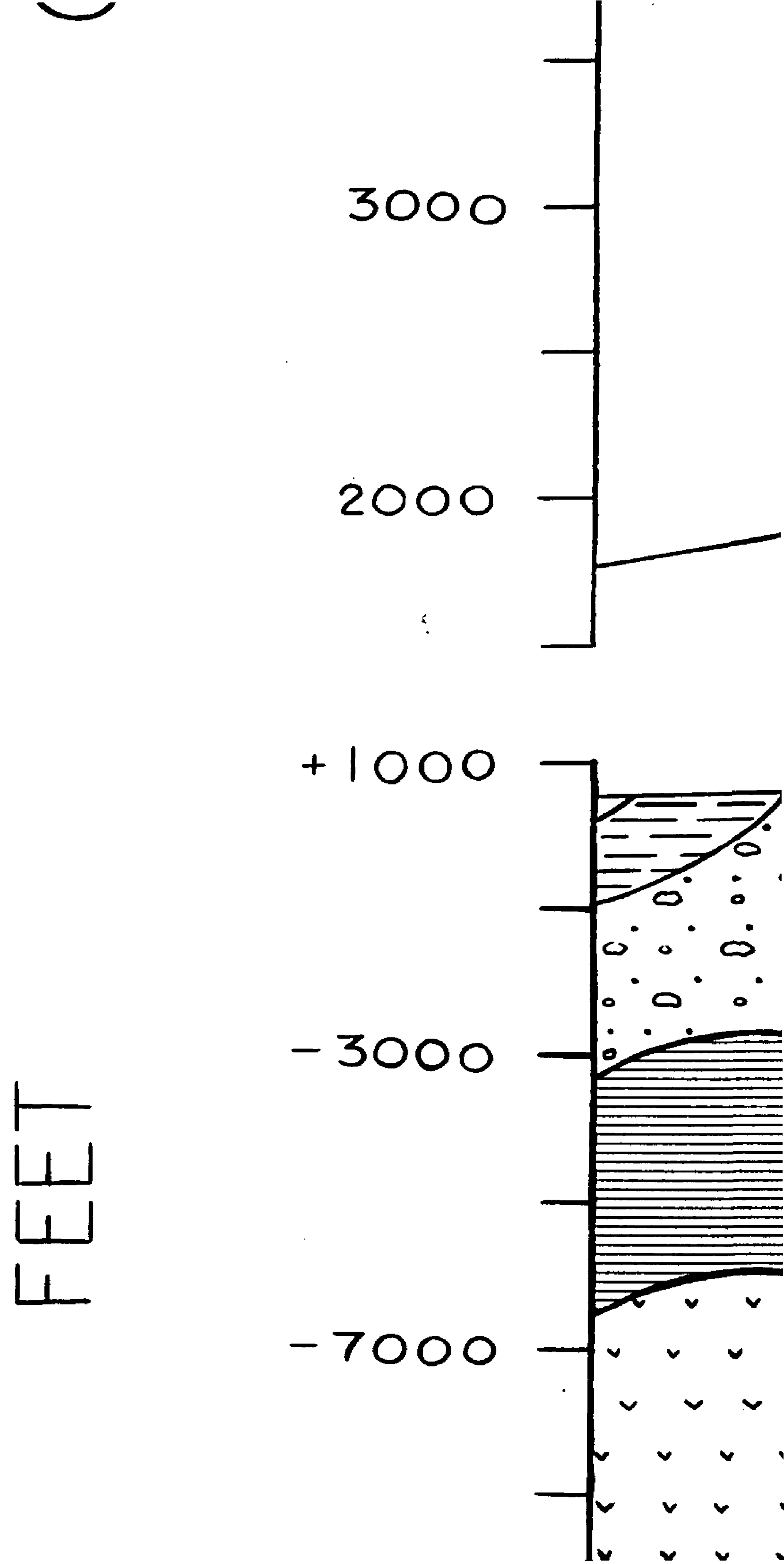
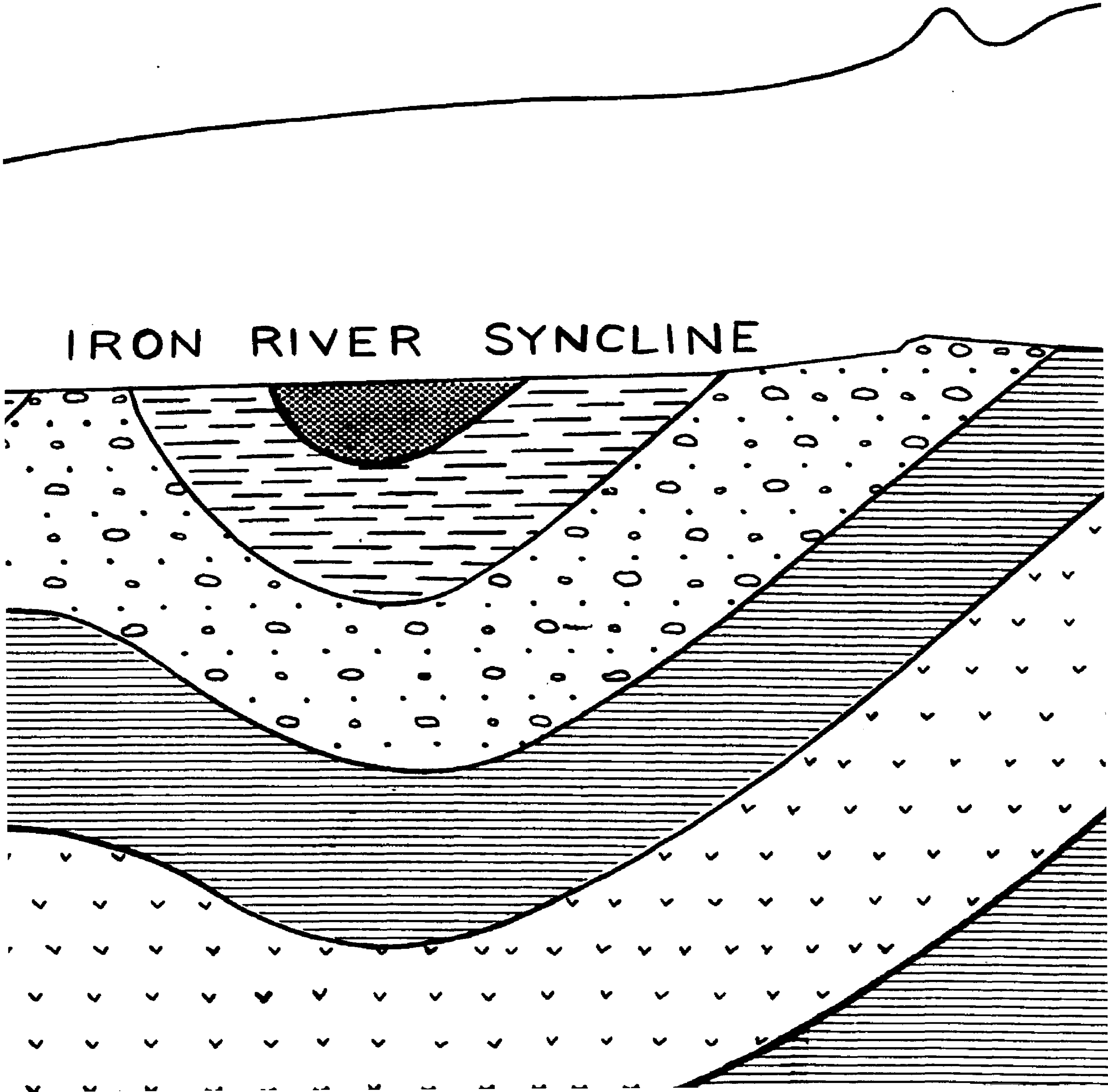
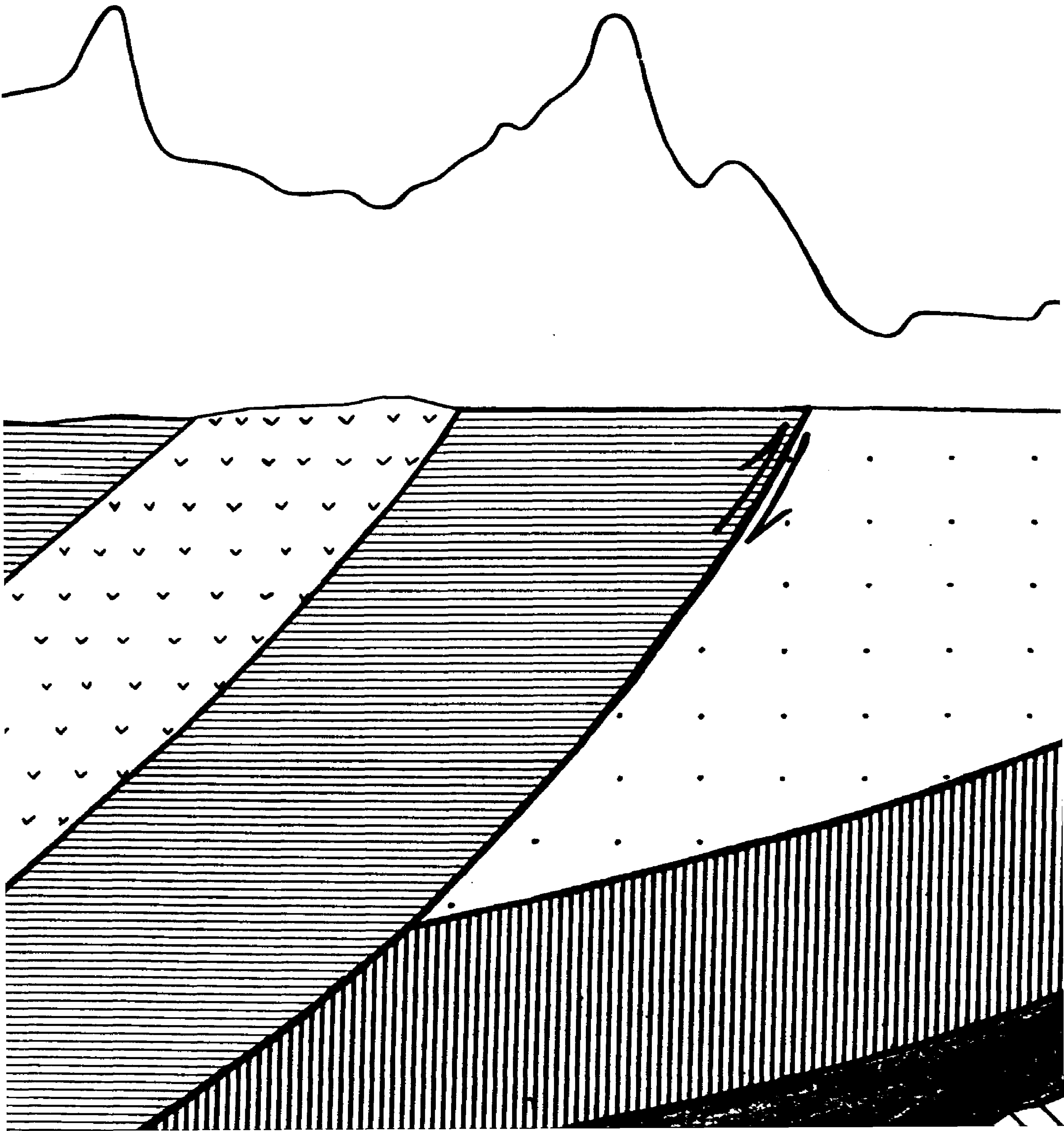

PR

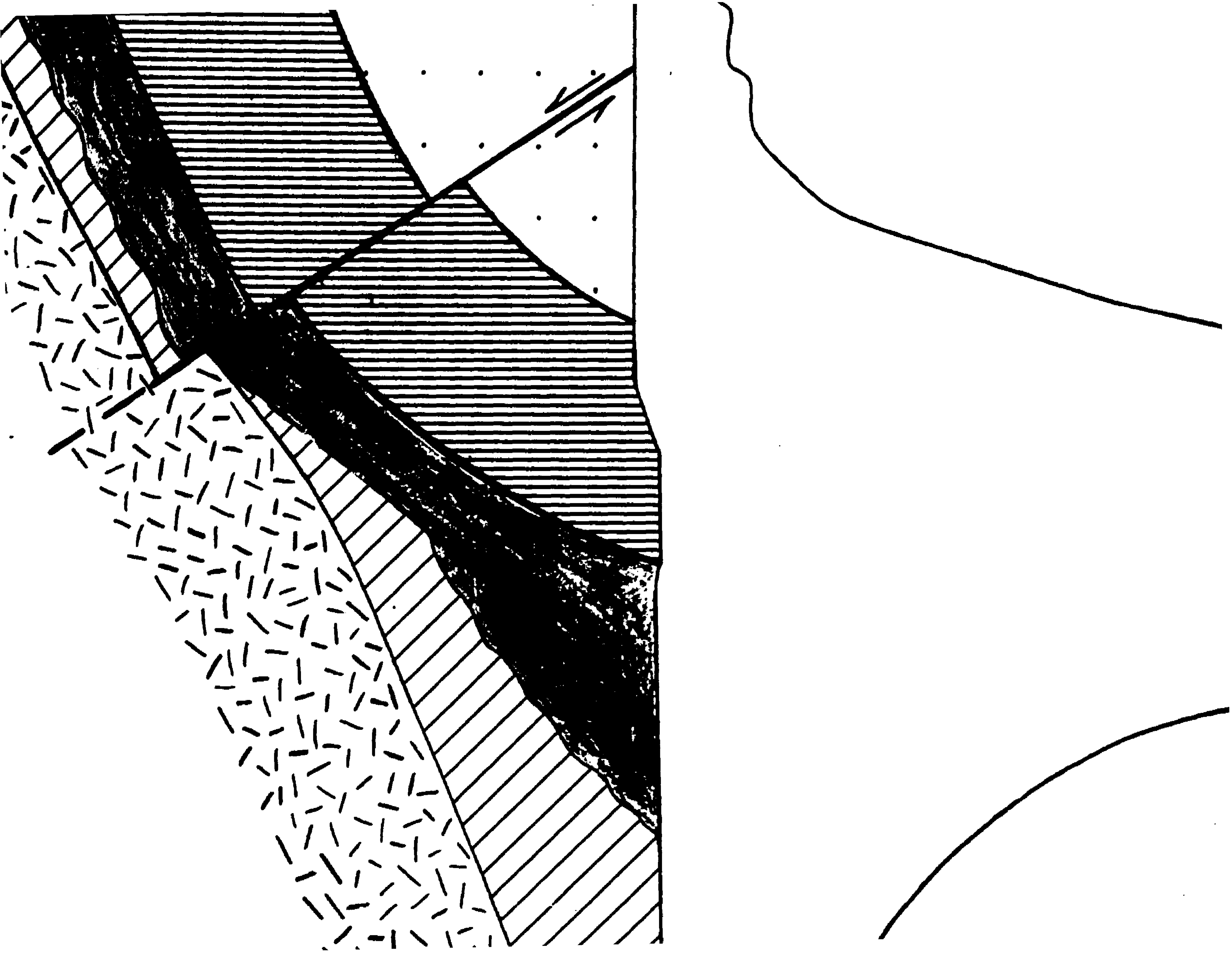
PROFILE A – Á

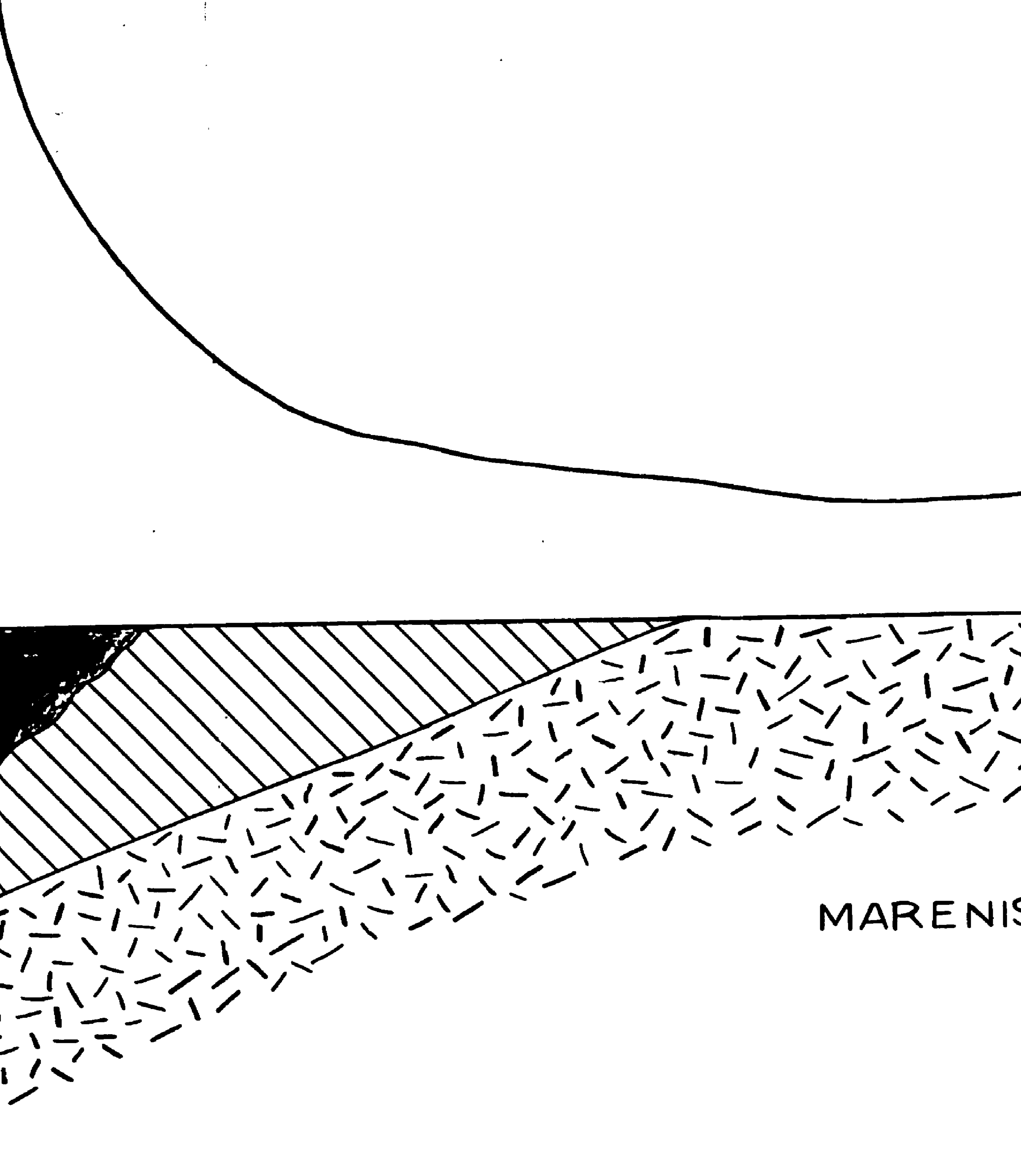
S

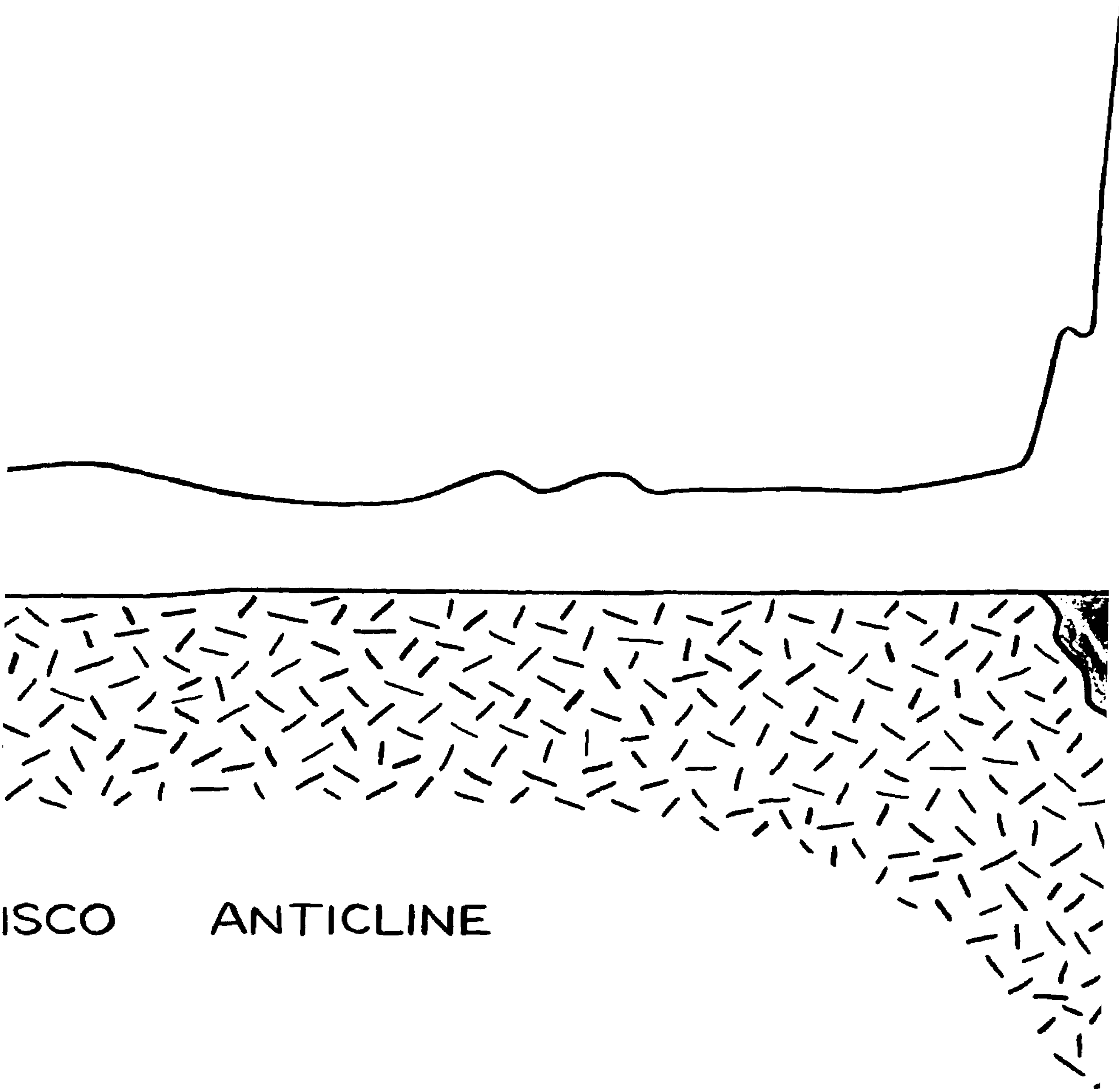

3000
2000
+1000
-3000
-7000
FEET

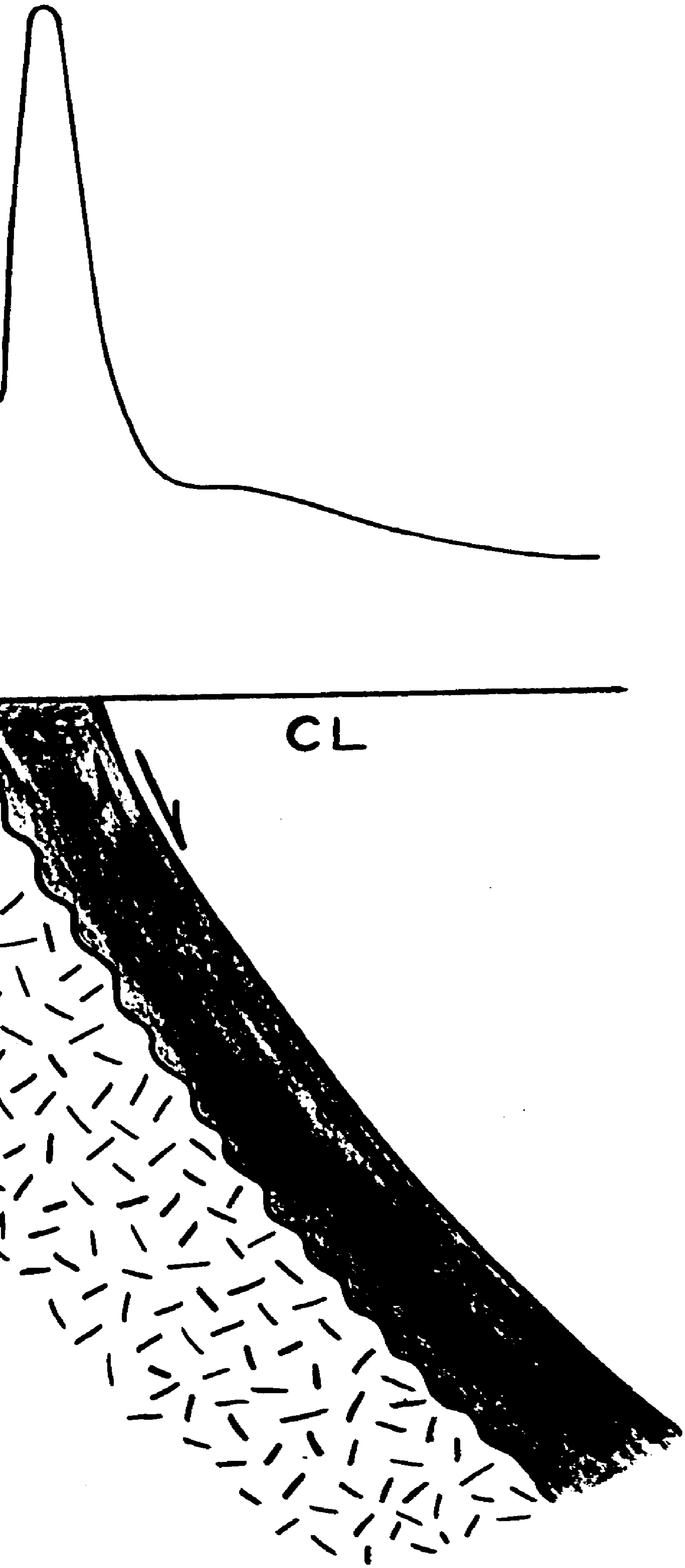

IRON RIVER SYNCLINE

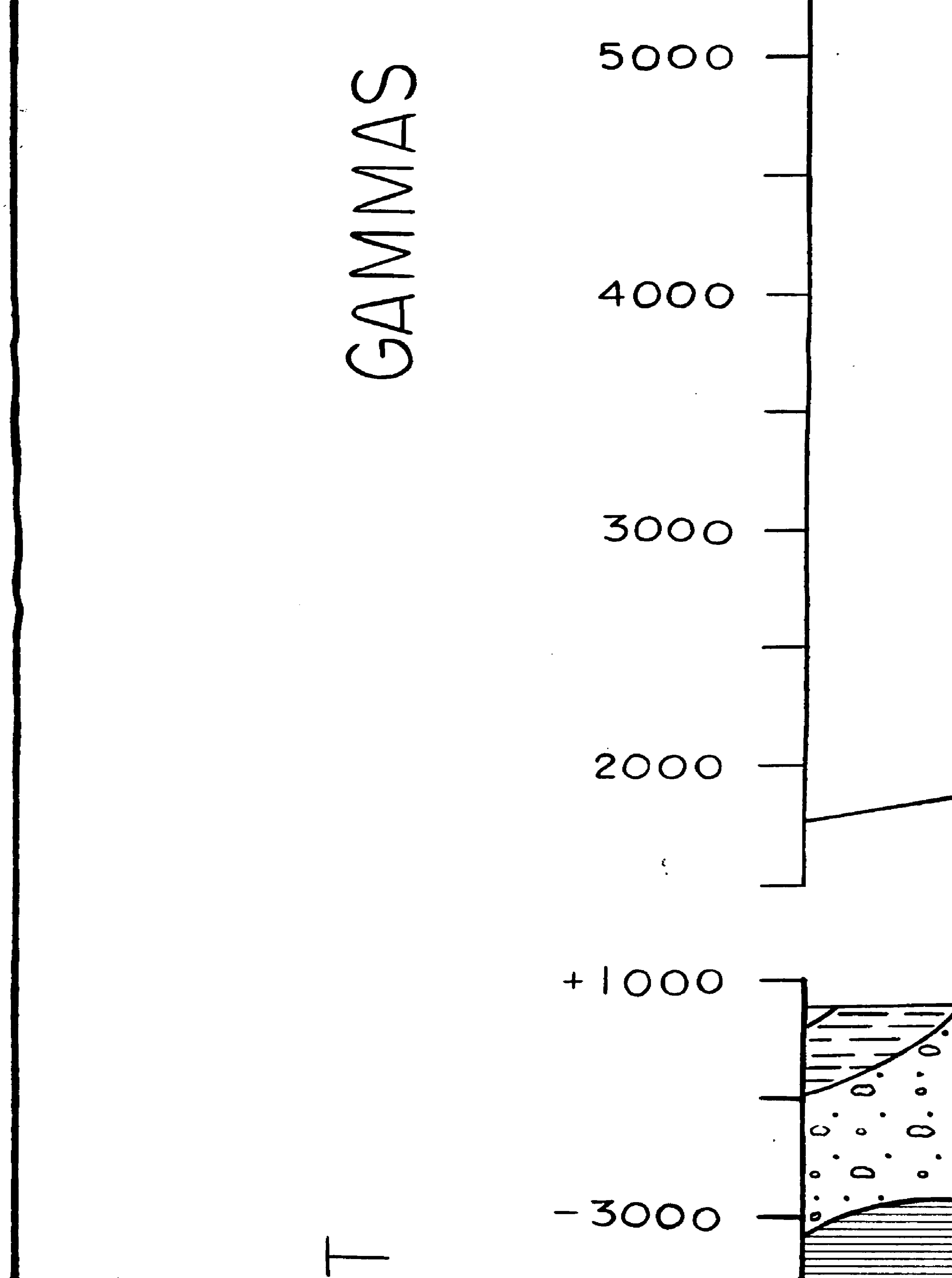


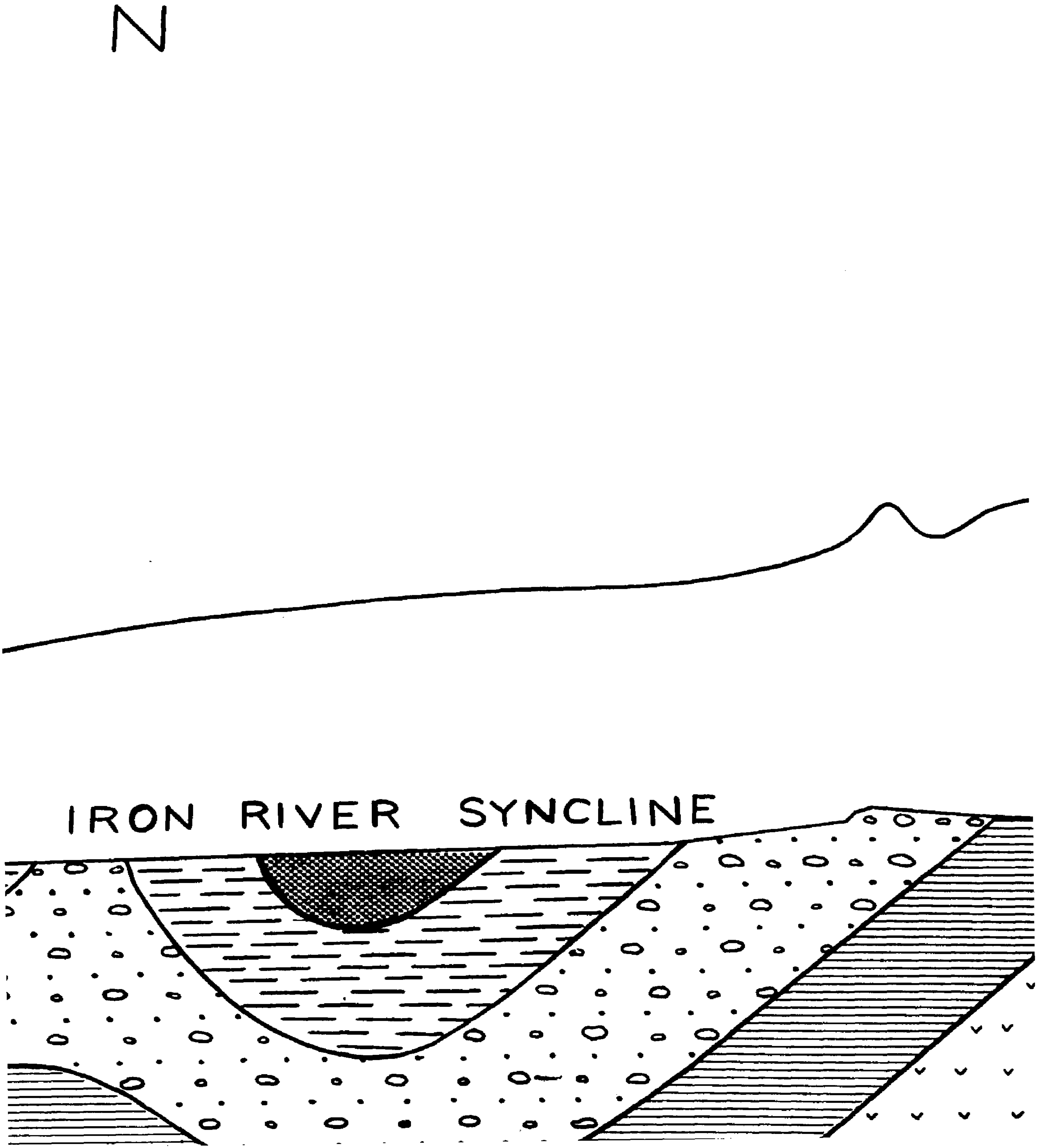


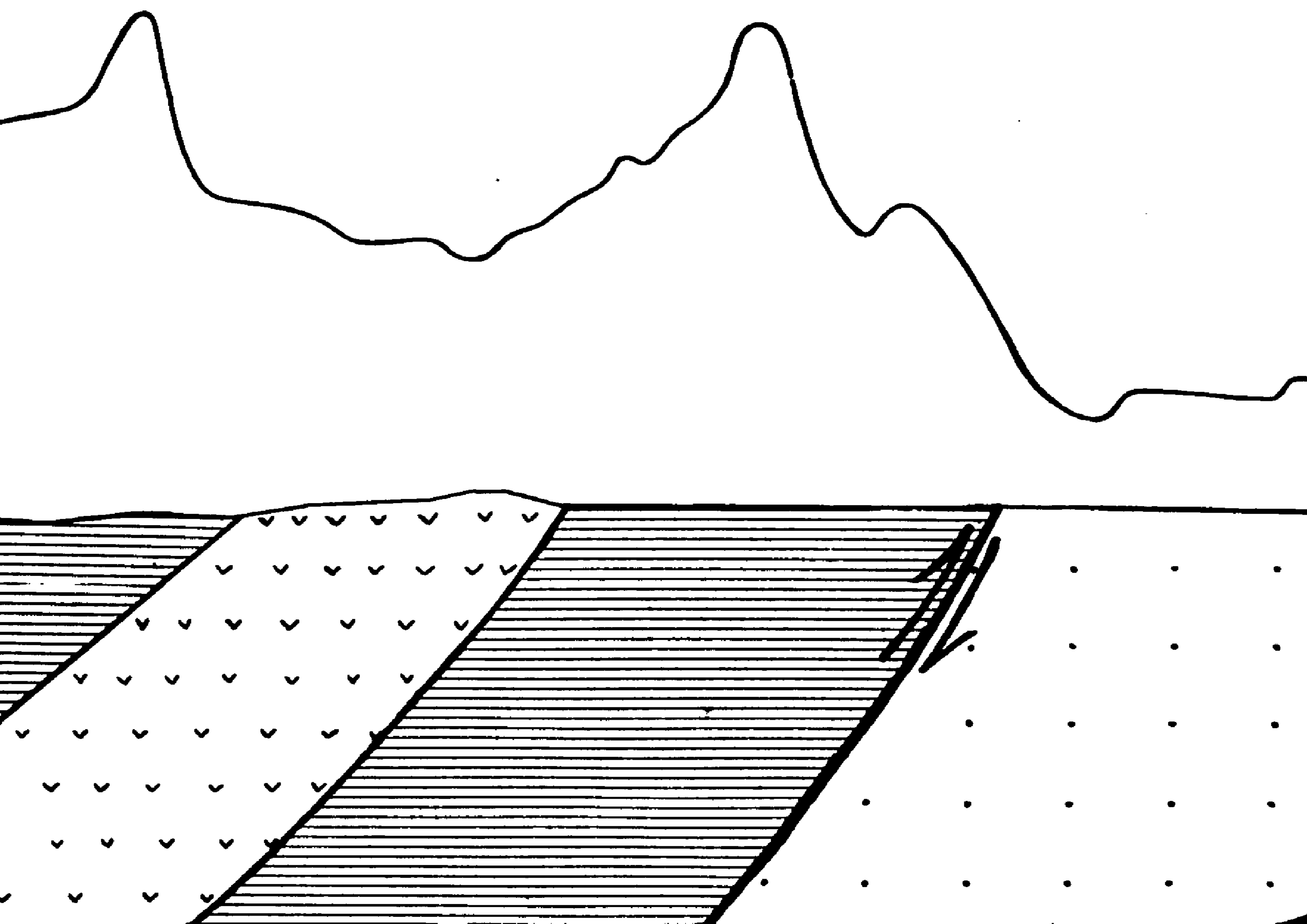

MARENIS

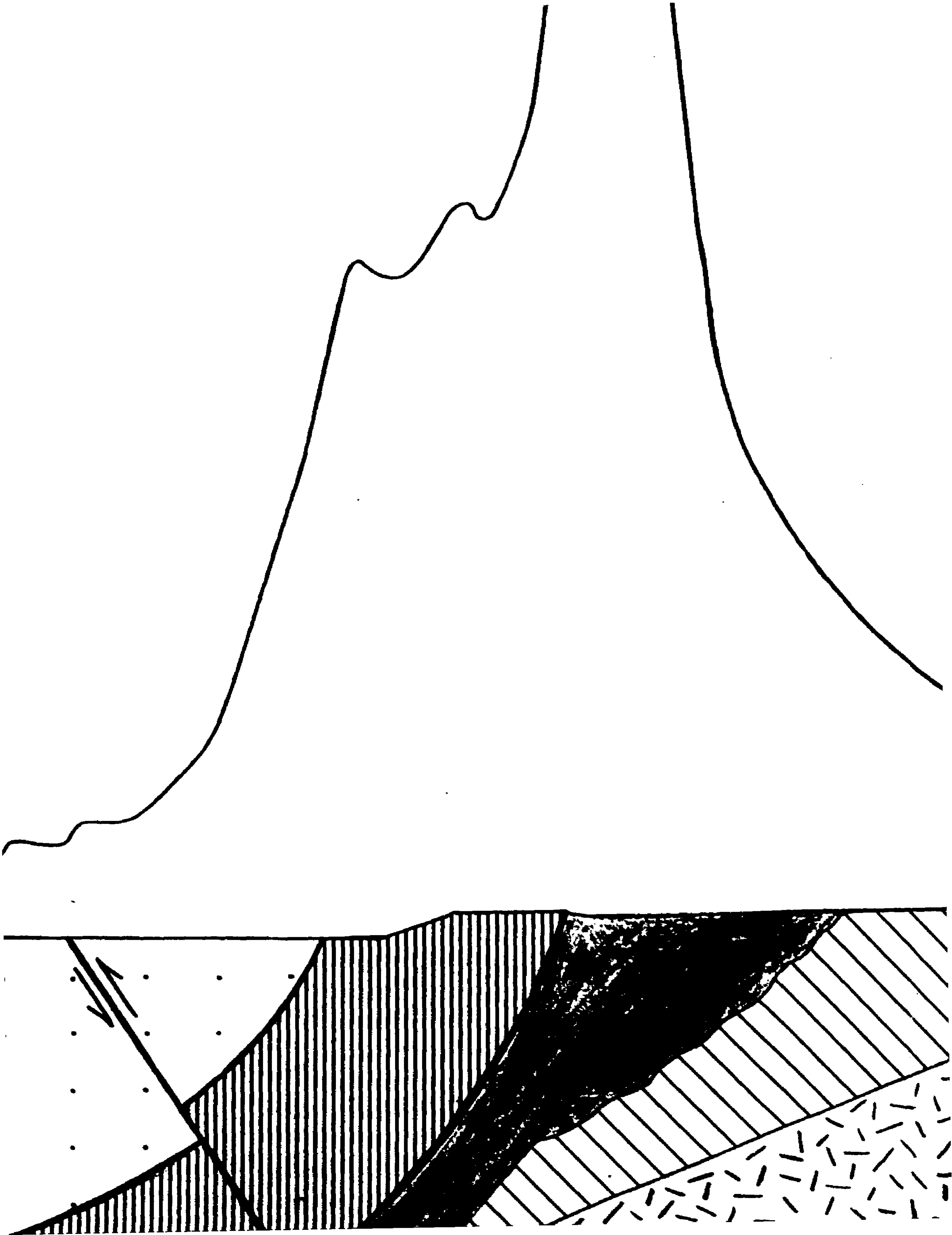

ISCO ANTICLINE

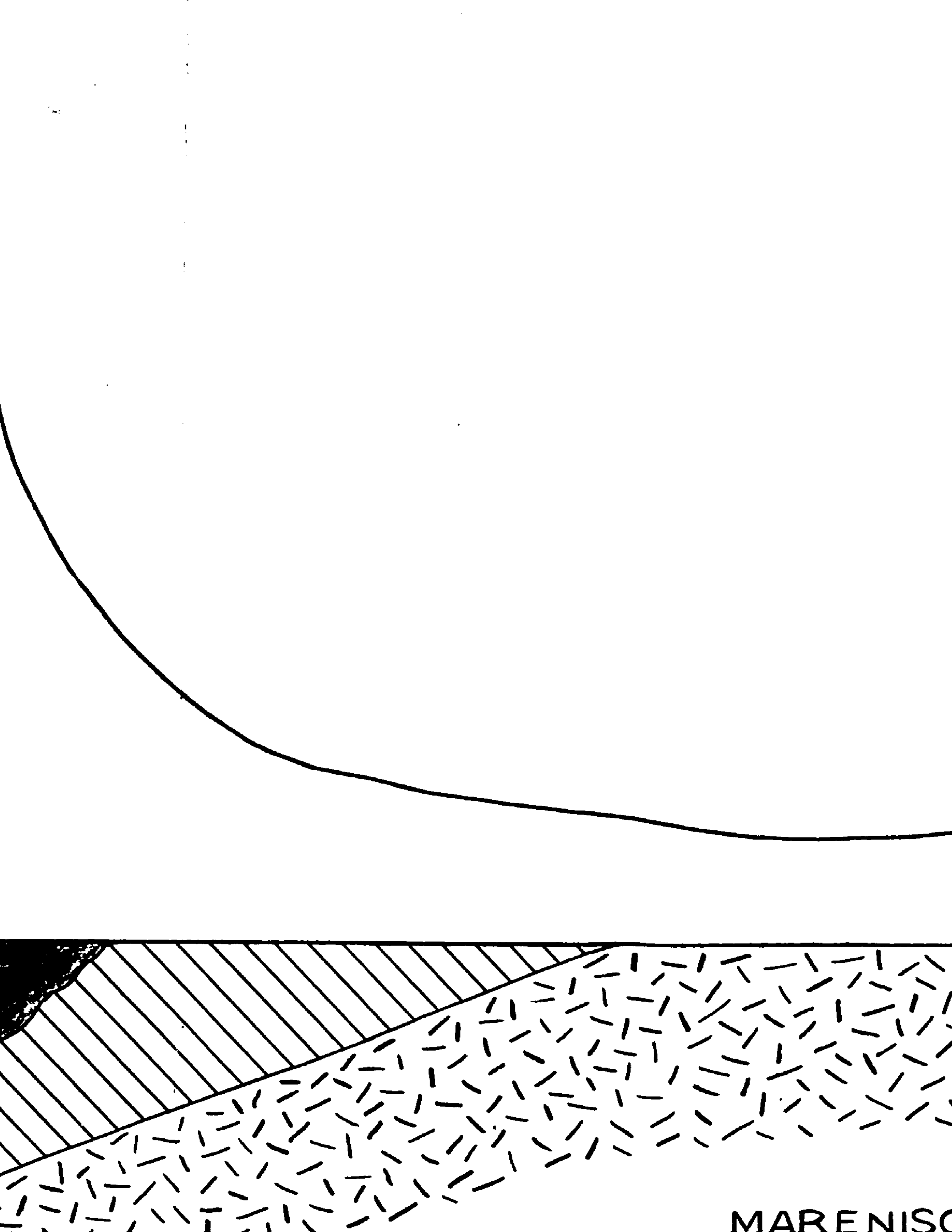

CL

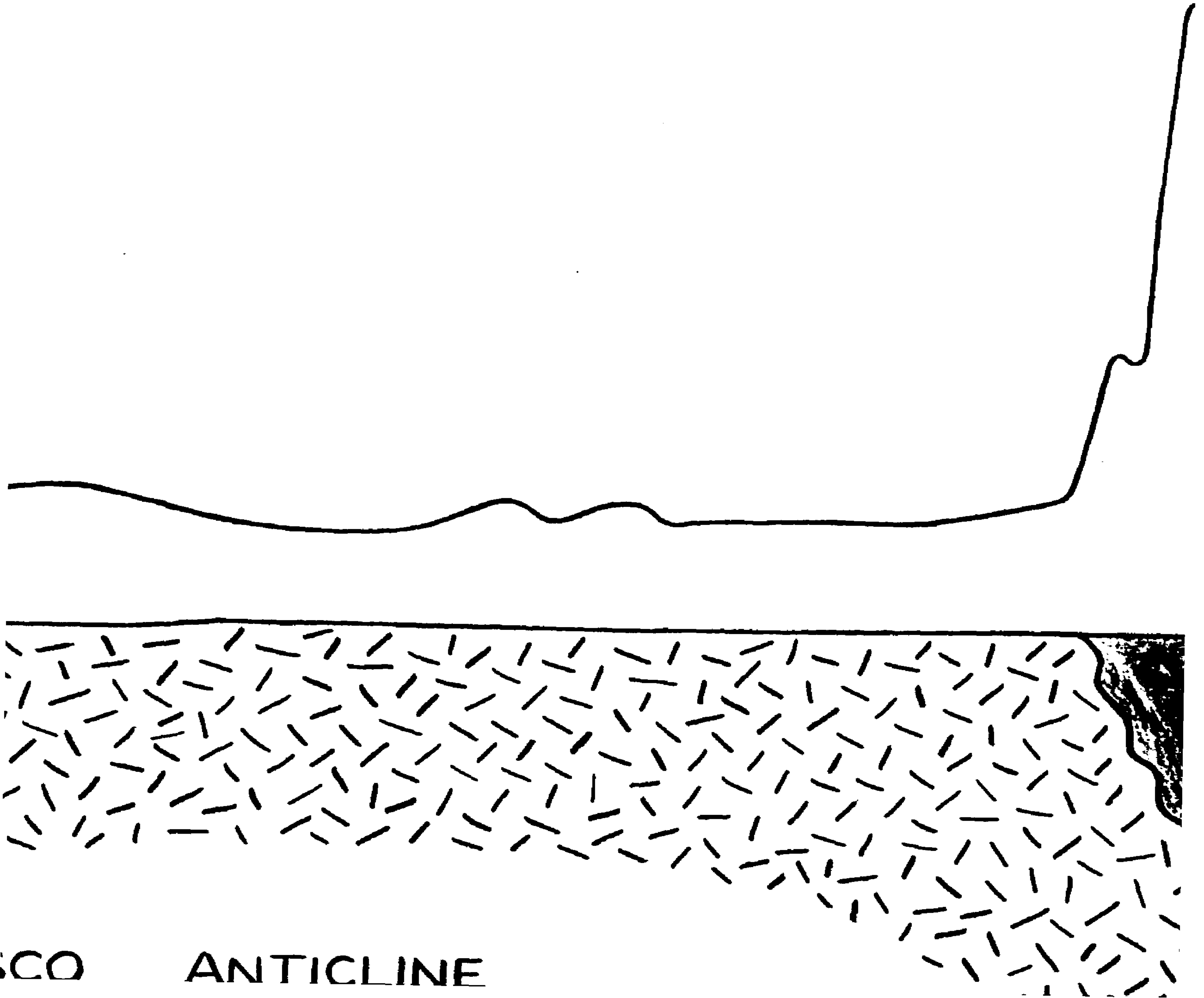

GAMMAS
5000
4000
3000
2000
+1000
-3000


N
IRON RIVER SYNCLINE

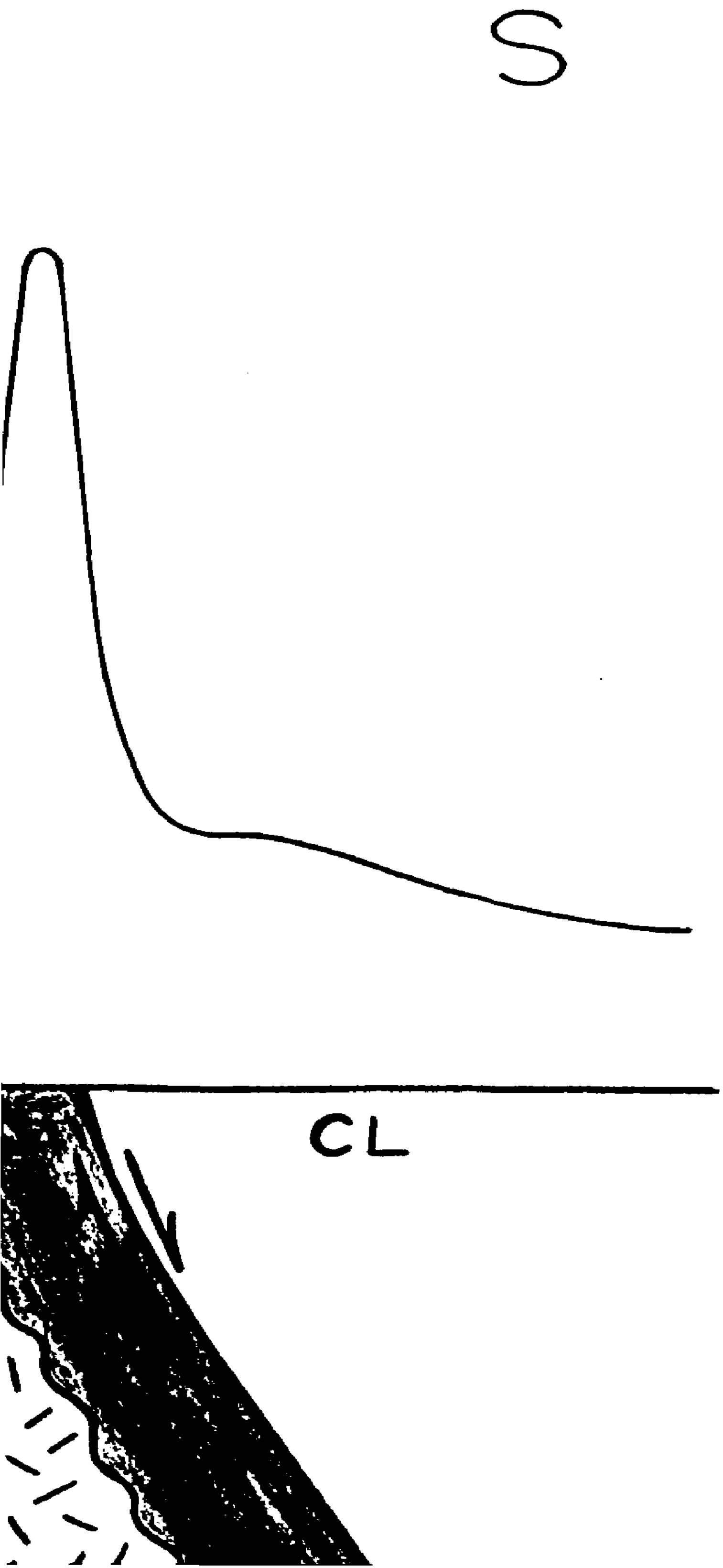


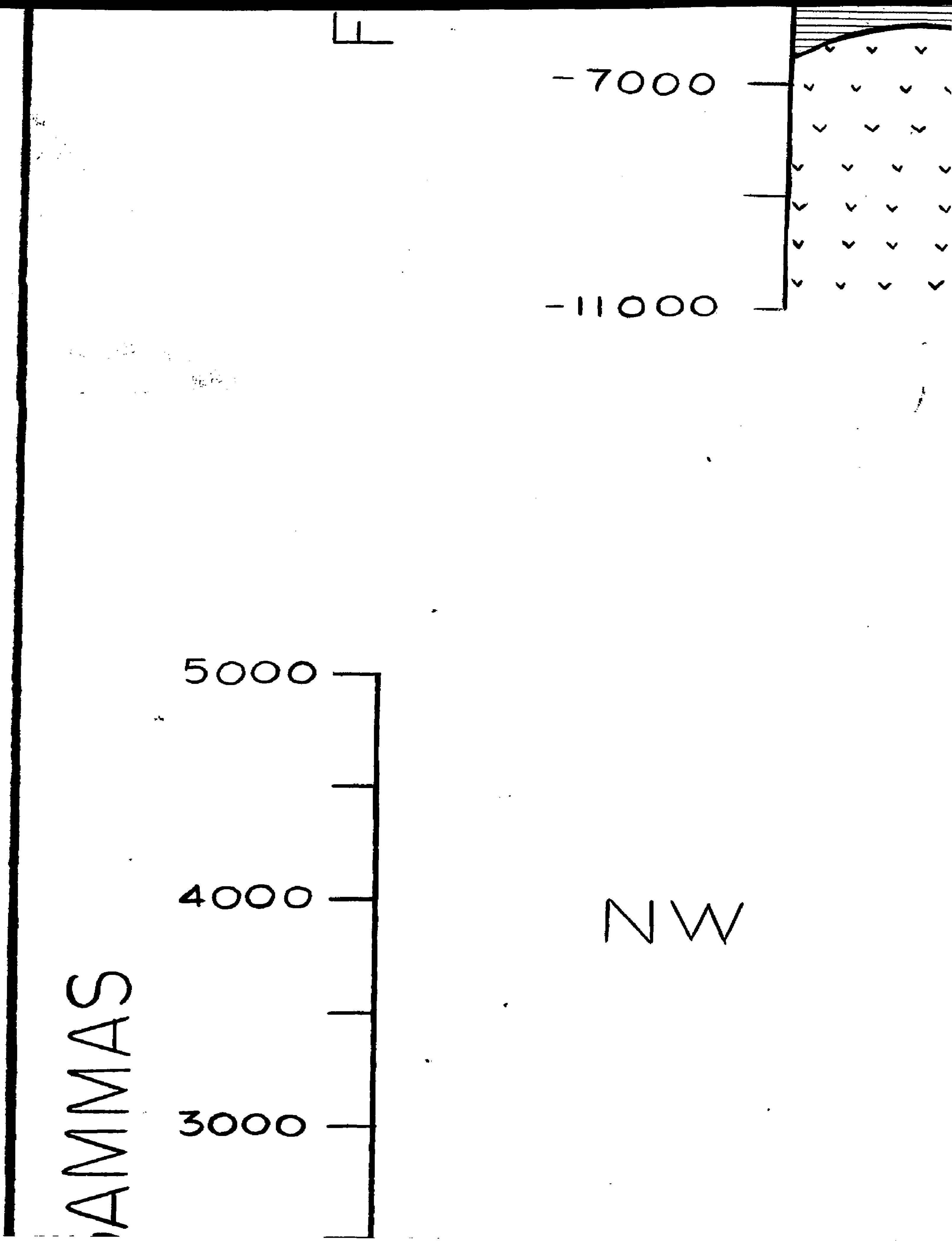



MARENISC

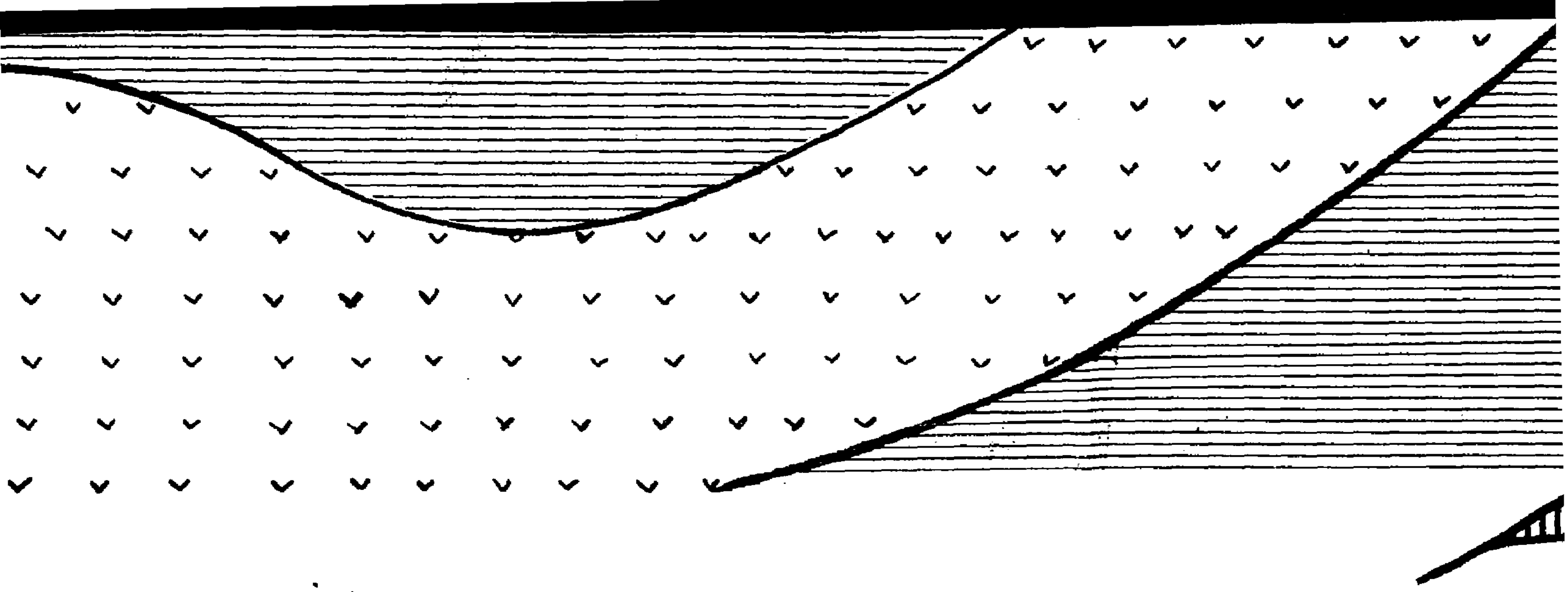


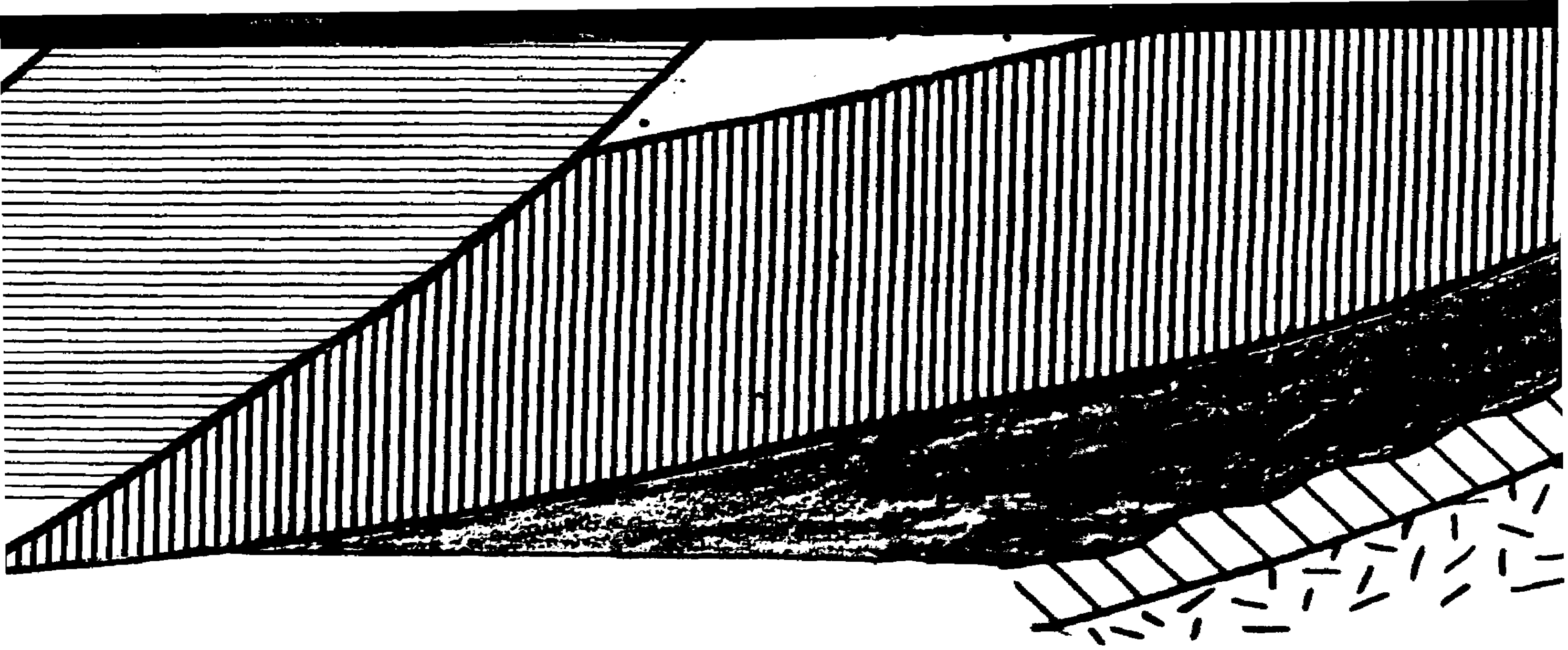
SCO ANTICLINE

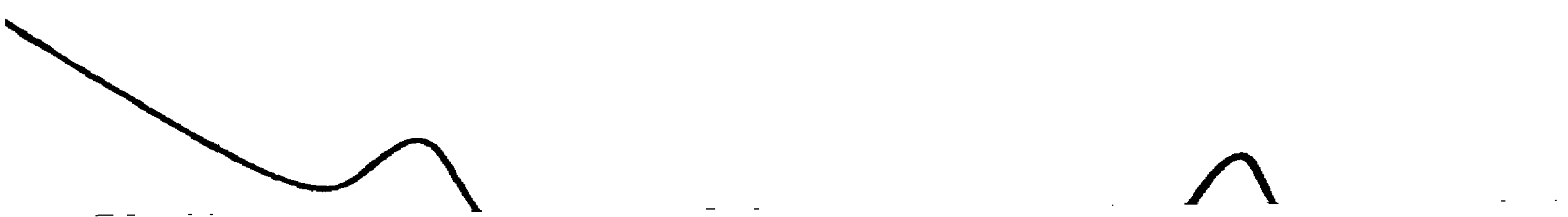

S
CL

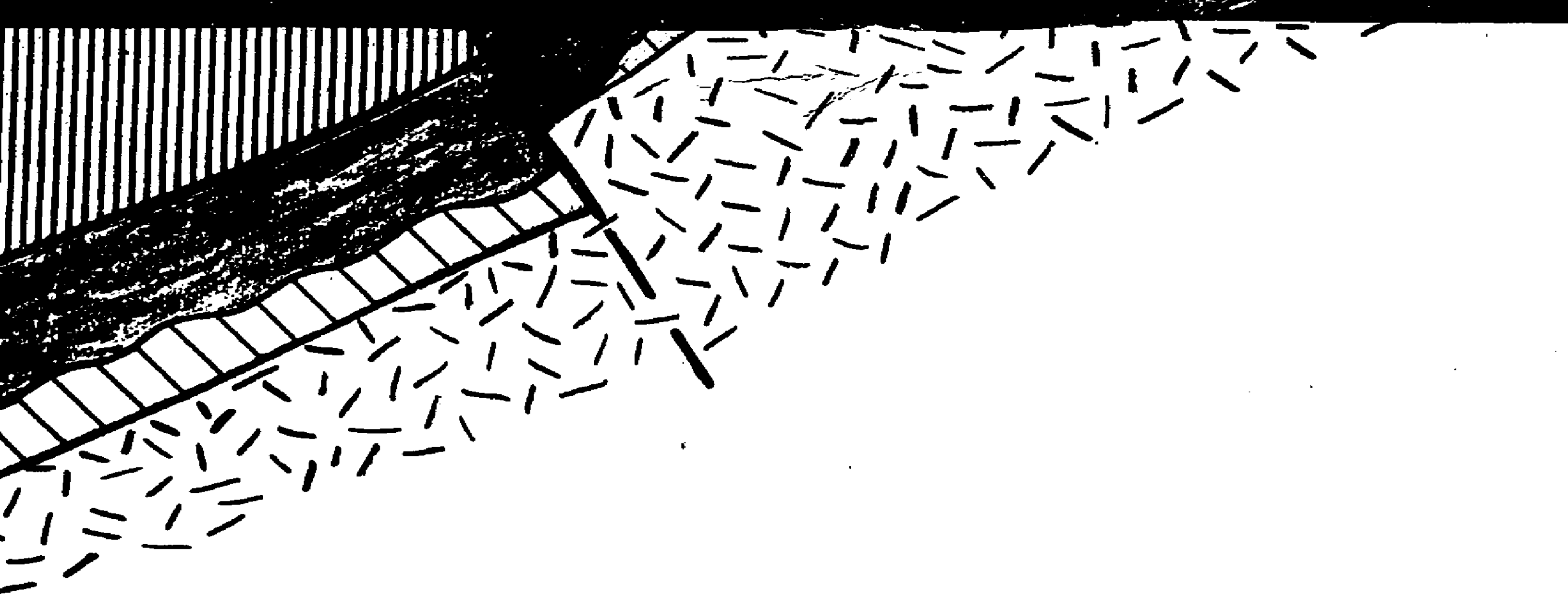


-7000
-11000
5000
4000
3000
NW
AMMAS

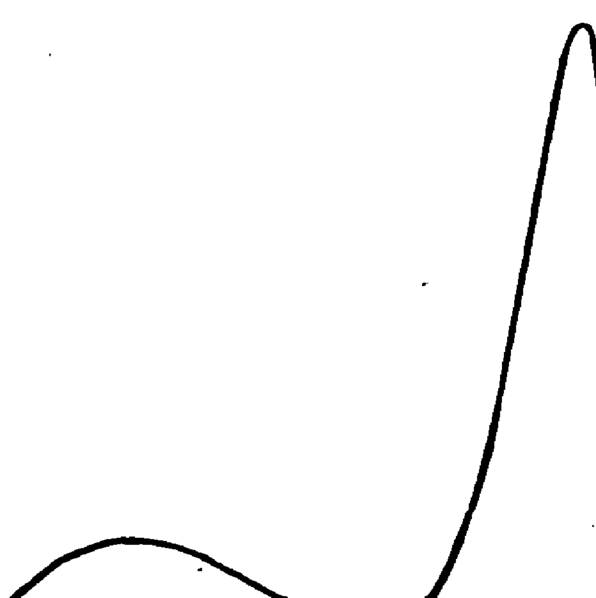




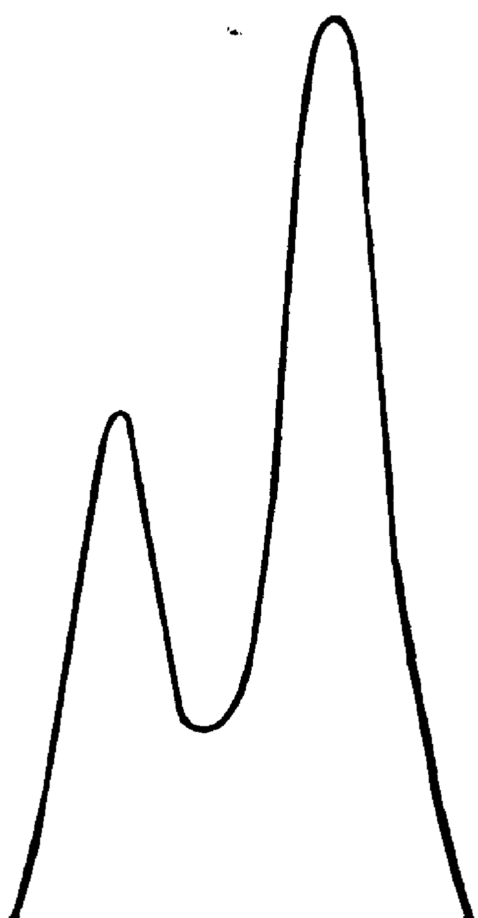




PROF



PROFILE B — B′



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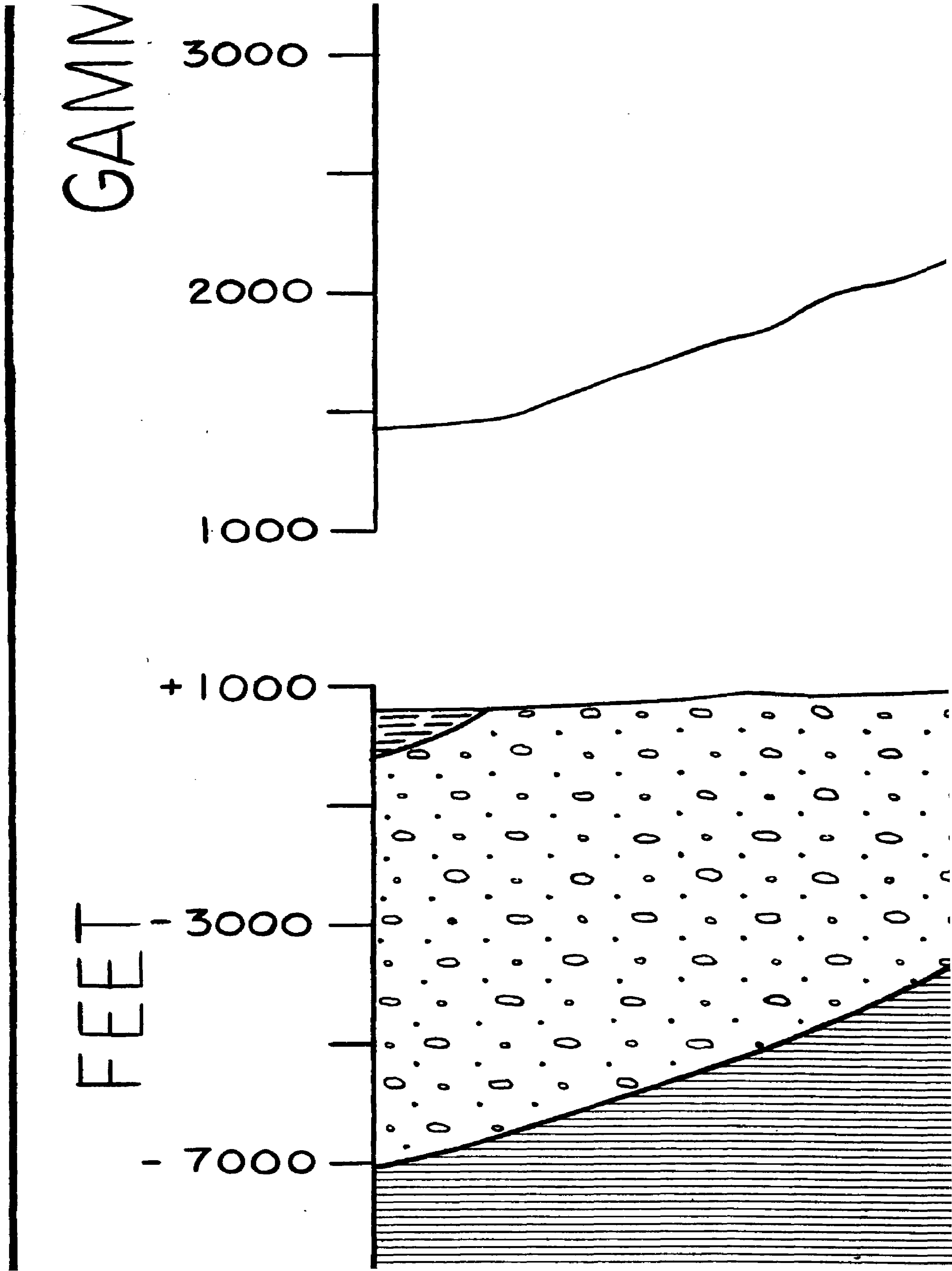
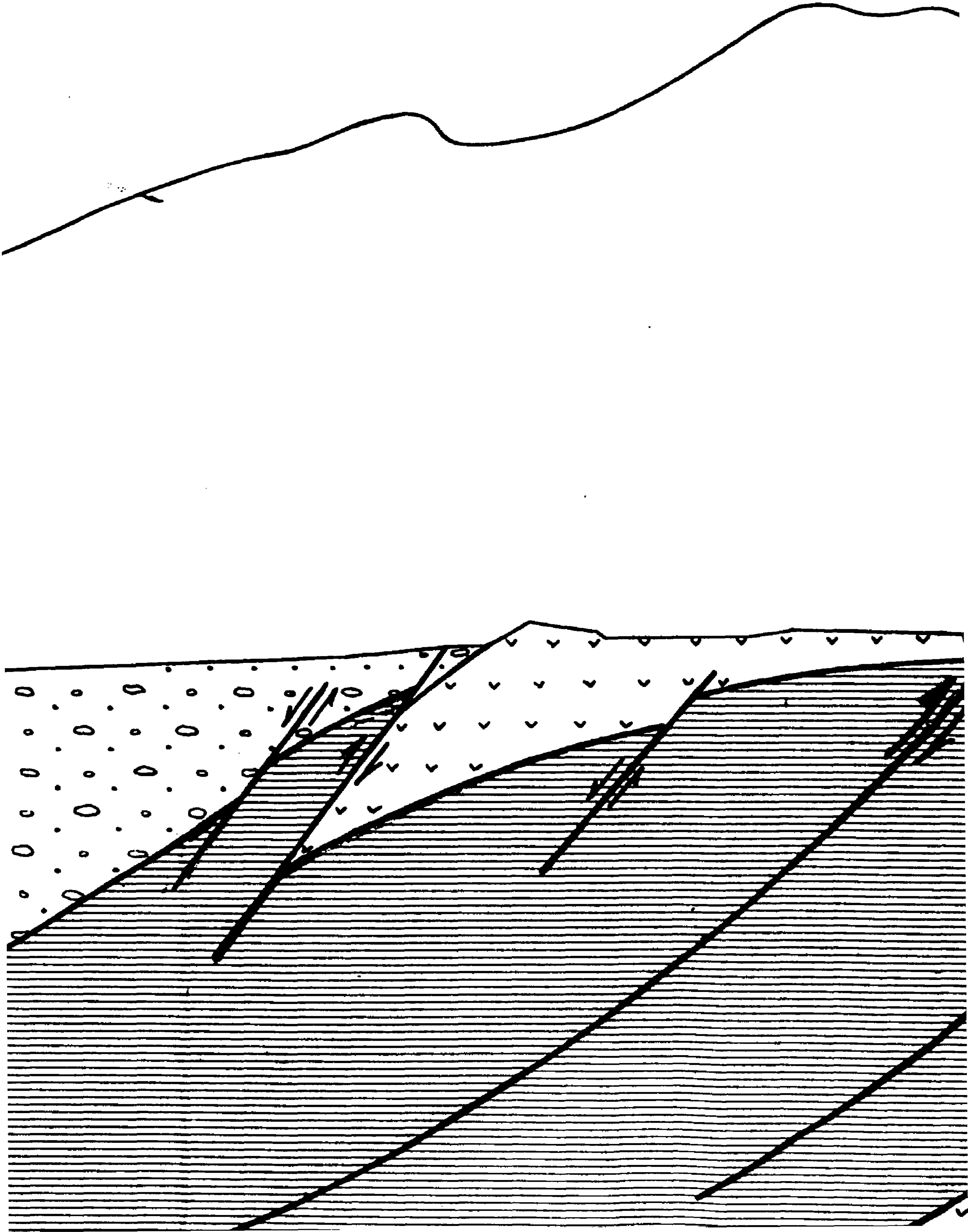
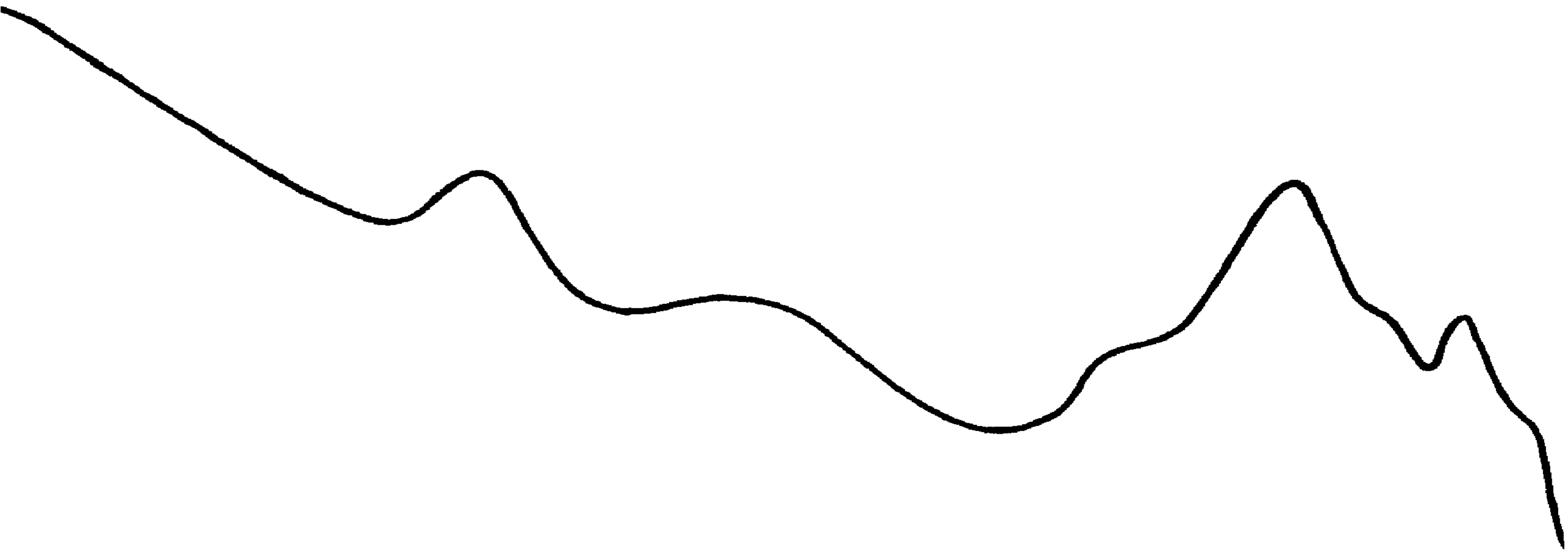
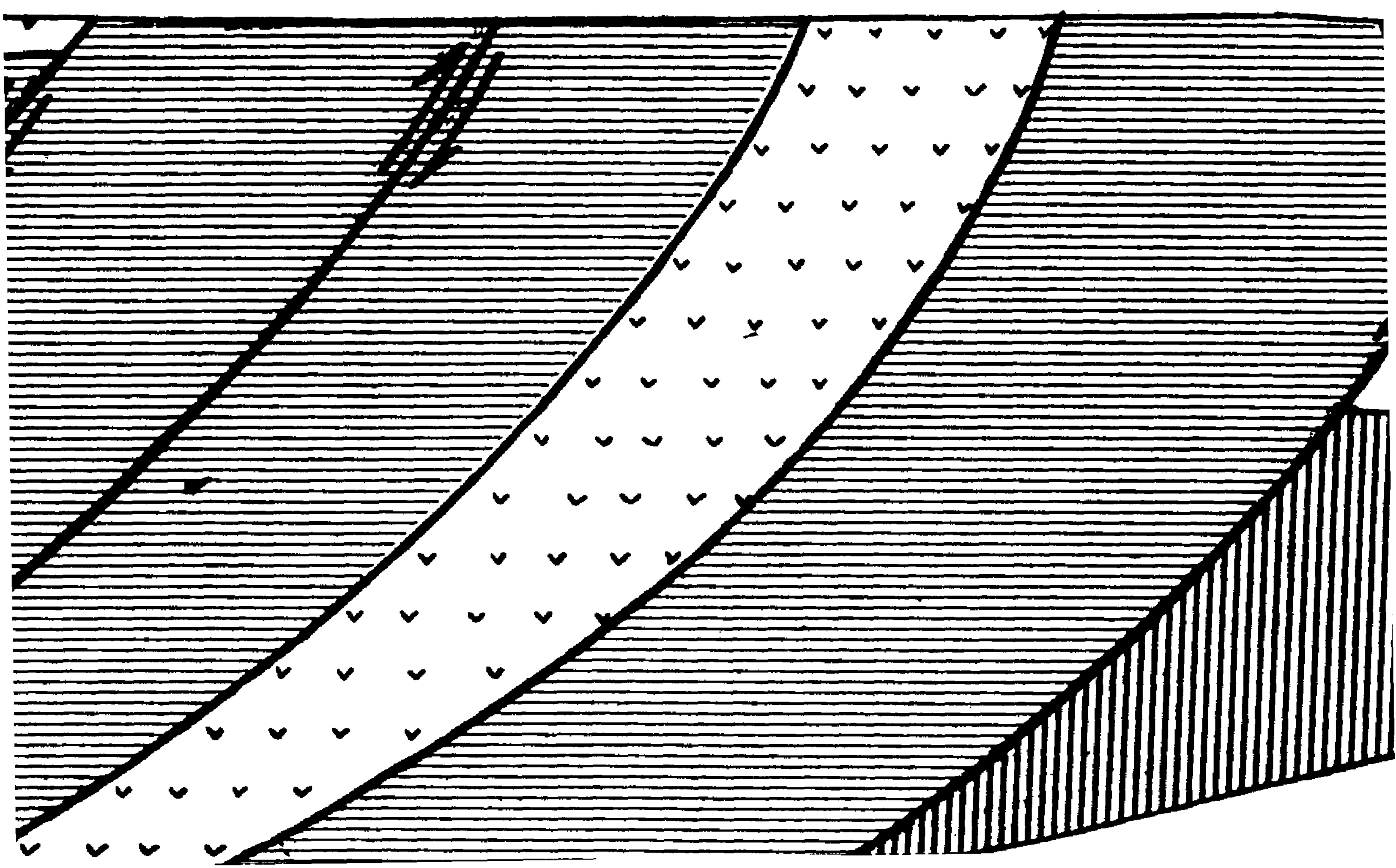
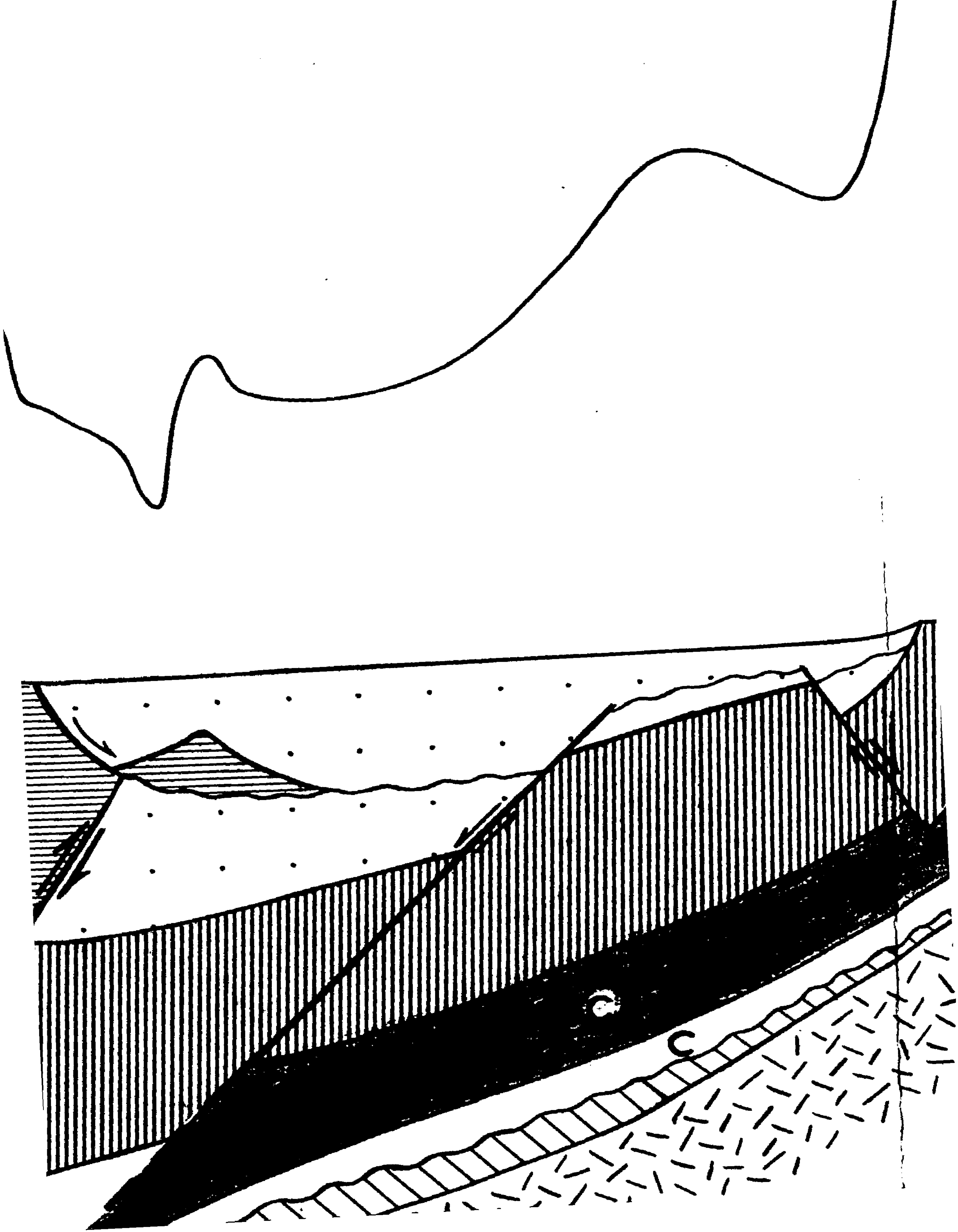
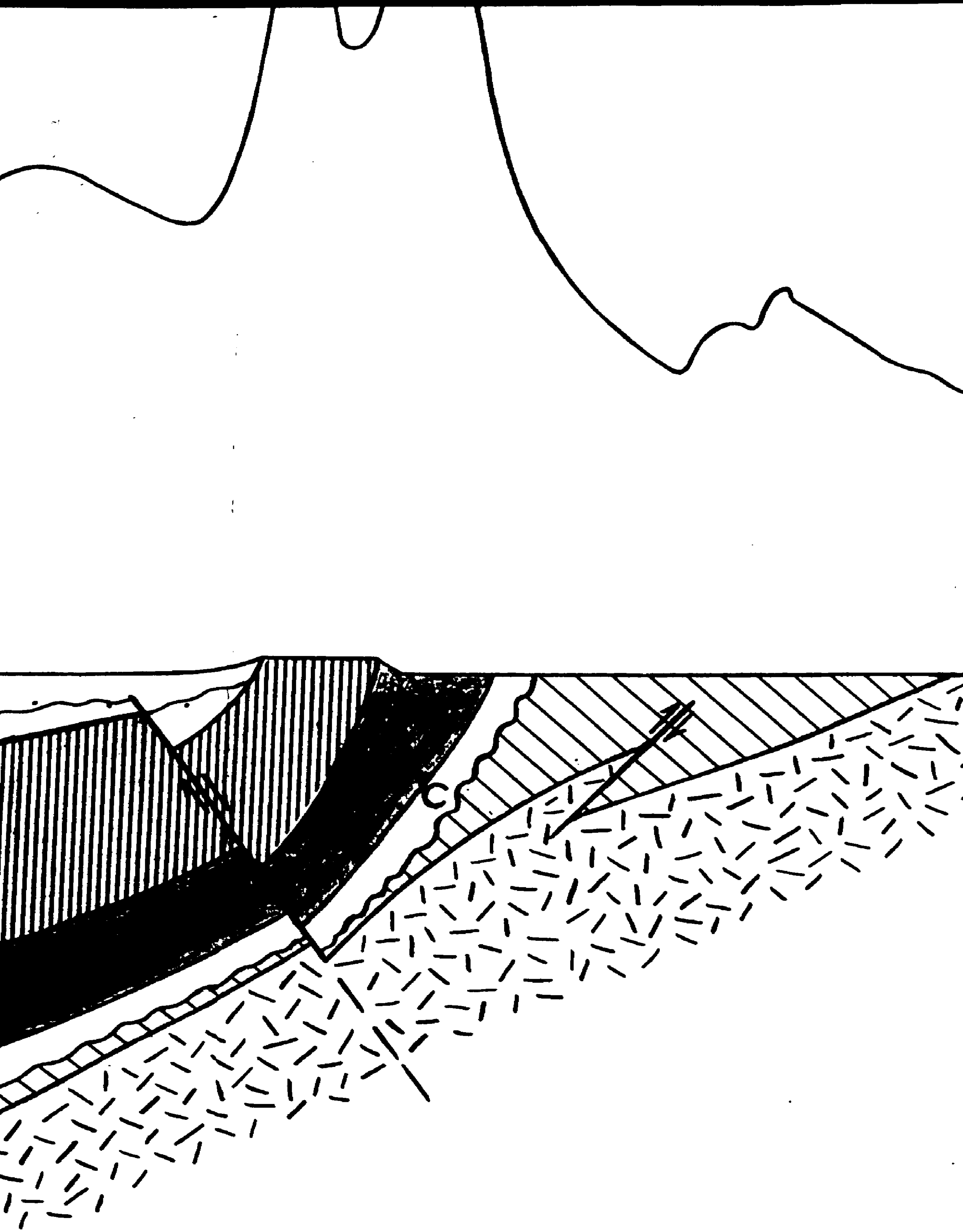

3000
2000
1000
+1000
-3000
-7000
FEET

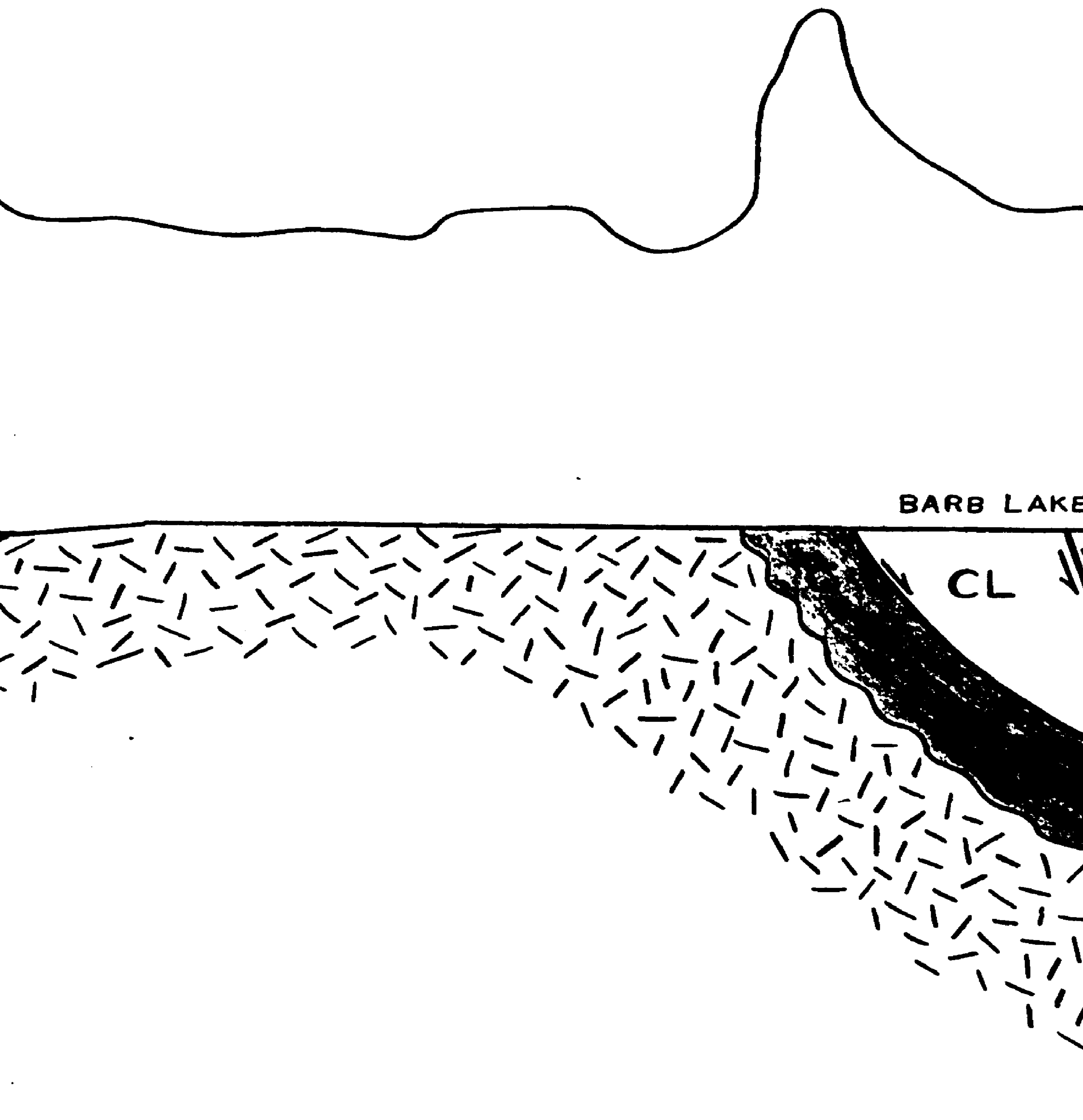




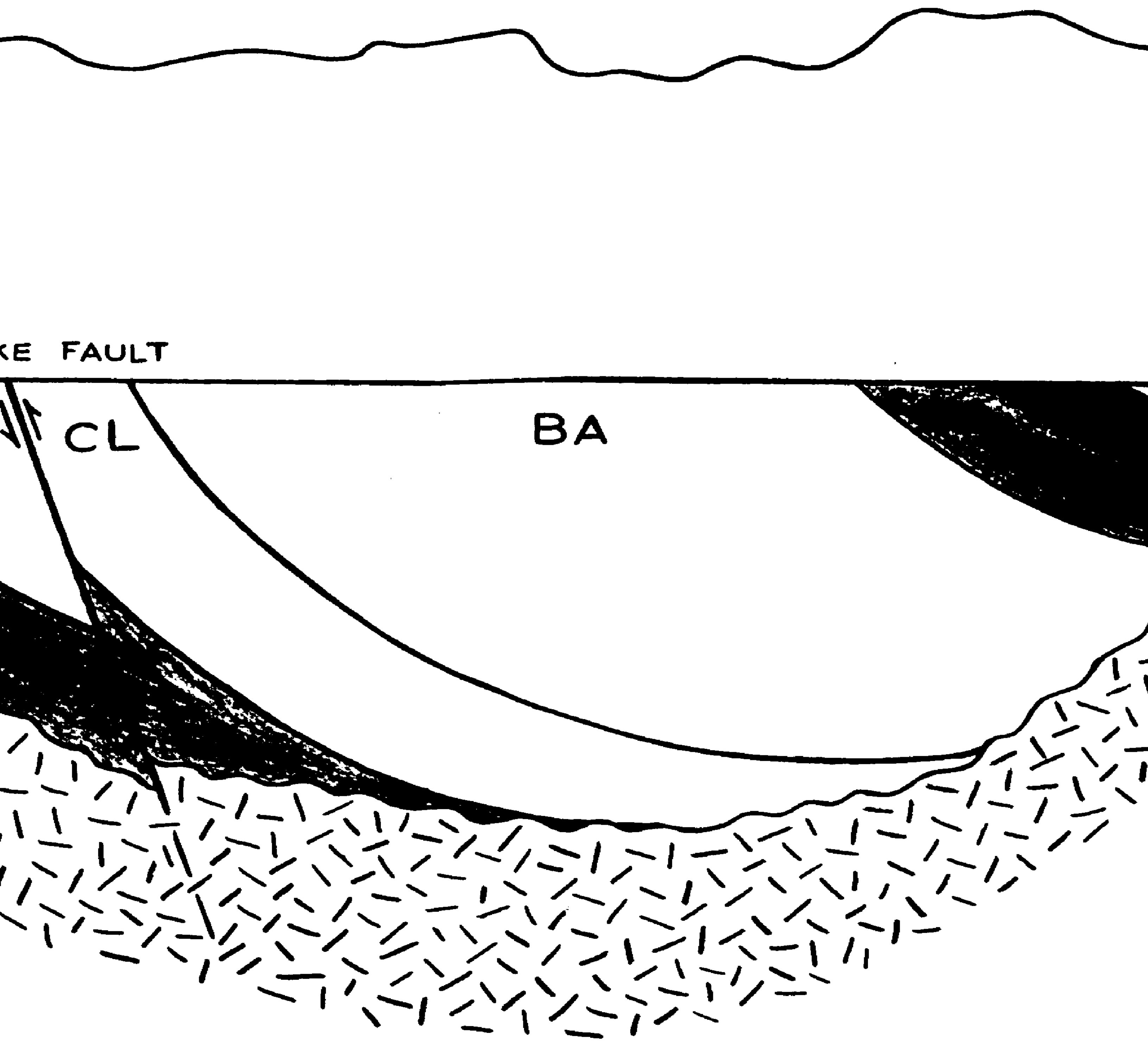


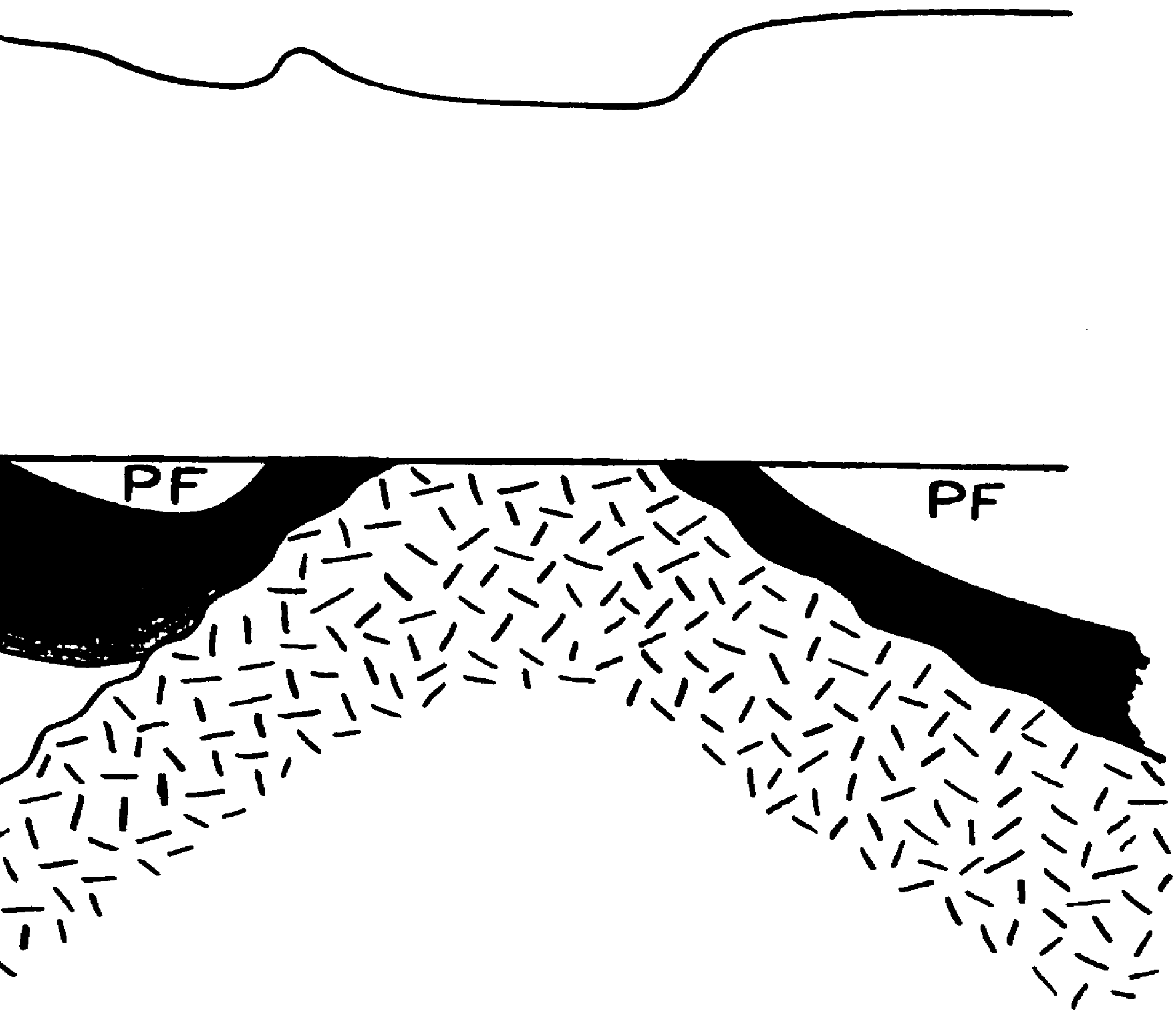

C

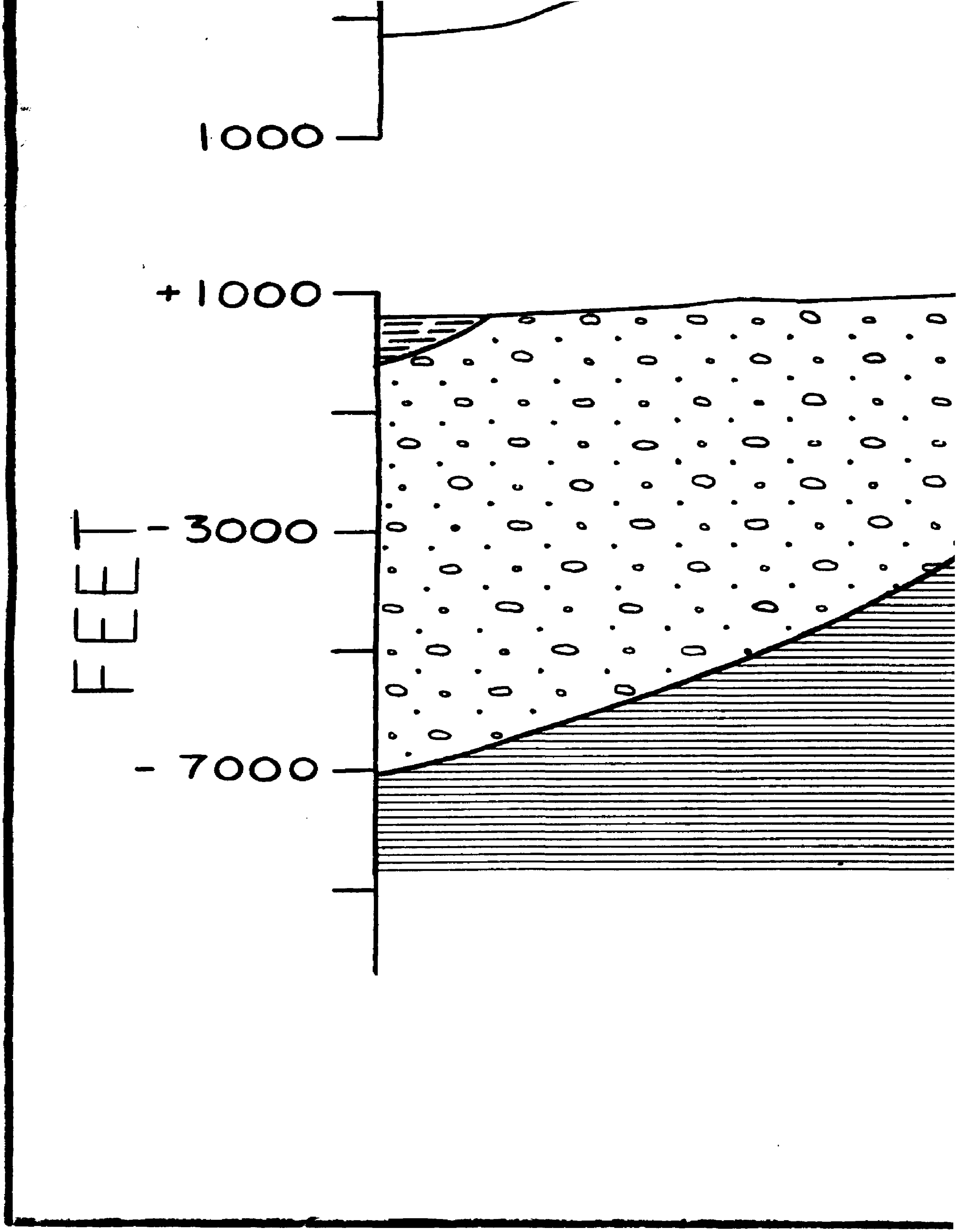

C



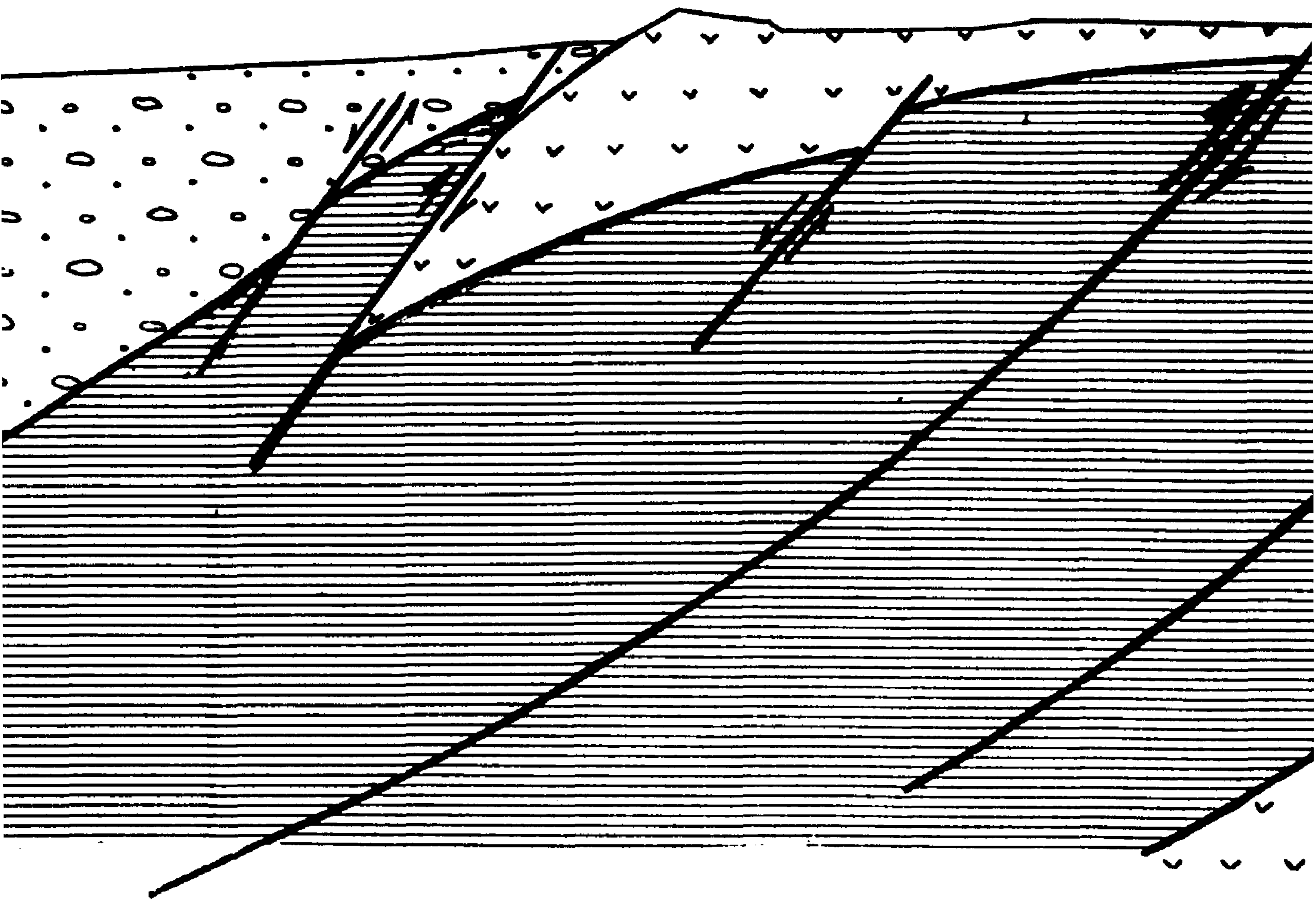
BARB LAKE
CL

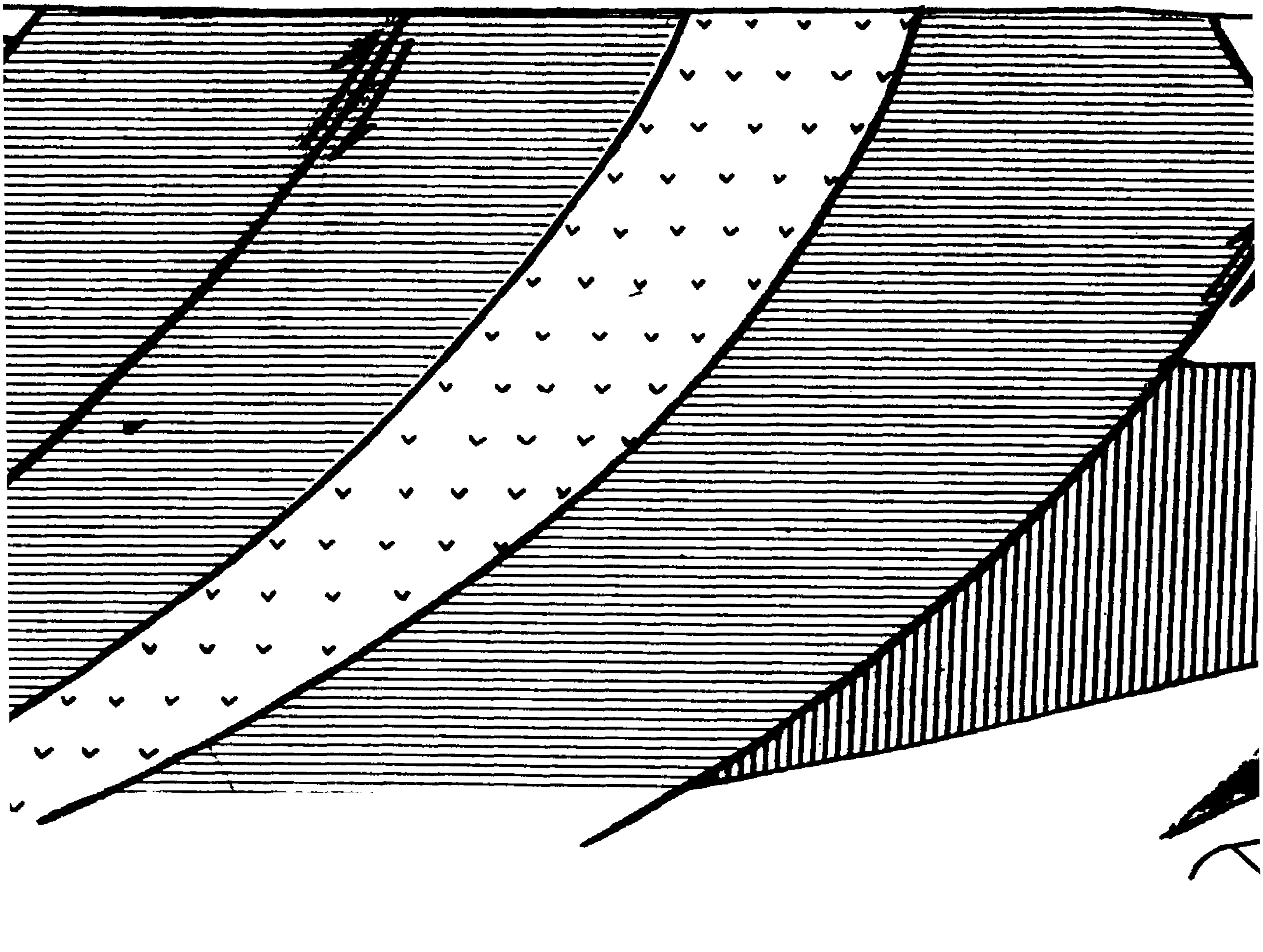

‹E FAULT
CL
BA

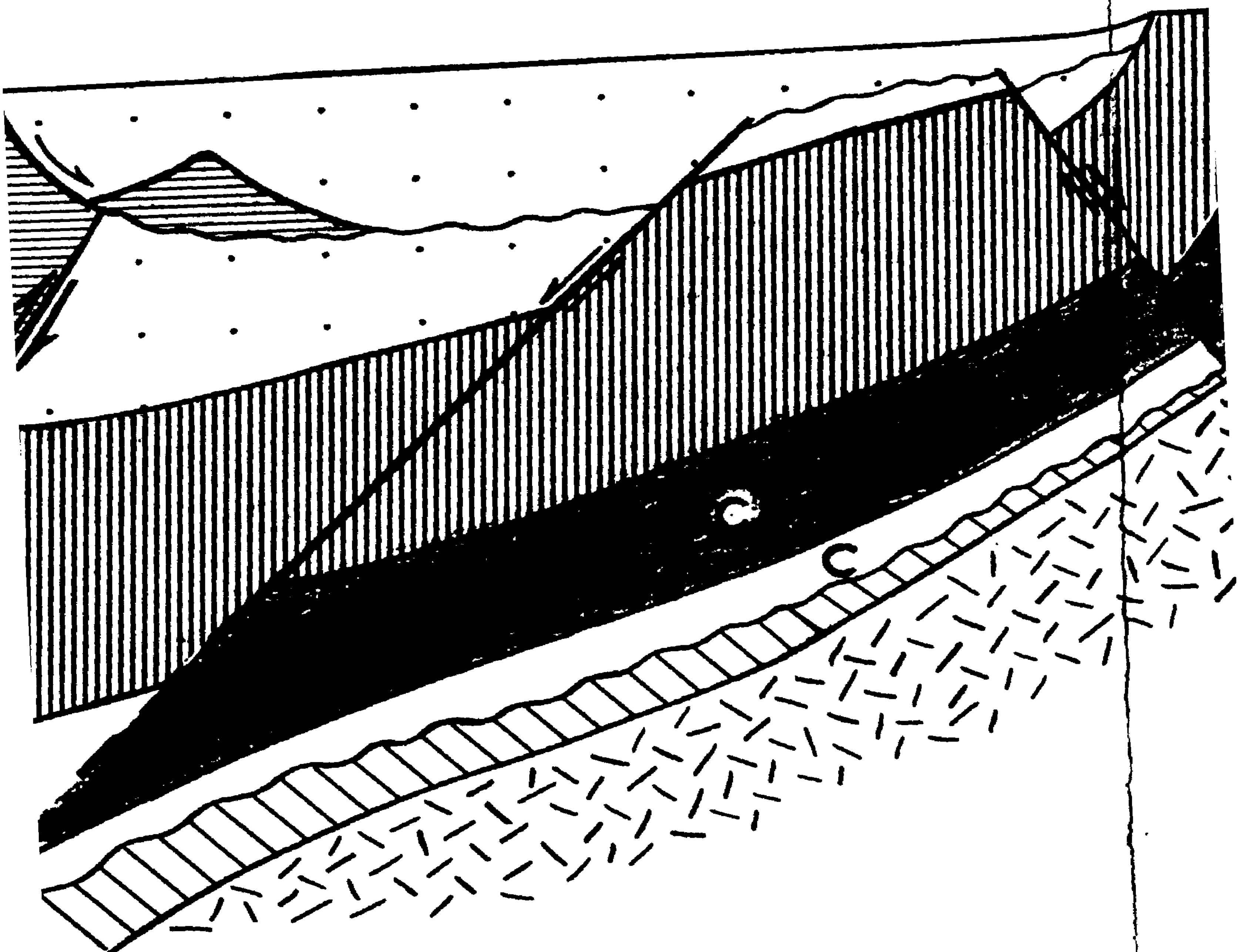

PF
PF

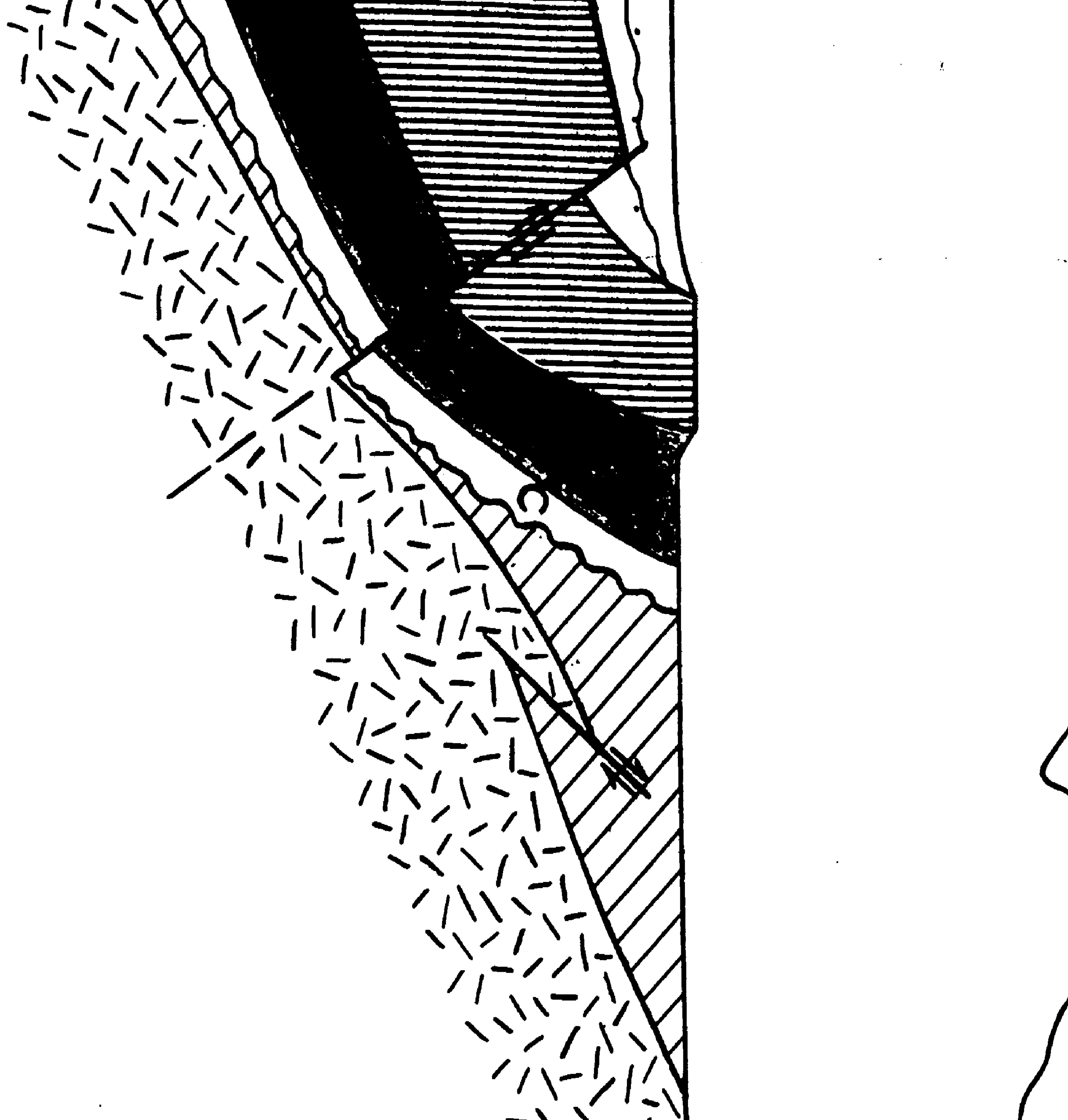


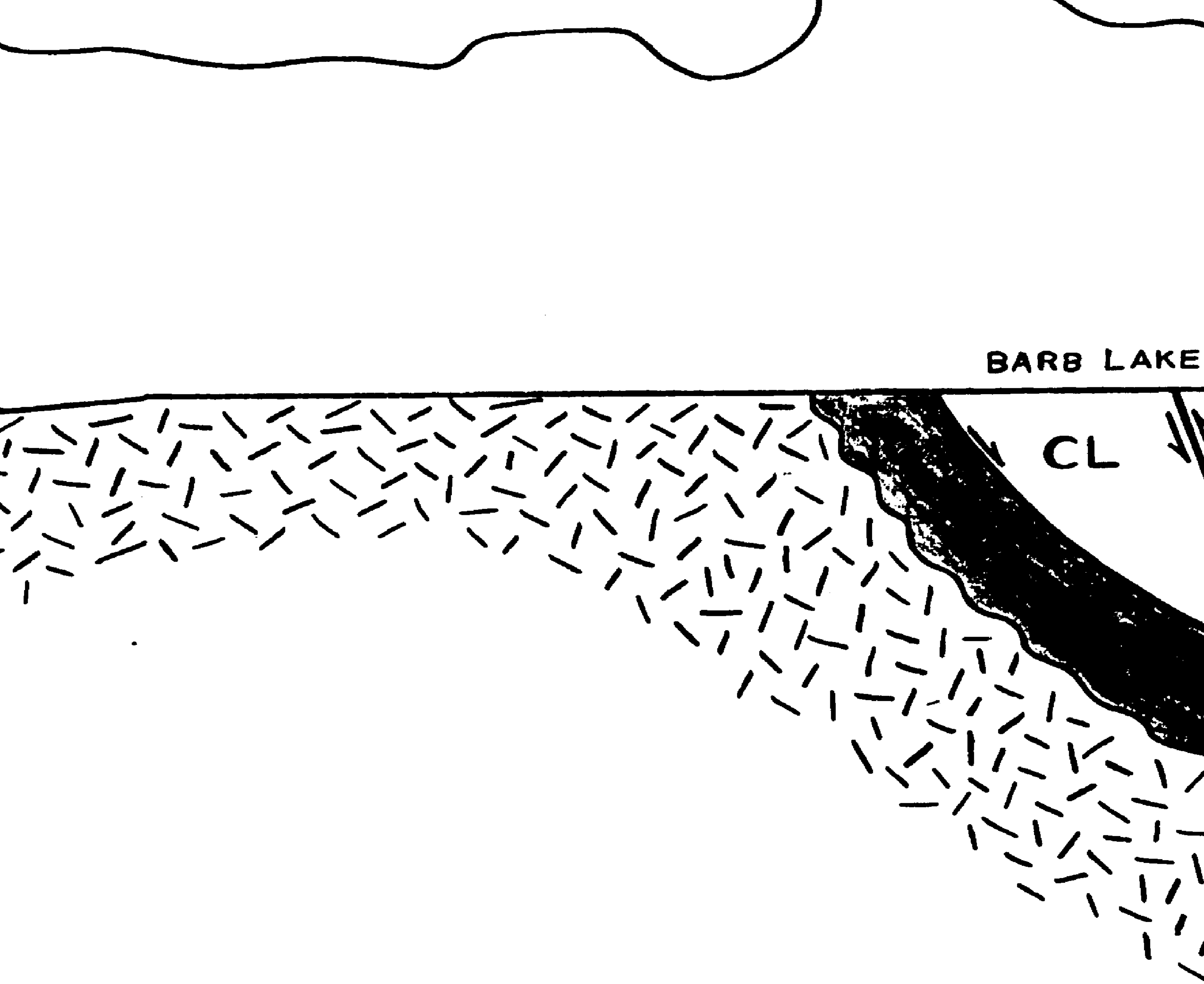
1000
+1000
FEET
-3000
-7000

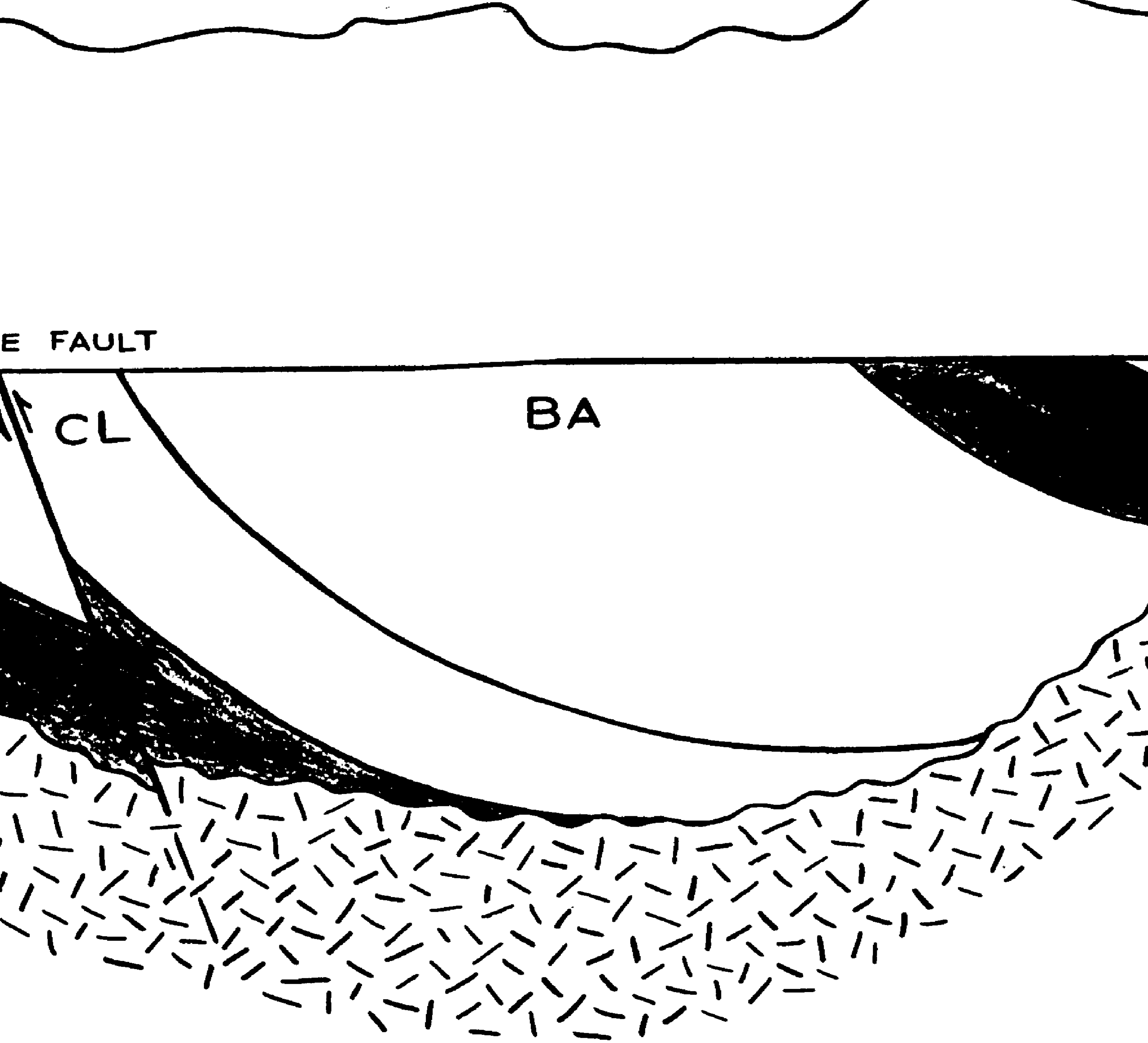


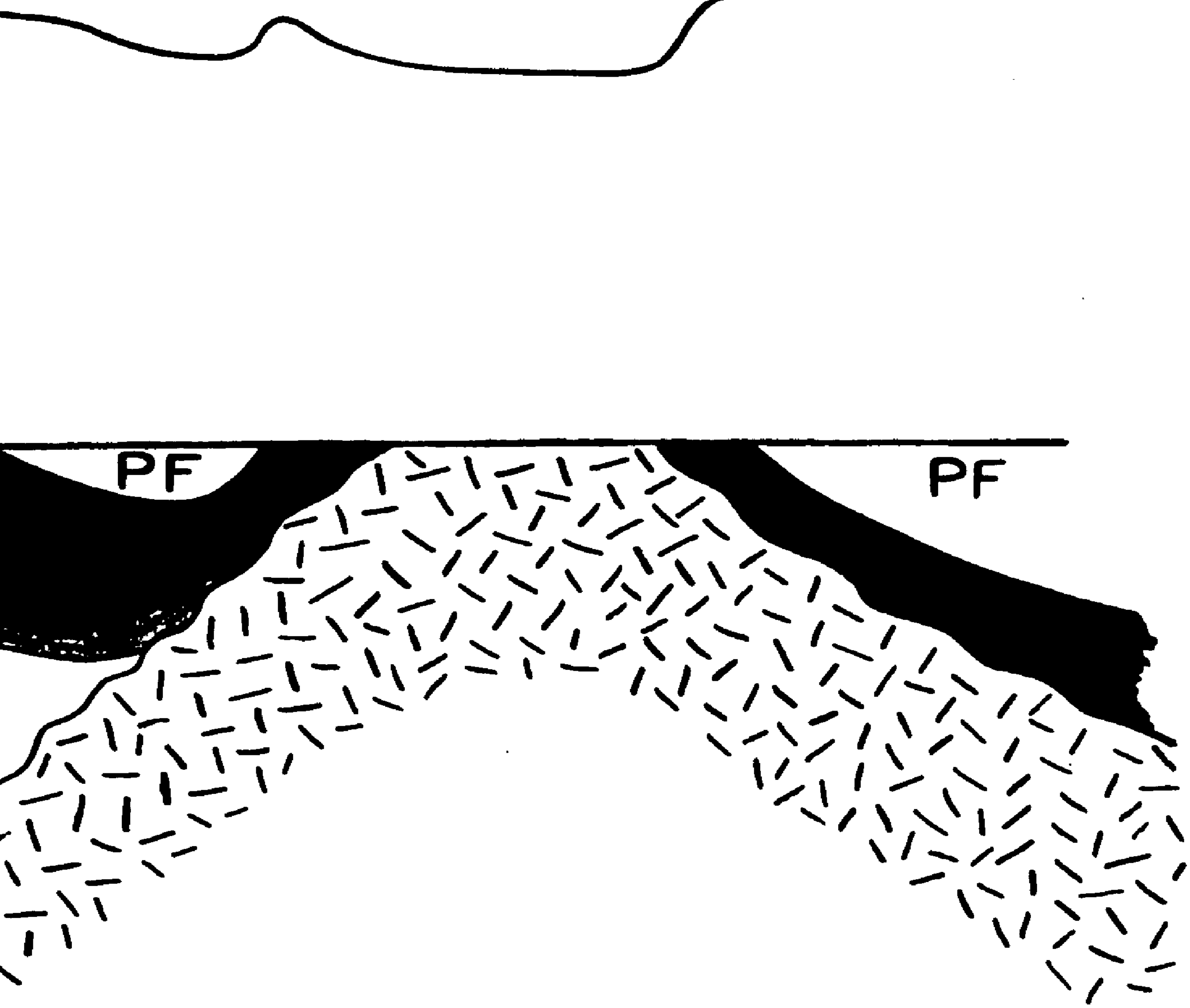


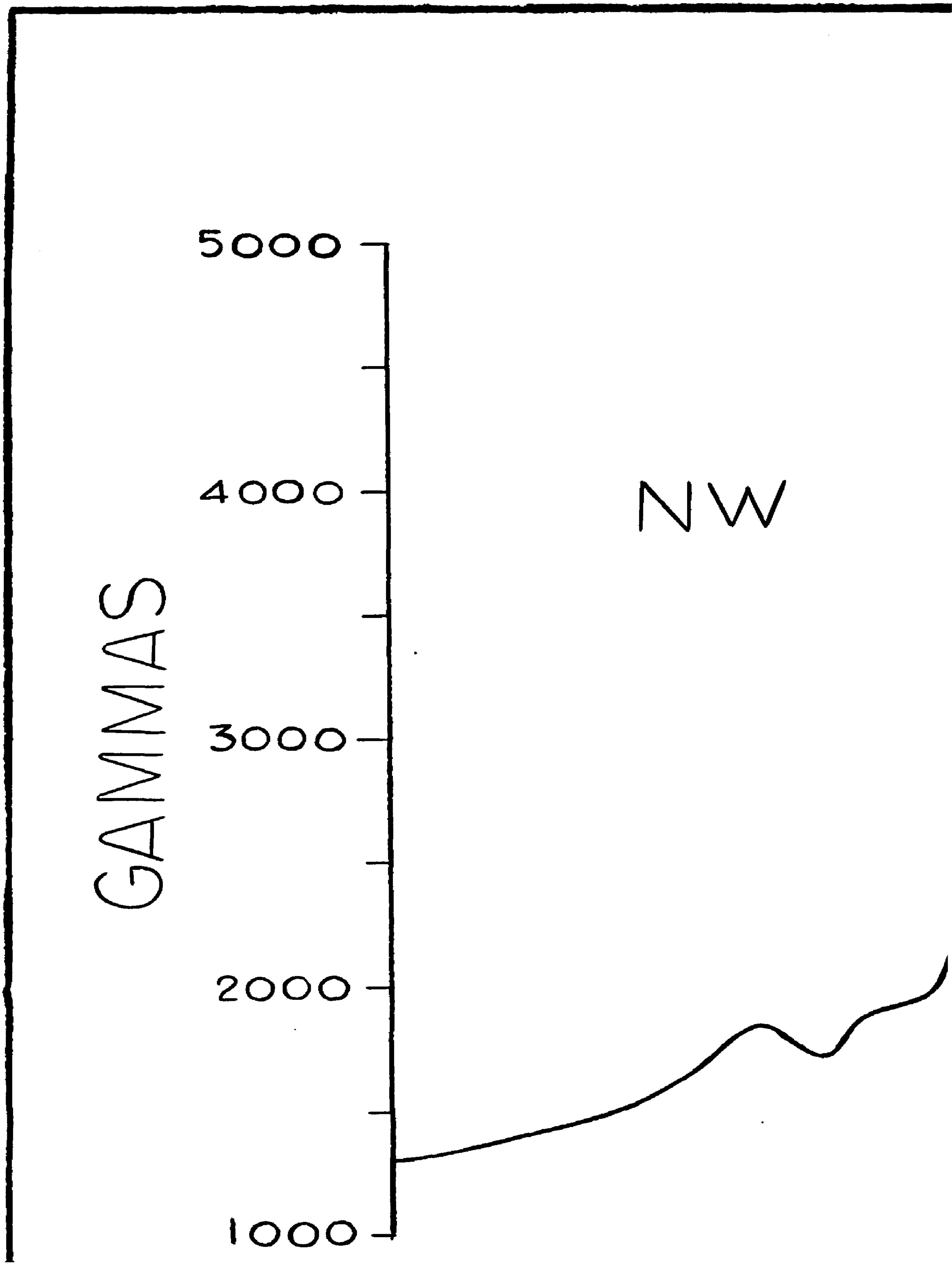

C

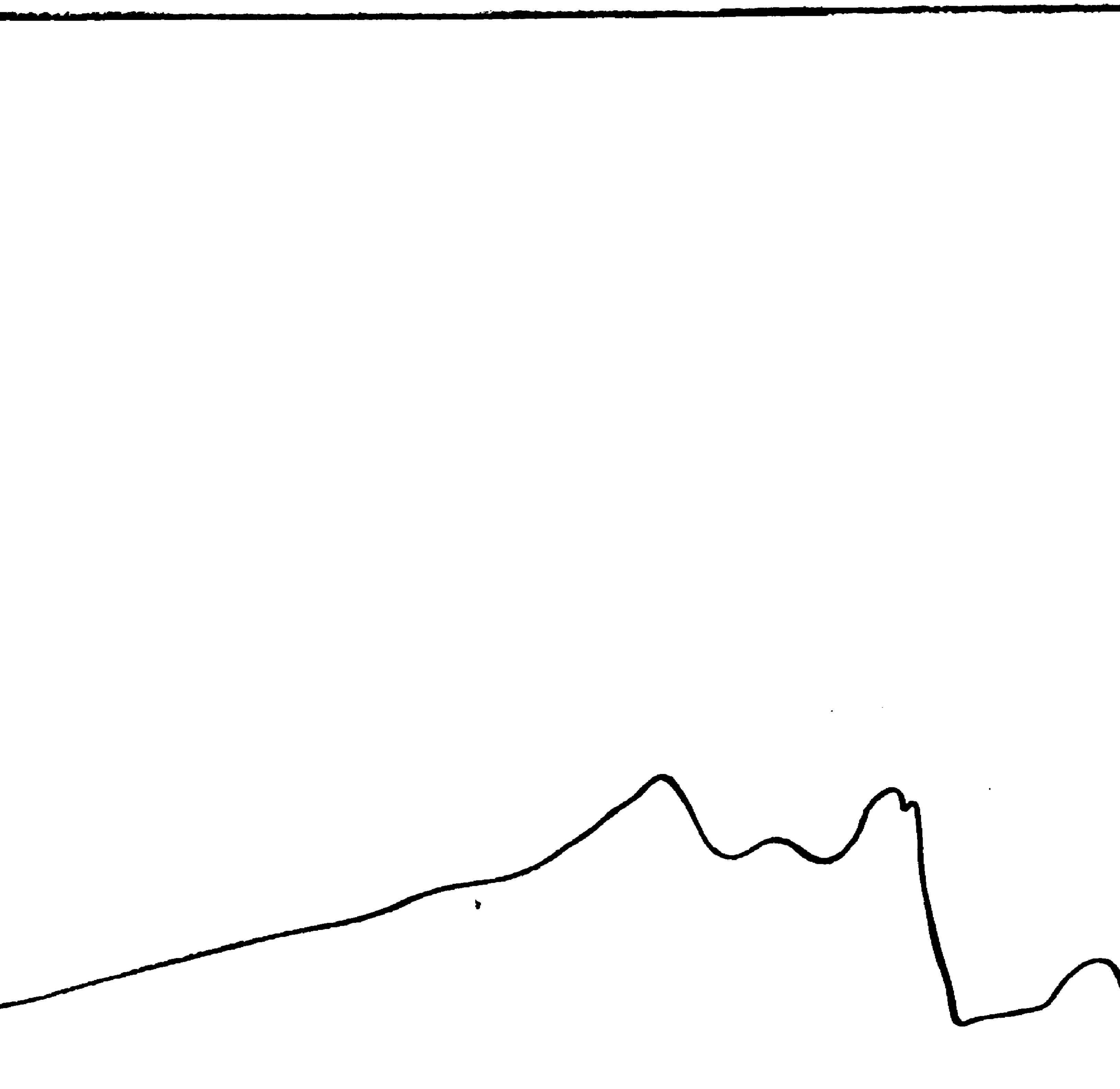


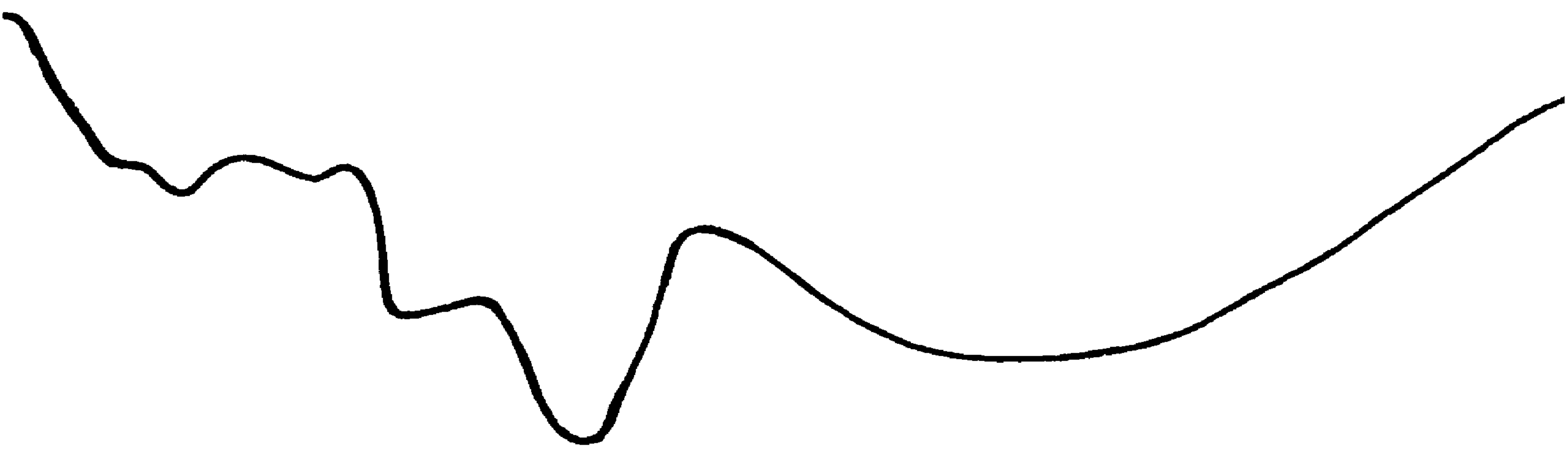

BARB LAKE
CL


E FAULT
CL
BA

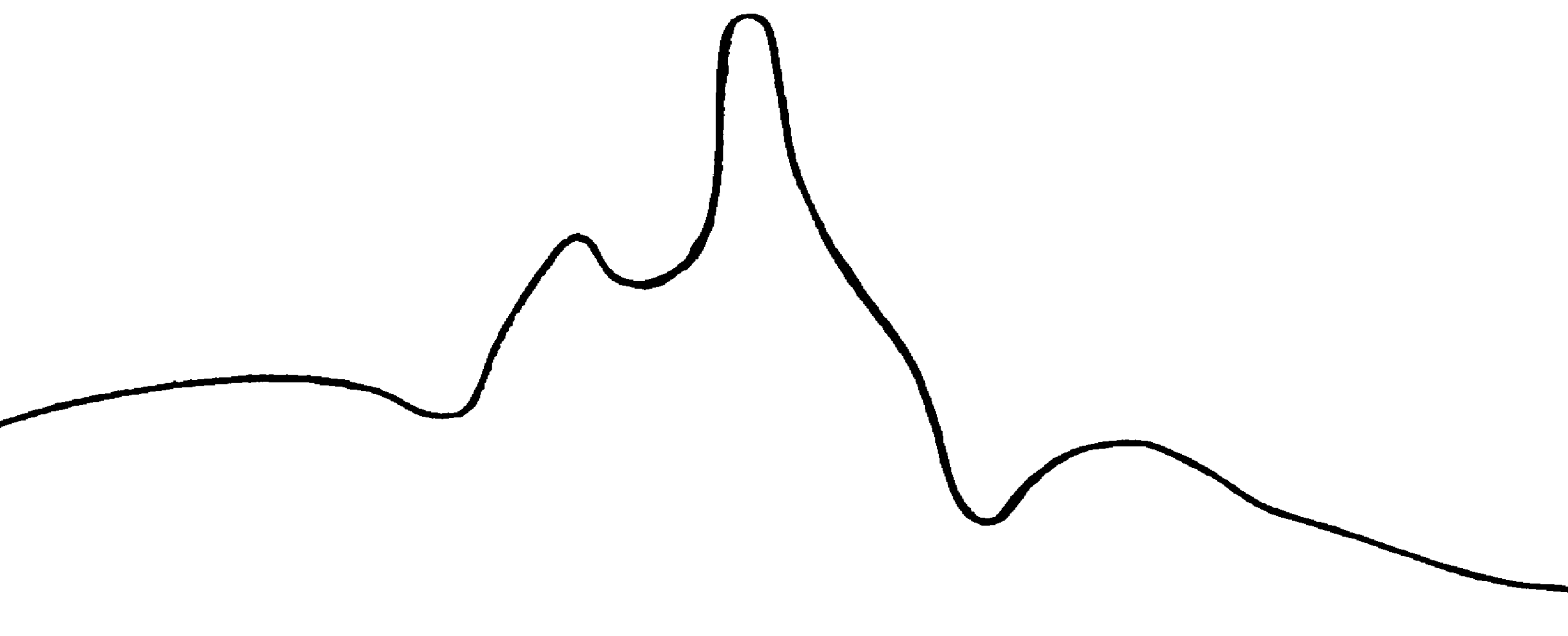

PF
PF

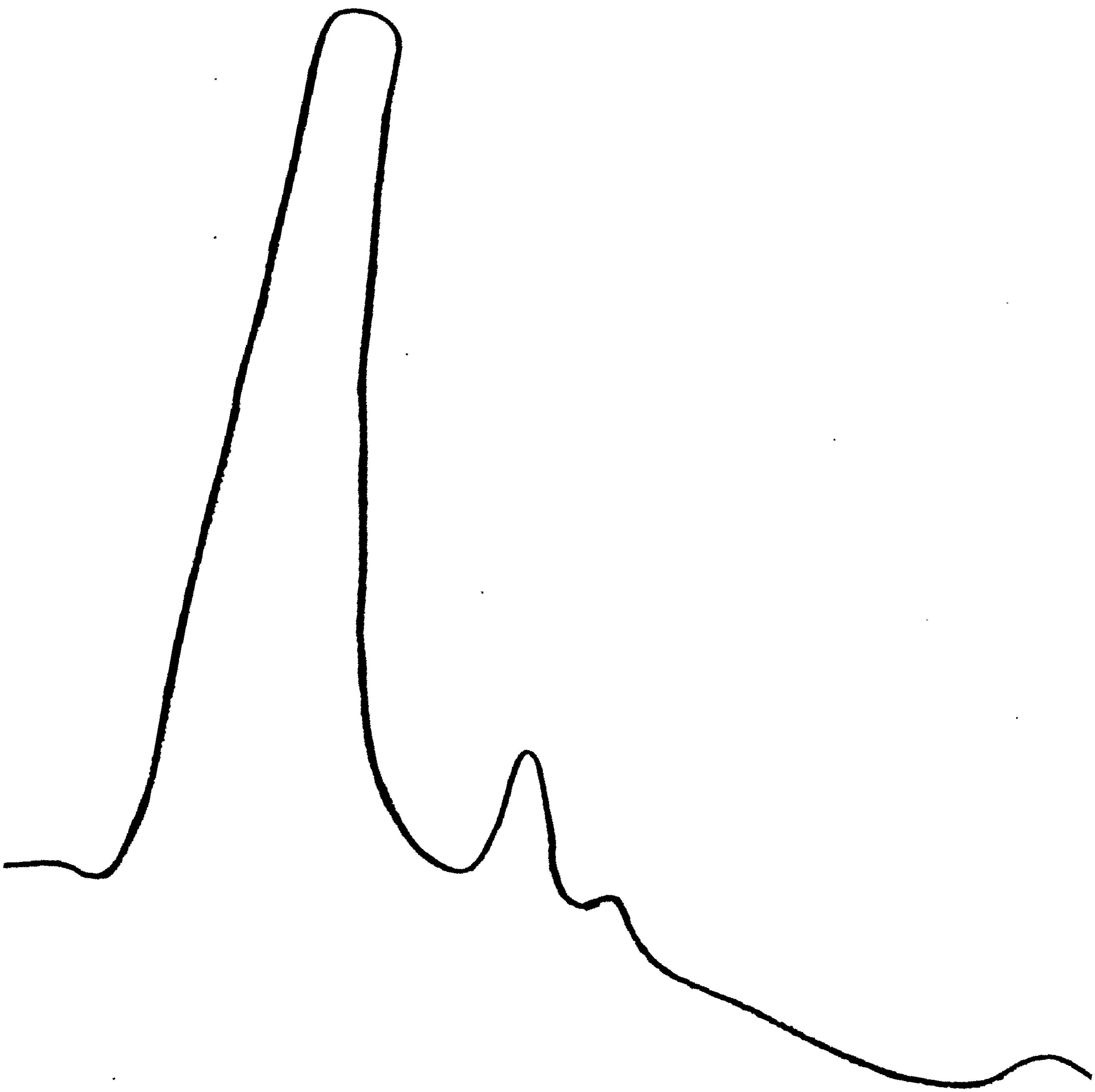

5000
4000
3000
2000
1000
GAMMAS
NW



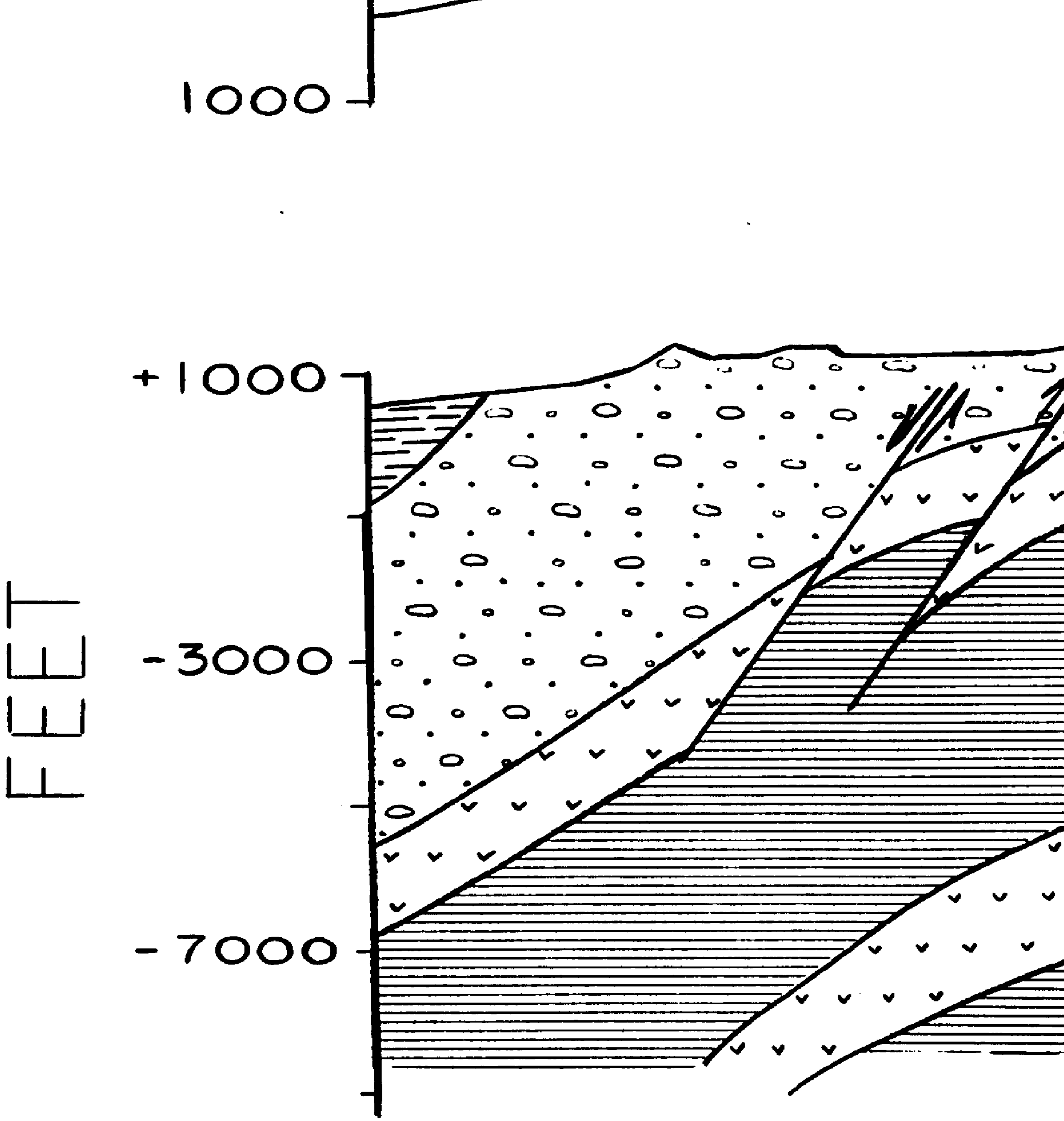


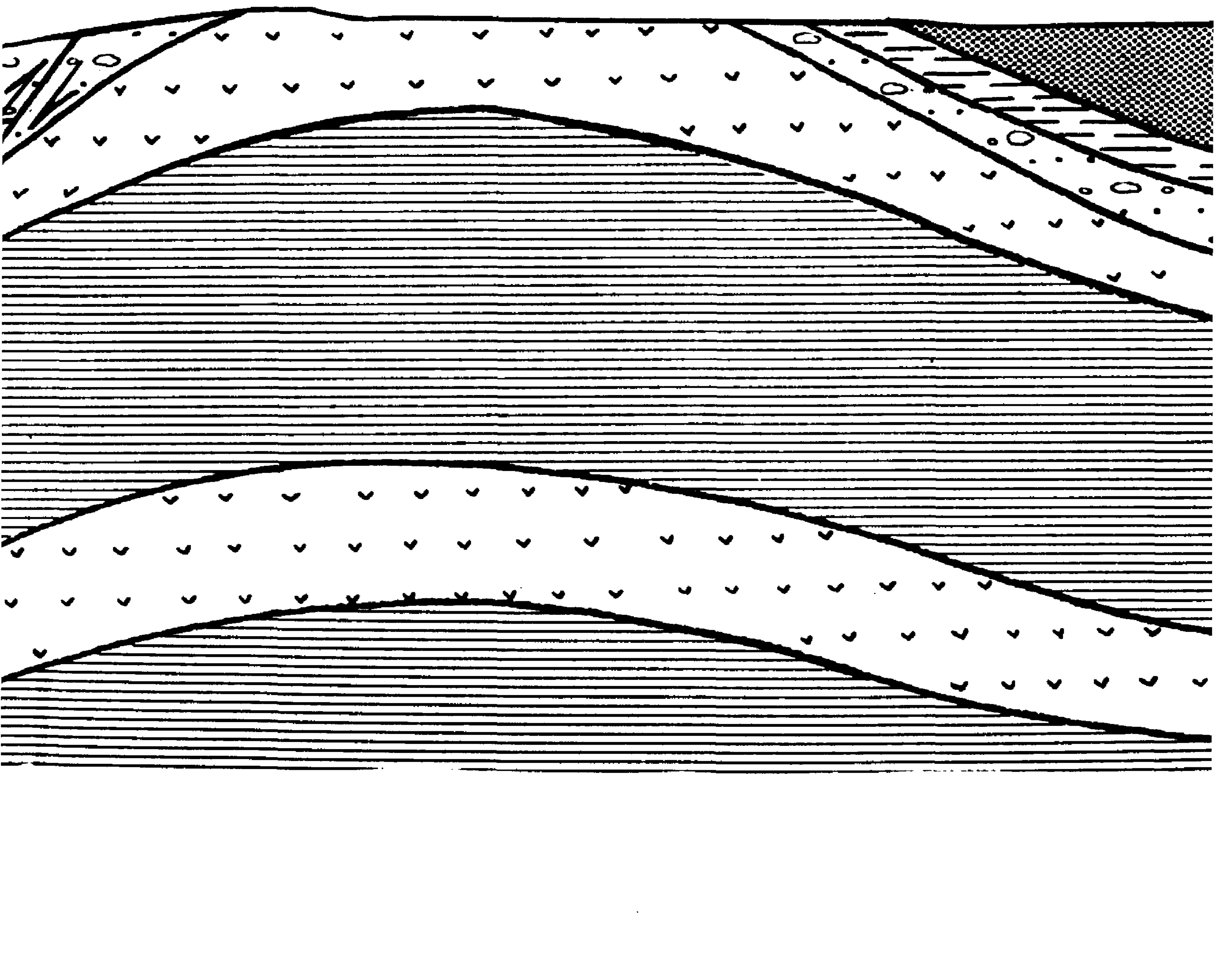
PROFILE C - C'

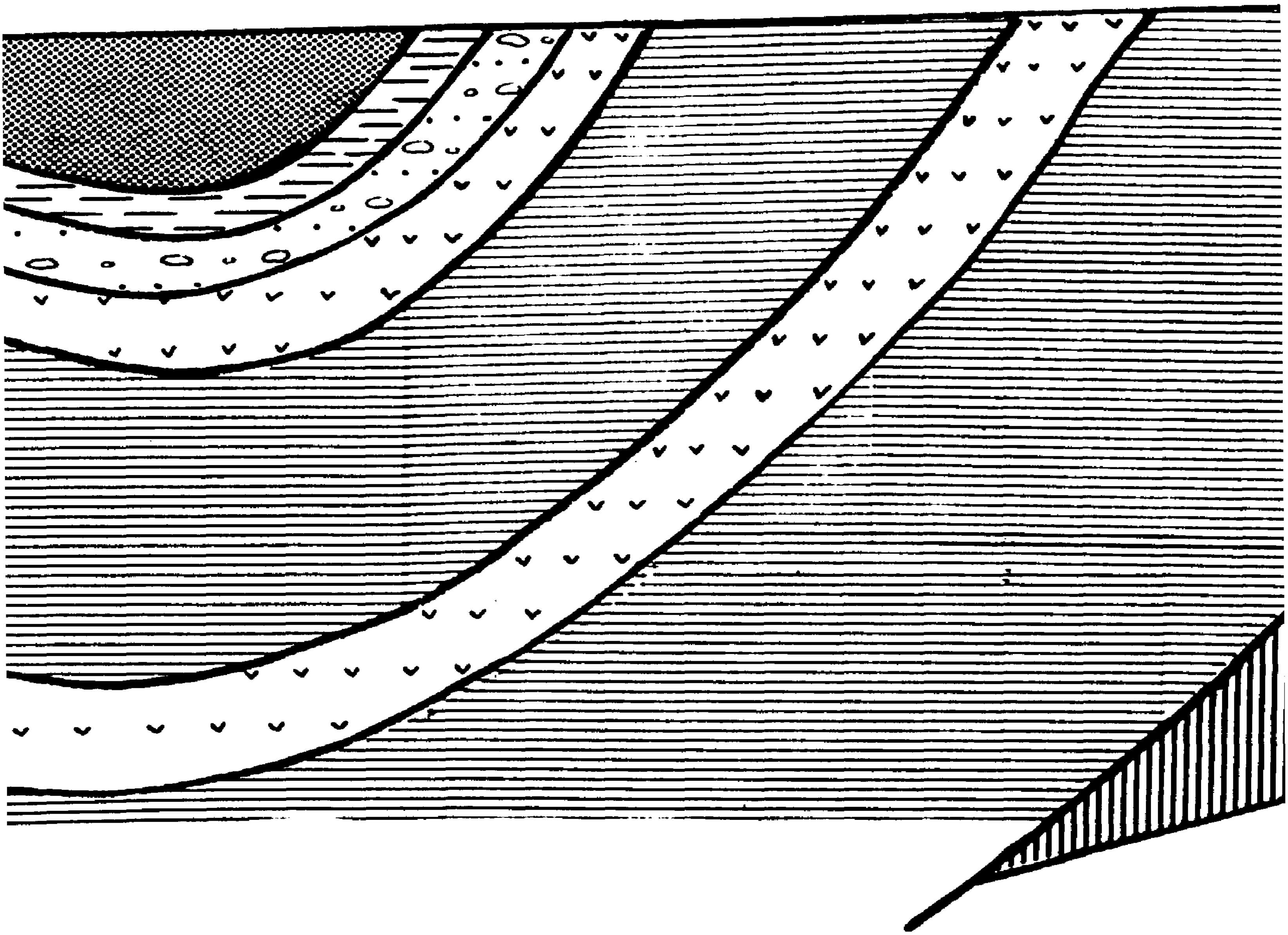


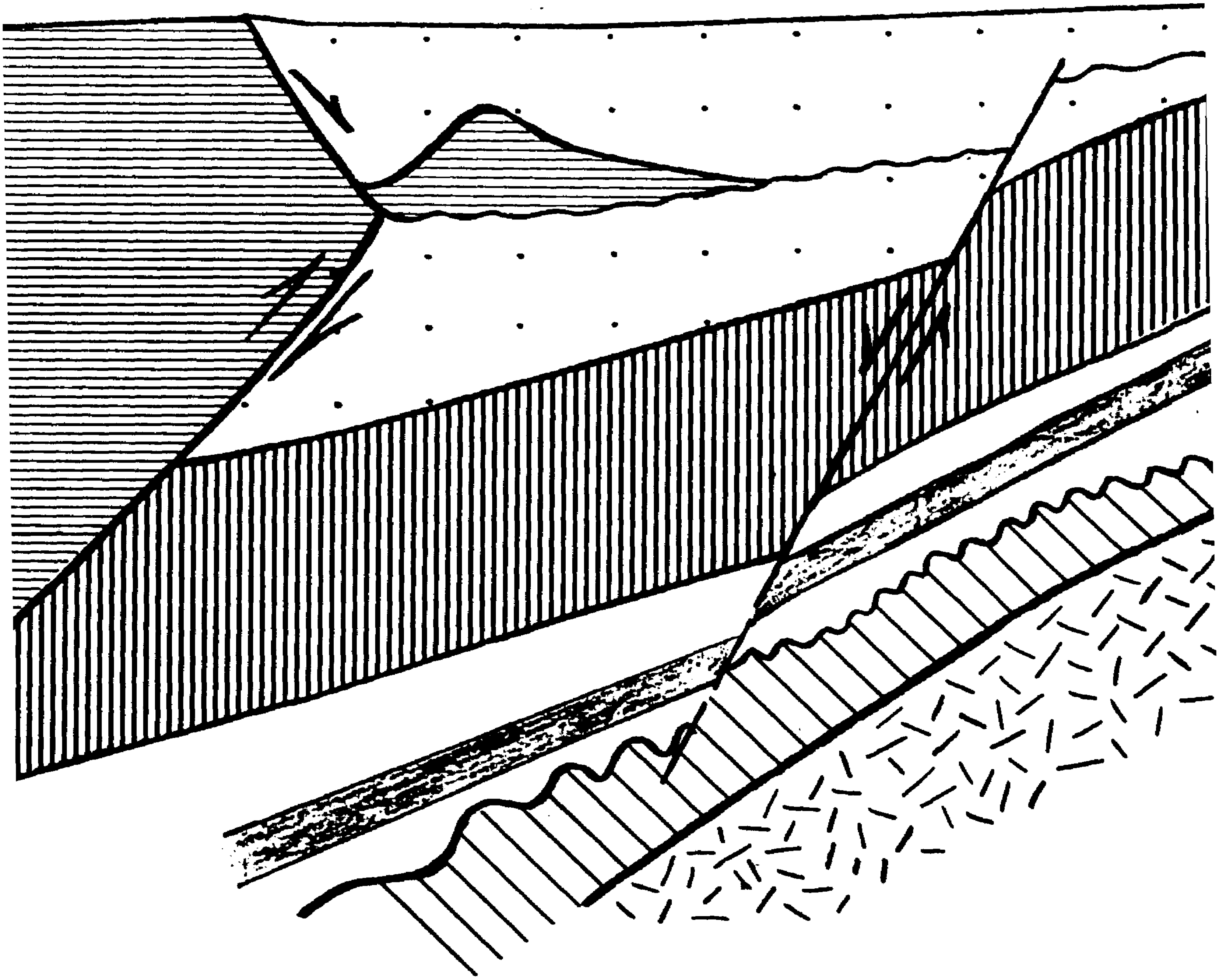


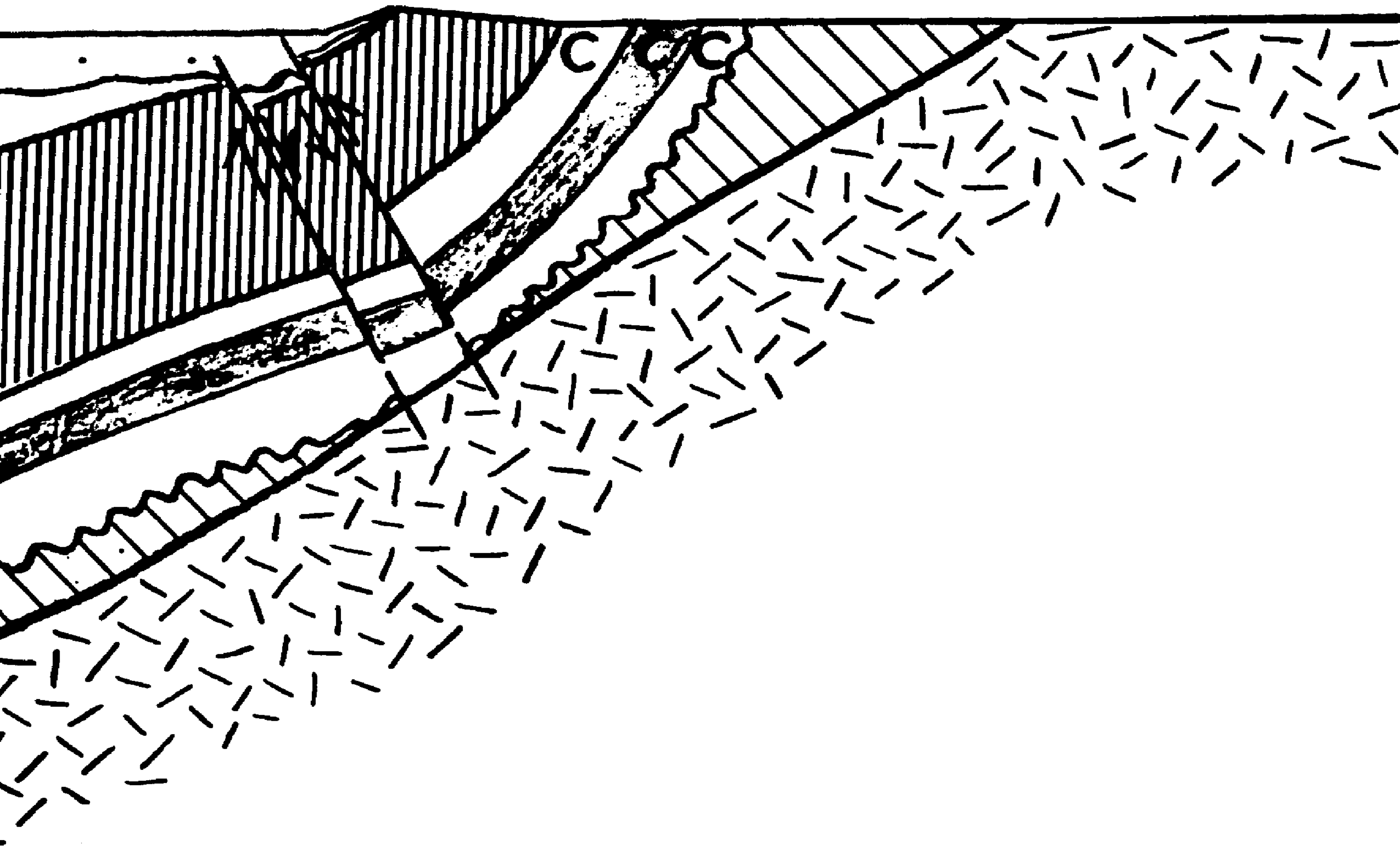
SE


1000
+1000
-3000
-7000
FEET

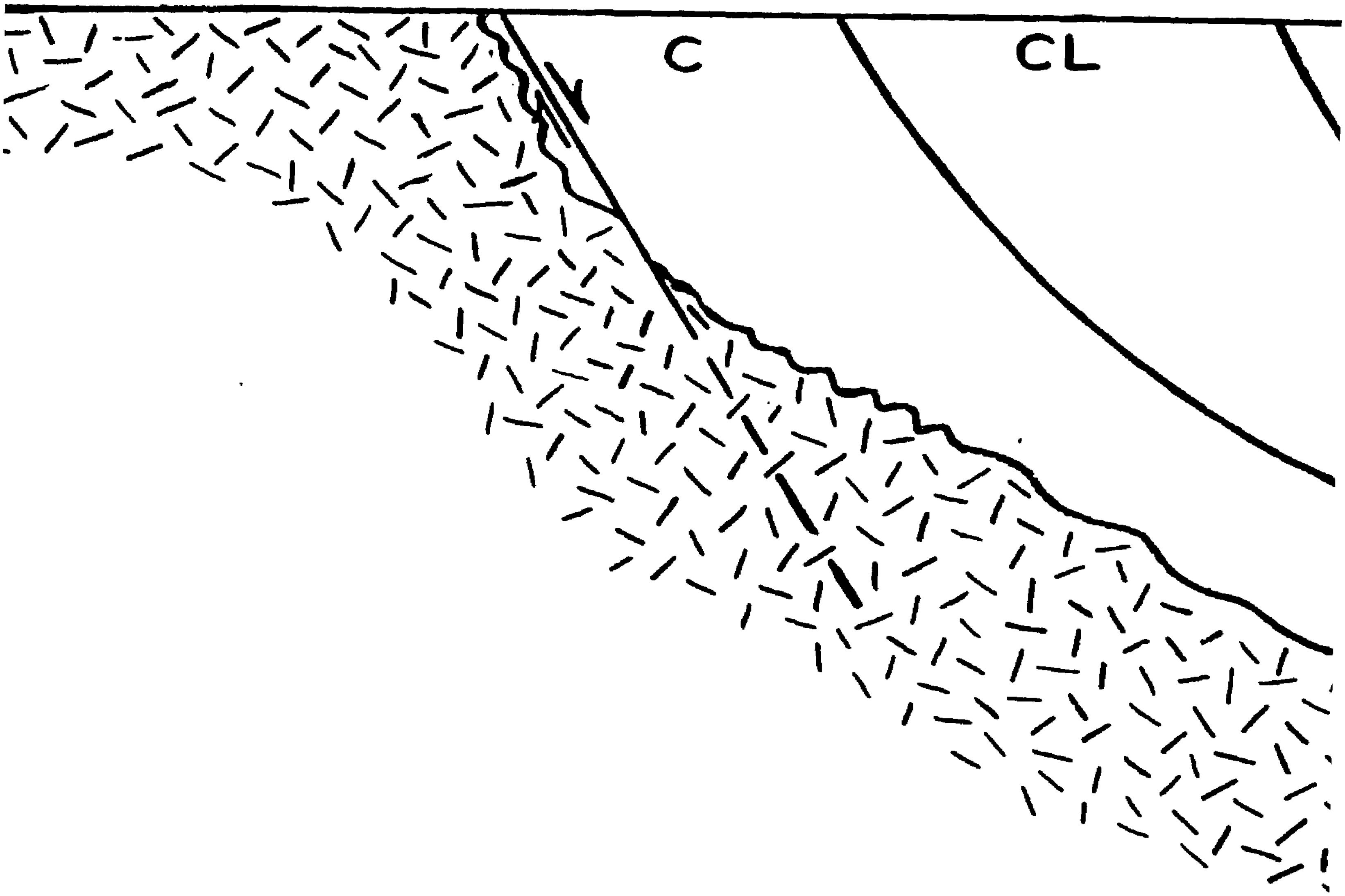


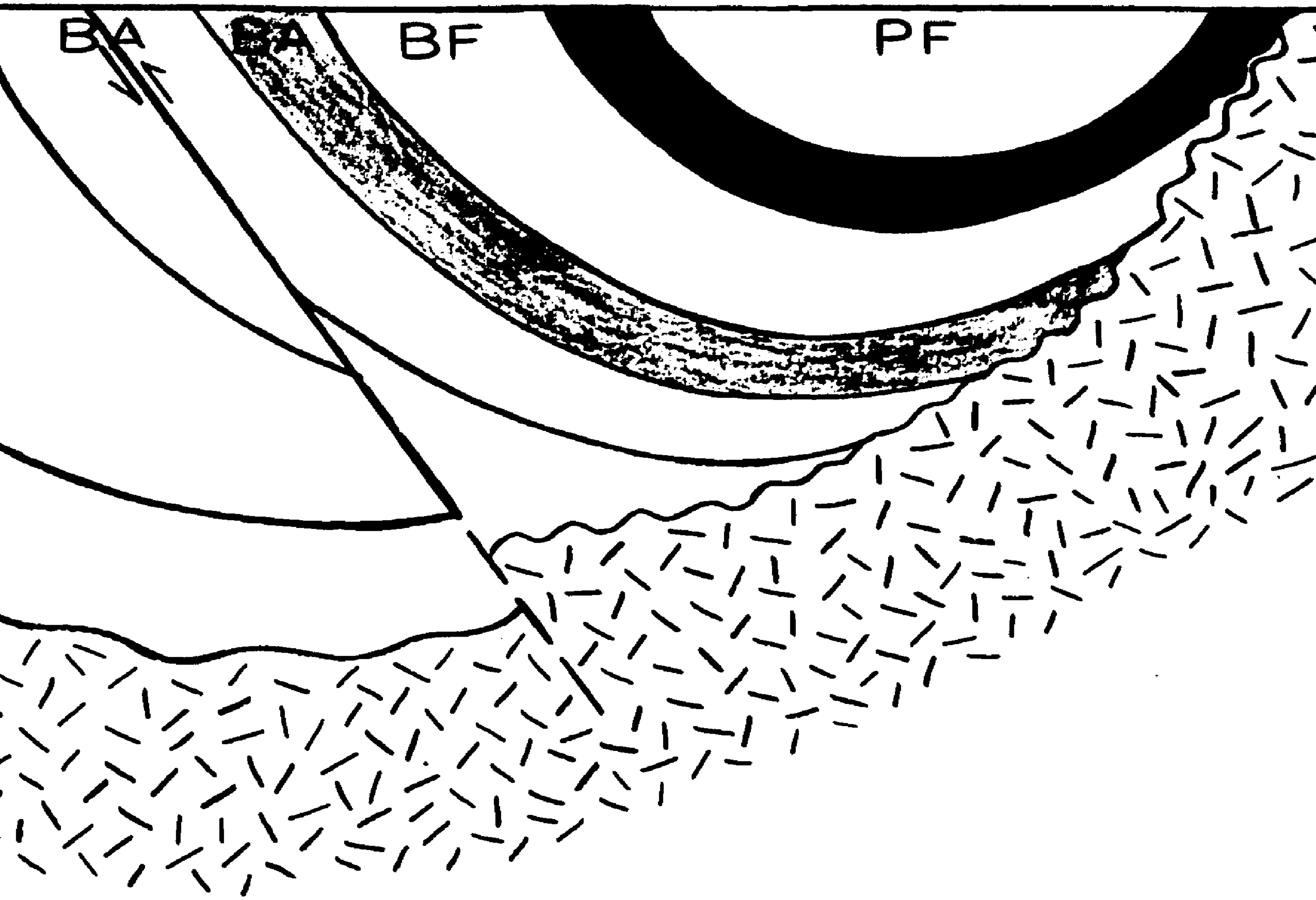


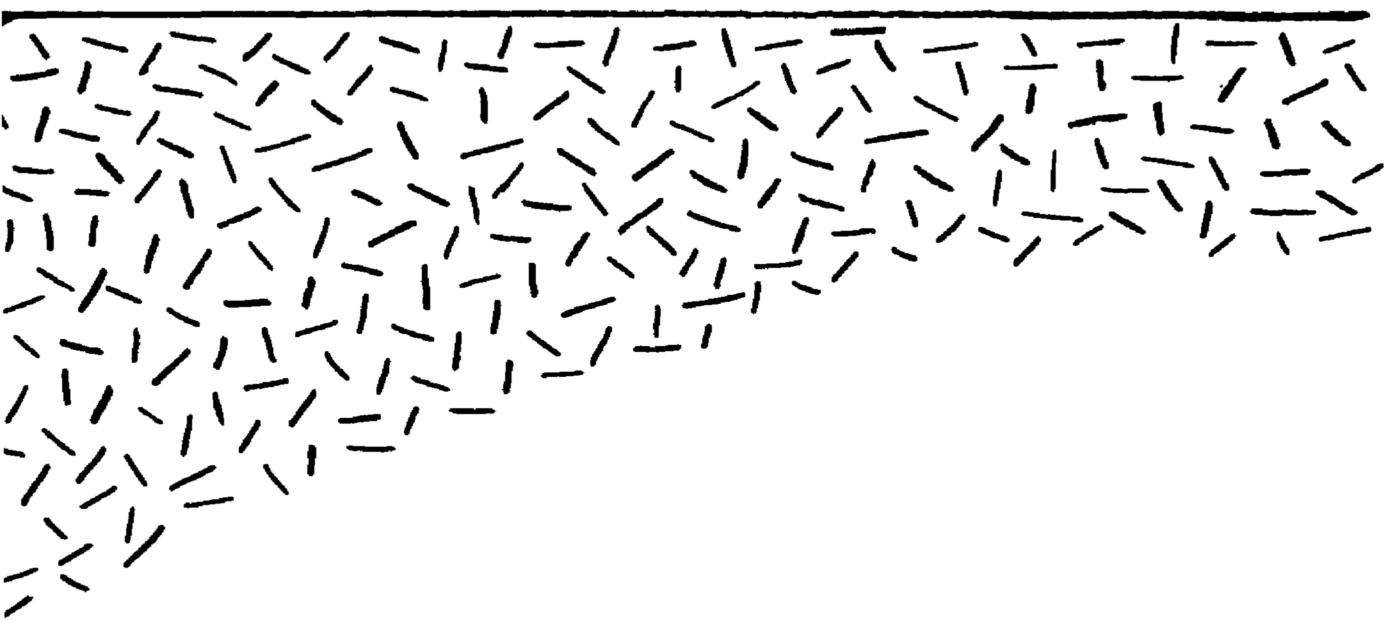


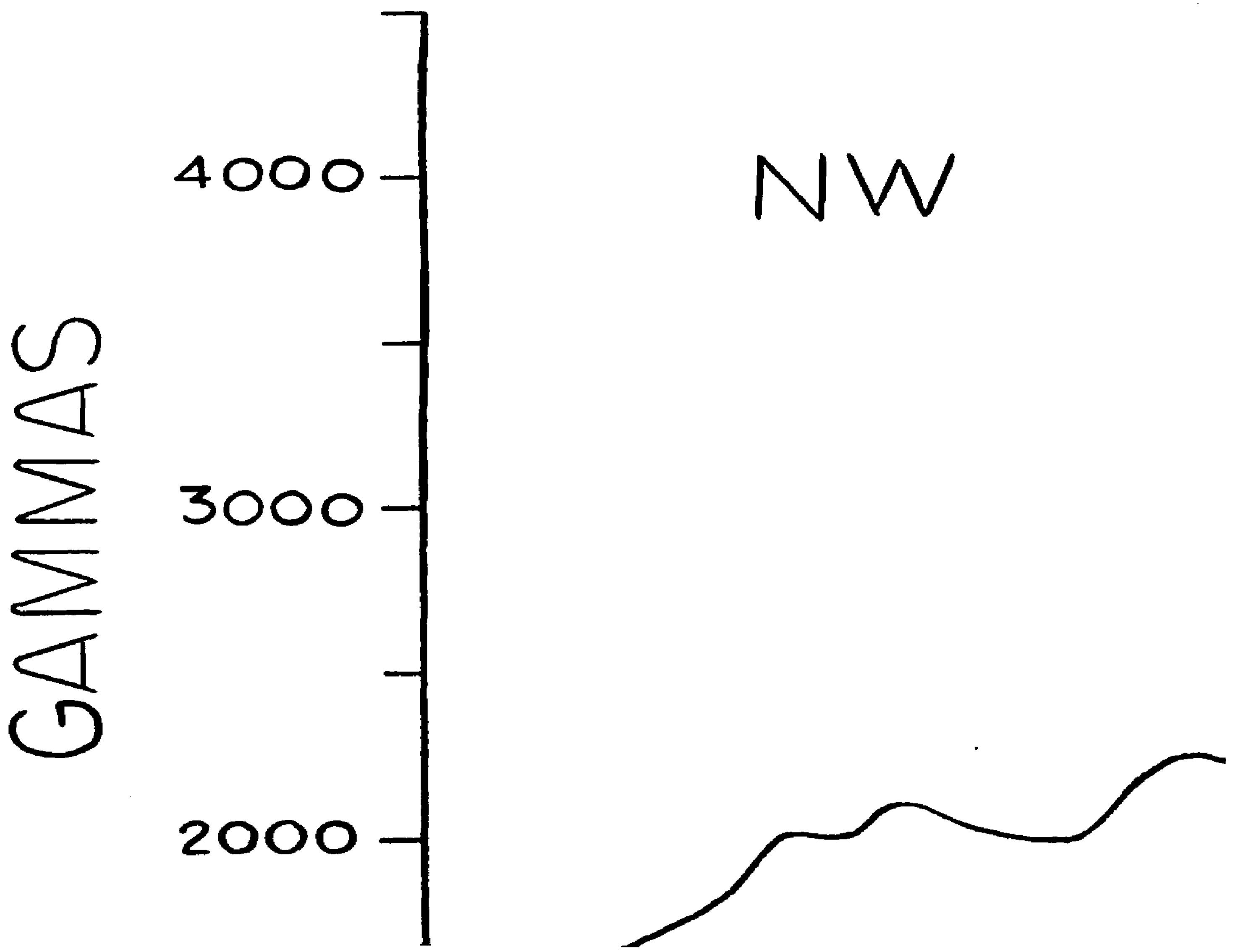


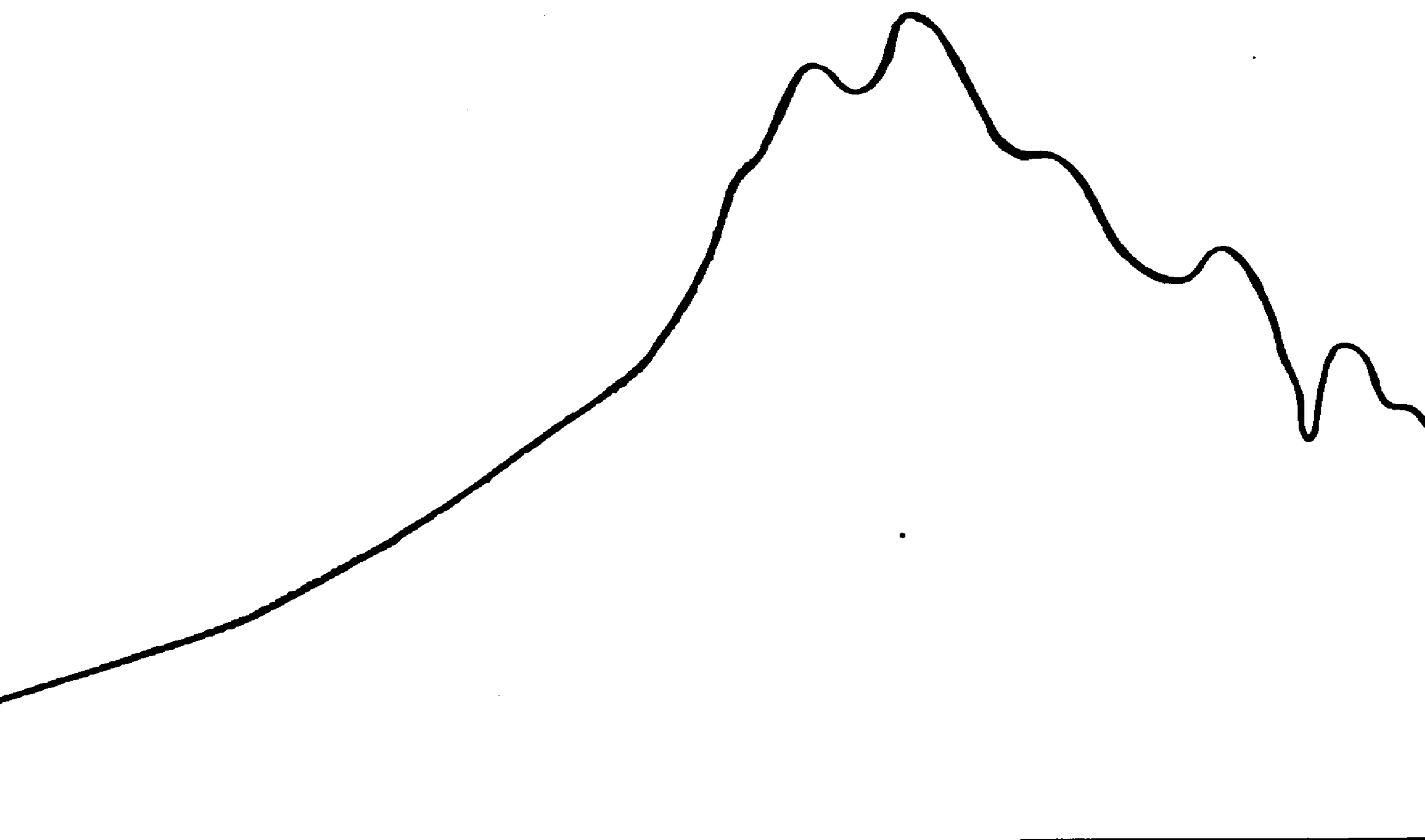
C
C
C

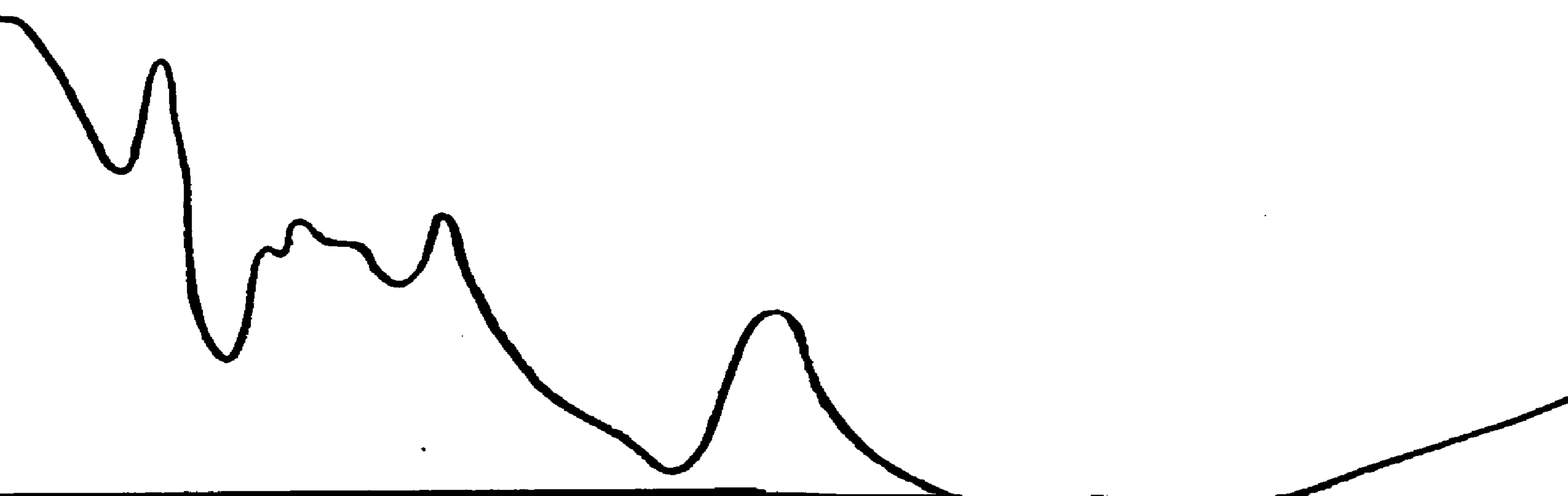

C
CL


BA
BA
BF
PF

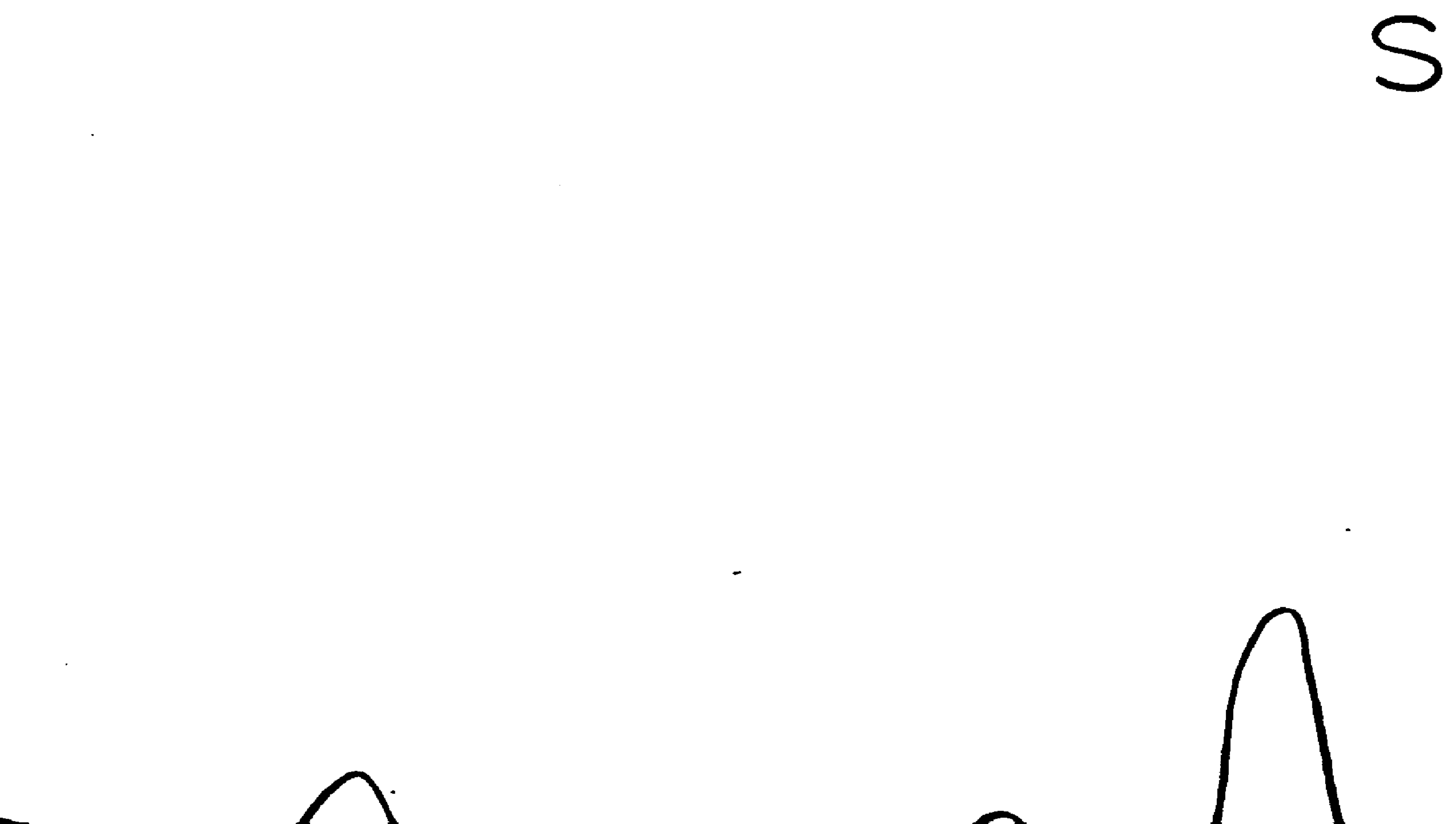



GAMMAS
4000
3000
2000
NW





PROFILE D – D′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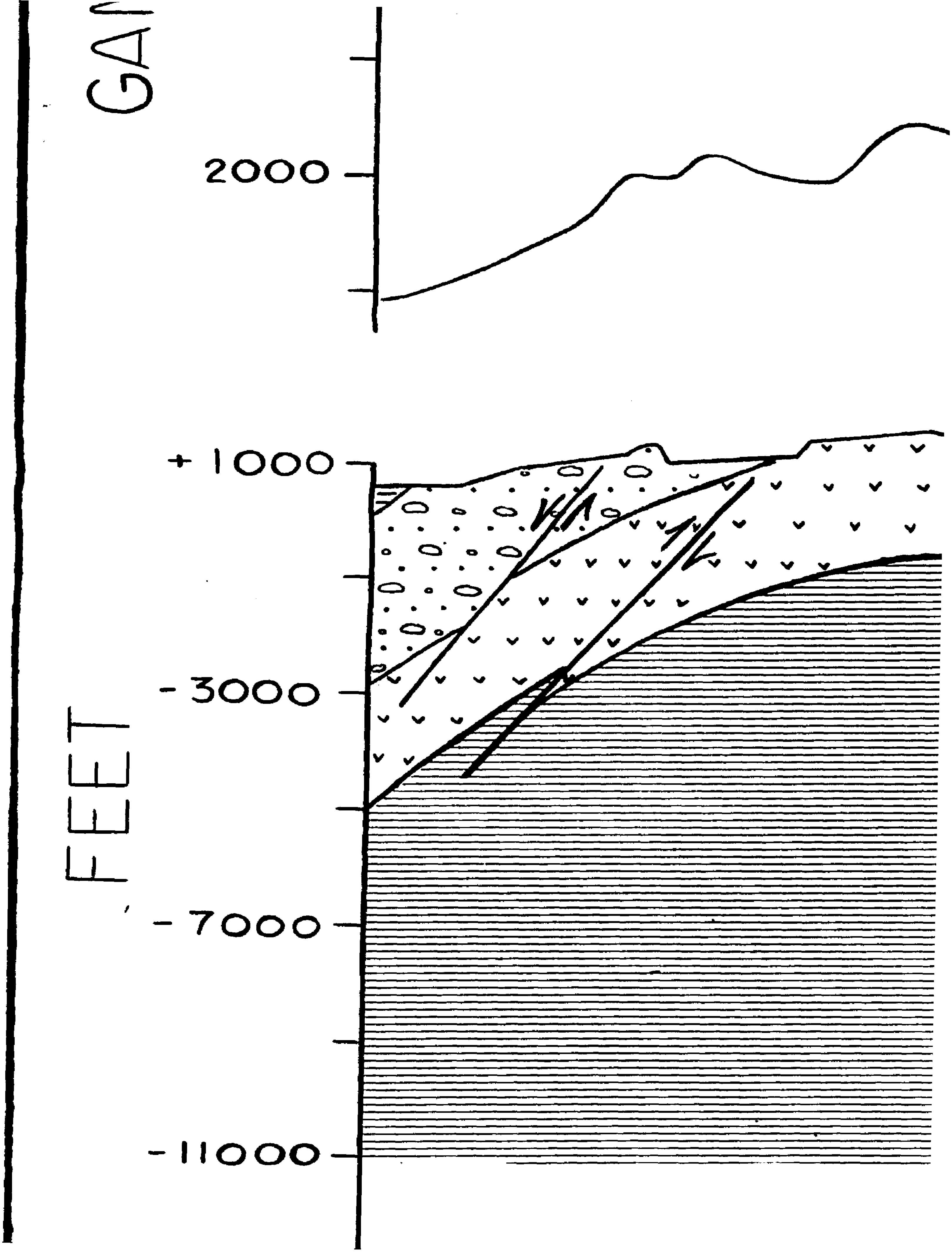
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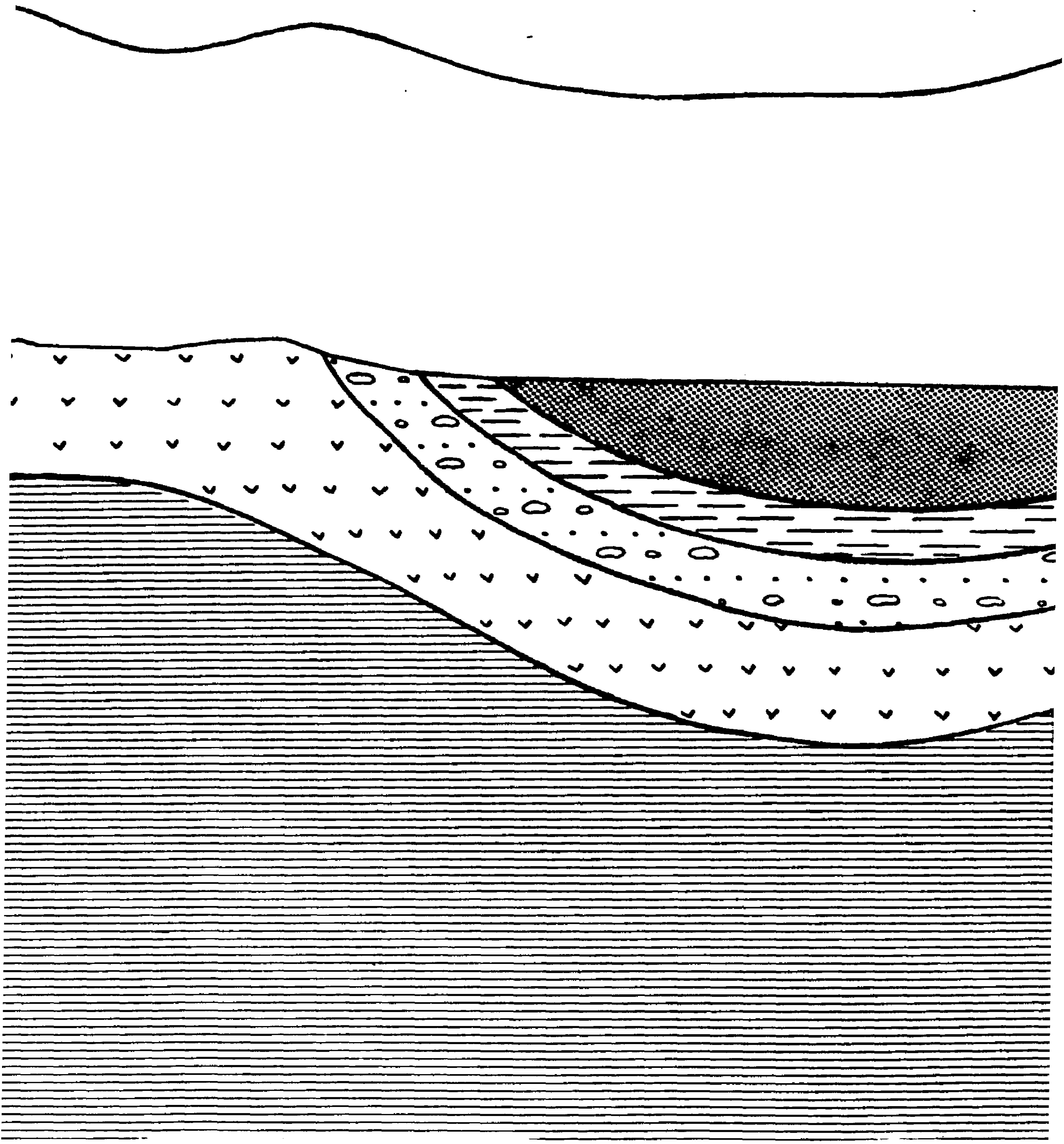
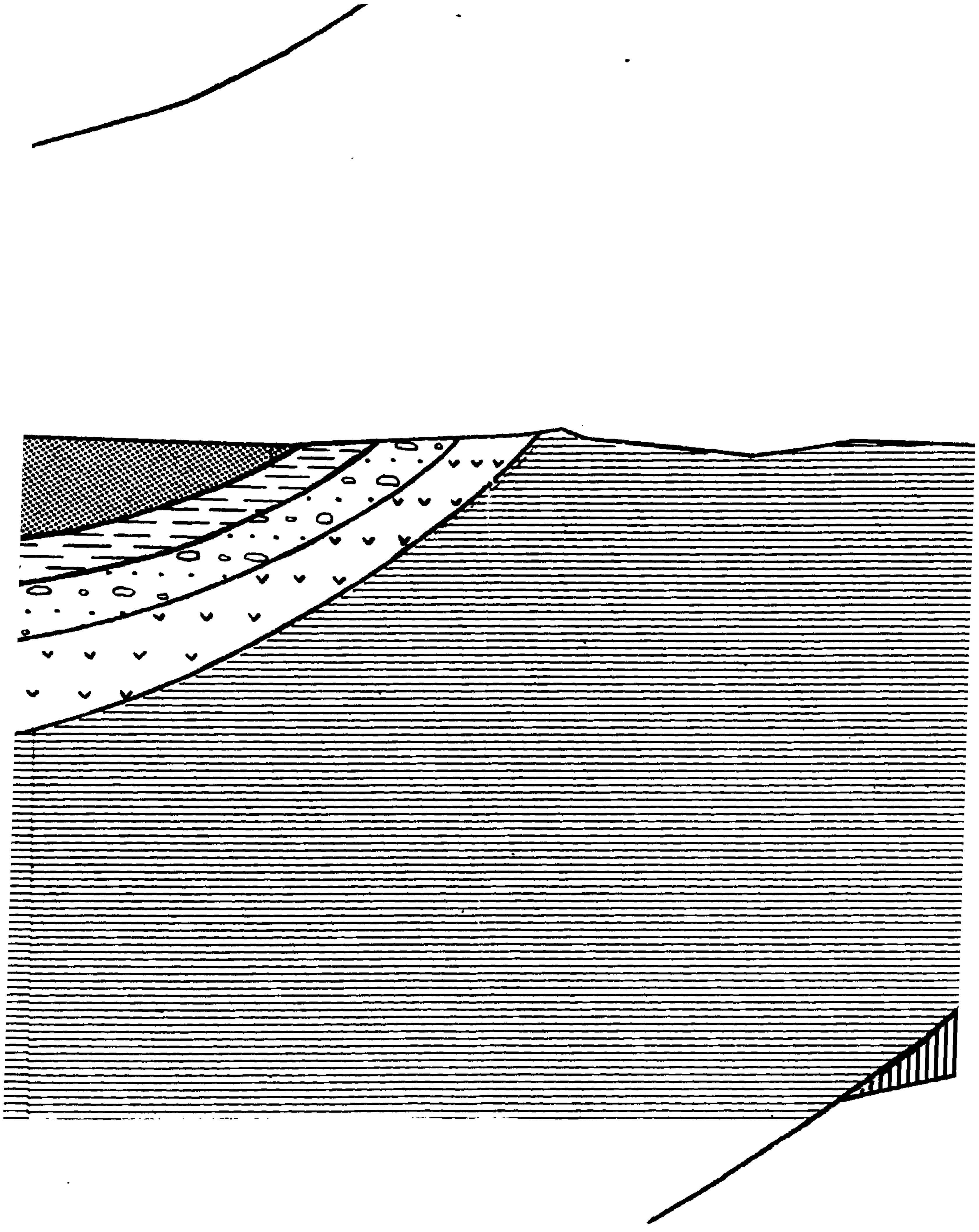
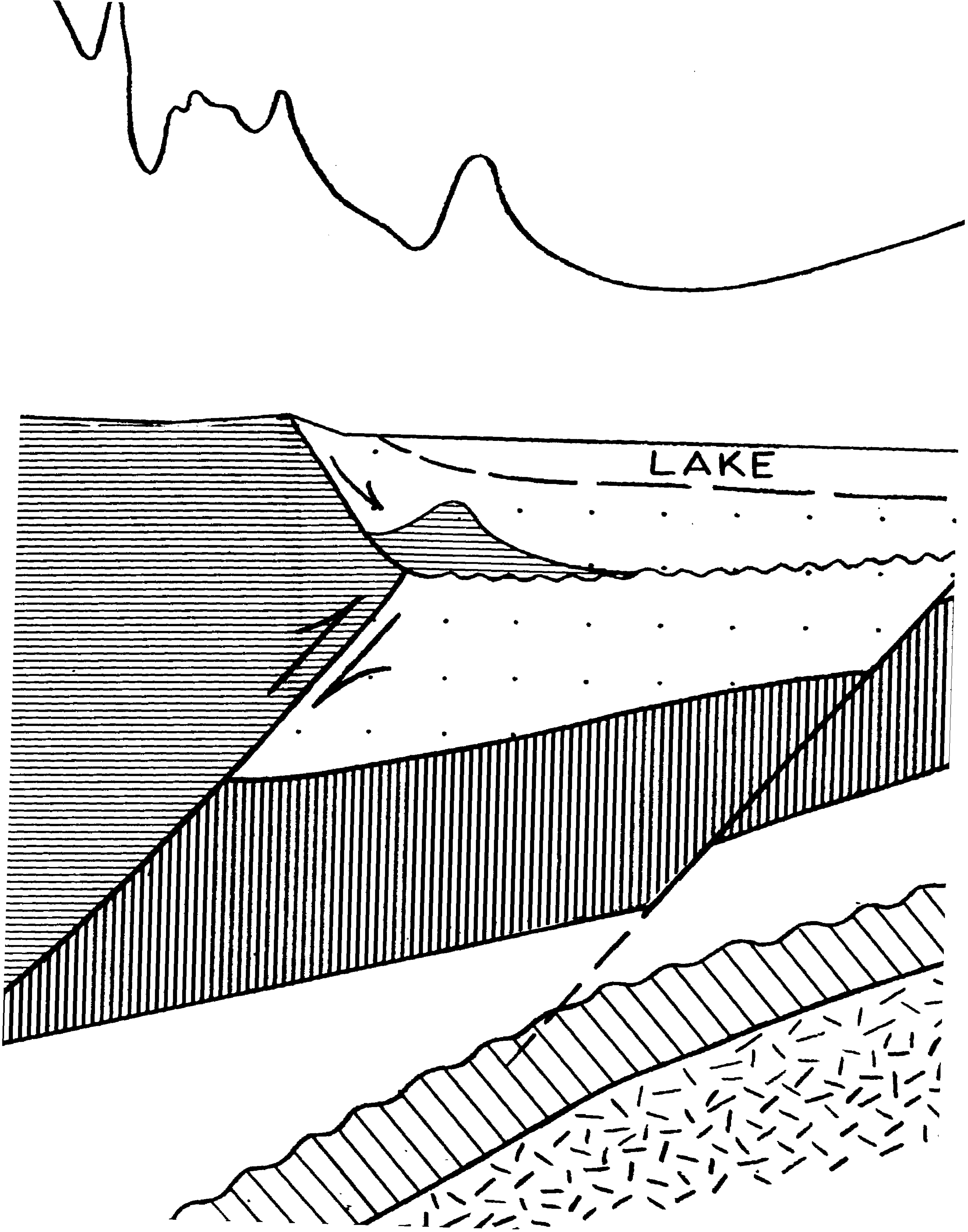
FEET
- 7000
- 11000



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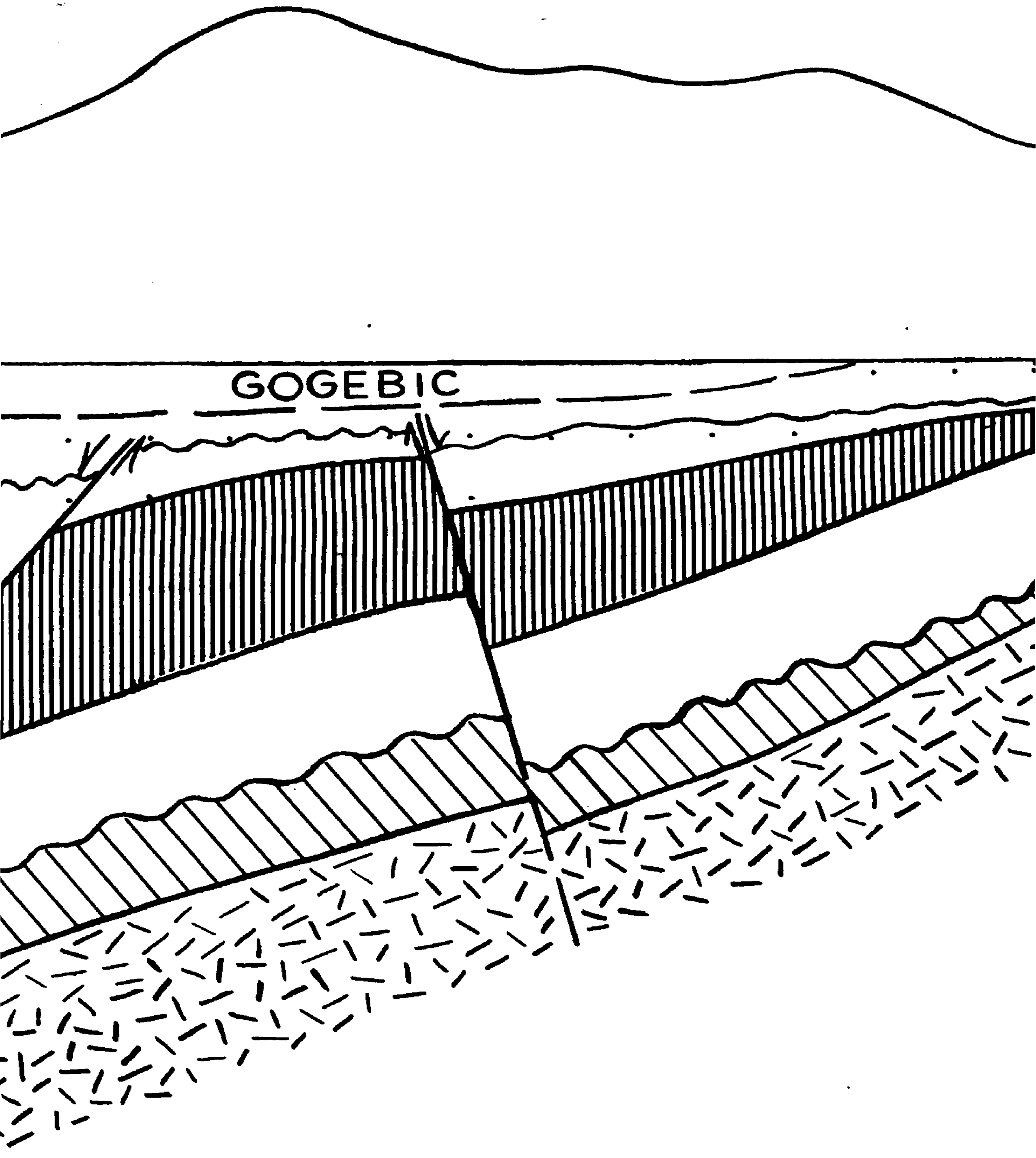
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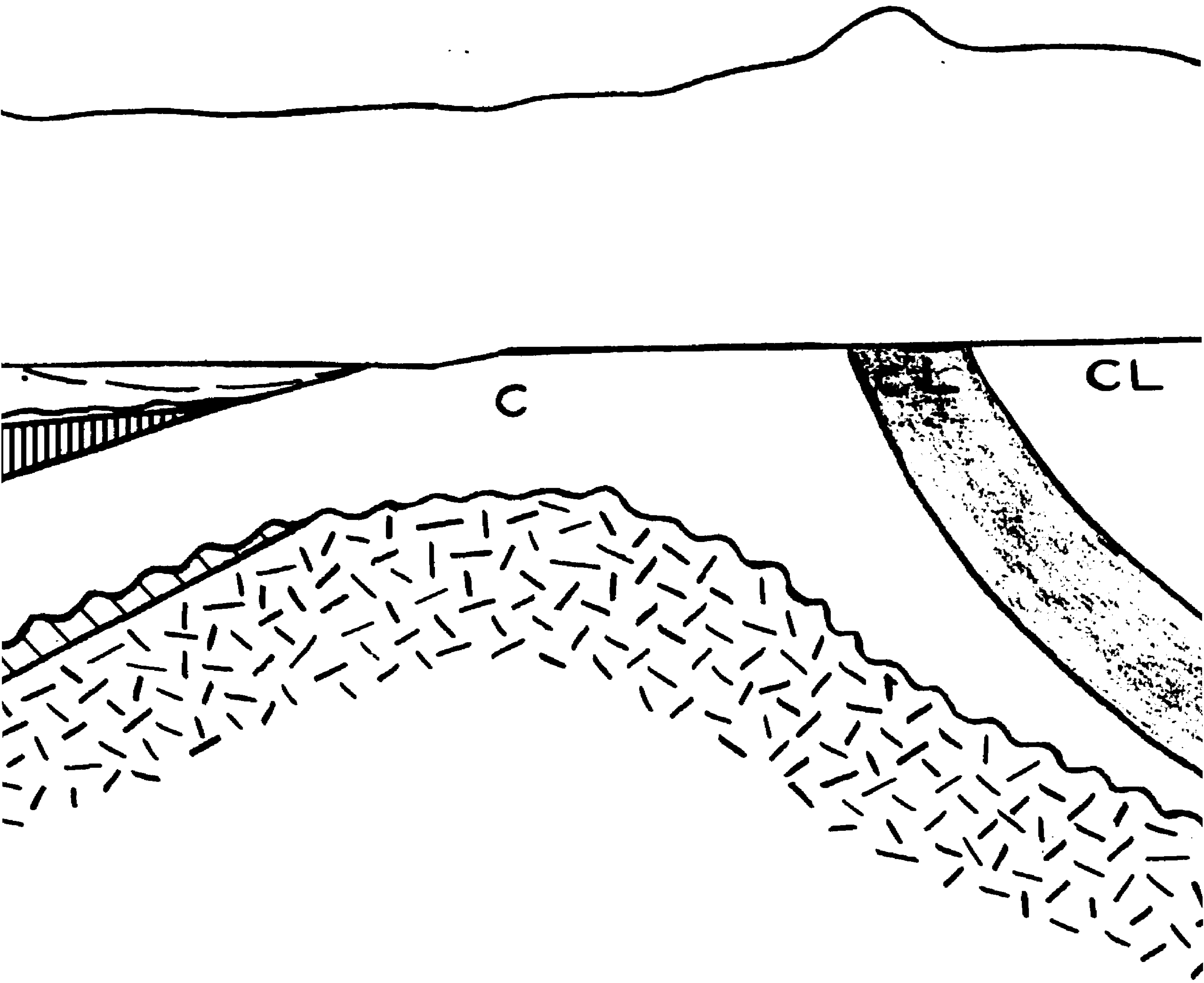
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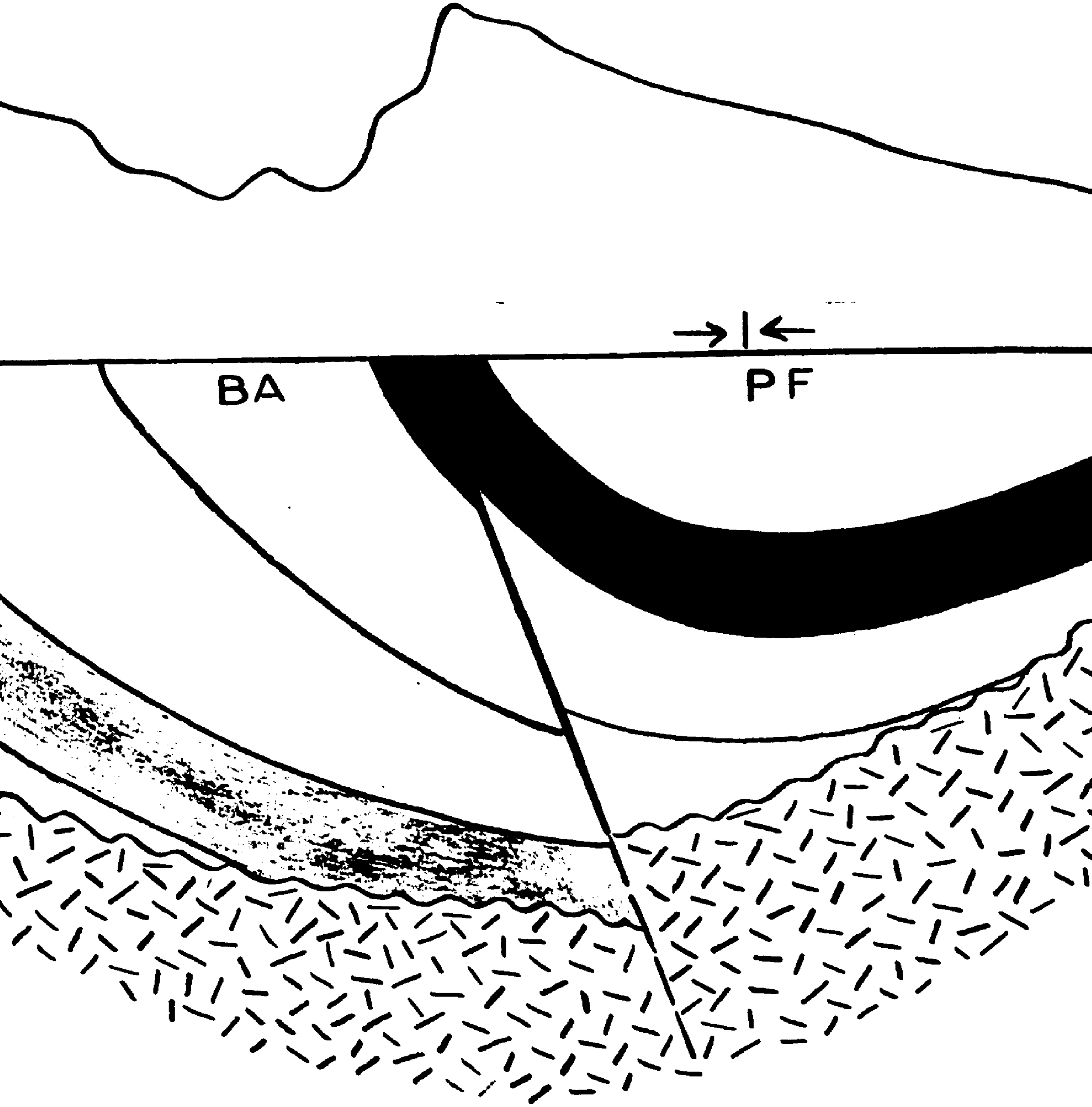
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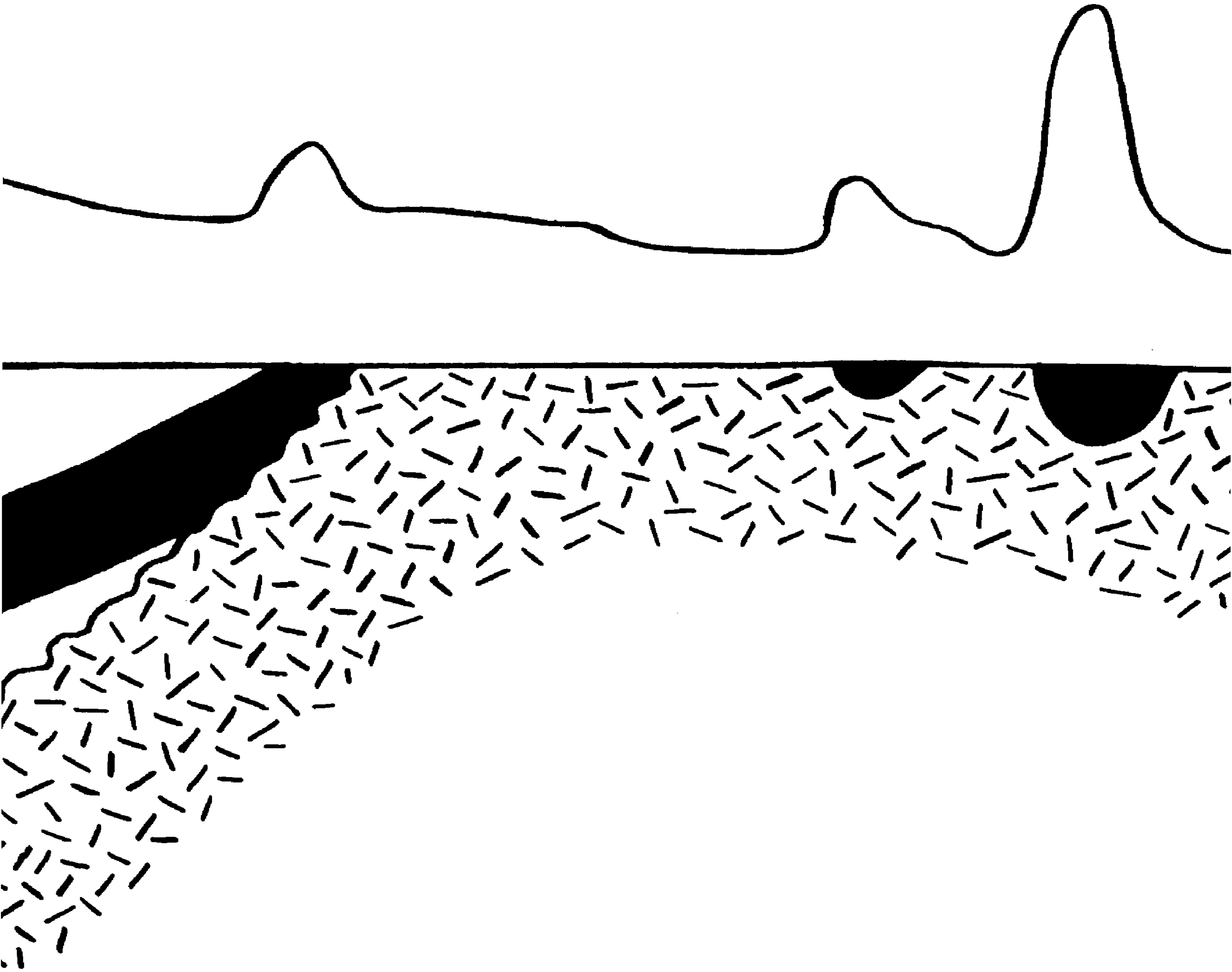

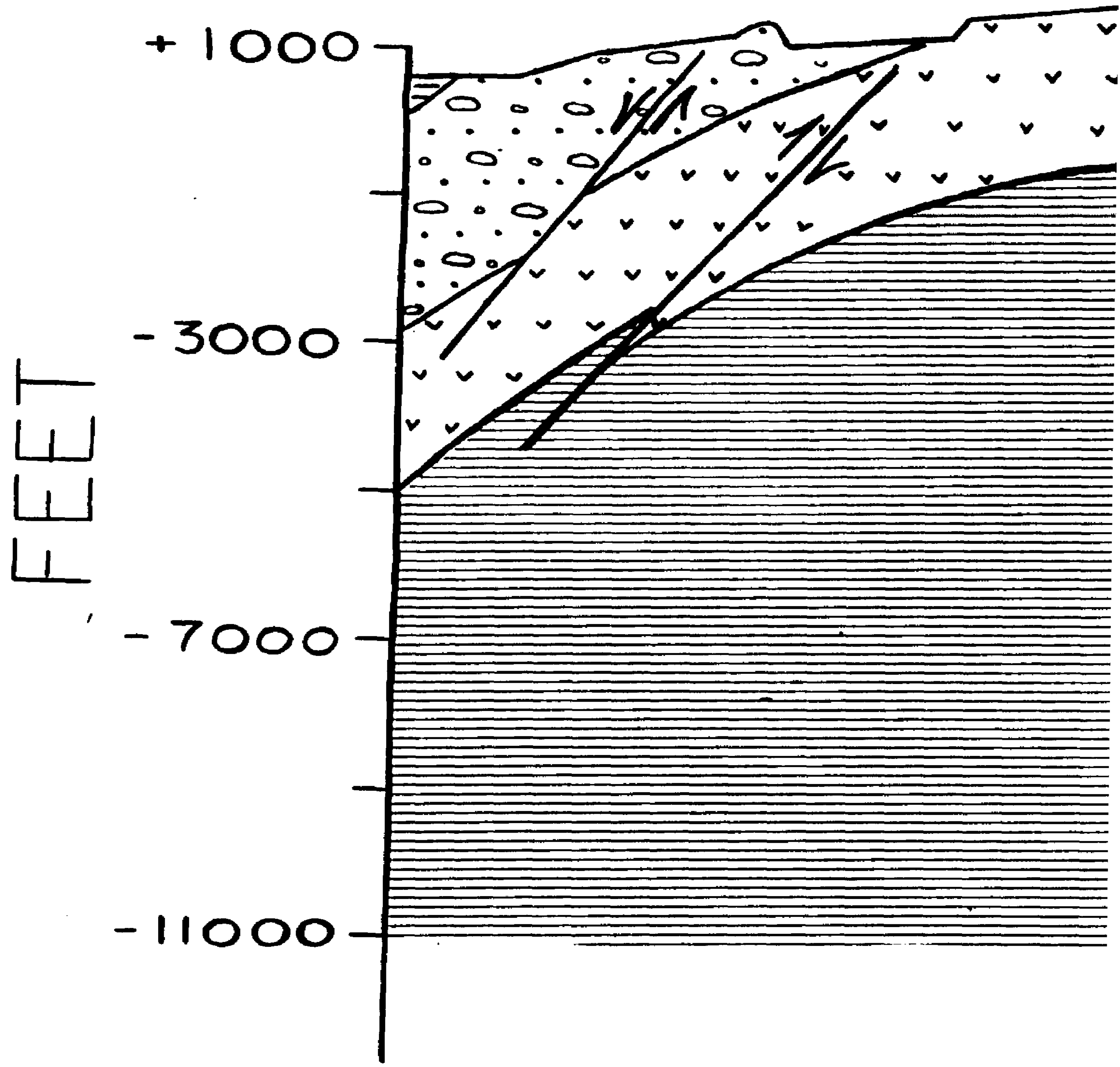

FEET
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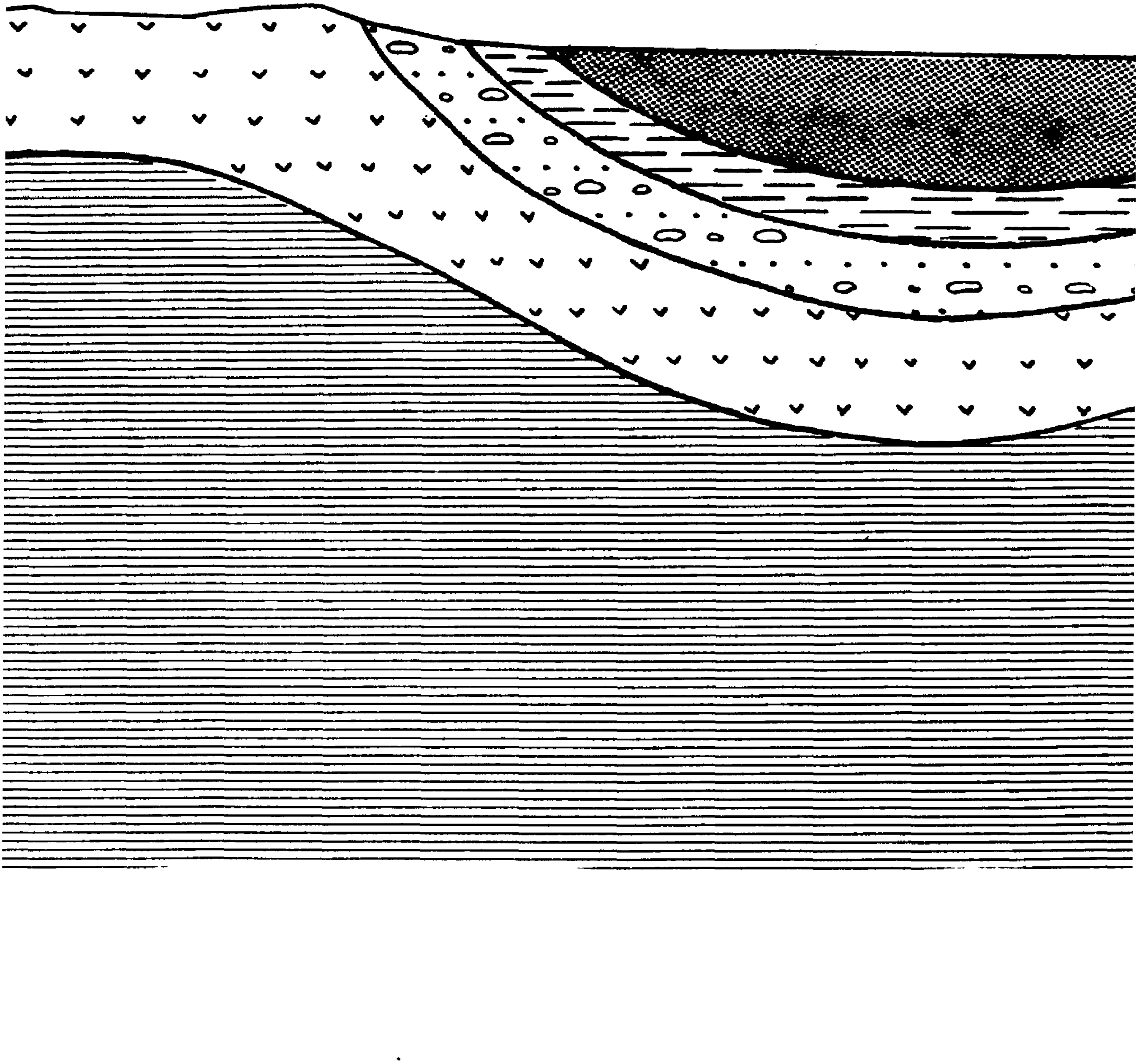

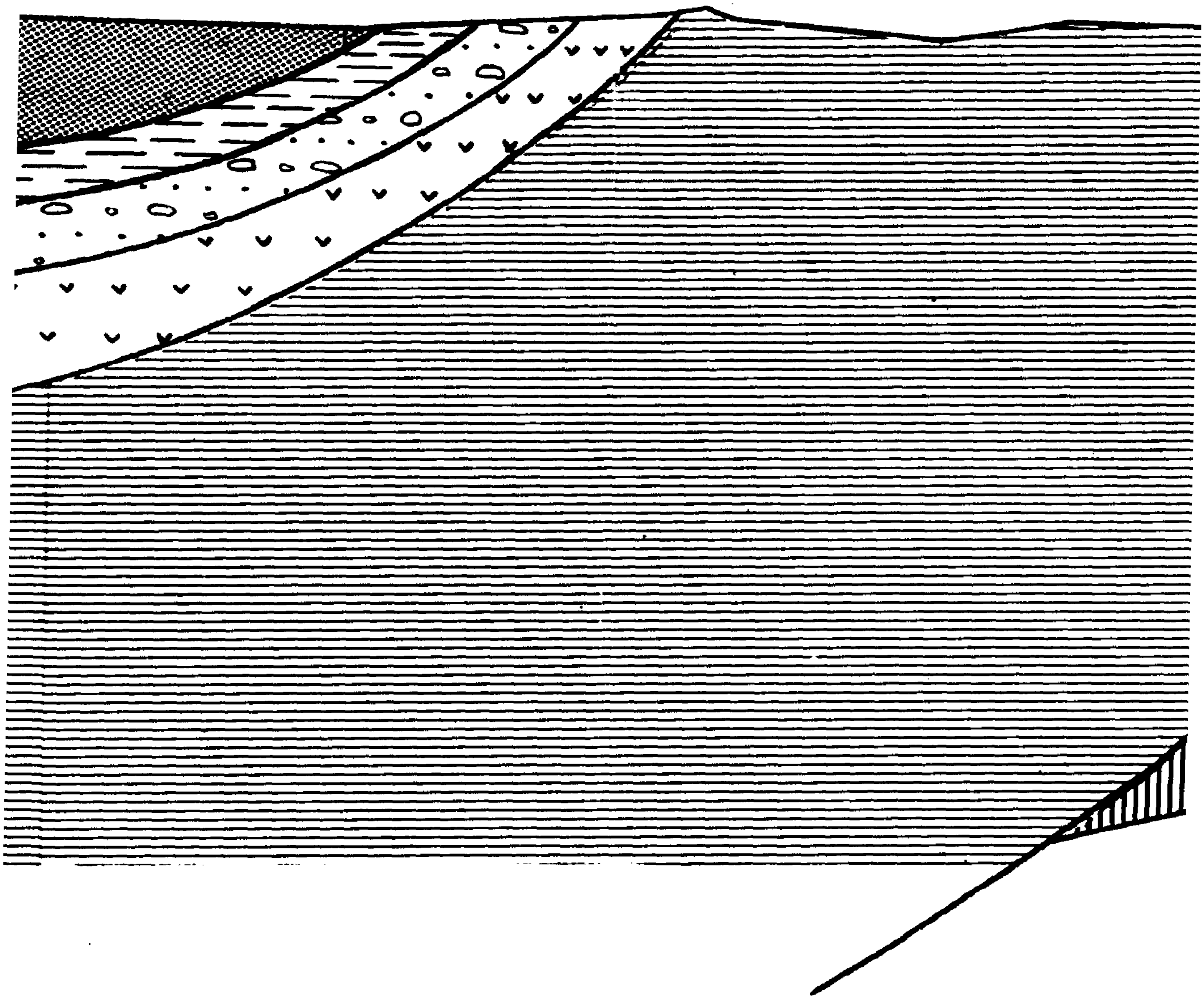

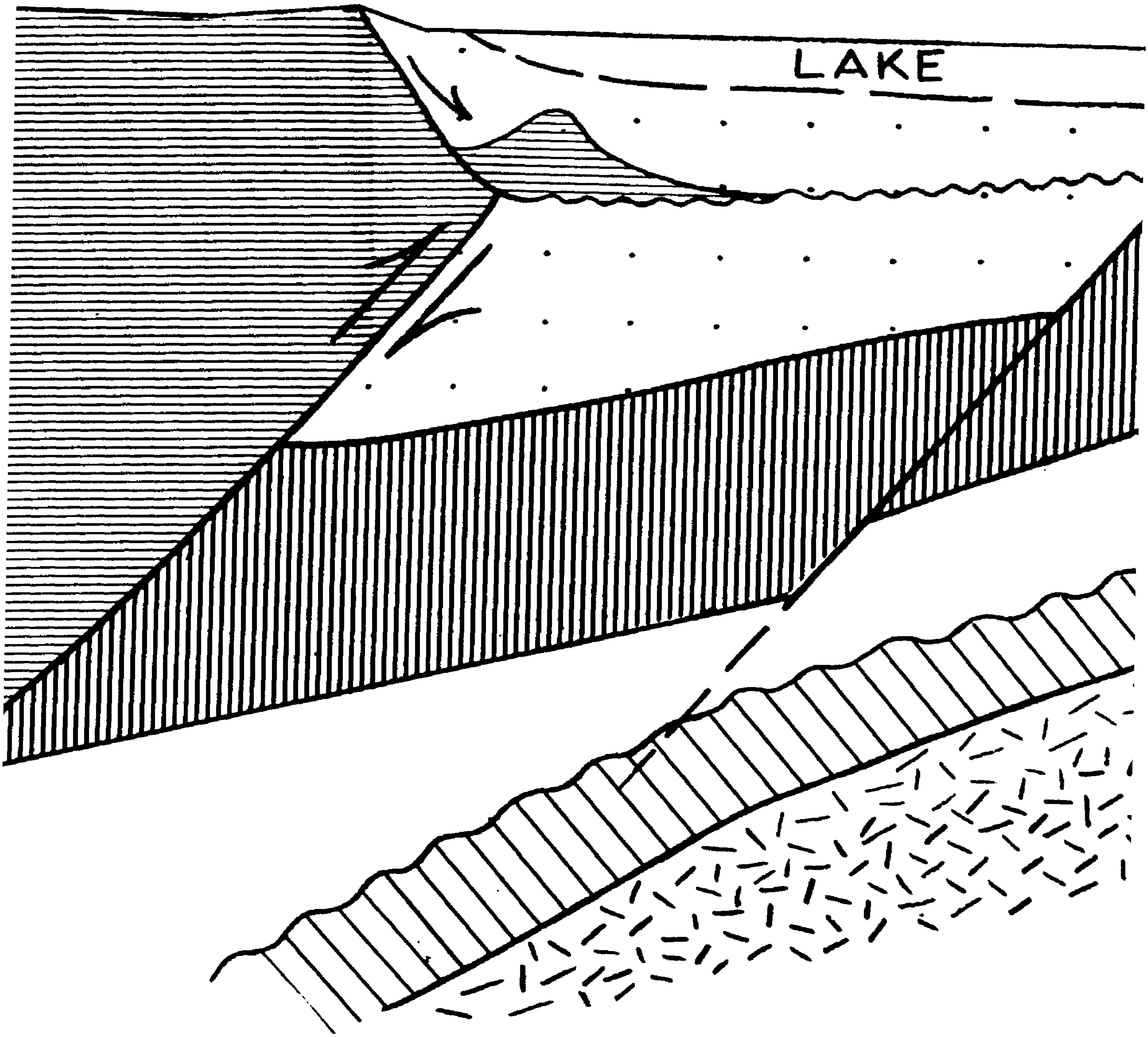
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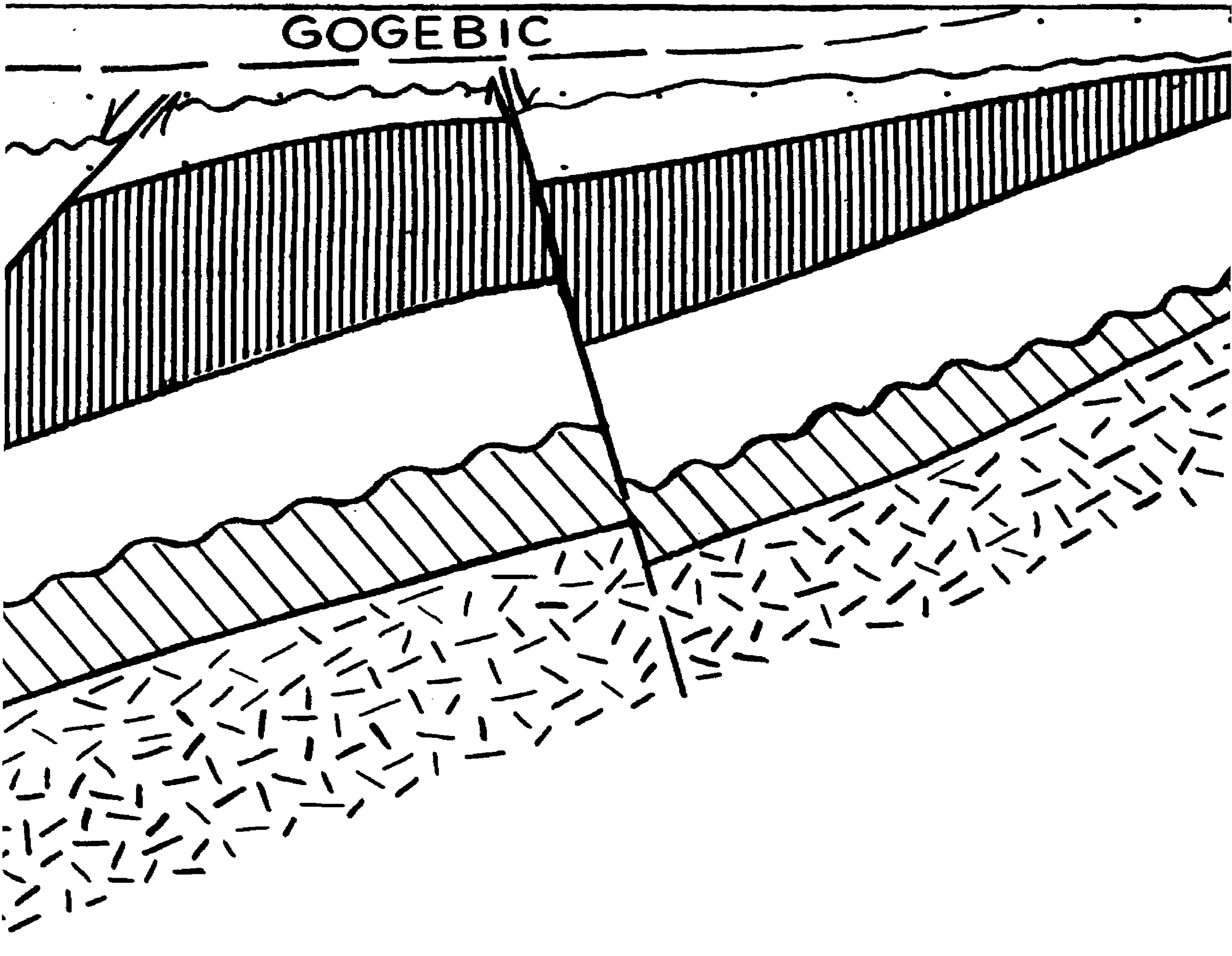
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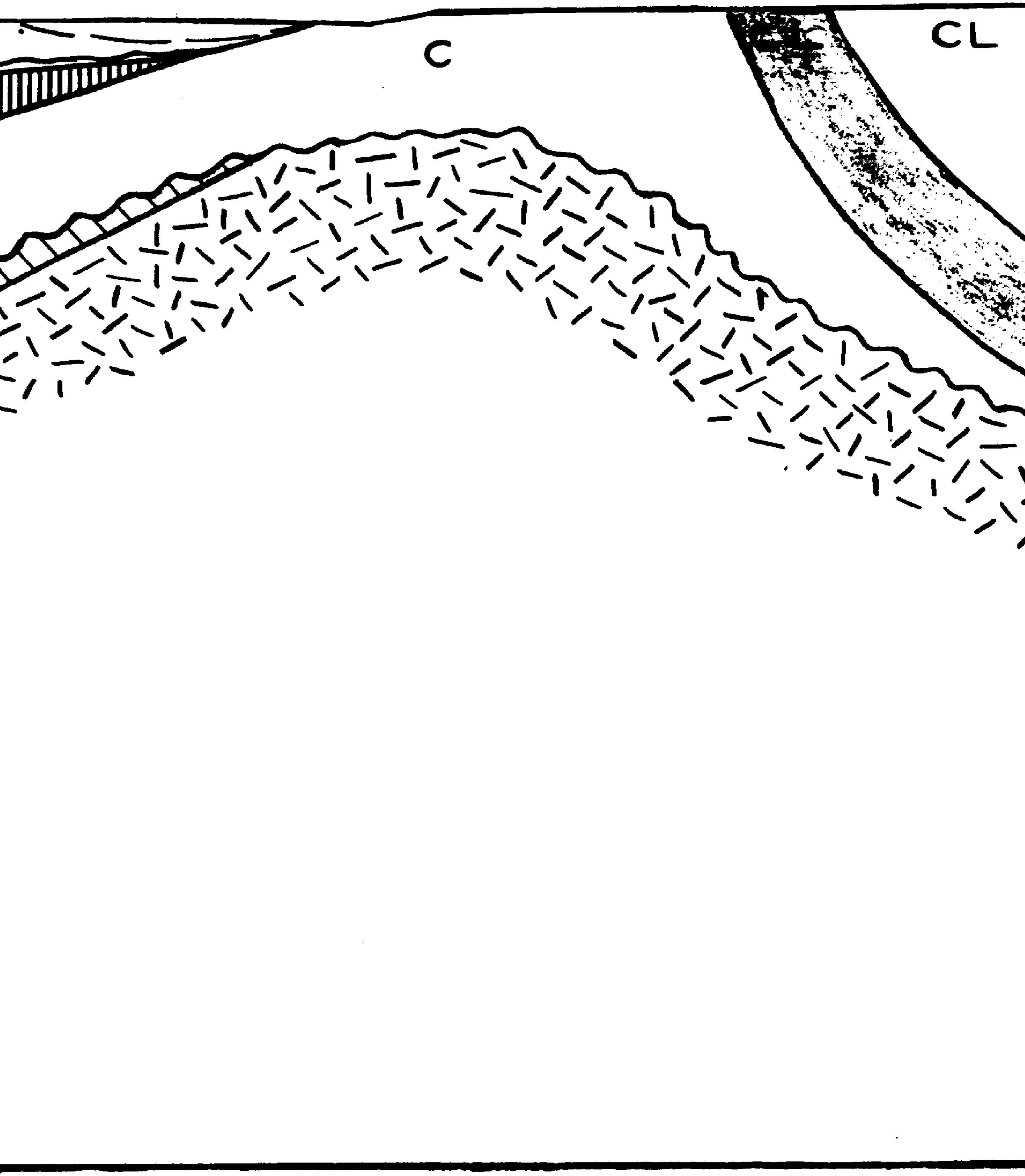
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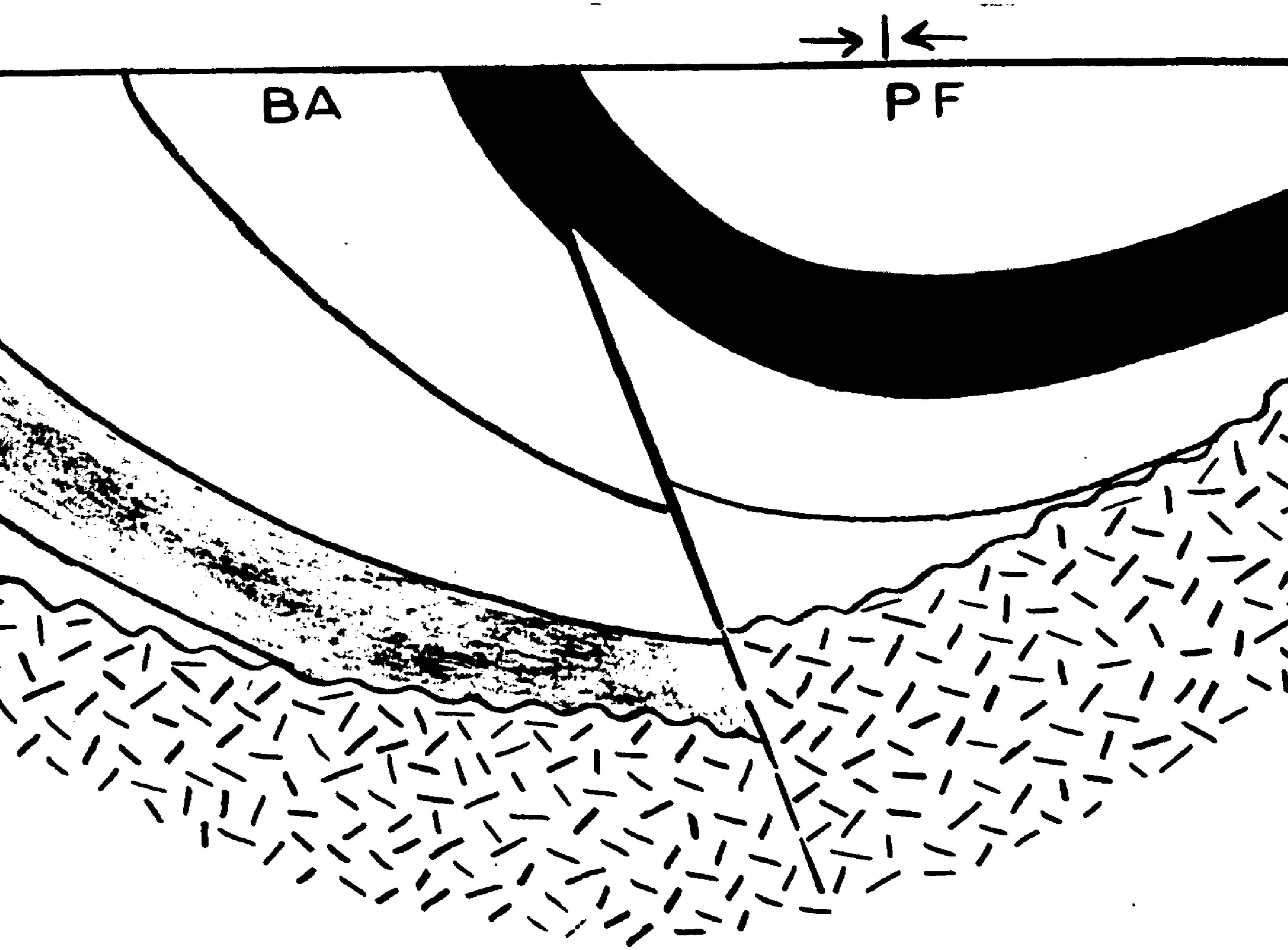
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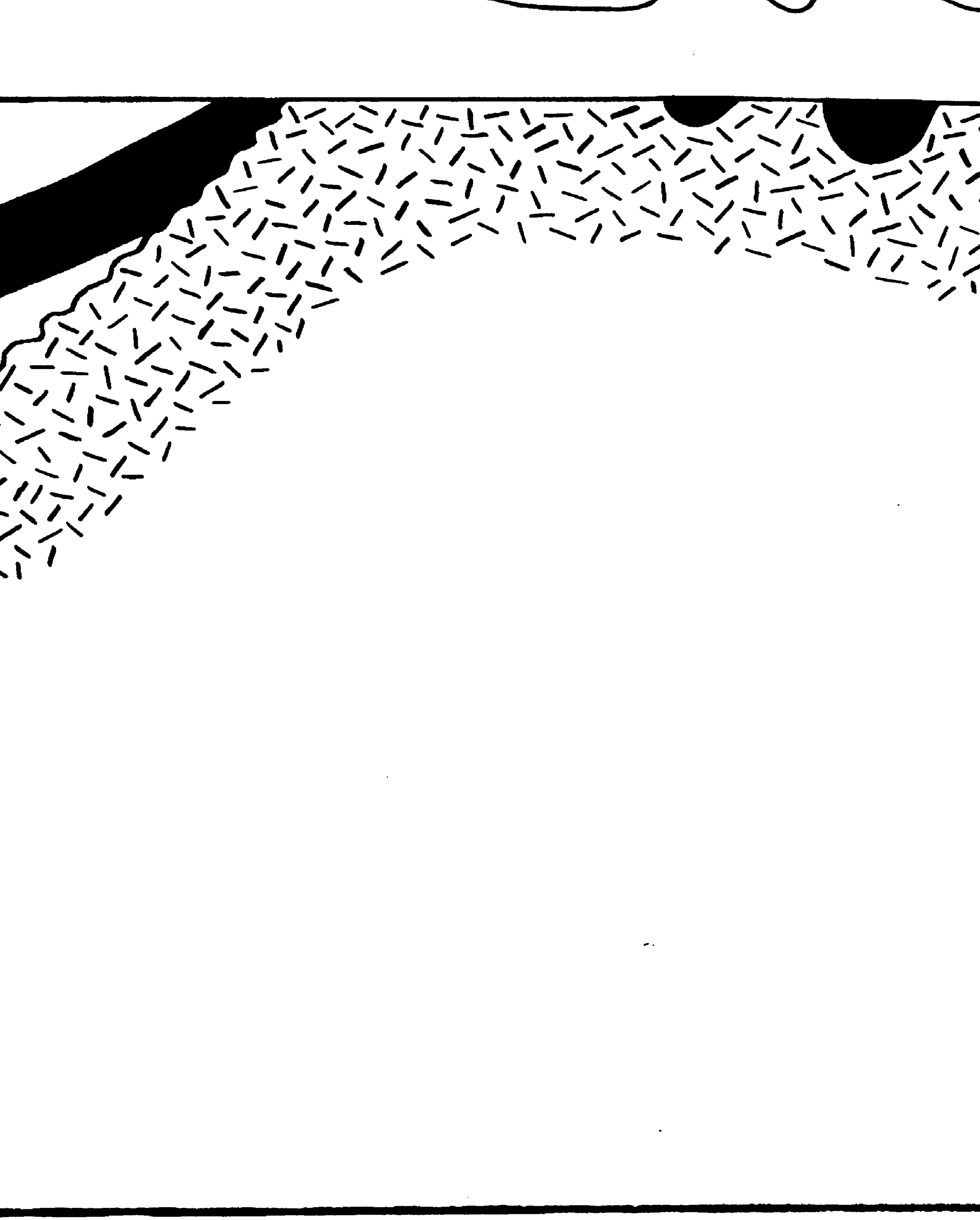

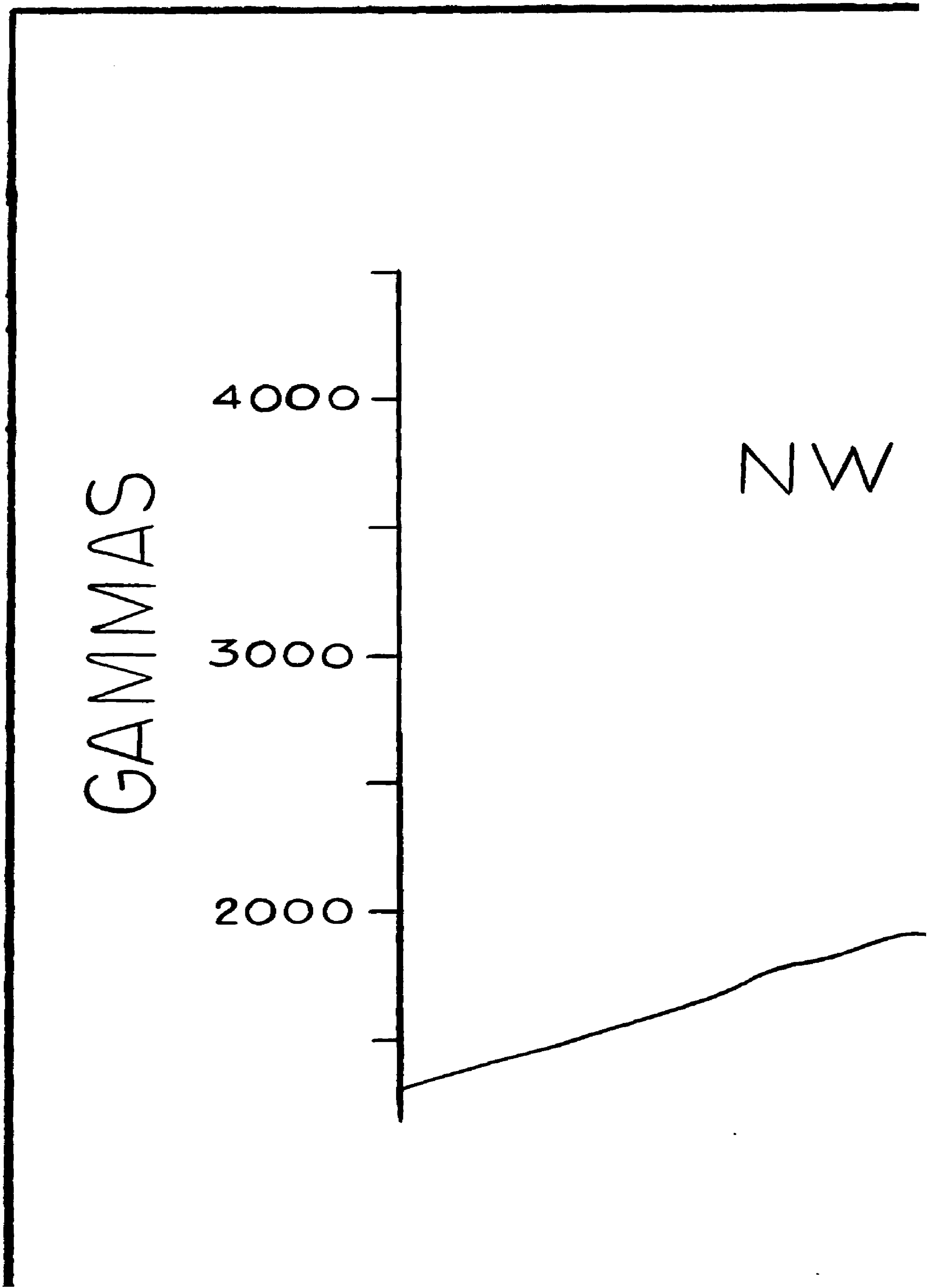
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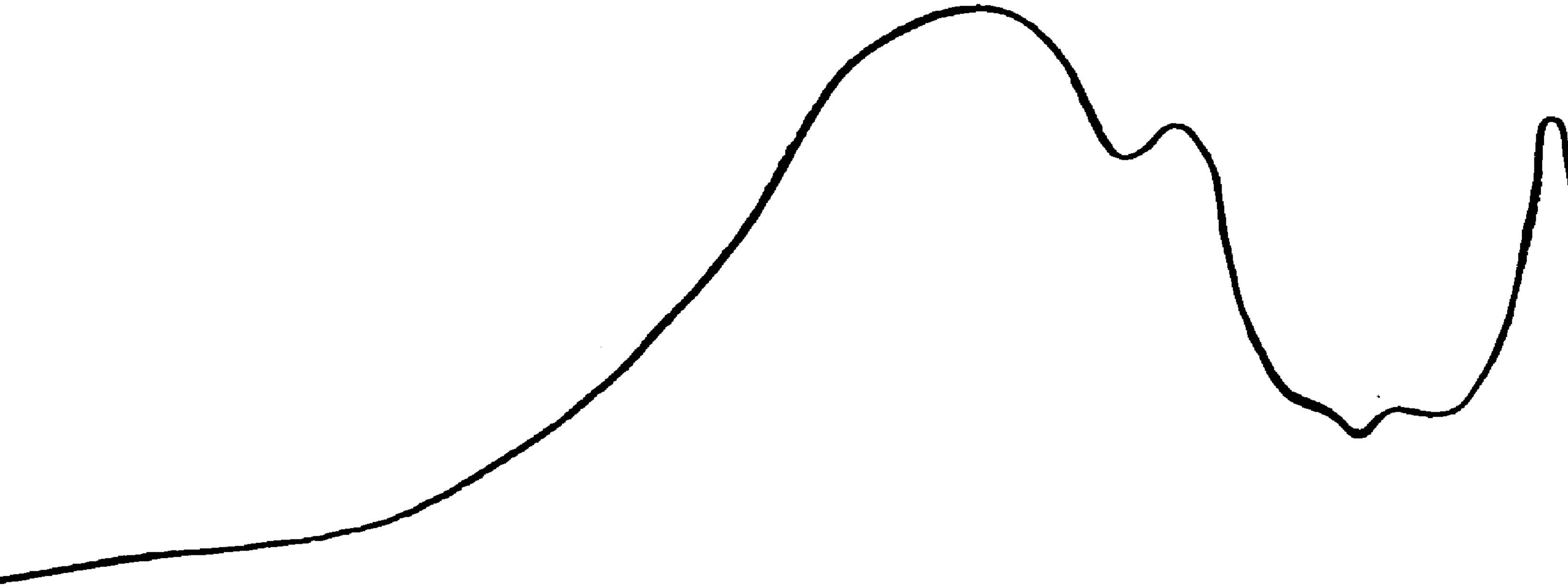
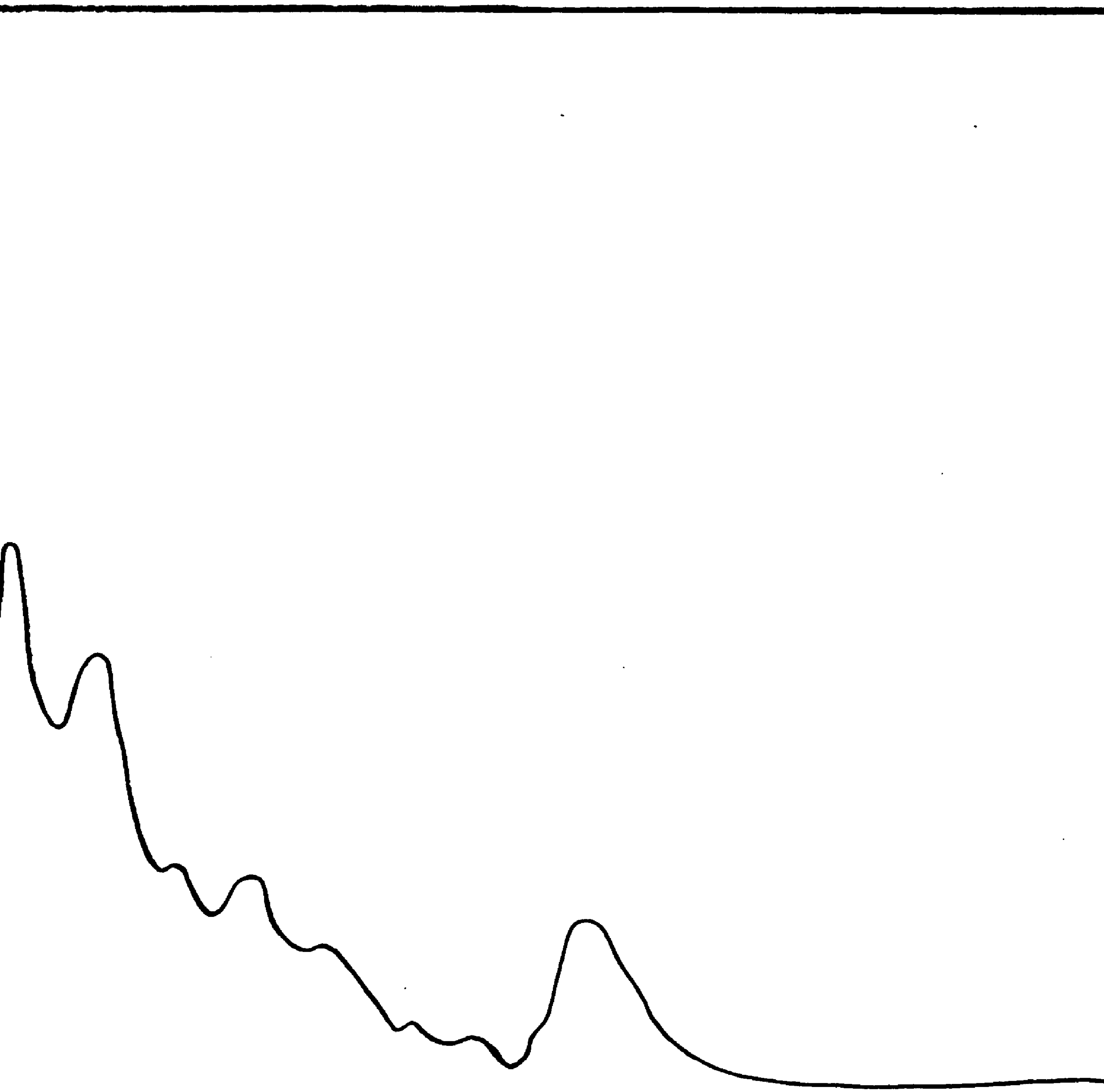
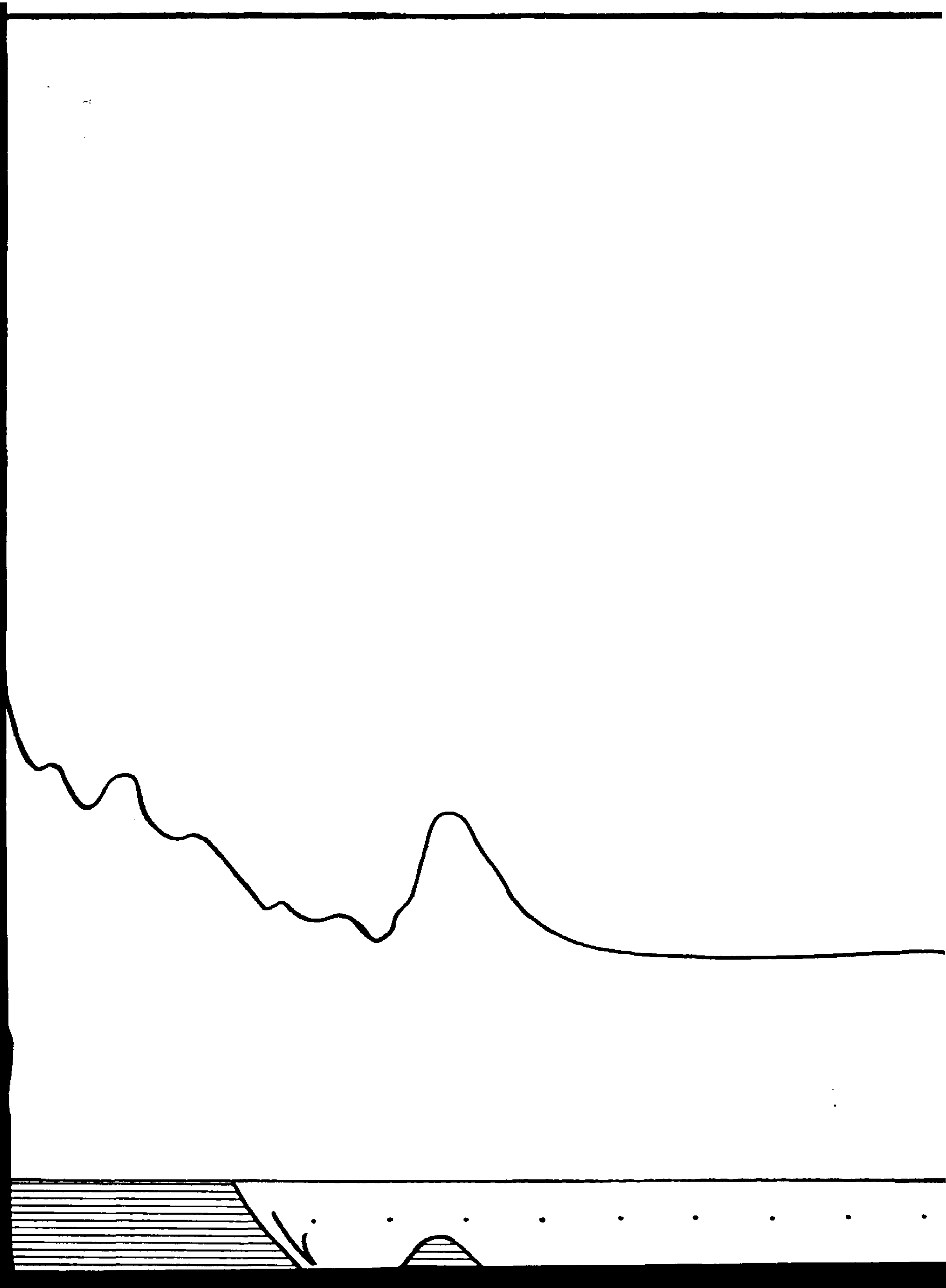
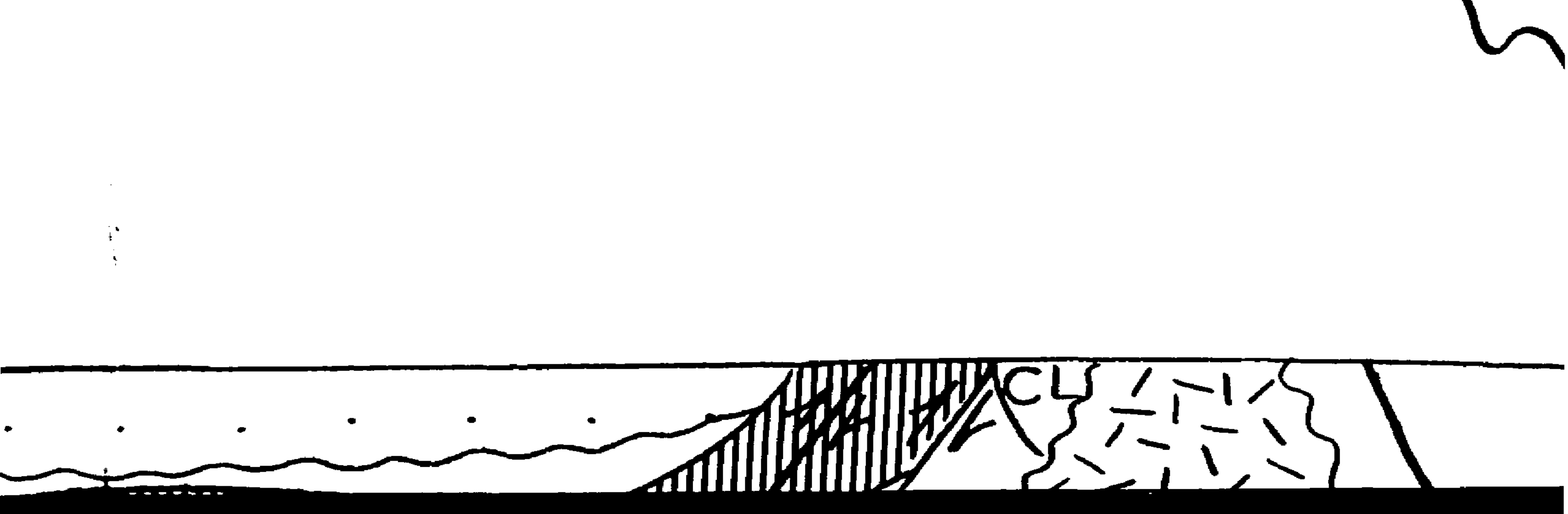
2000
NW







PROFILE E - E′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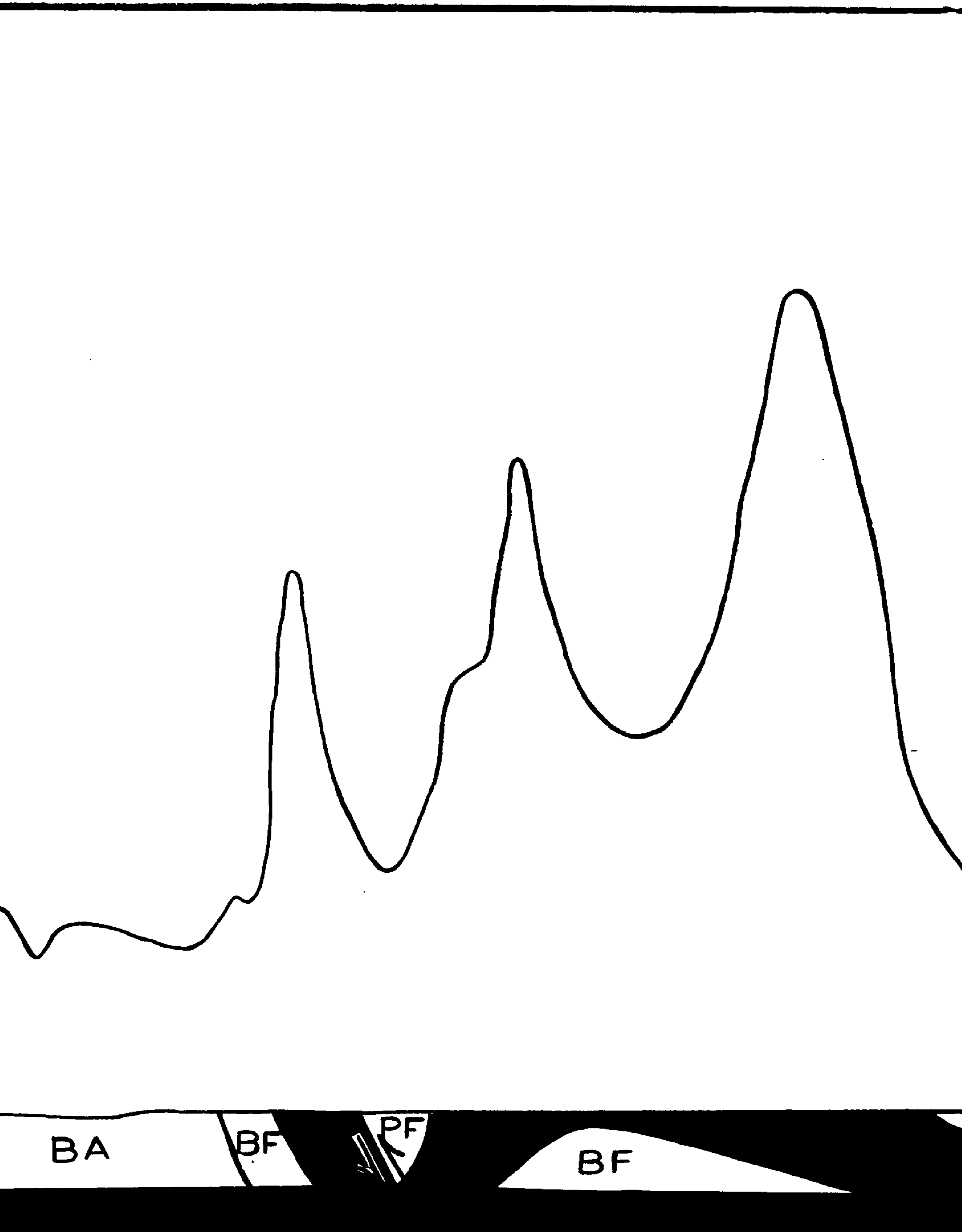
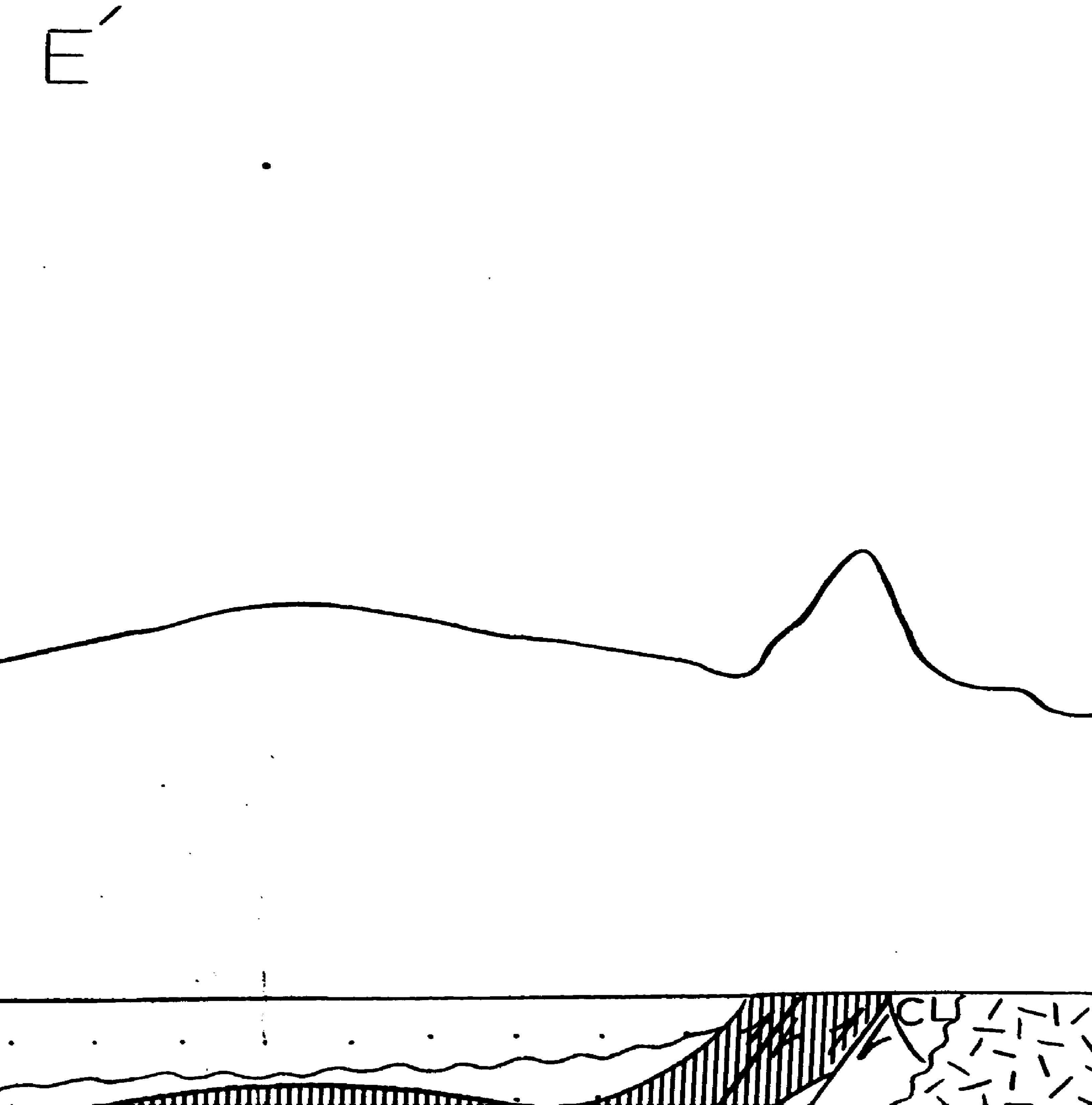
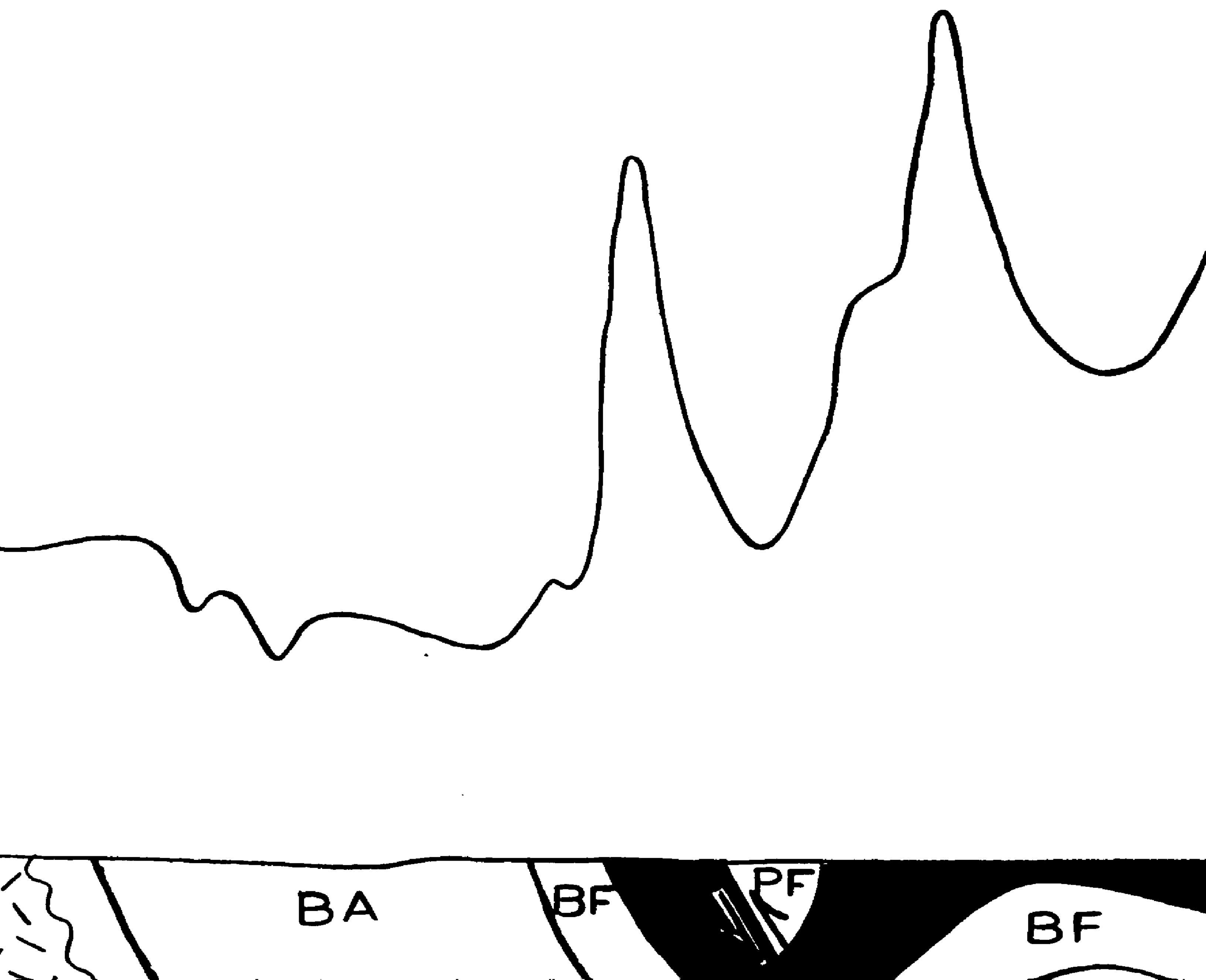

BA
BF
PF
BF


E′
CL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BF
PF
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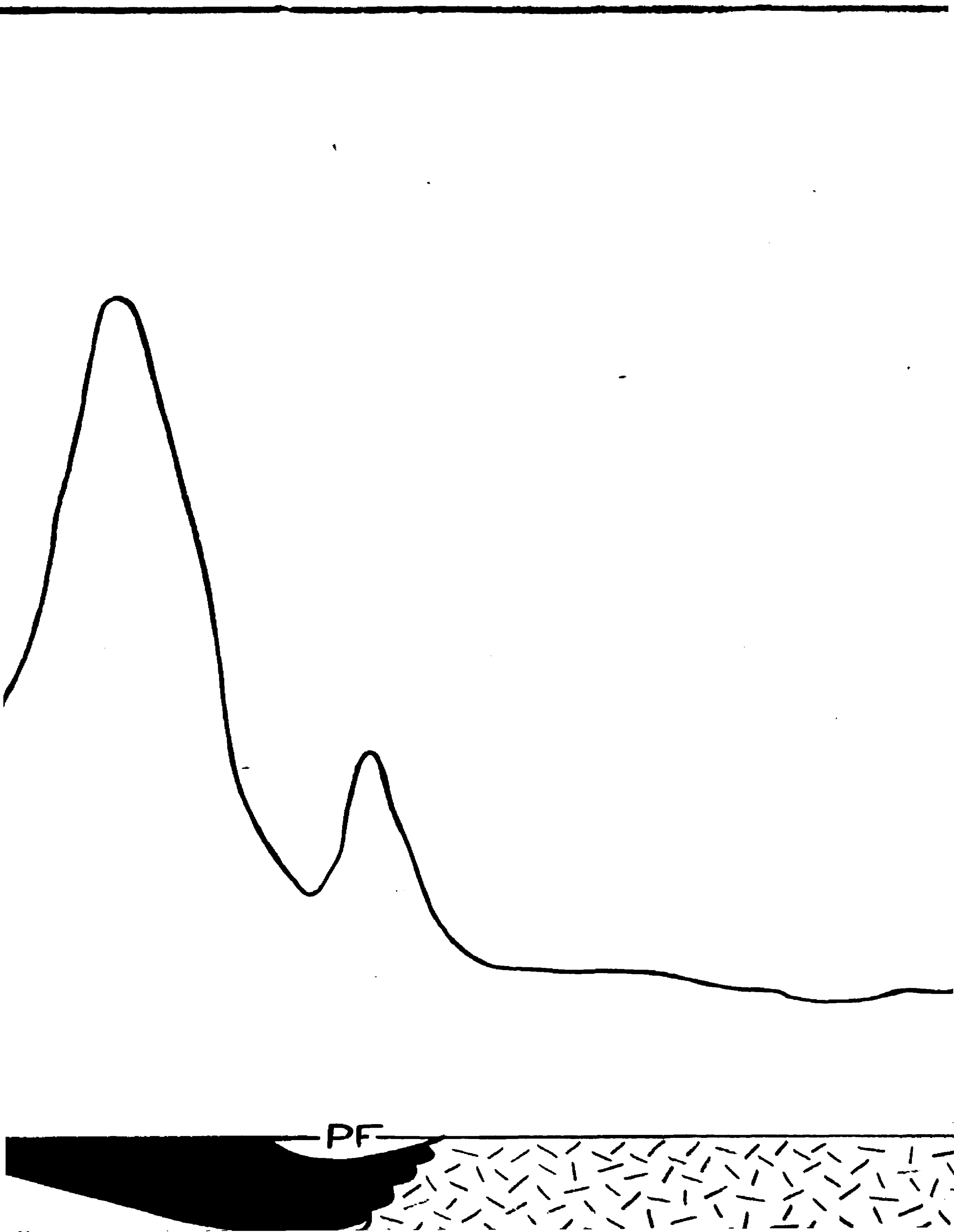
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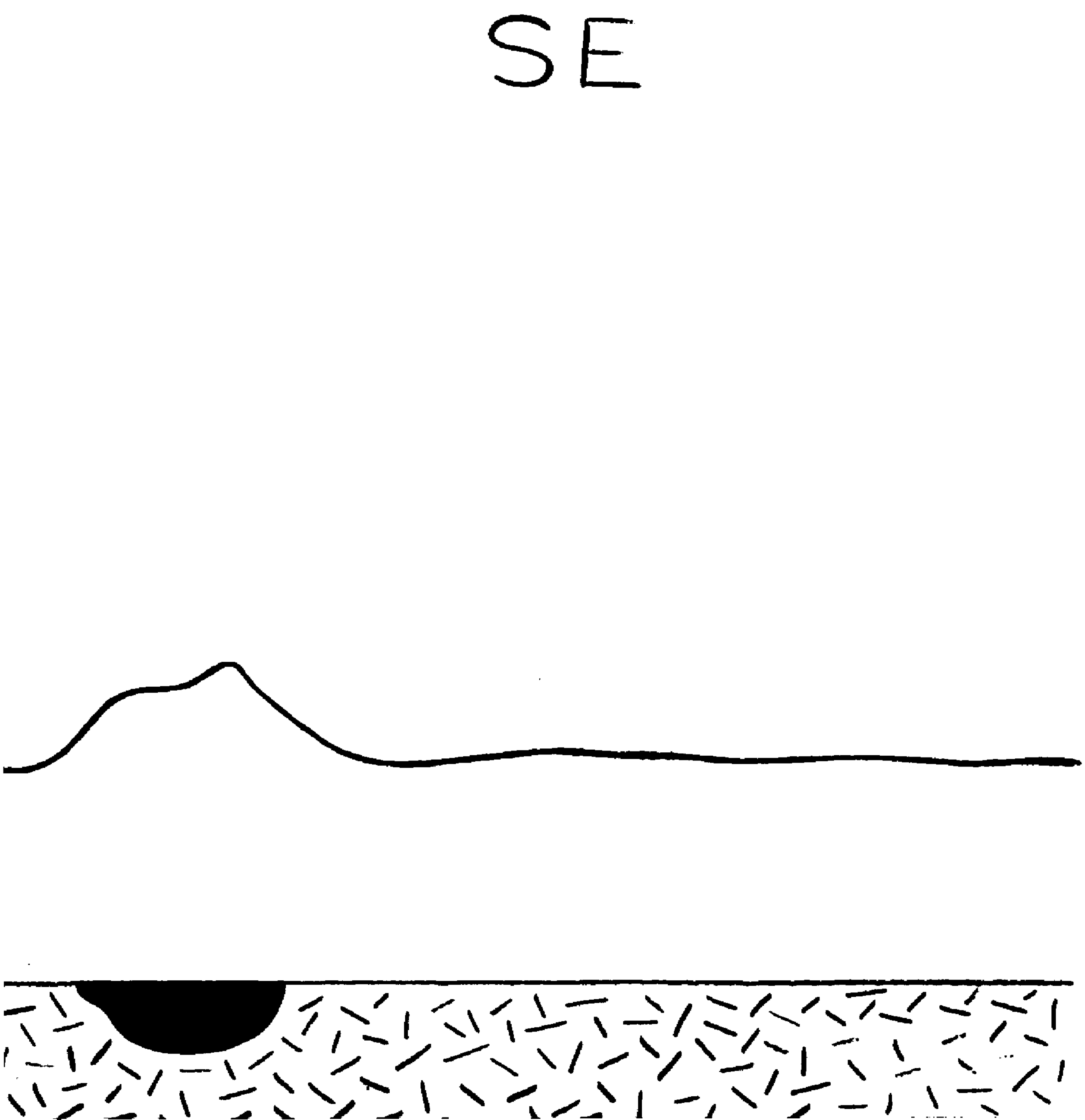
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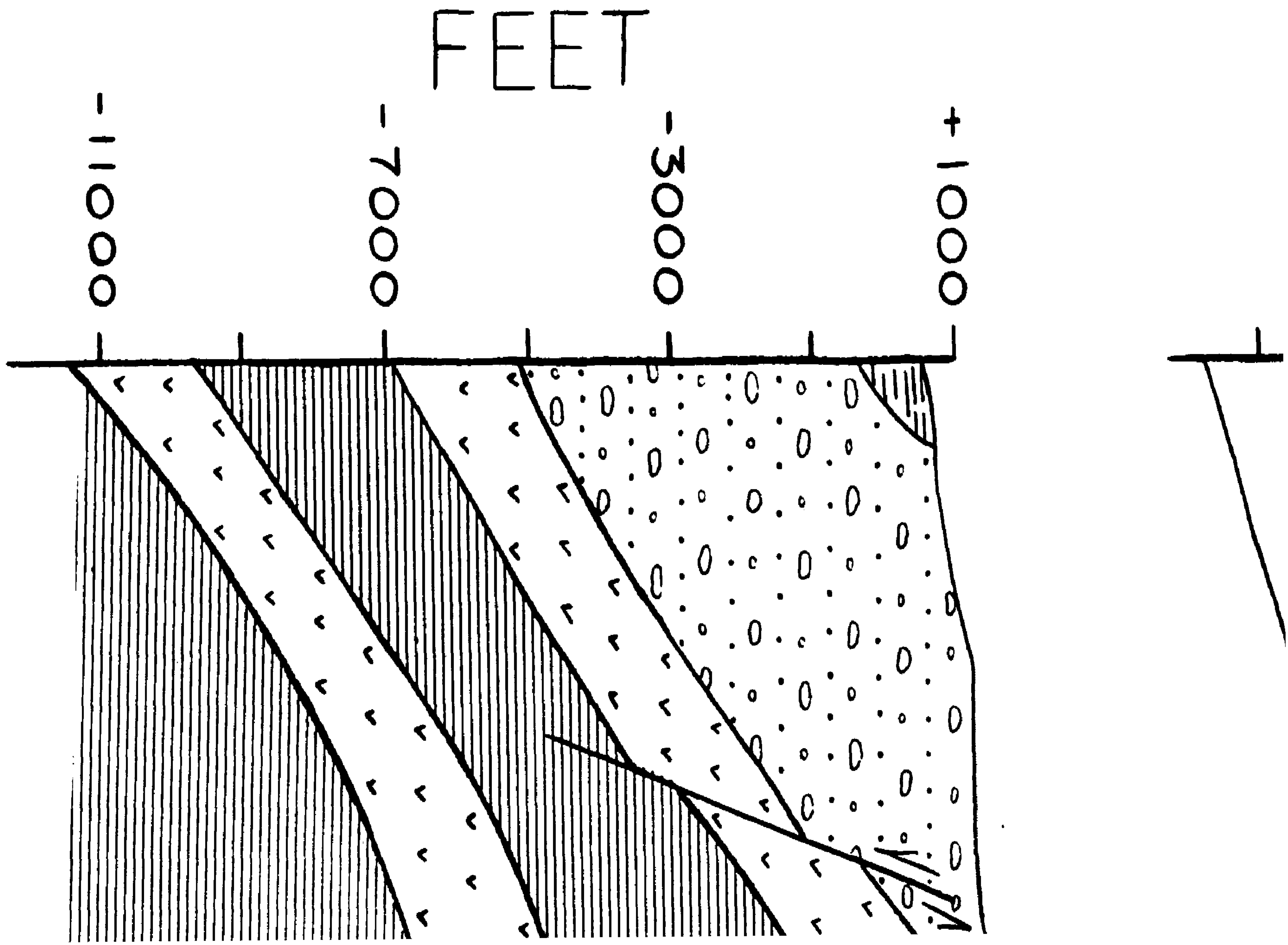
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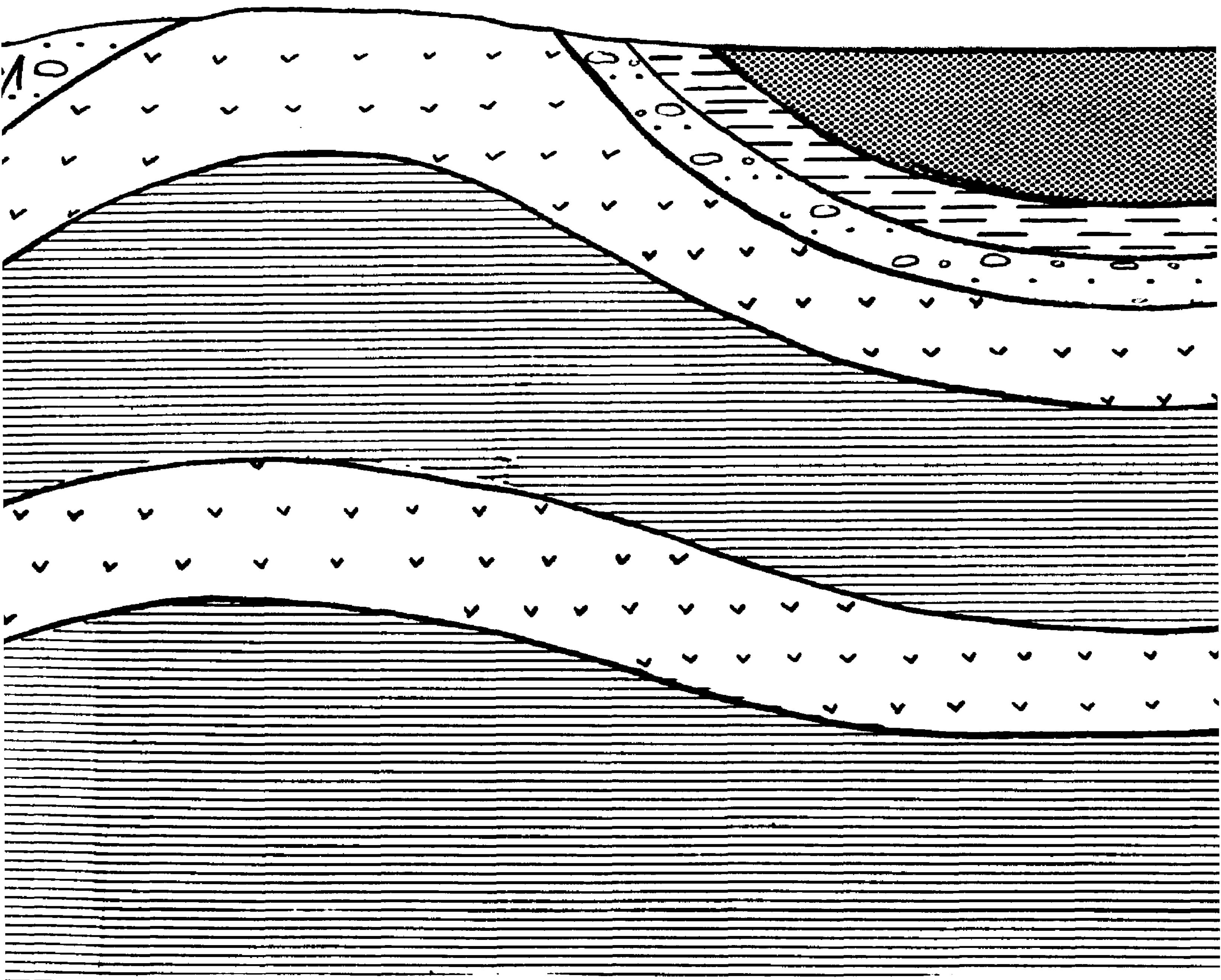
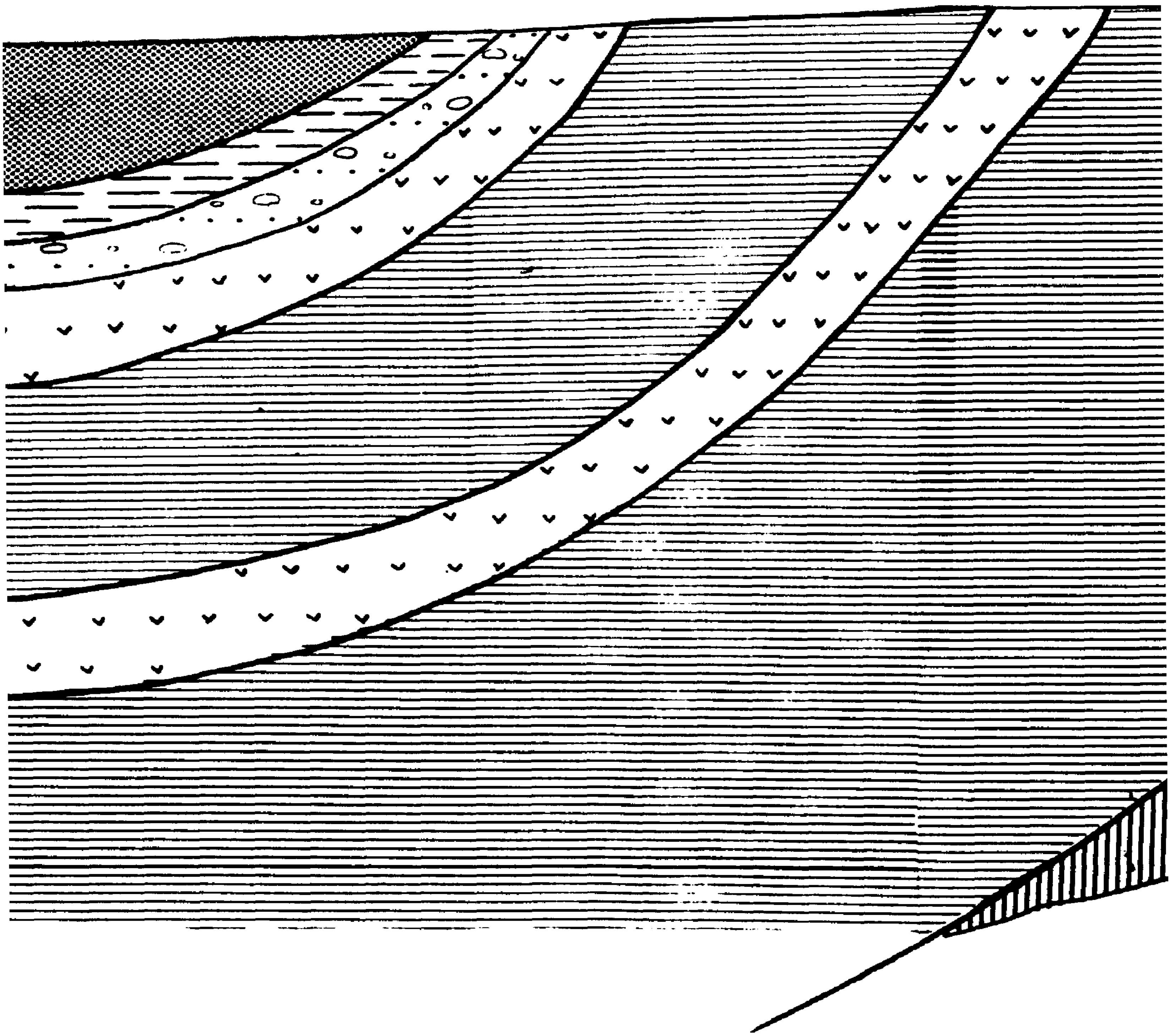
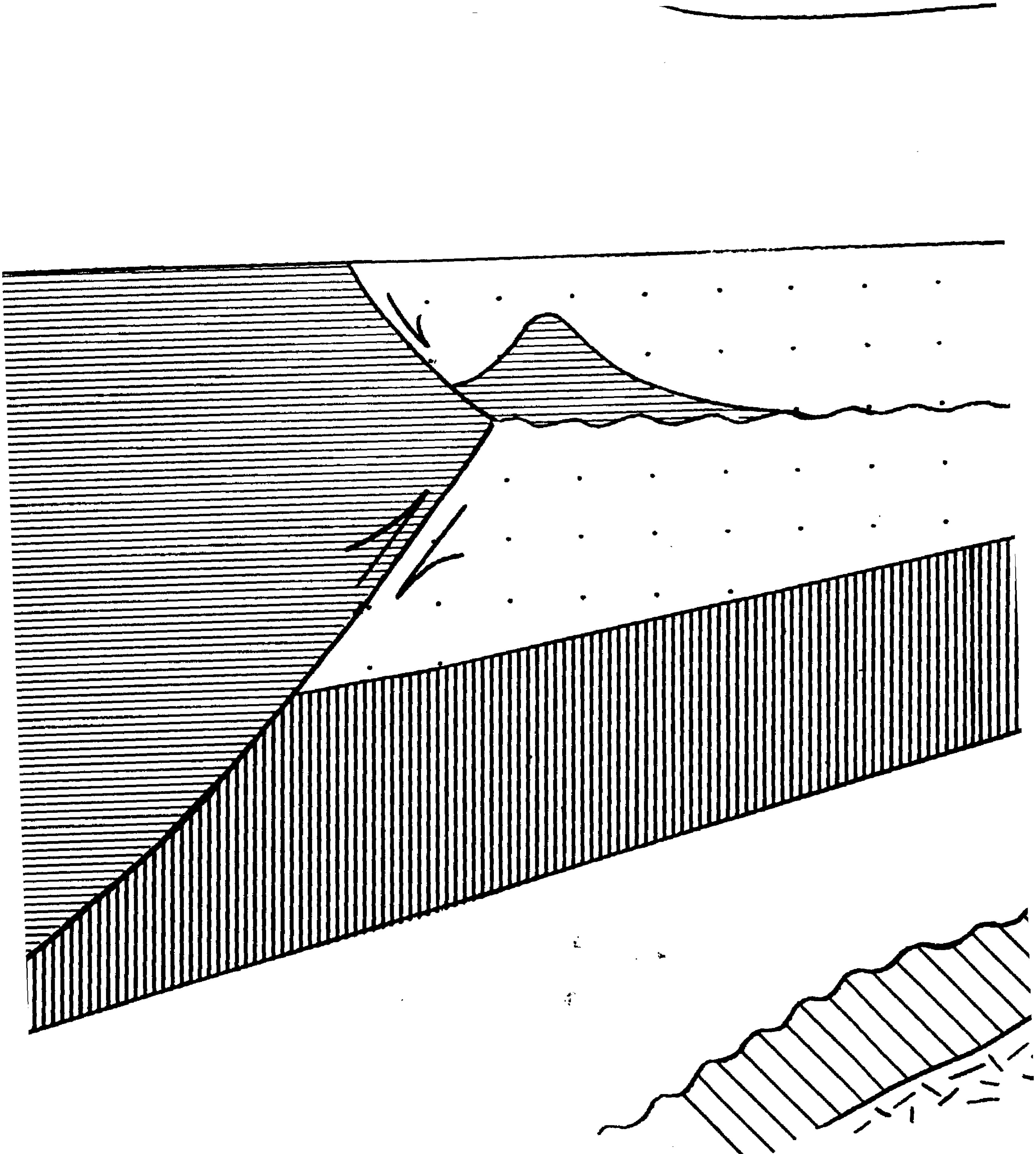
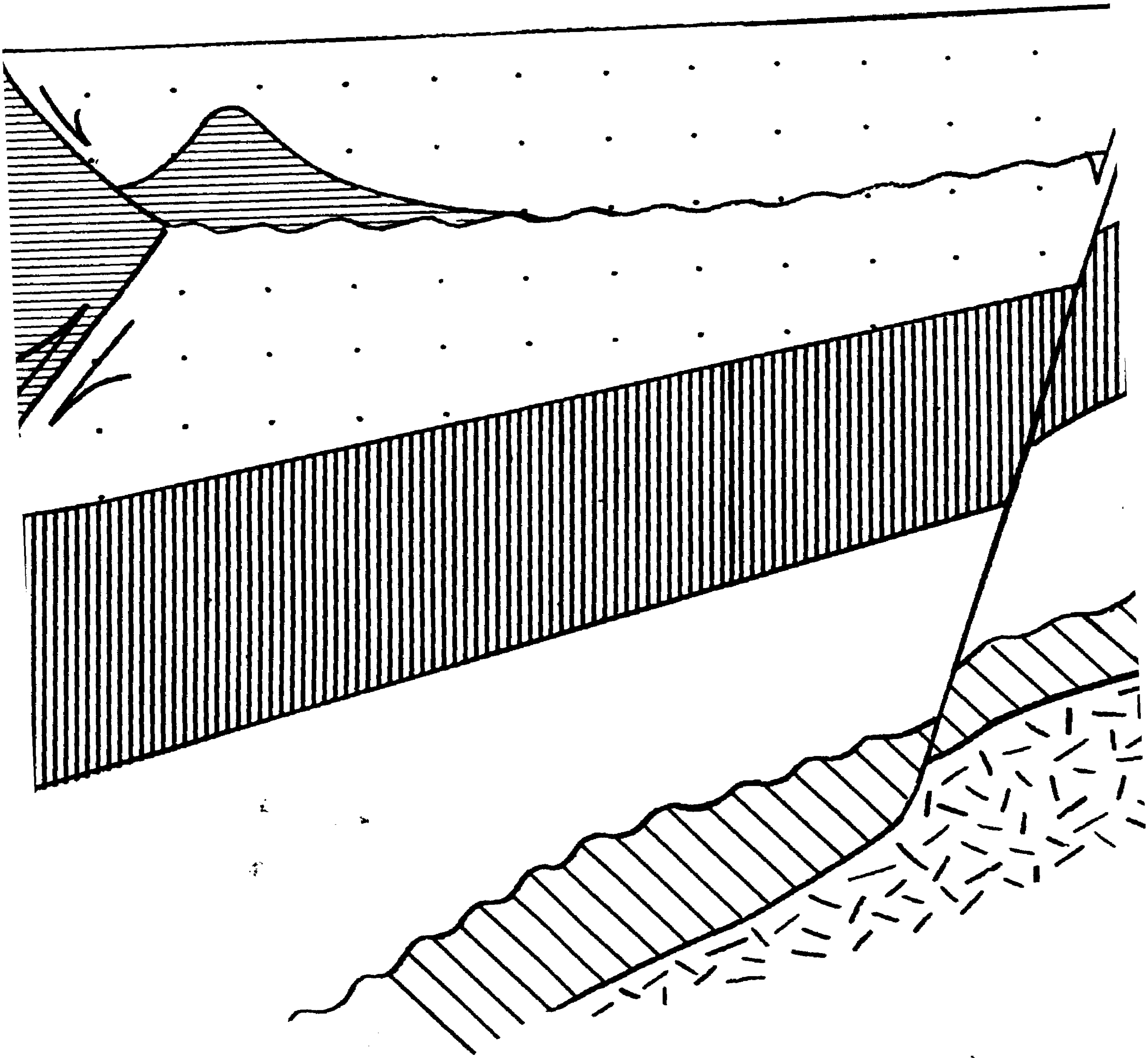
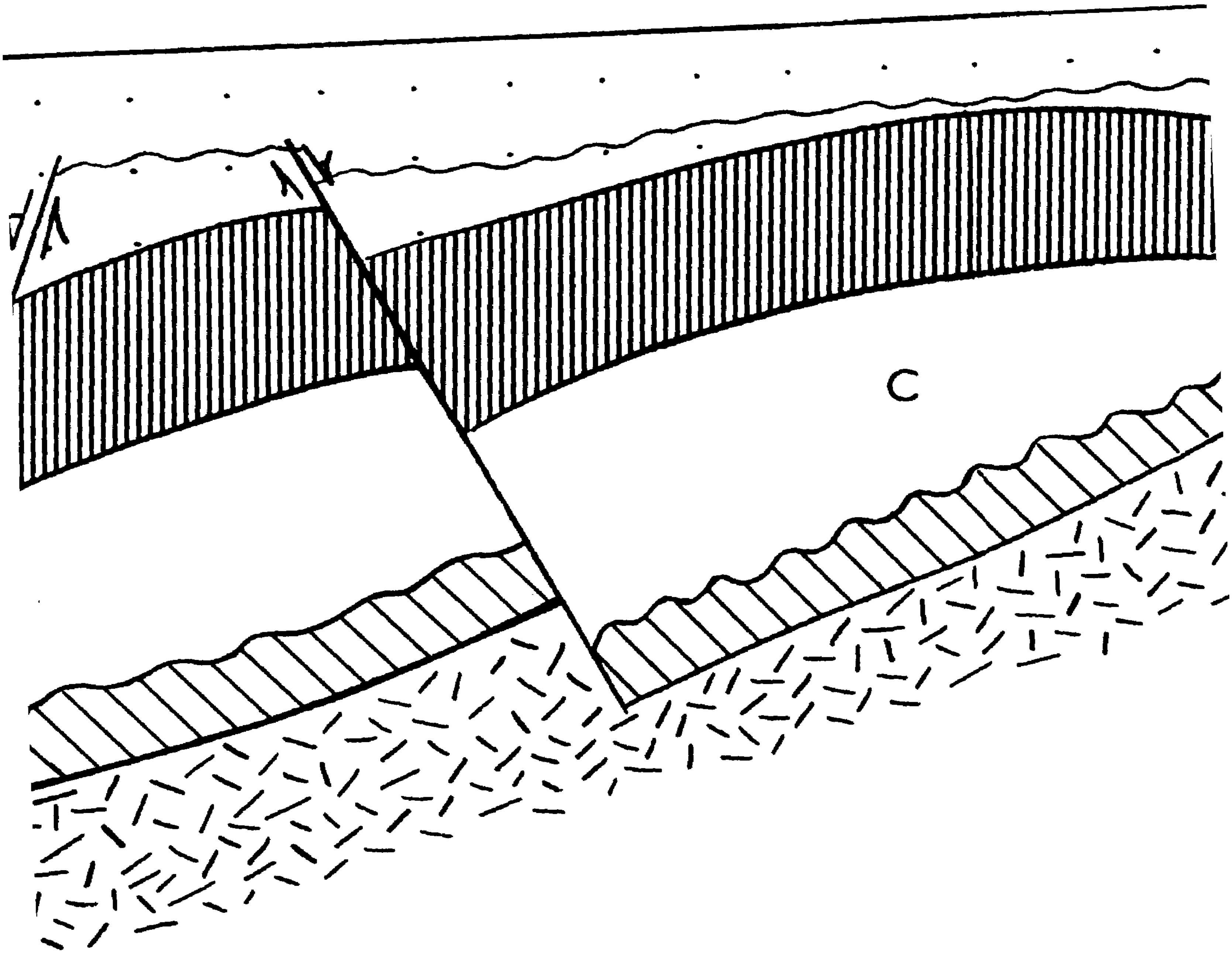
+1000







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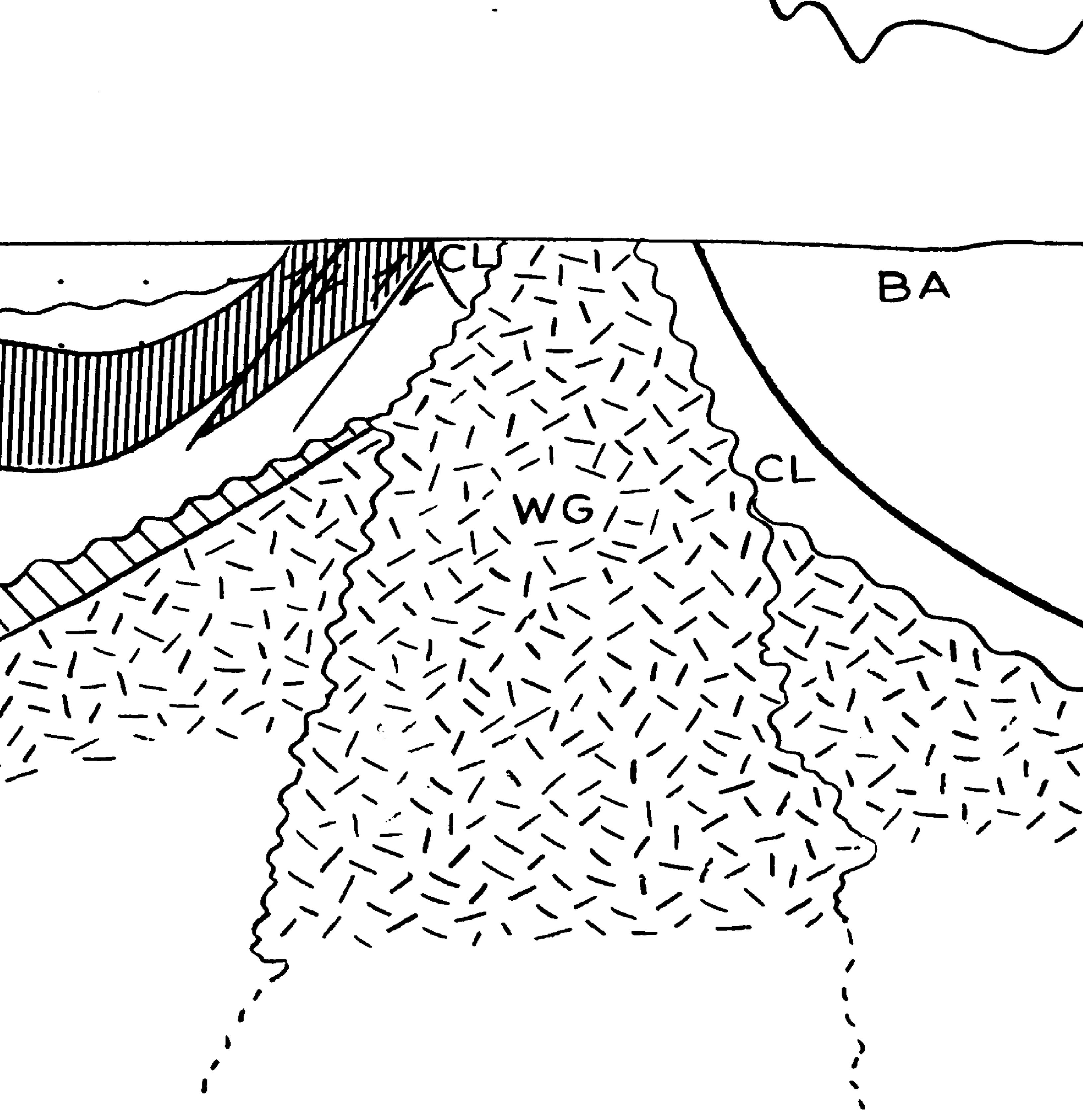
CL
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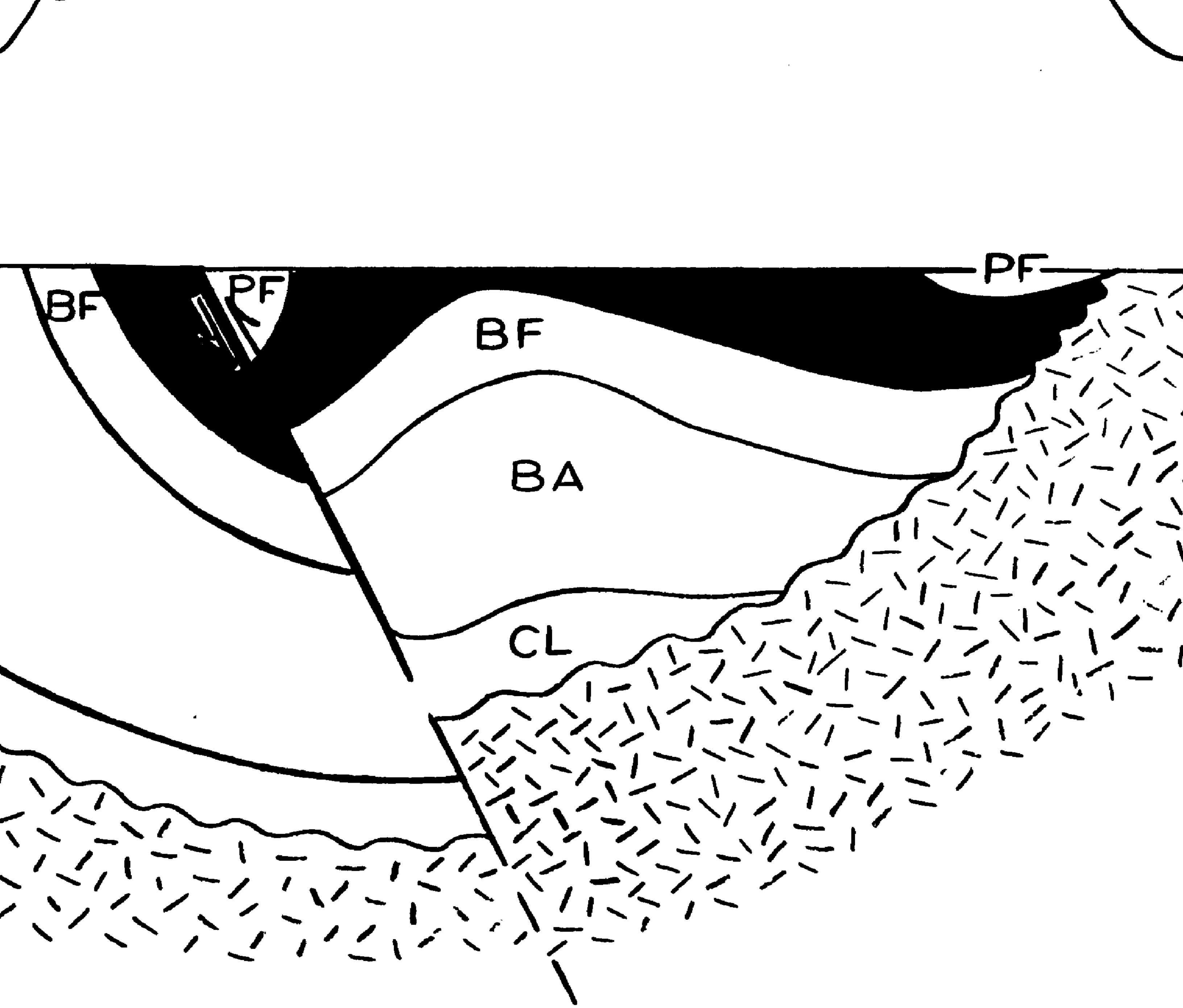
CL
WG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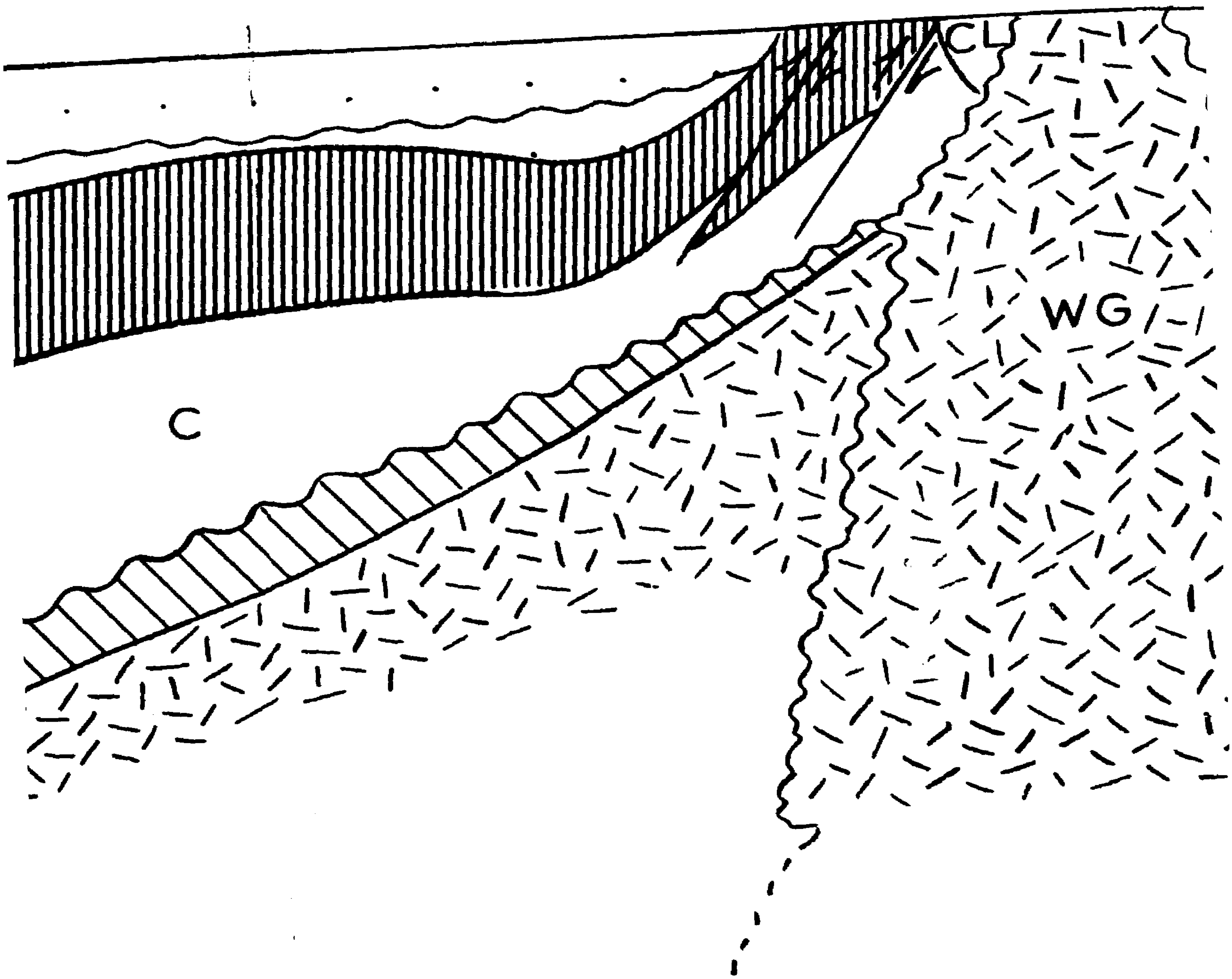
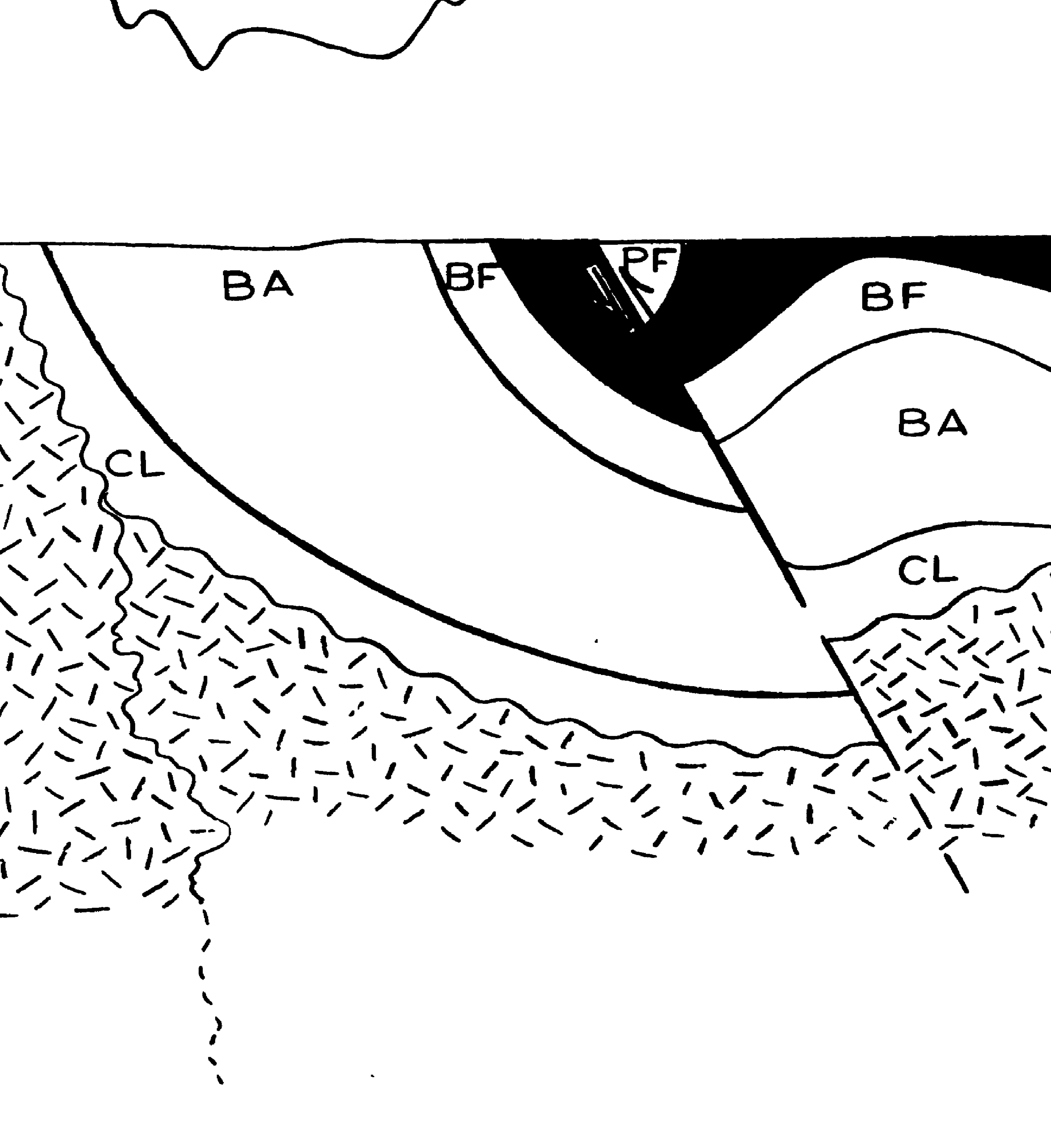
PF
BF
PF
BA
CL


CL
WG
C



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PF
BF
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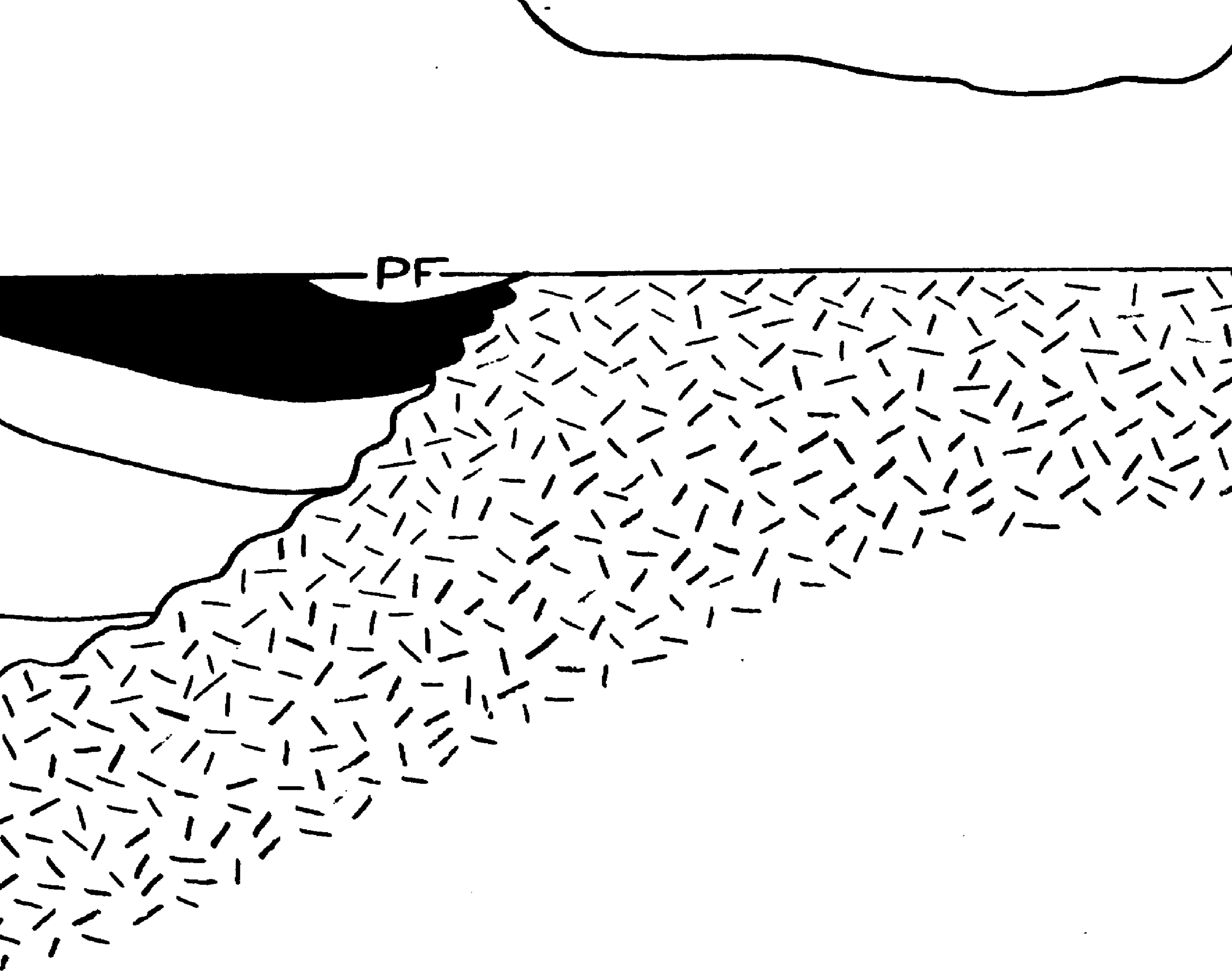
CL
CL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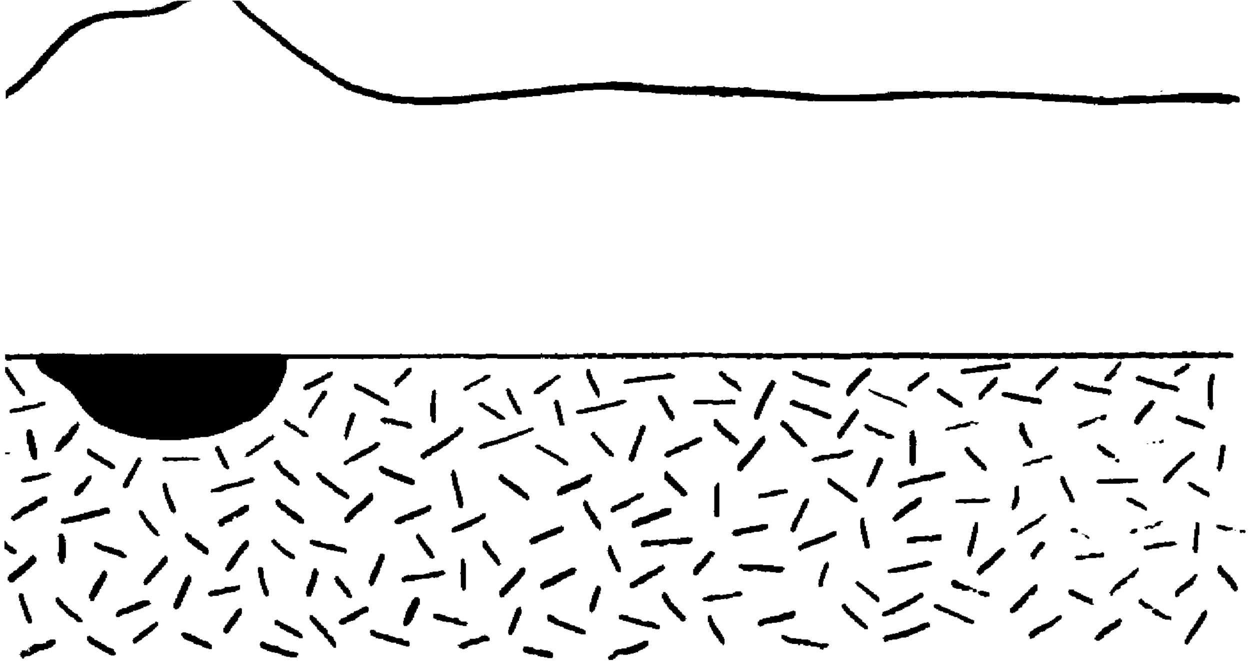

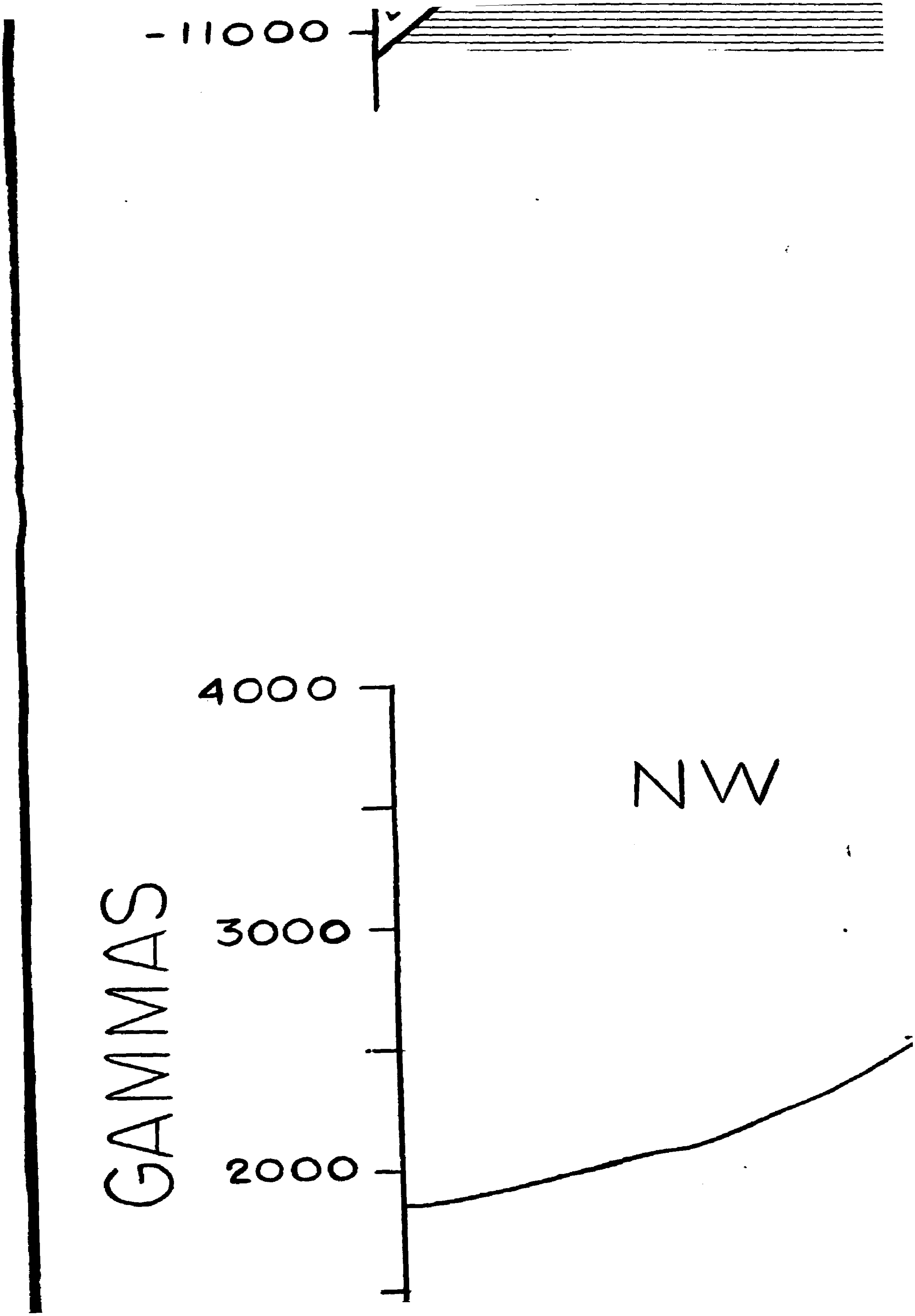
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GAMMAS
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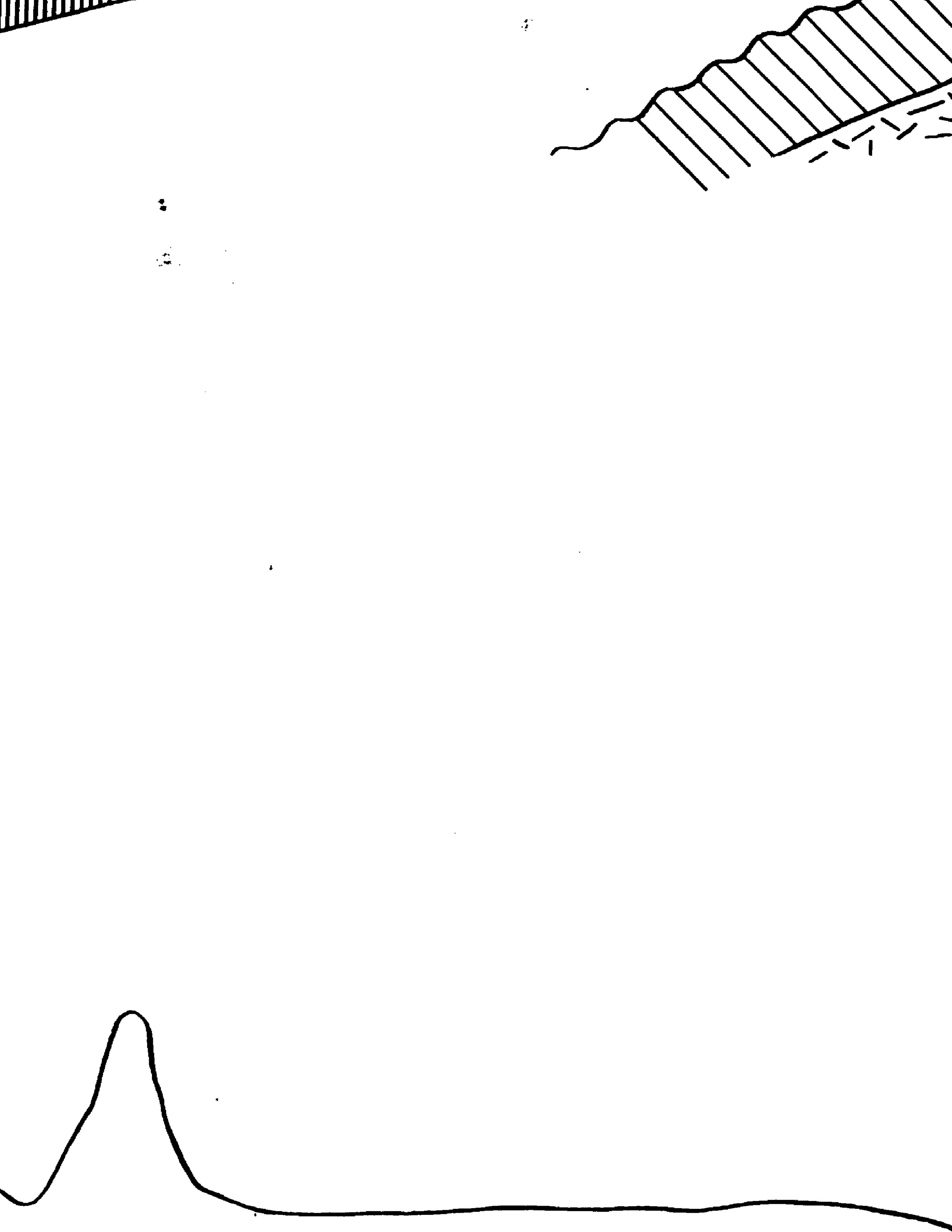
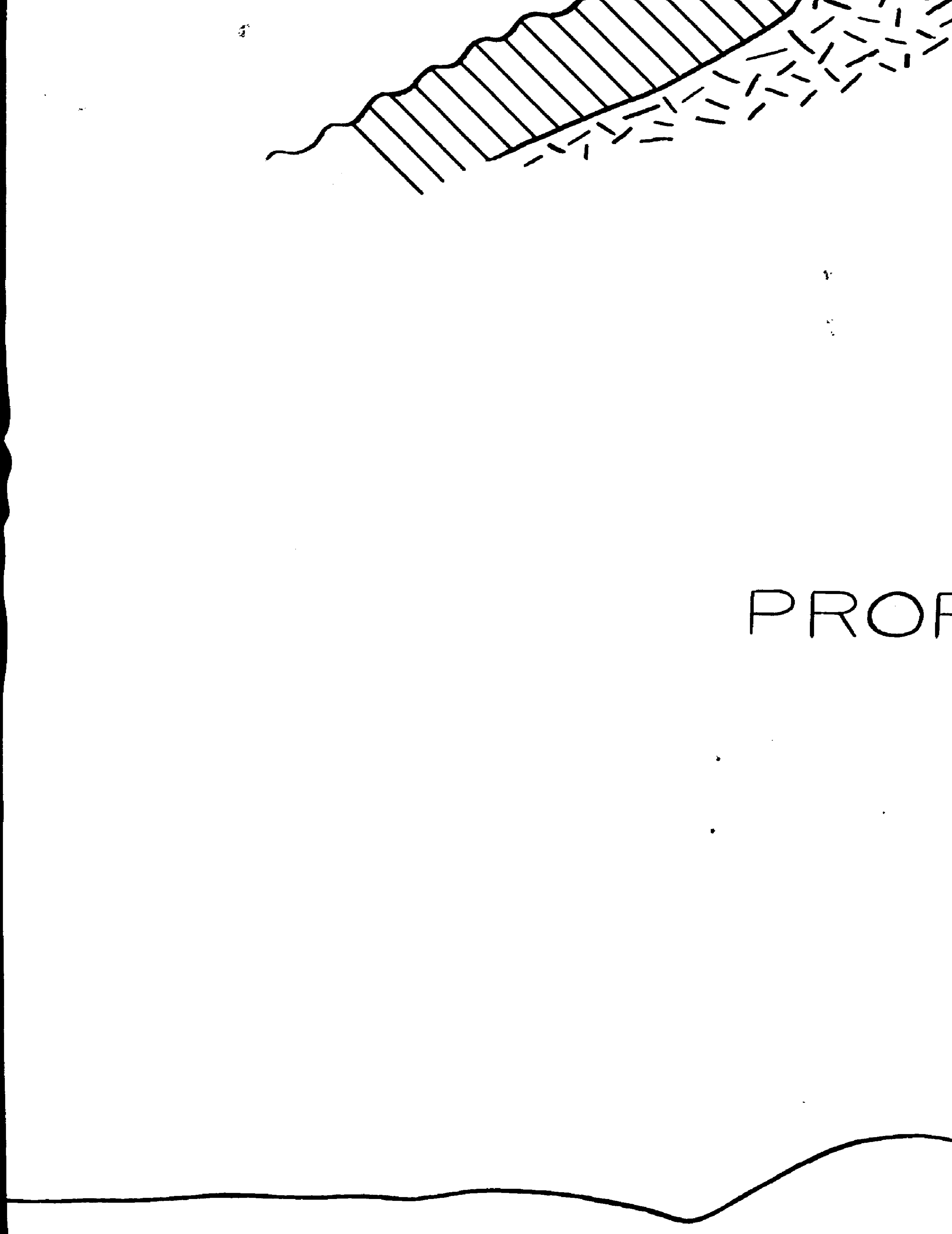
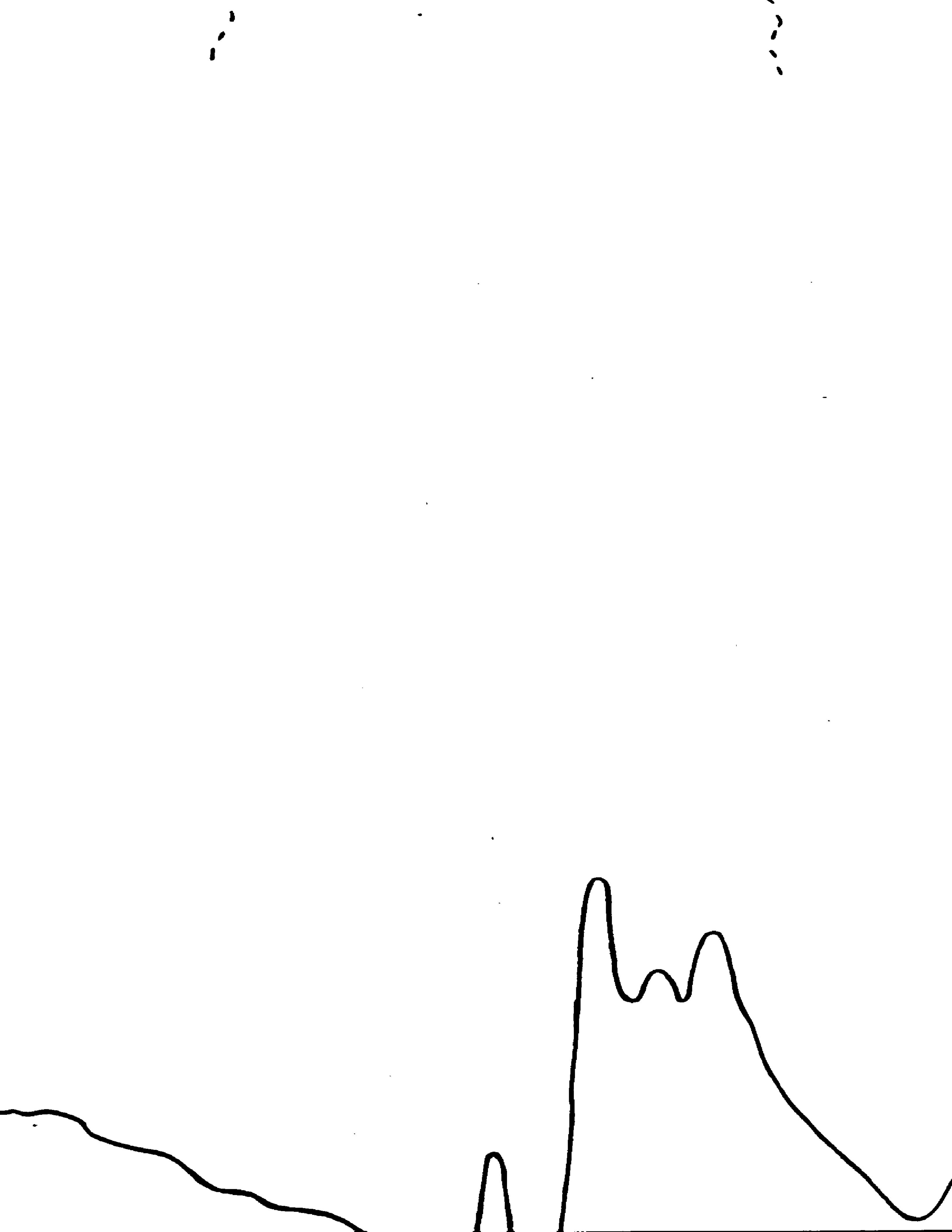
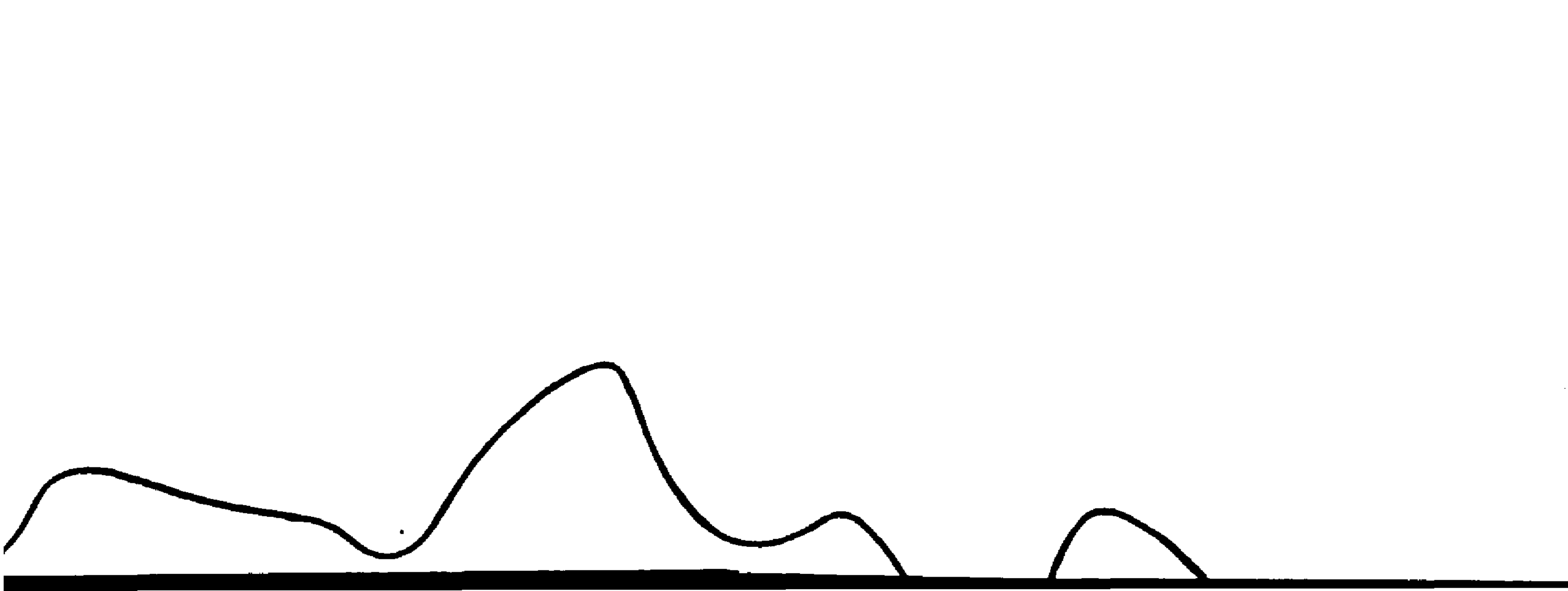


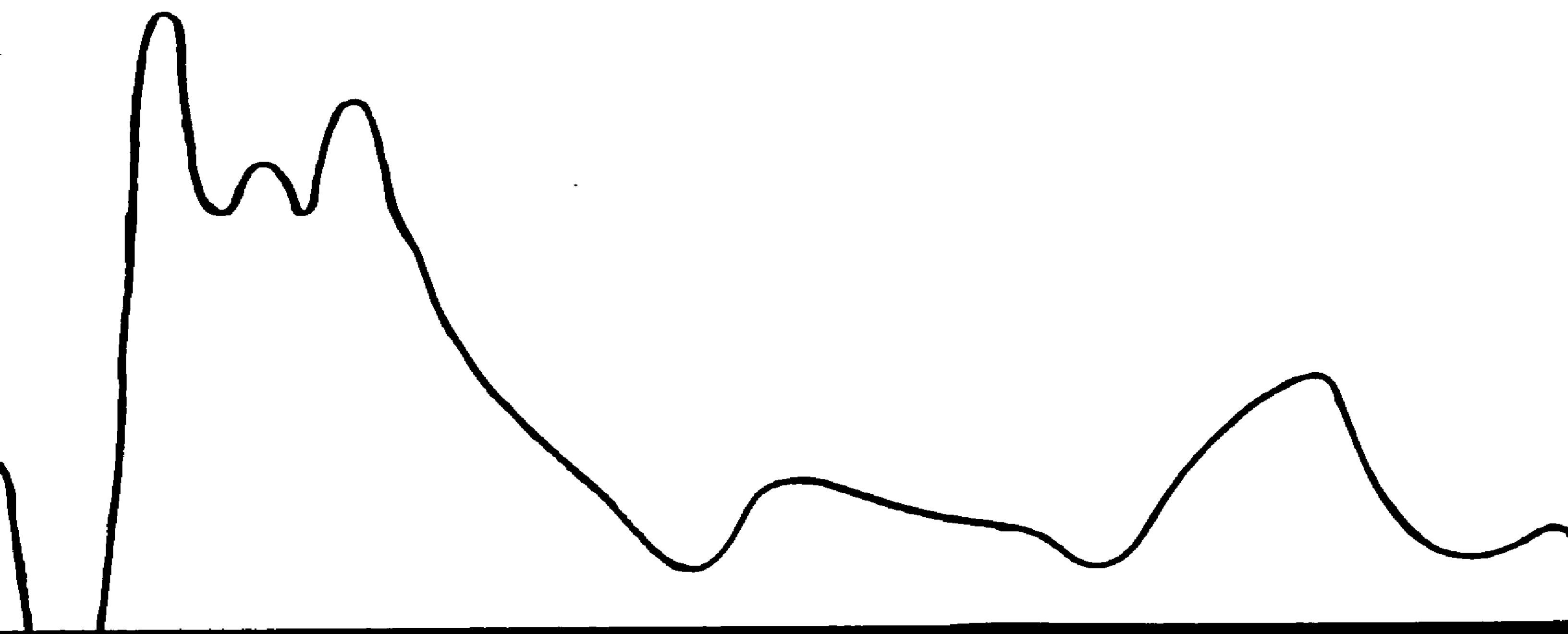

PRO

FILE F – F′





F′



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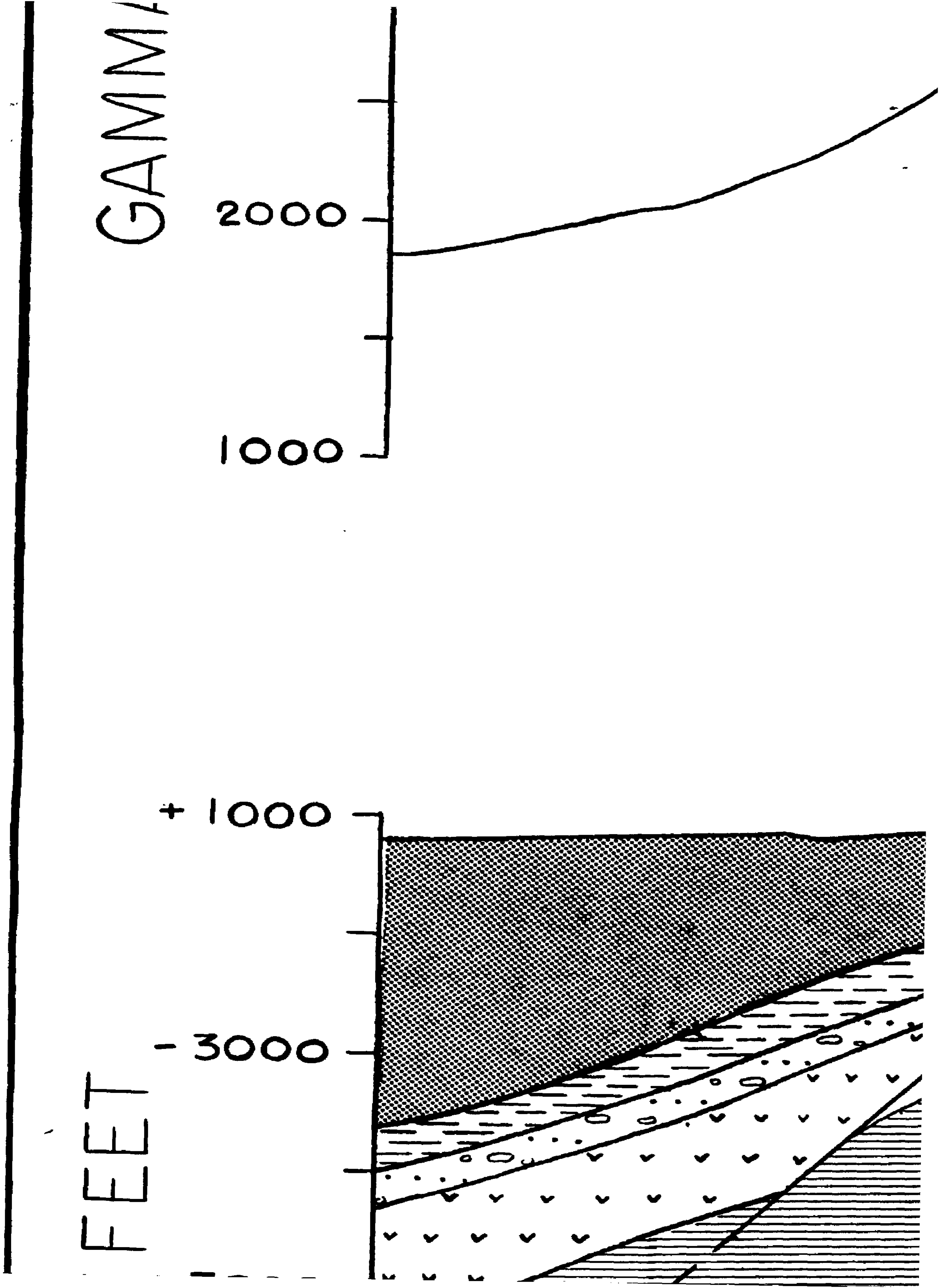
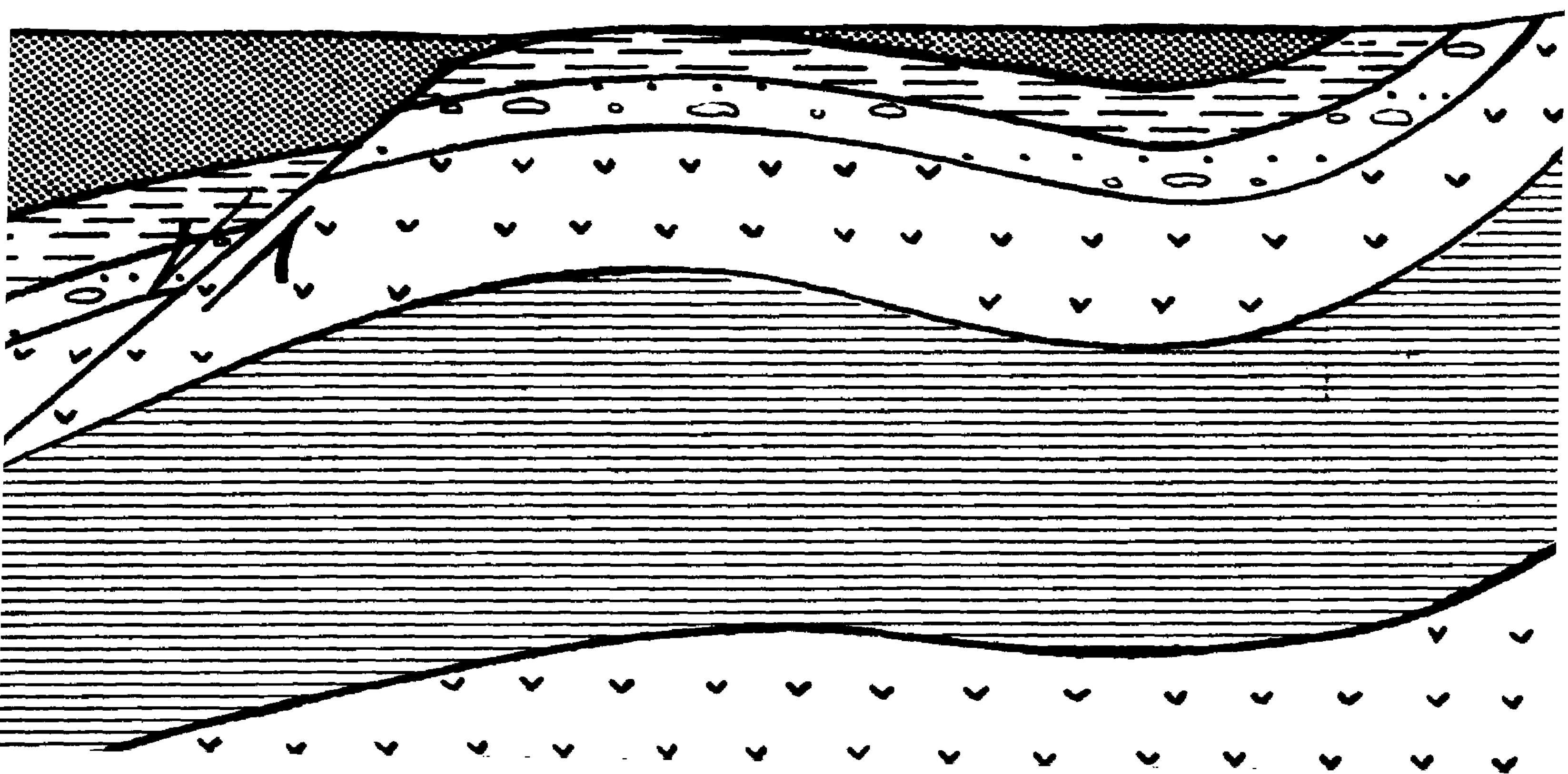
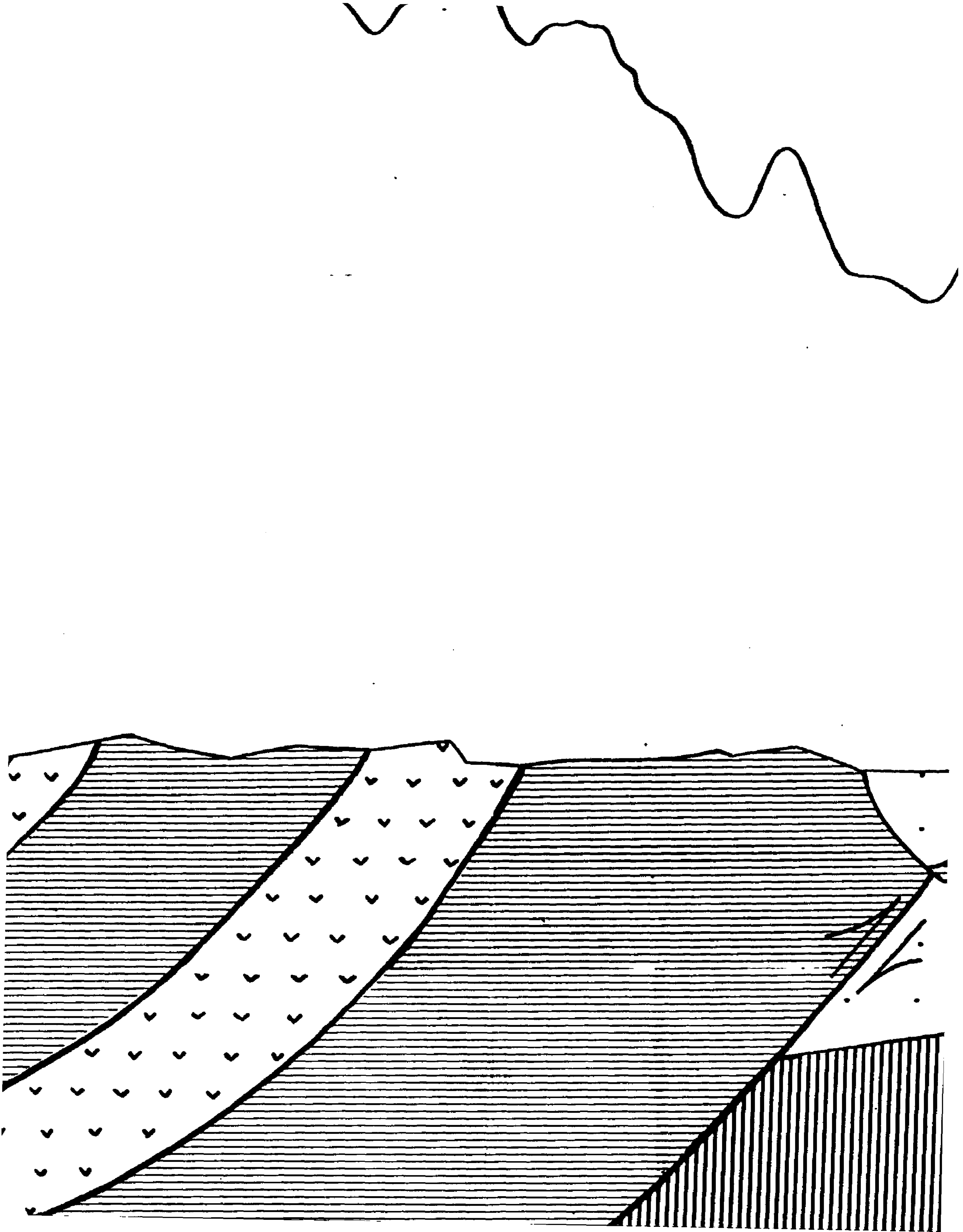
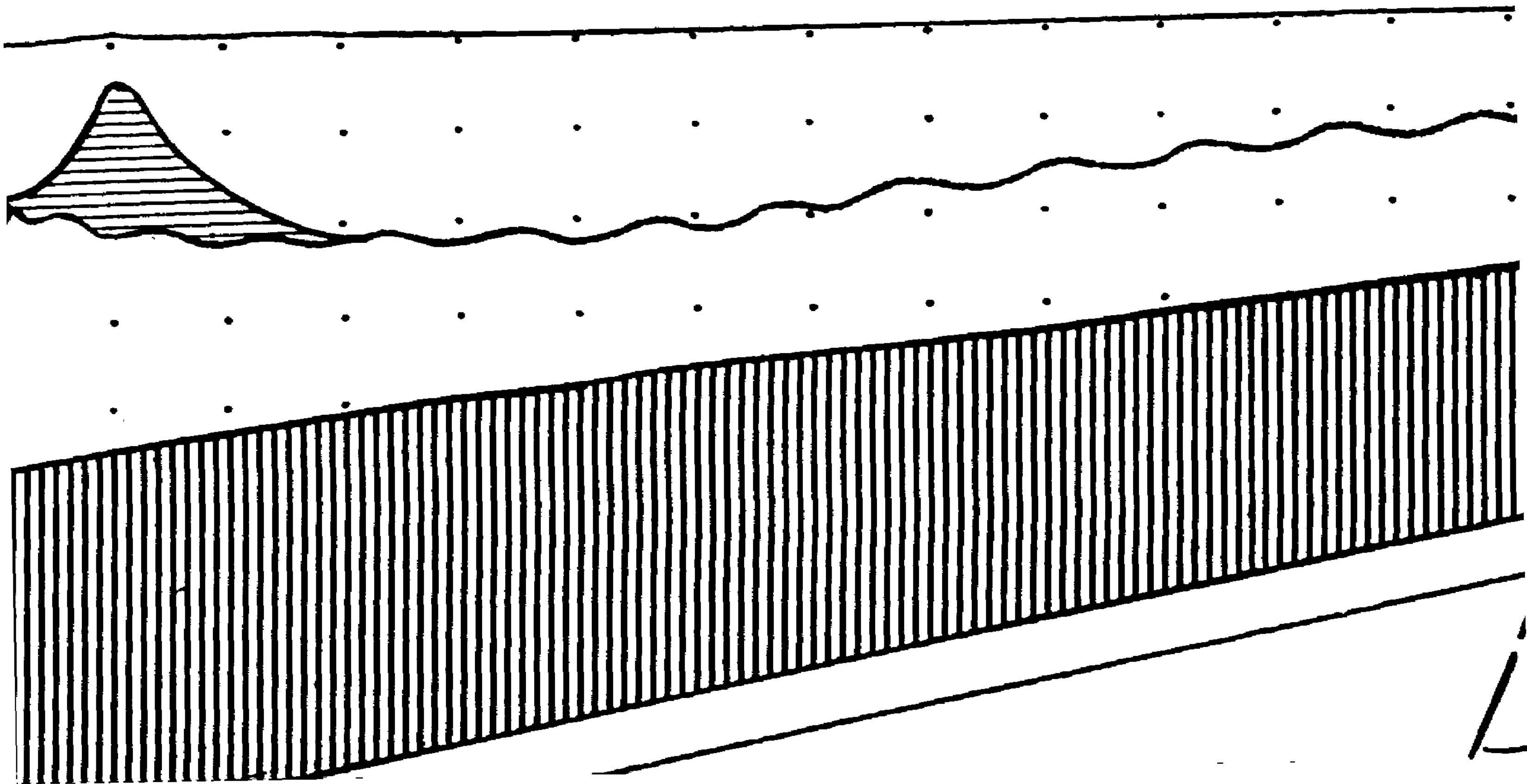
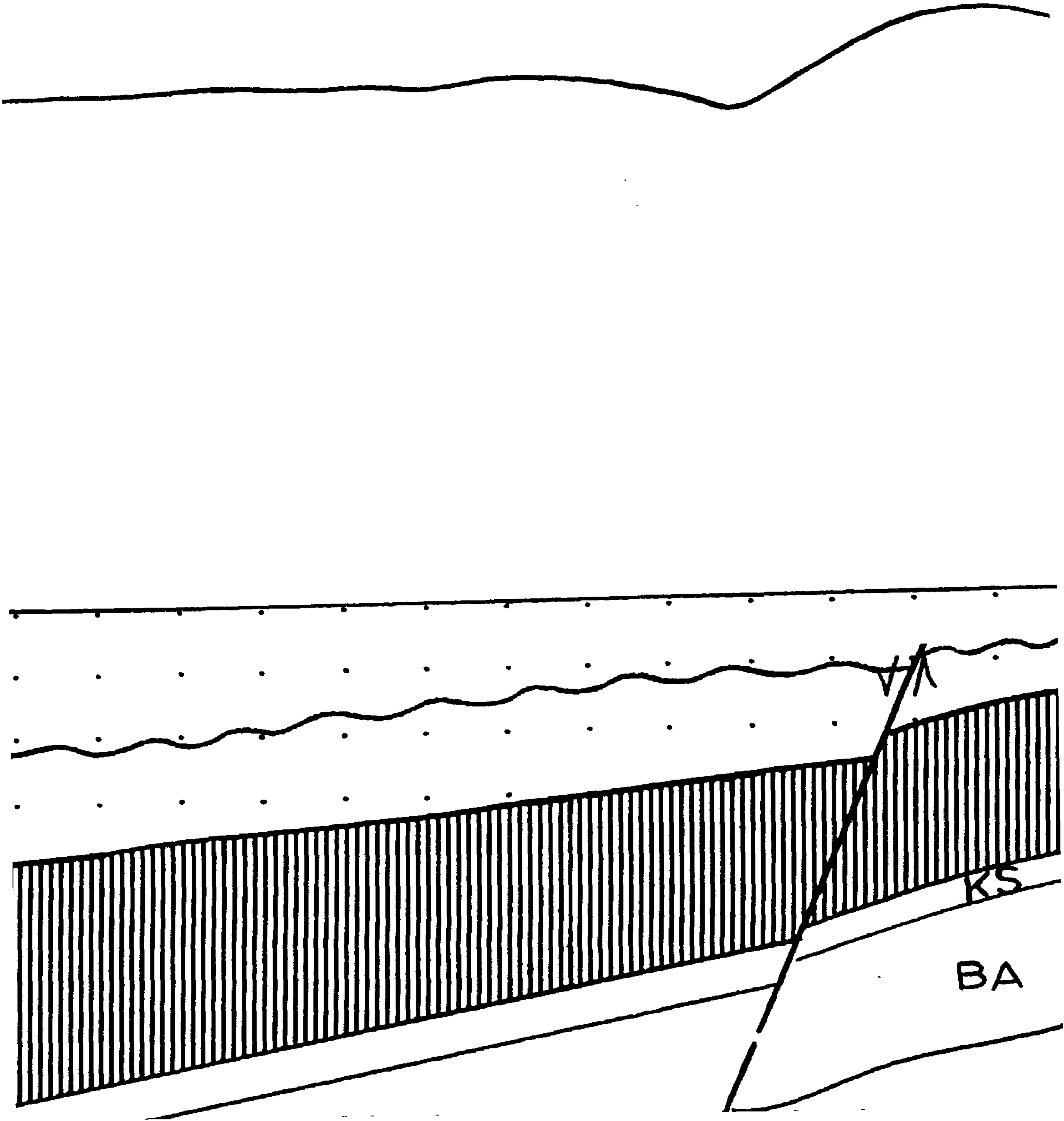

GAMM
2000
1000
+ 1000
- 3000
FEET





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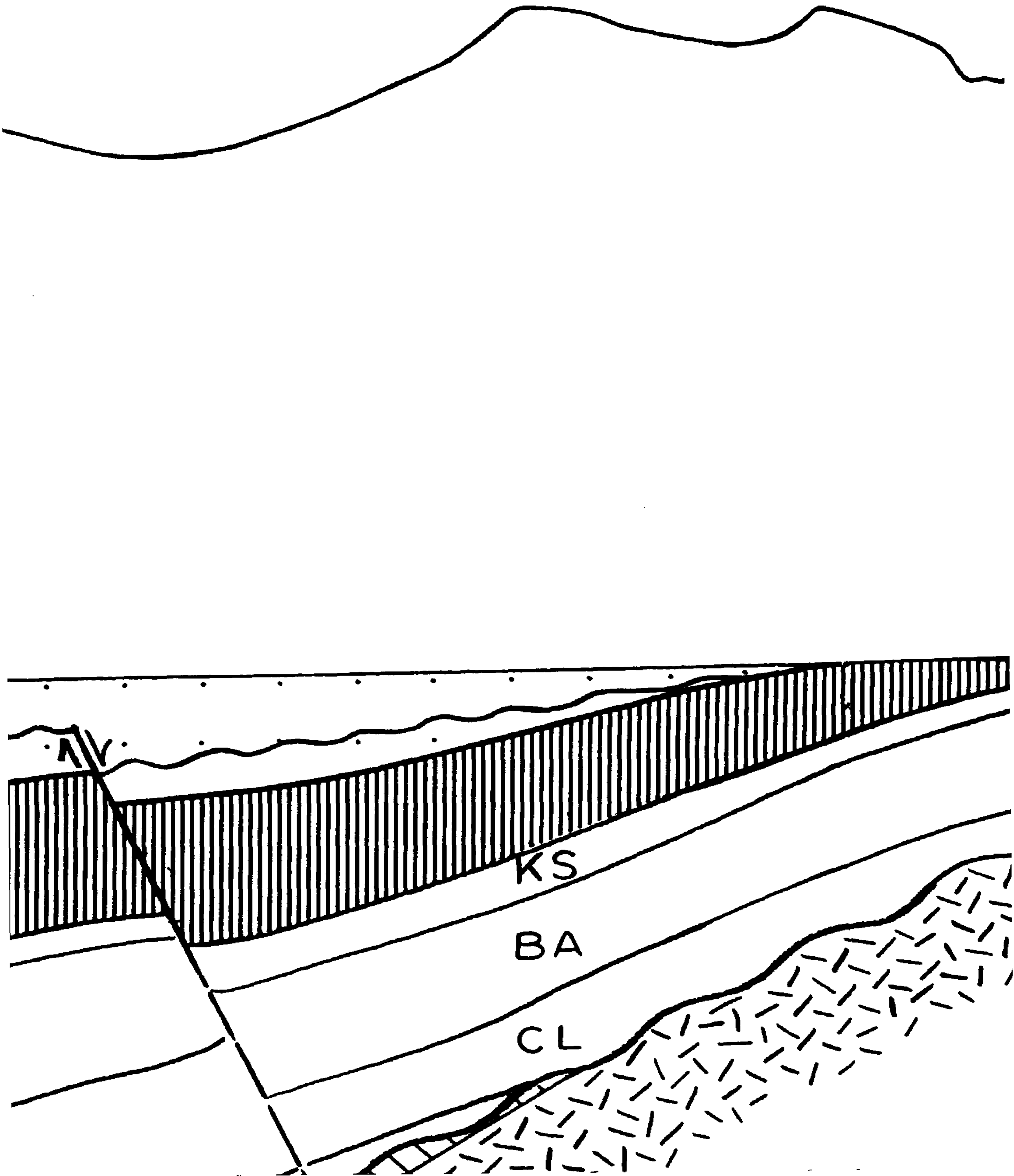
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BA
CL


B
A
BF
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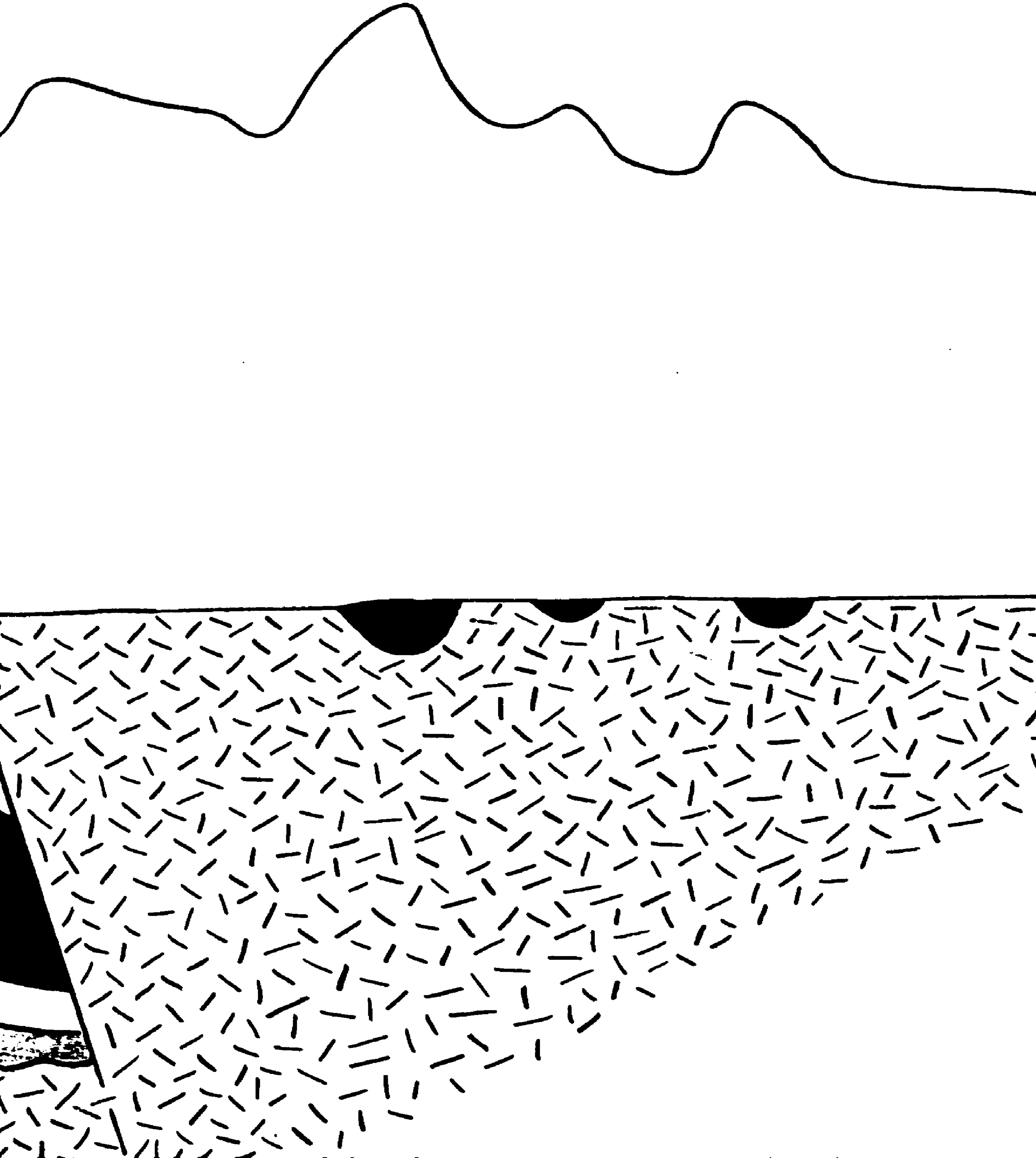

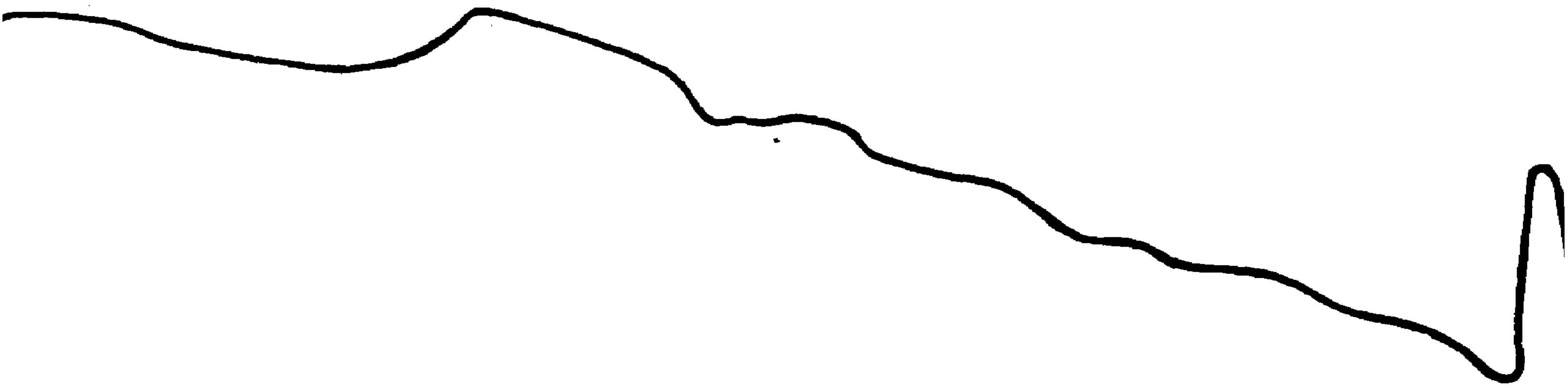

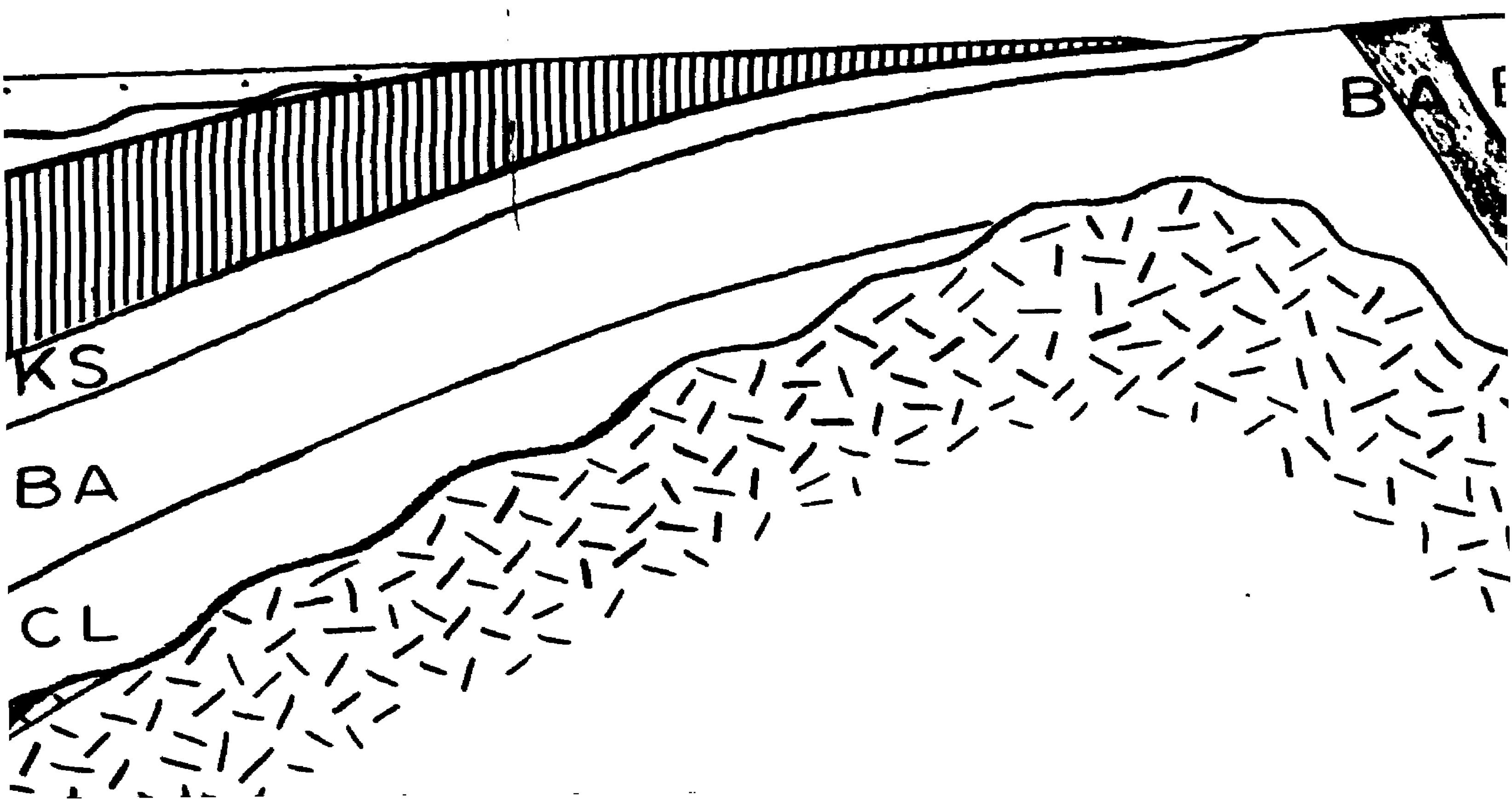
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KS
BA
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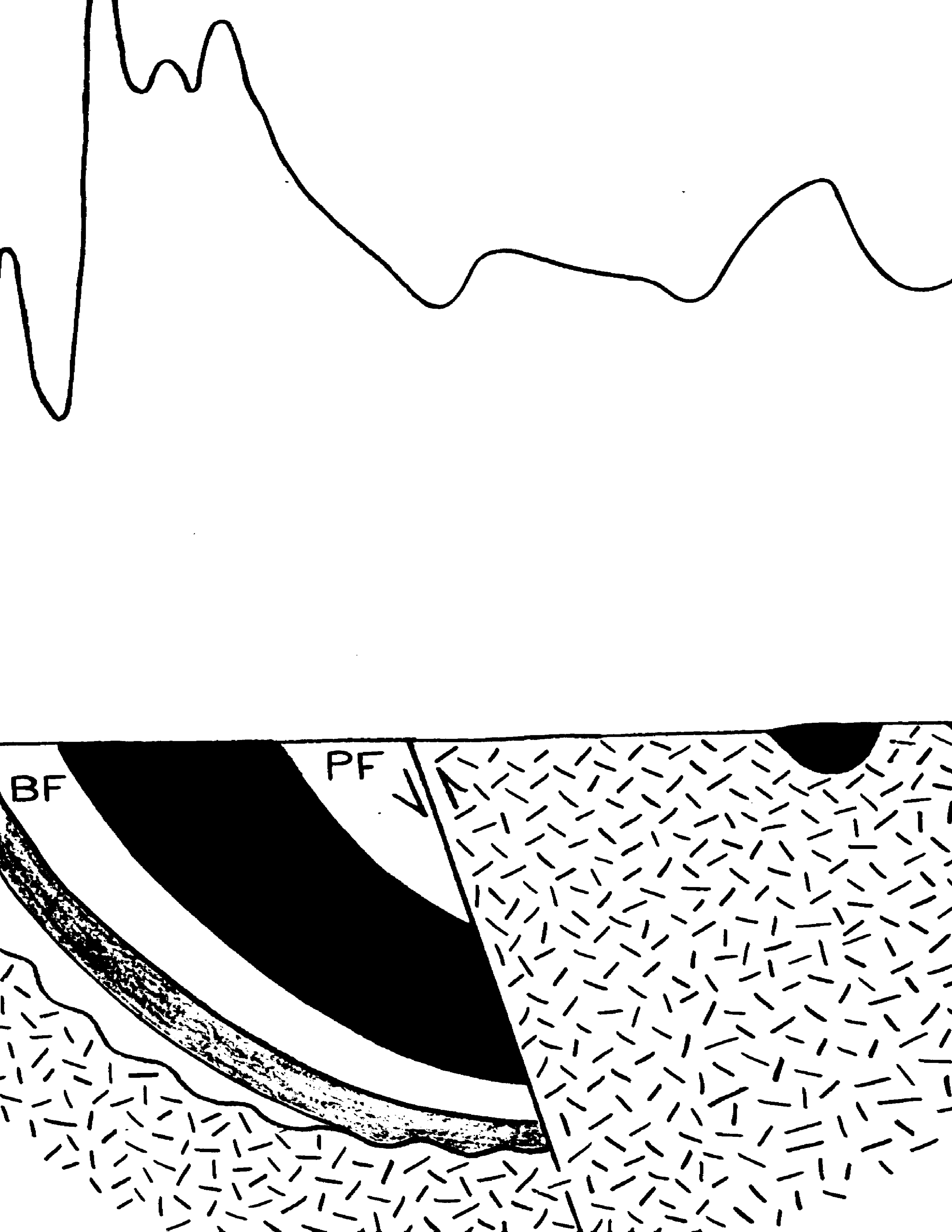
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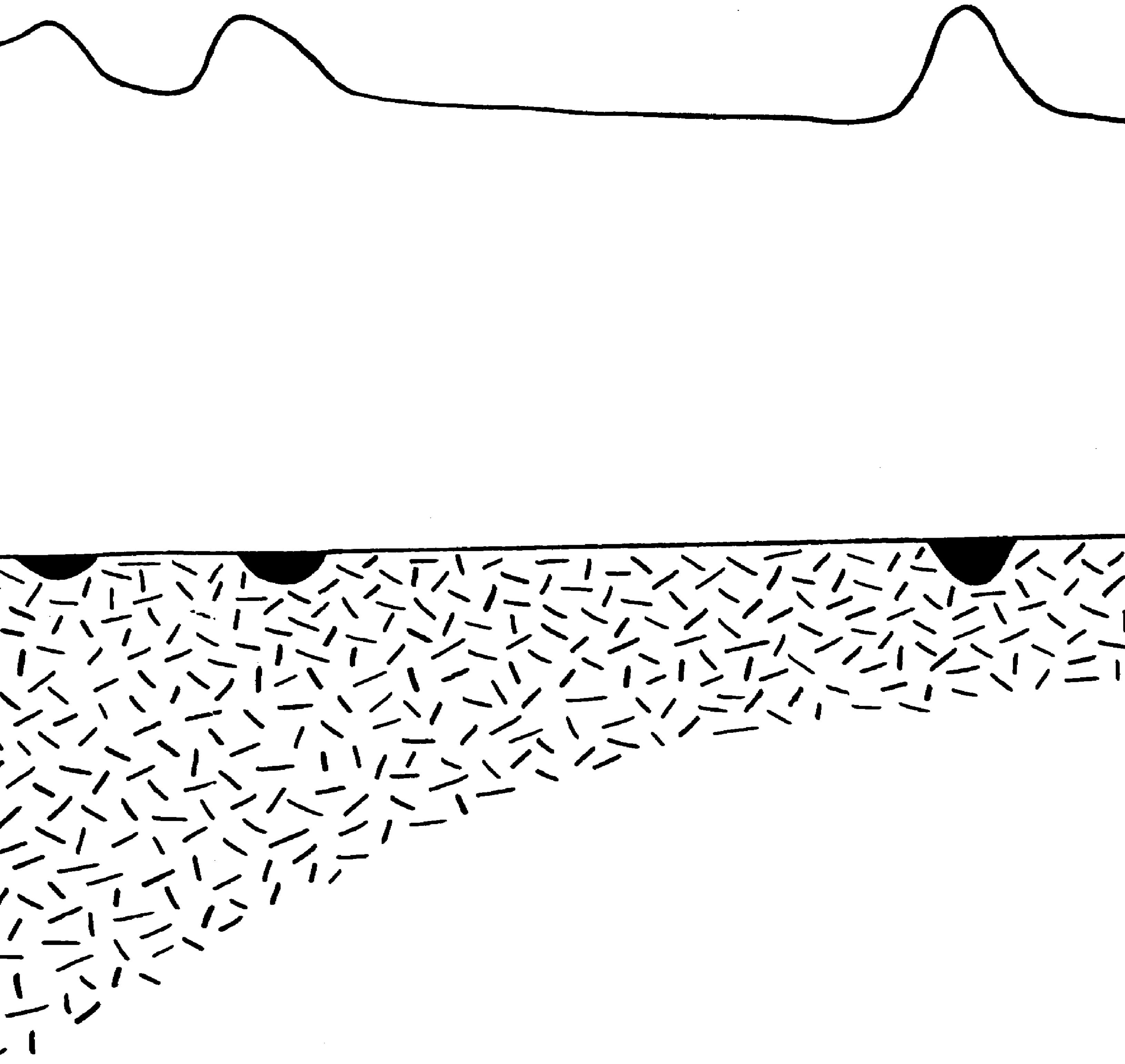

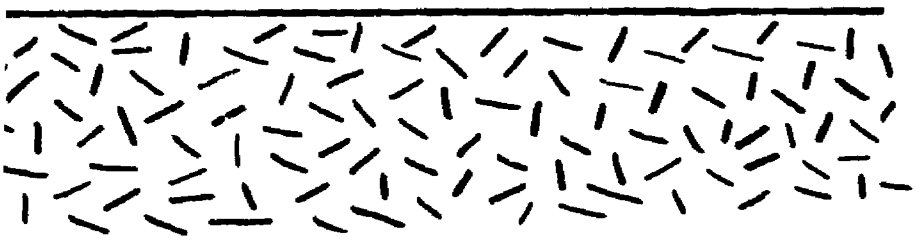

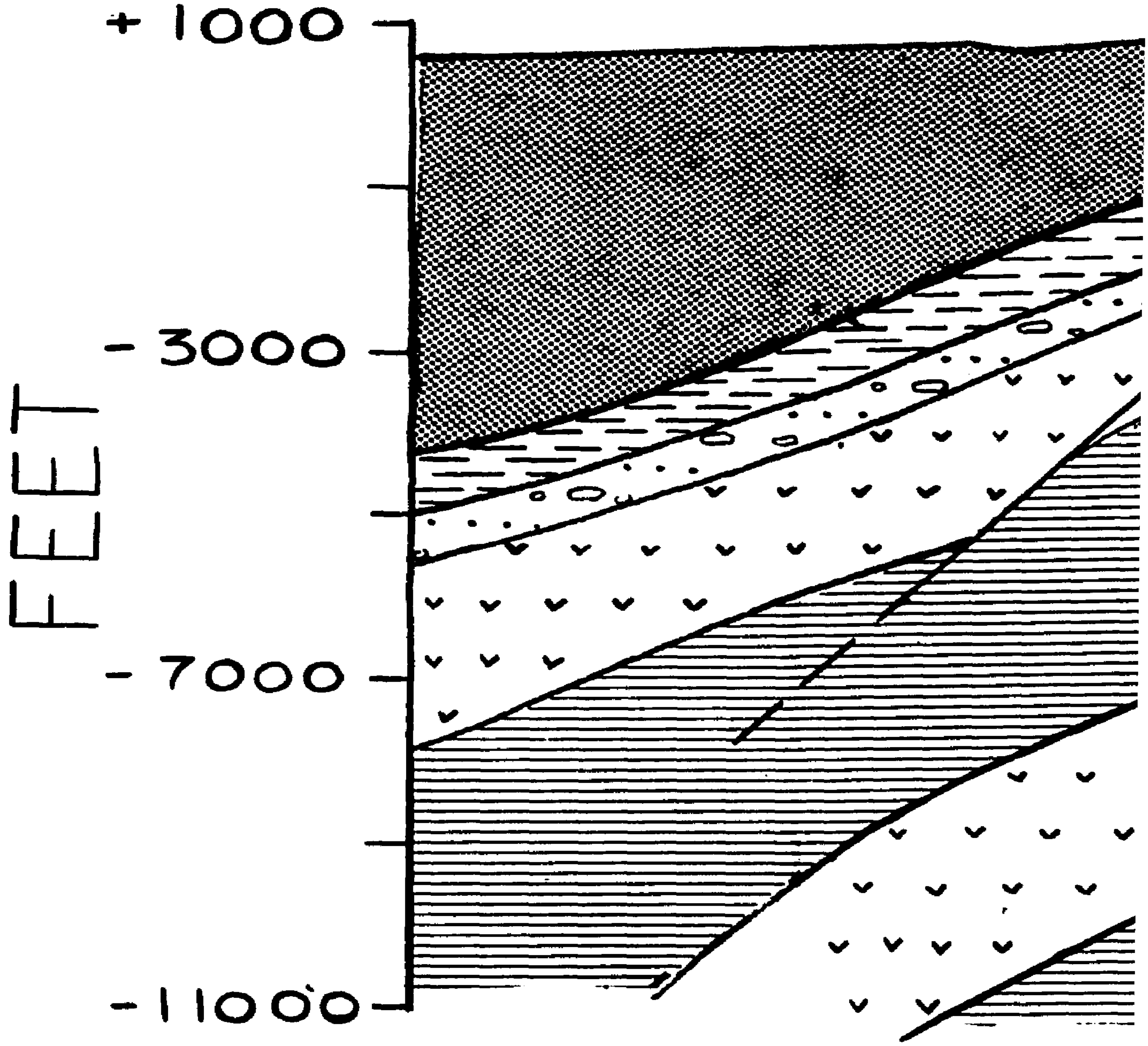

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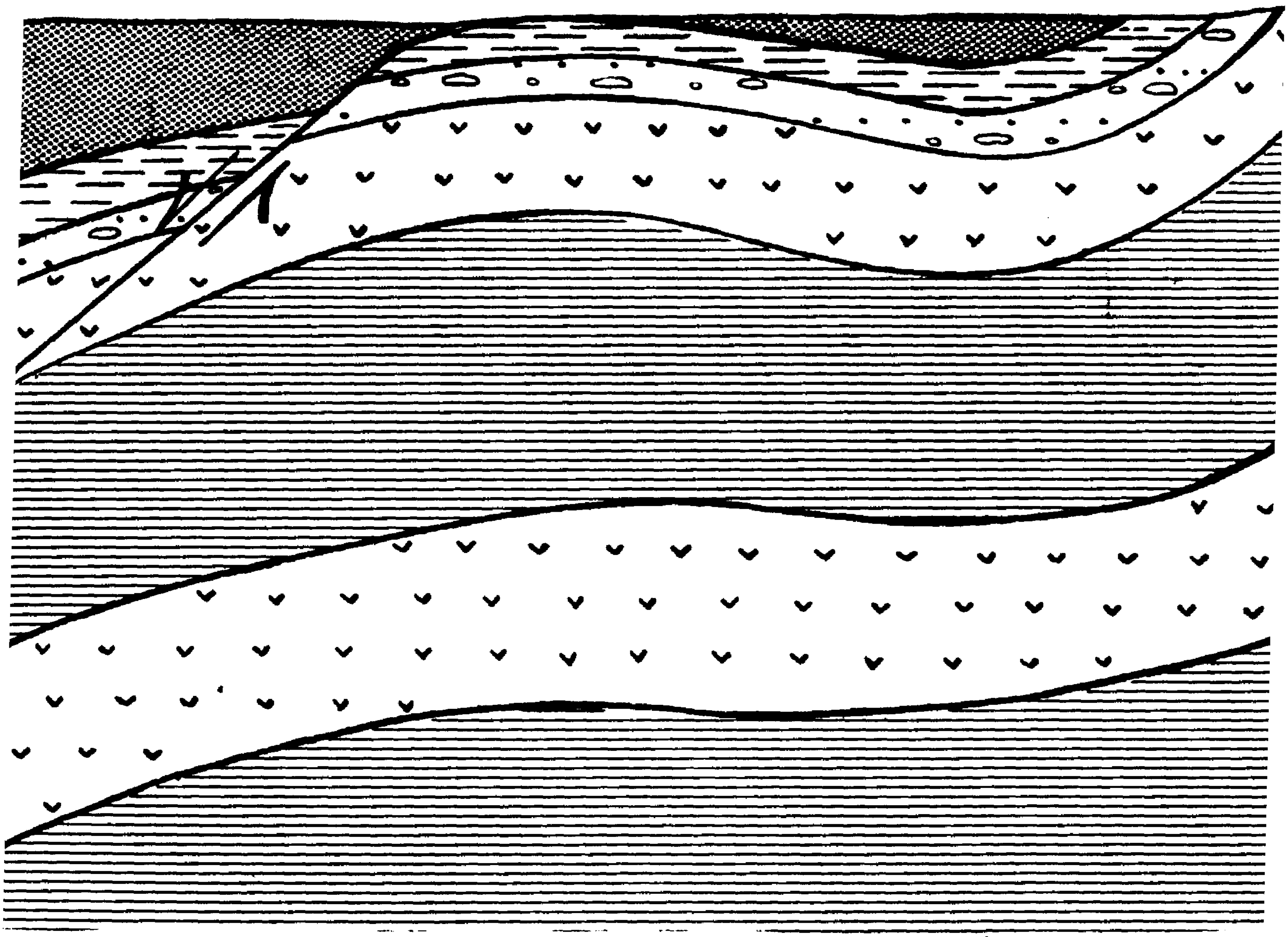

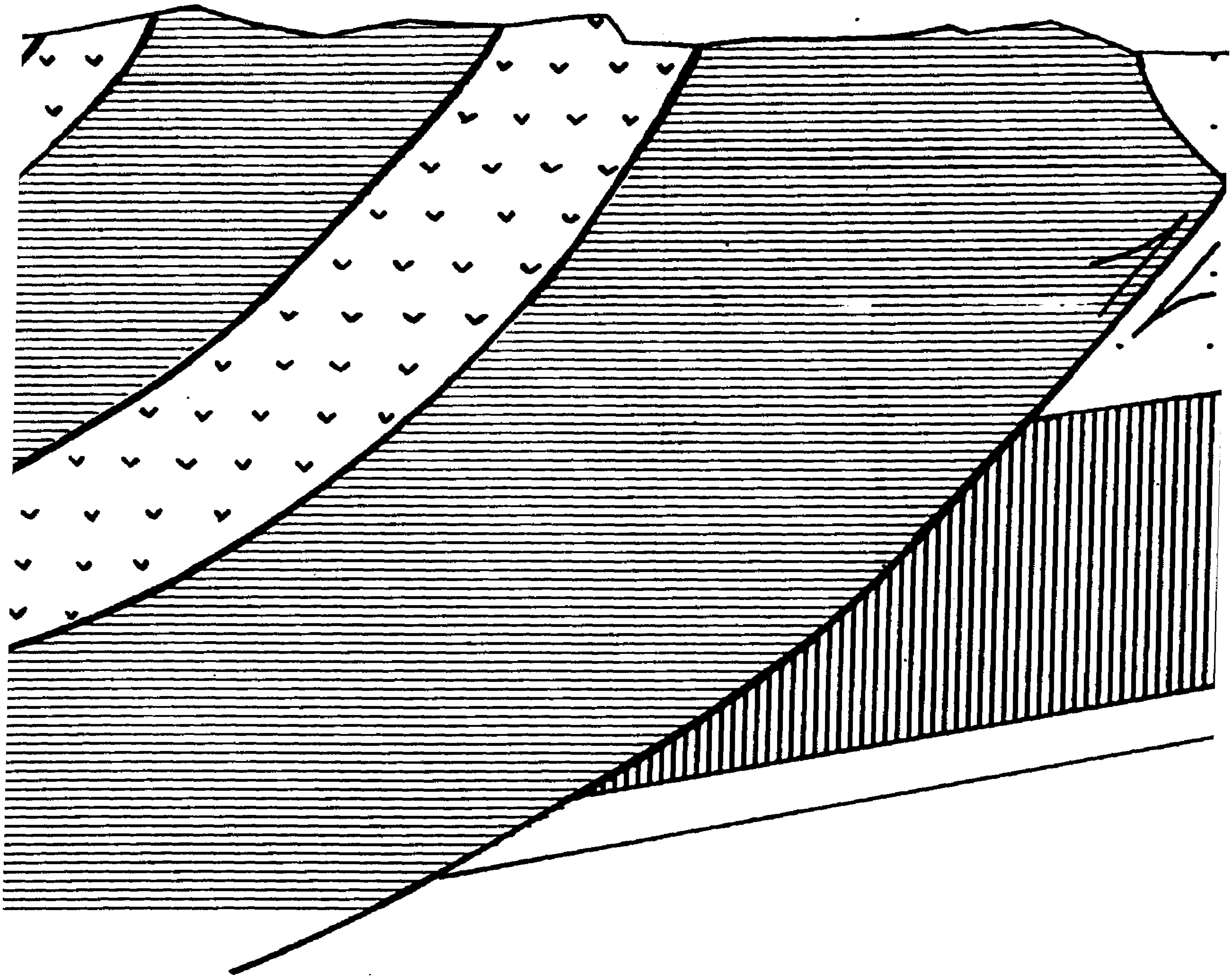

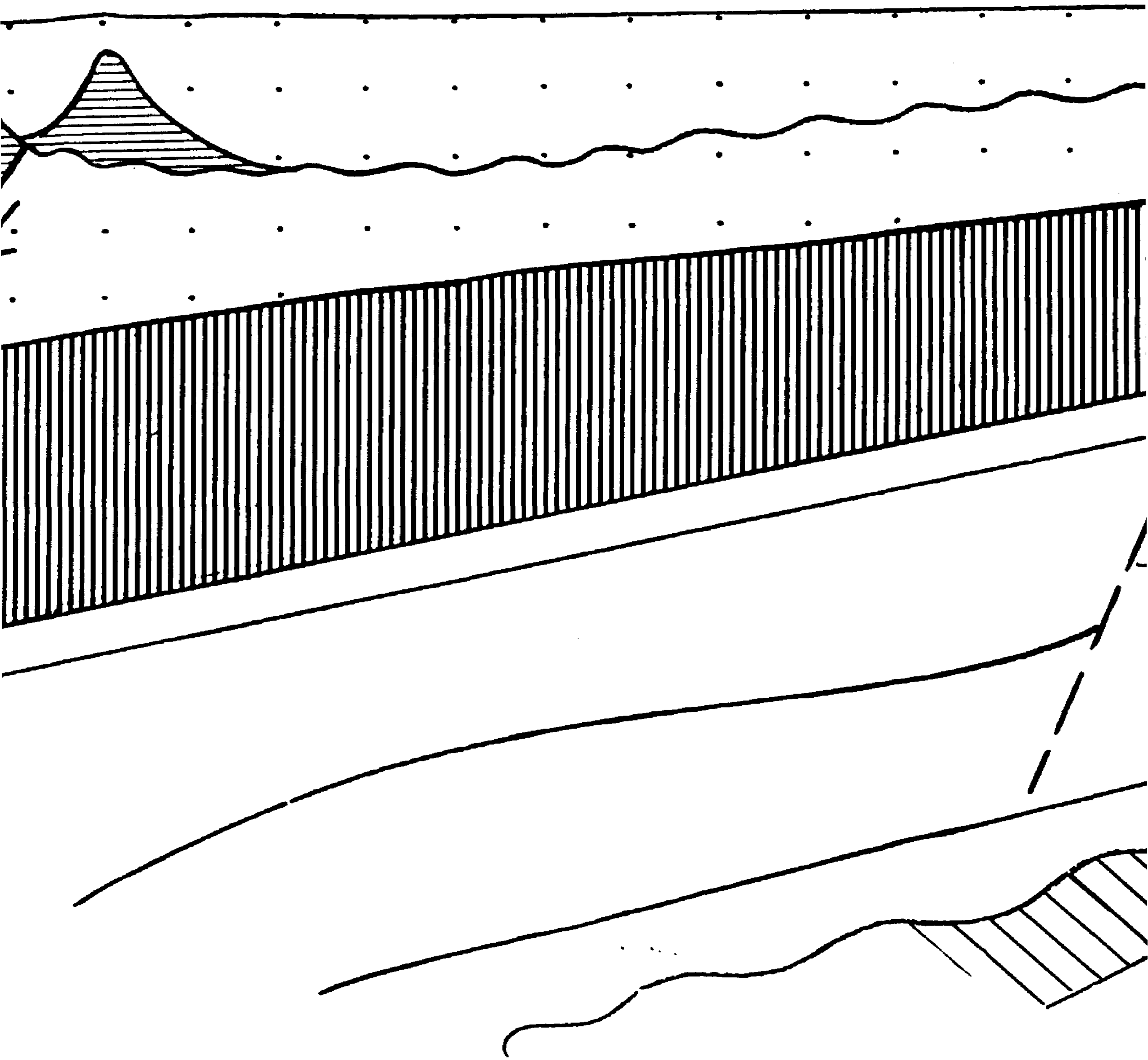

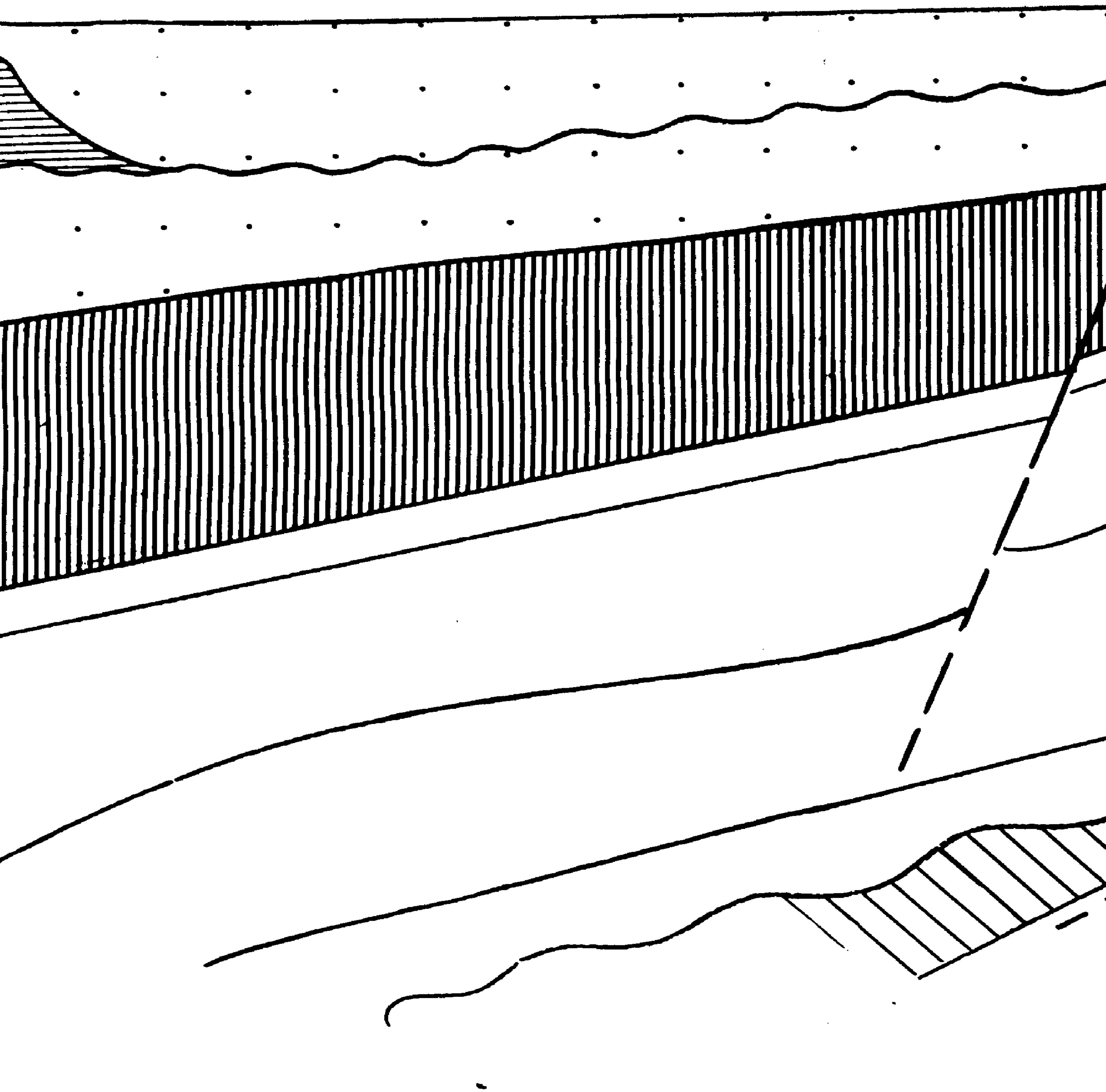

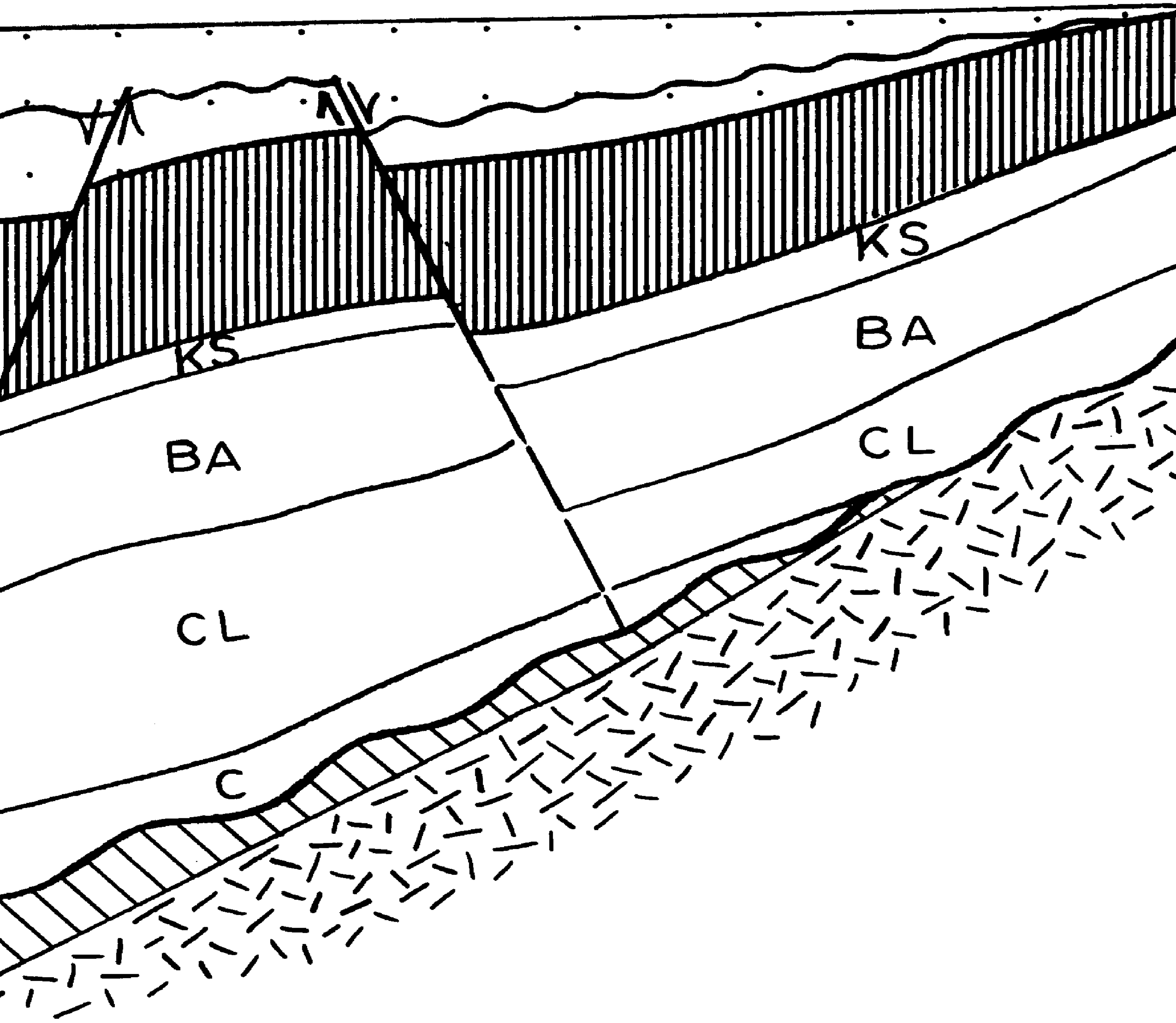
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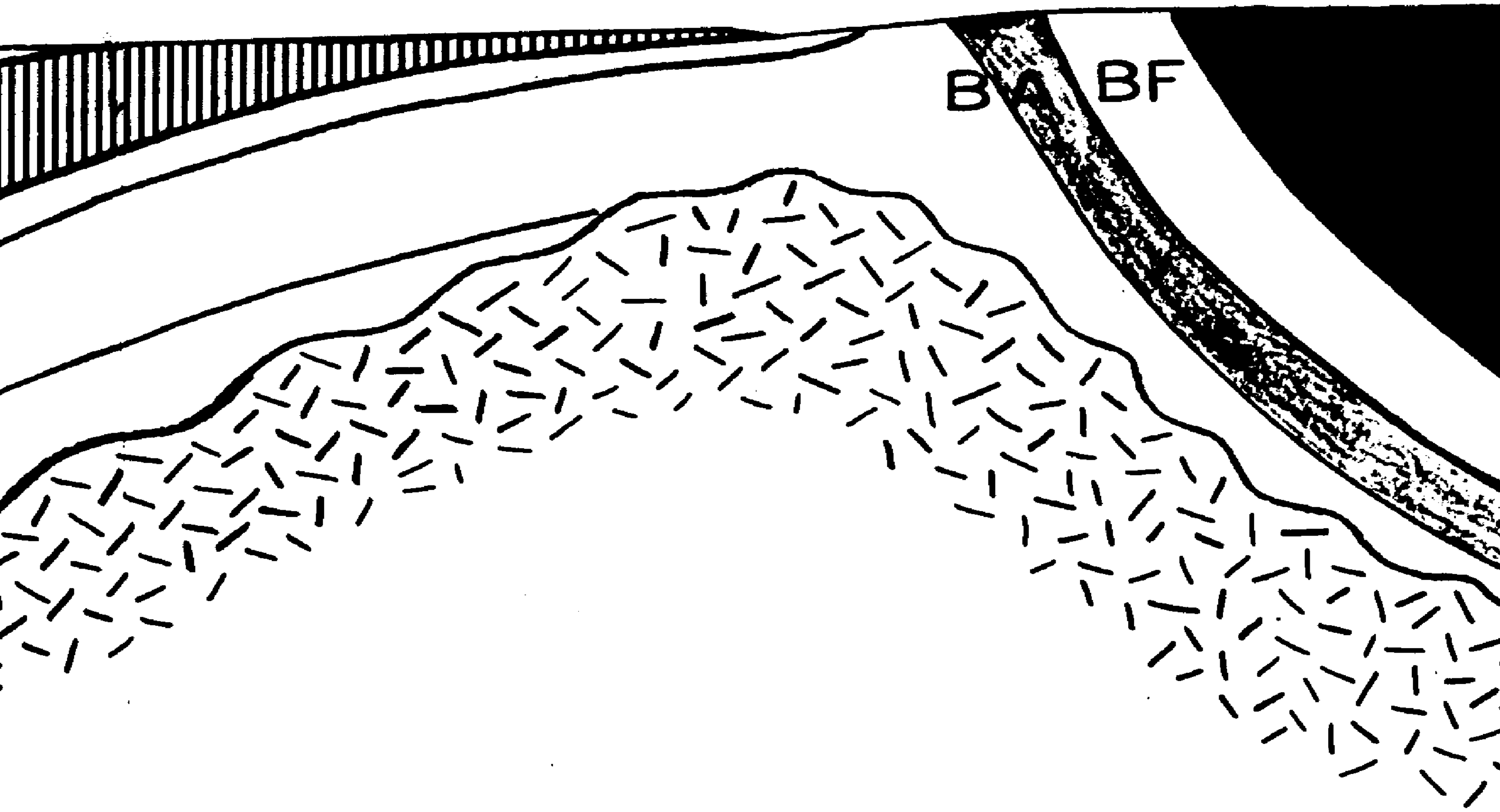
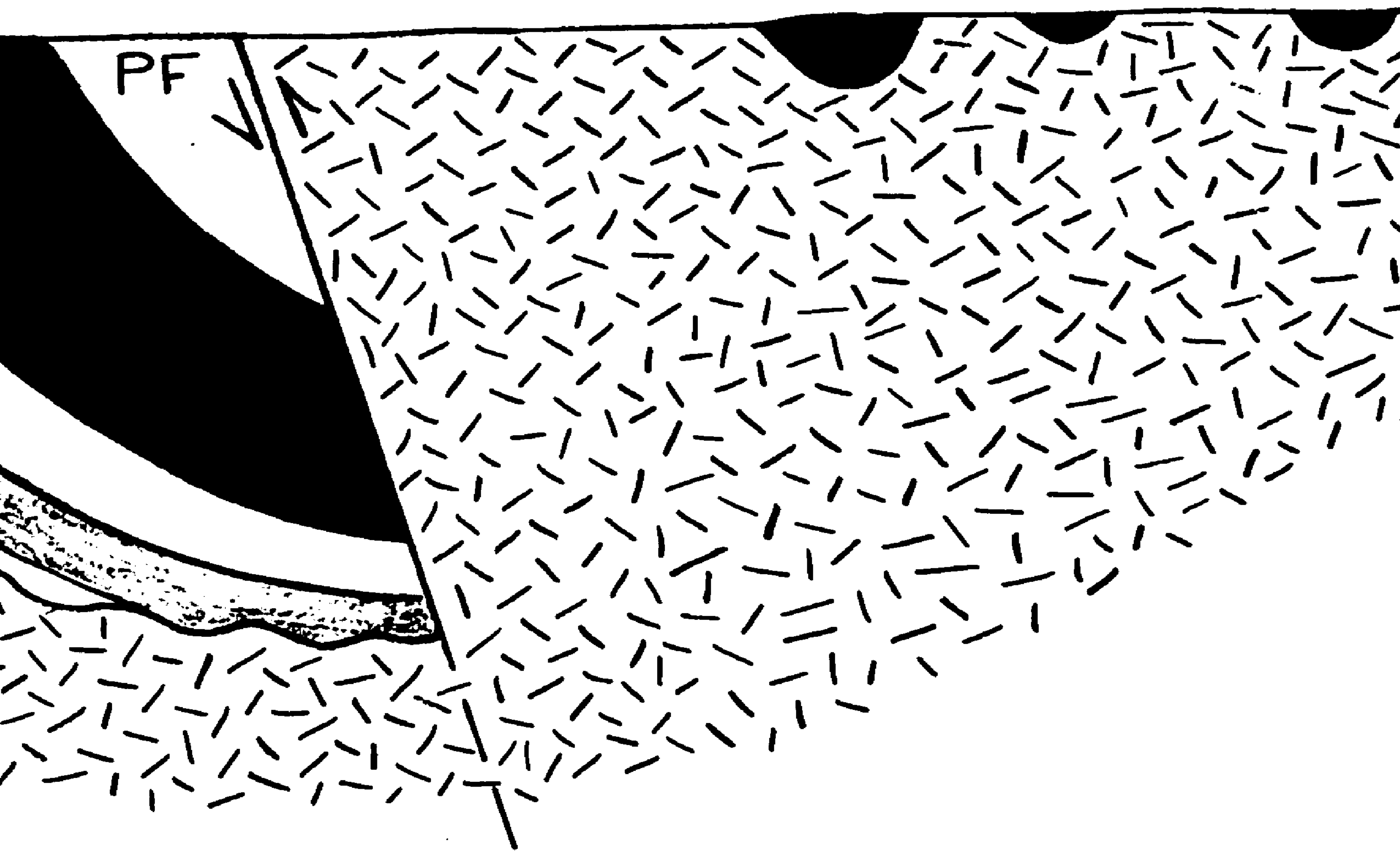
BA
CL
C
KS
BA
CL


B A BF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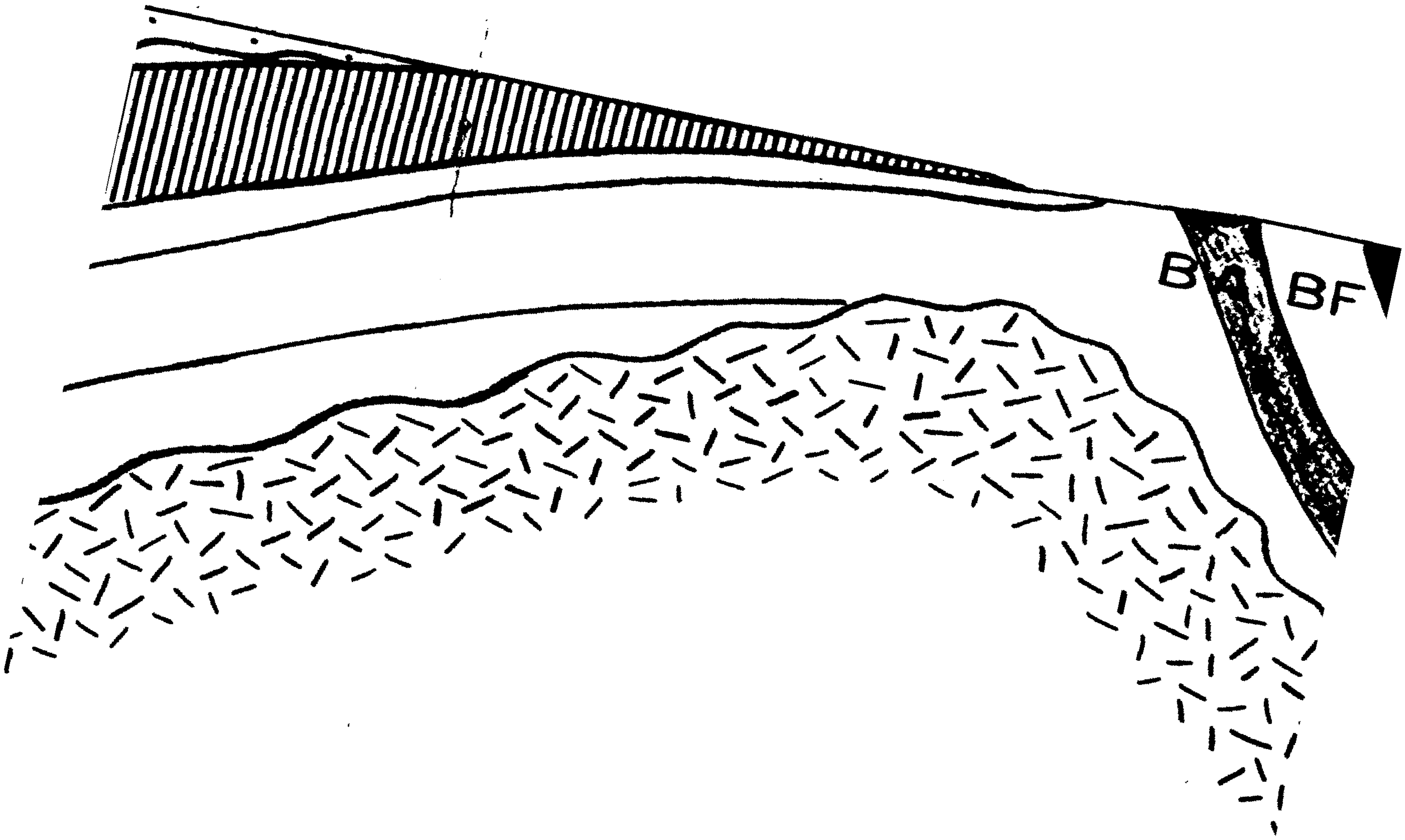
B
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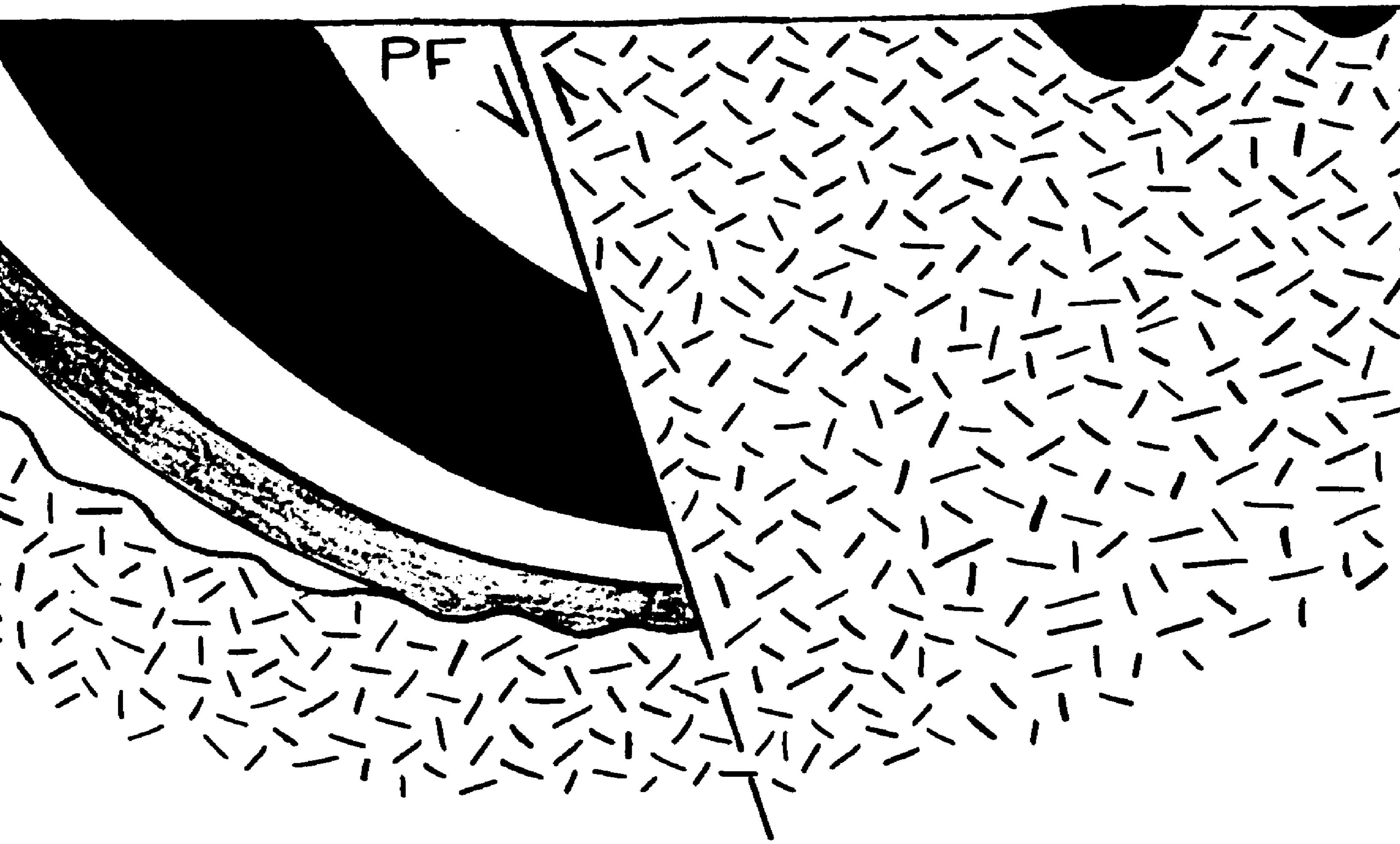
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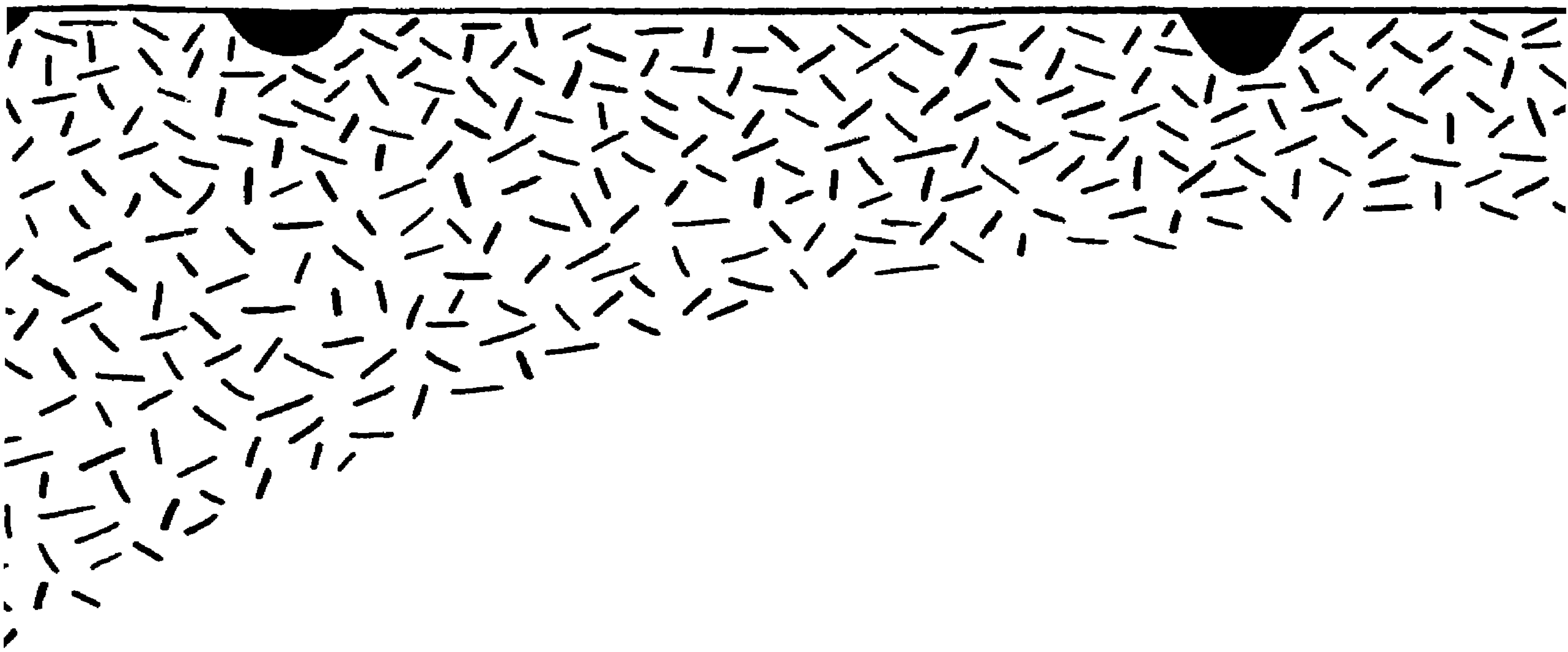

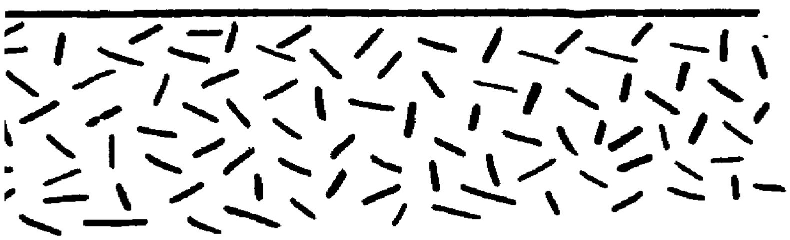

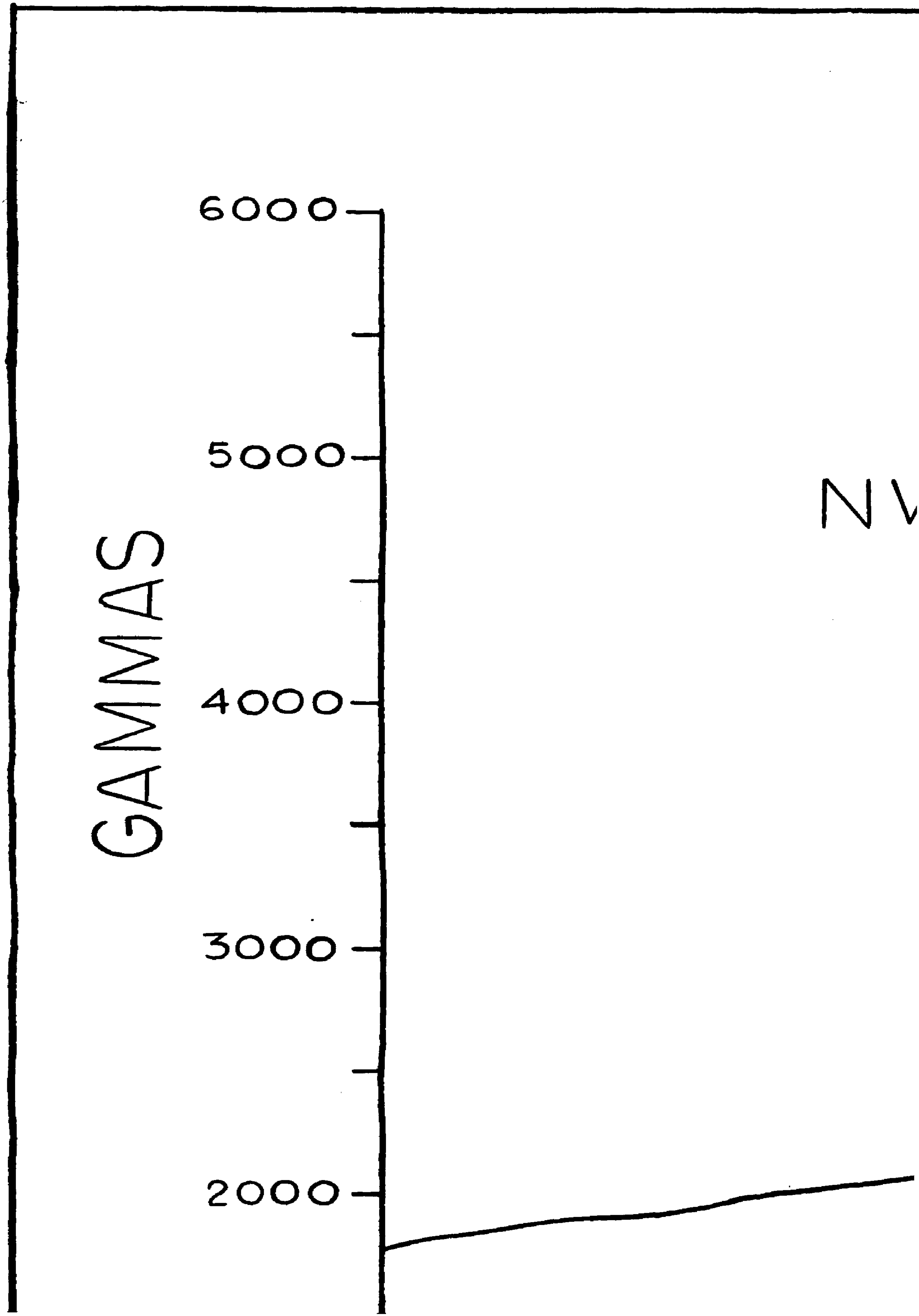
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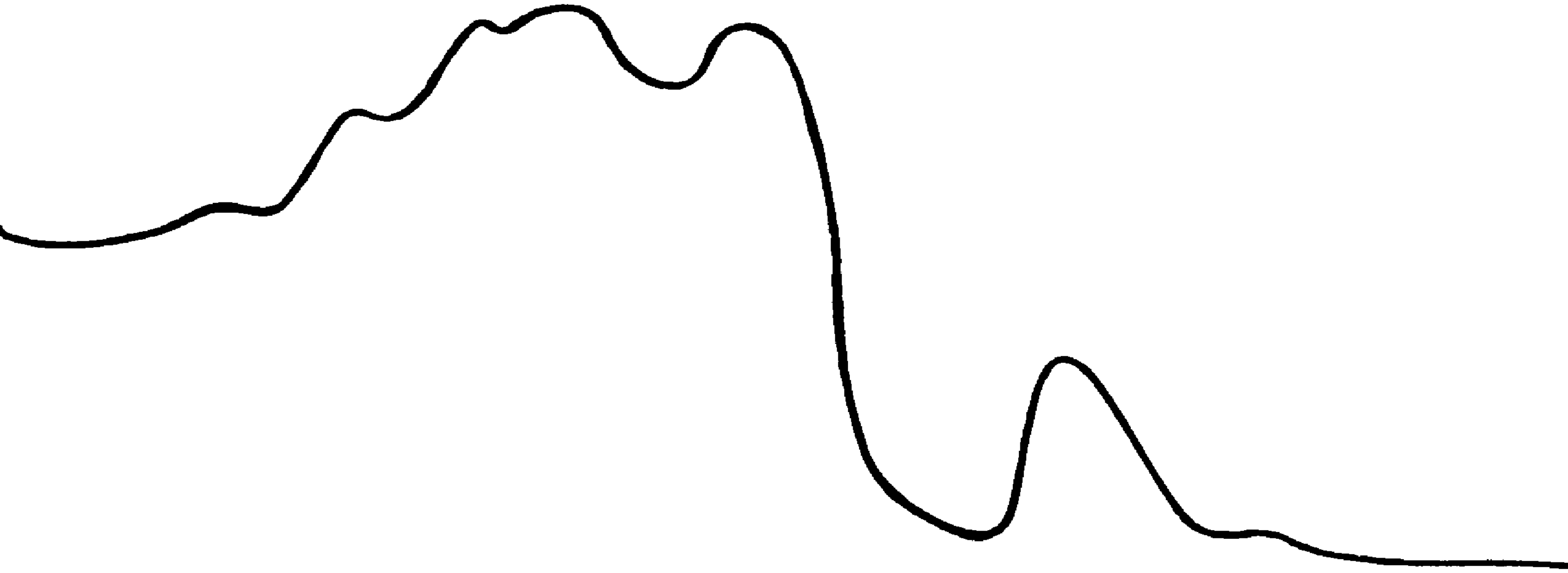
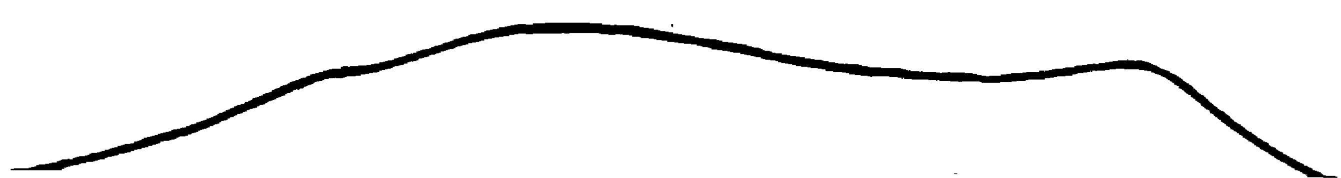
3000
2000
GAMMAS

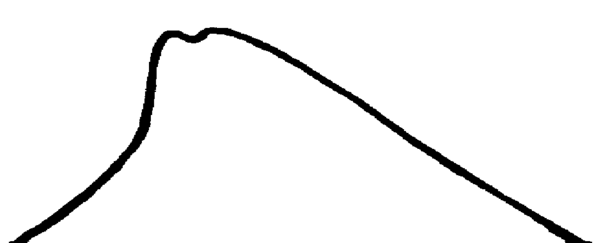

W

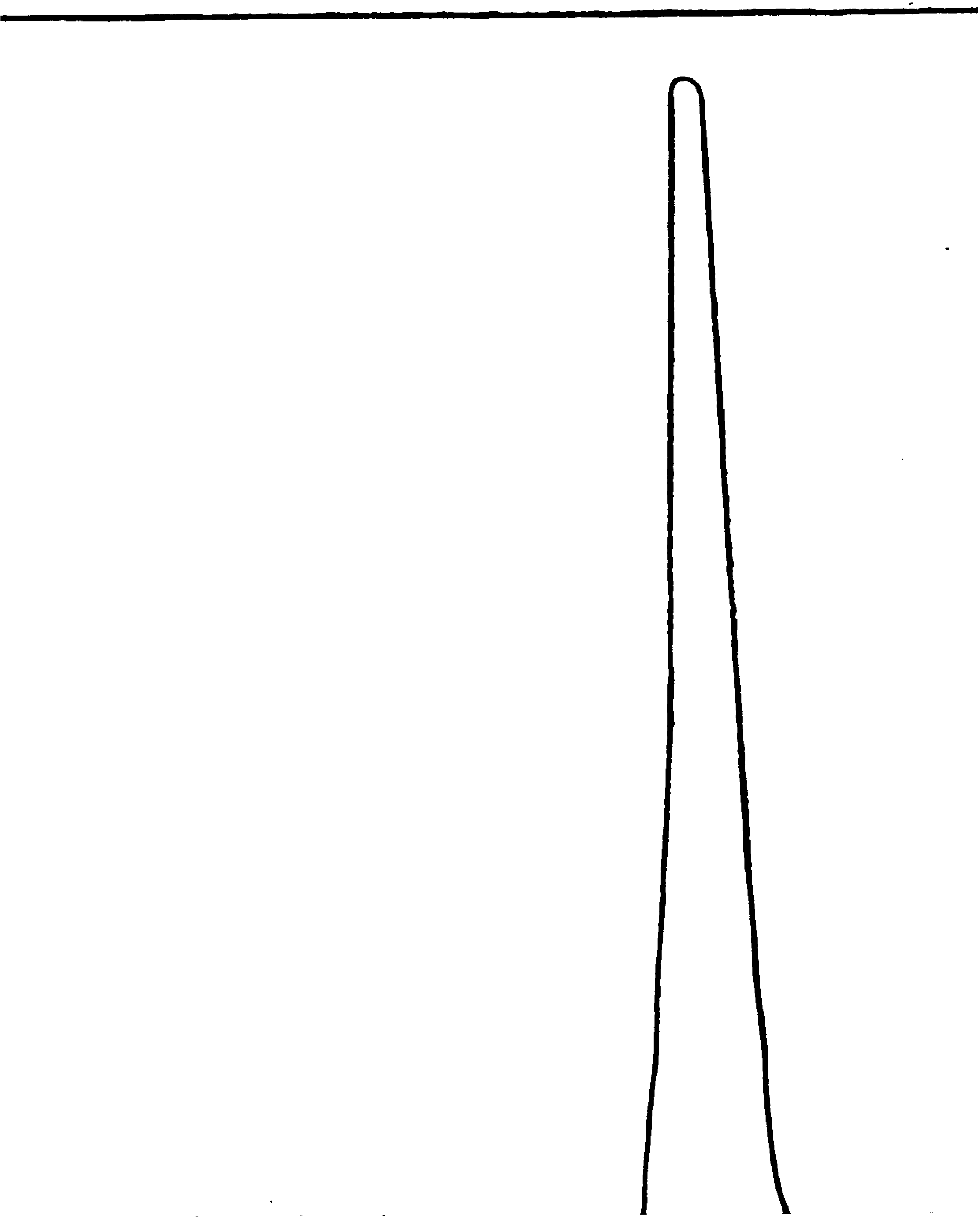


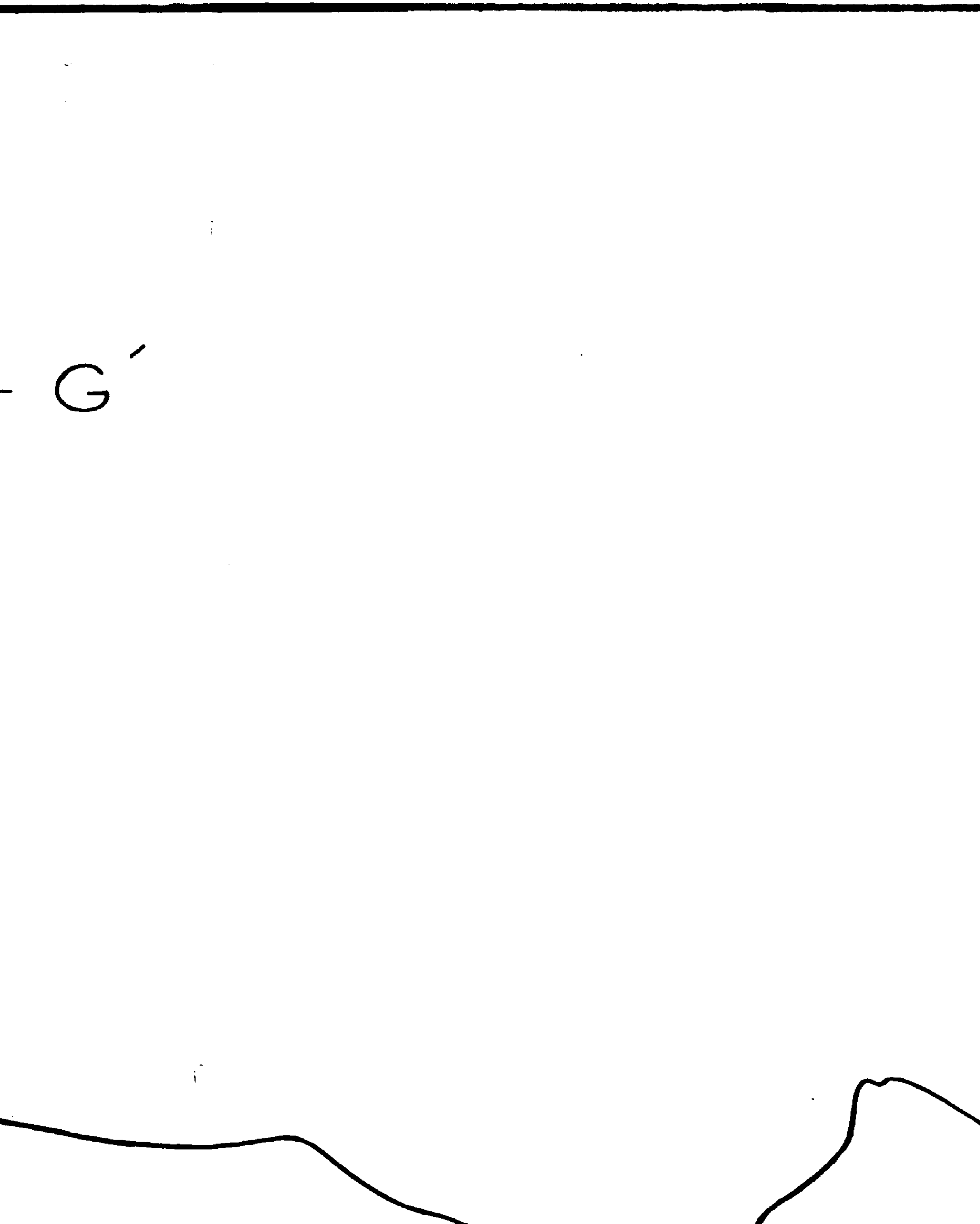
PROF

FILE G – G′





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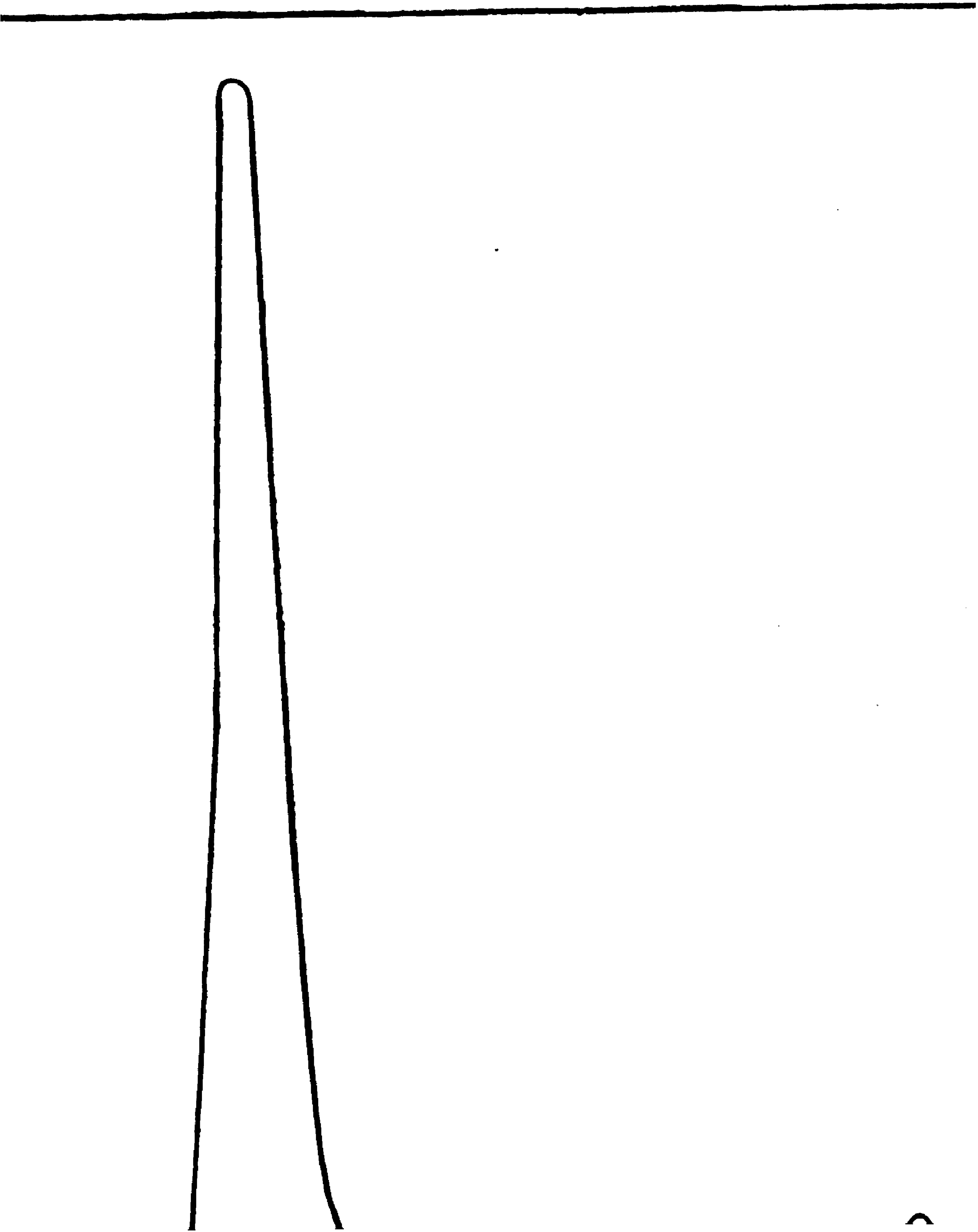

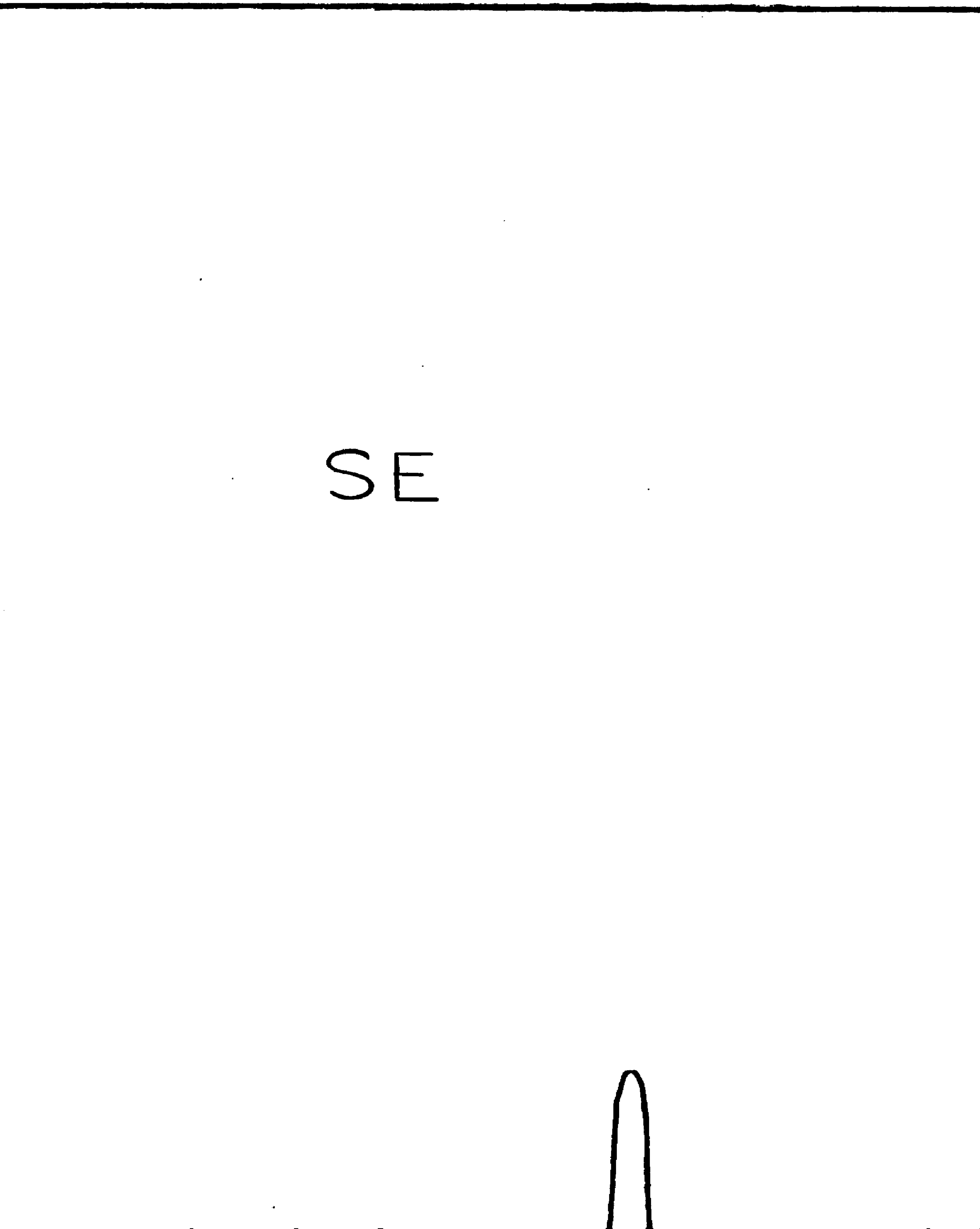
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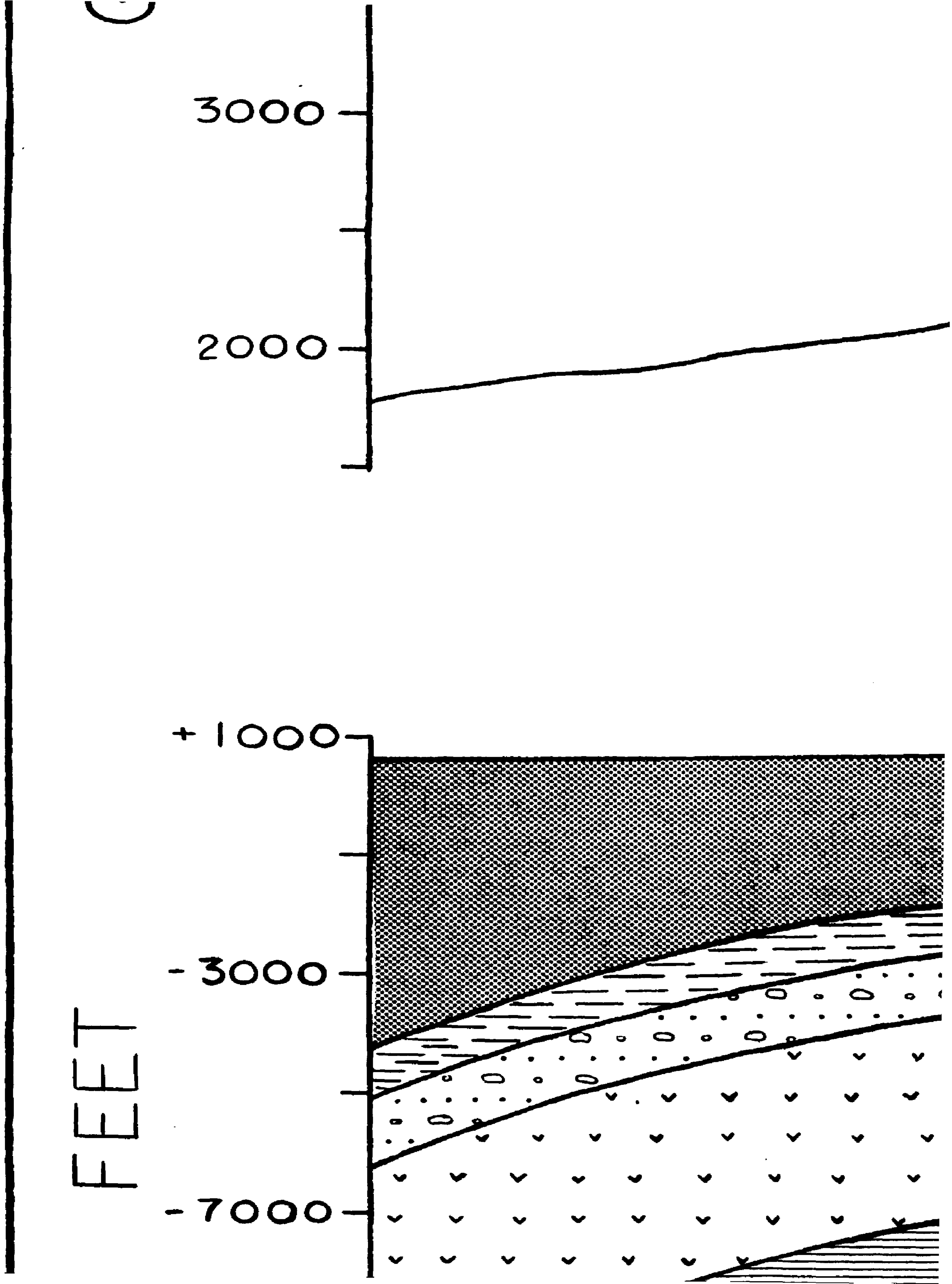
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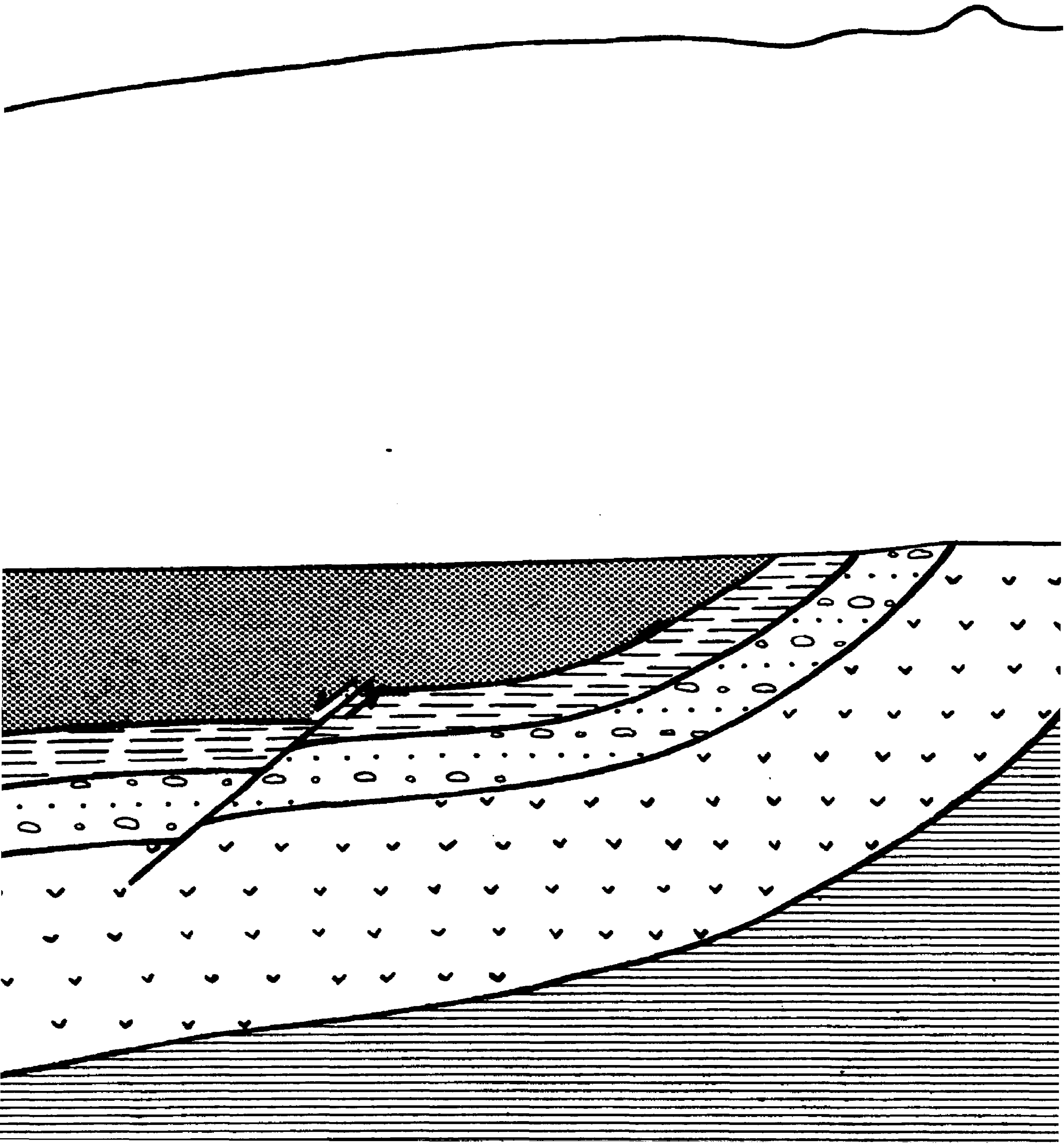

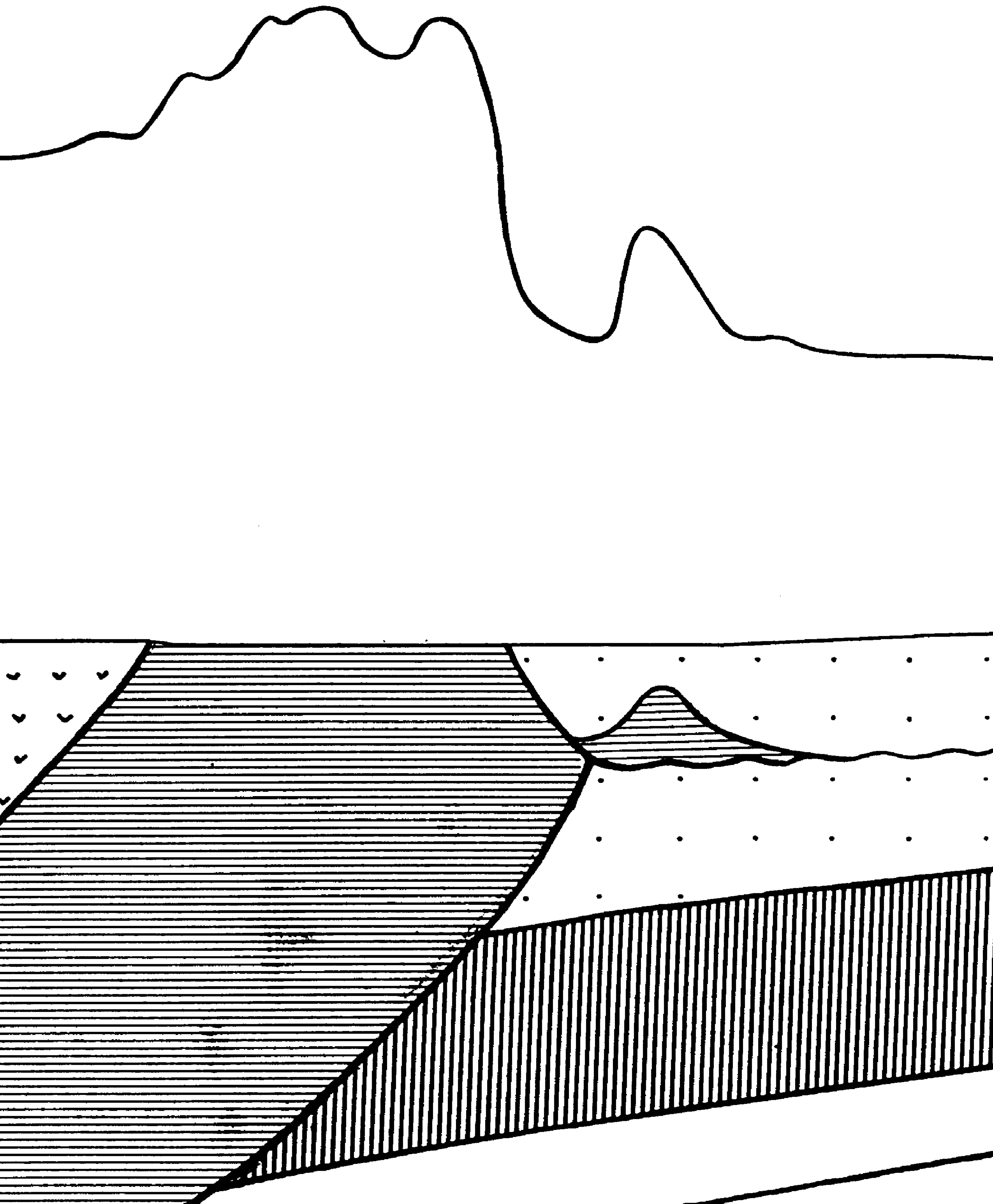

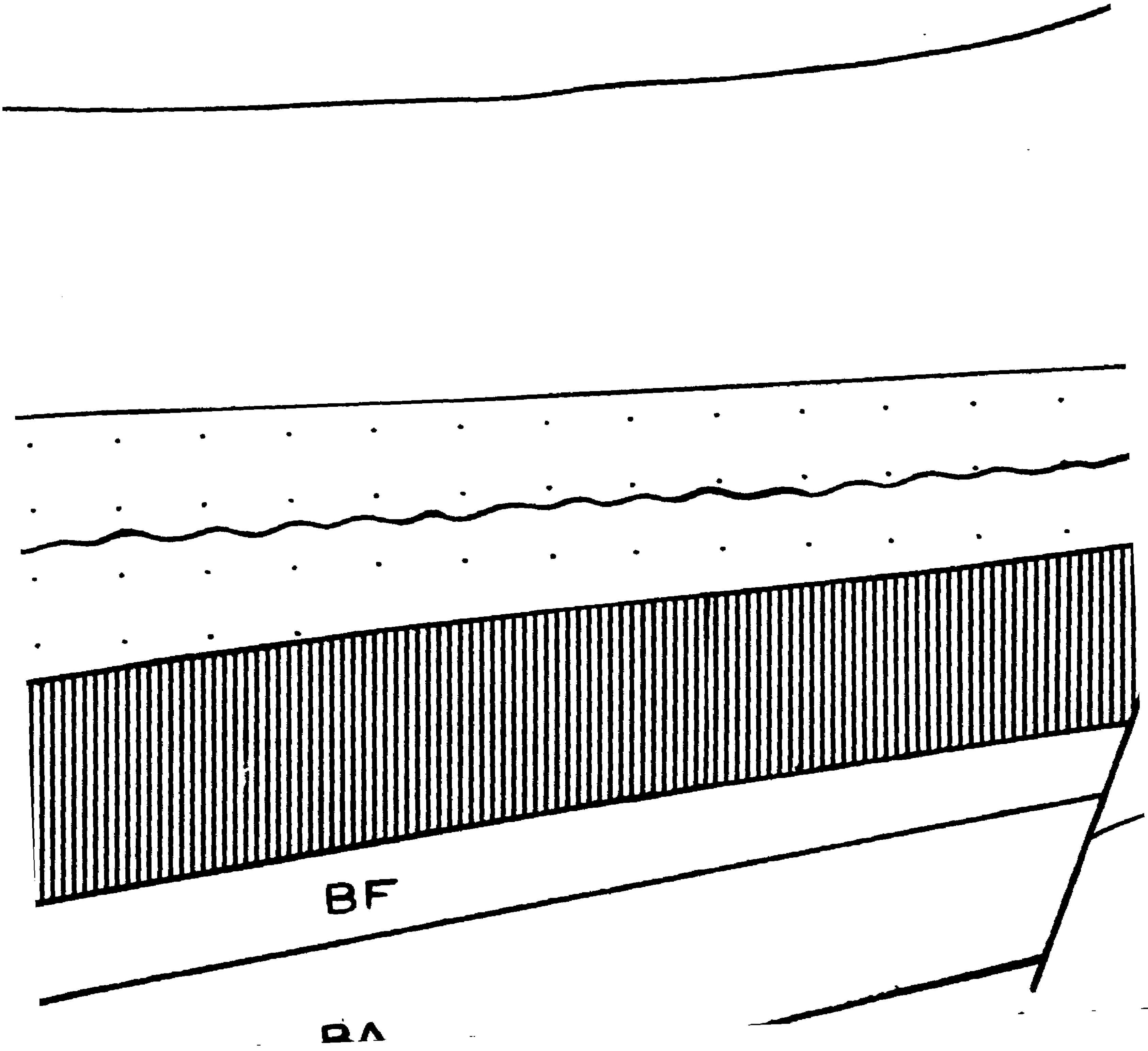
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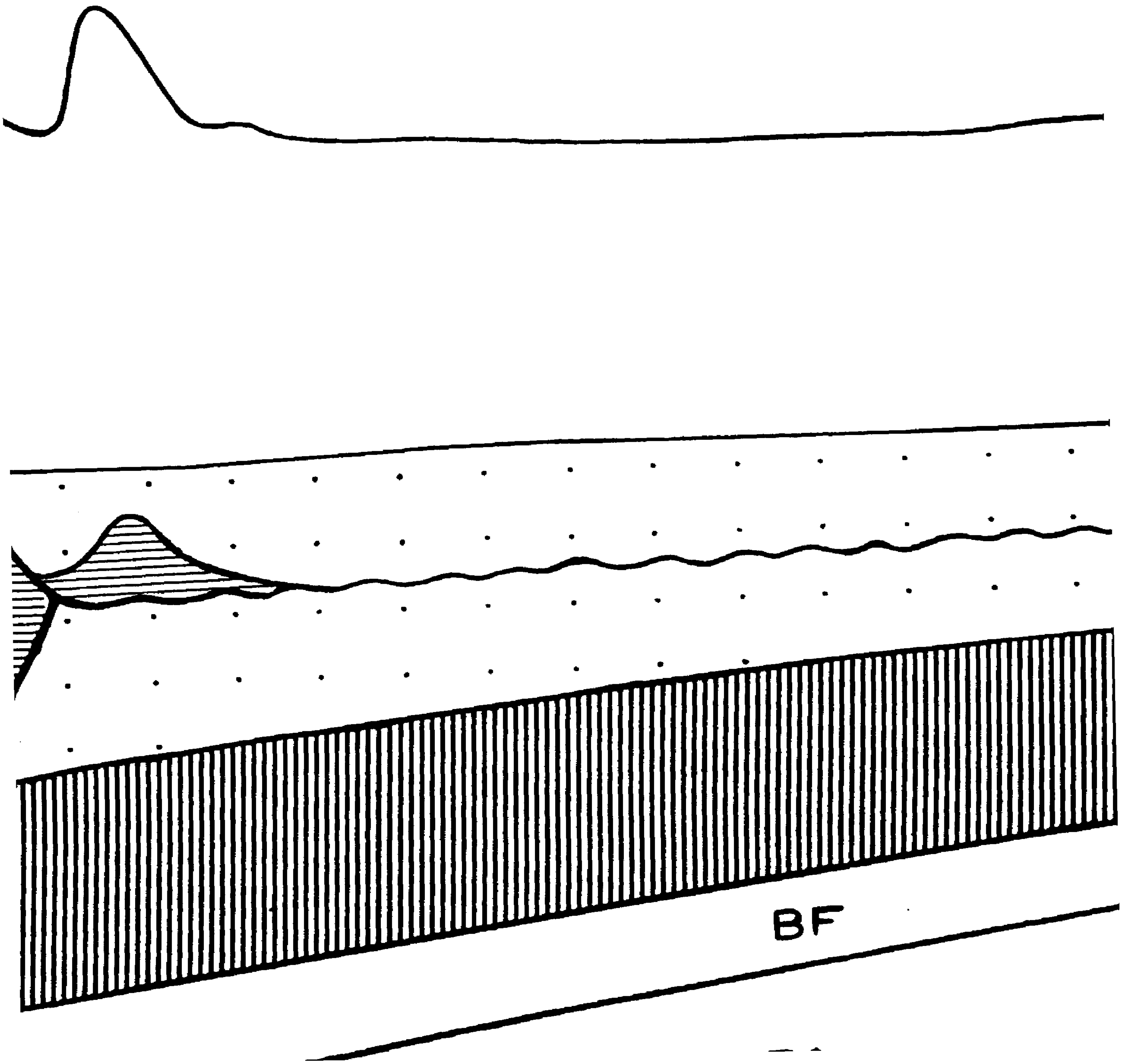
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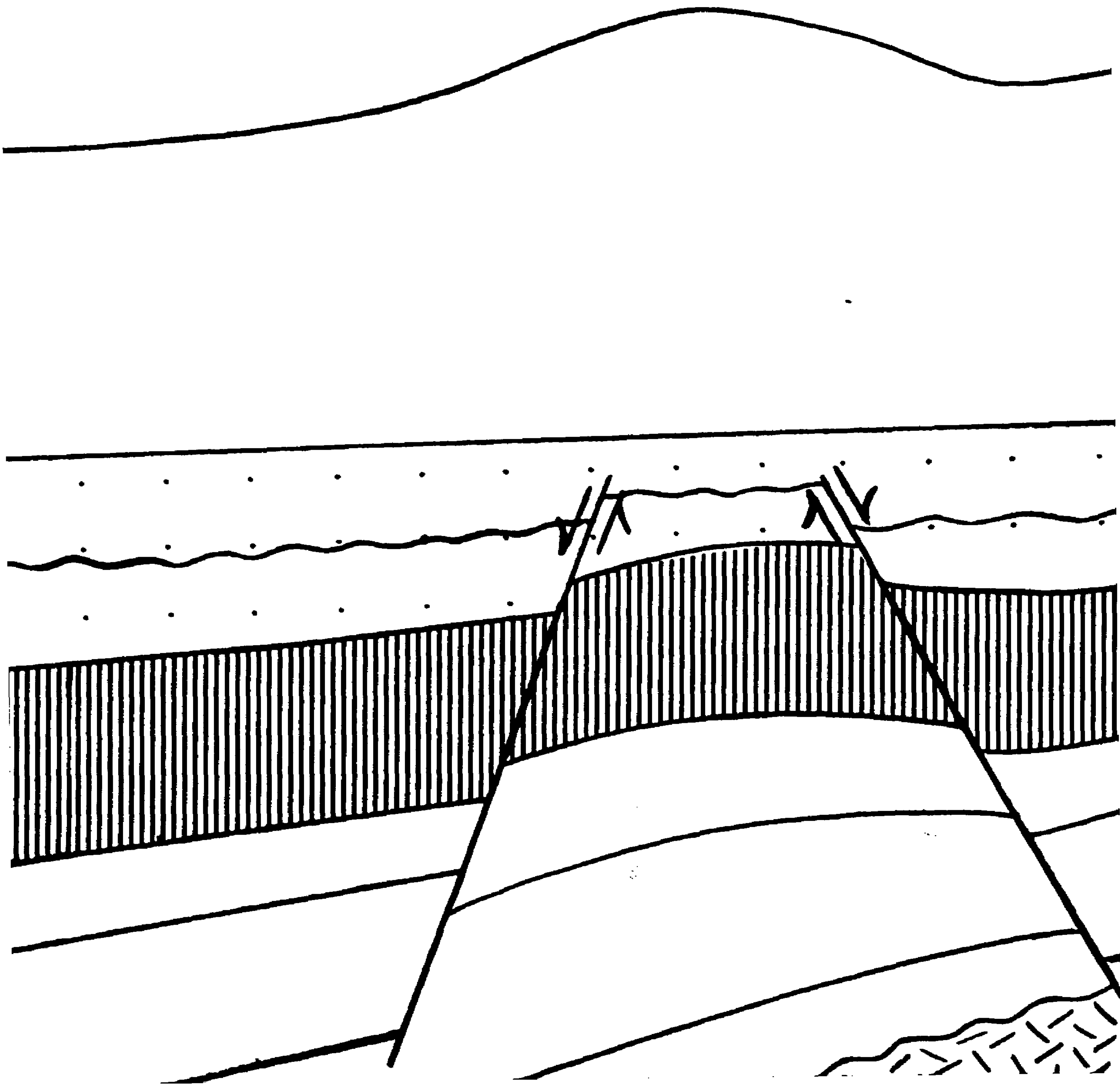

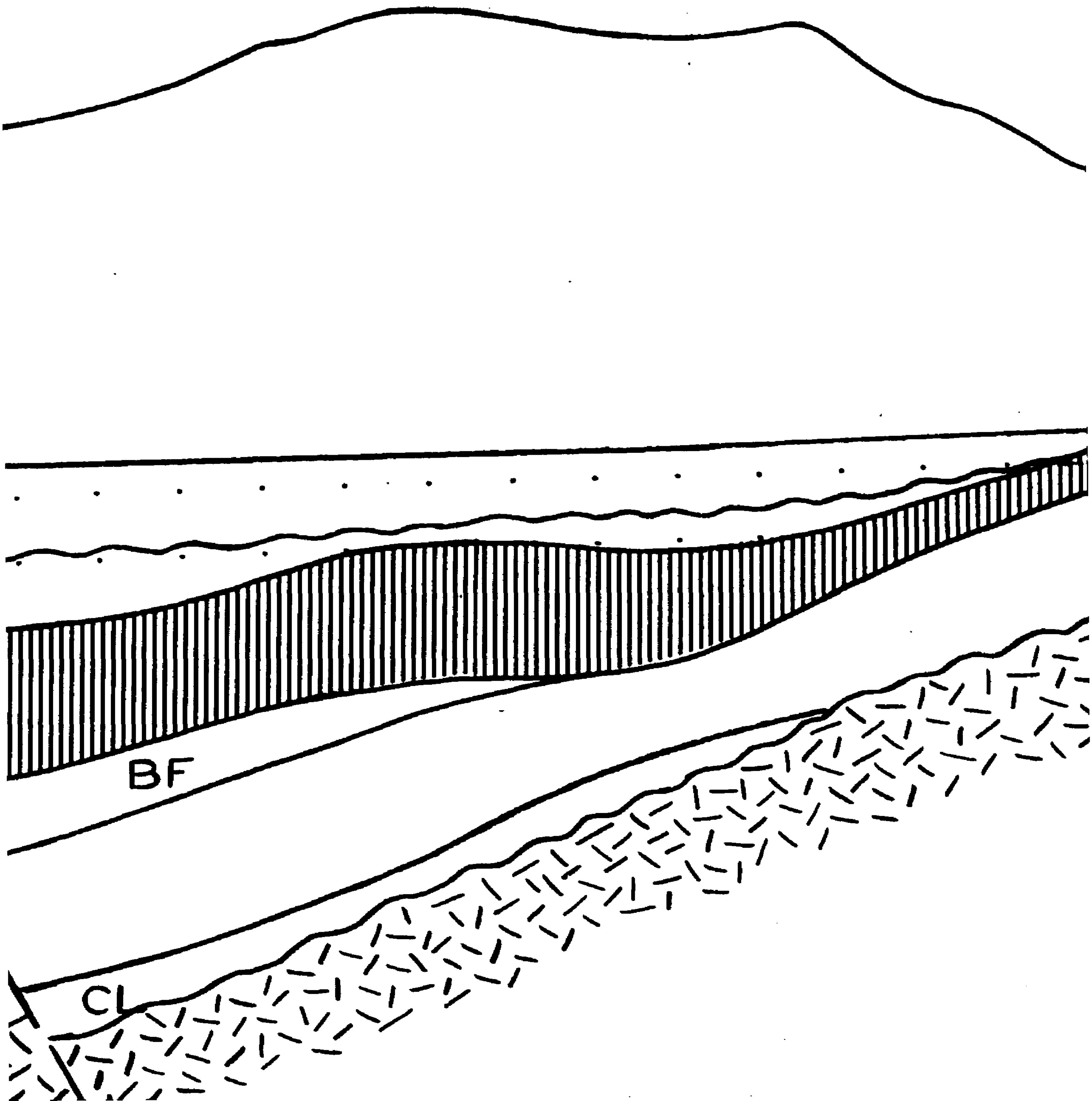
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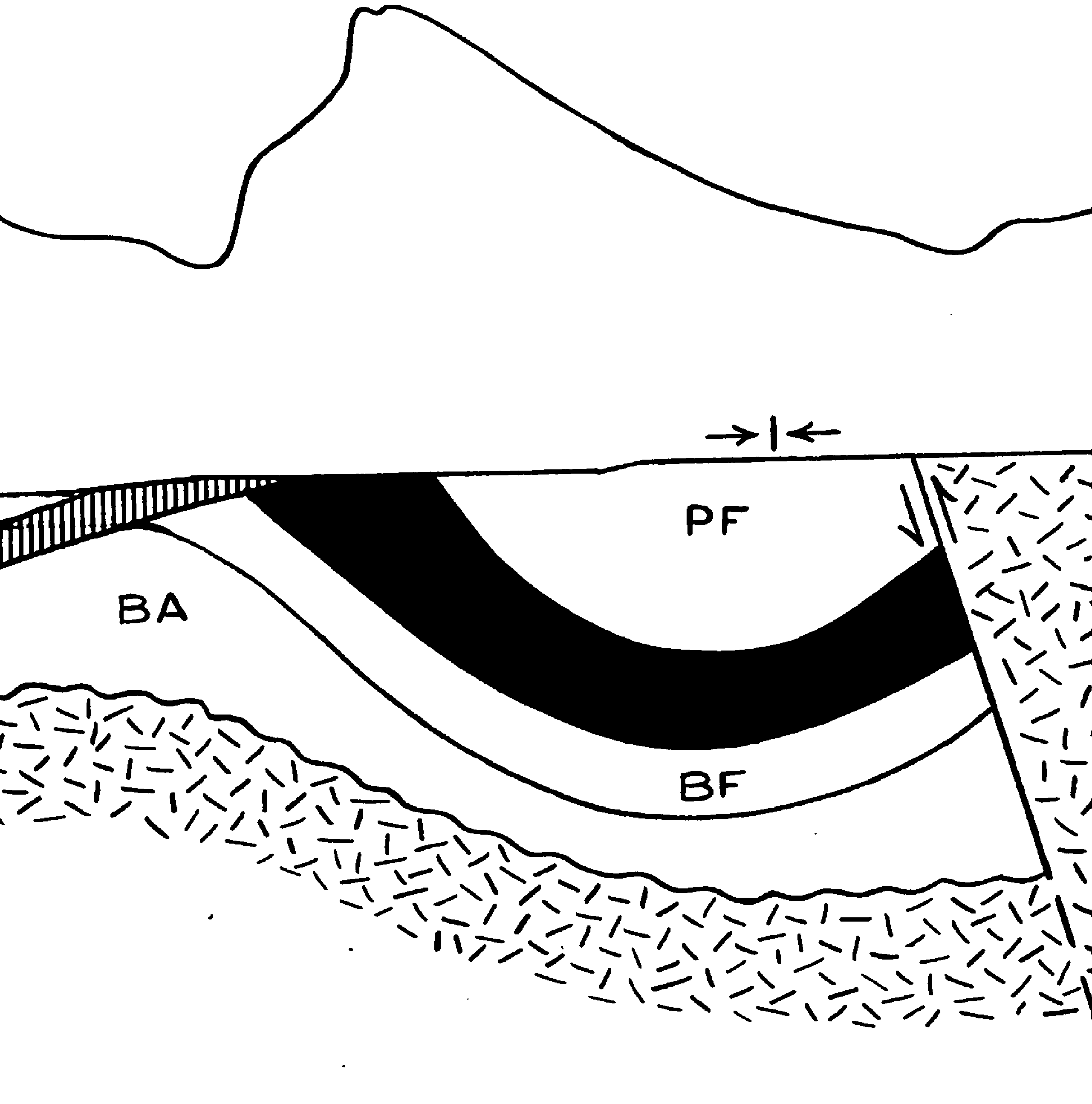
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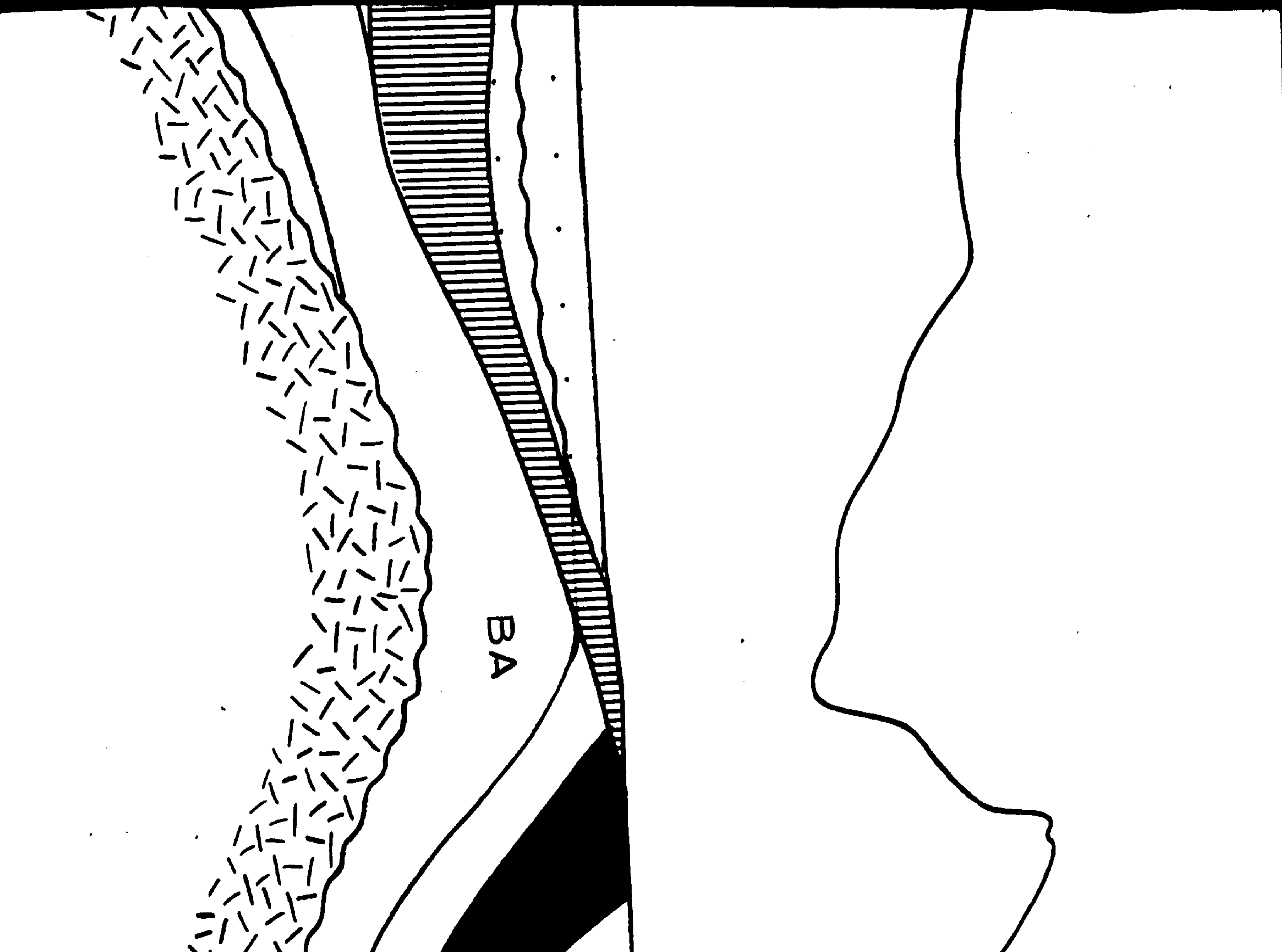
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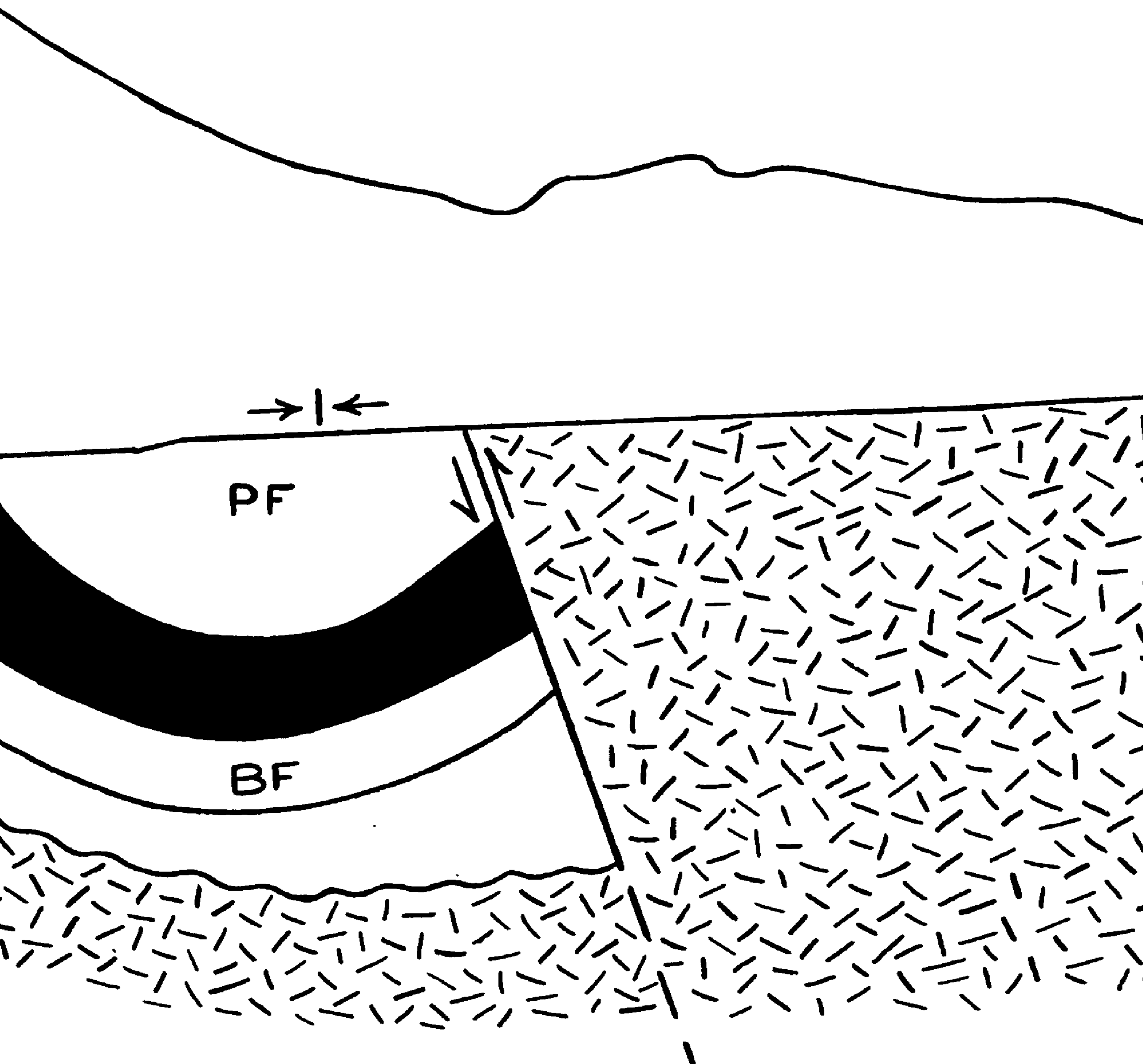
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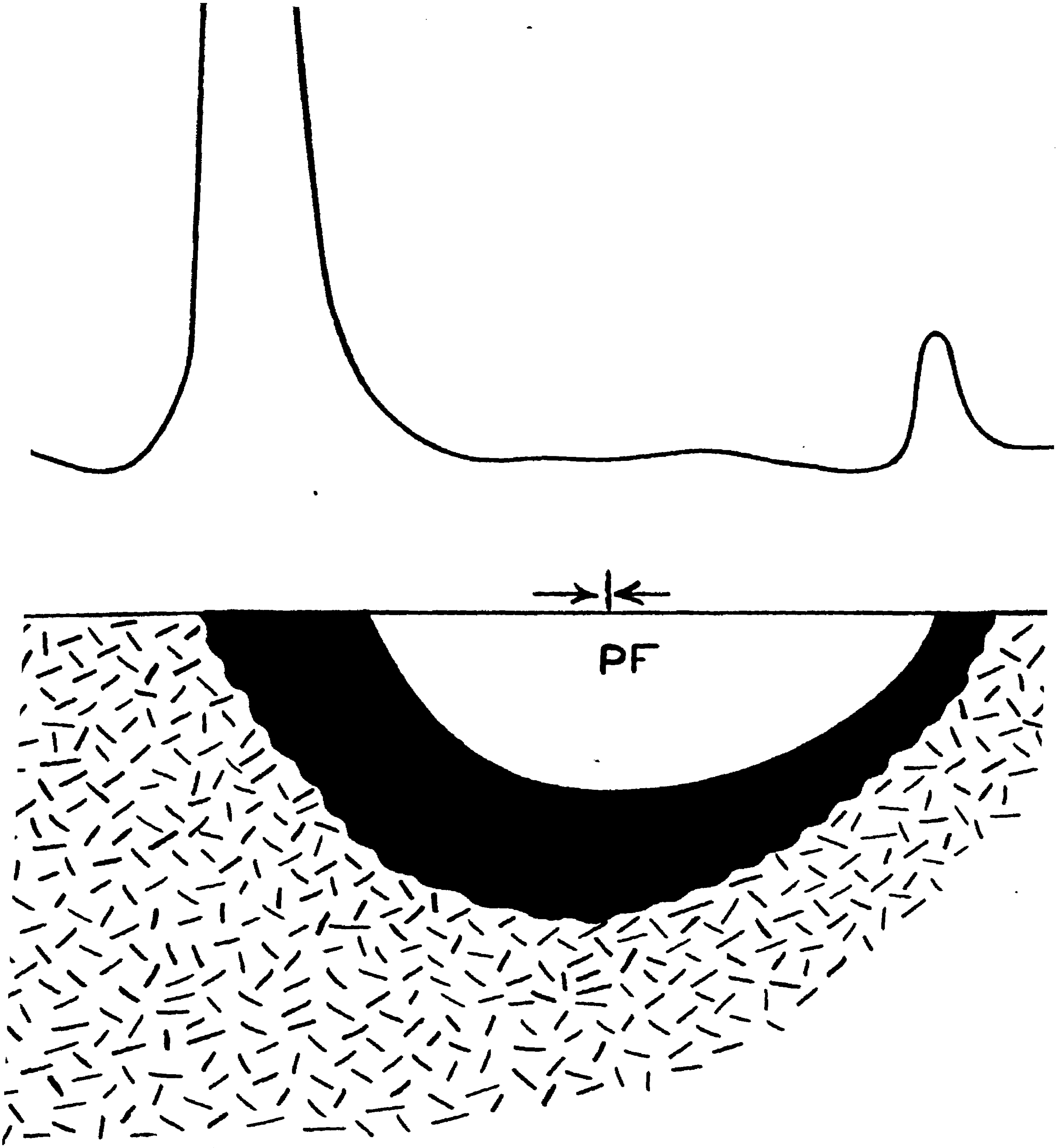
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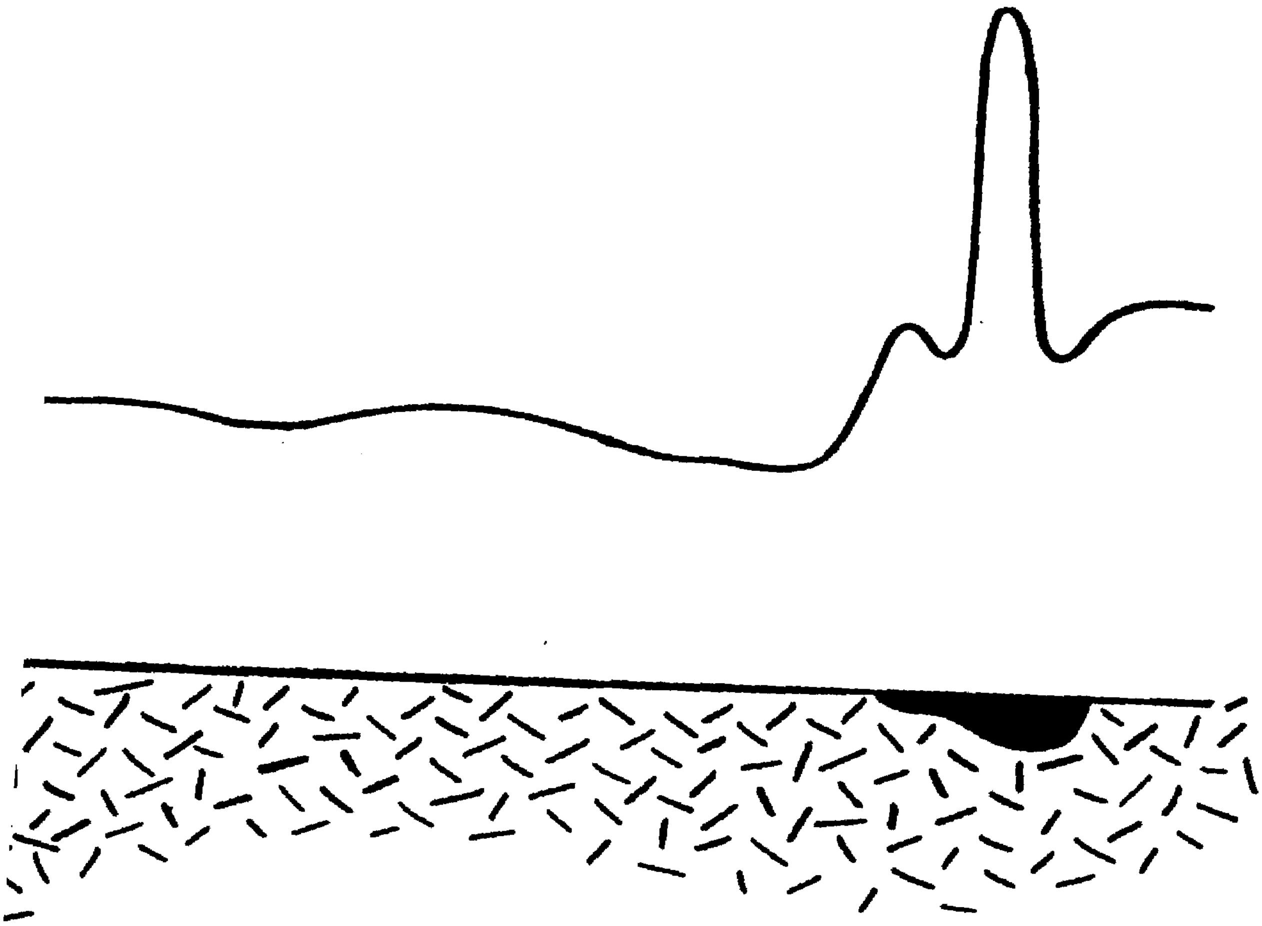

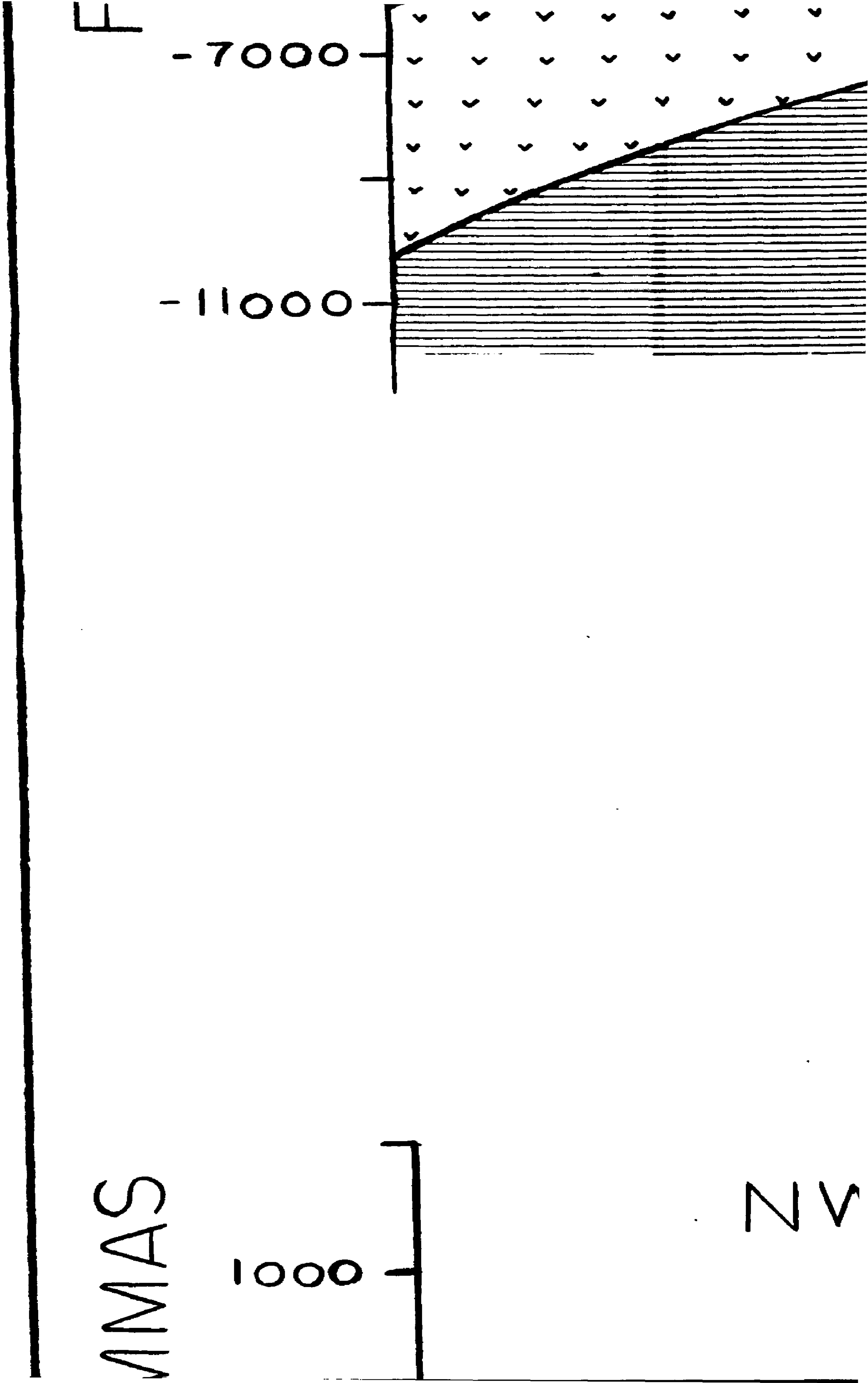

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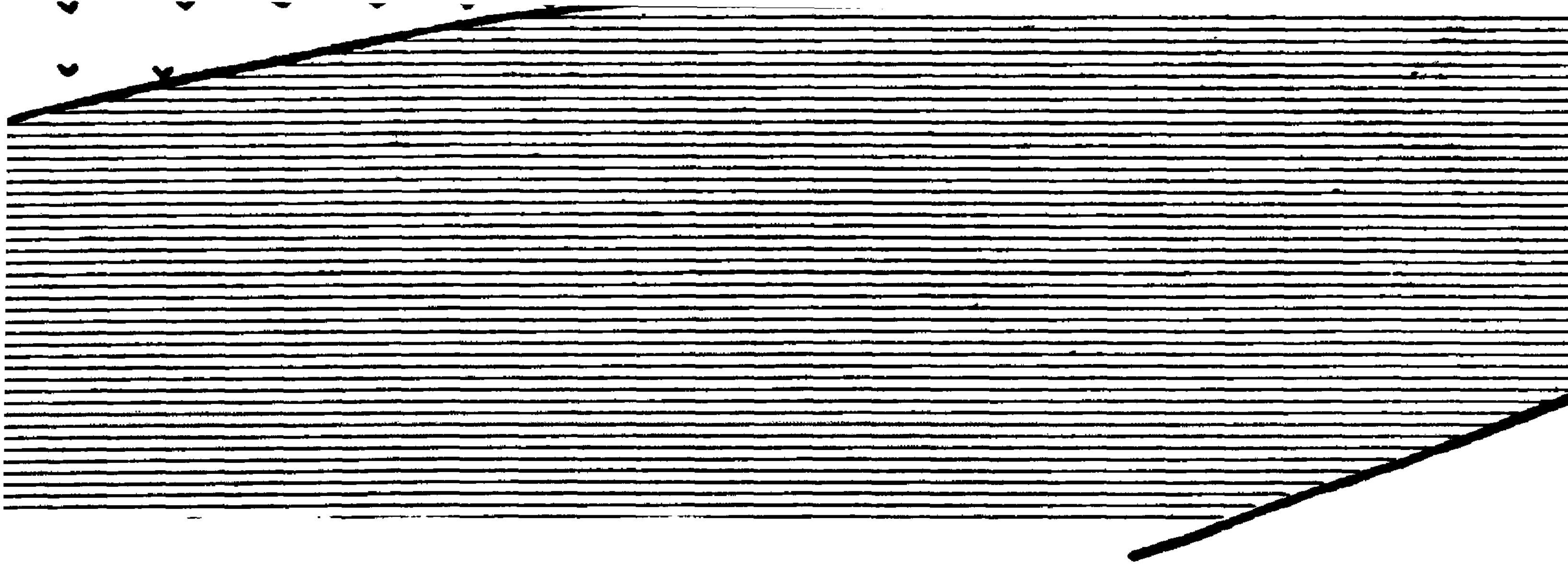

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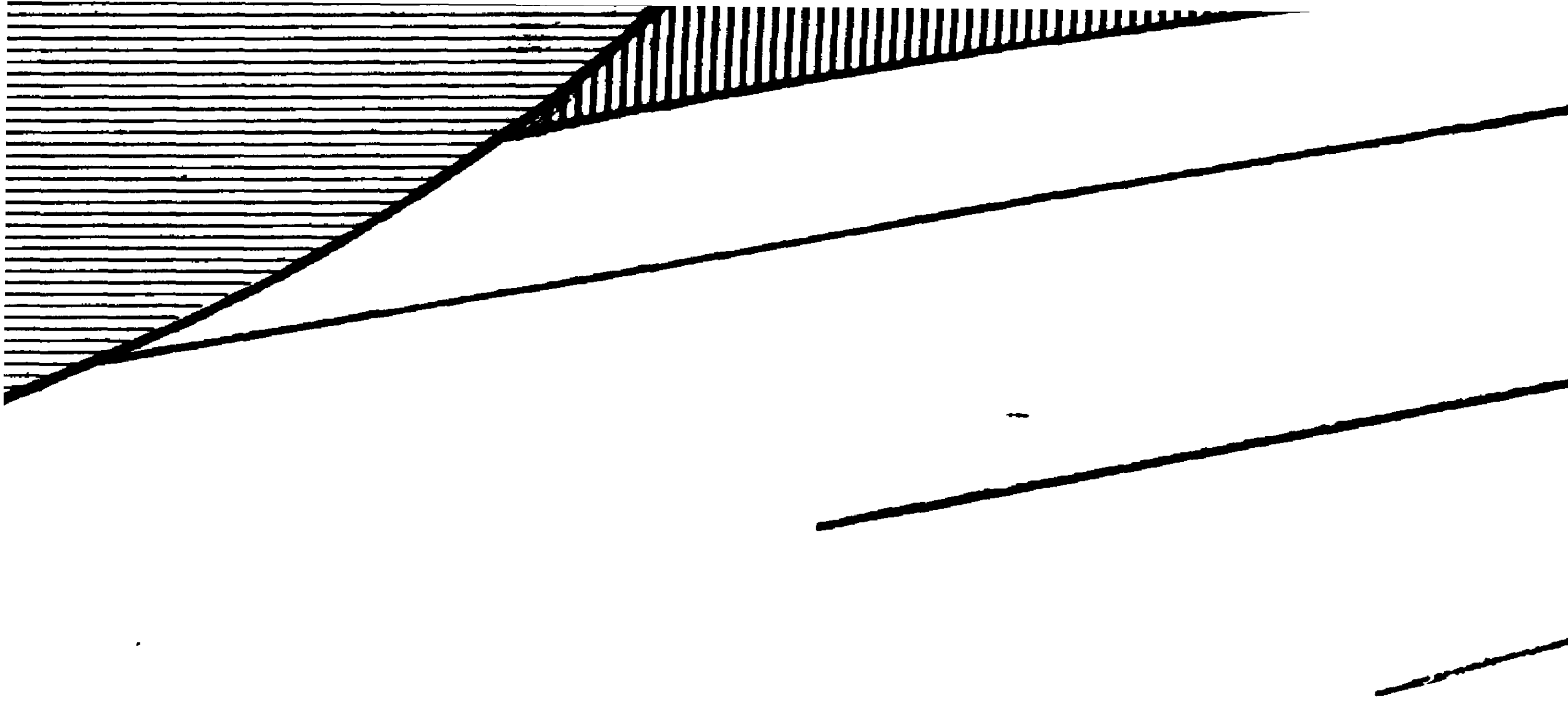

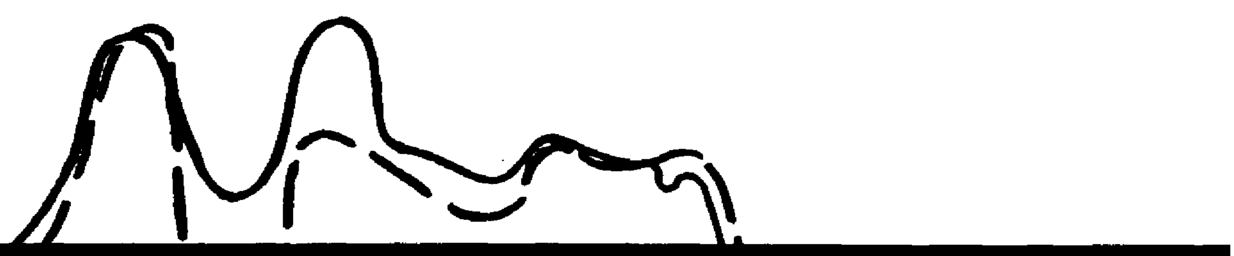

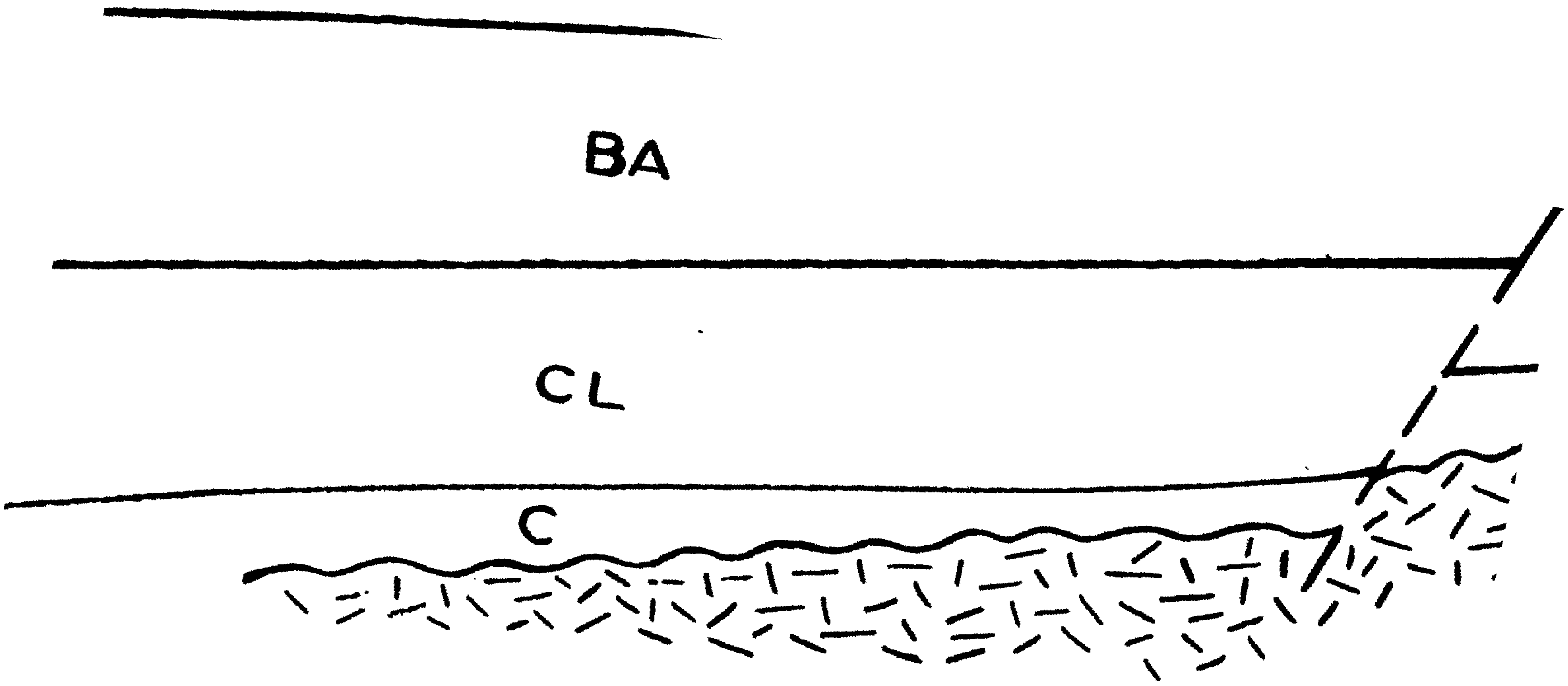
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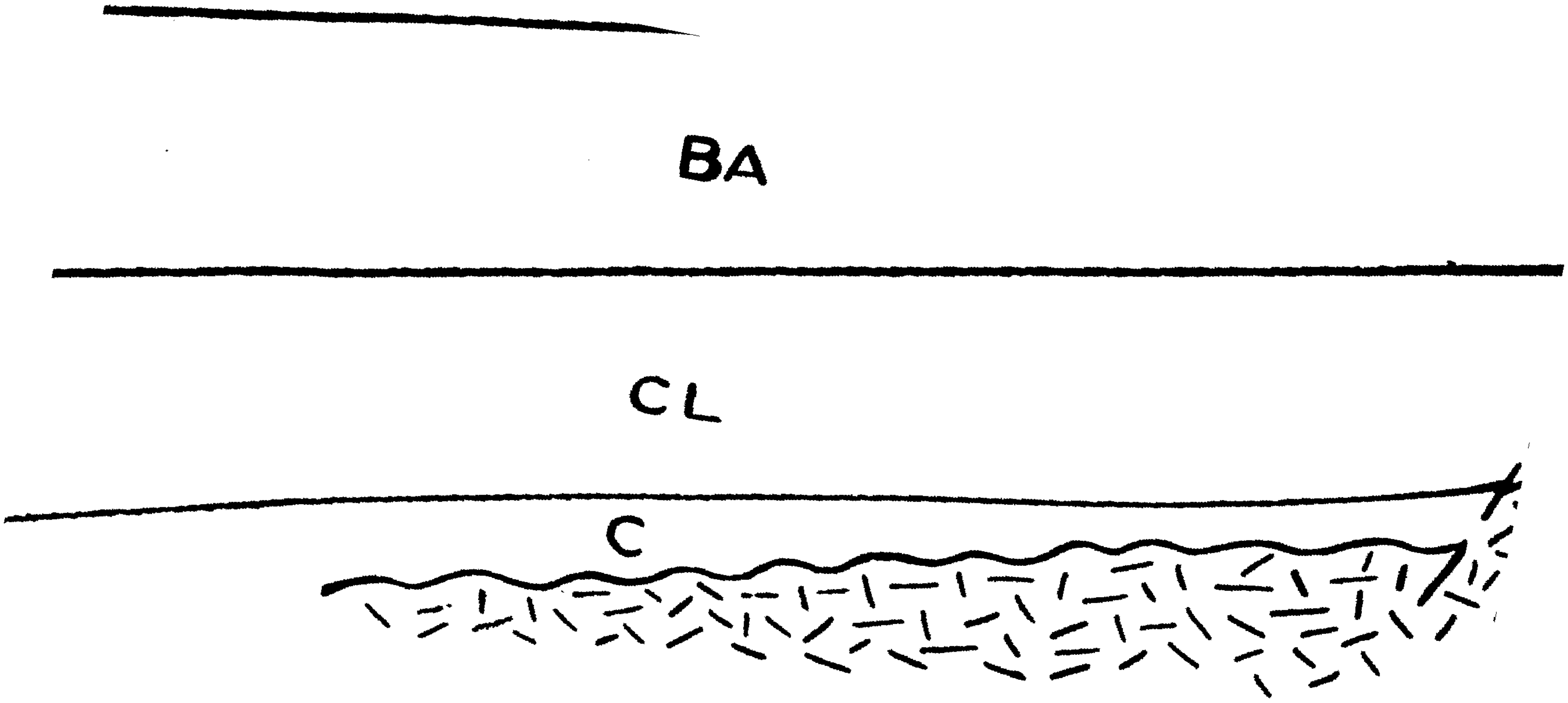
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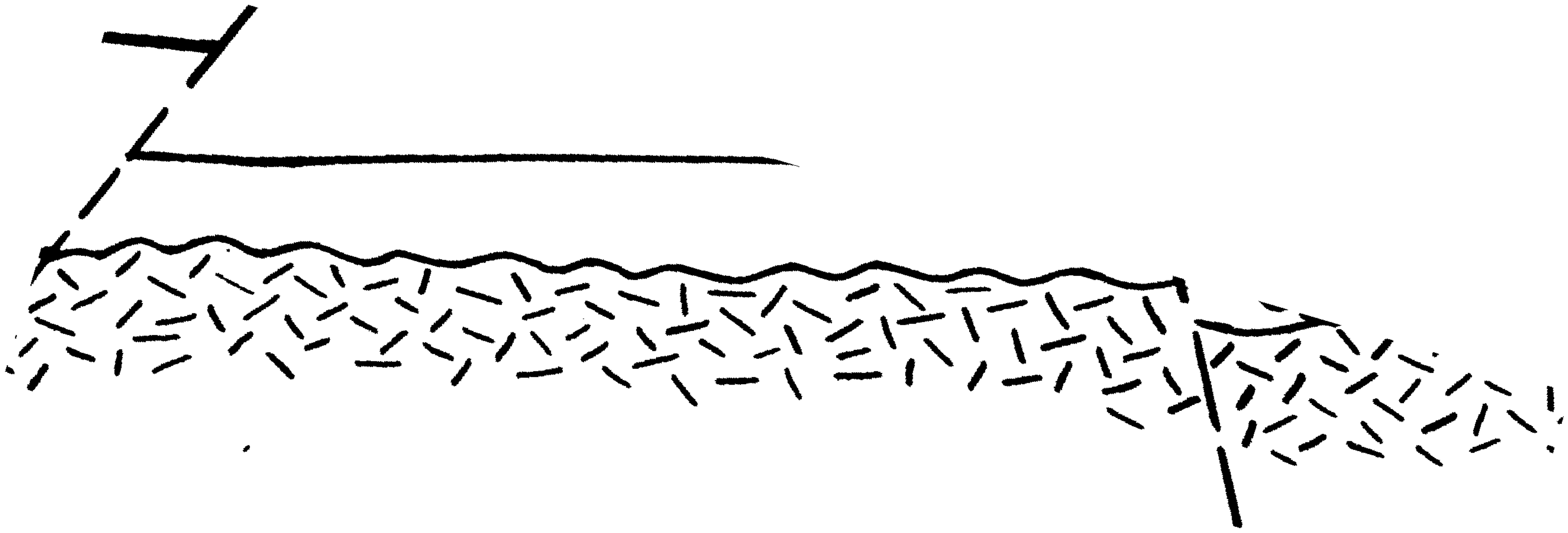

PROFILE

$H - H'$

- H´

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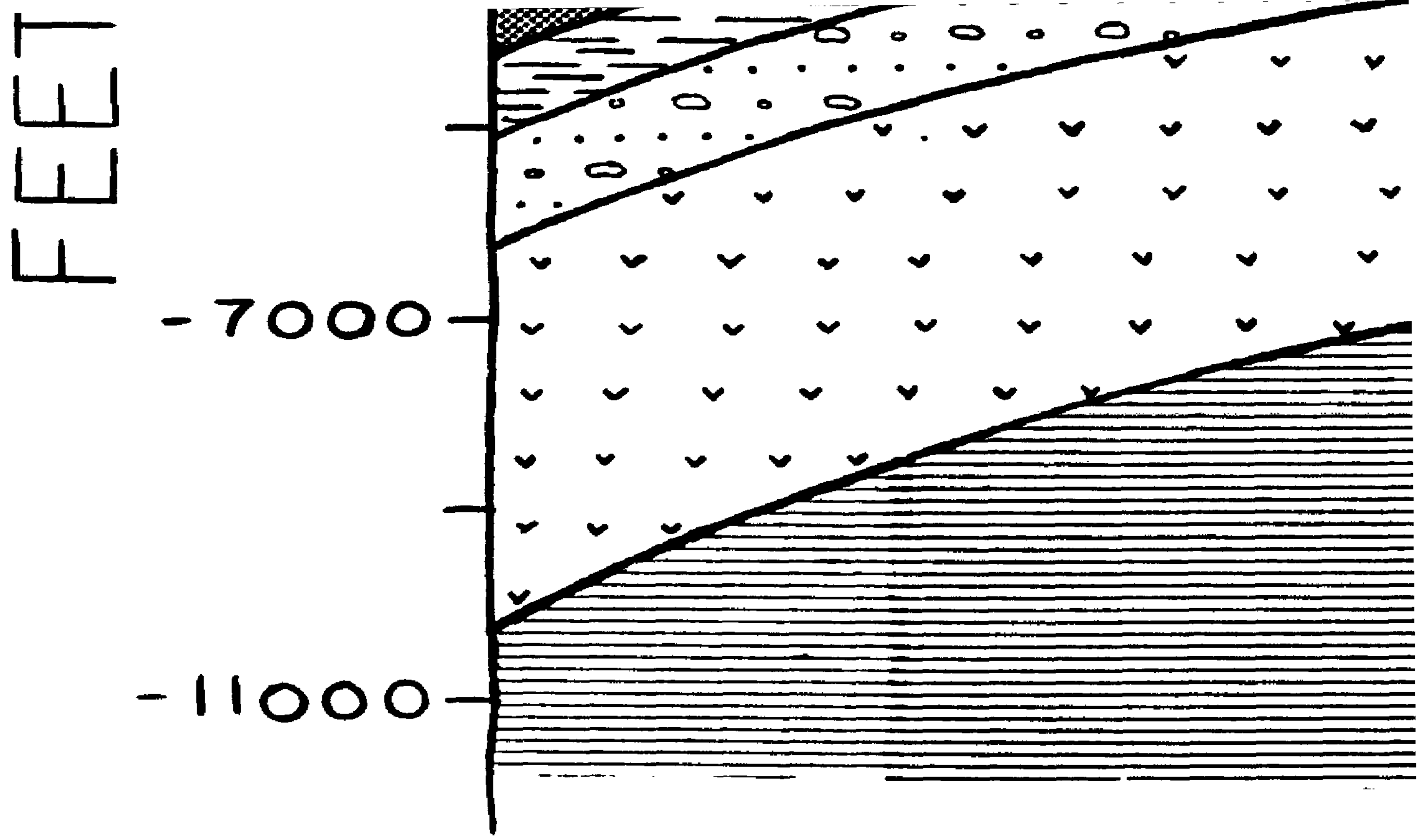
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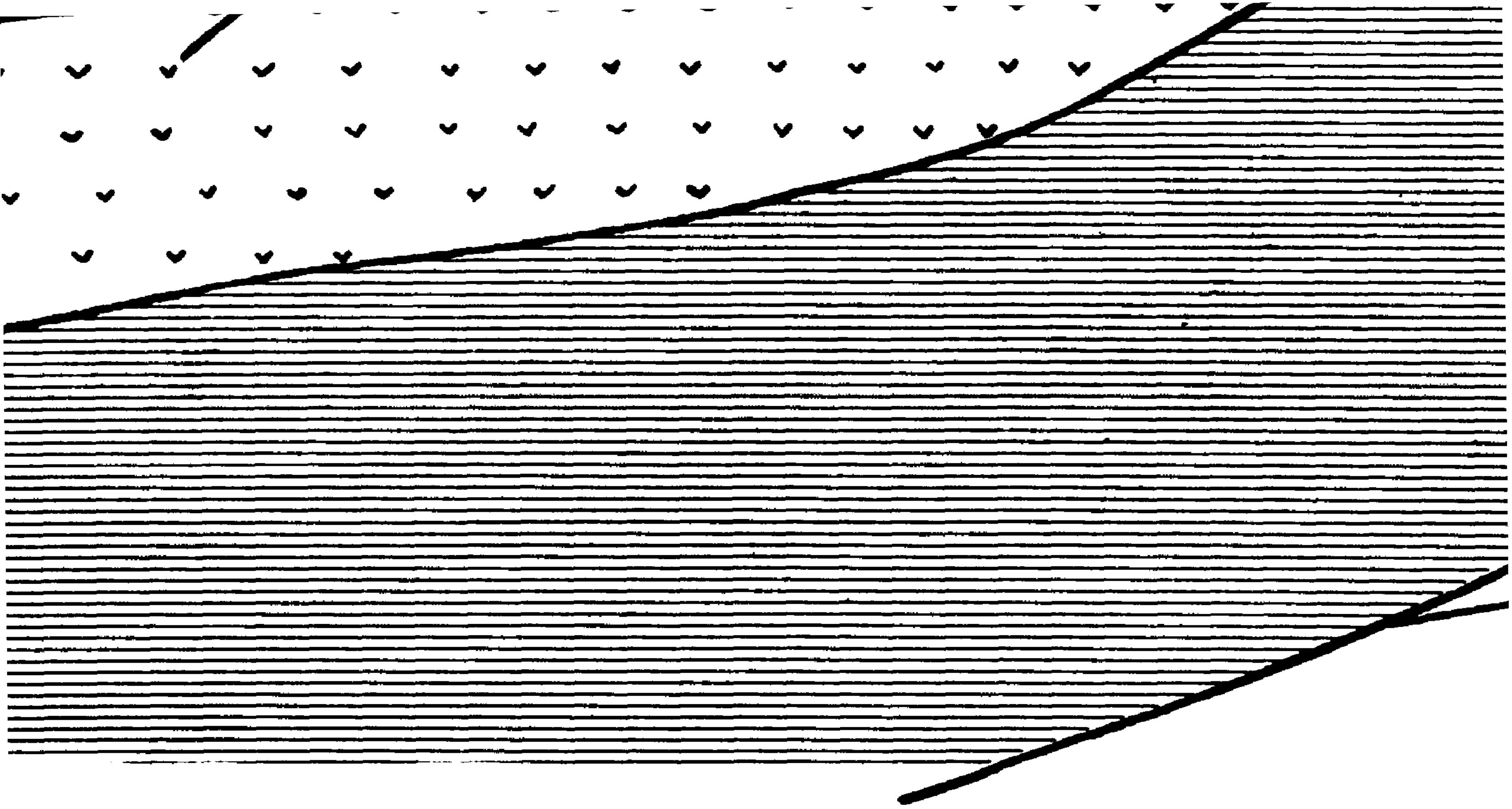

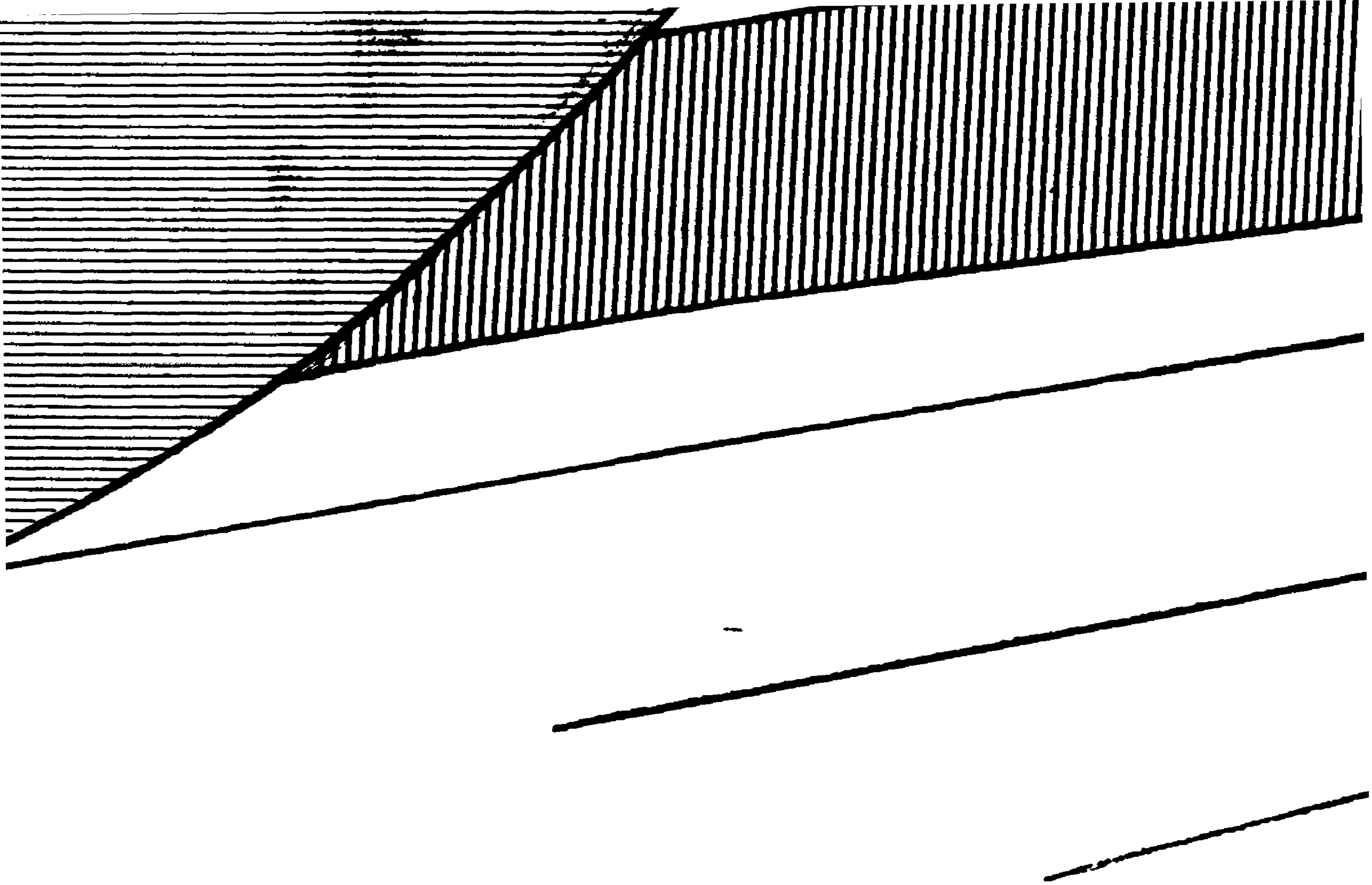

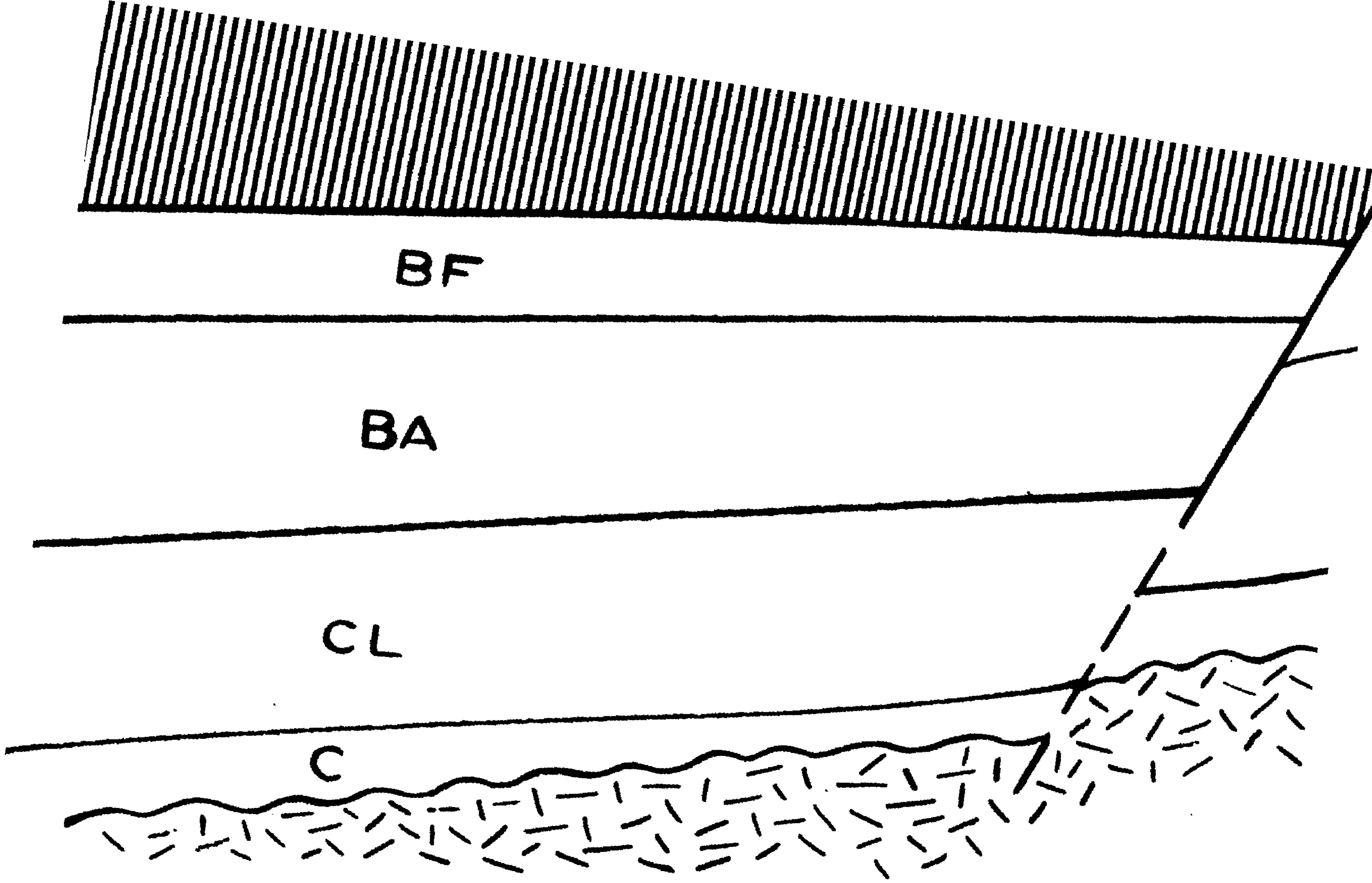
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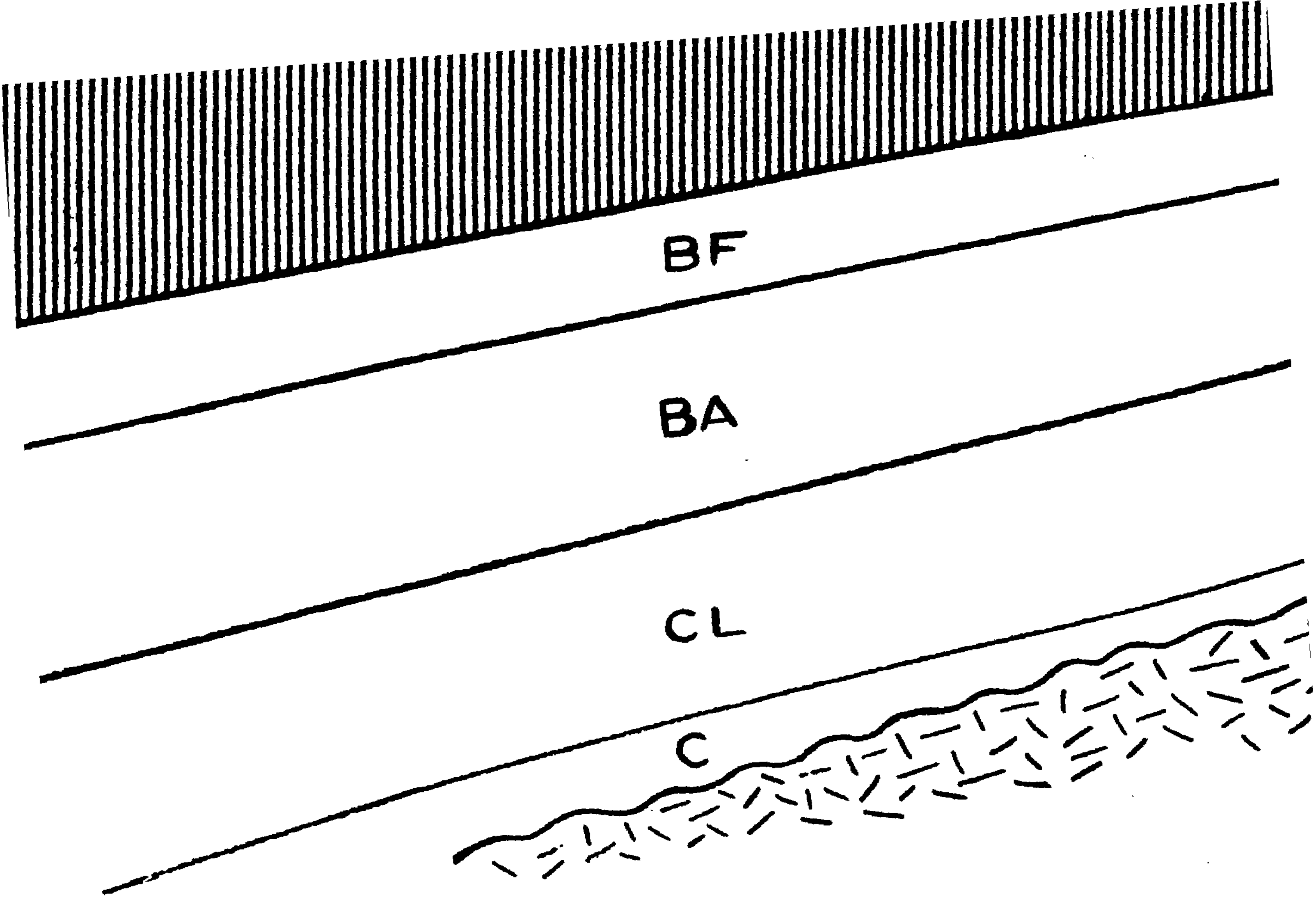
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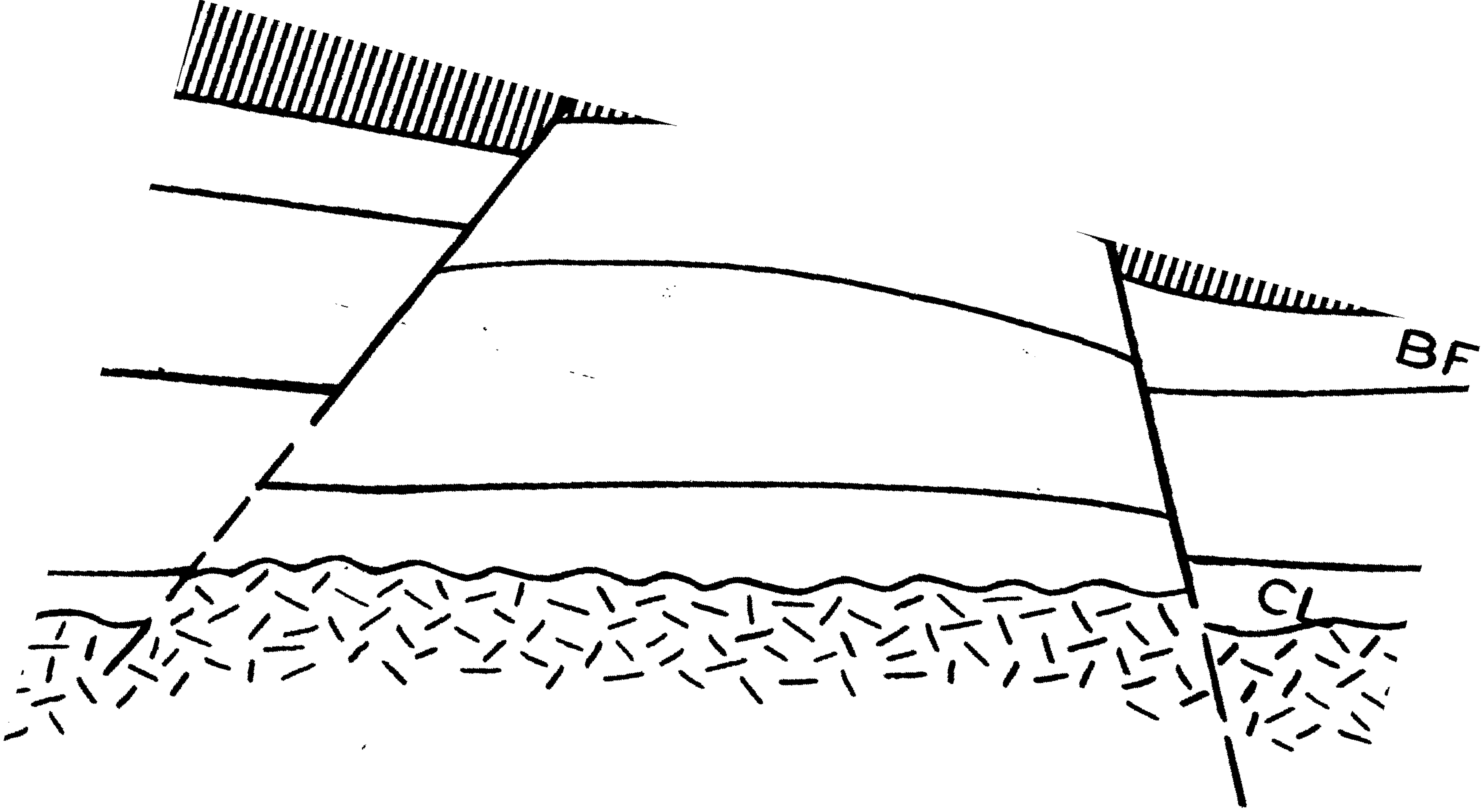

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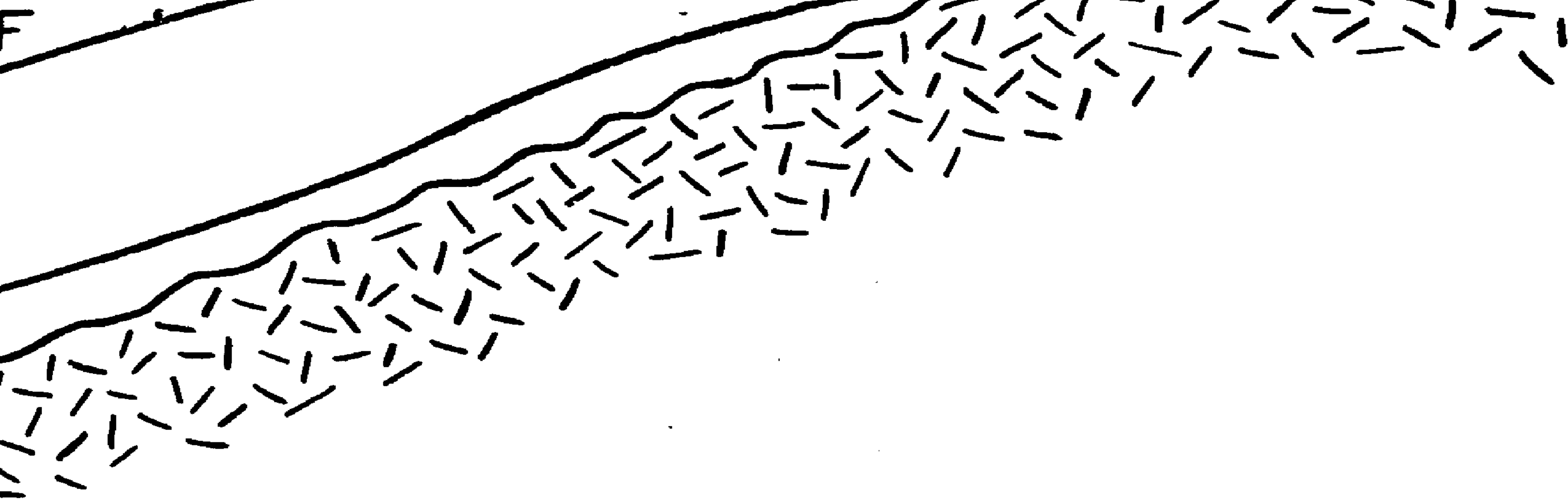

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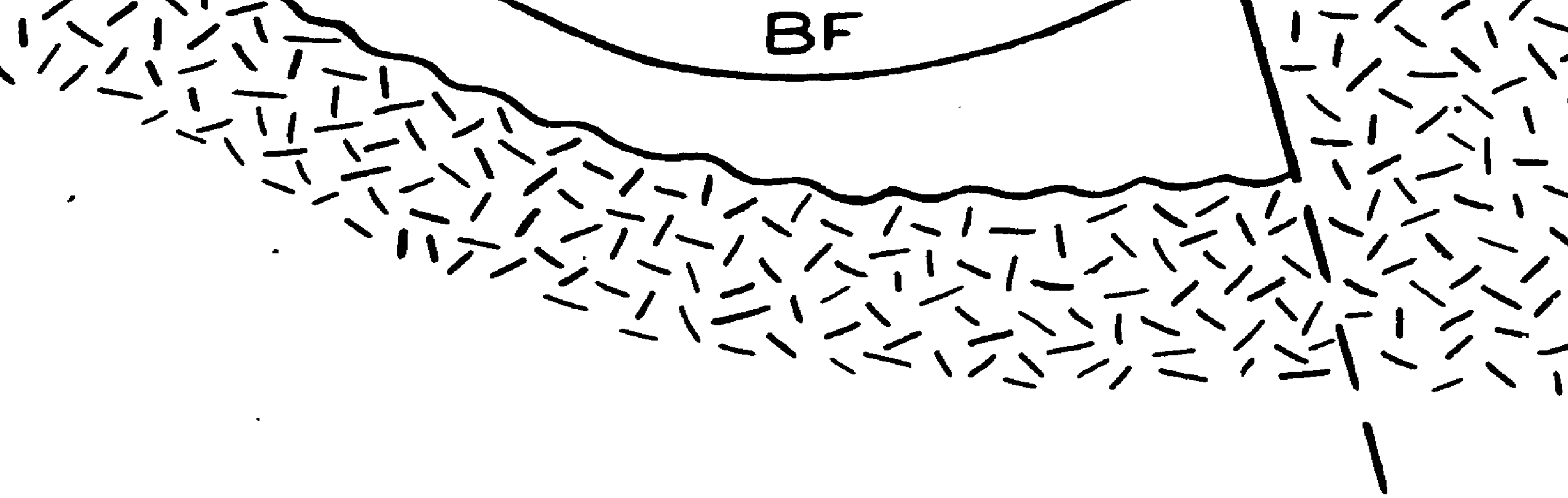
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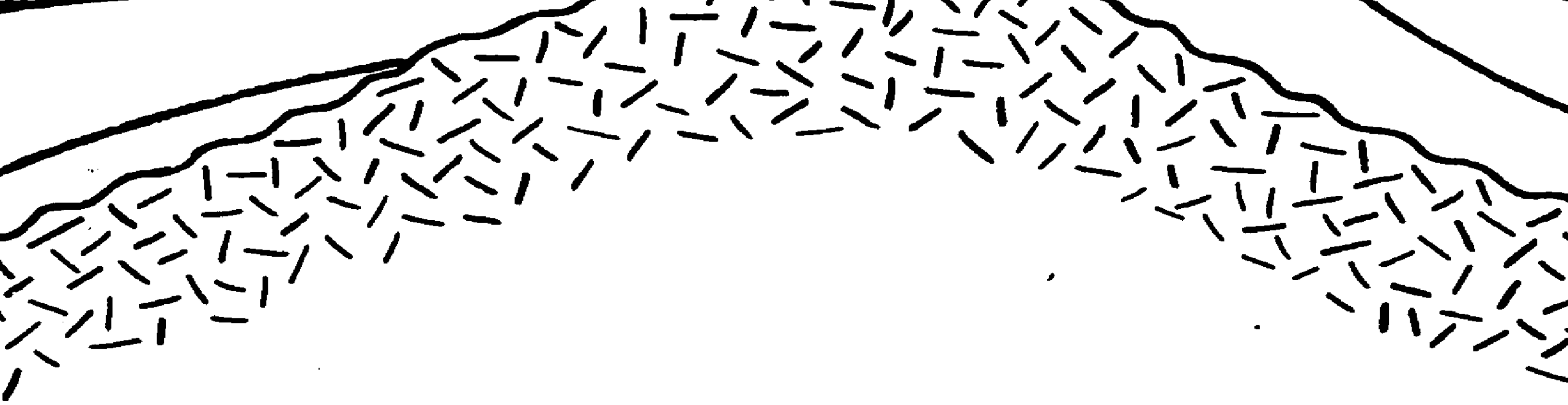

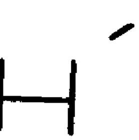

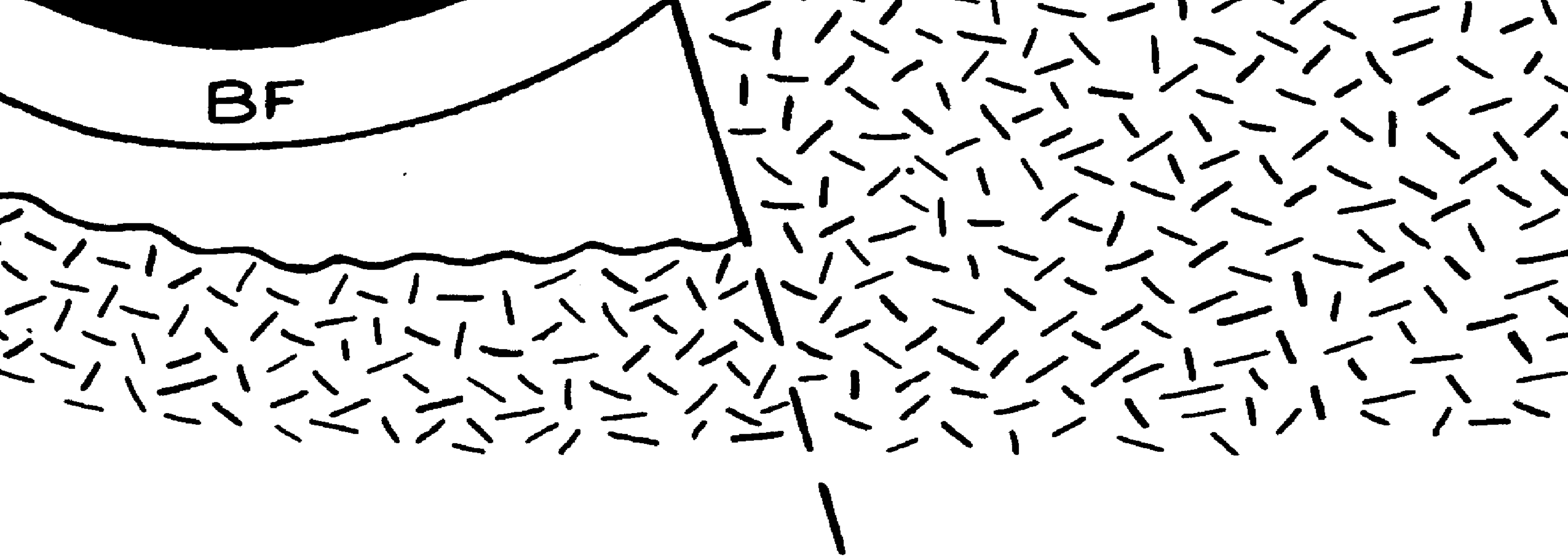
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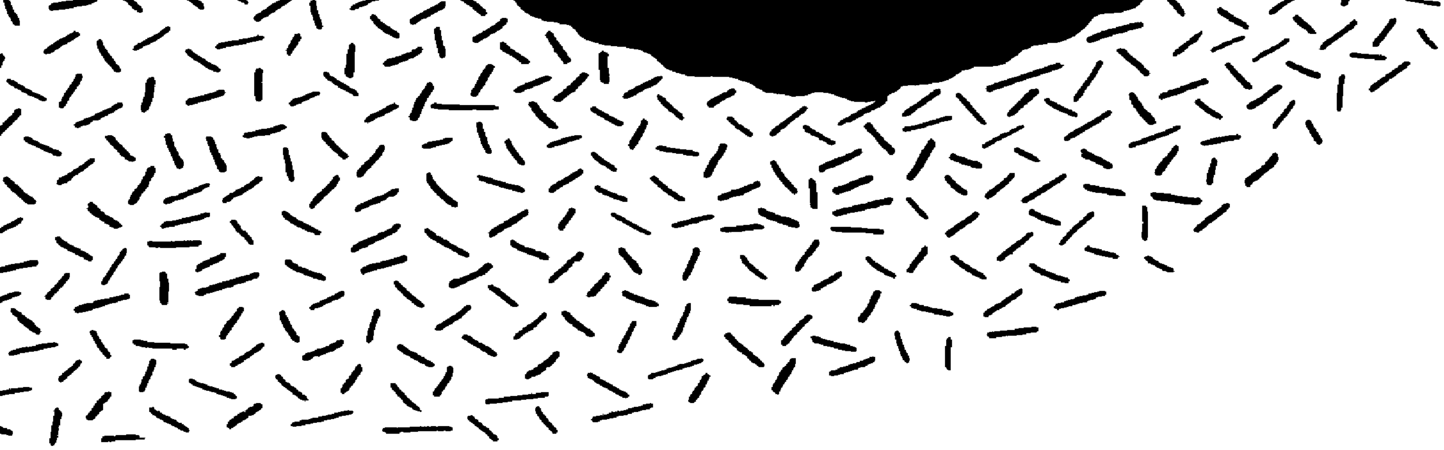

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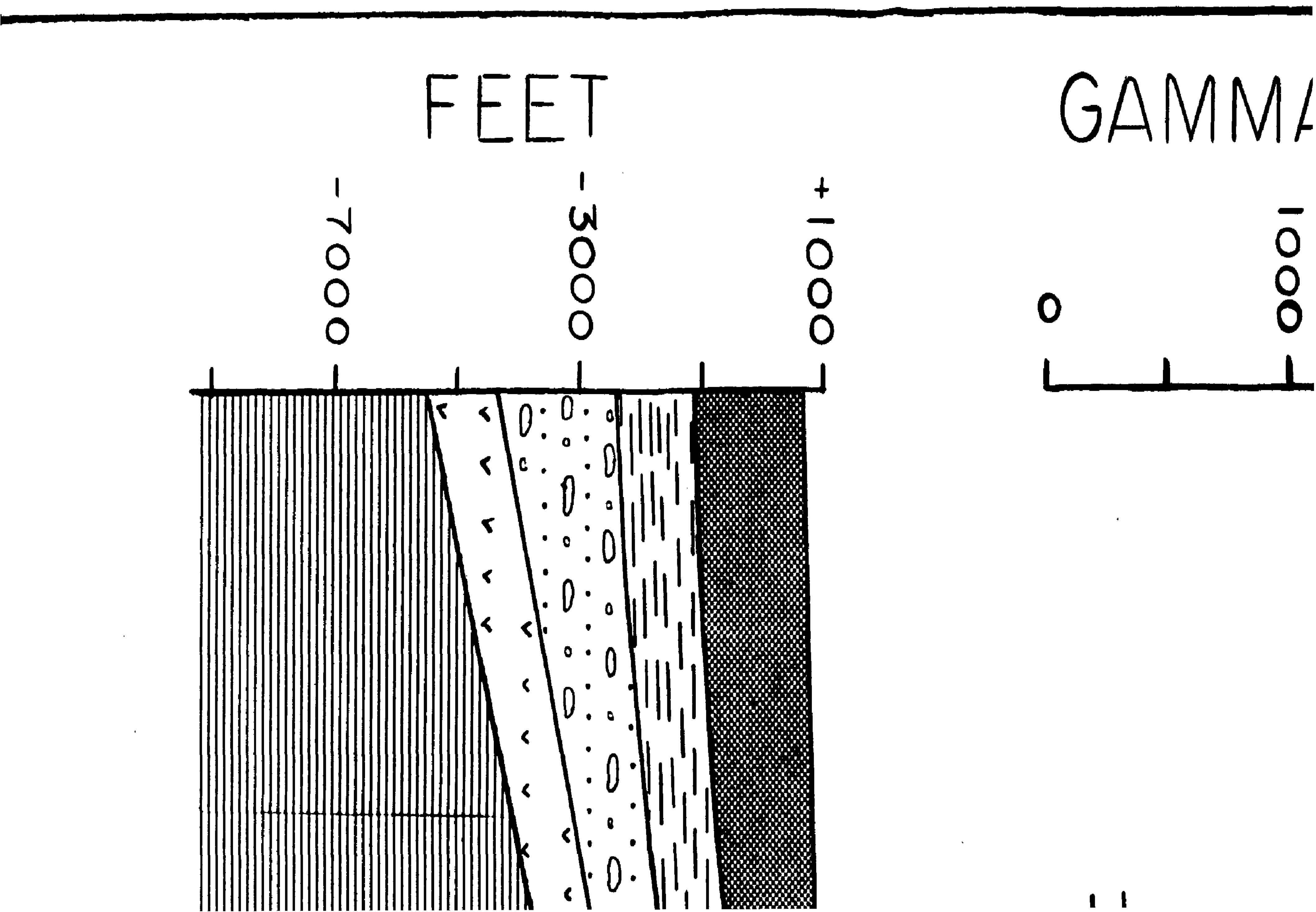
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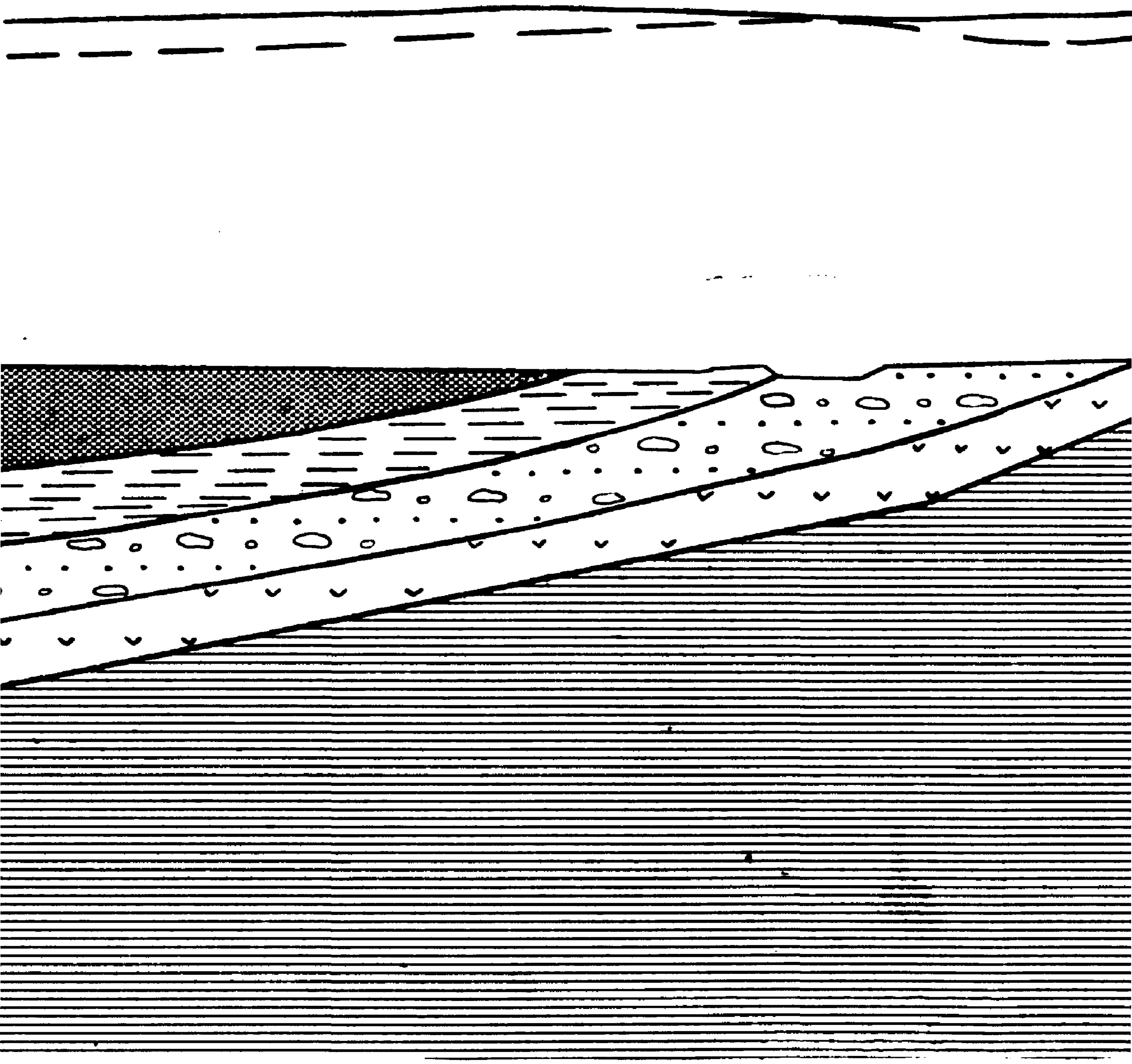

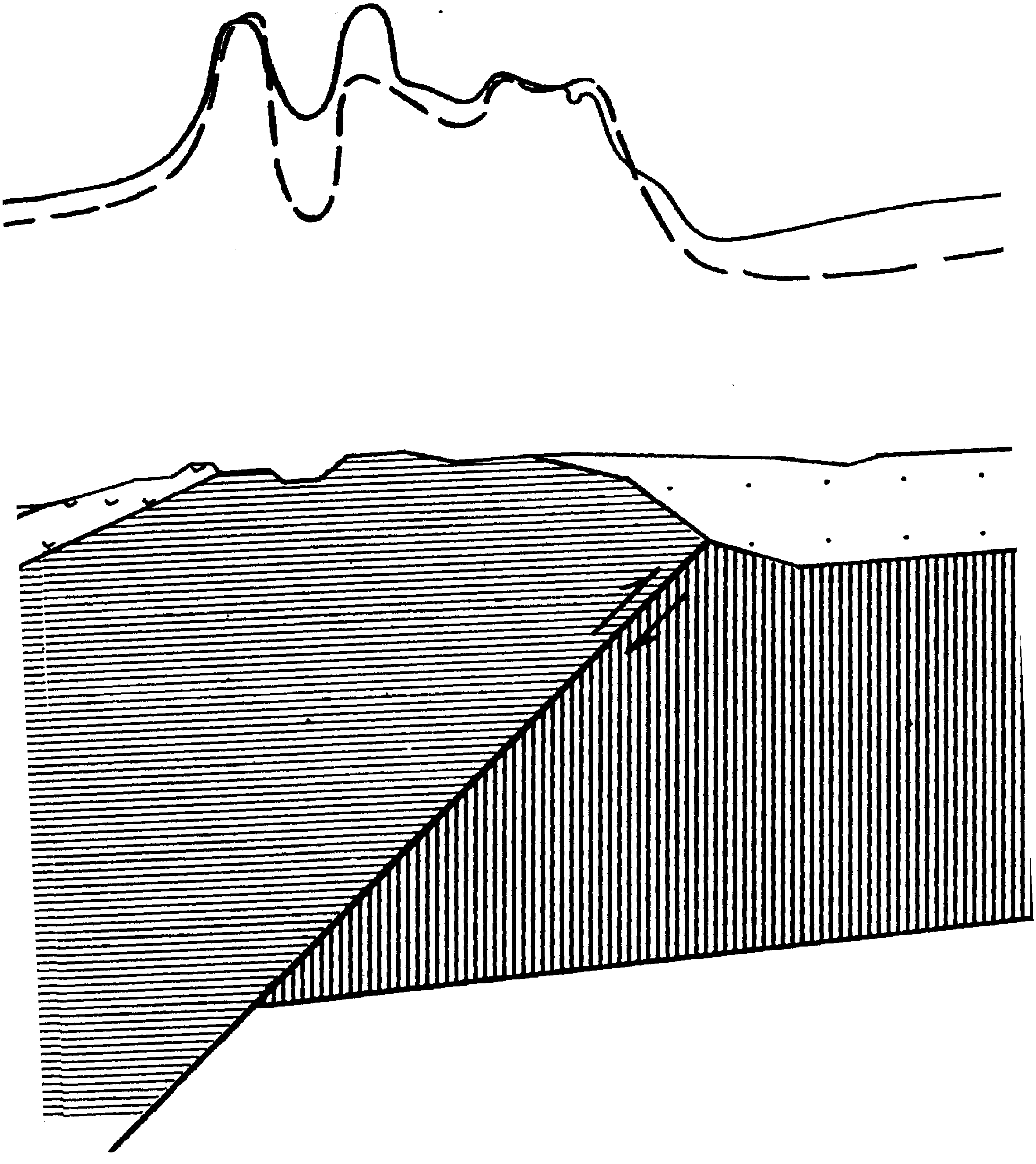

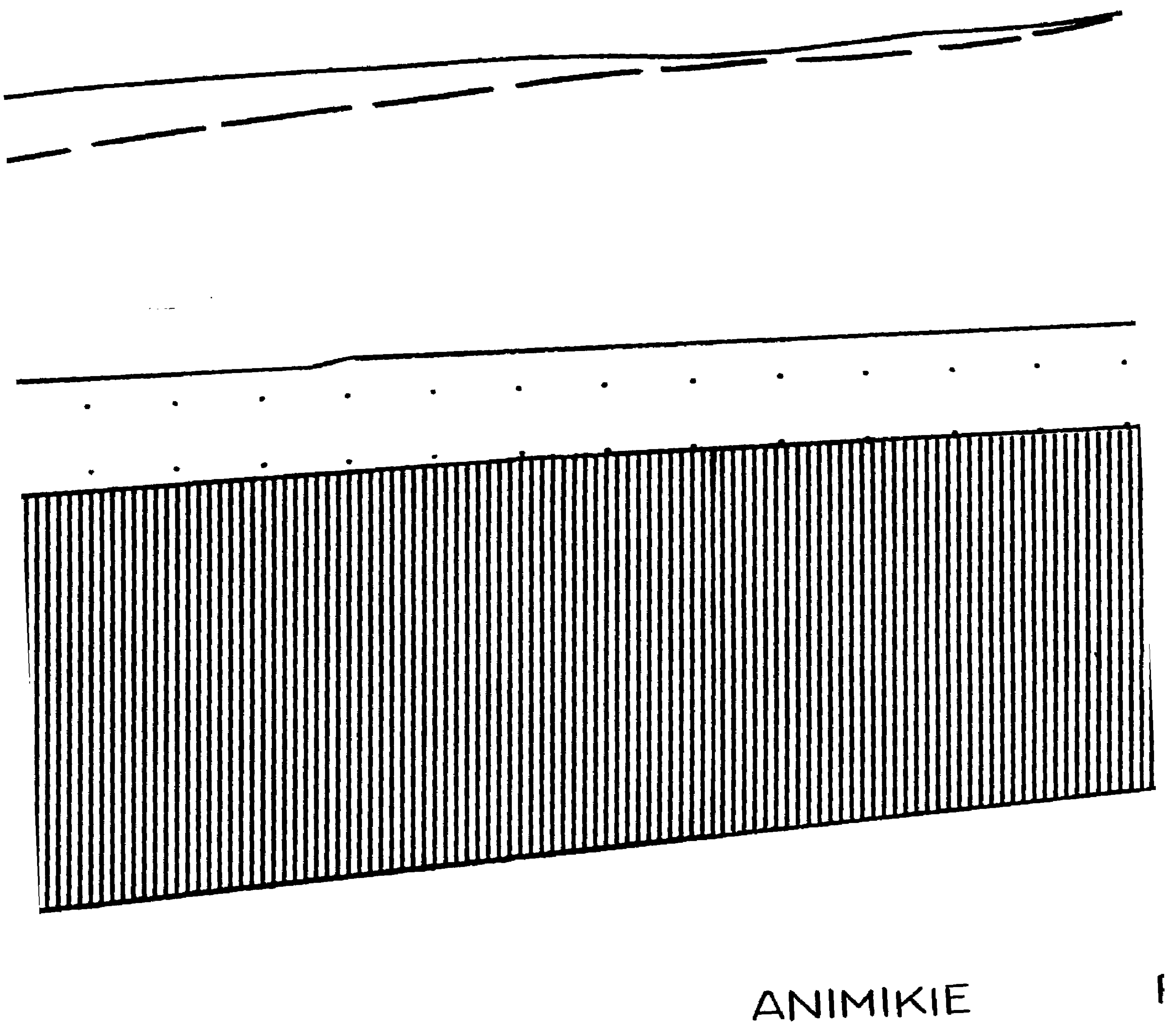
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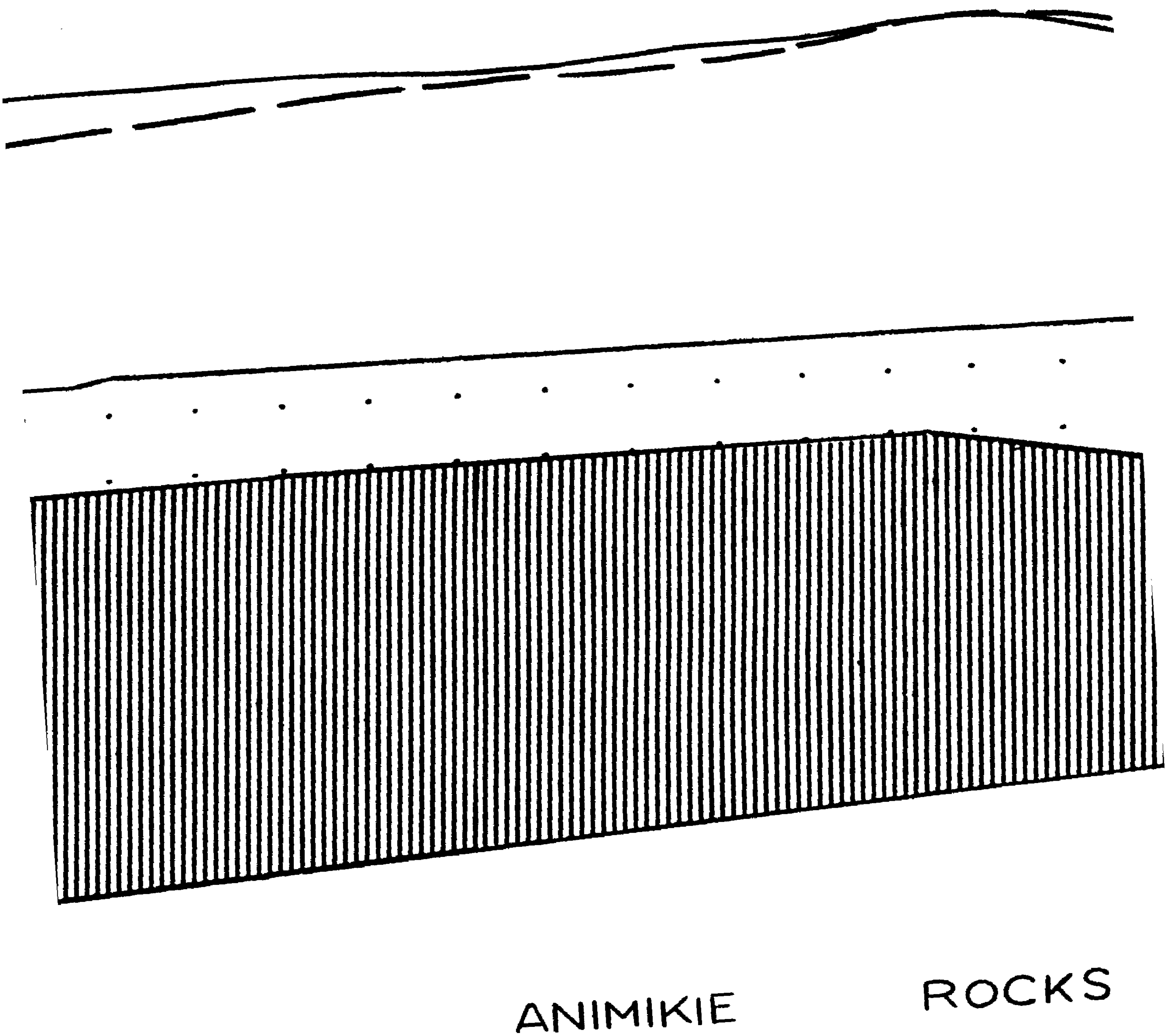
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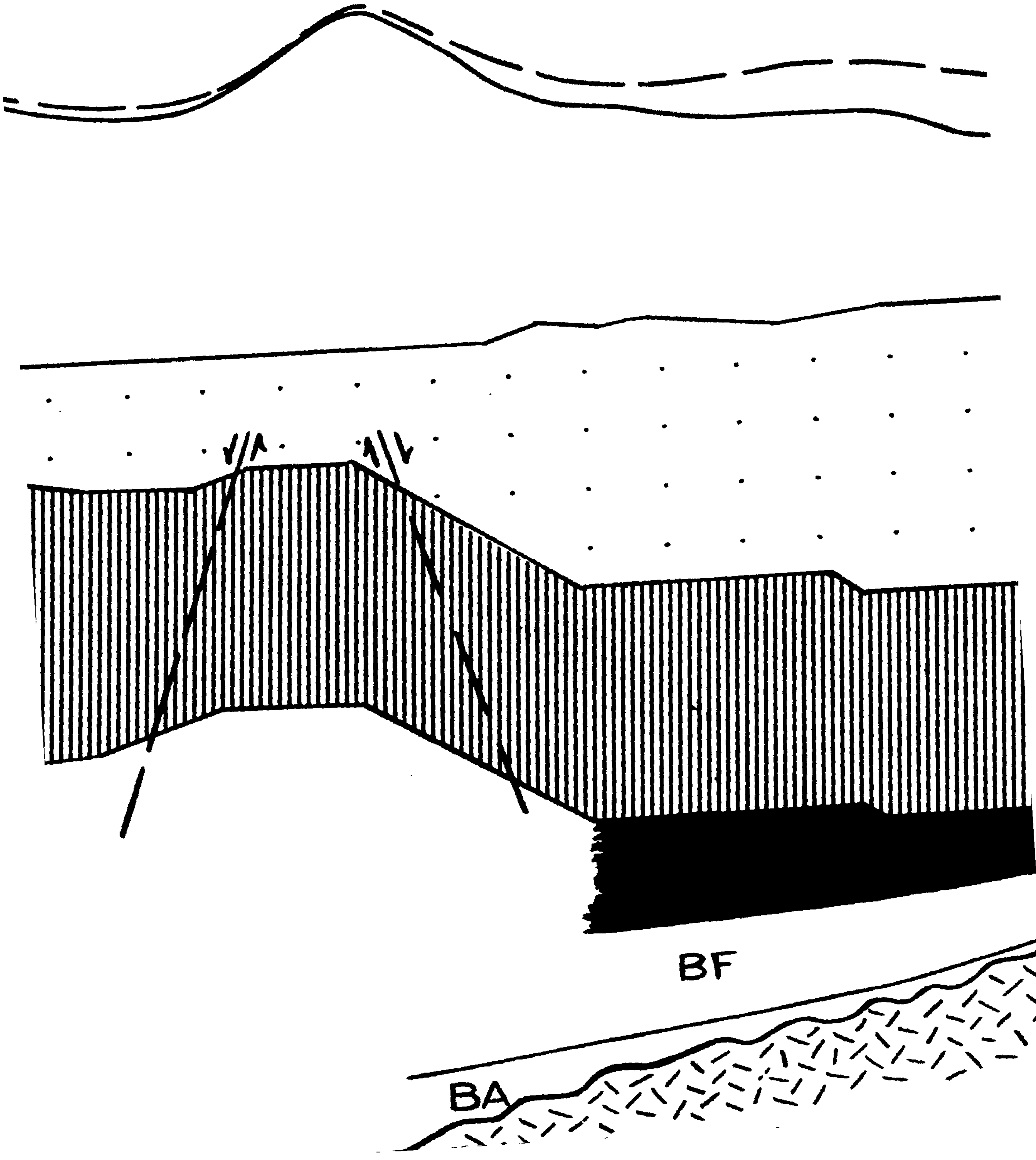
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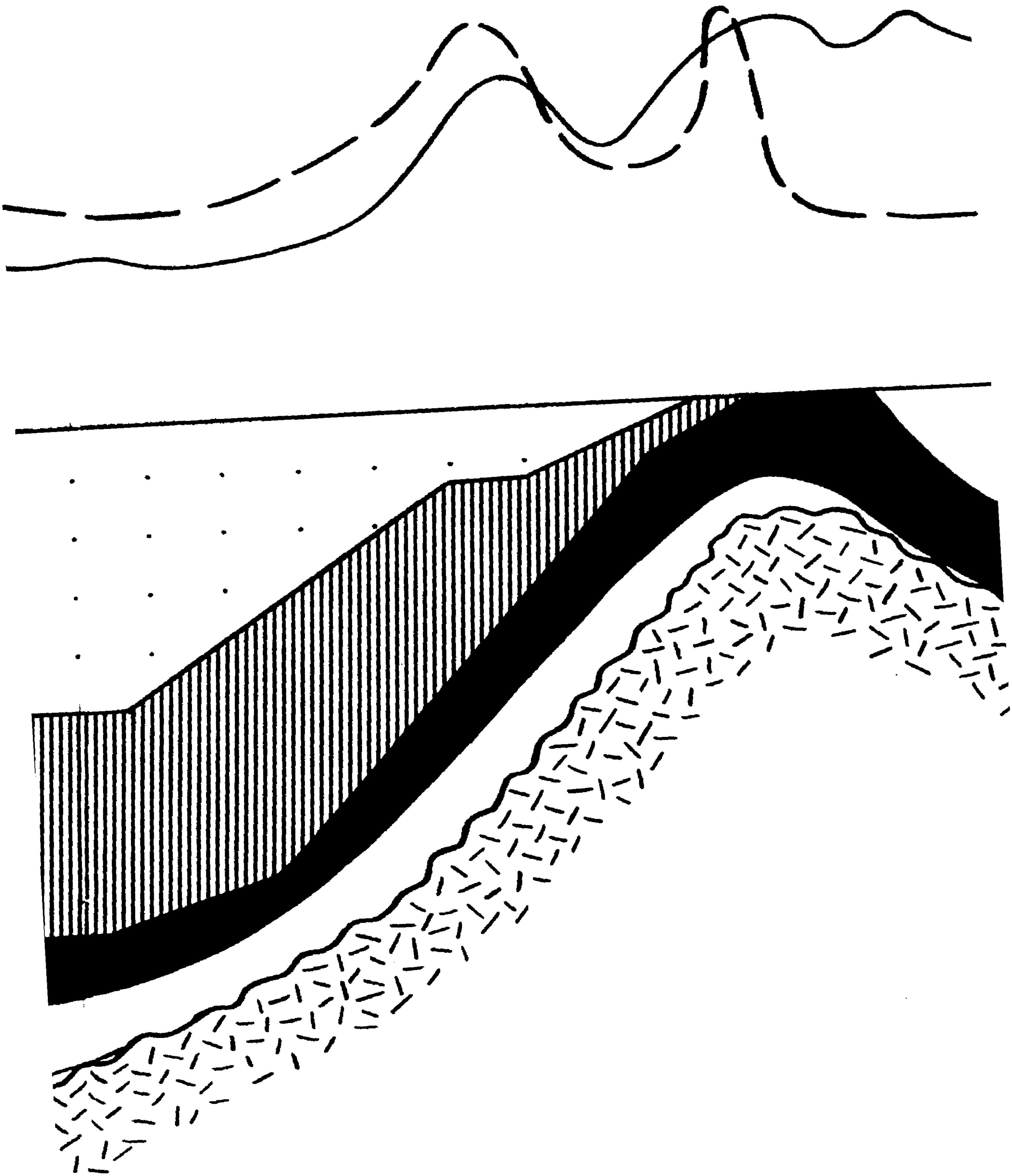

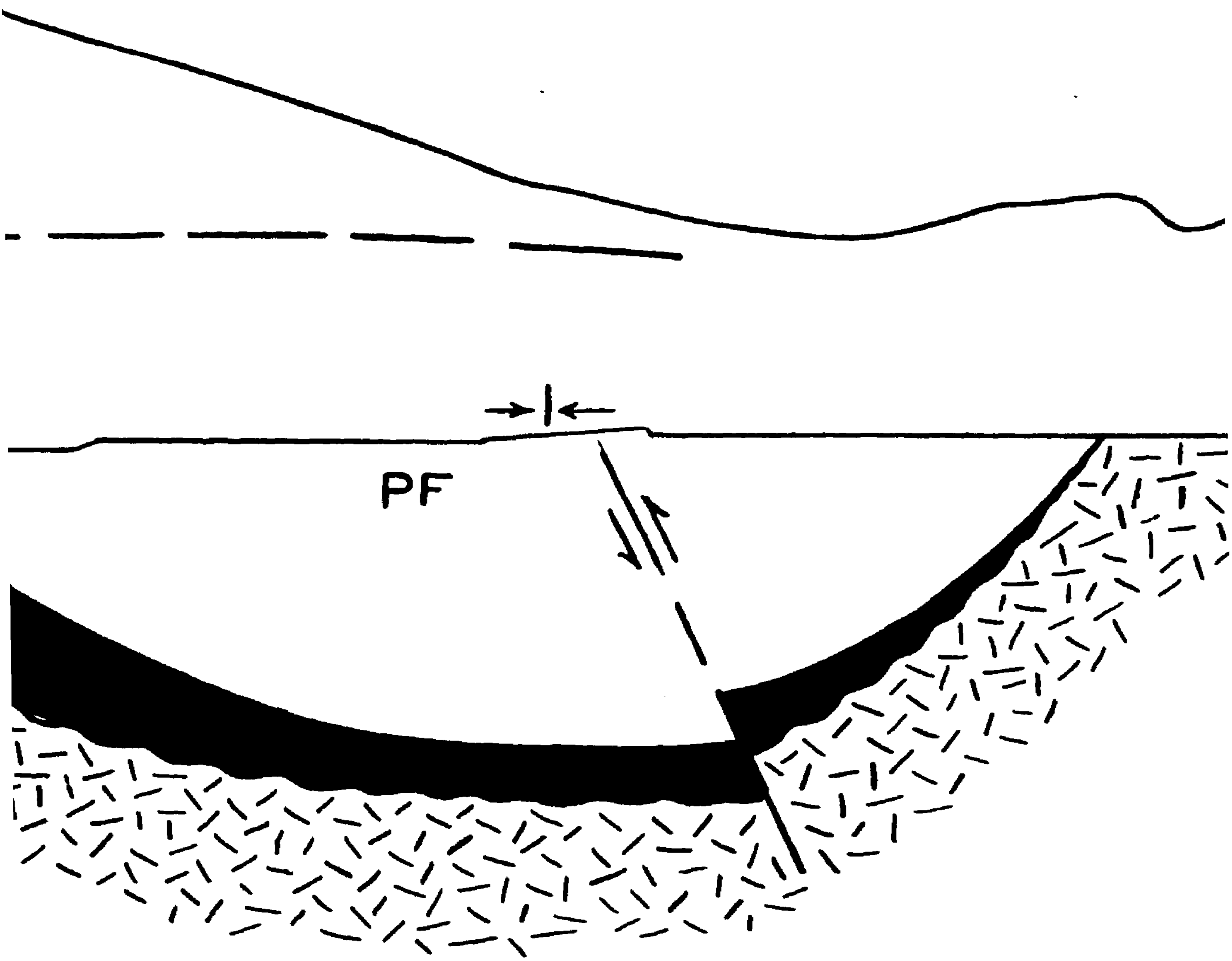
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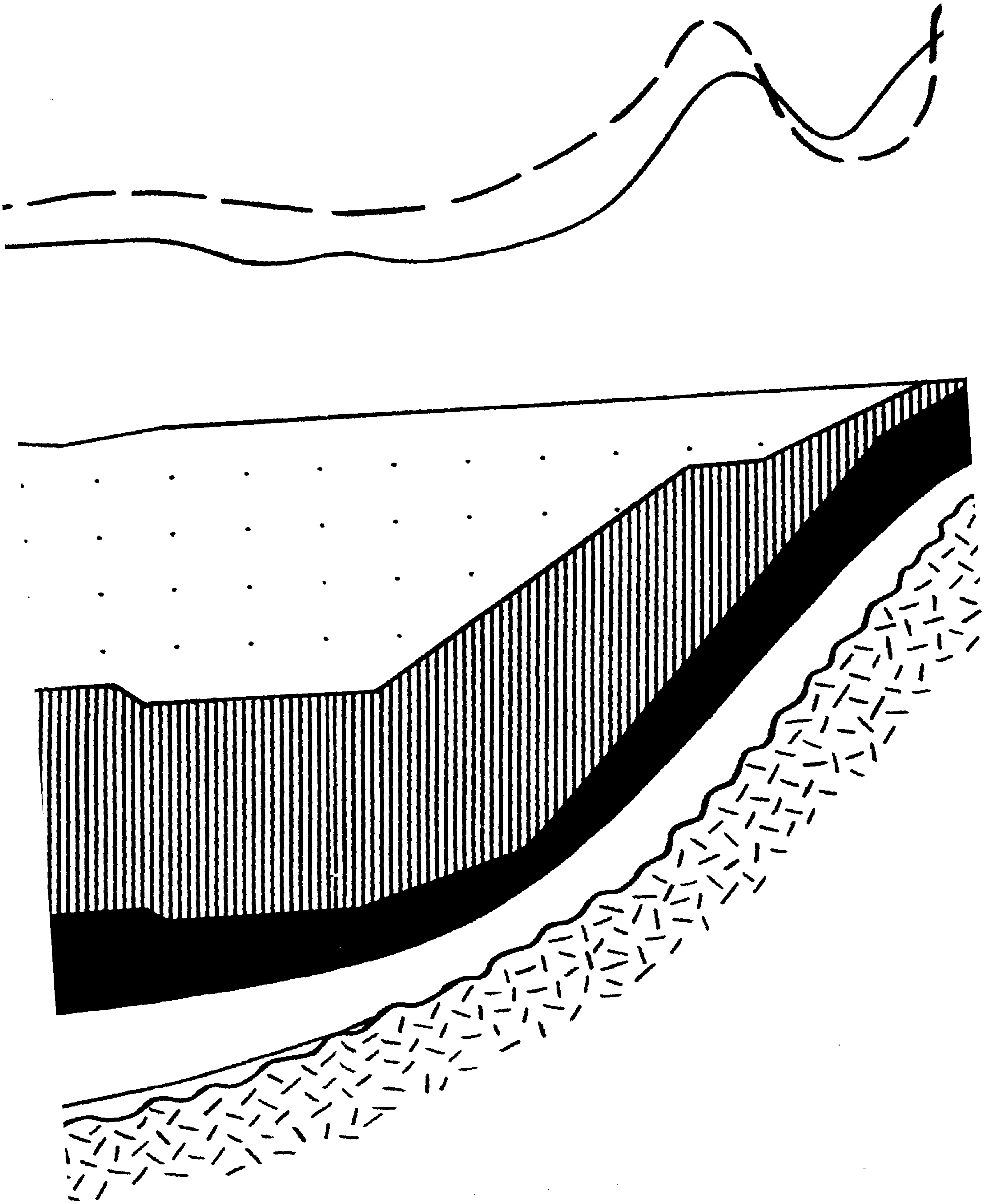

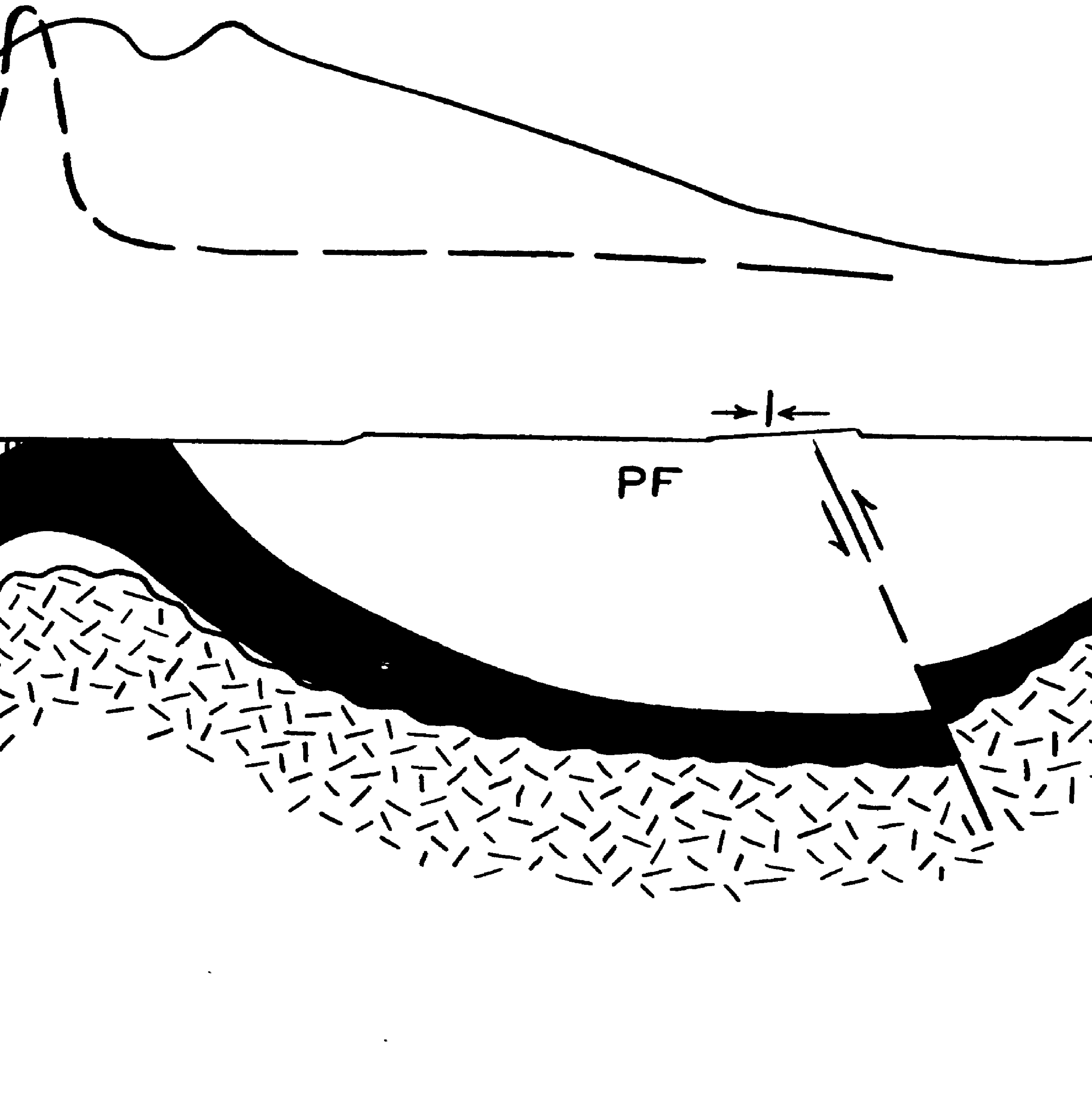
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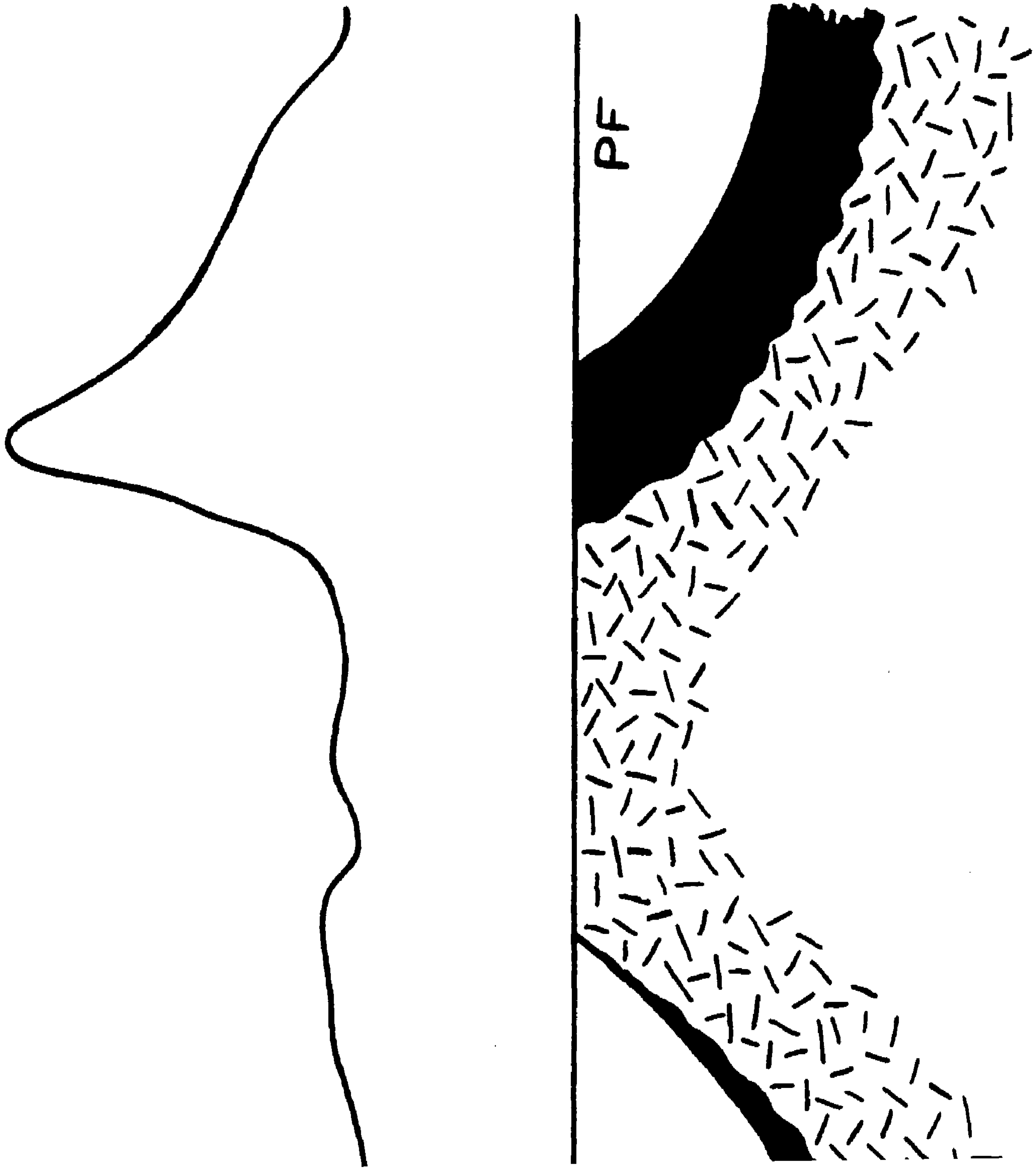
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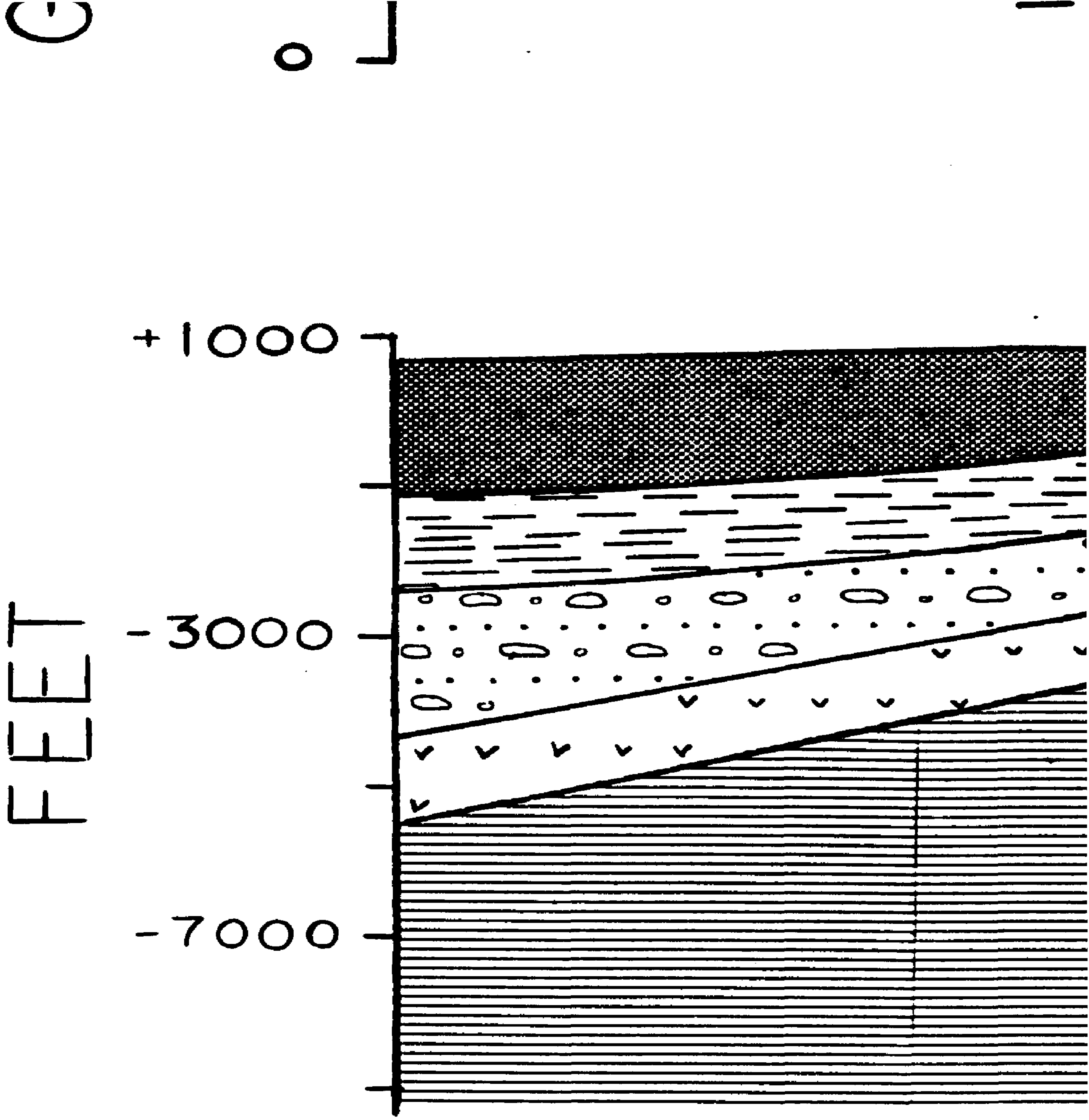

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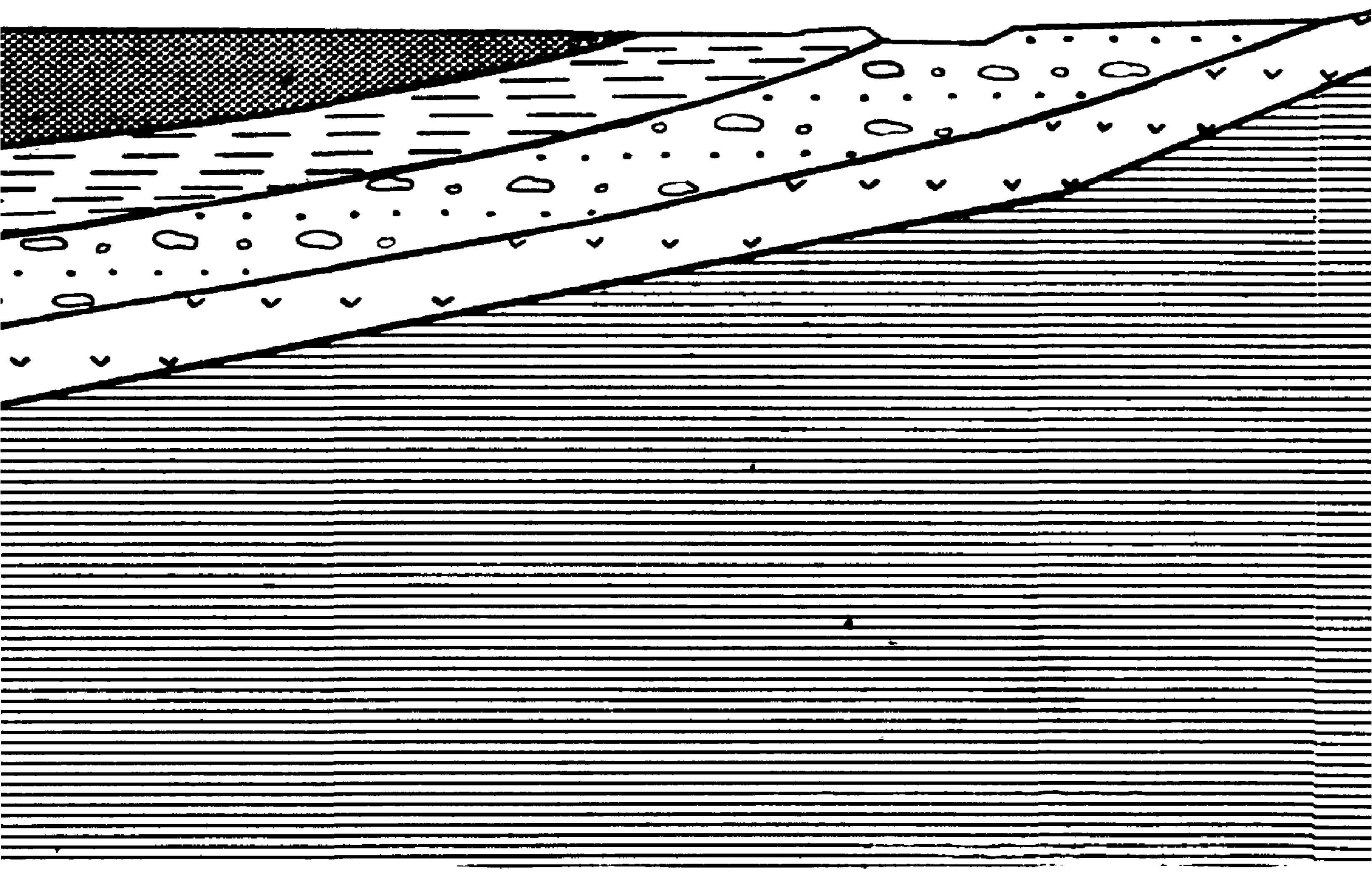

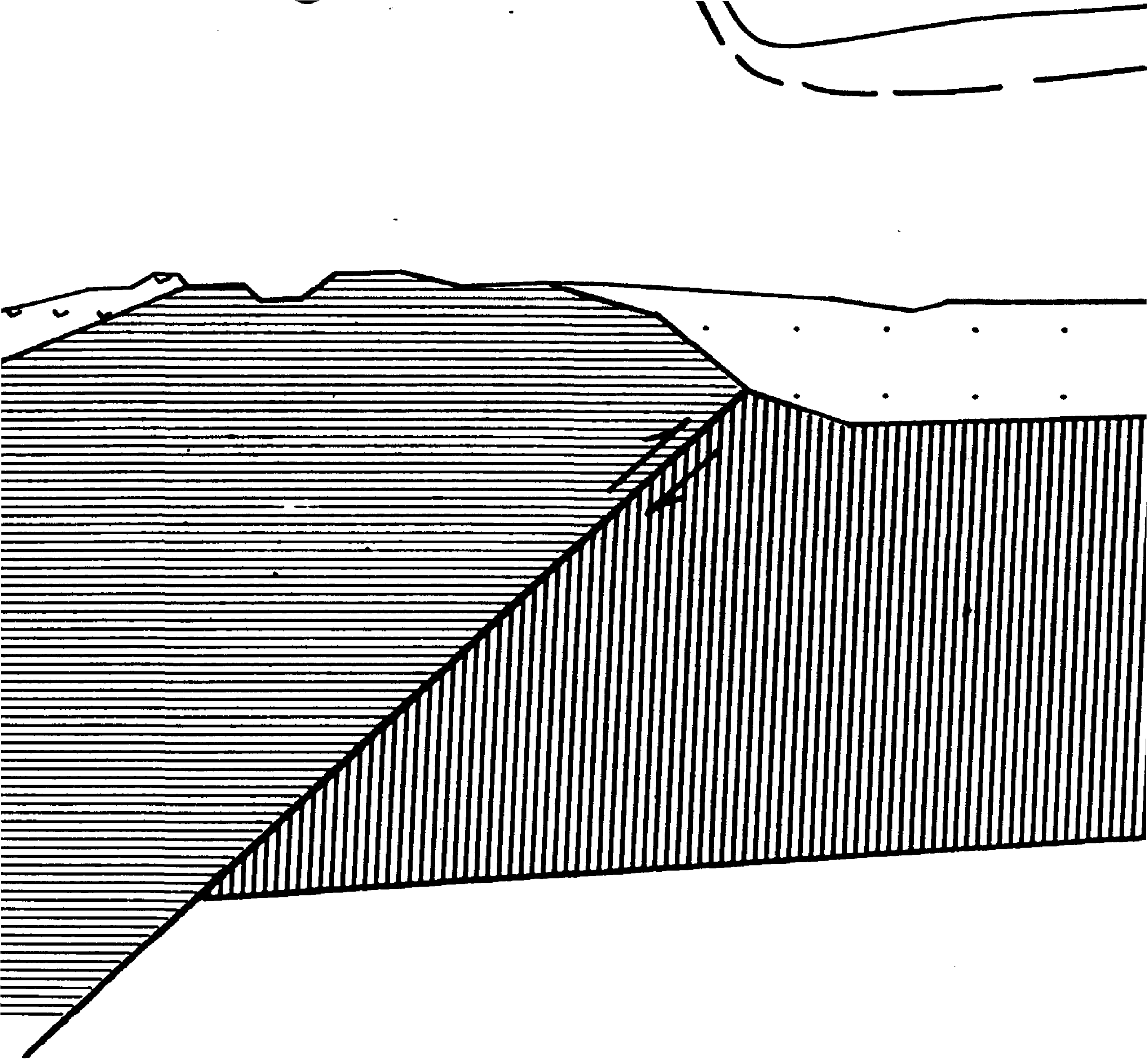

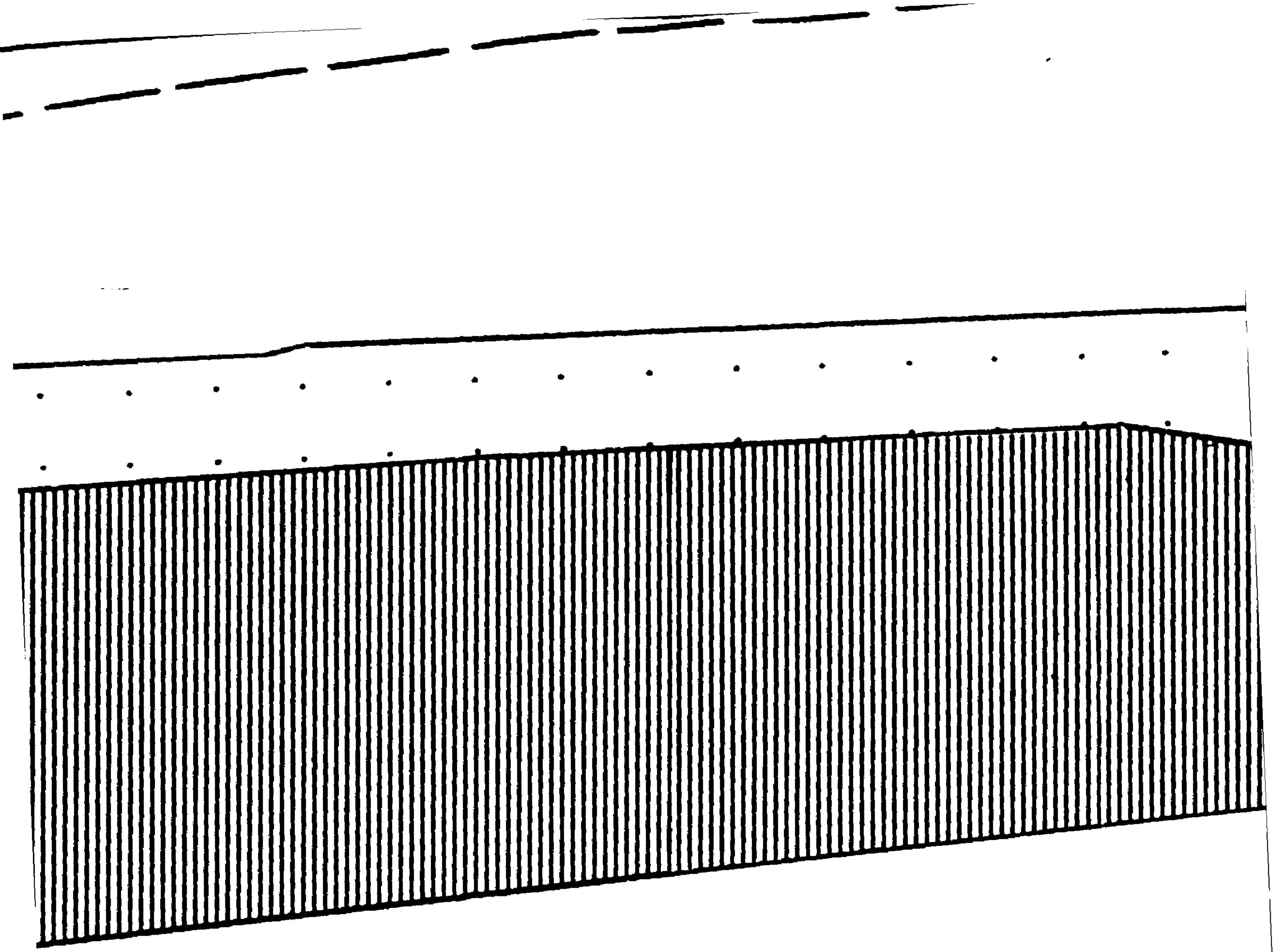

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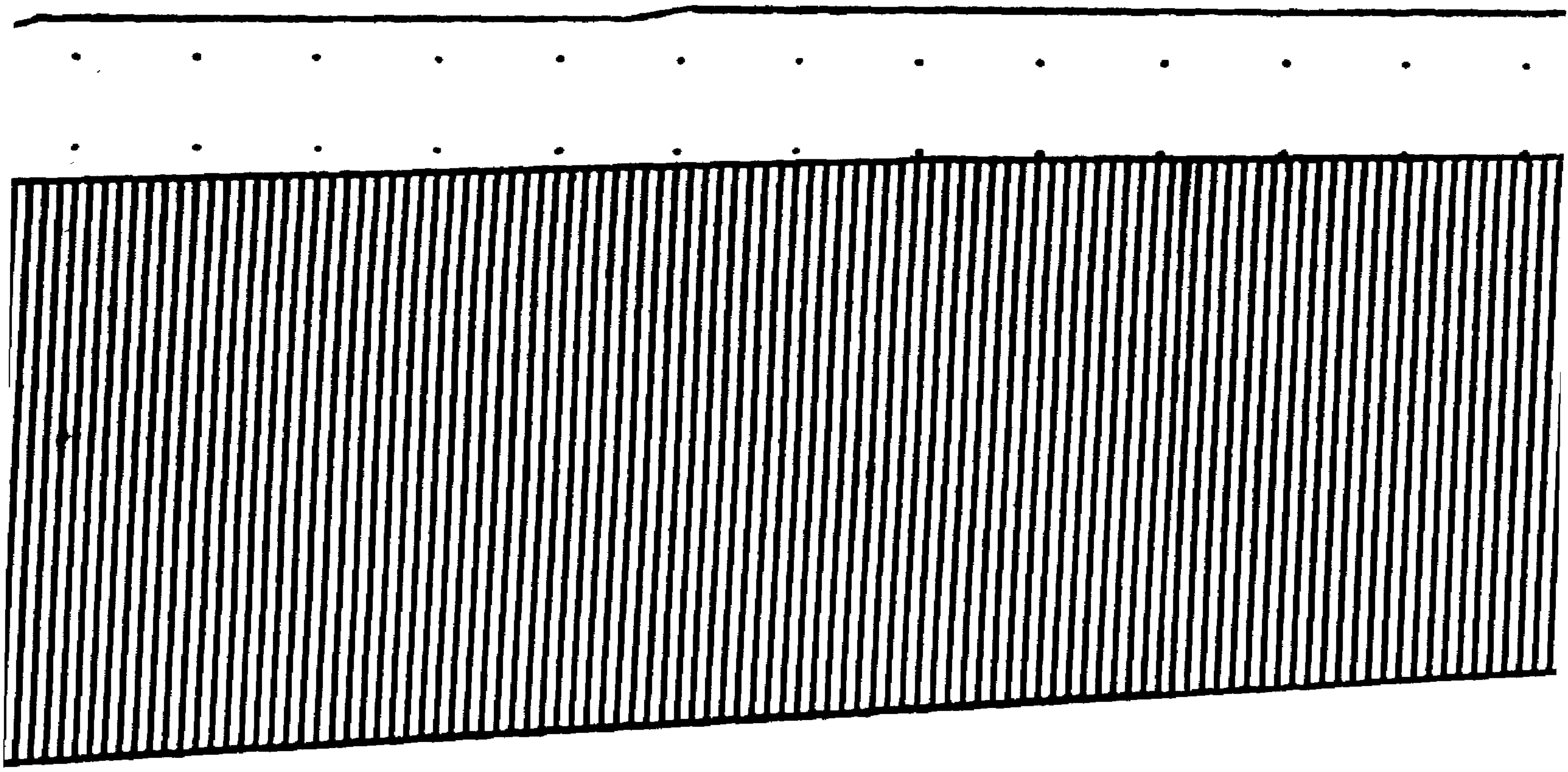

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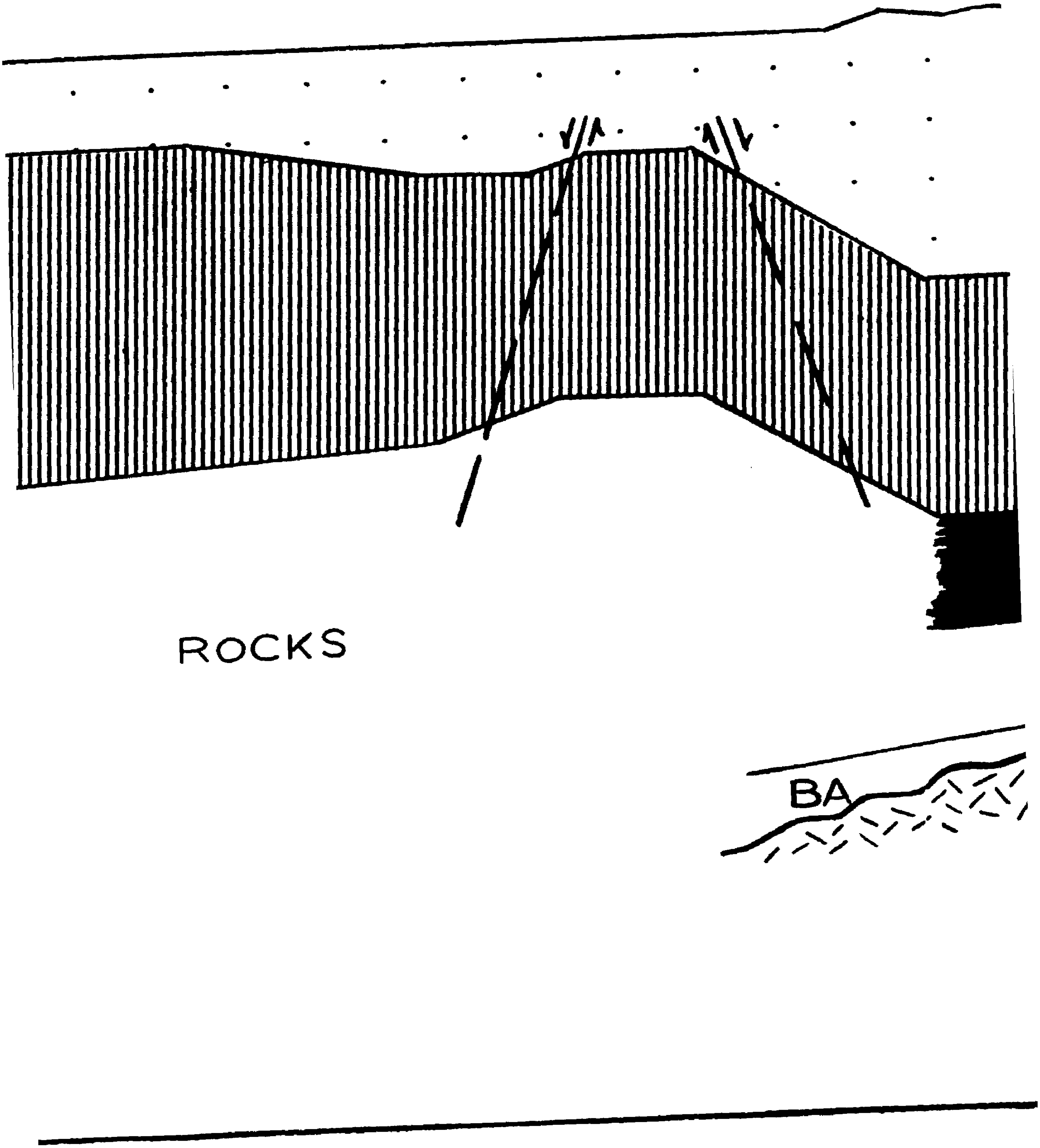
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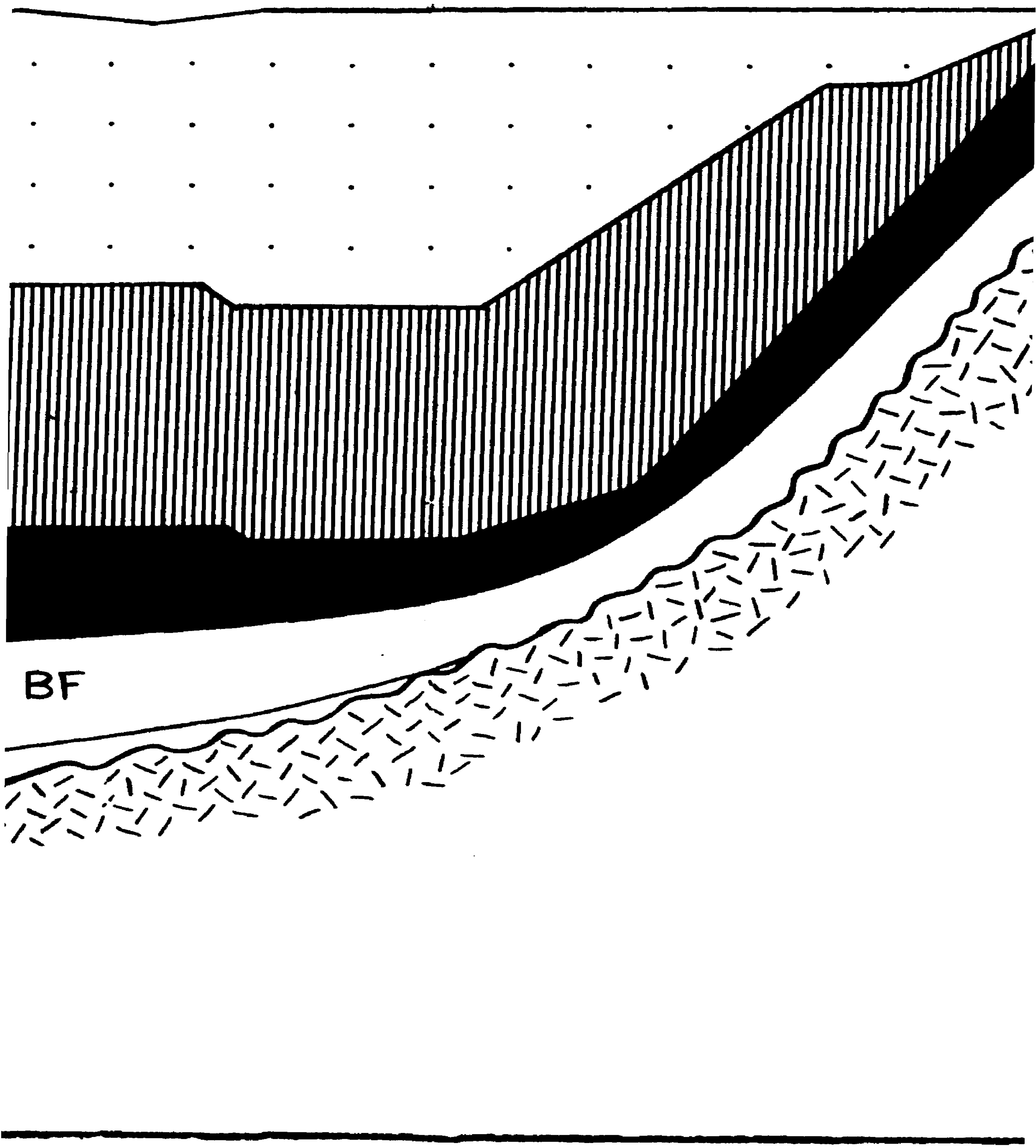
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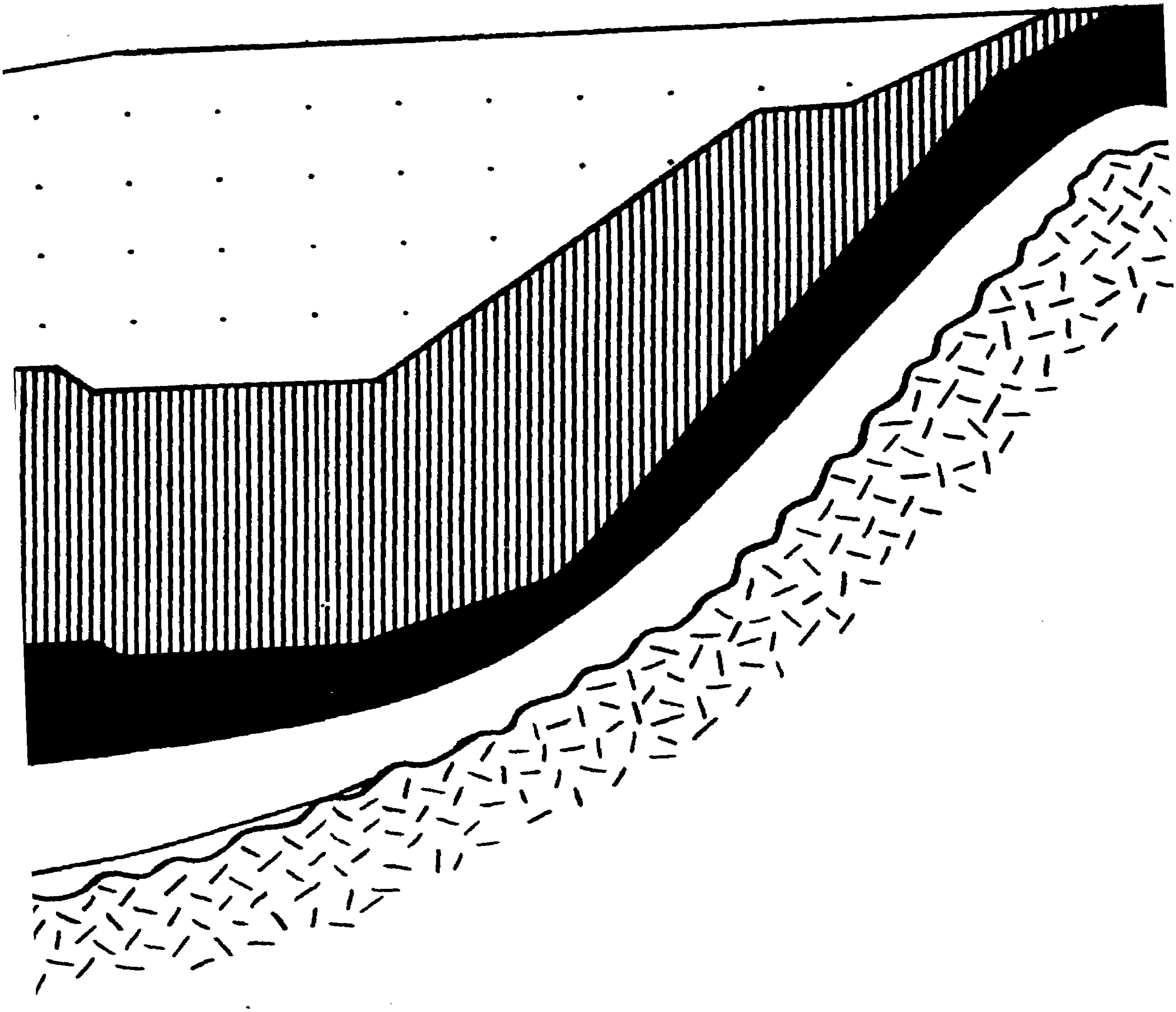

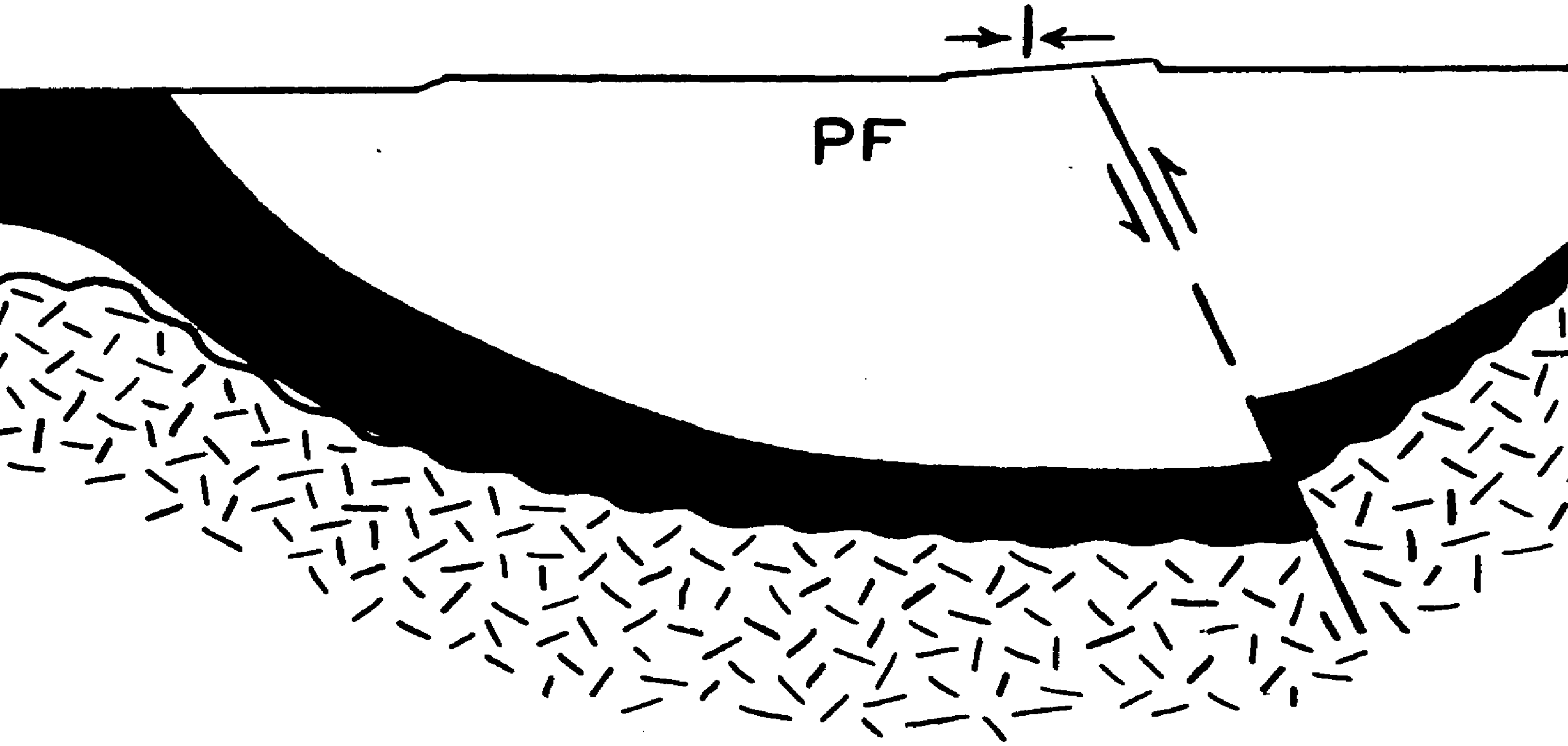
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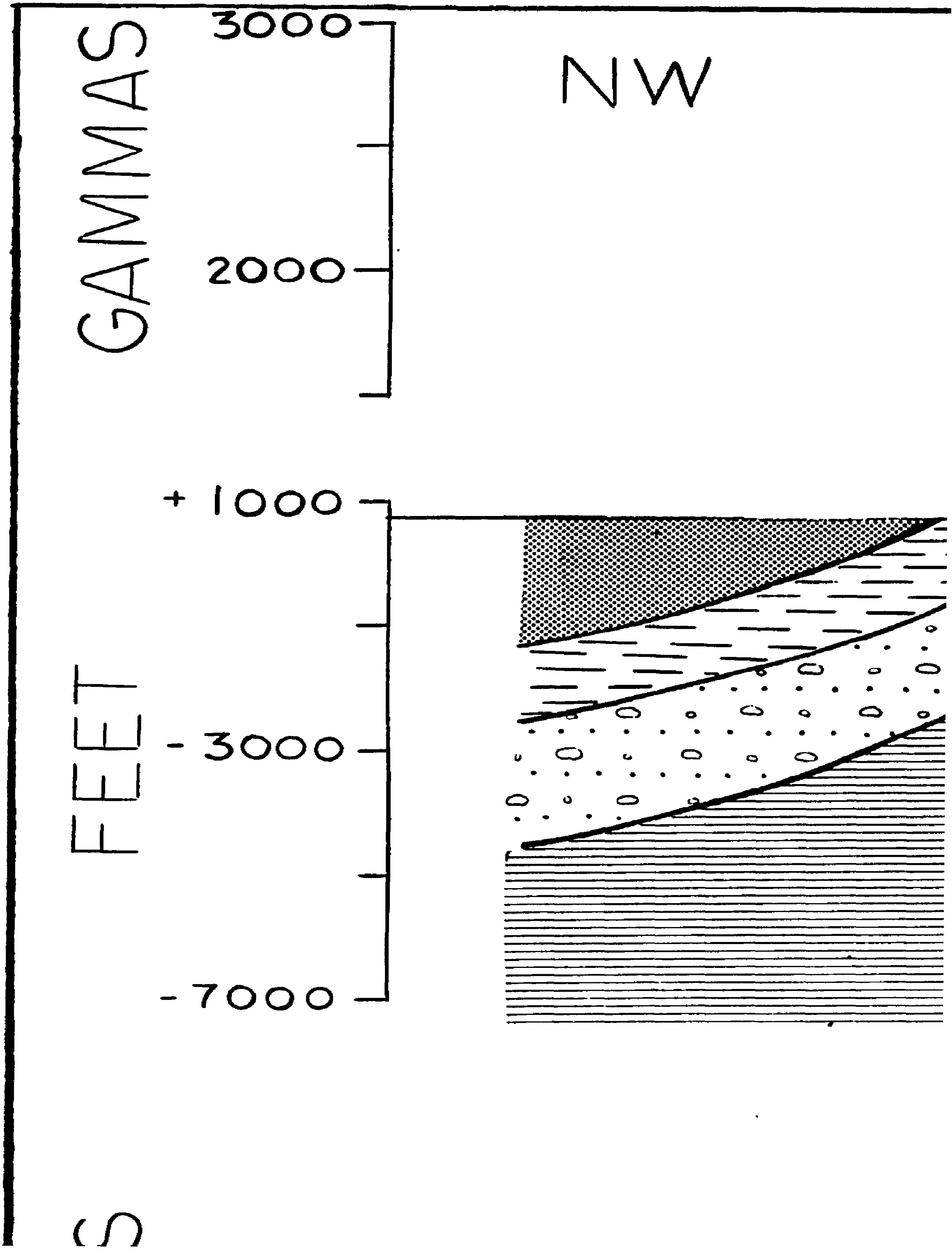
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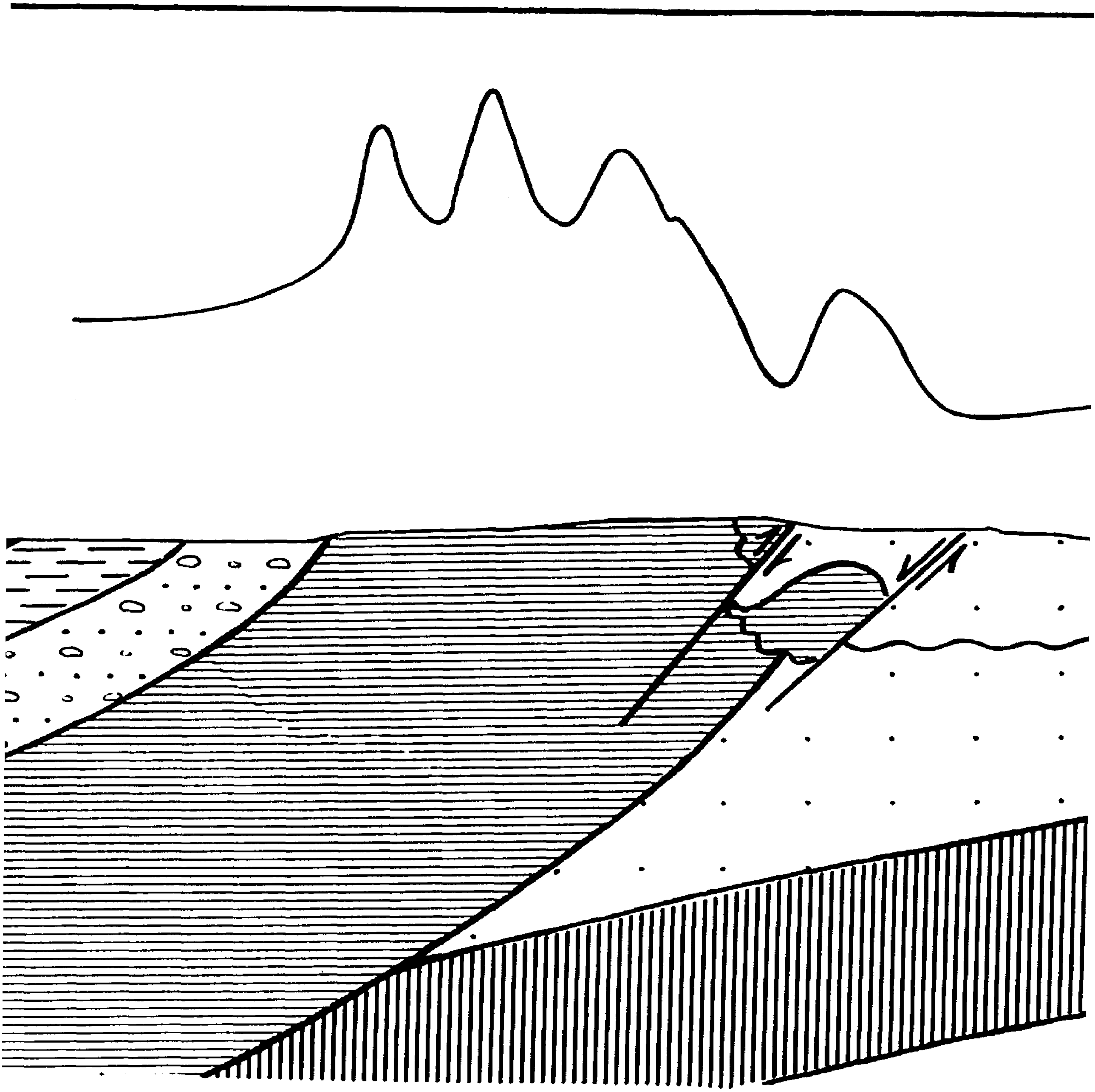

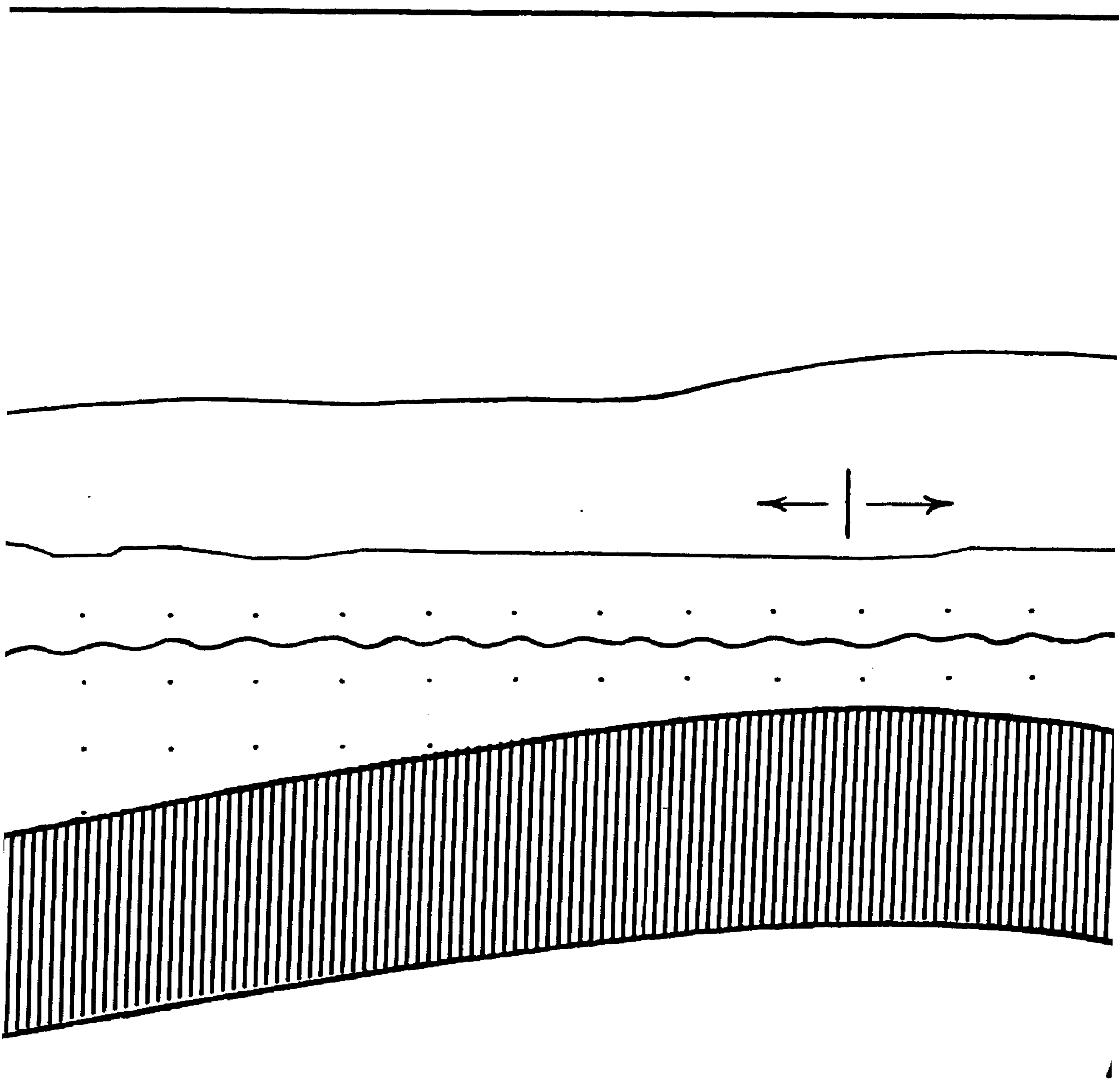

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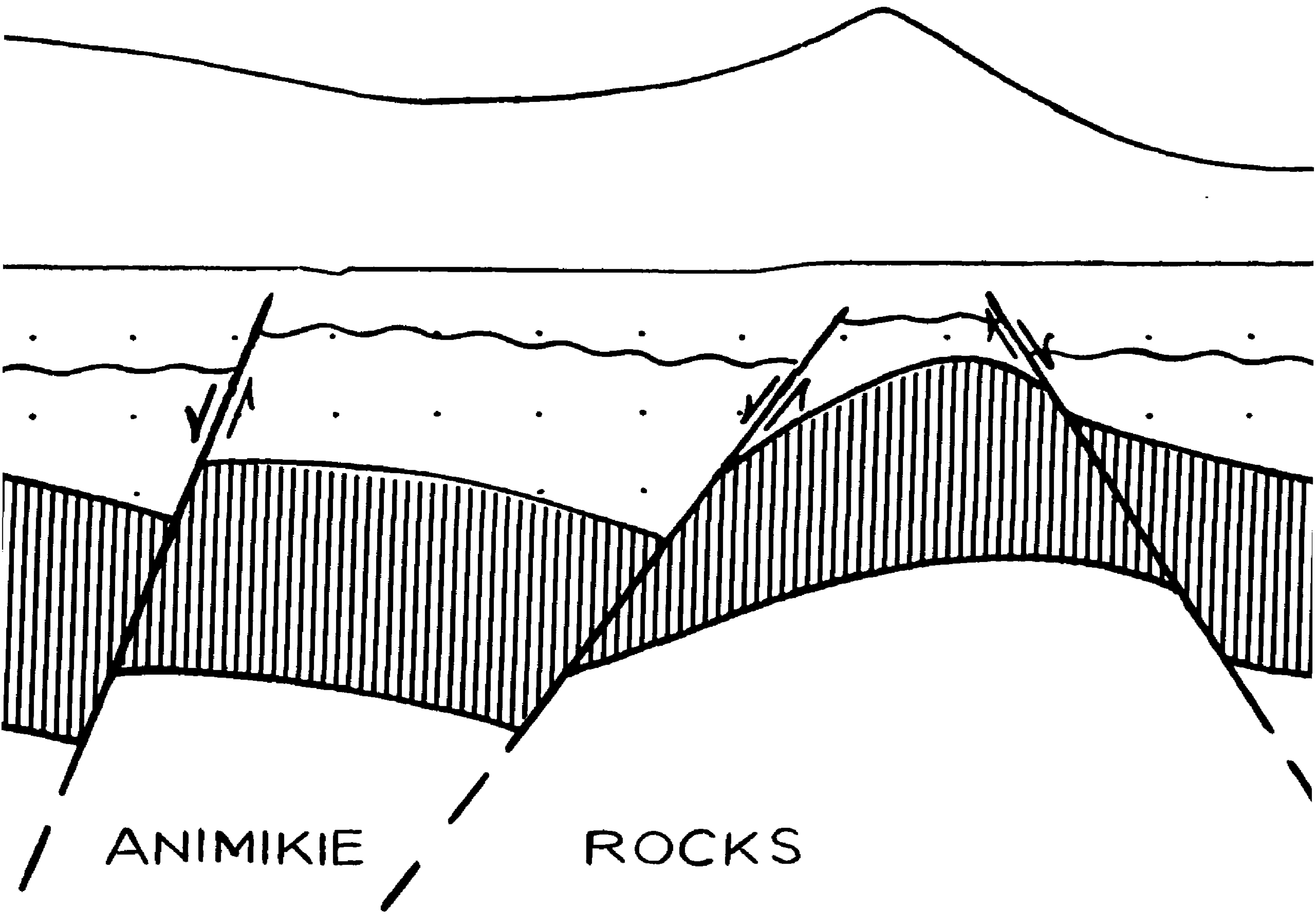

PROFIL

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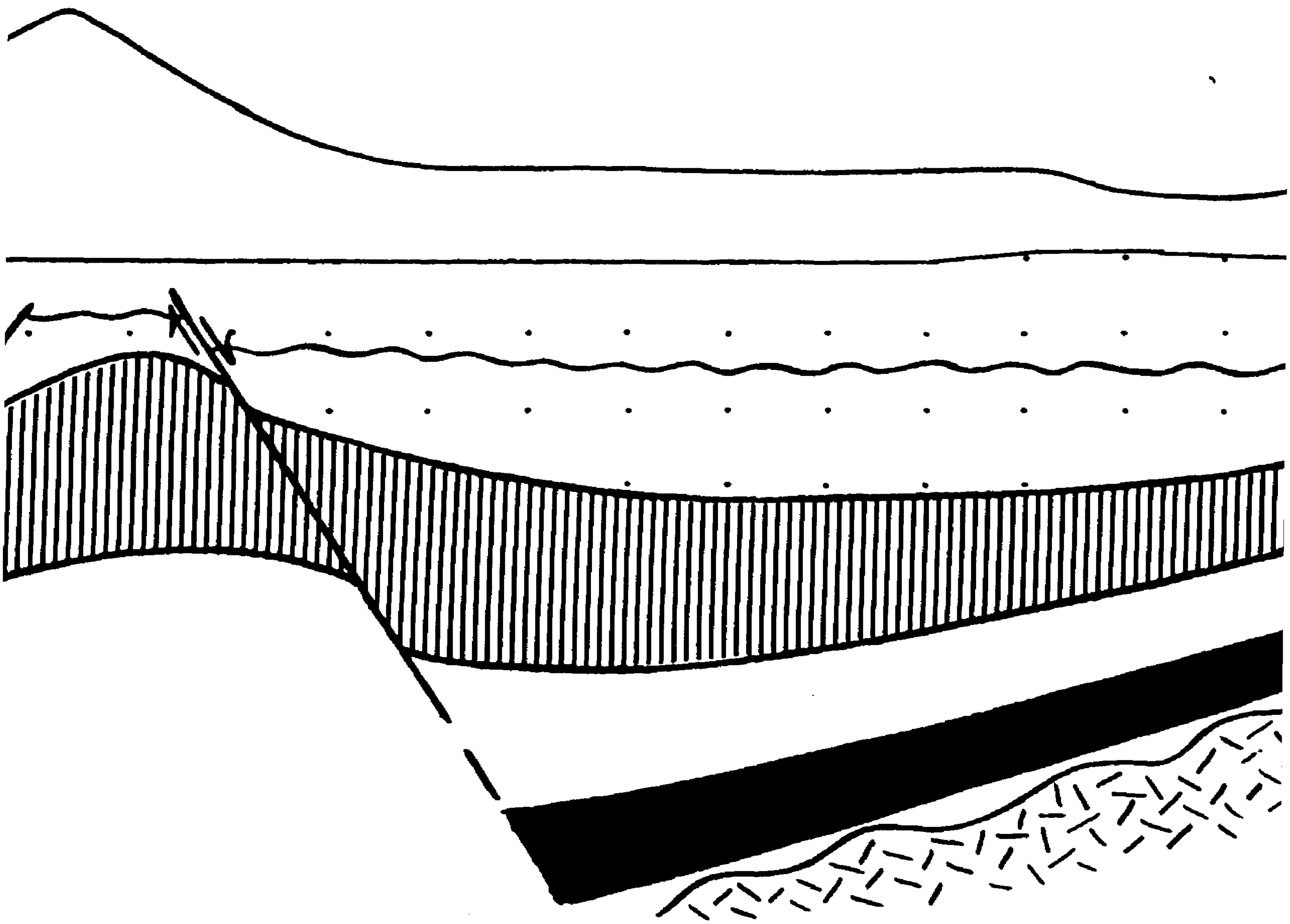

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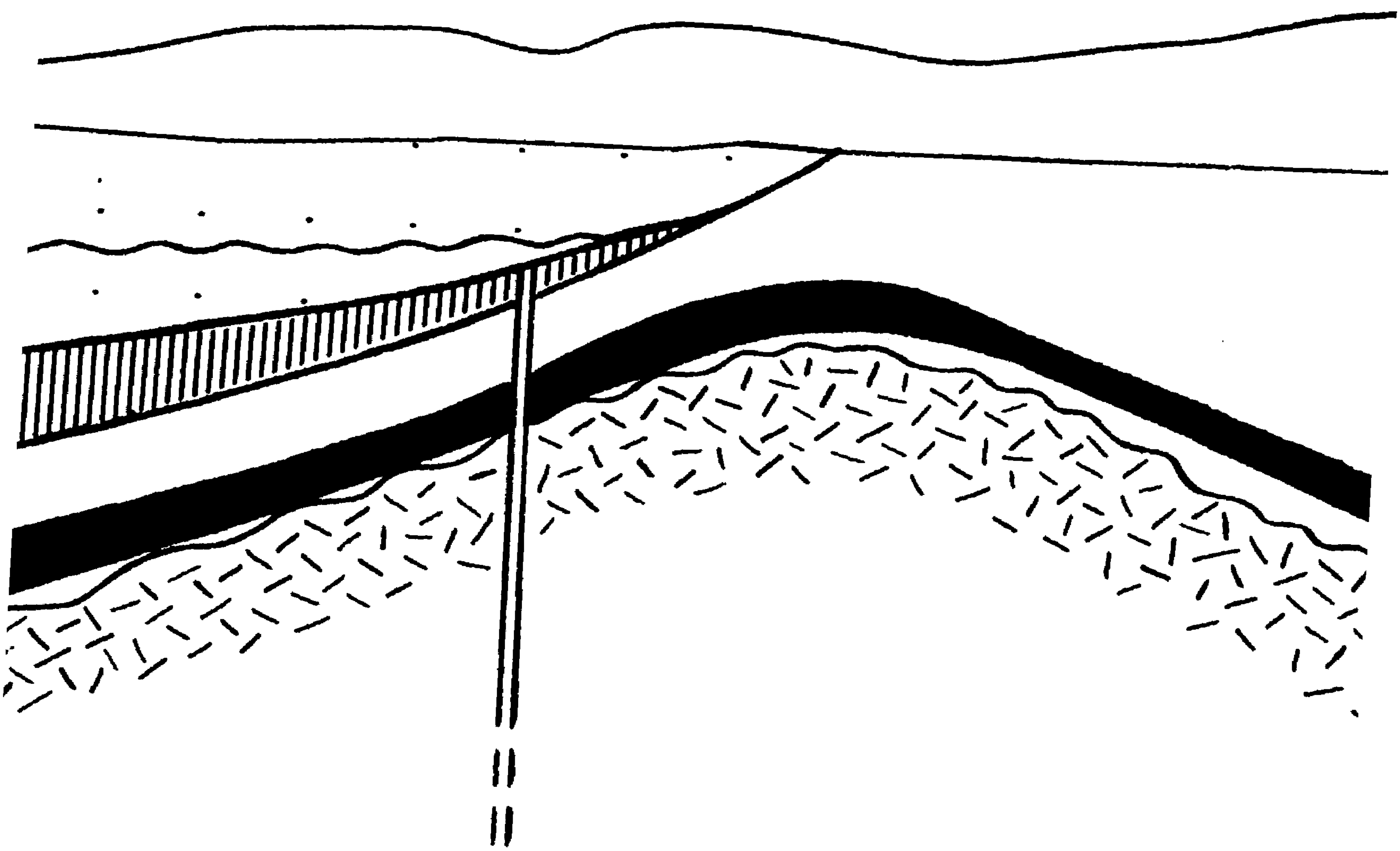

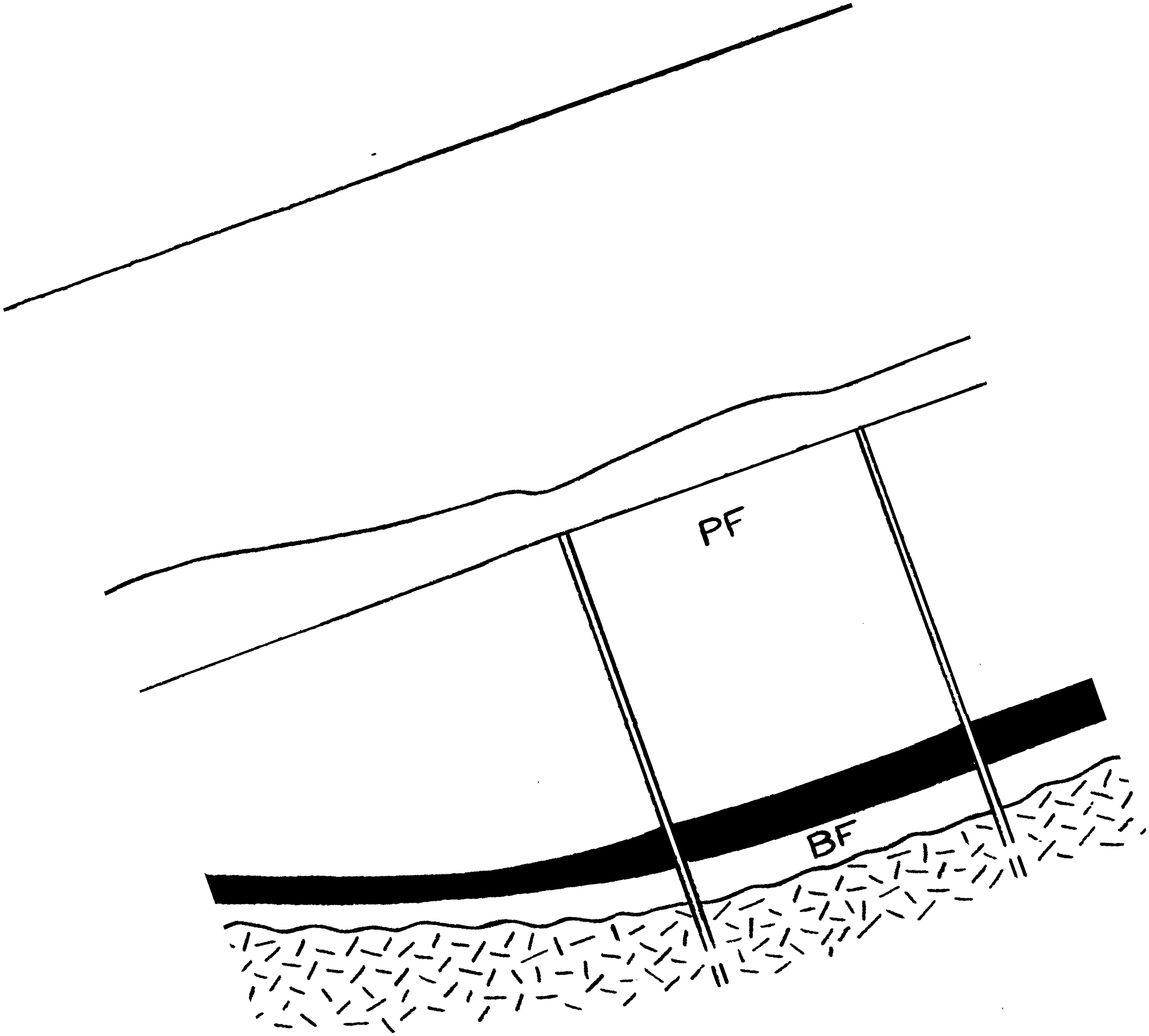
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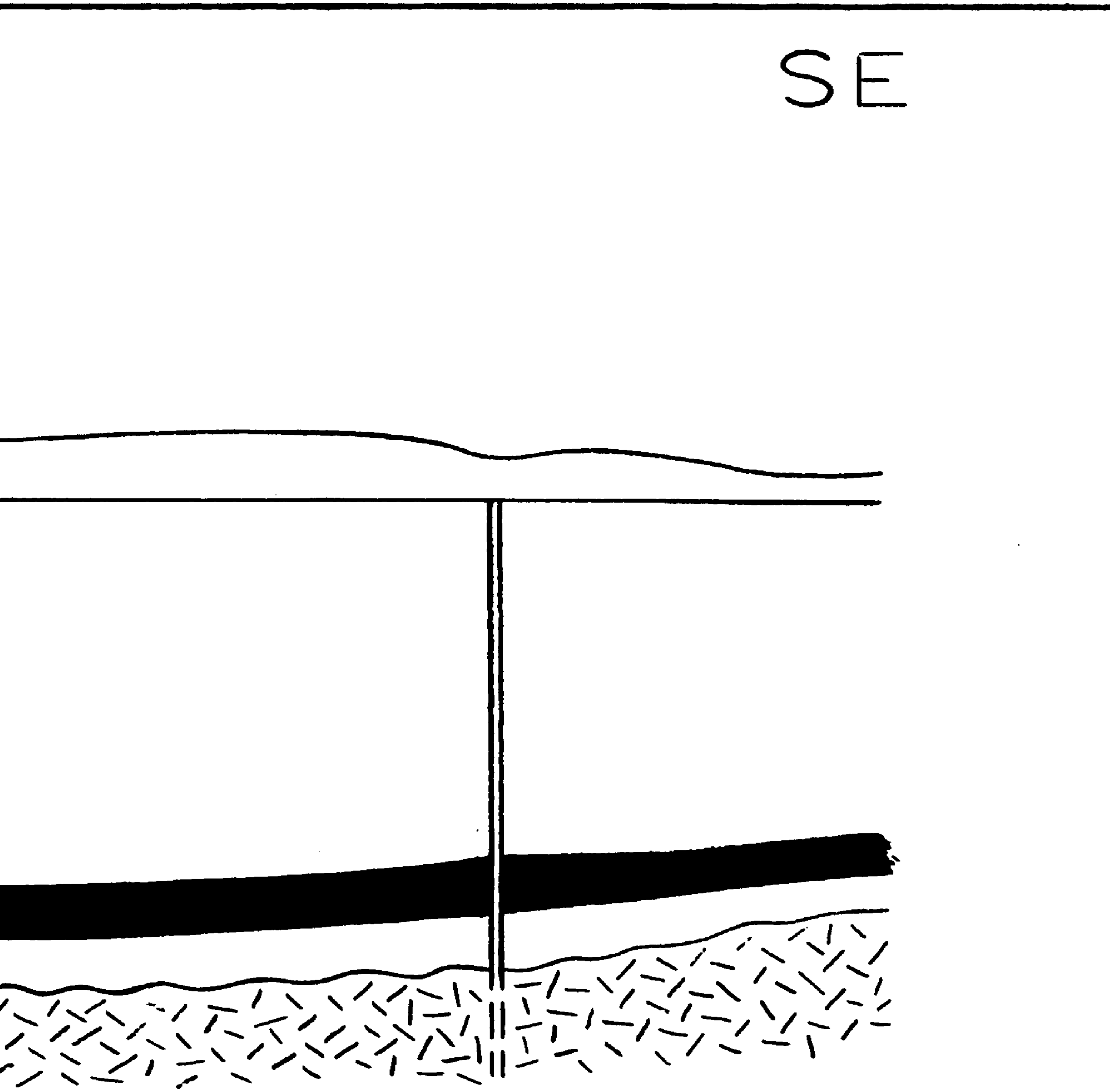
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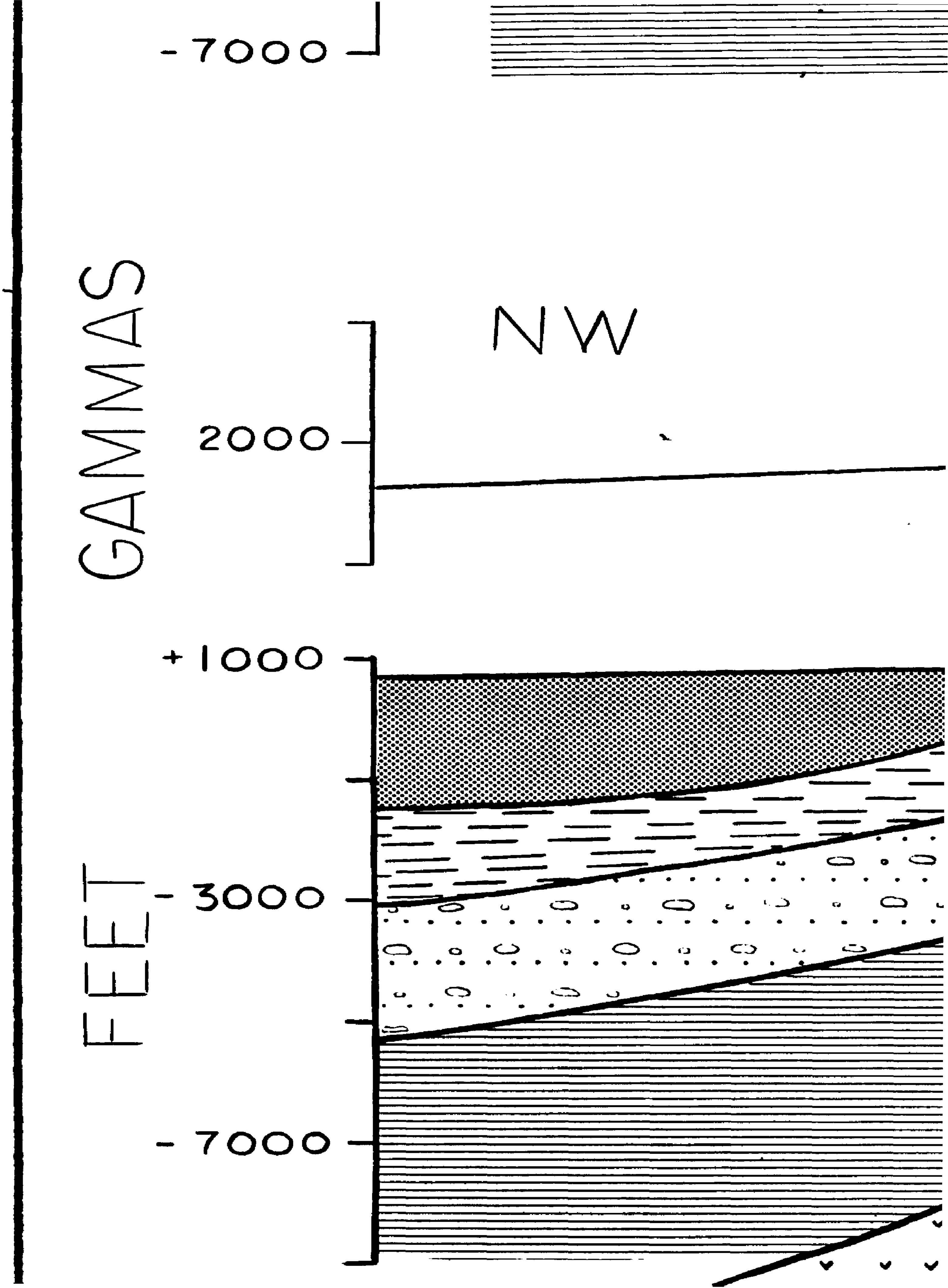

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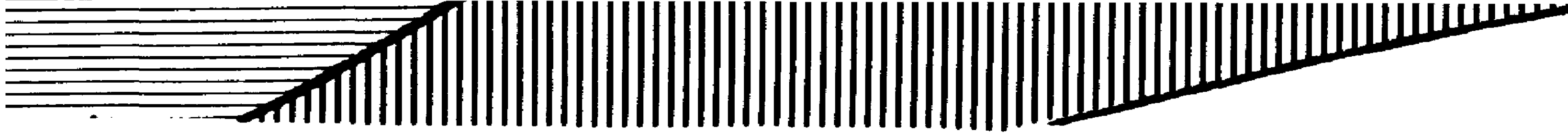
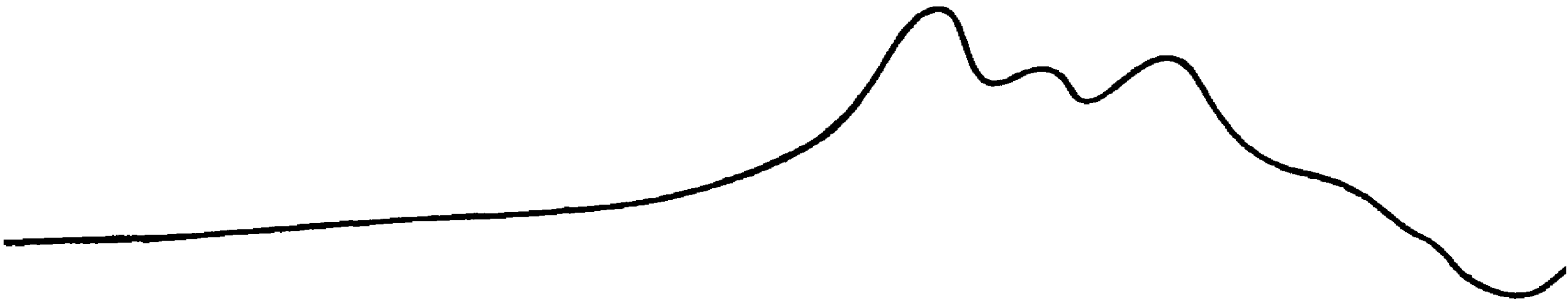
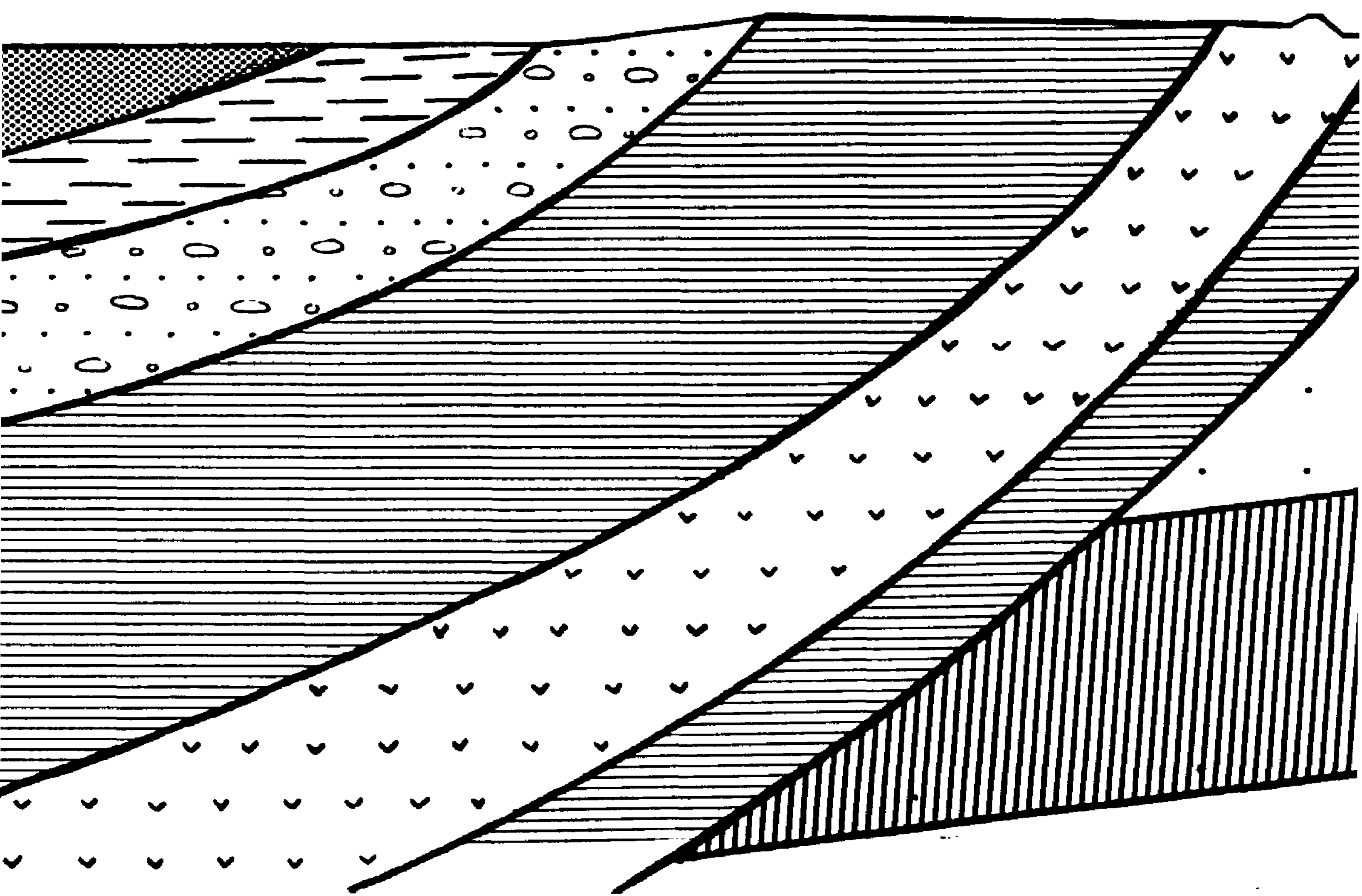
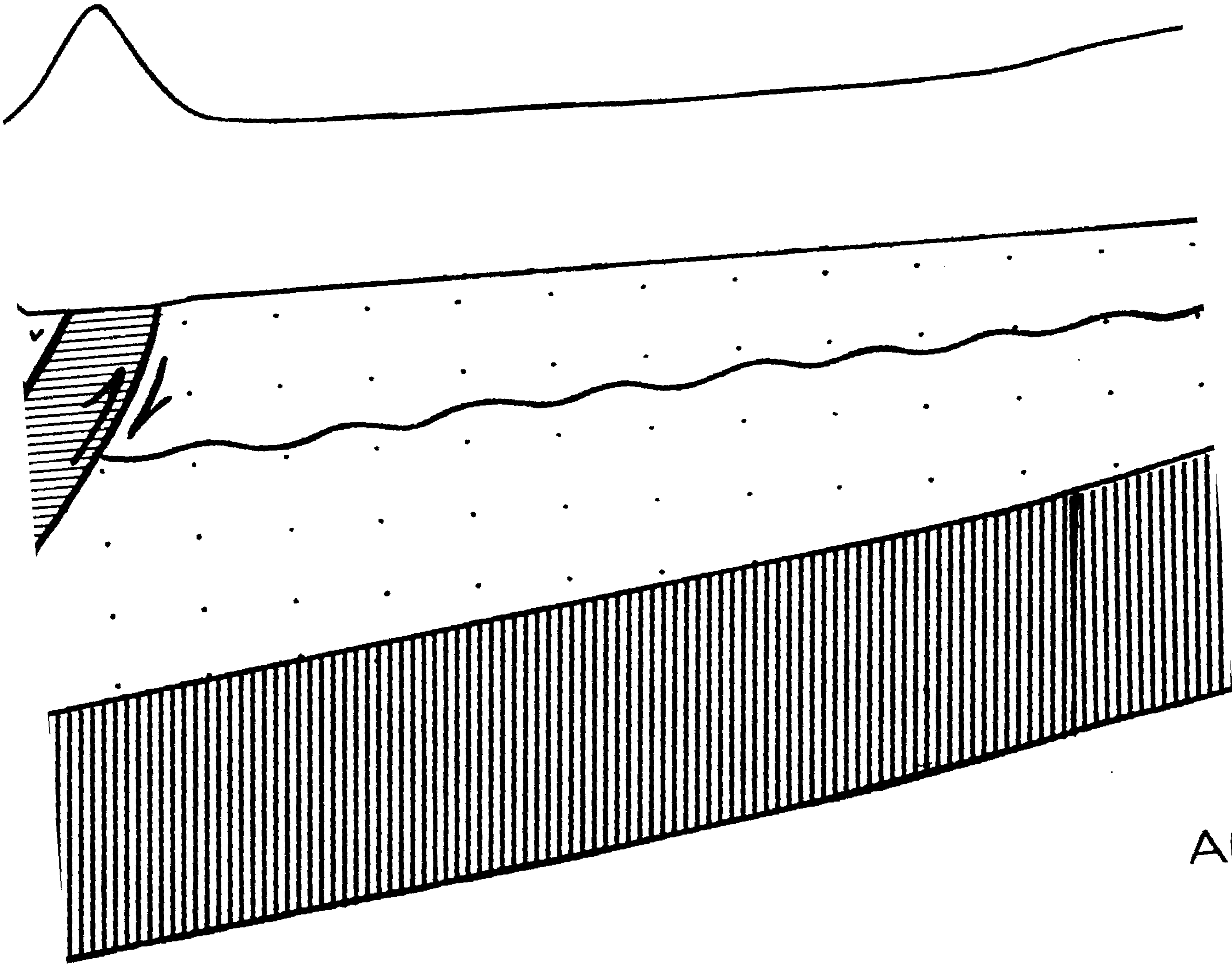




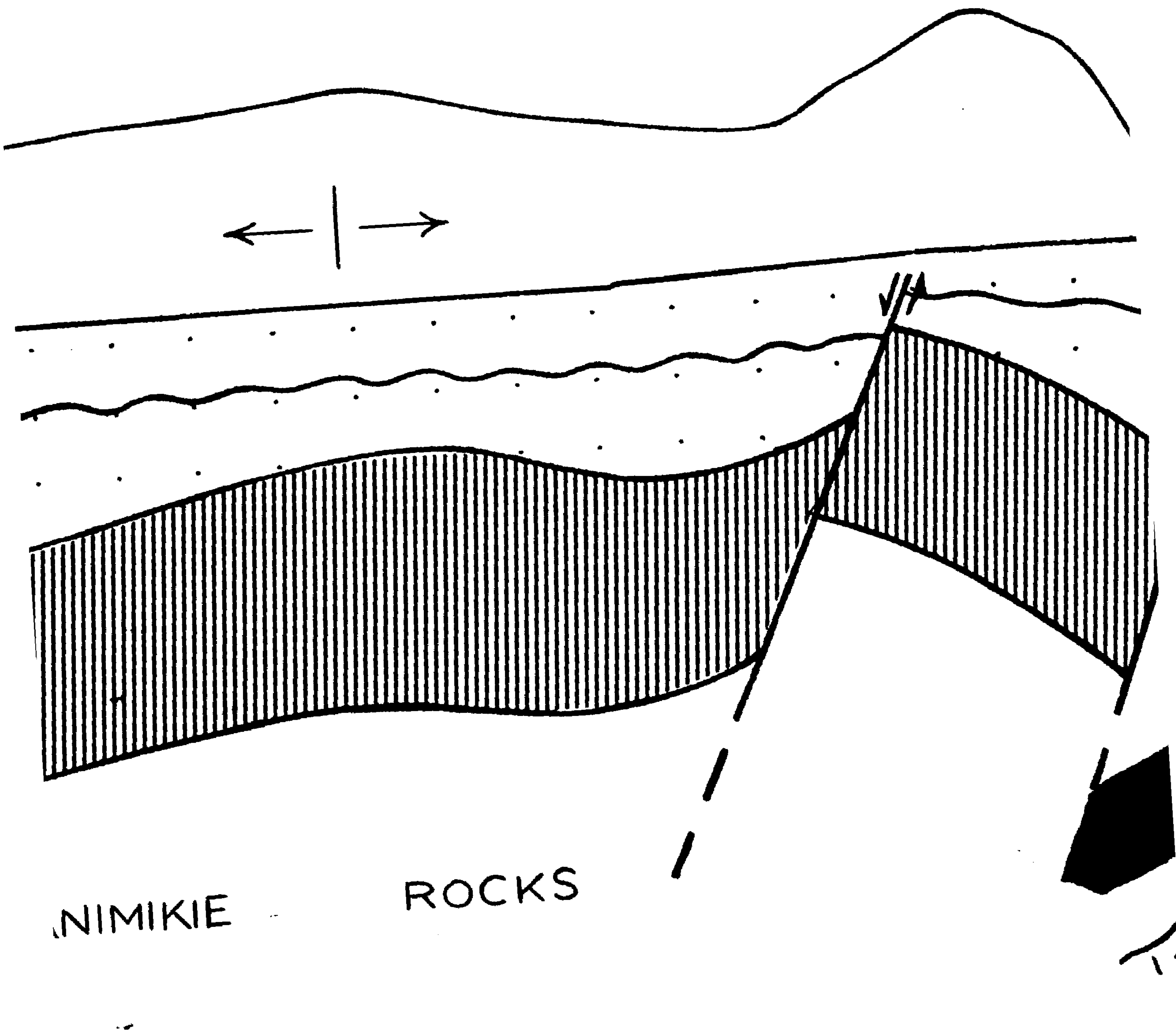




AN

ANIMIKIE ROCKS

PROFILE



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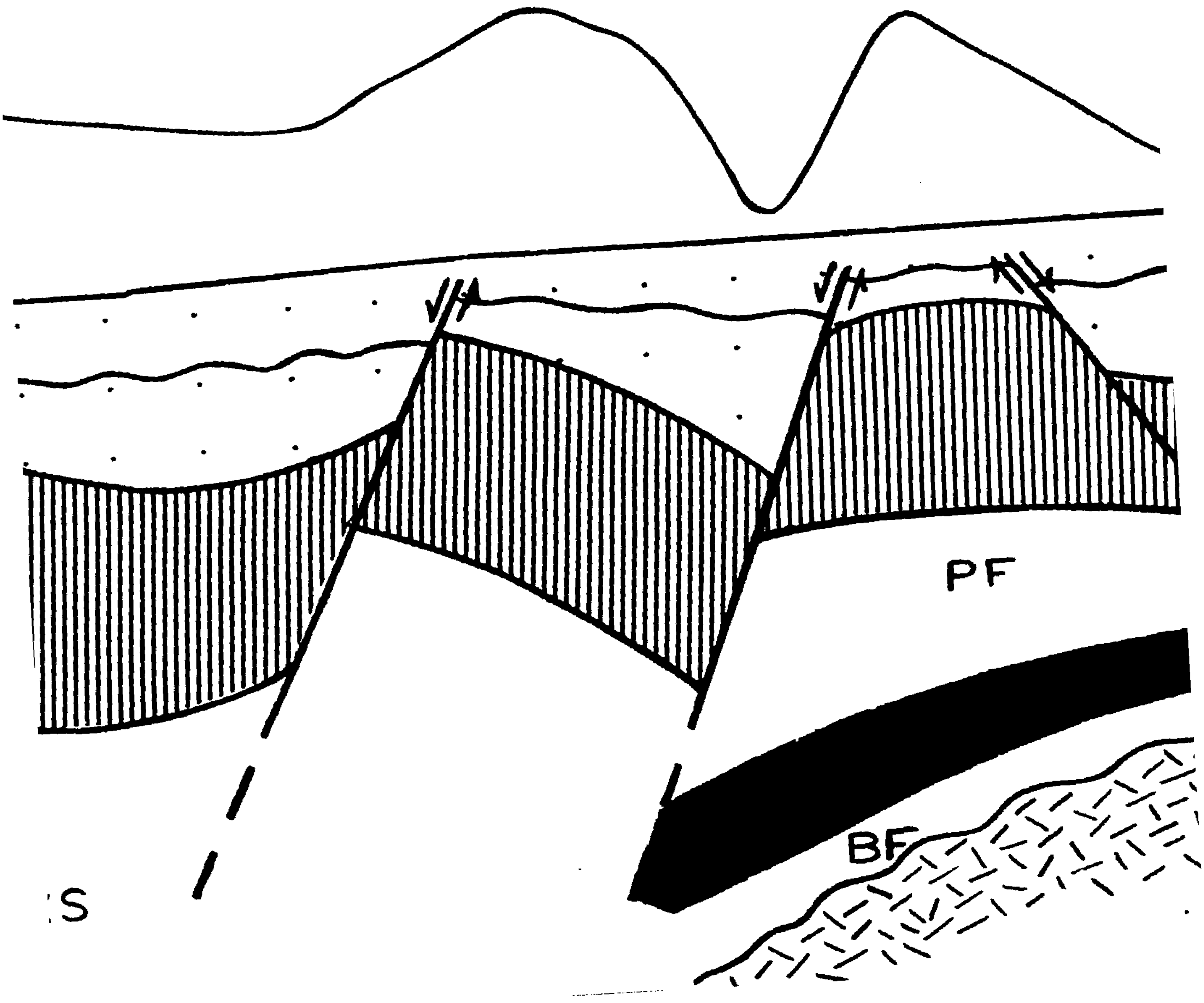

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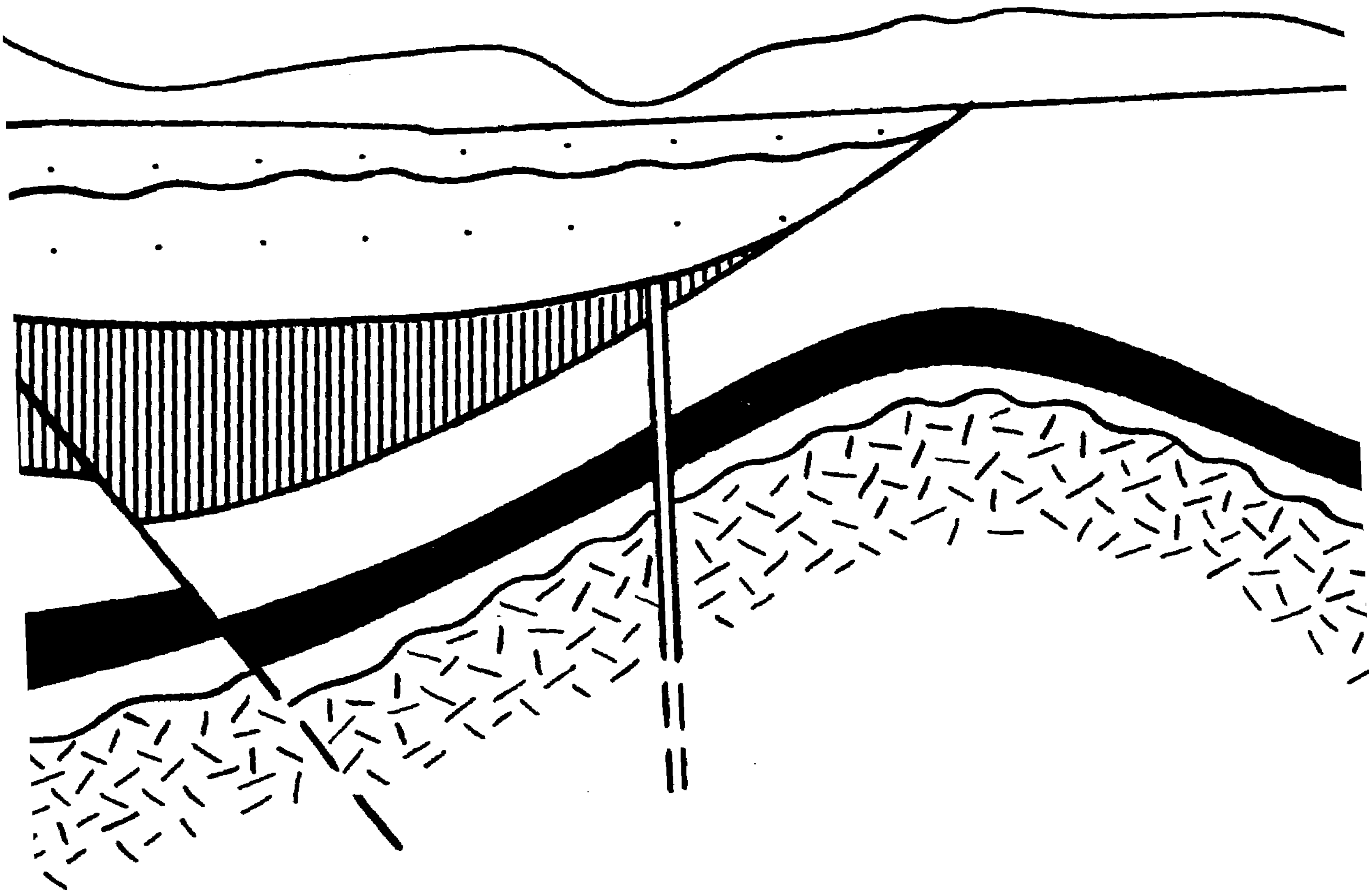

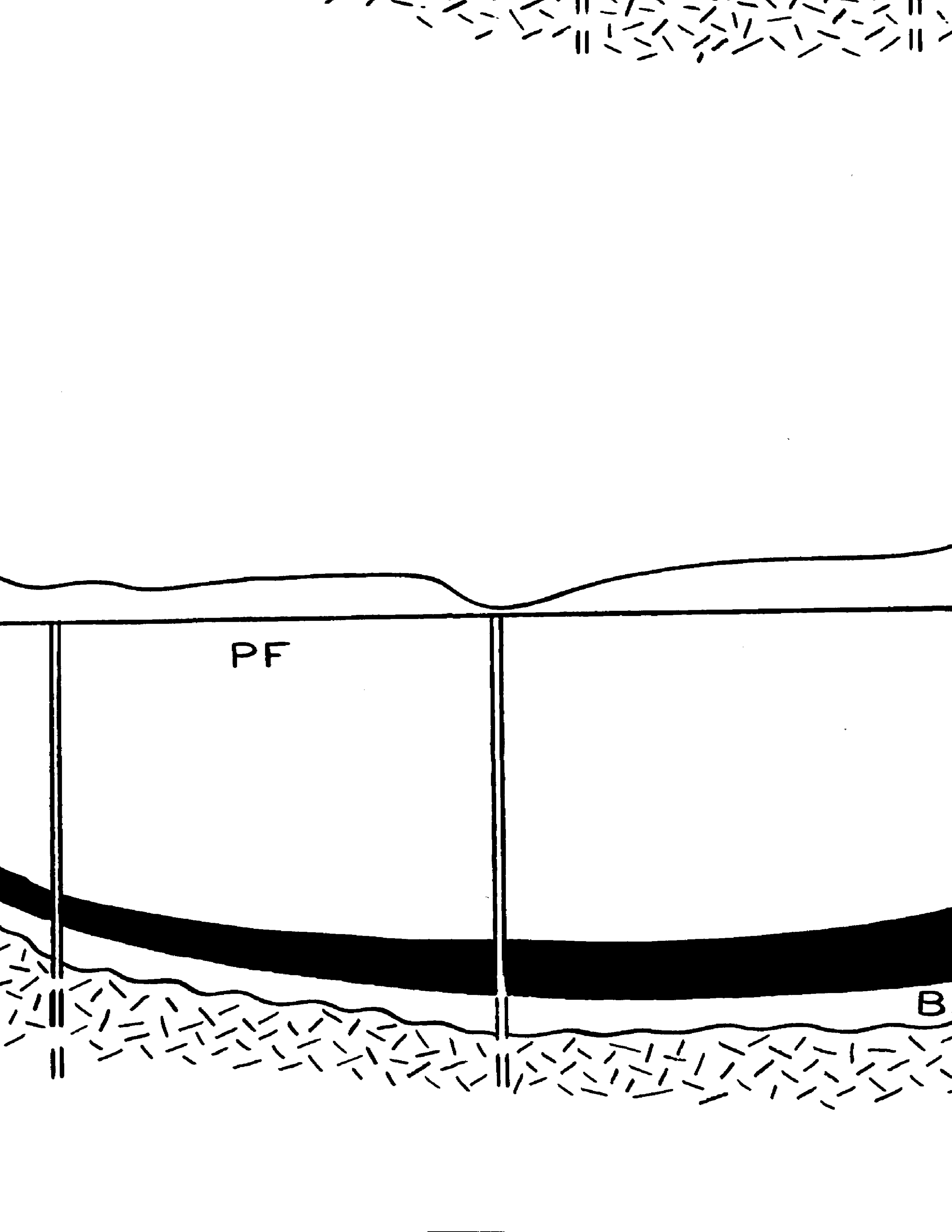
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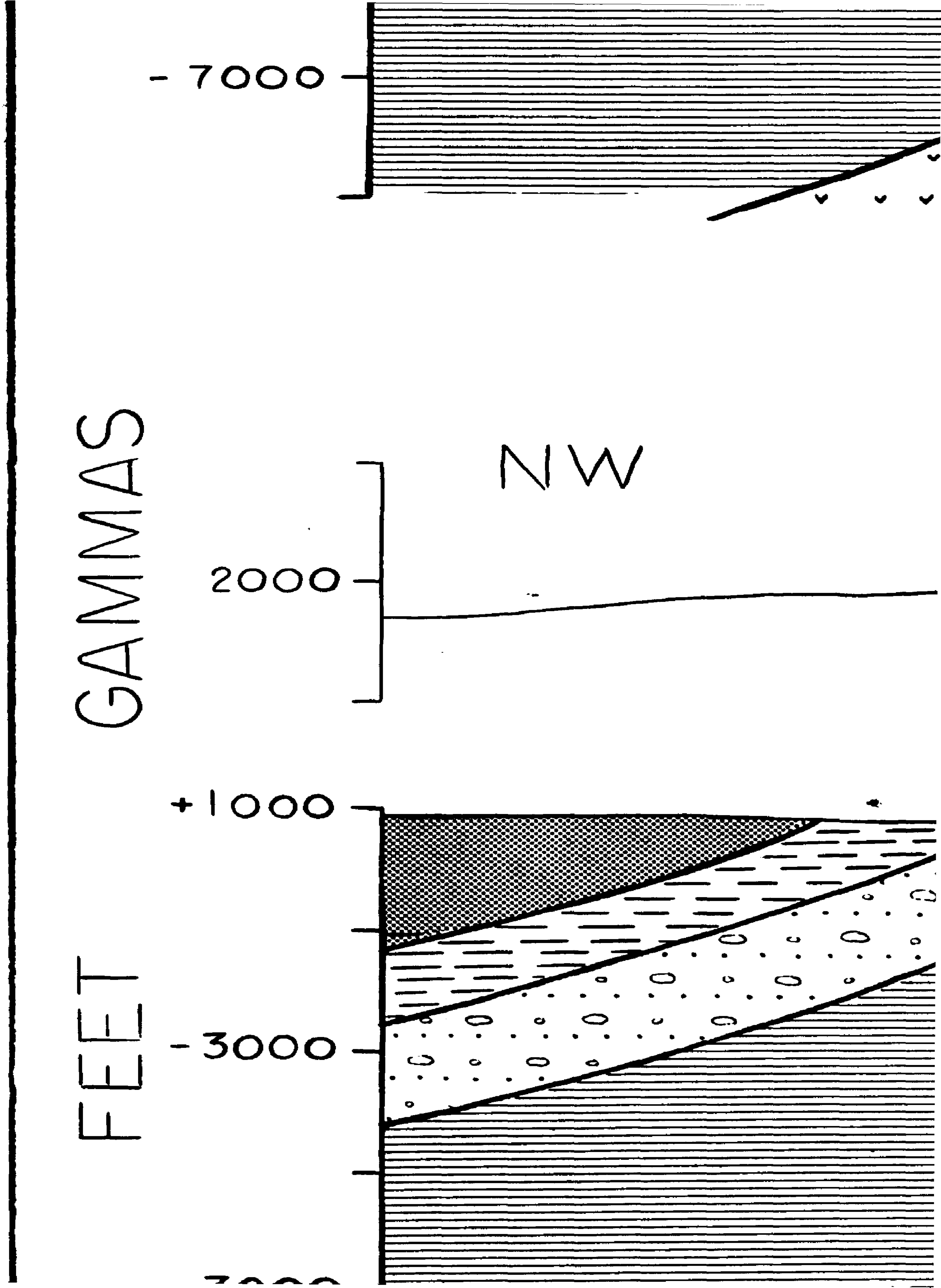

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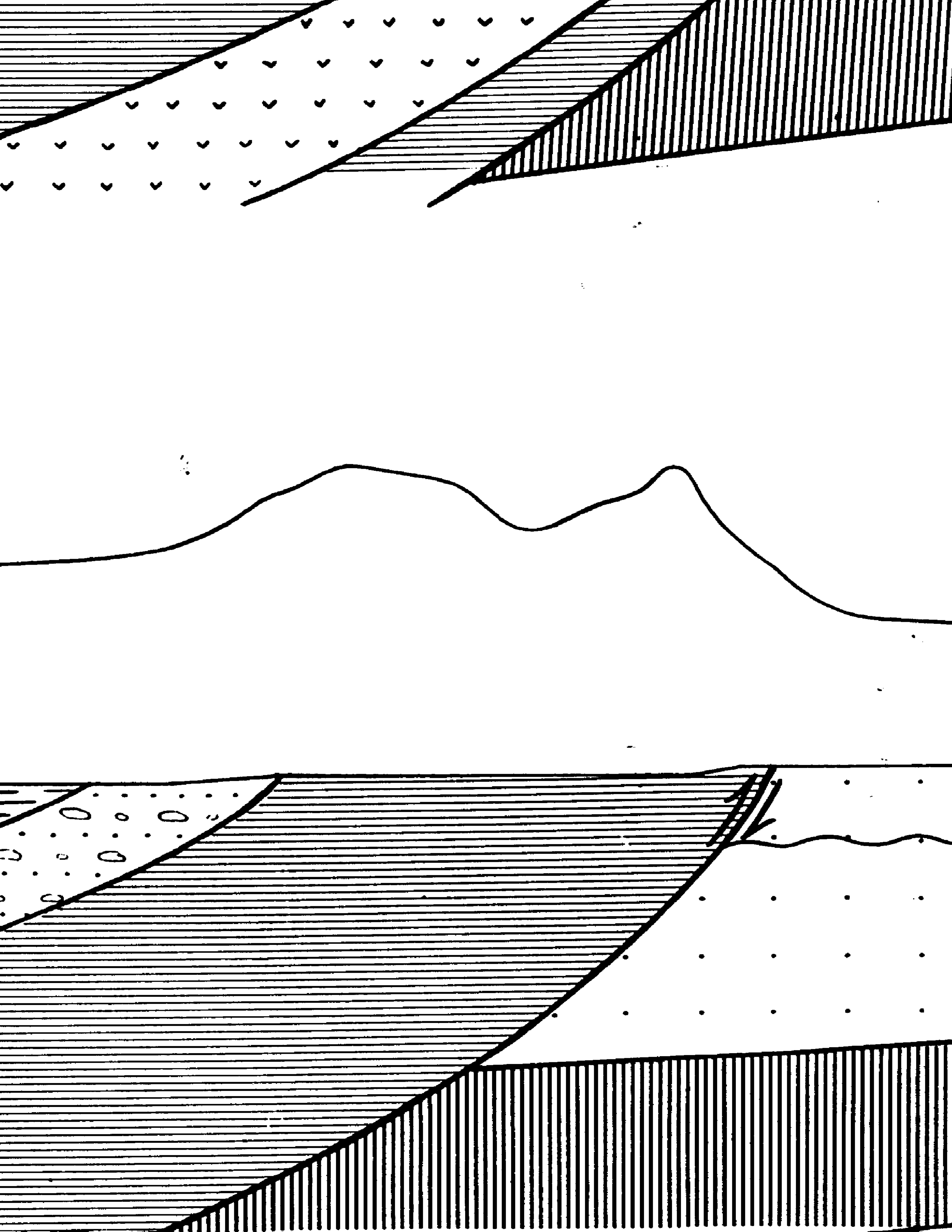

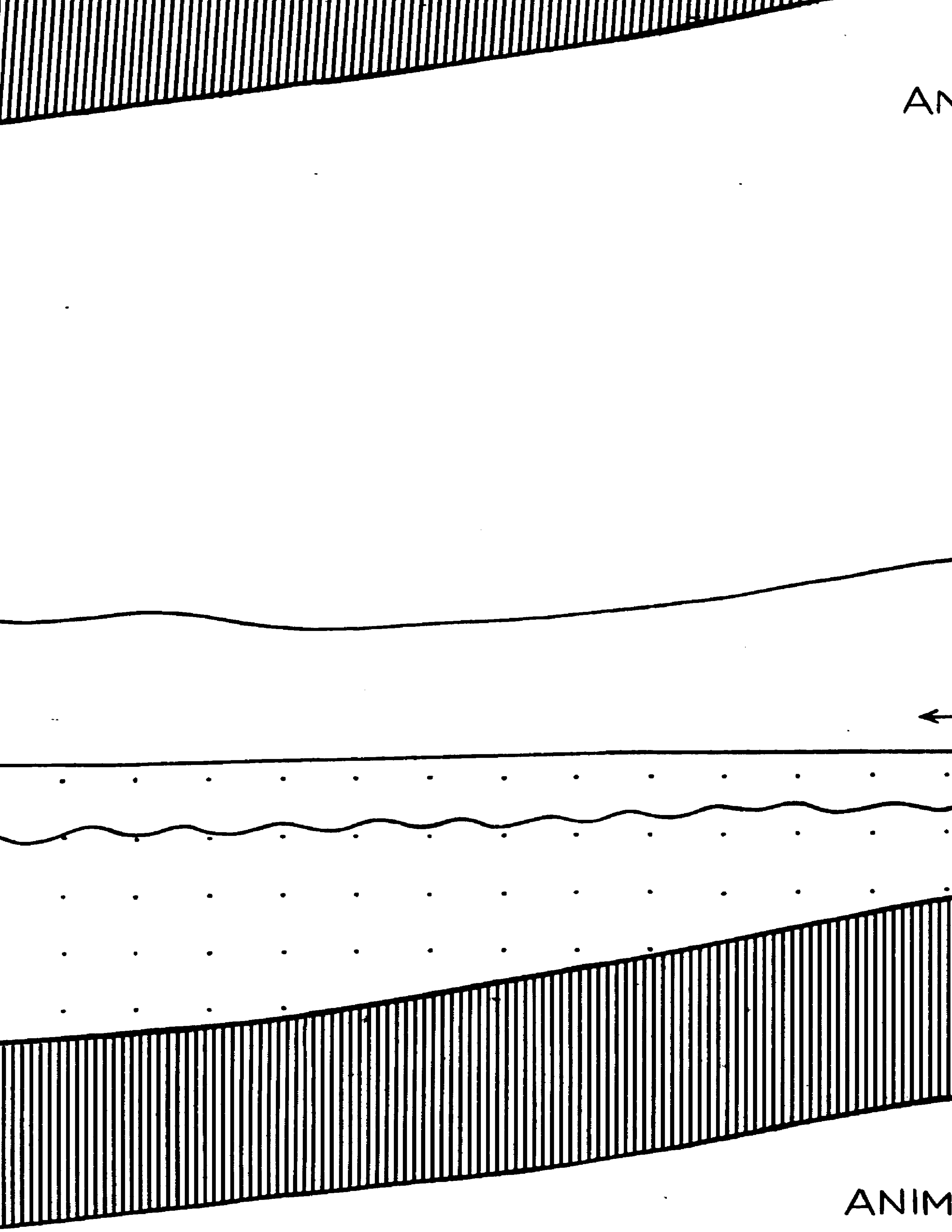
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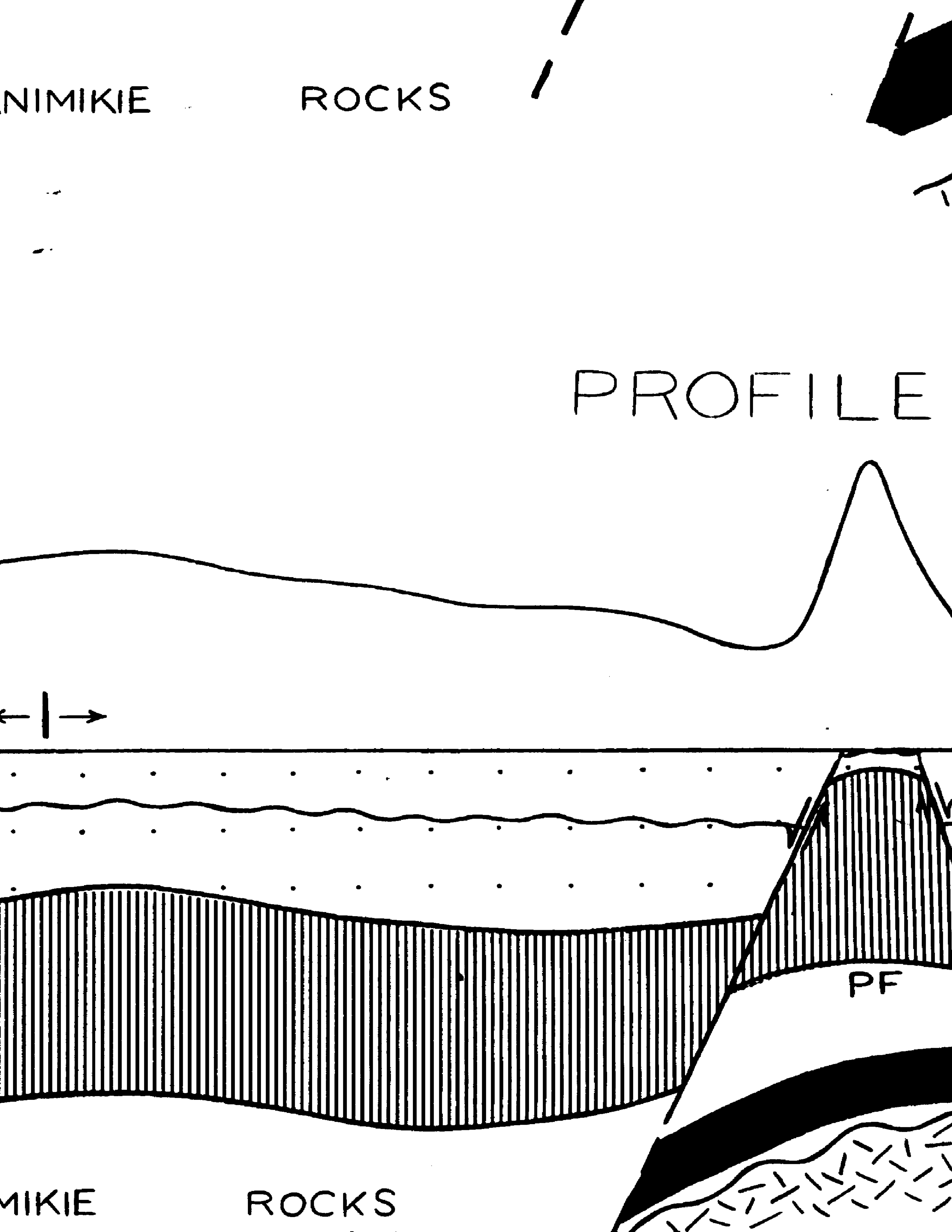
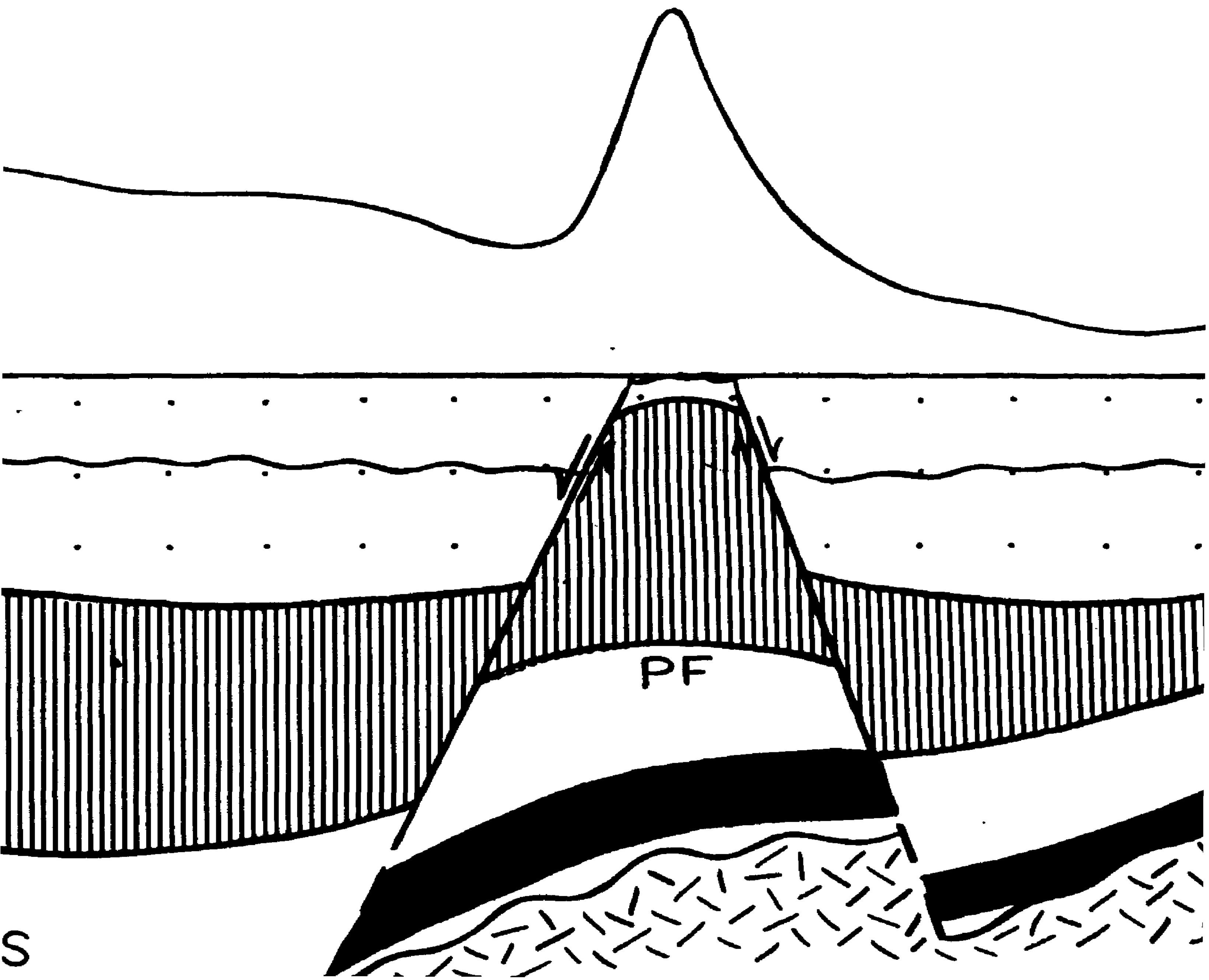
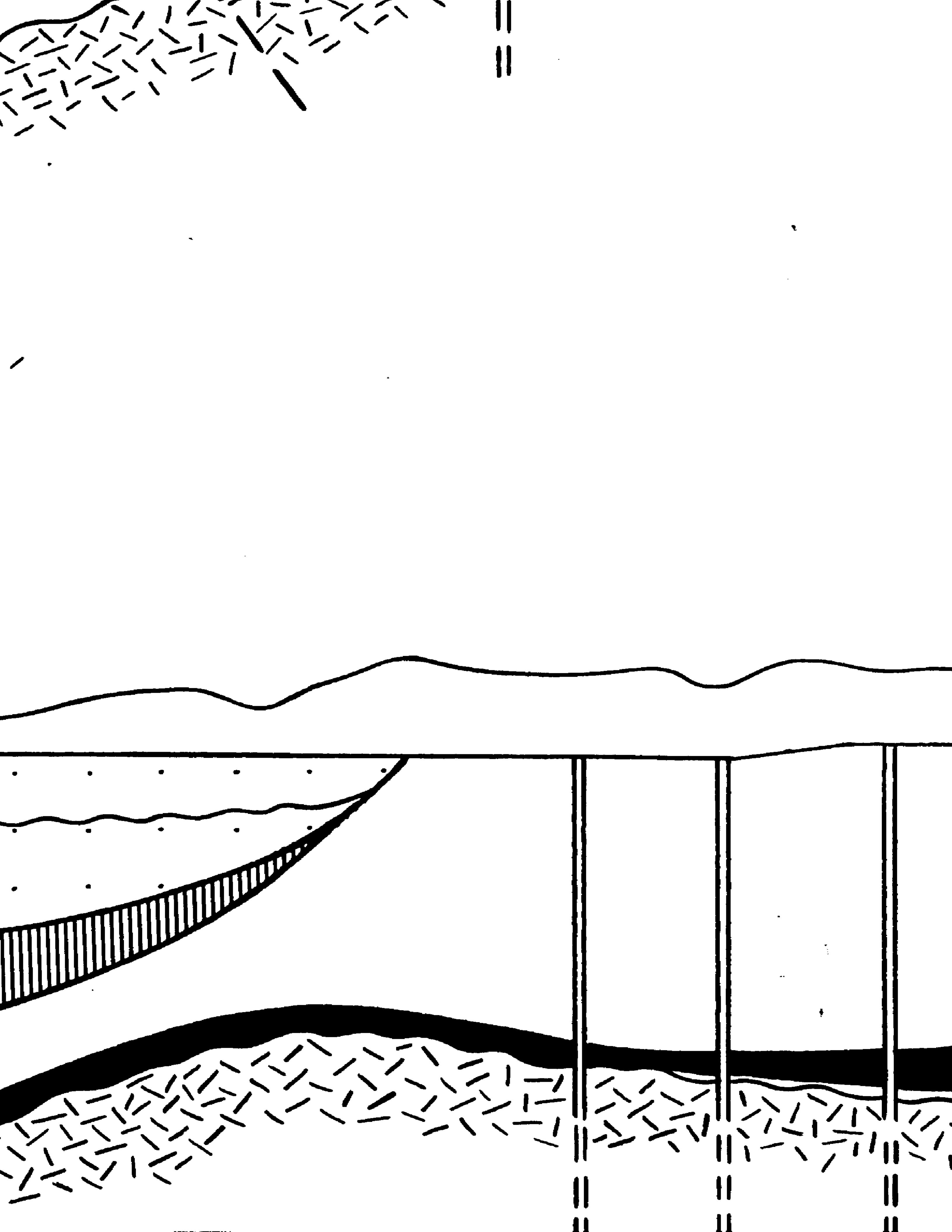
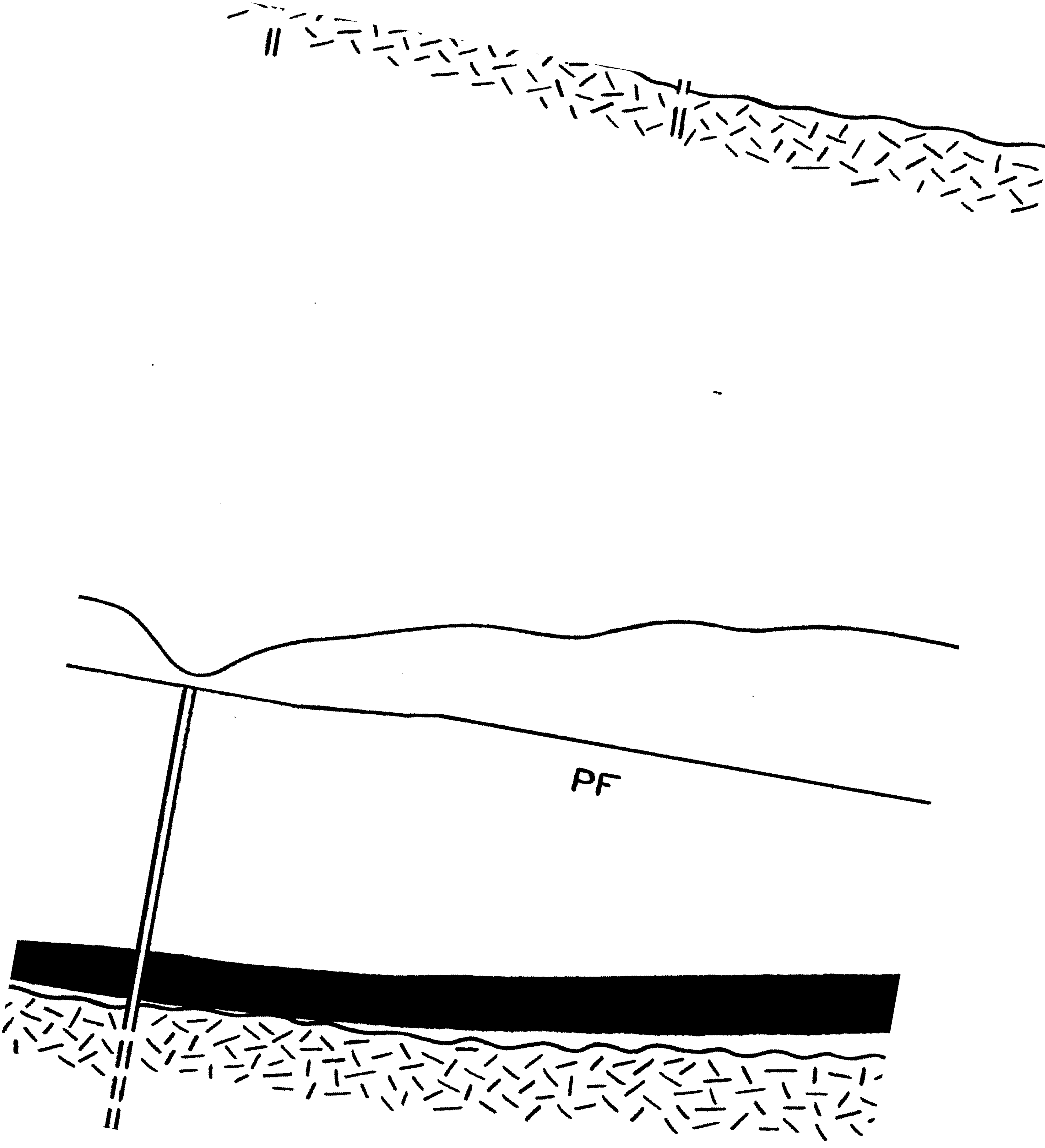


NIMIKIE
ROCKS
PROFILE
PF
MIKIE
ROCKS

PROFILE K – K′



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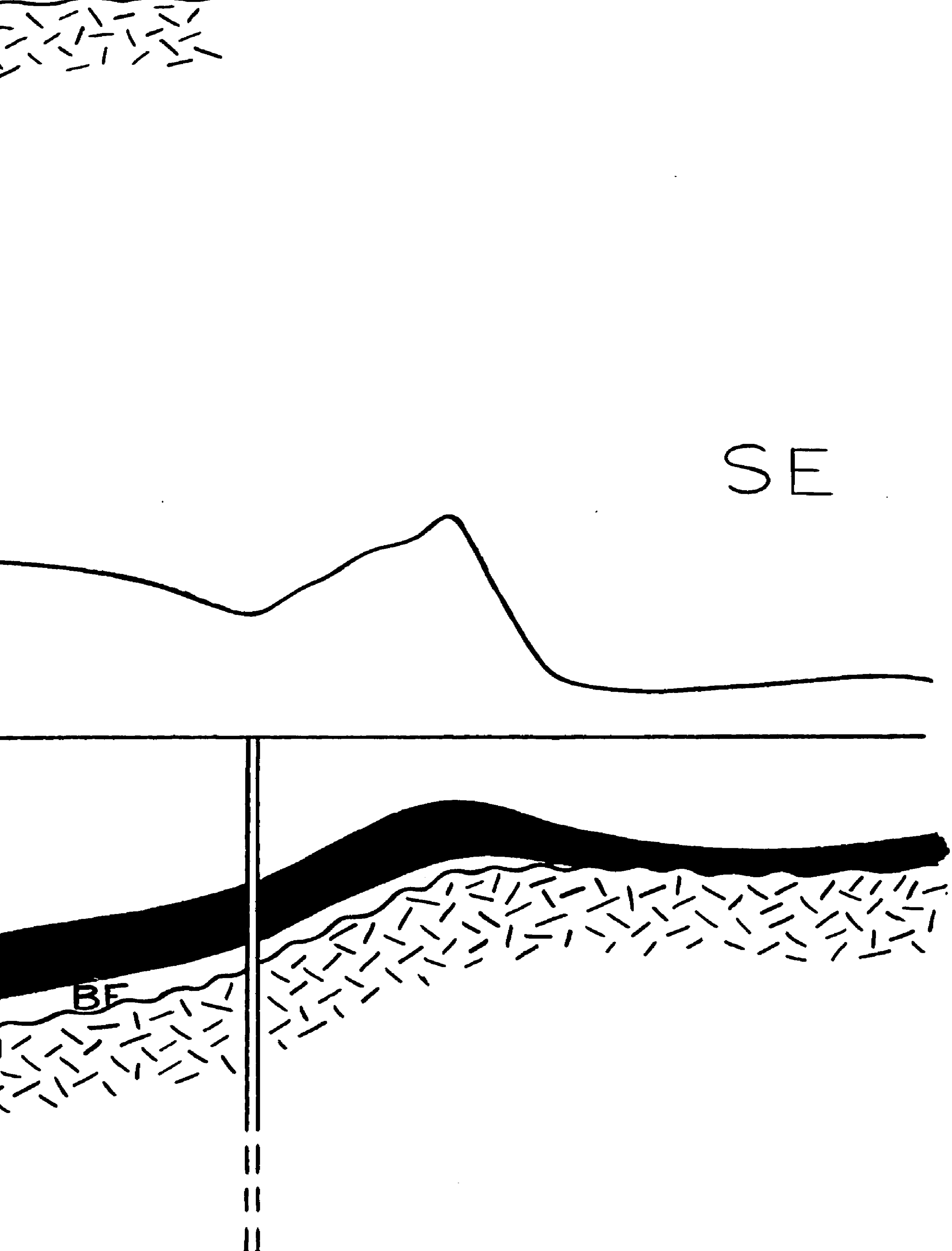
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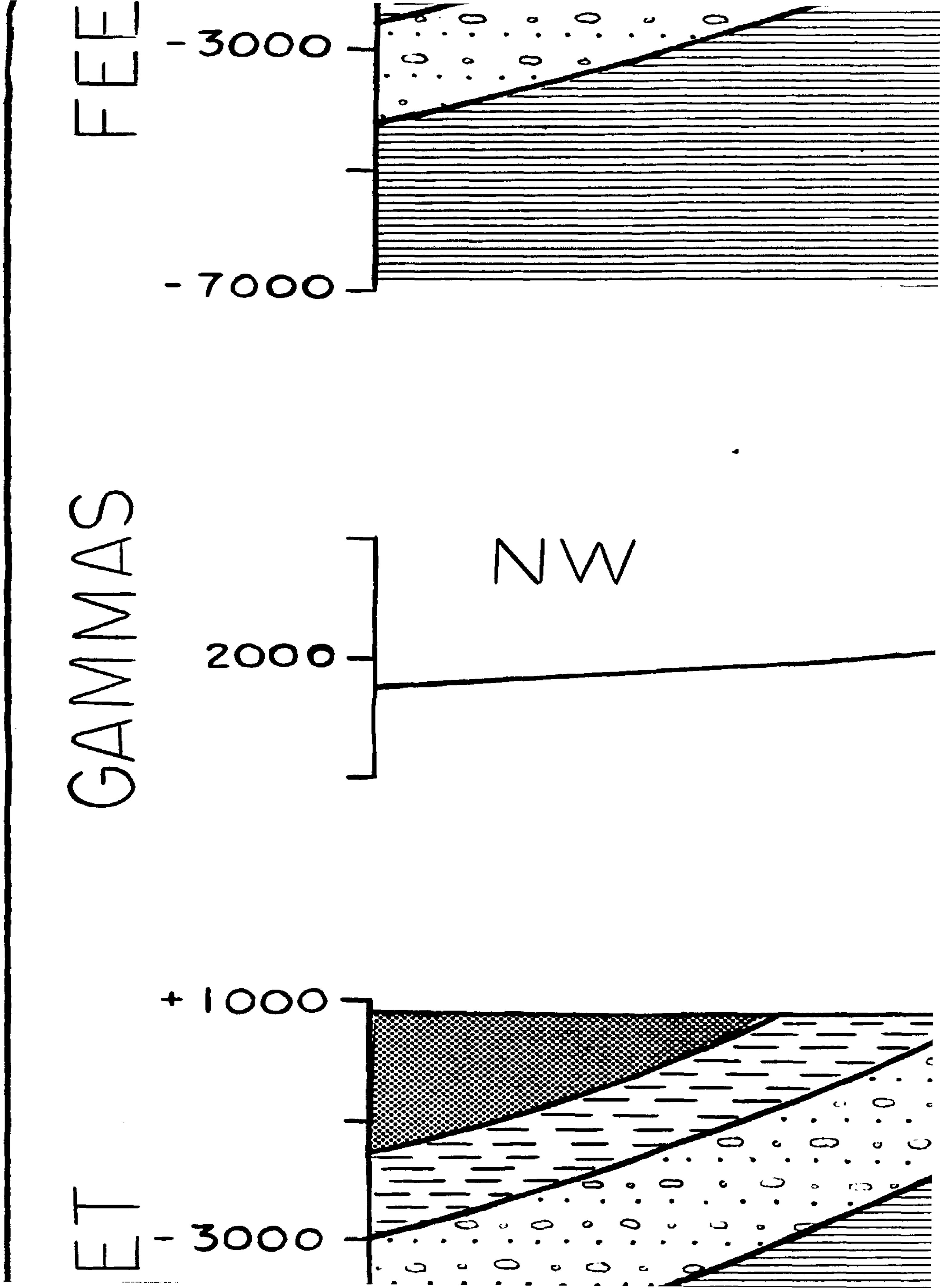

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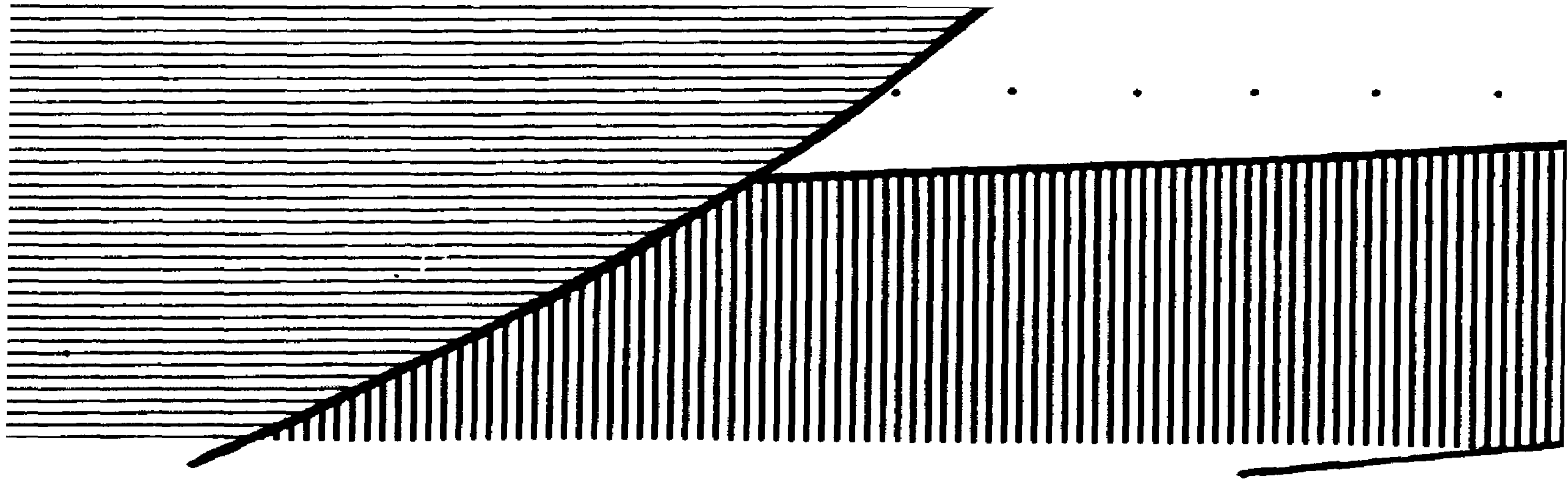

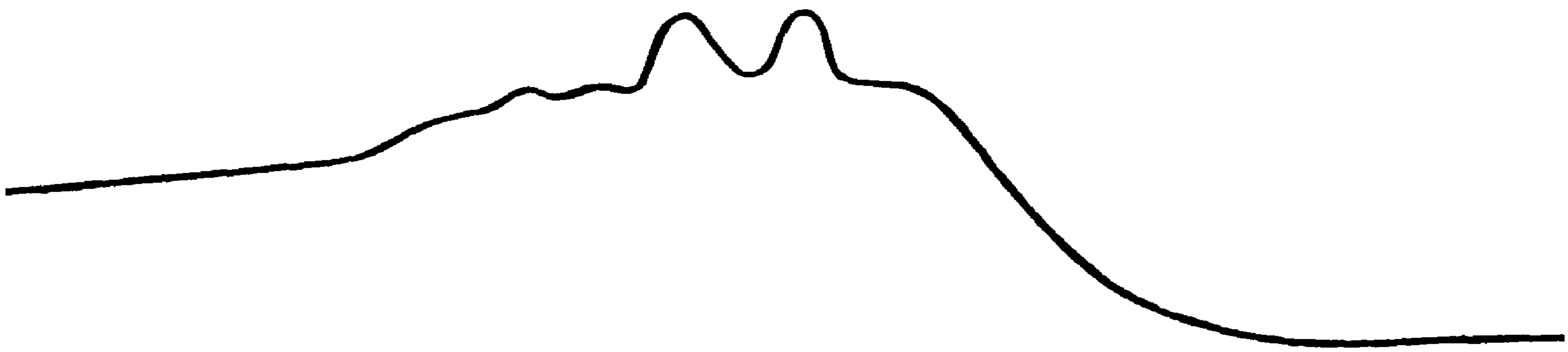

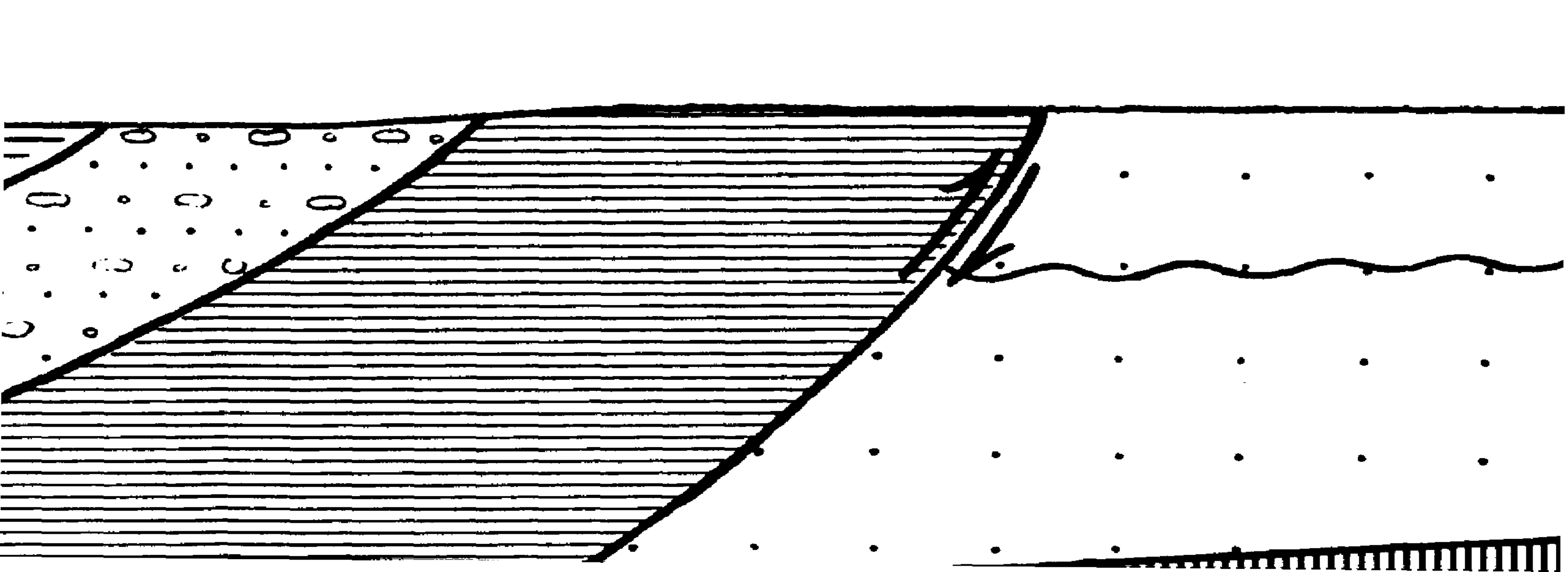

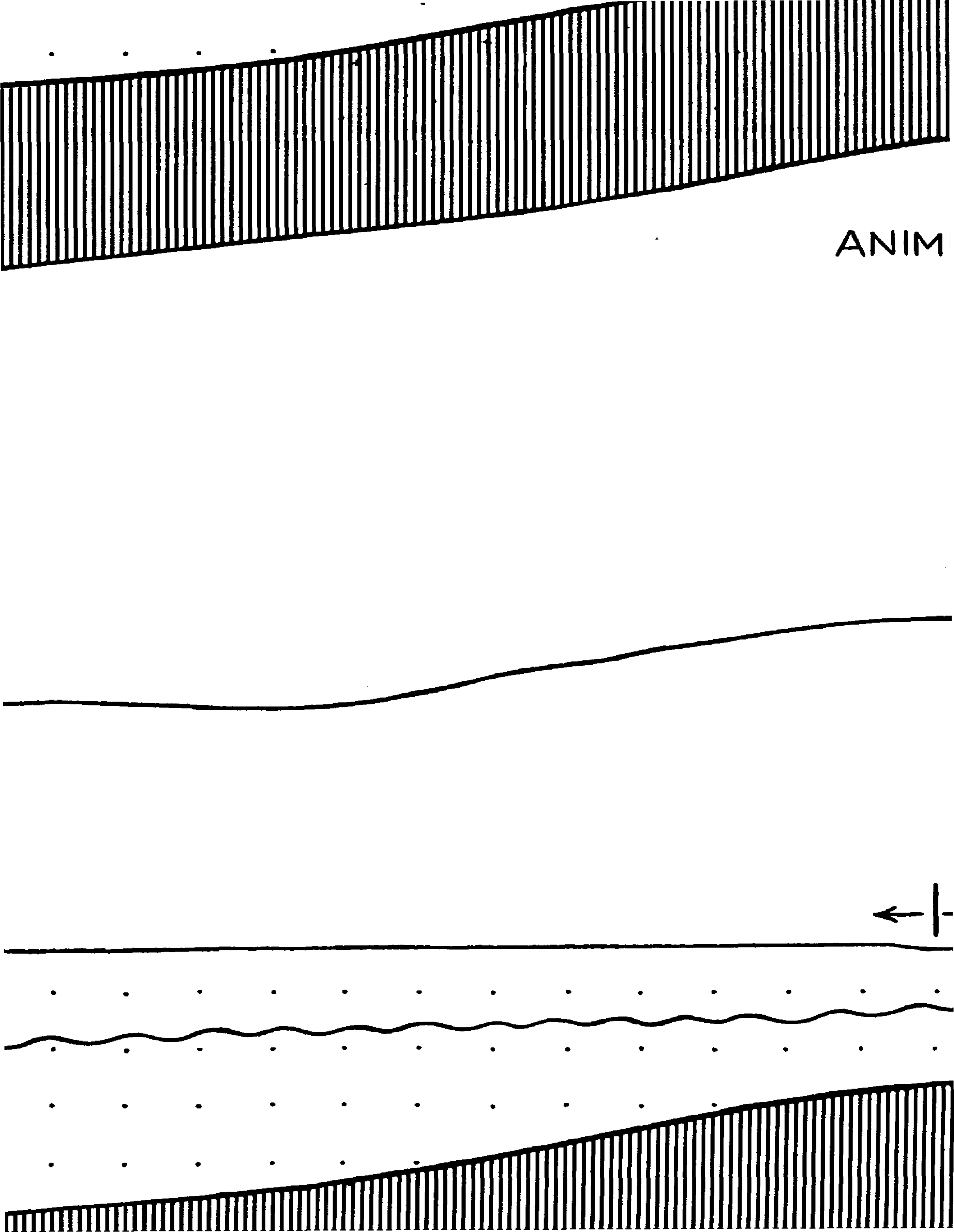
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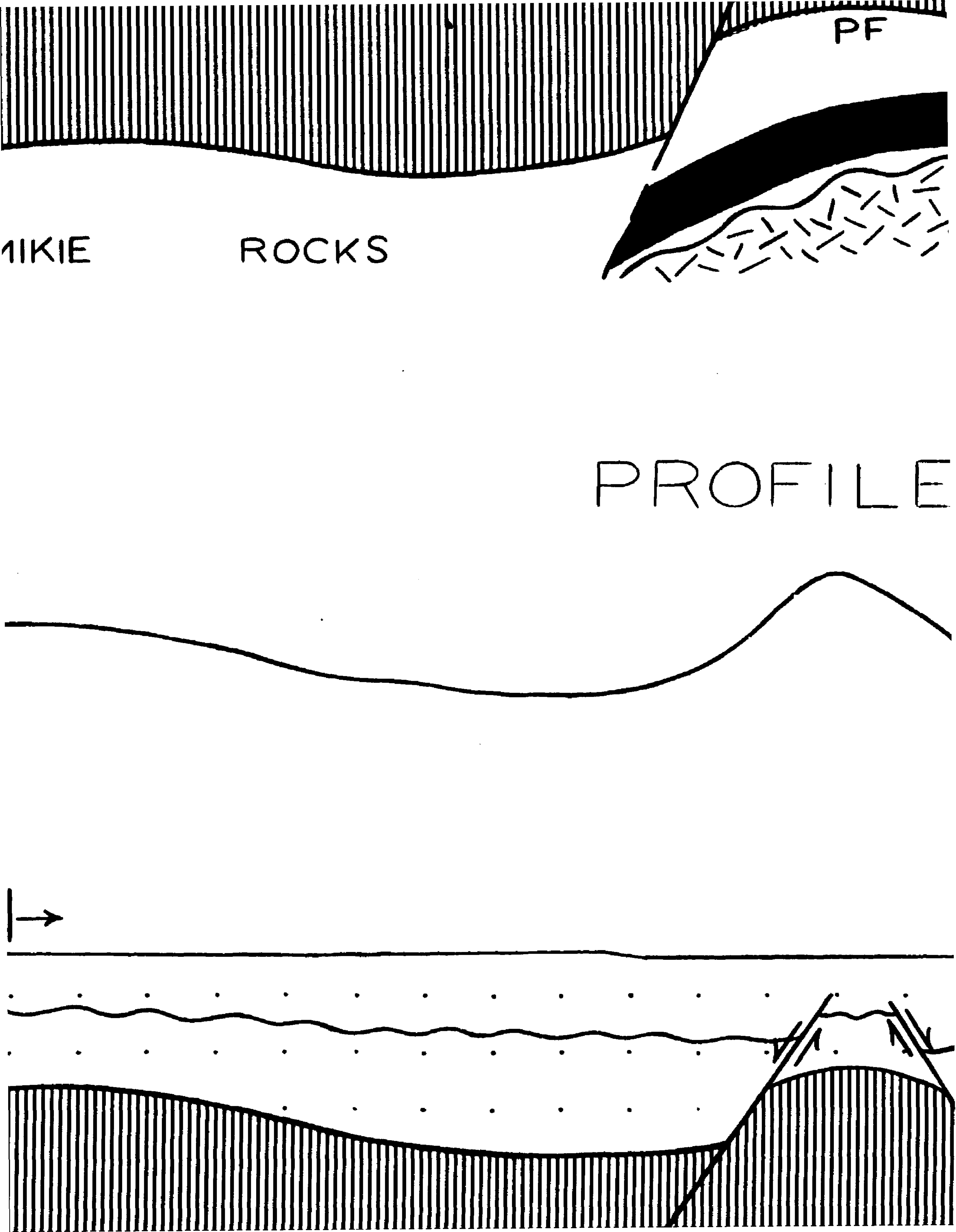
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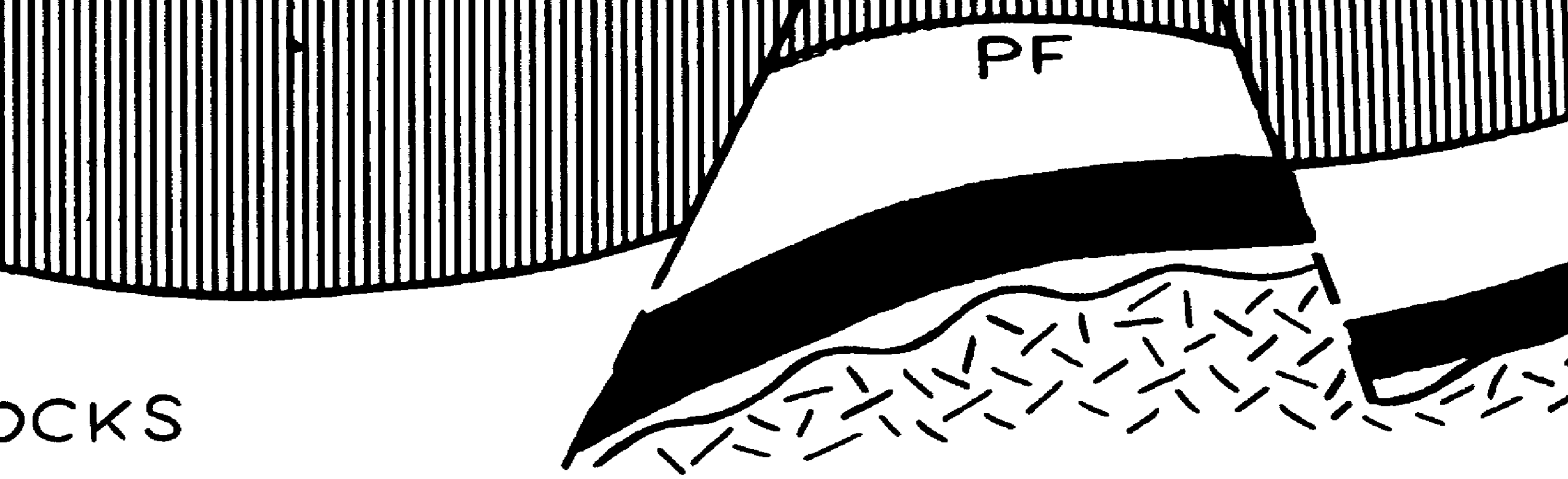
IKIE ROCKS
PROFILE



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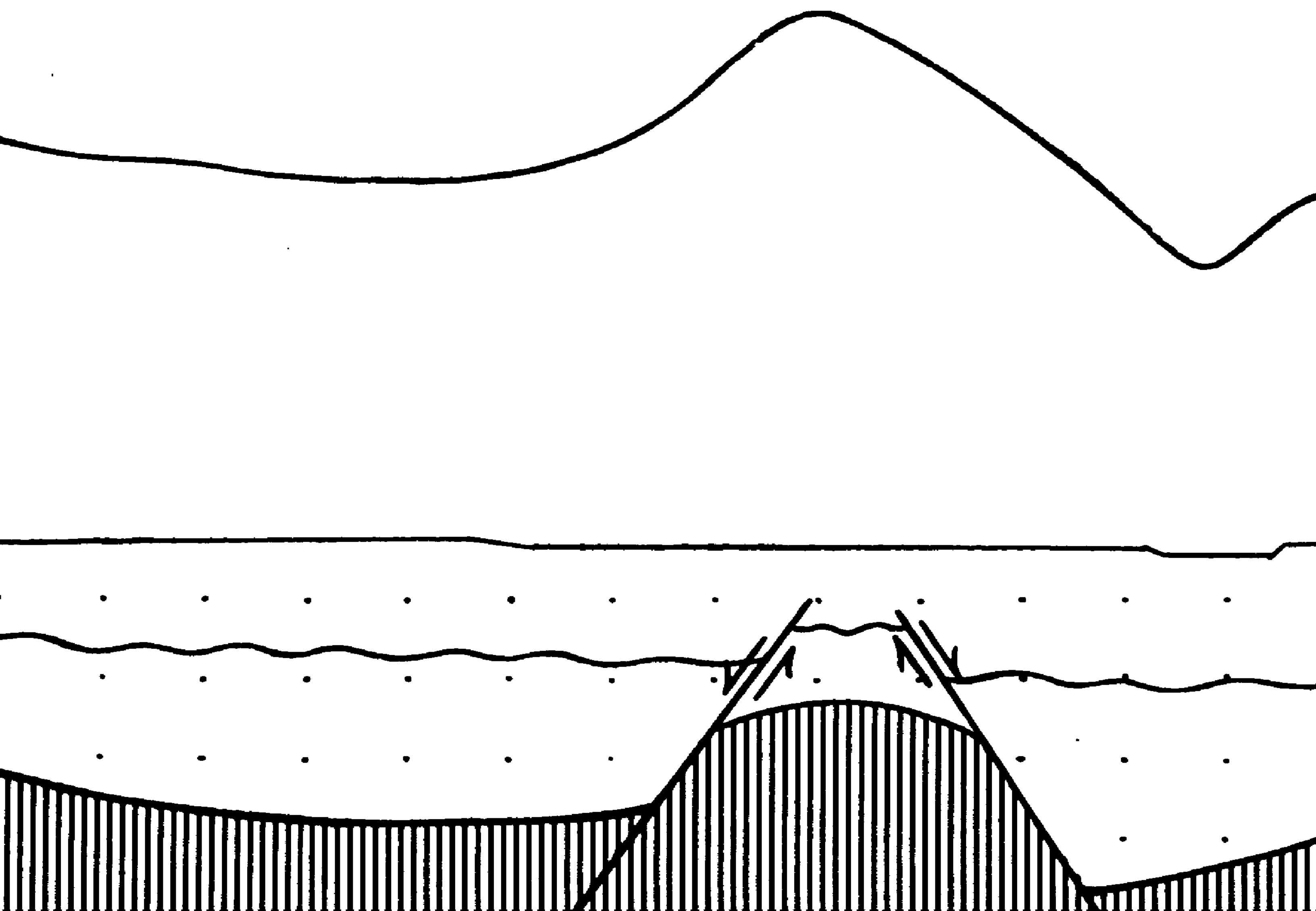

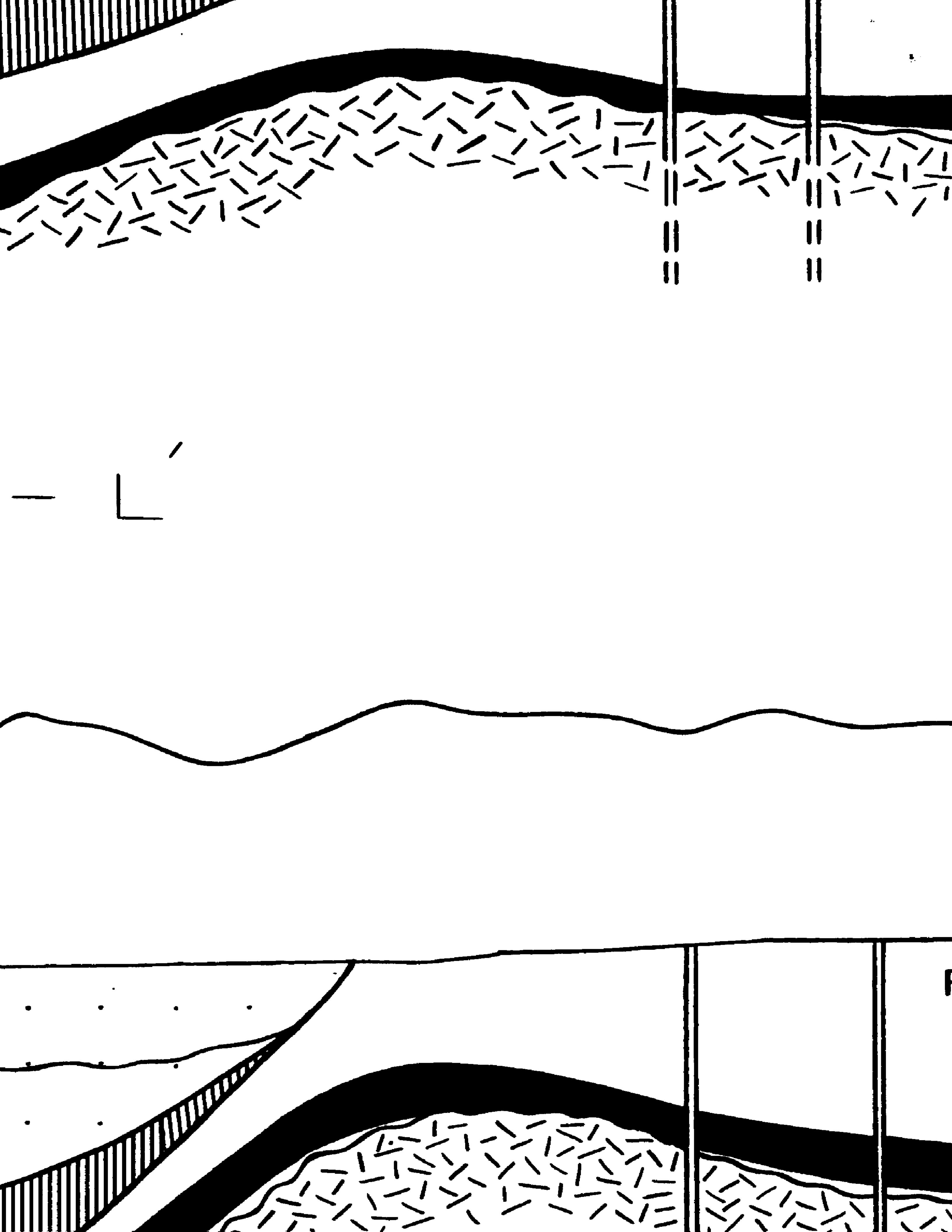

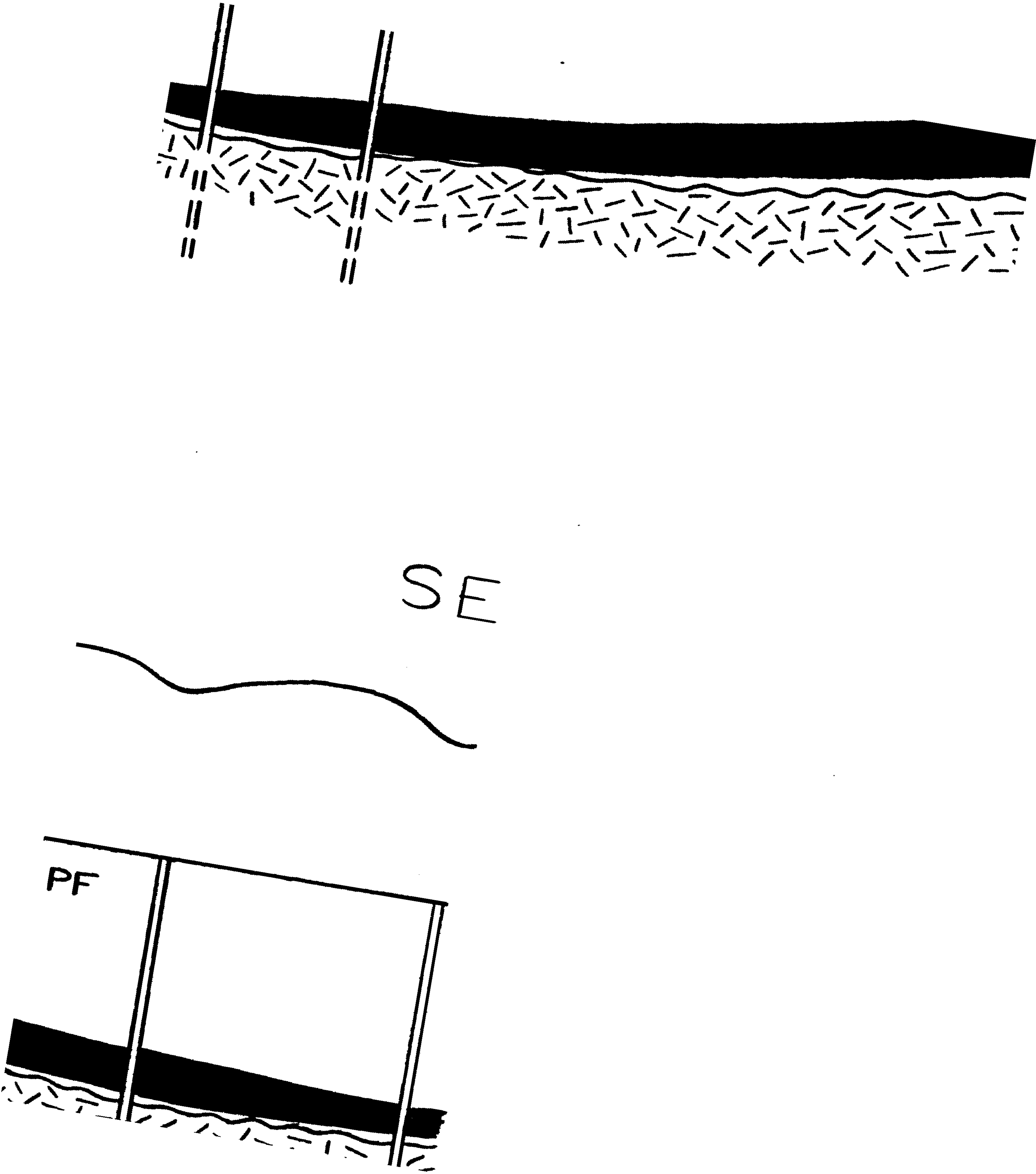
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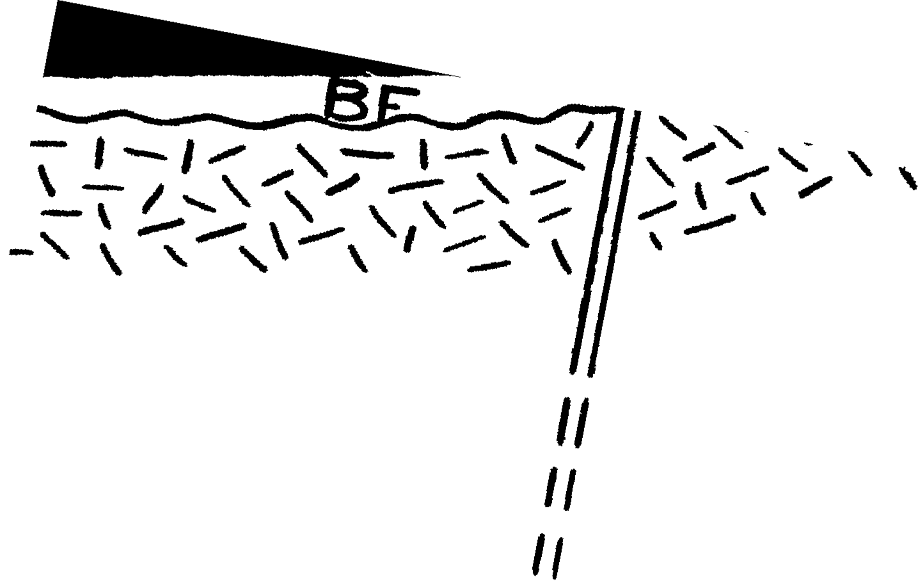
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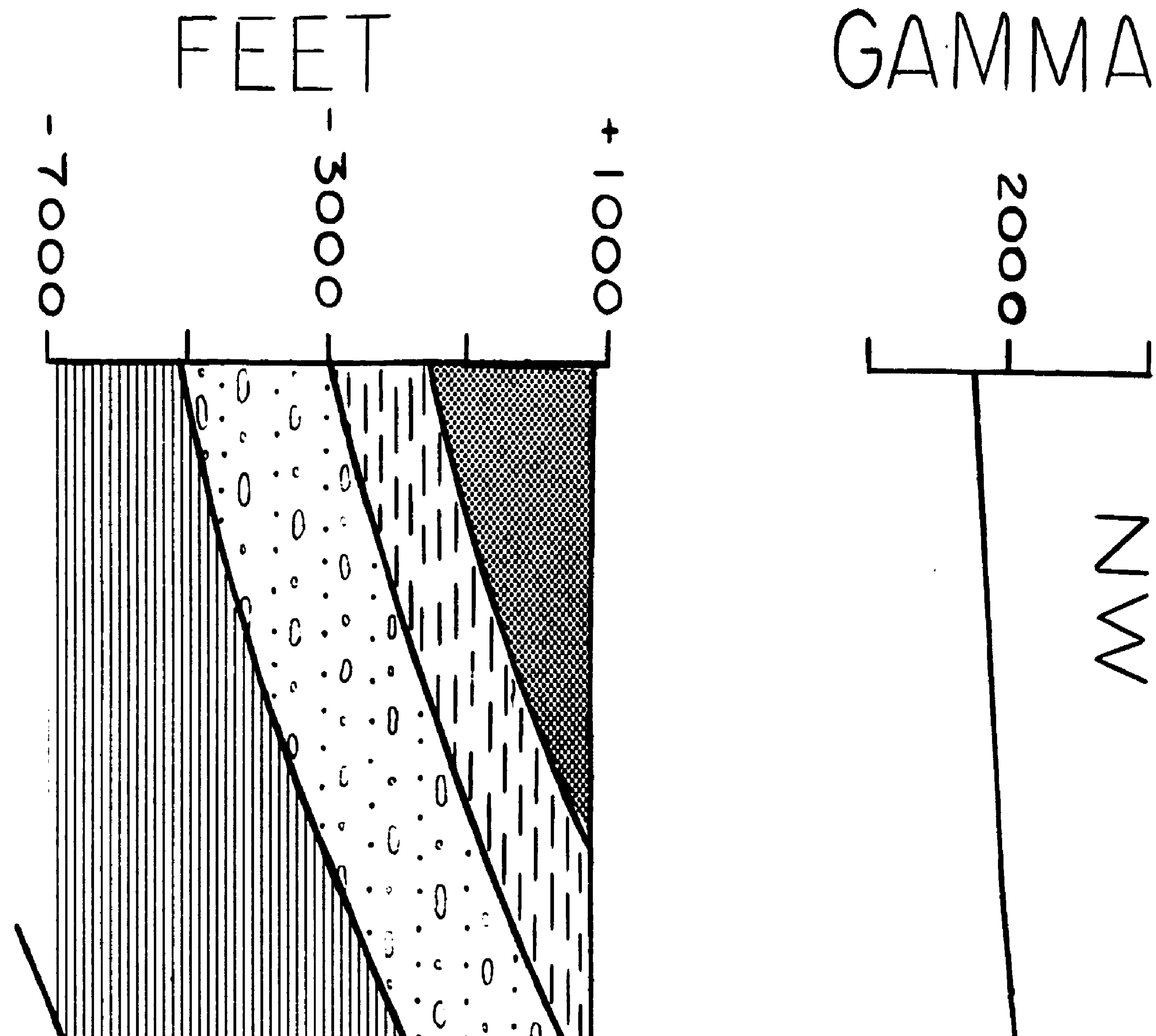

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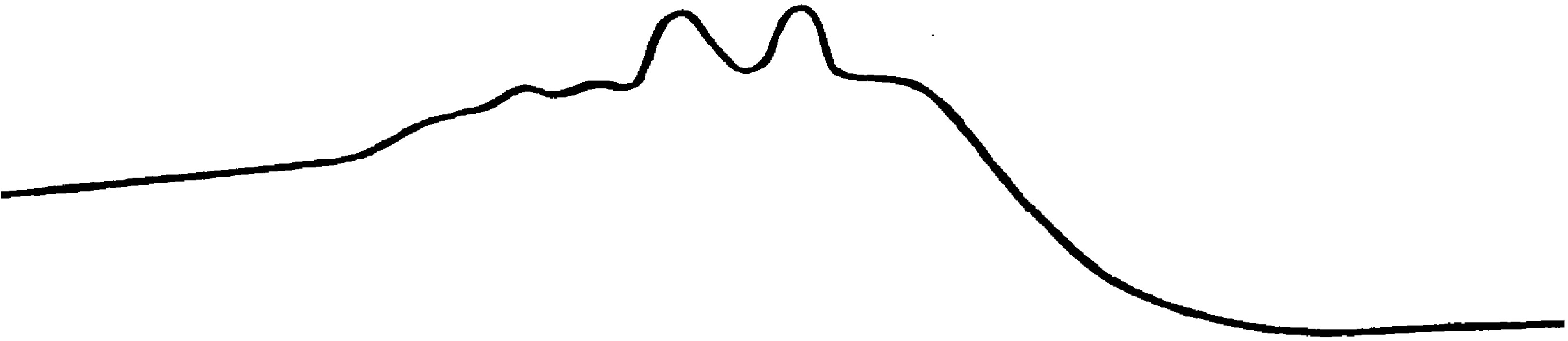

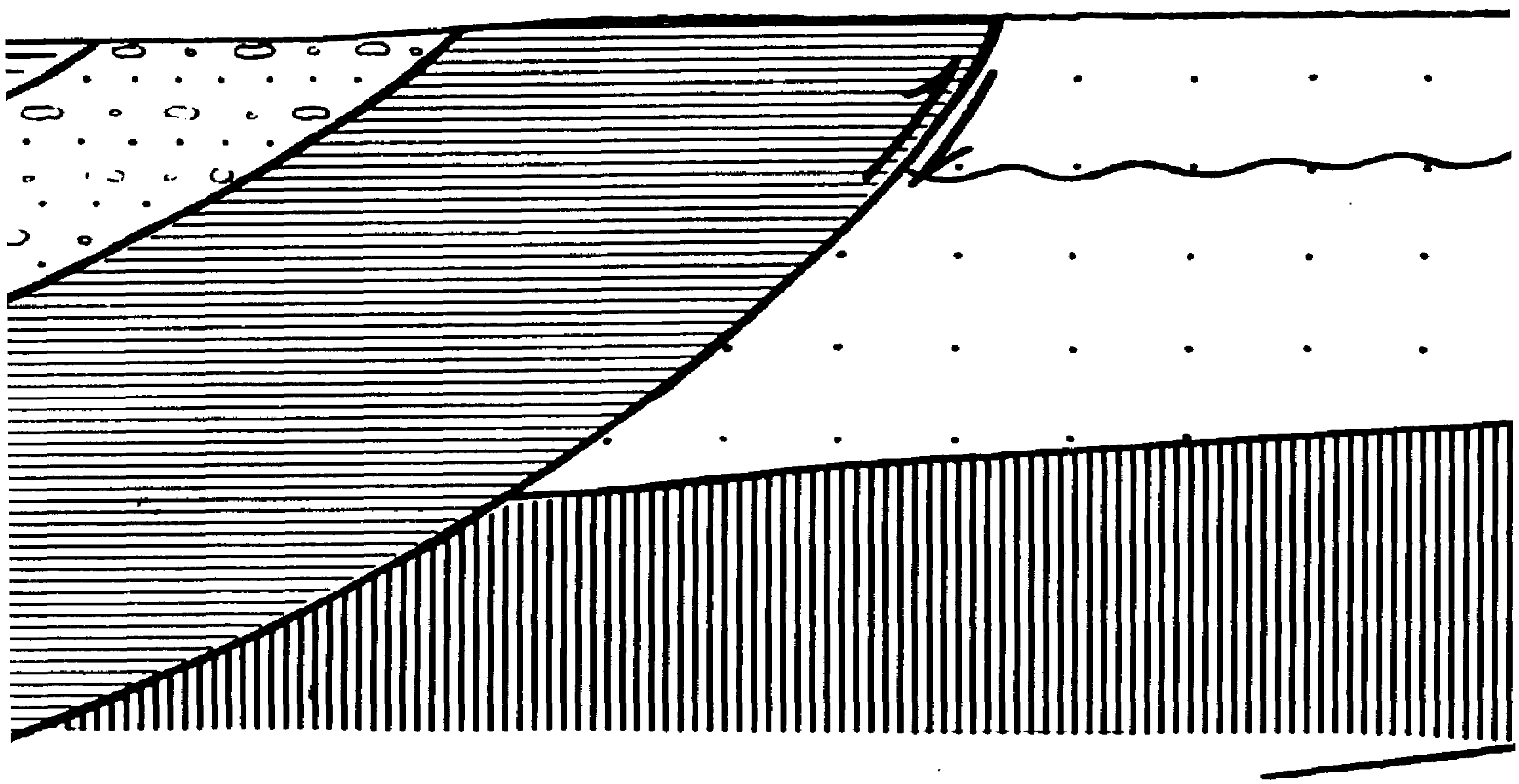

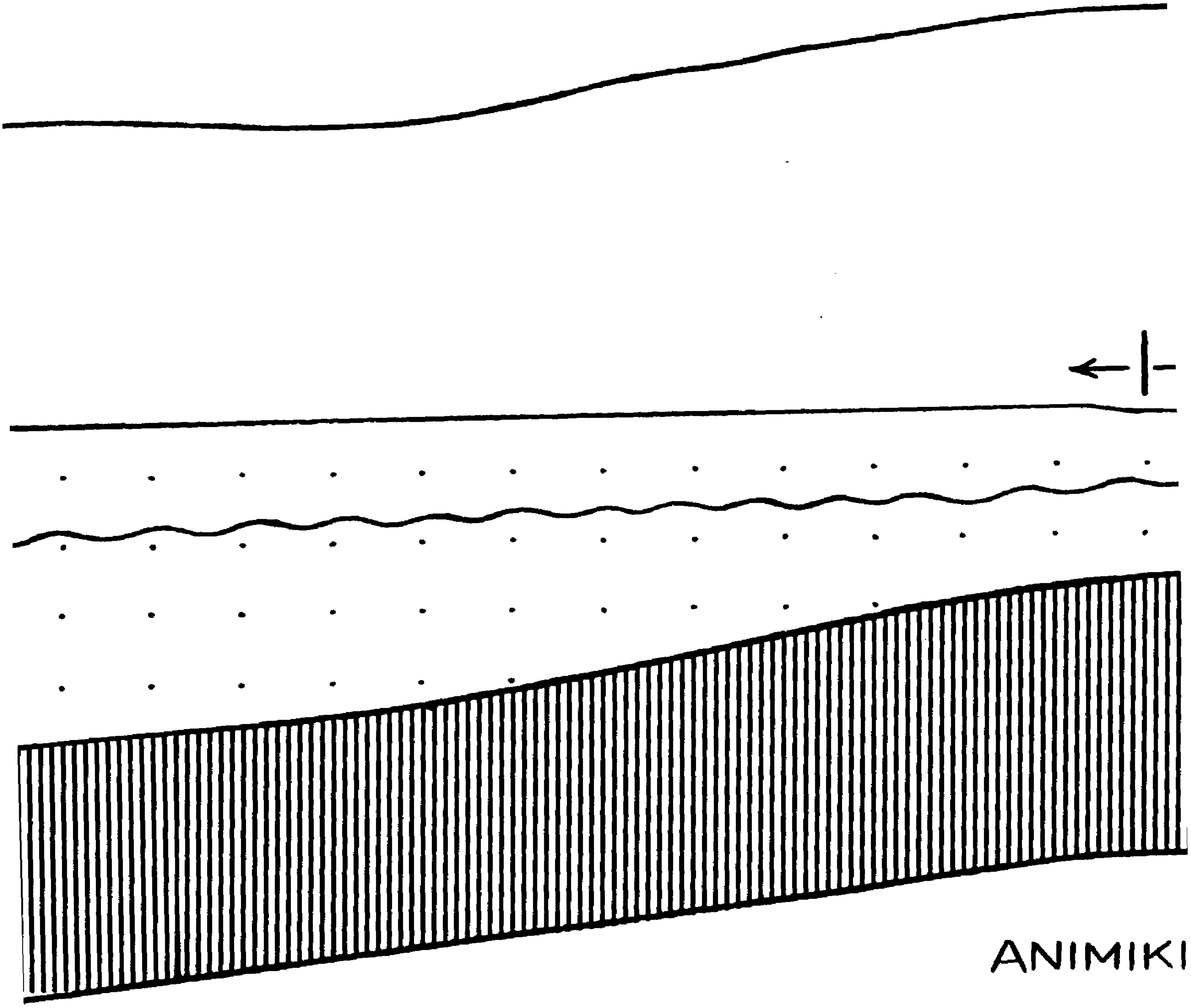
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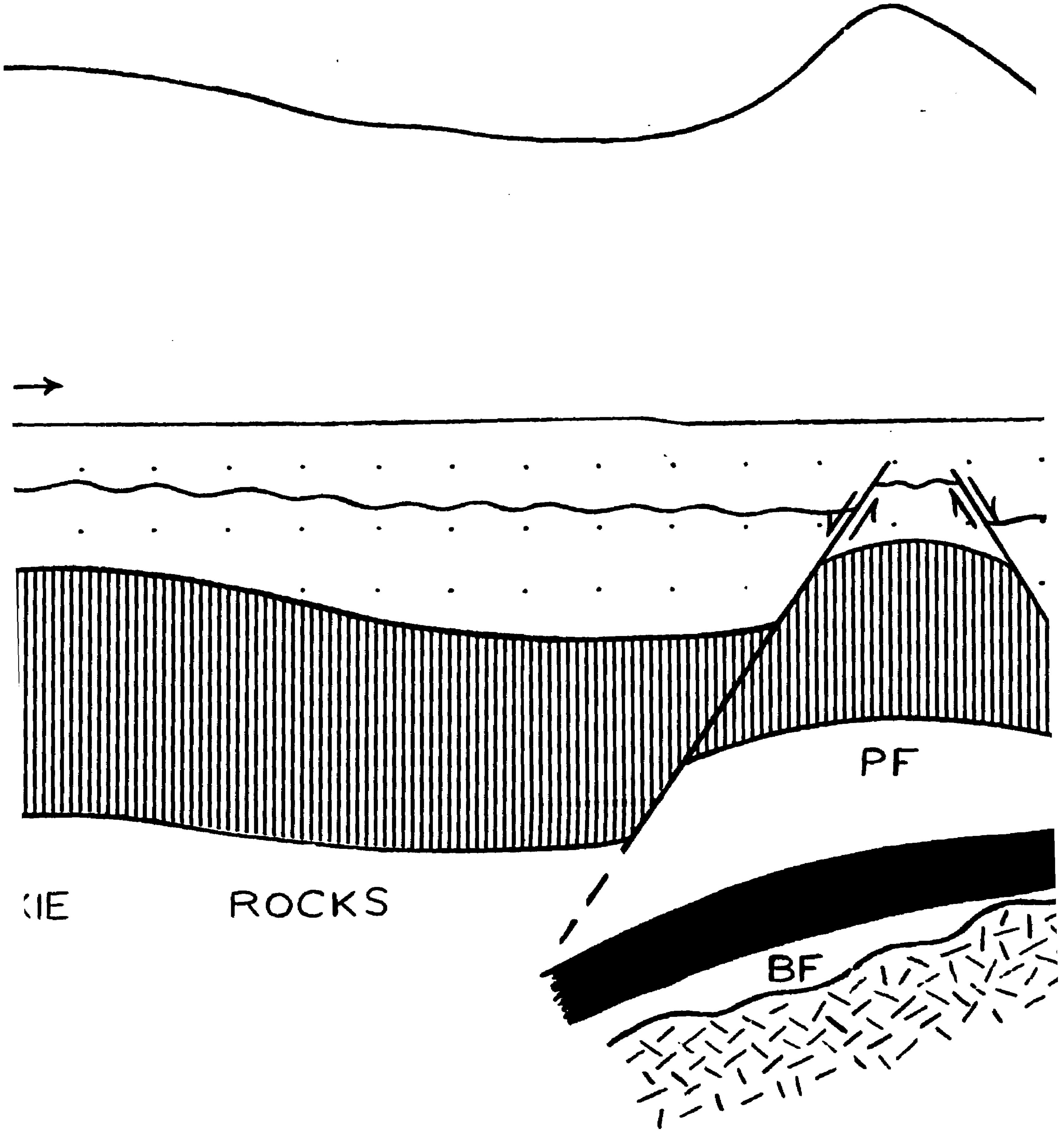
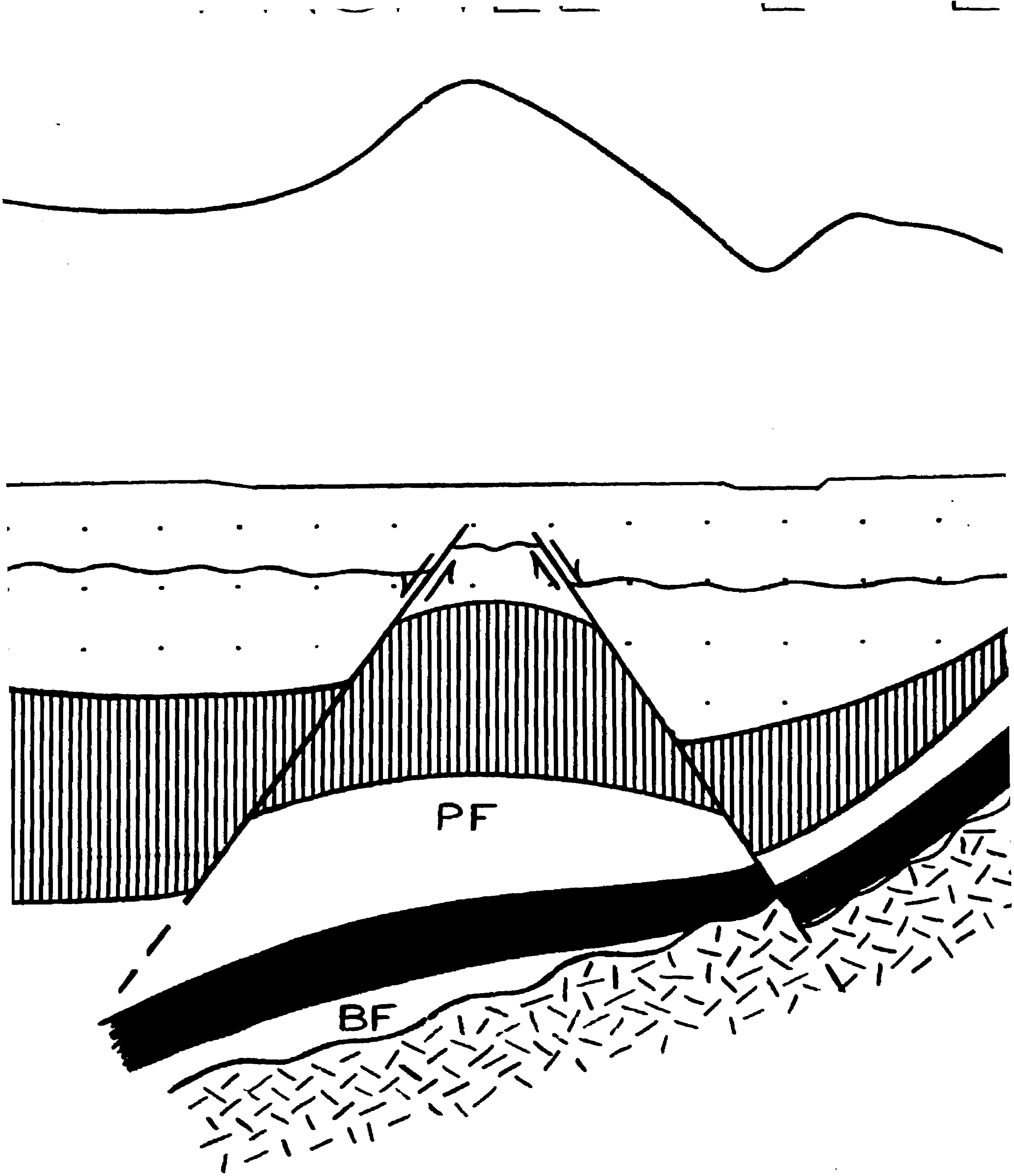
PROFILE

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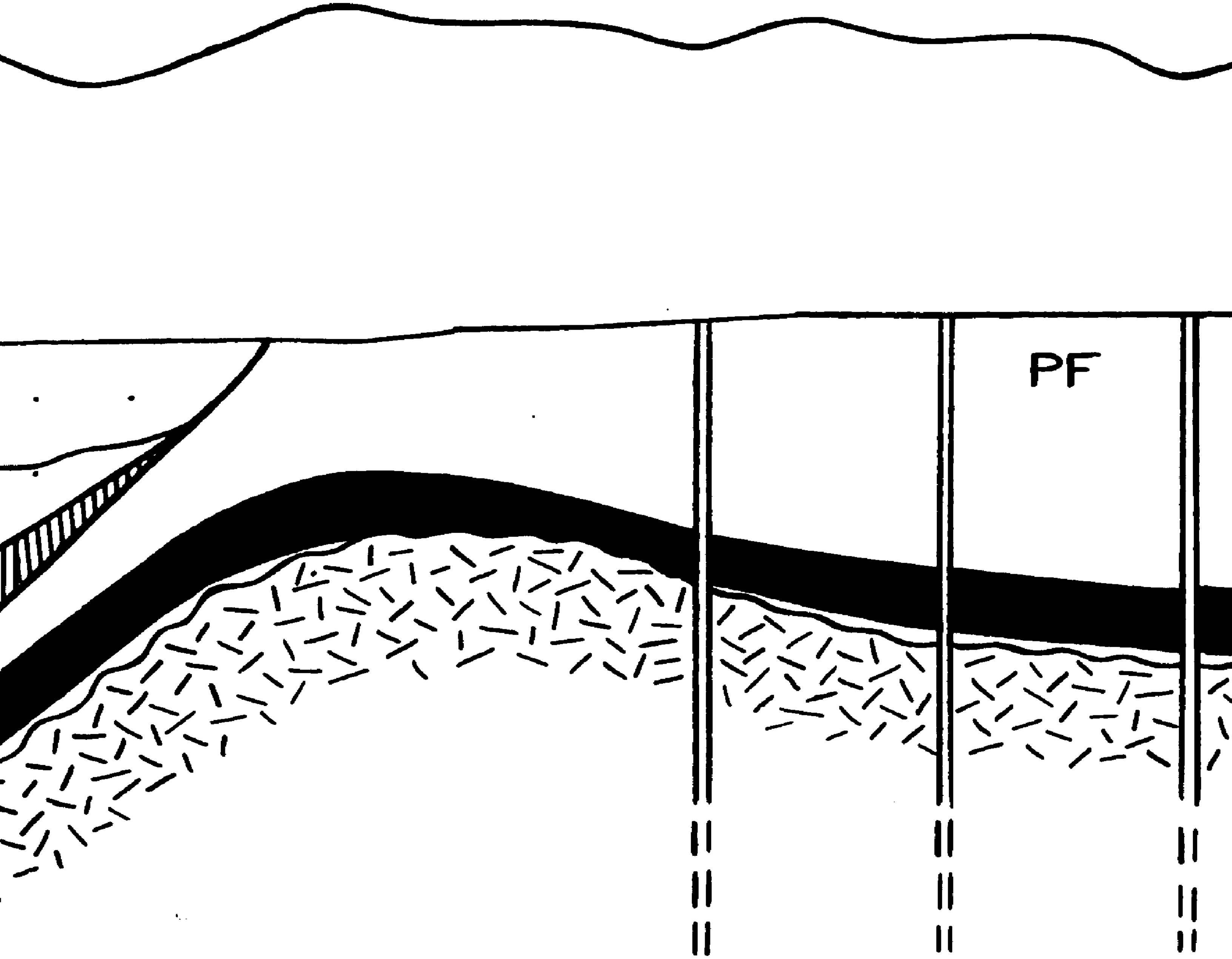
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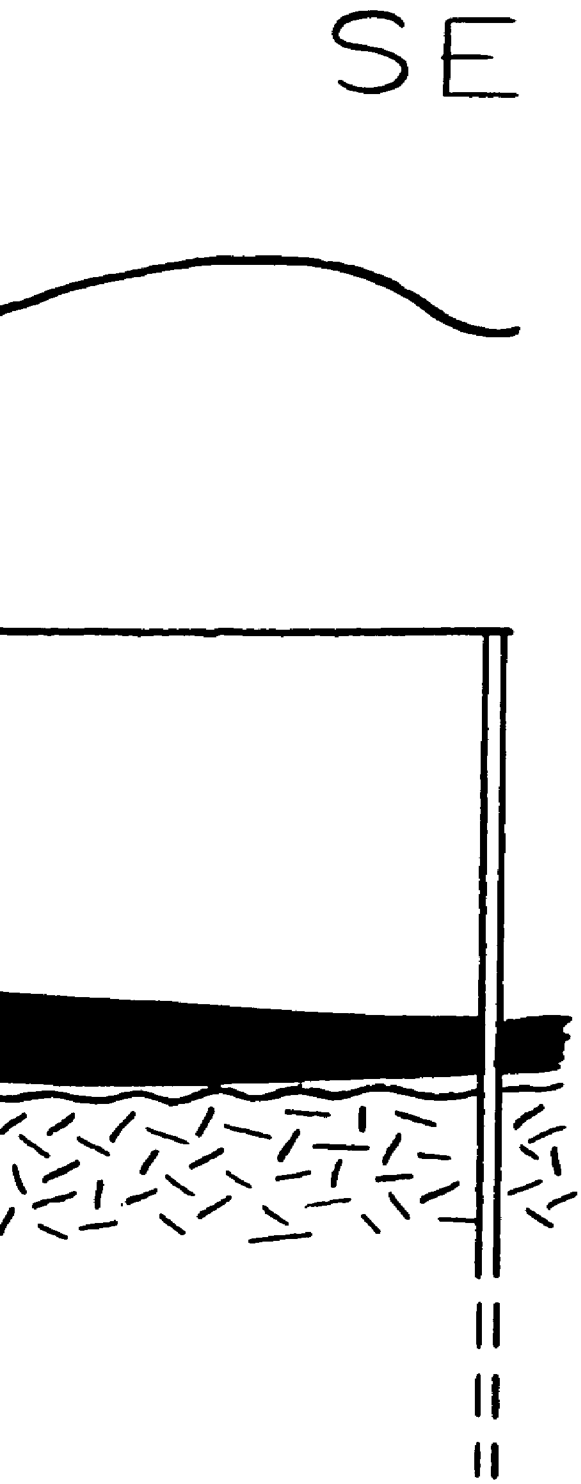
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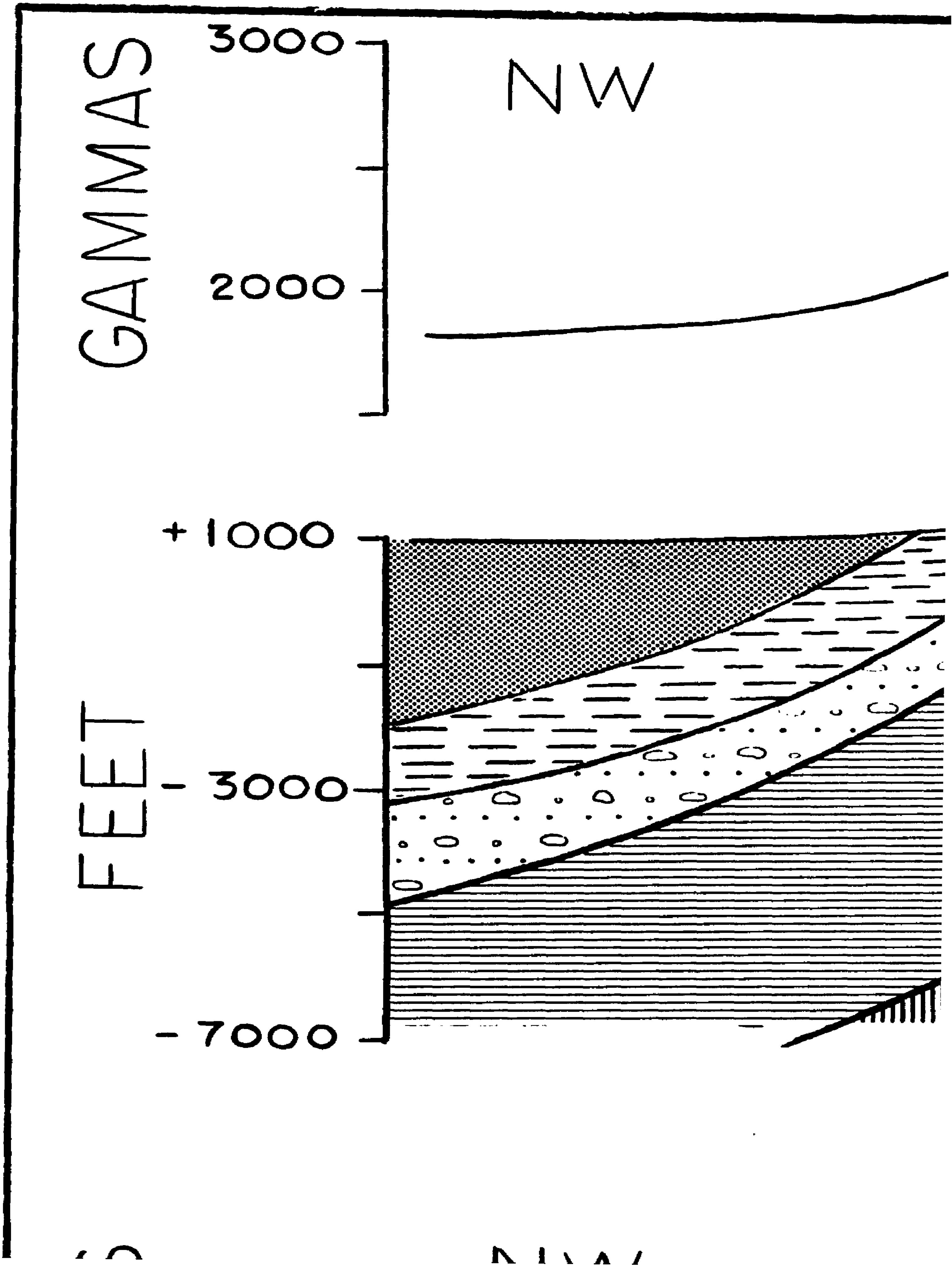
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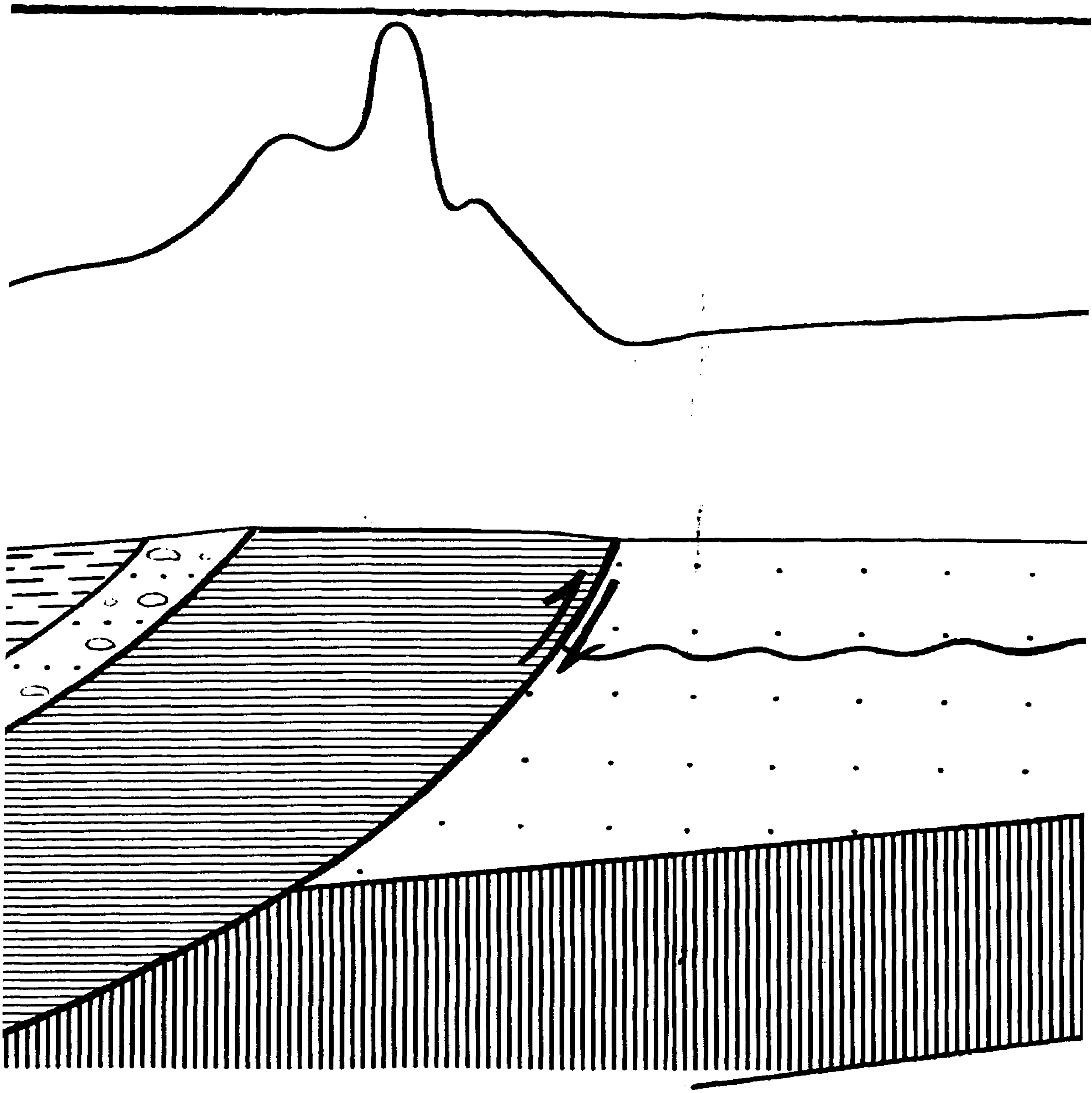
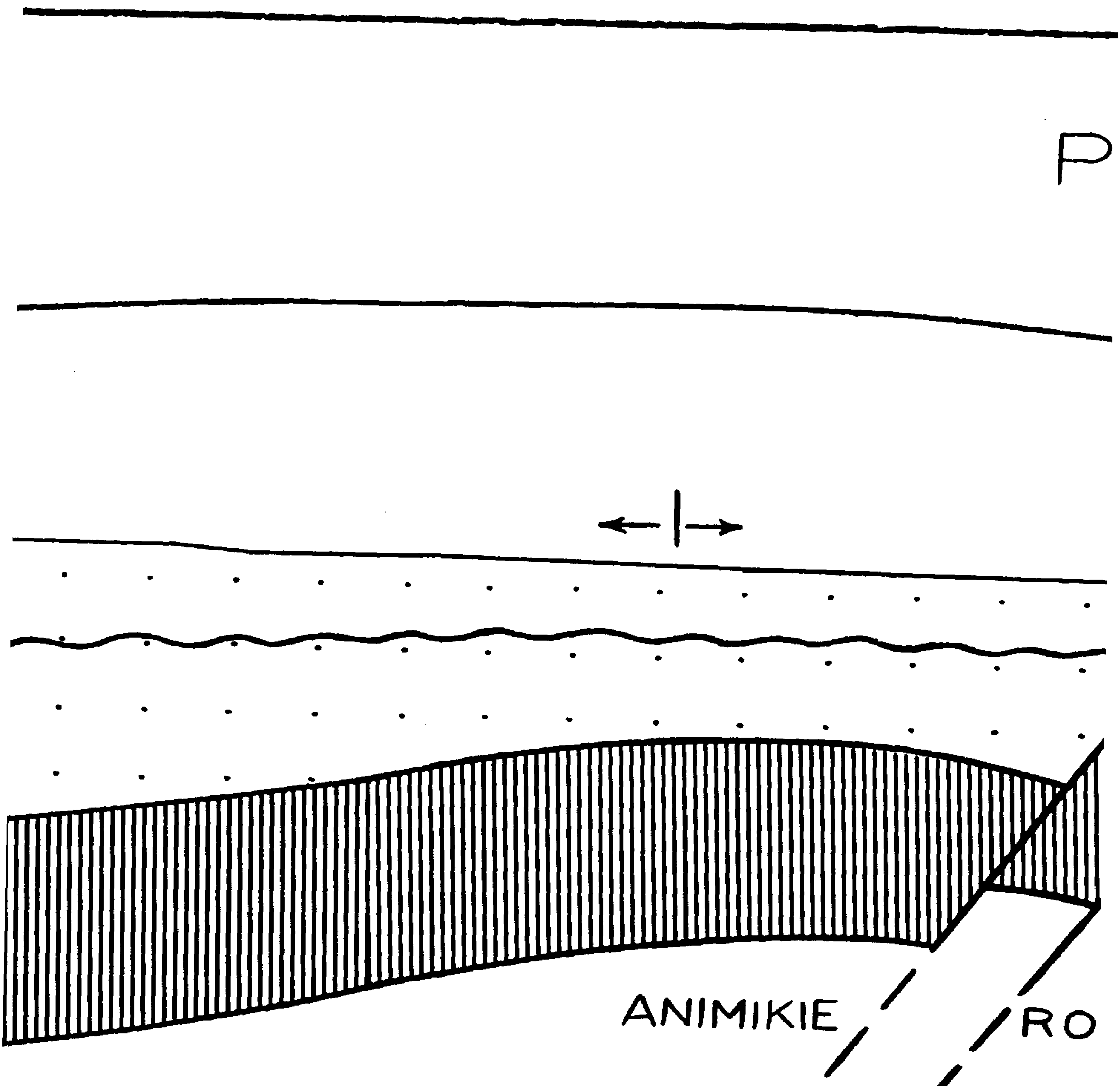
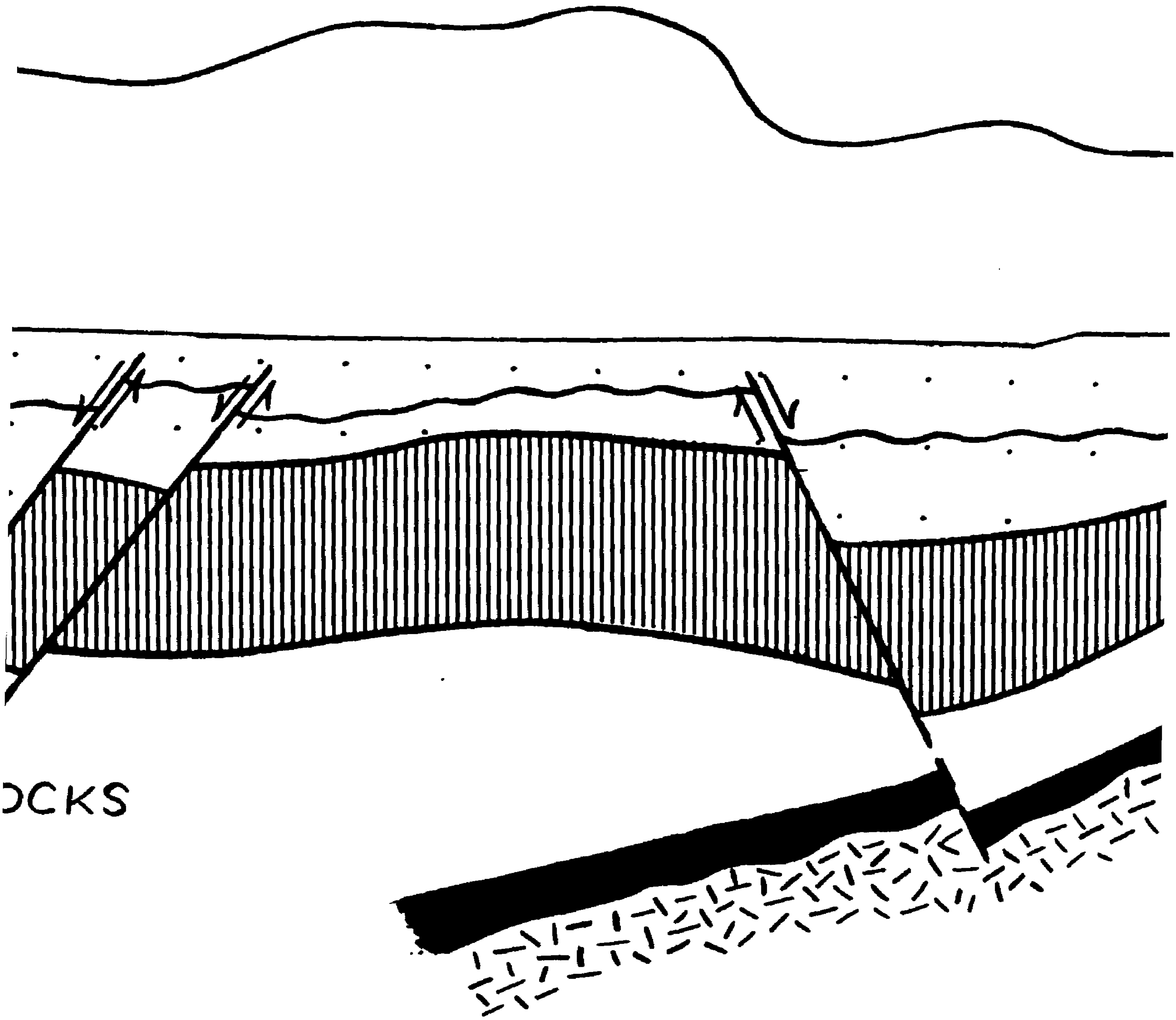
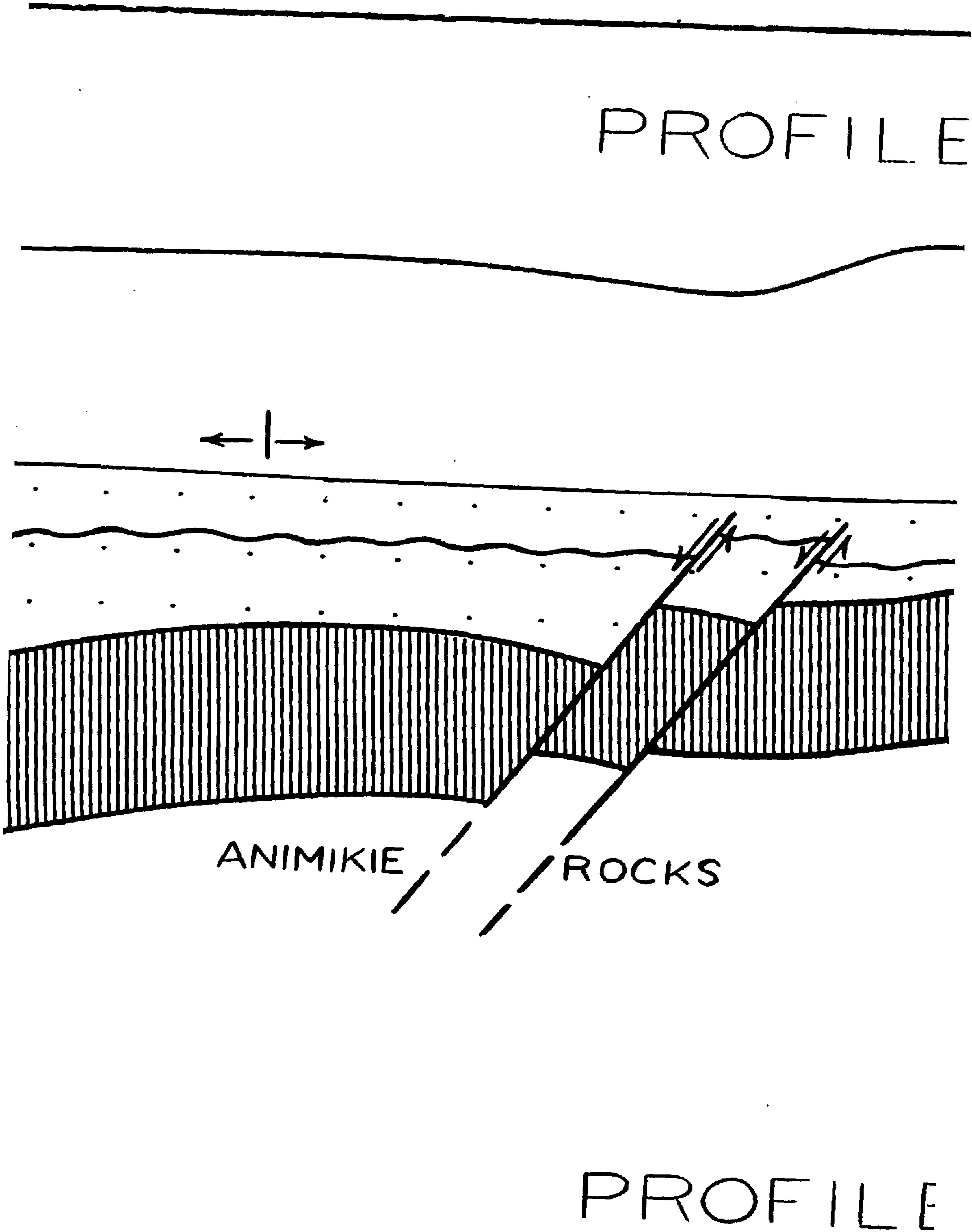




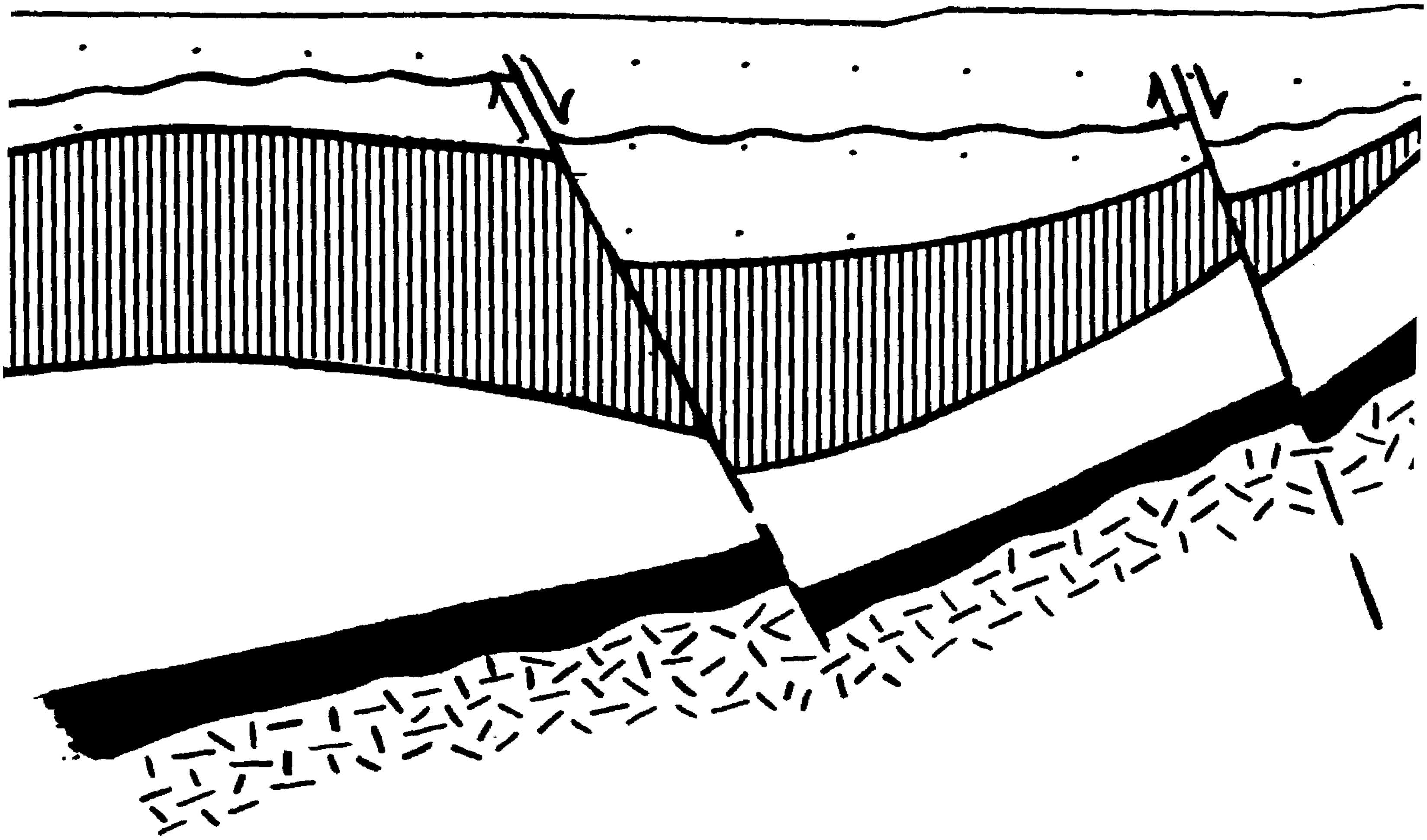
P
ANIMIKIE
RO

PROFILE M – M′




PROFILE
ANIMIKIE ROCKS
PROFILE

E M — M′



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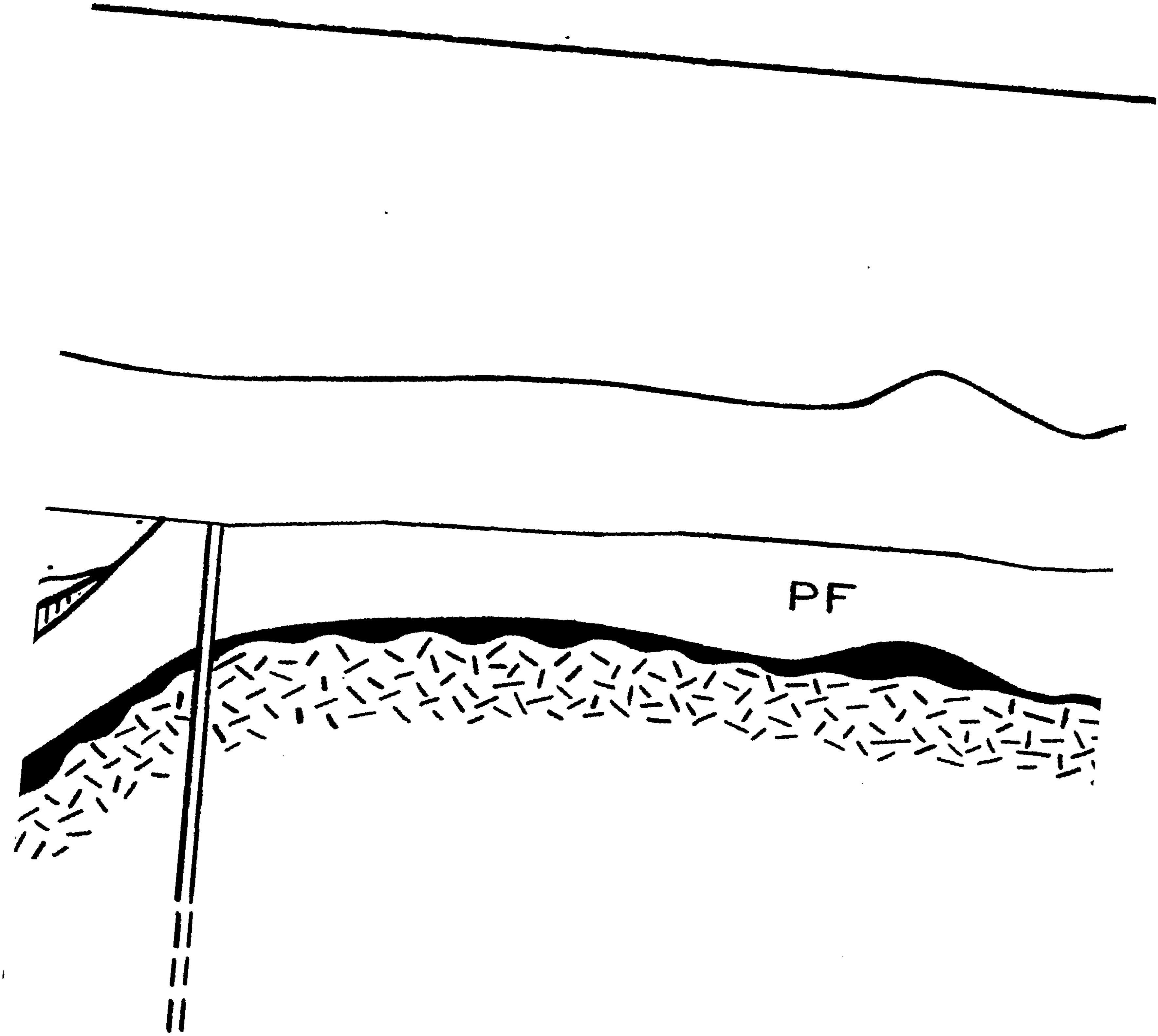
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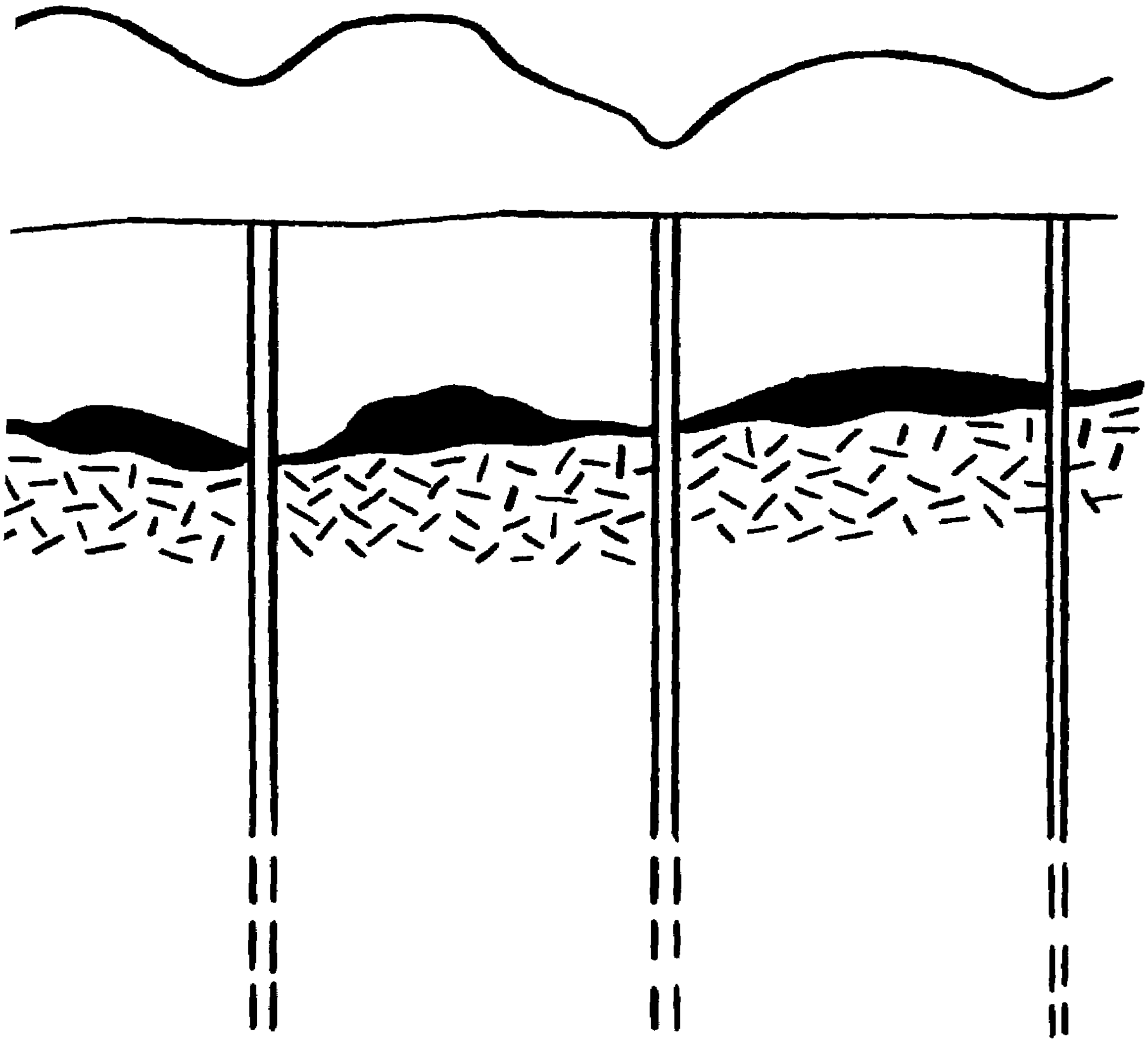

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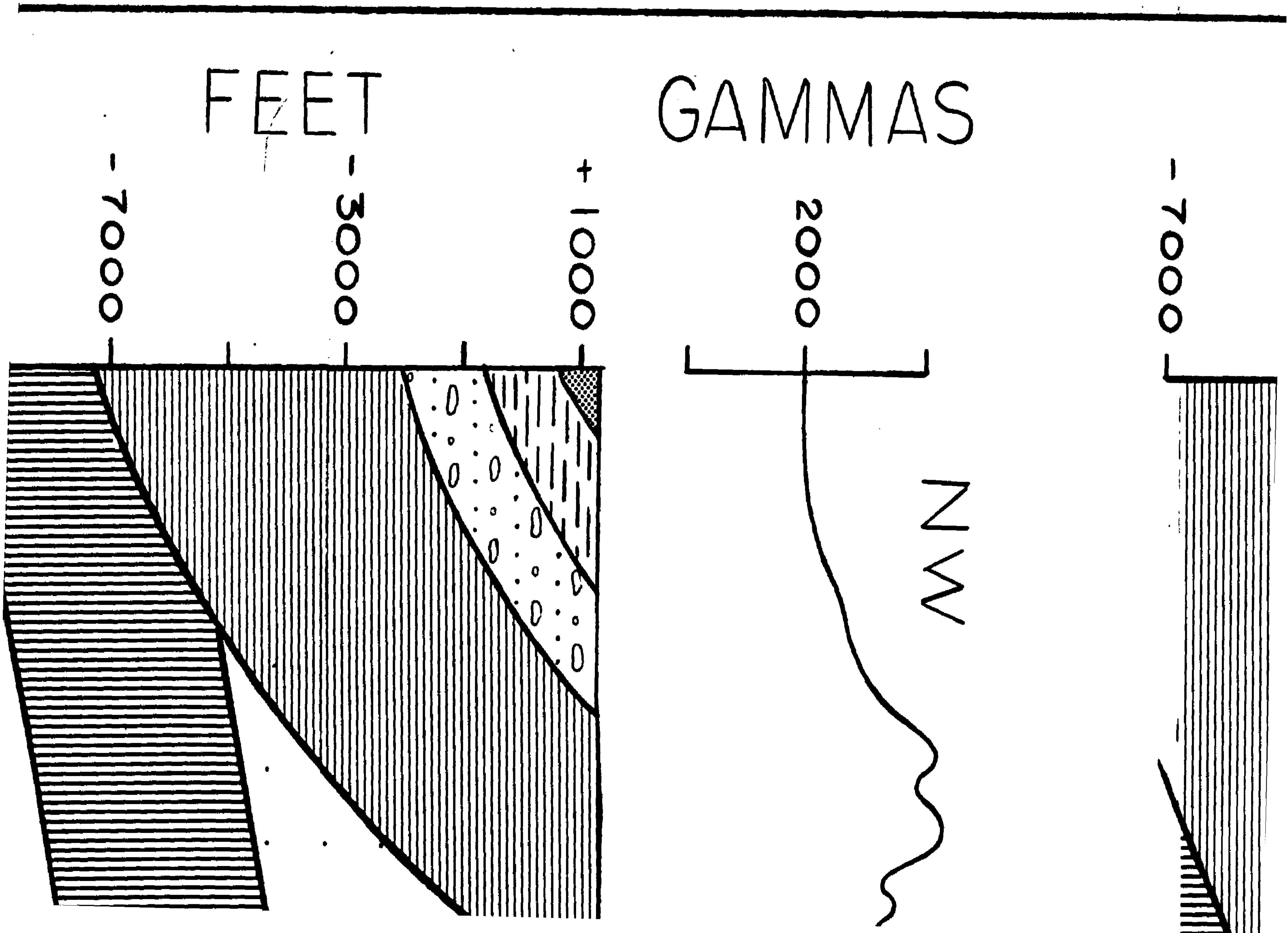
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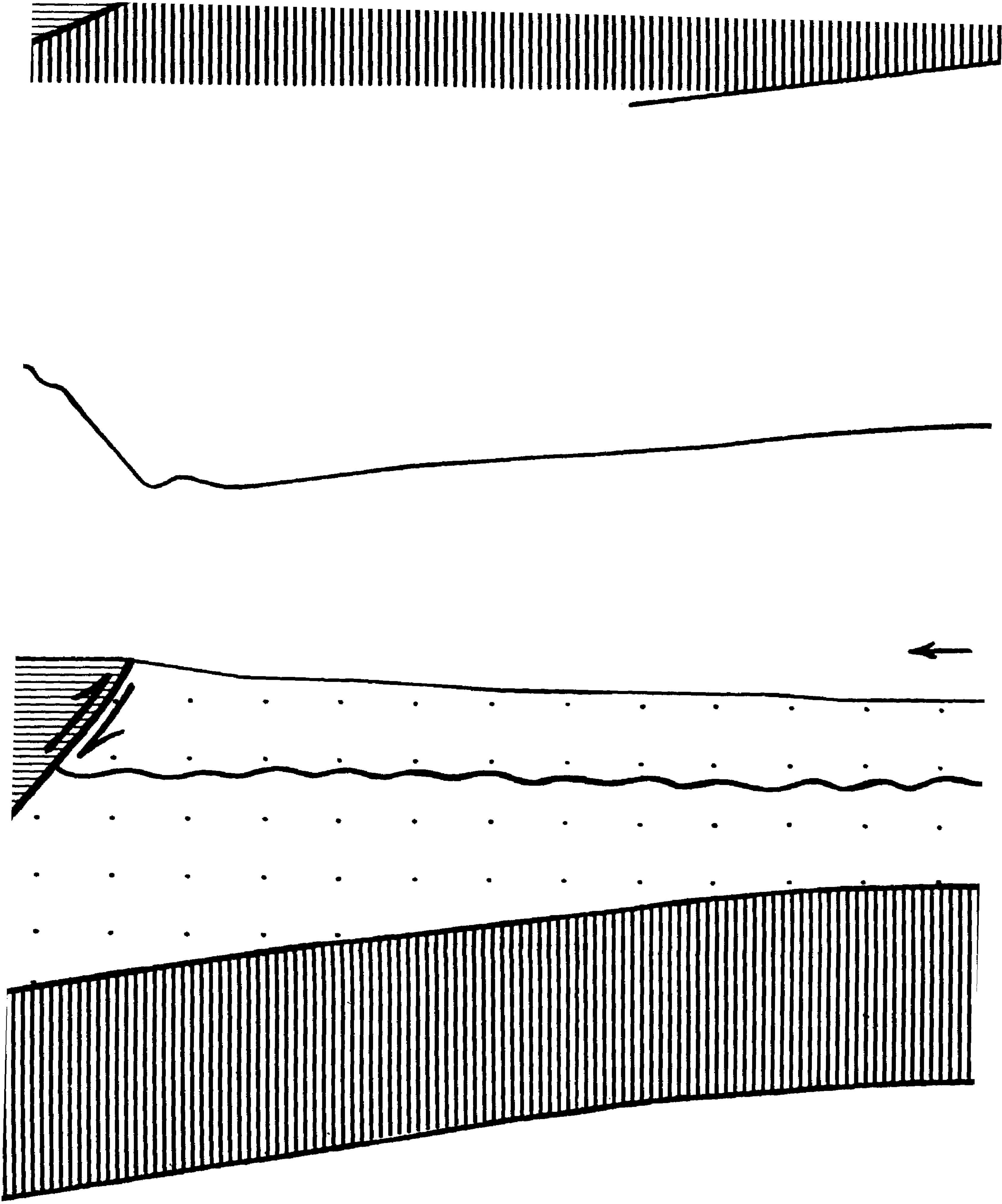

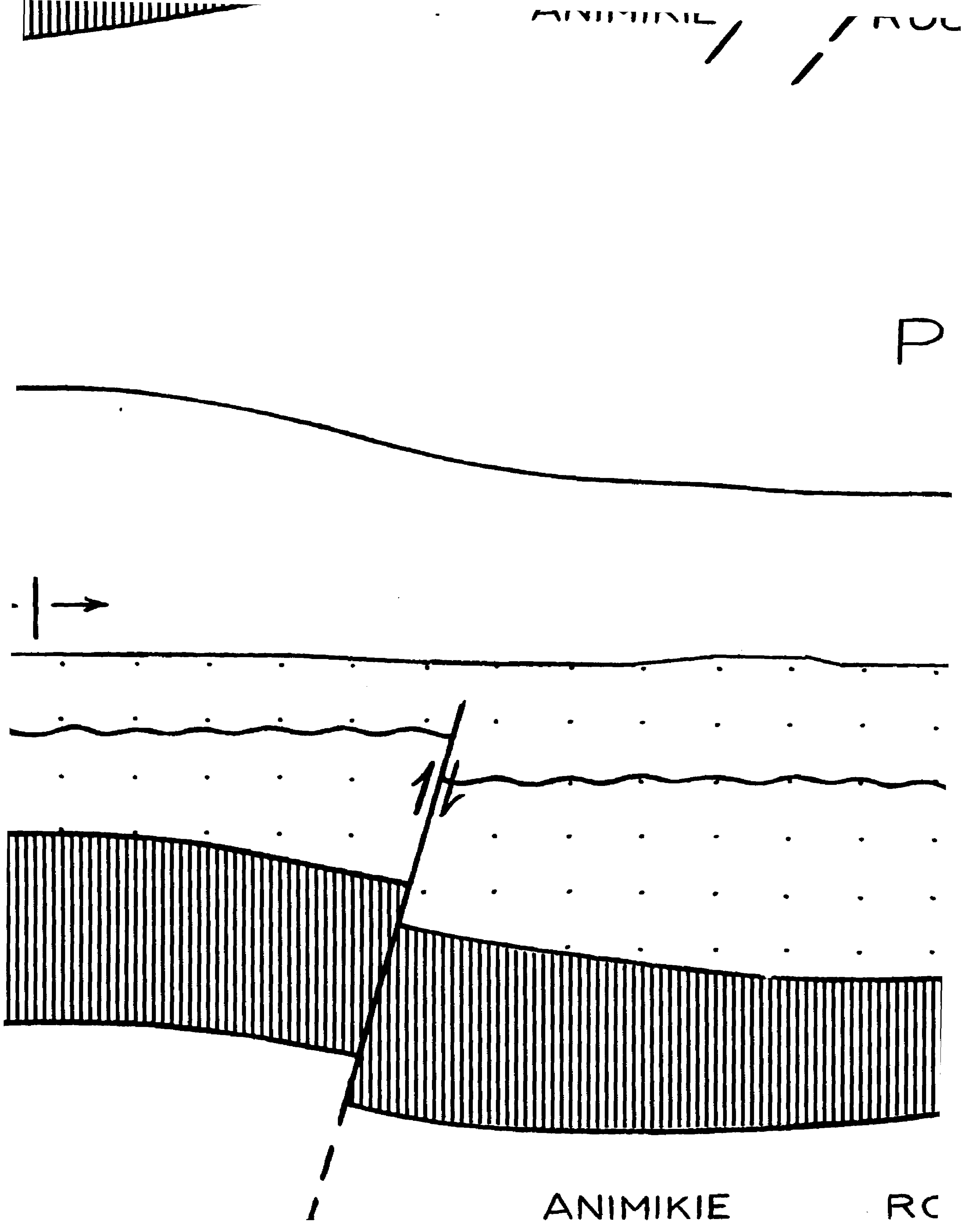

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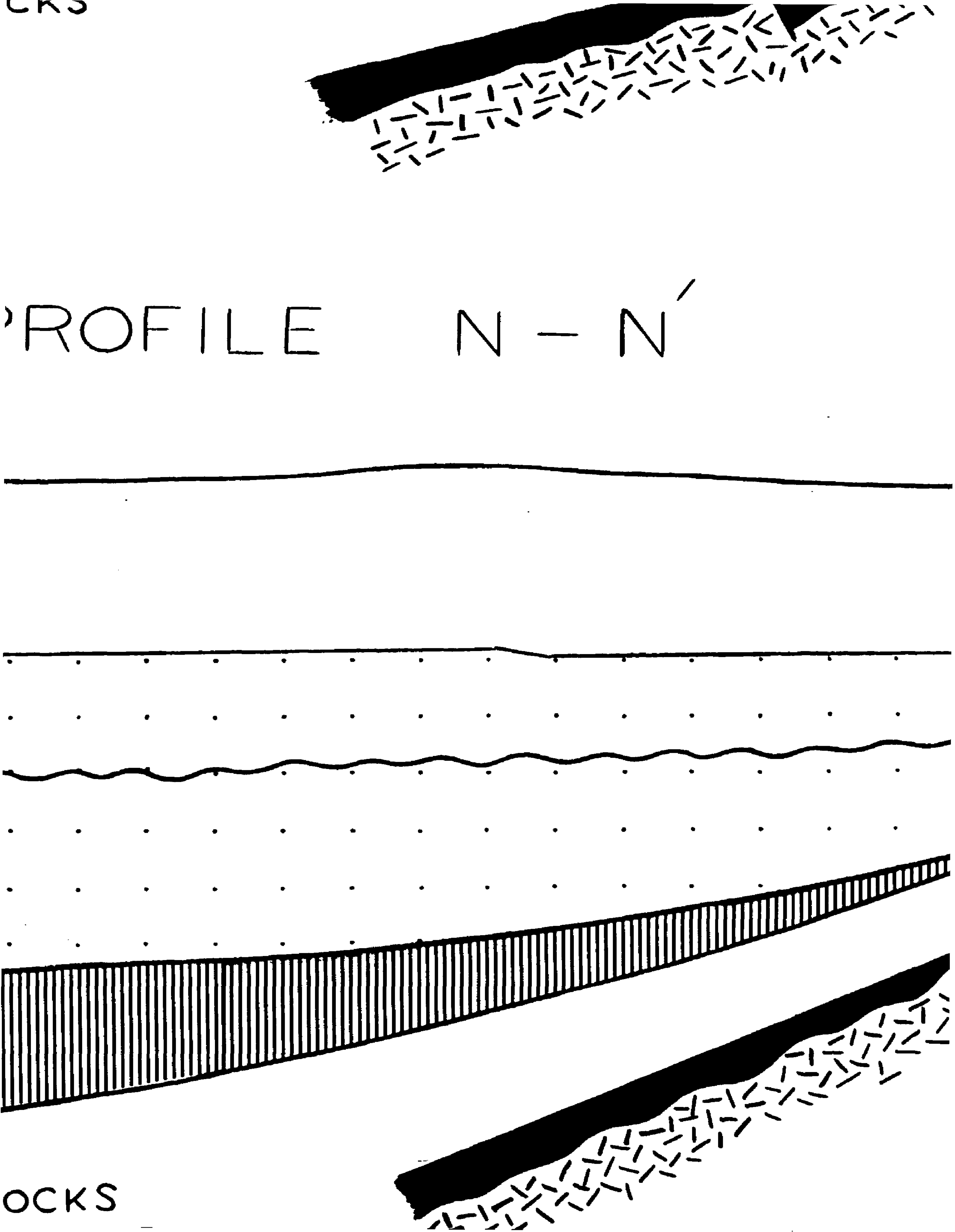
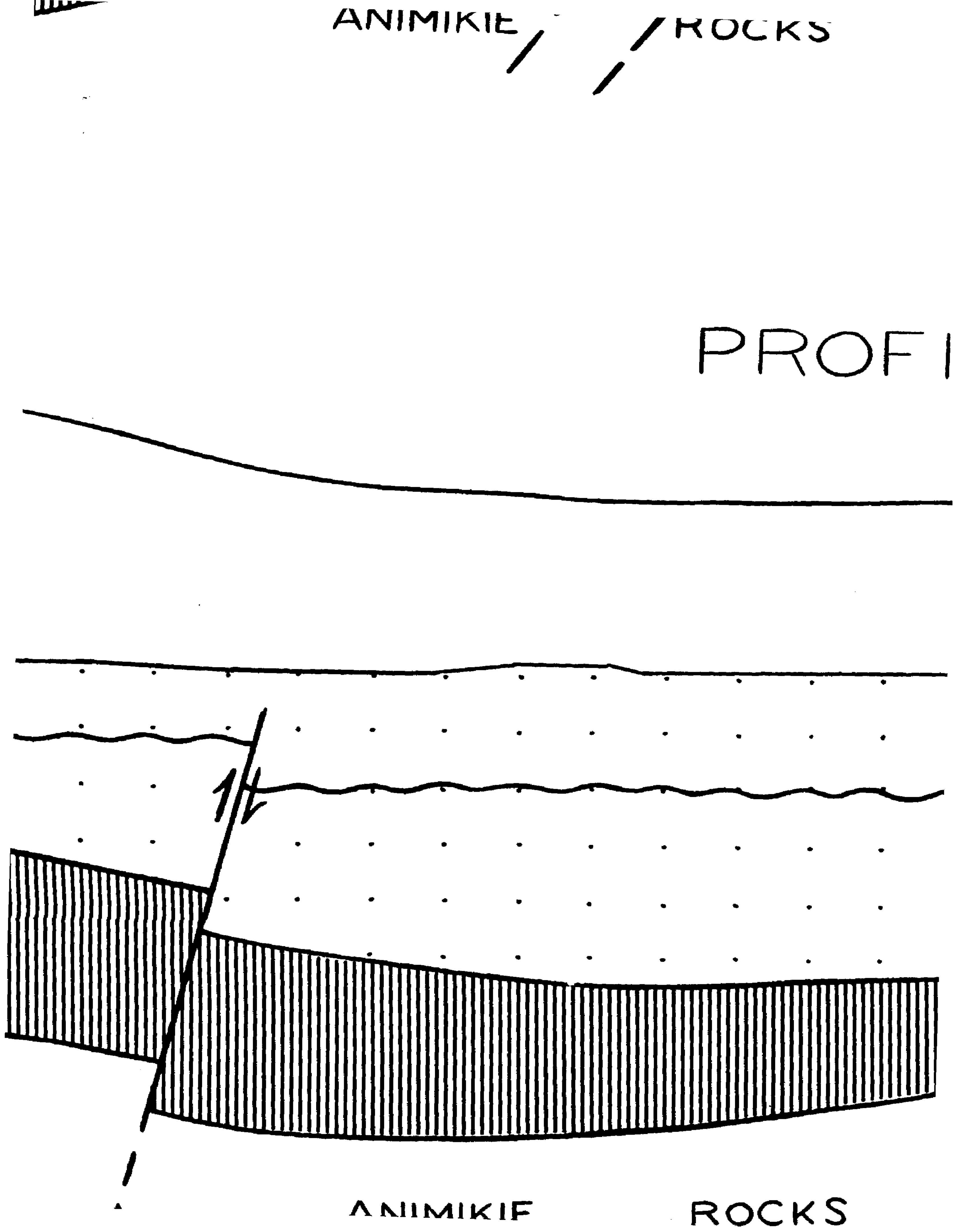
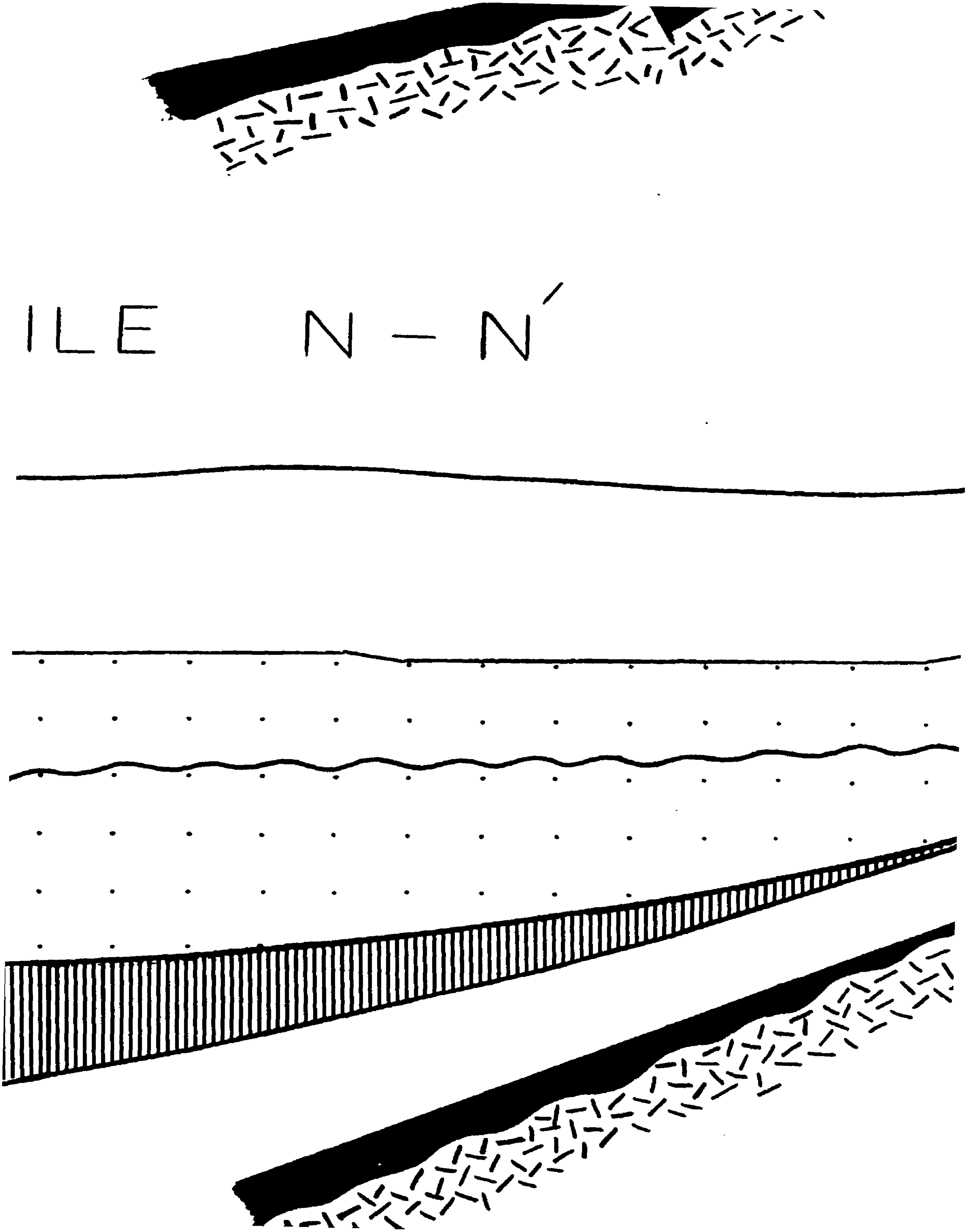


ROFILE N – N′
OCKS



ANIMIKIE ROCKS
PROFI
ANIMIKIE ROCKS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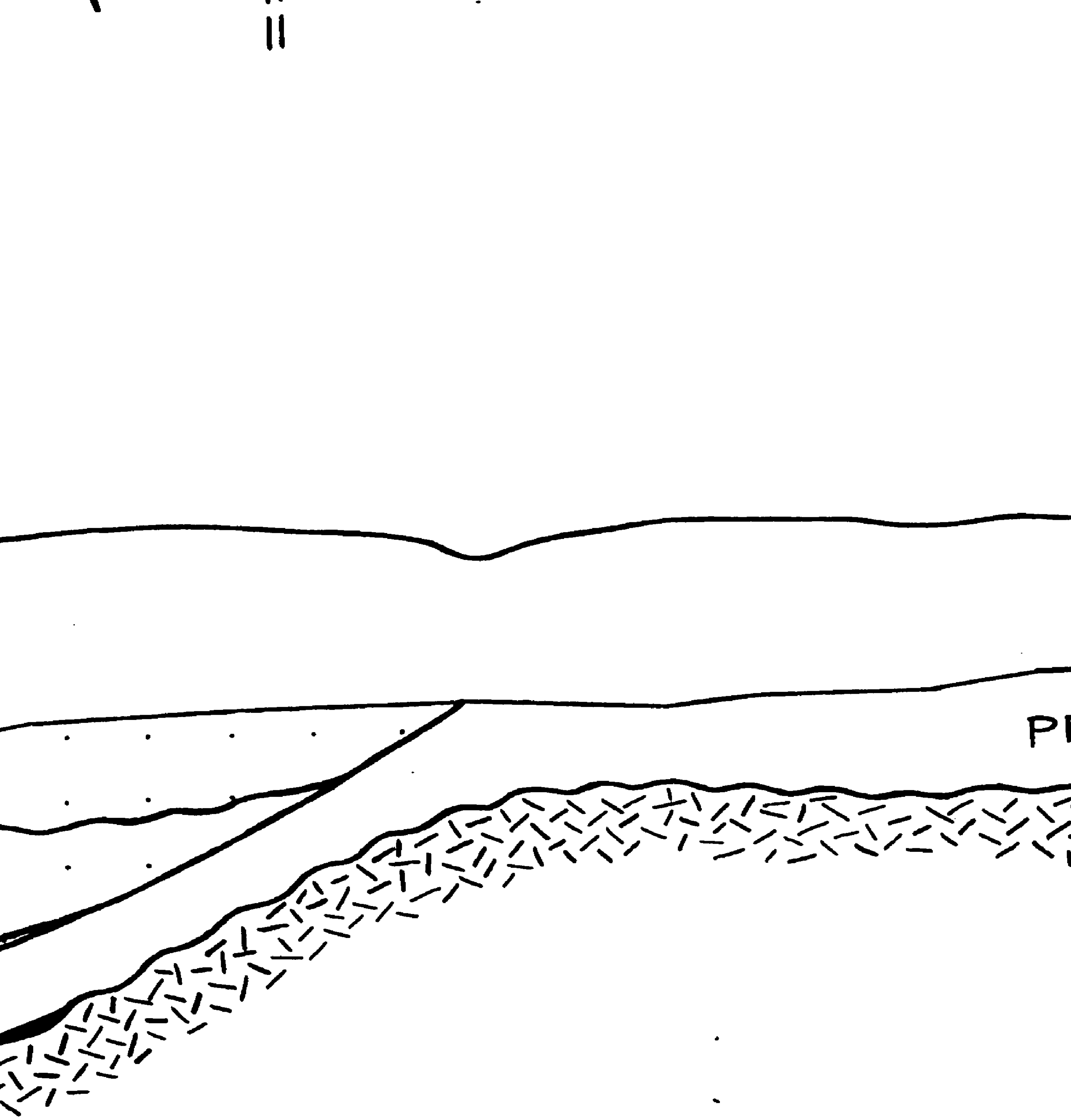

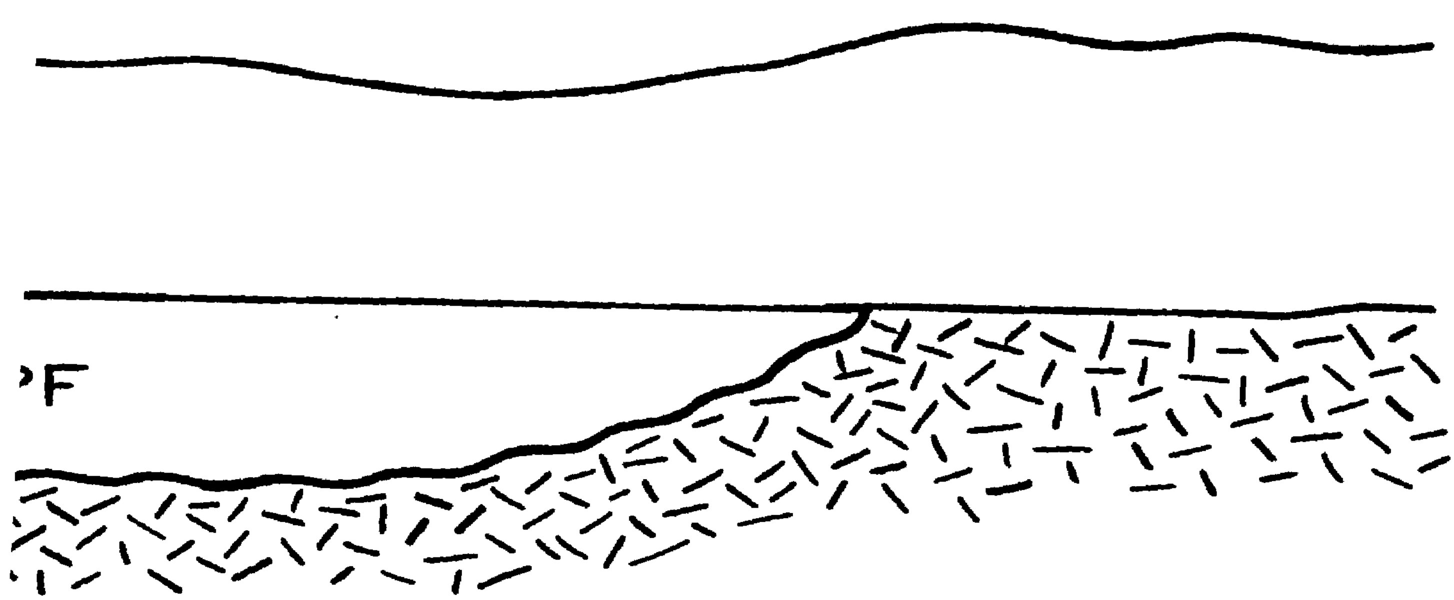
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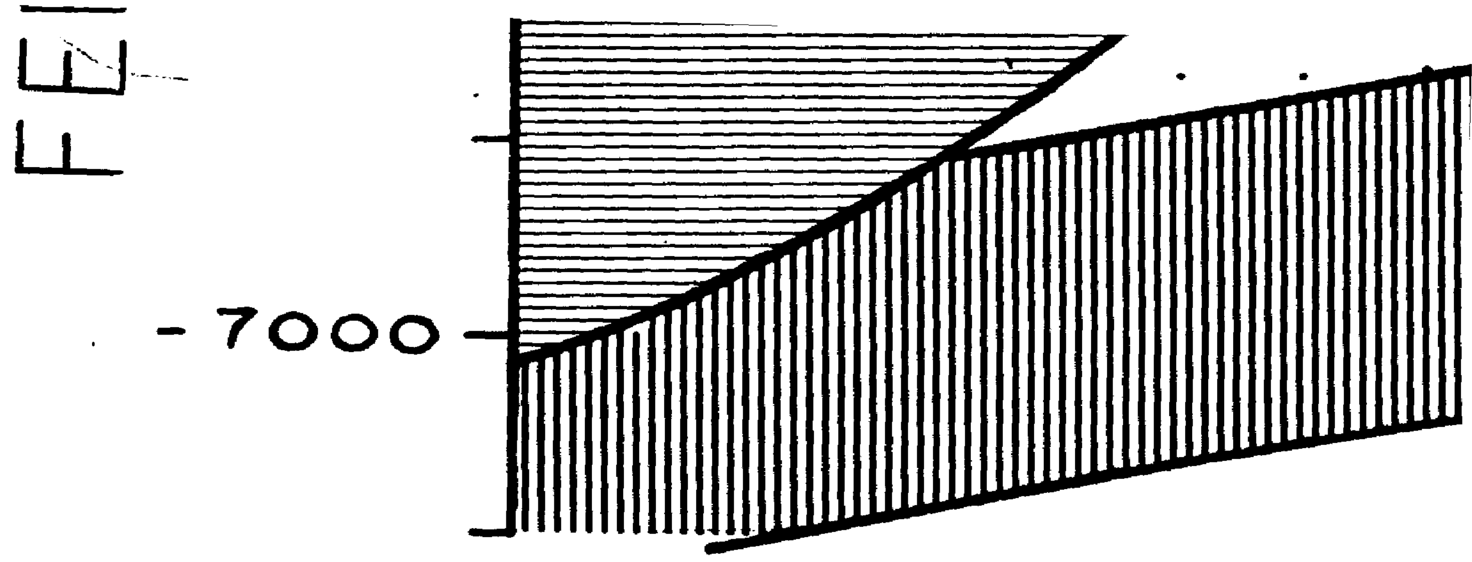

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PI ATE IV-A :
IV-B :
IV-C :
IV-D :
IV-E :
IV-F :

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VERTICAL S

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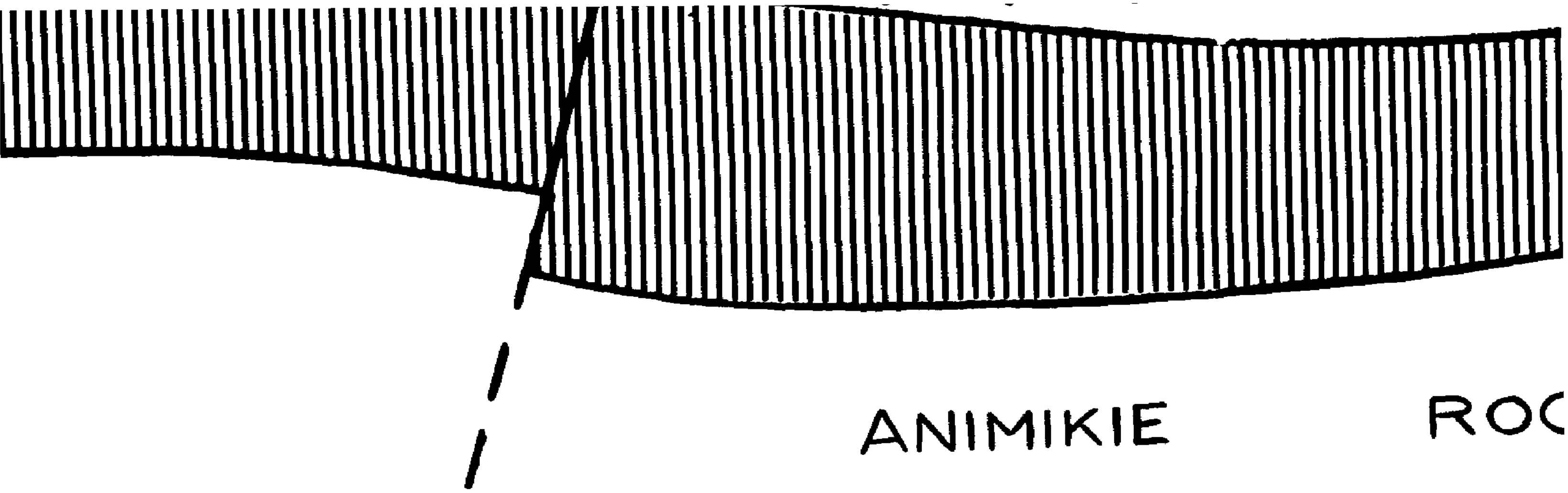
C-C′, D-D′
E-E′, F-F′
G-G′, H-H′
I-I′, J-J′, K-K′, L-L′
M-M′, N-N′

SCALE 1:62500

SCALE 1 INCH = 2000 FEET



GE

K E W E E

UPPER PRECAMBRIAN

Jacobs

Freda

Nonesu

Copper

Portage

South

KS Quartzi

P R E – K E W

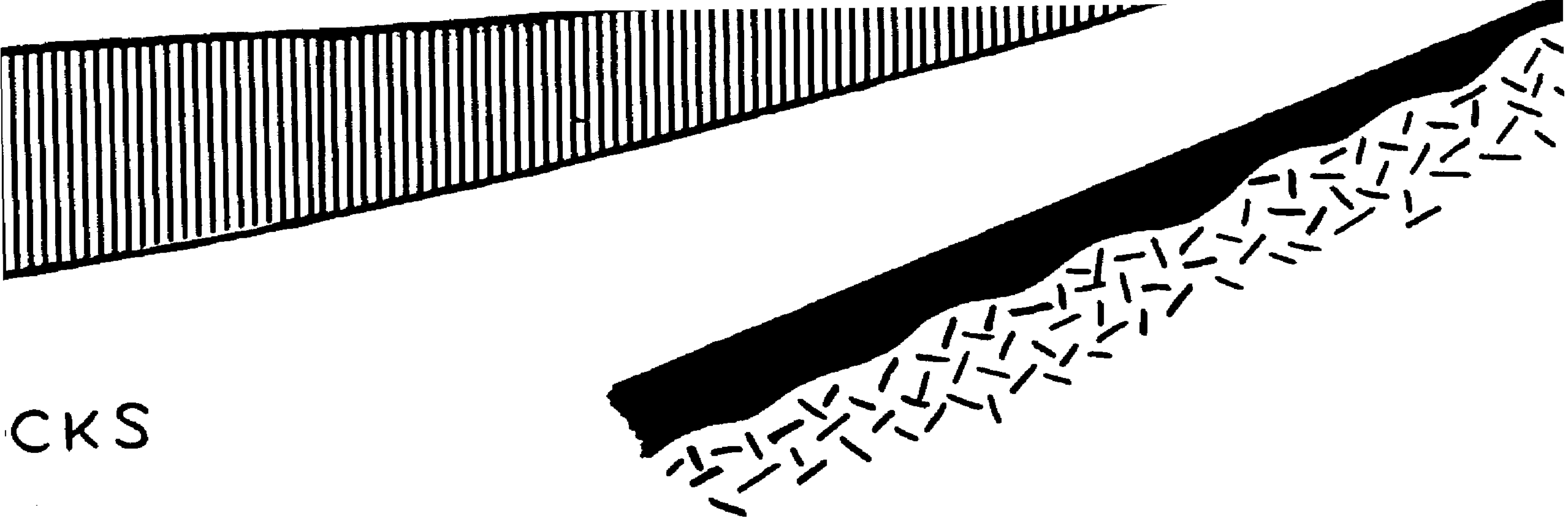
LAKE GC

MBRIAN

W,9 Wolf

PF Michigar

Metatuff



ΞOLOGIC COLUMN

Ξ N A W A N ROCKS

ısville Sandstone

Sandstone

ıuch Shale

r Harbor Sandstone and Conglomerate

ge Lake Lava Series

Trap Range Lavas

ıitic Sandstone

Rhyolite and Felsitic Rocks

Diobase Dikes

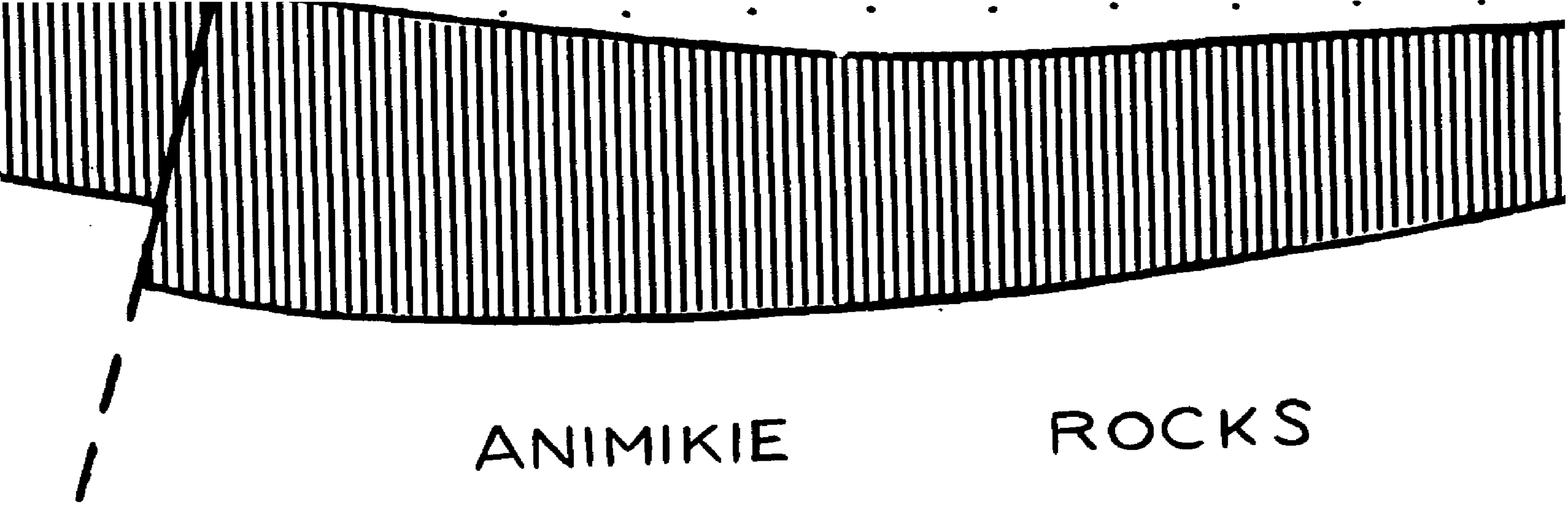
E E N A W A N ROCKS

ıOGEBIC AREA

Lake Granite

amme Slate

ff and Metasediment



GEOLOGIC

K E W E E N A W A

UPPER PRECAMBRIAN

KS

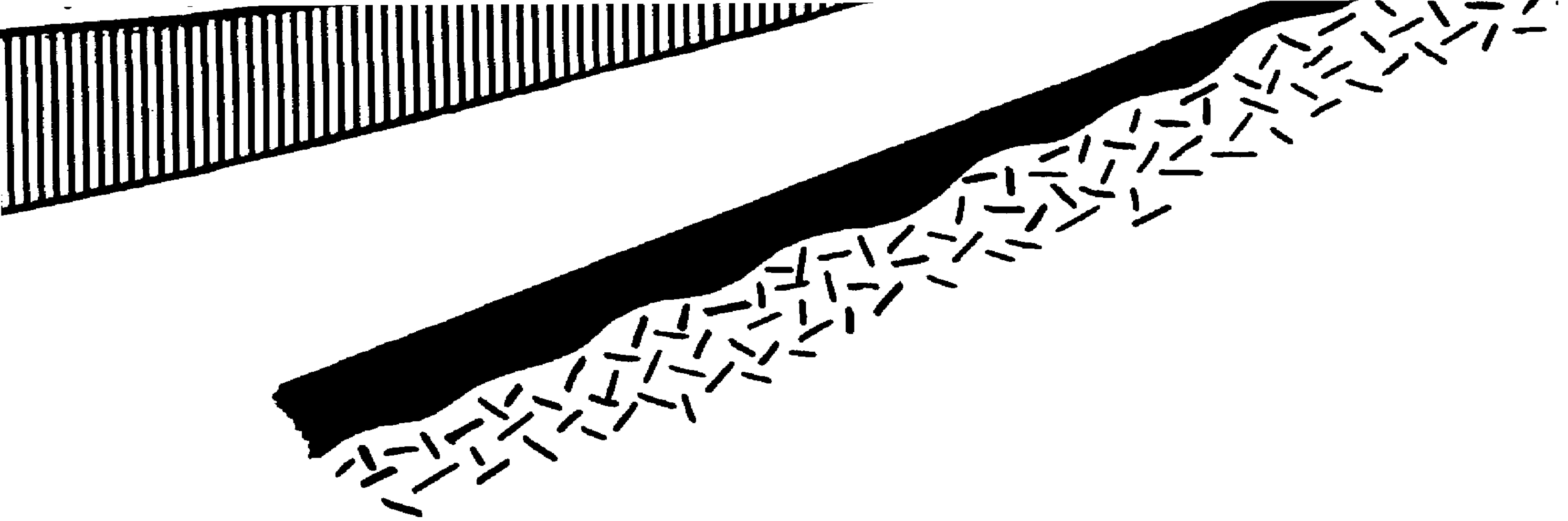
- Jacobsville Sandstone
- Freda Sandstone
- Nonesuch Shale
- Copper Harbor Sandstone
- Portage Lake Lava Seri
- South Trap Range Lavas
- KS Quartzitic Sandstone

P R E — K E W E E N A

LAKE GOGEBIC AREA

BRIAN

- W.g. Wolf Lake Granite
- PF Michigamme Slate



COLUMN

A N ROCKS

Rhyolite and Felsitic Rocks

Diabase Dikes

and Conglomerate

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A W A N ROCKS

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Iron

Diabase

Anticli

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rved Magnetic Profile

ritical Magnetic Profile

Formation

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PI ATE IV-A
IV-B
IV-C
IV-D
IV-E
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HORISONTAL

VERTICAL

X FOR PLATE IV

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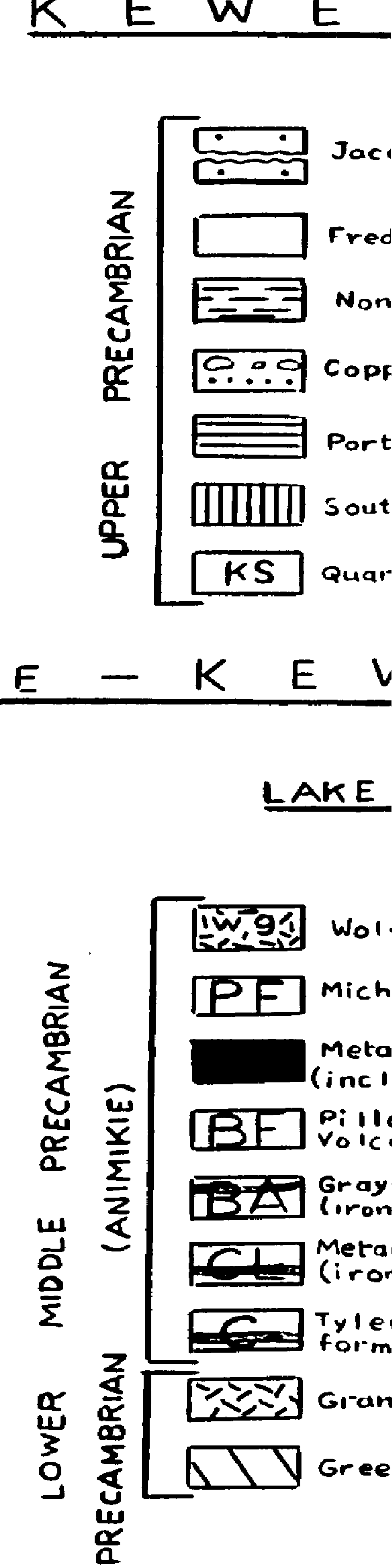
: C-C′, D-D′
: E-E′, F-F′
: G-G′, H-H′
: I-I′, J-J′, K-K′, L-L′
: M-M′, N-N′

SCALE 1:62500

SCALE 1 INCH = 2000 FEET

PLATE



IV - AEROMAGNETIC

E N A W A N   R O C K S

icobsville Sandstone

eda Sandstone

Rhyolite and Felsitic Rocks

onesuch Shale

Diabase Dikes

pper Harbor Sandstone and Conglomerate

rtage Lake Lava Series

uth Trap Range Lavas

artzitic Sandstone

W E E N A W A N   R O C K S

E GOGEBIC AREA

olf Lake Granite

chigamme Slate

tatuff and Metasediment
clude magnetic iron formation)

low Lava and Fragmental
canic Rocks

ywacke near Banner Lake
on formation in upper part)

tatuff and Tuffaceous Metagraywacke
on formation in lower part)

er Slate (include Ironwood iron
mation)

anites and Gneisses

eenstones

C   AND   GEOLOGIC

UPPER PRECAMBRIAN

- Jacobsville Sandstone
- Freda Sandstone
- Nonesuch Shale
- Copper Harbor Sandstone and
- Portage Lake Lava Series
- South Trop Range Lavas
- KS Quartzitic Sandstone

PRE-KEWEENAW

LAKE GOGEBIC AREA

MIDDLE PRECAMBRIAN (ANIMIKIE)

- W,9 Wolf Lake Granite
- PF Michigamme Slate
- Metatuff and Metasediment (include magnetic iron formatio
- BF Pillow Lava and Fragmental Volcanic Rocks
- BA Graywacke near Banner Lake (iron formation in upper part)
- CL Metatuff and Tuffaceous Meta (iron formation in lower part)
- C Tyler Slate (include Ironwood formation)

LOWER PRECAMBRIAN

- Granites and Gneisses
- Greenstones

AEROMAGNETIC AN

Rhyolite and Felsitic Rocks

Diabase Dikes

Conglomerate

WAN ROCKS

on)

tagraywacke
)

d iron

ND GEOLOGIC PI

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Observed

Theoritical

Iron Form

Diabase D

Anticlinal

Synclinal

ROFILES

D

Magnetic Profile

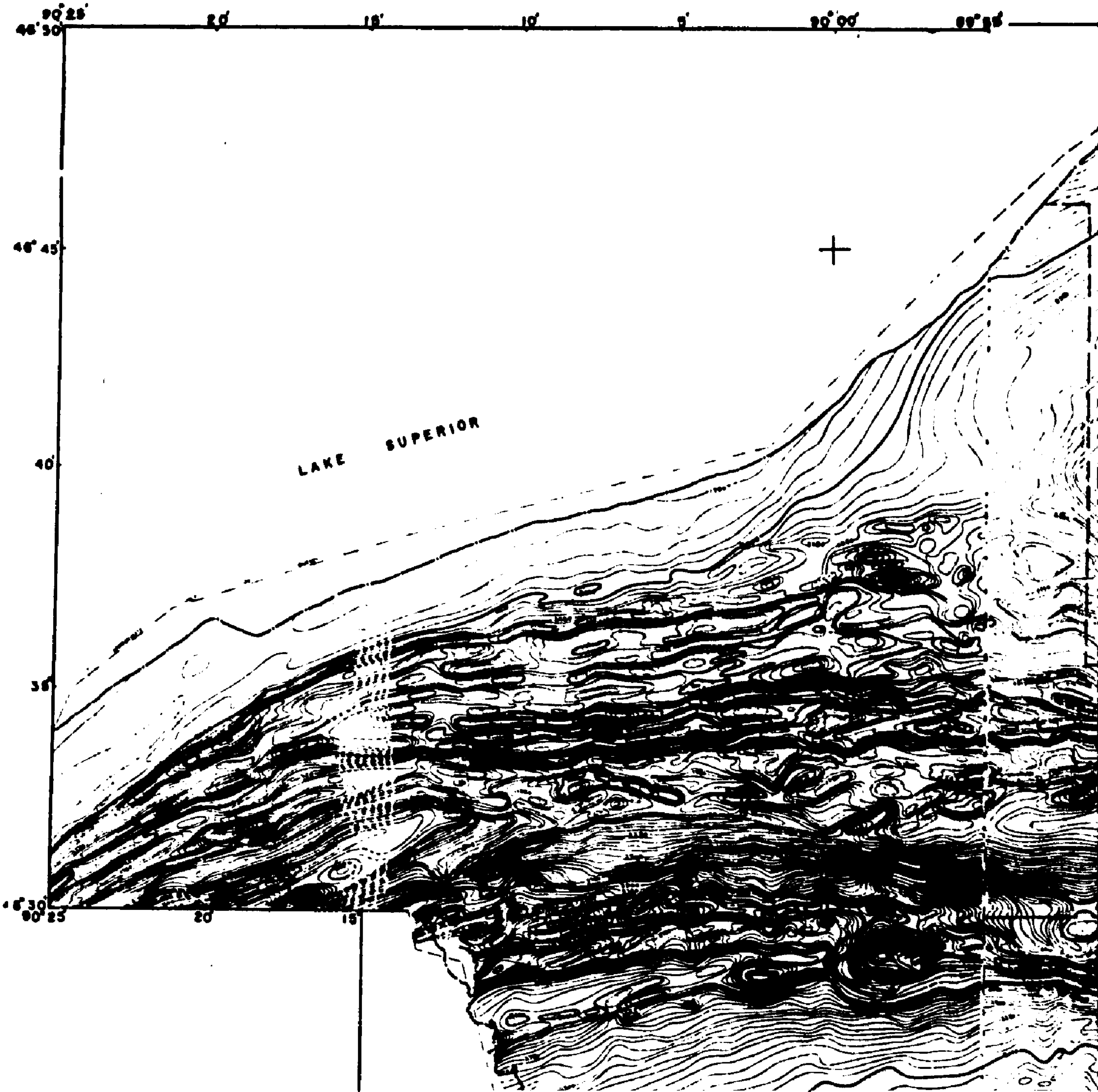
al Magnetic Profile

rmation

Dike

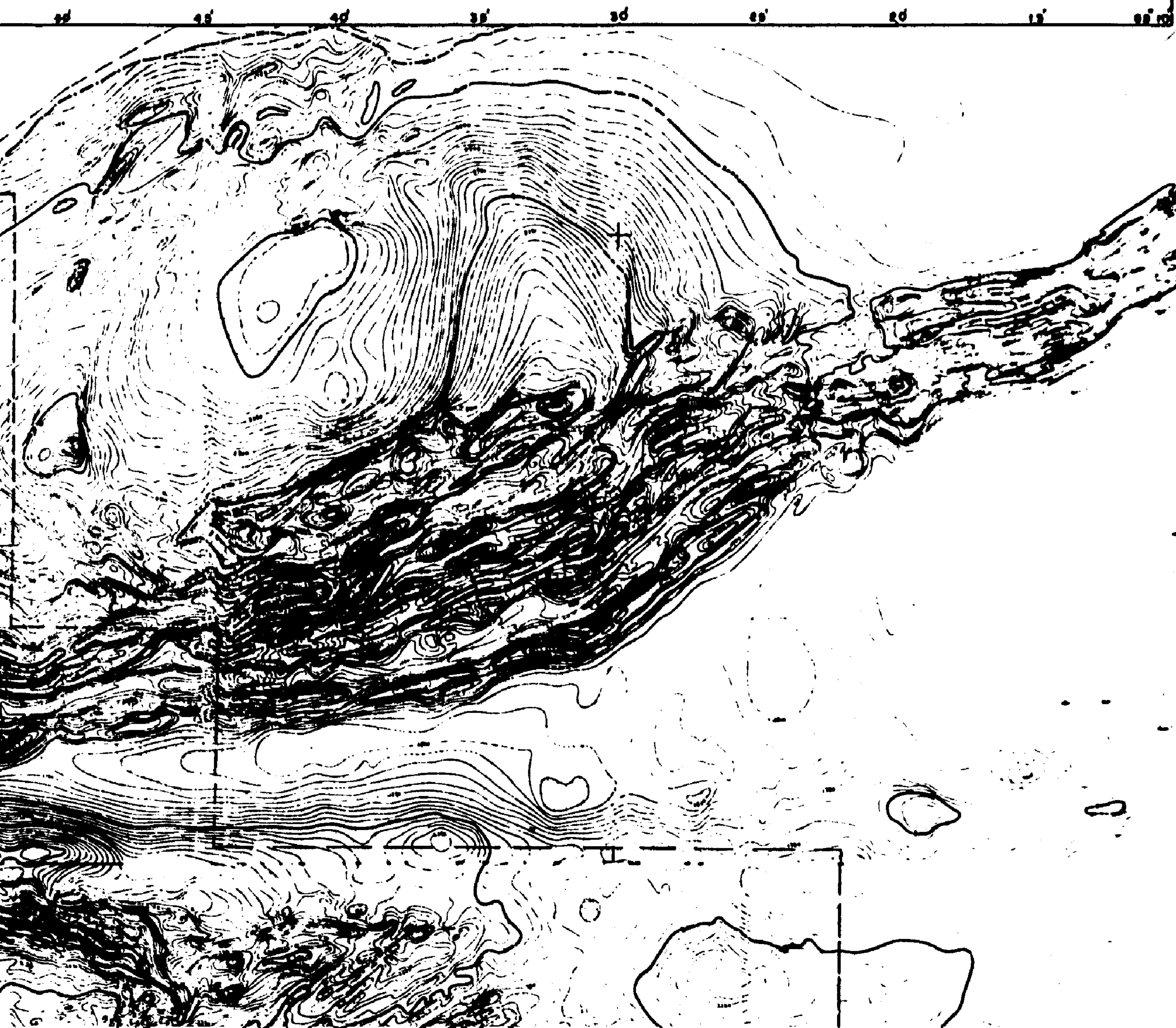
Axis

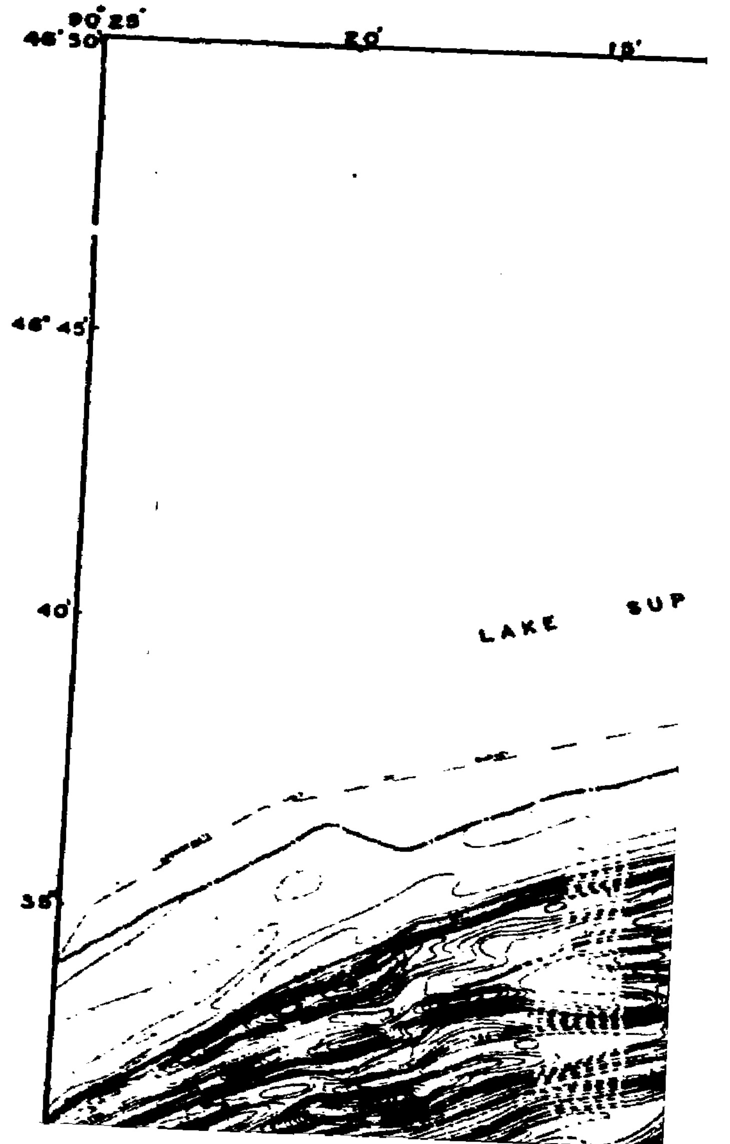
Axis

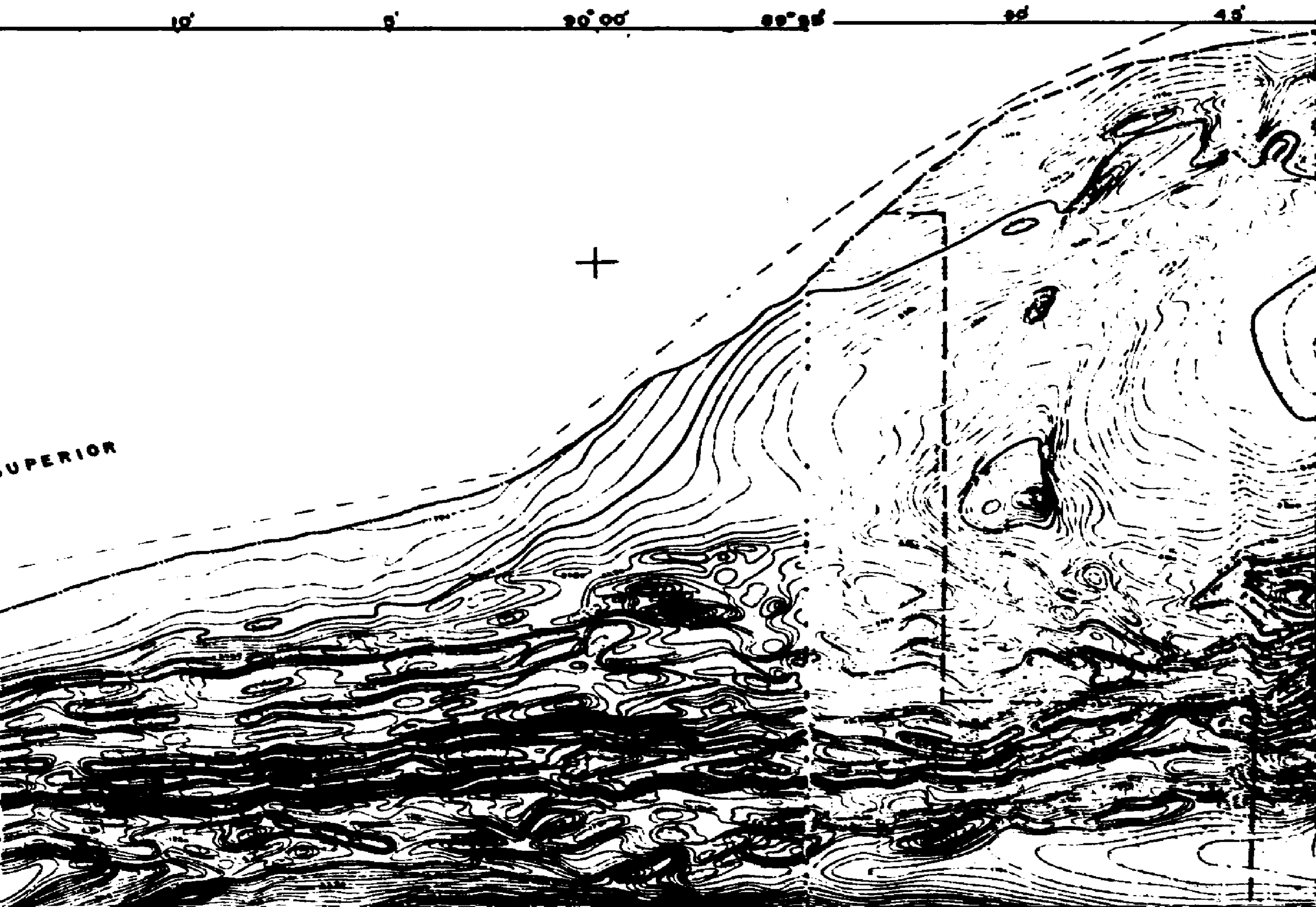


90°25'
20'
15'
10'
5'
90°00'
89°55'
46°50'
46°45'
40'
35'
46°30'
90°25'
20
15
LAKE SUPERIOR

PLATE 1-b

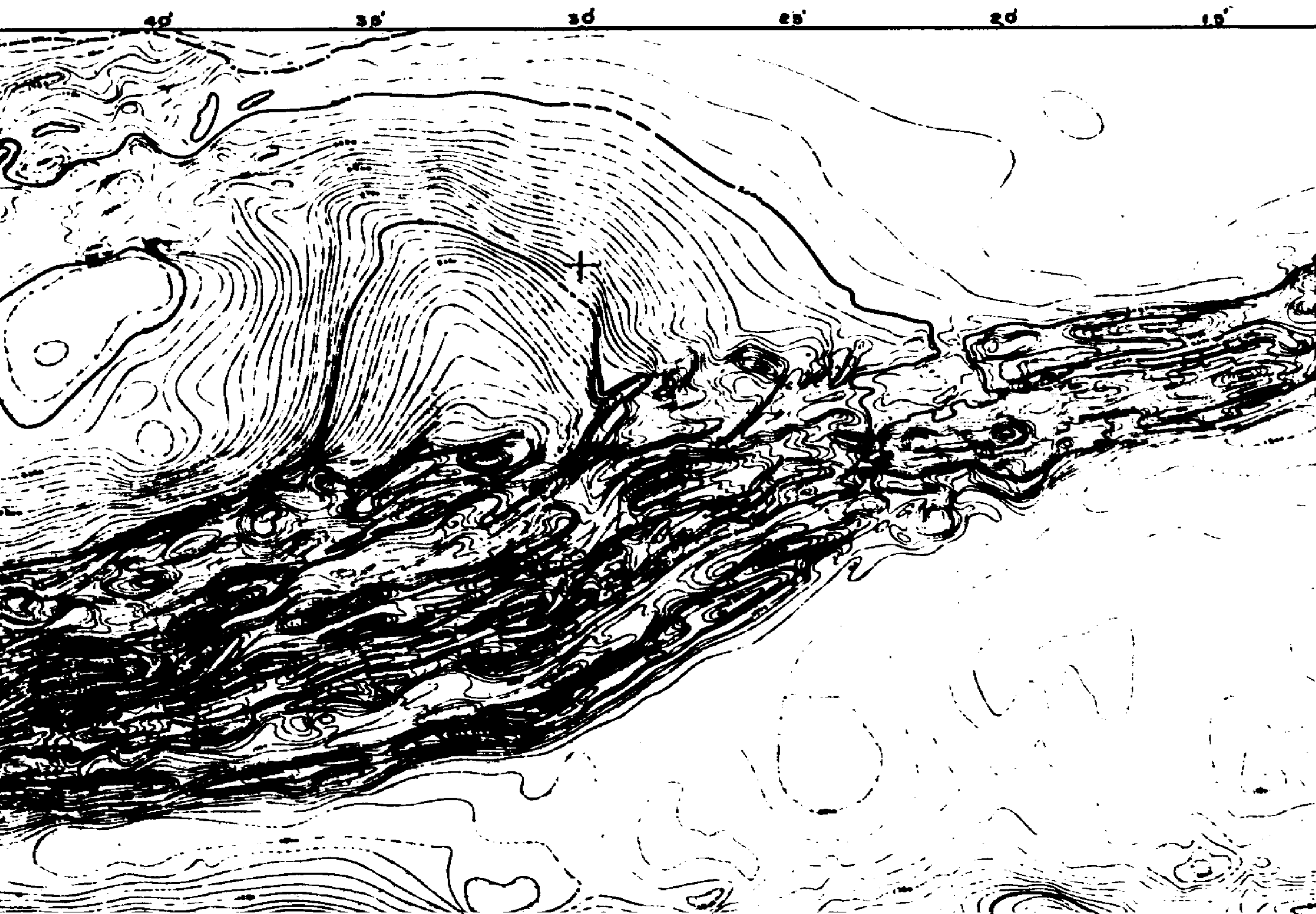


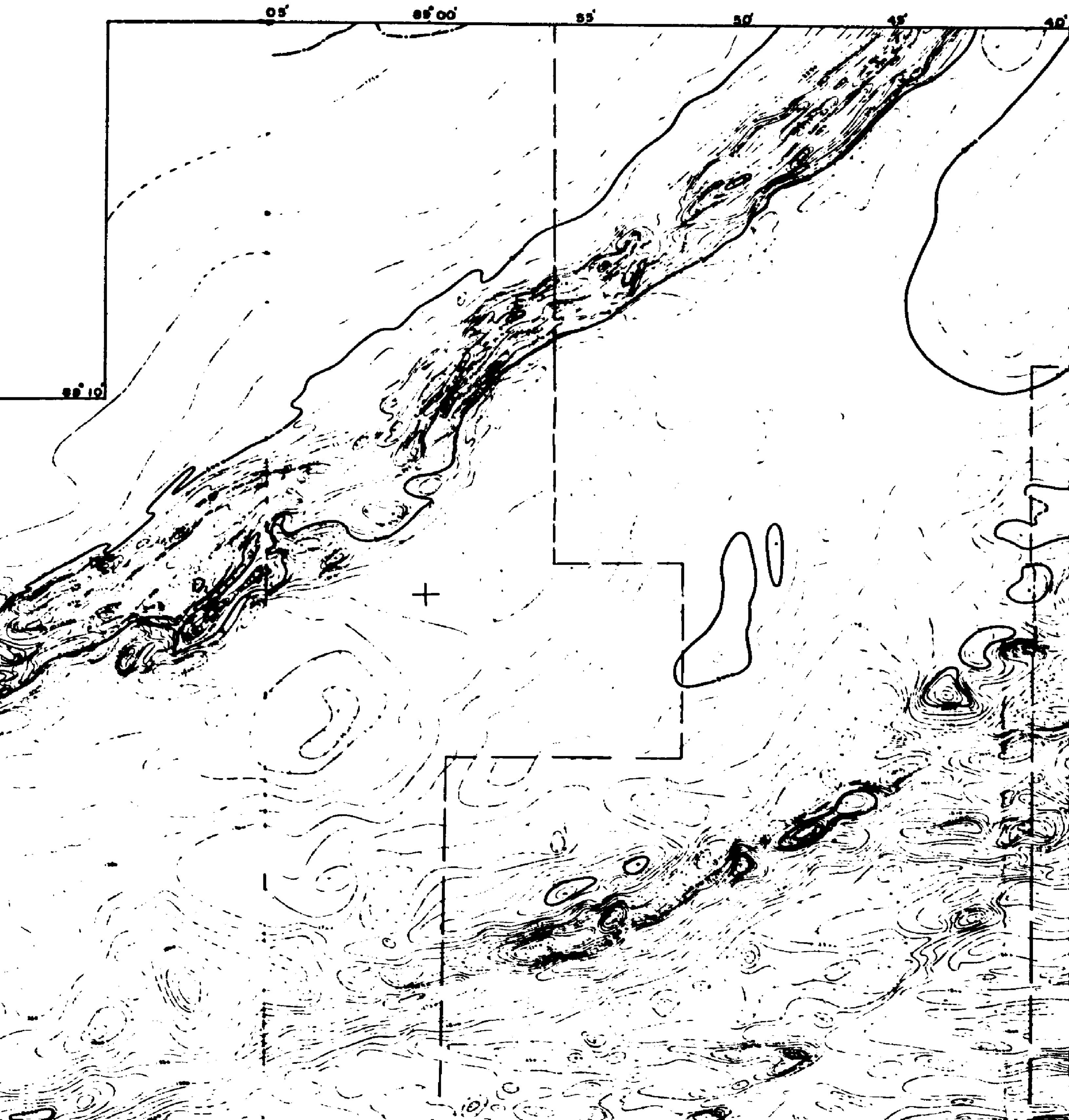

90°25'
46°50'
20'
15'
46°45'
40'
35'
LAKE SUP



10'
5'
90°00'
89°55'
50'
45'
UPERIOR

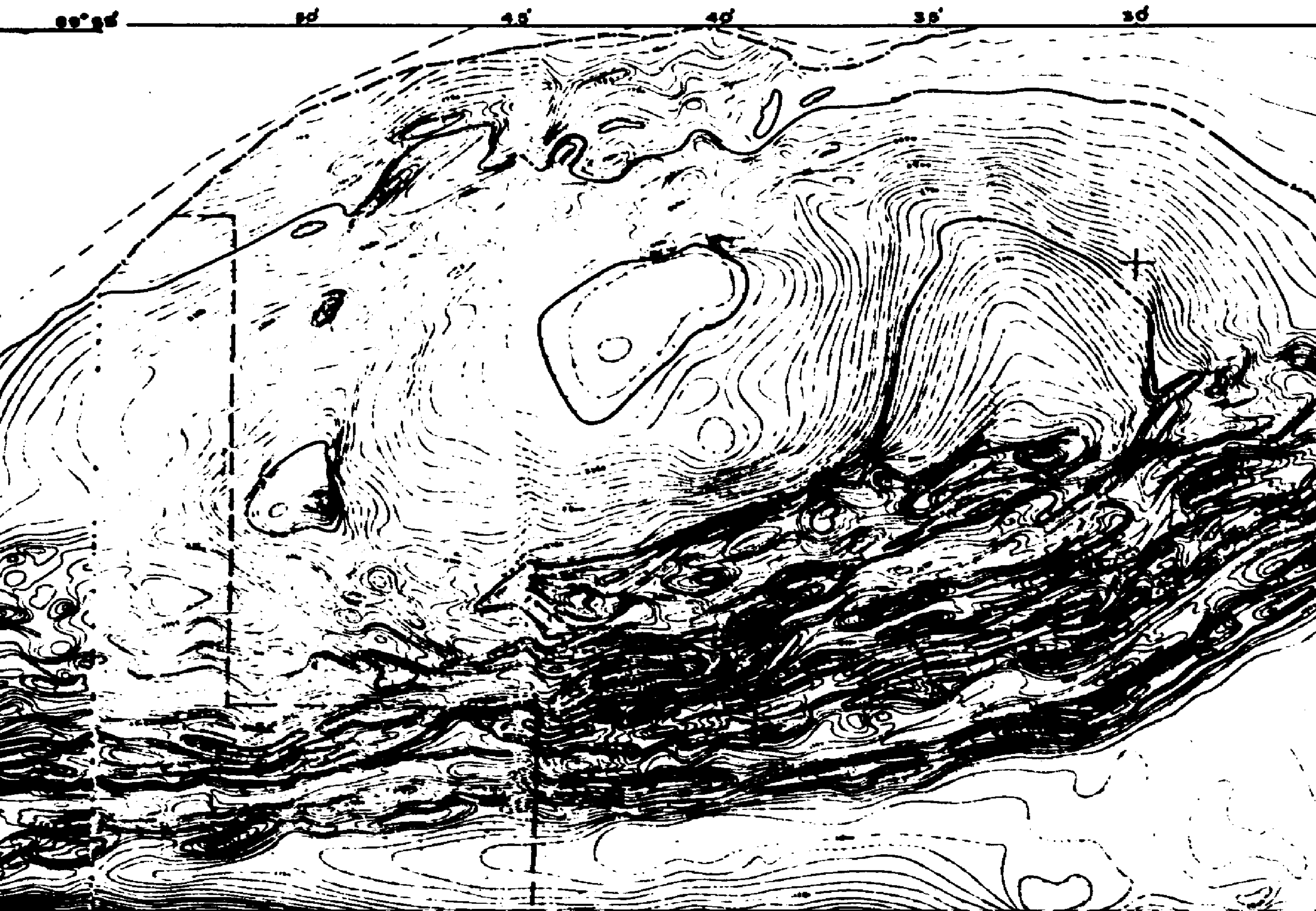
PLATE 1-b

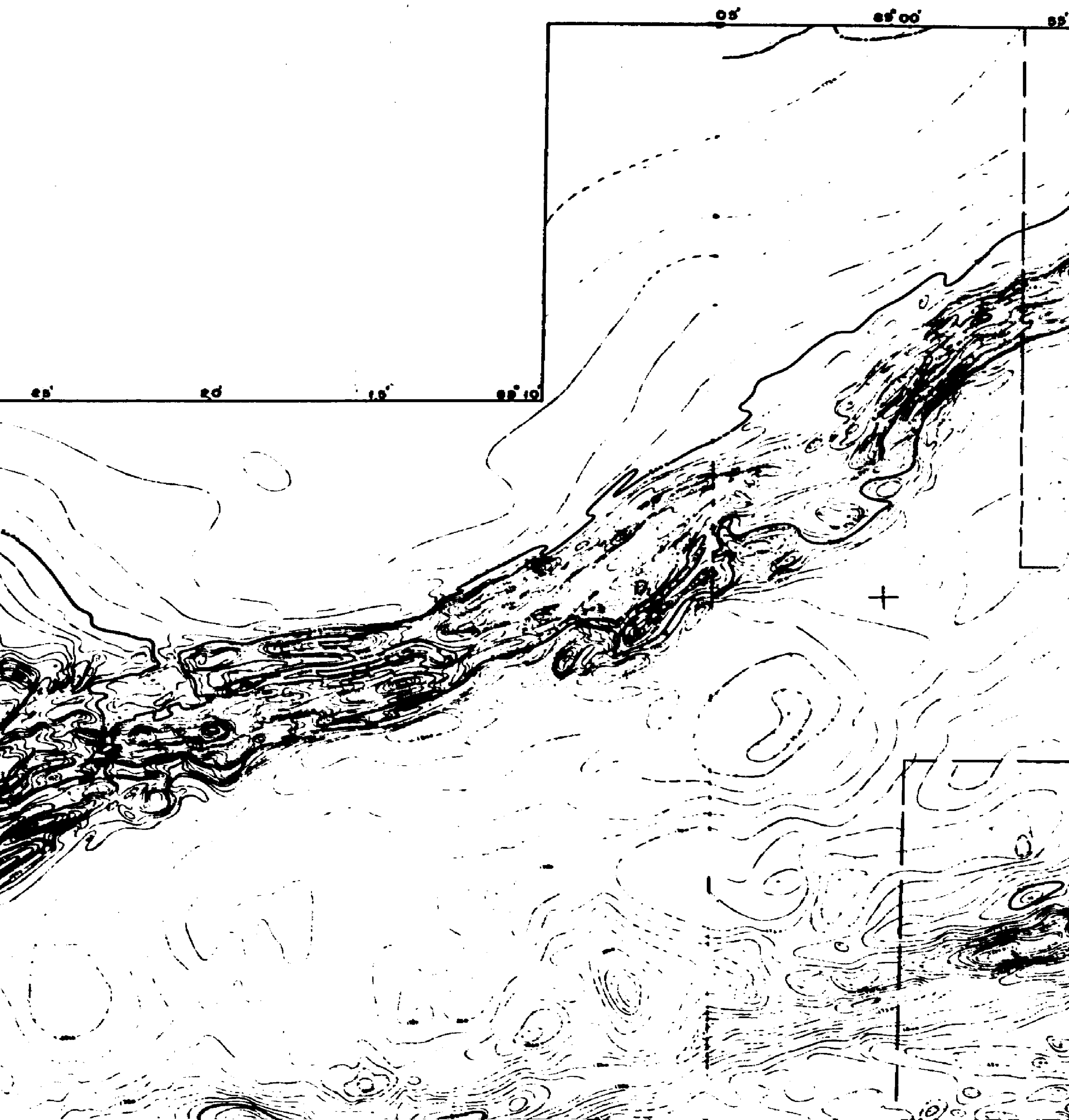




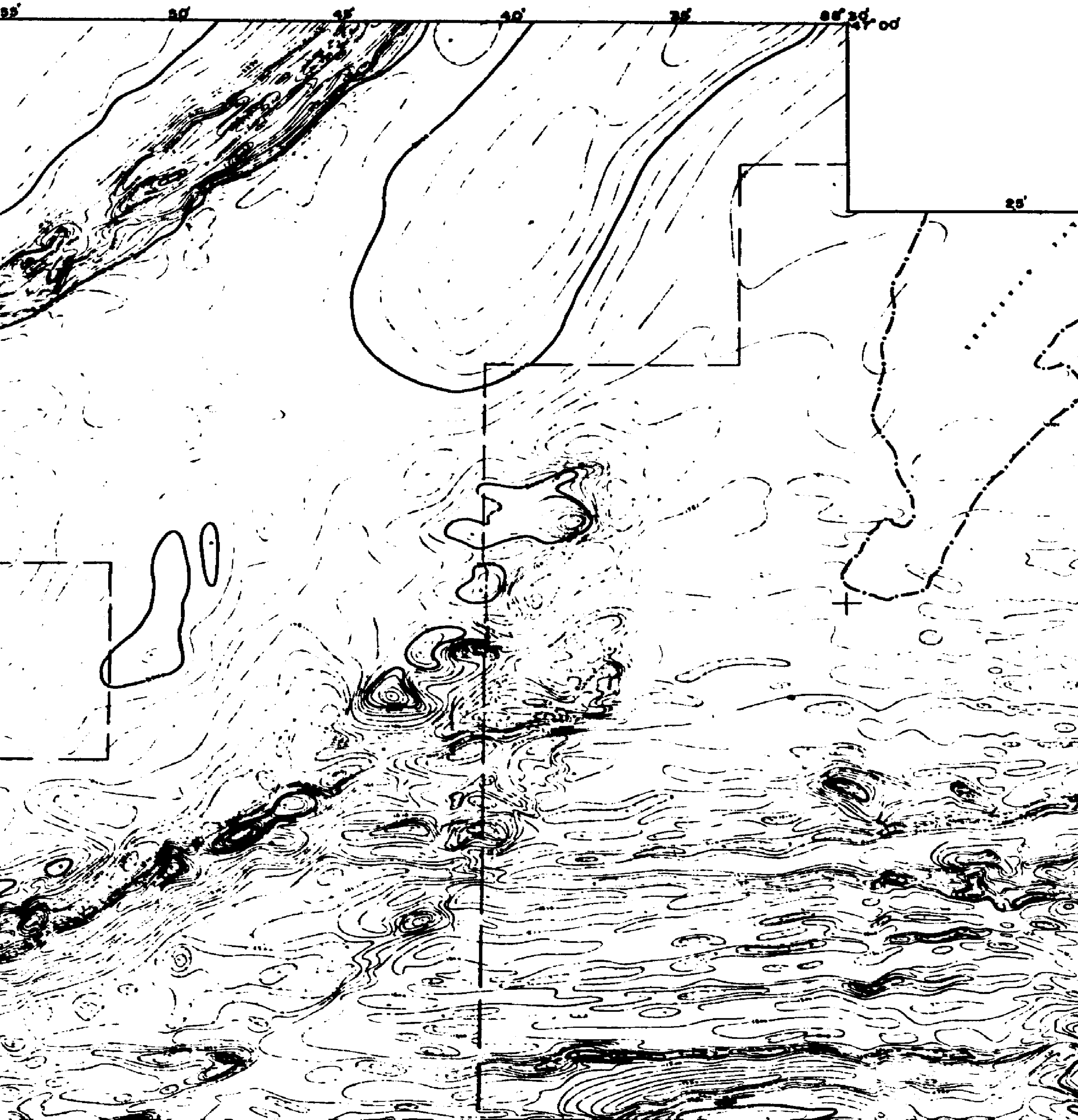
05'
89°00'
55'
50'
45'
40'
89°10'

PLATE I-b



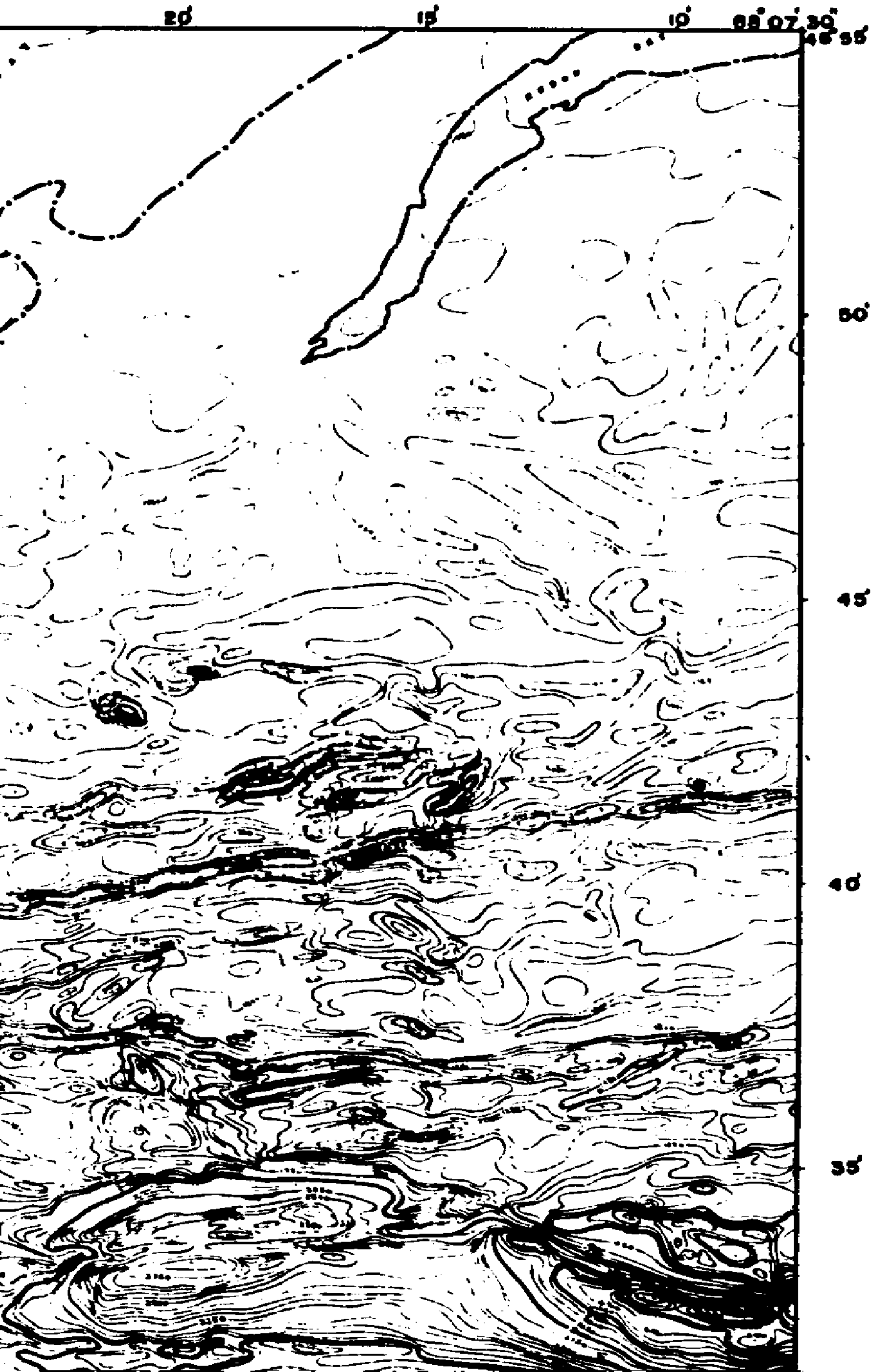


05'
85°00'
55'
25'
20'
15'
85°10'



50'
45'
40'
35'
88°30'
47°00'
25'

PLATE I-c



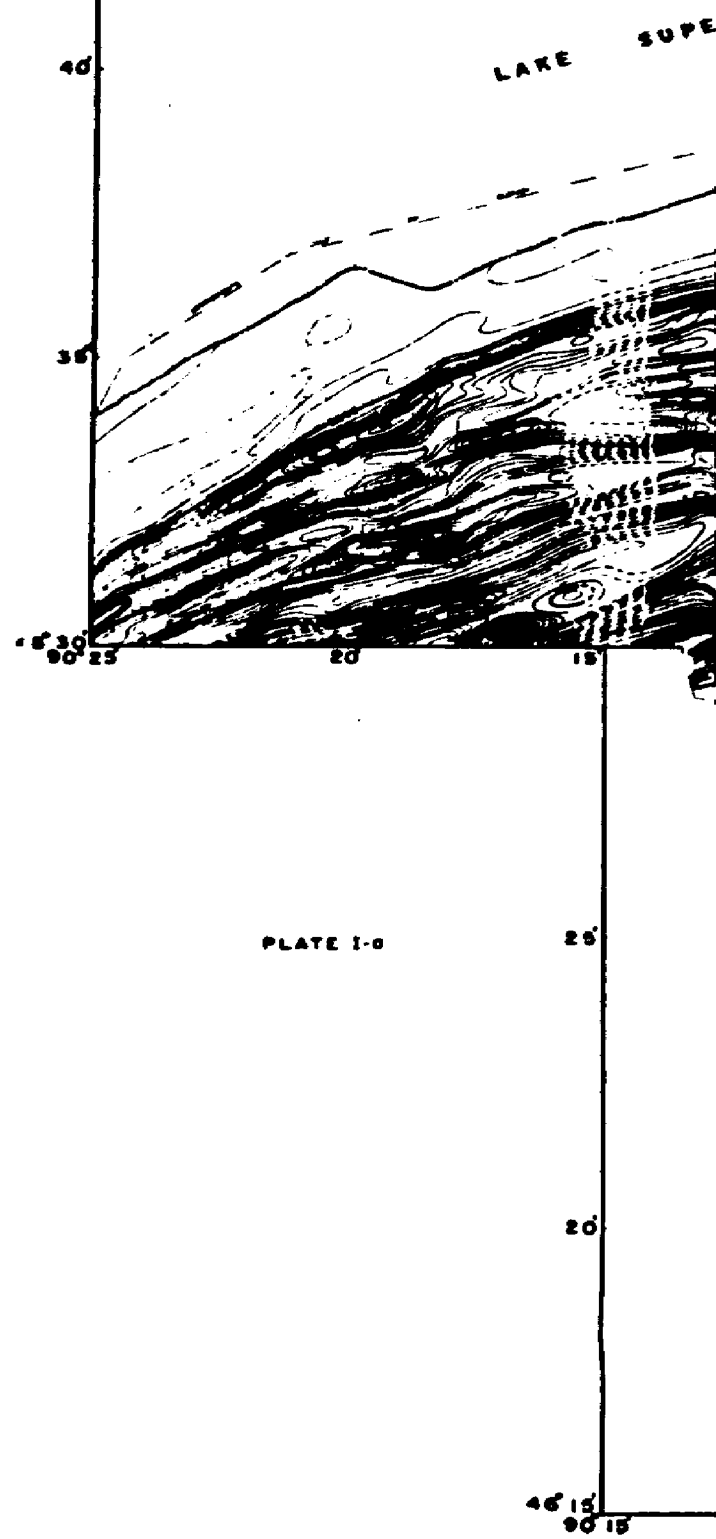


PLATE I-0

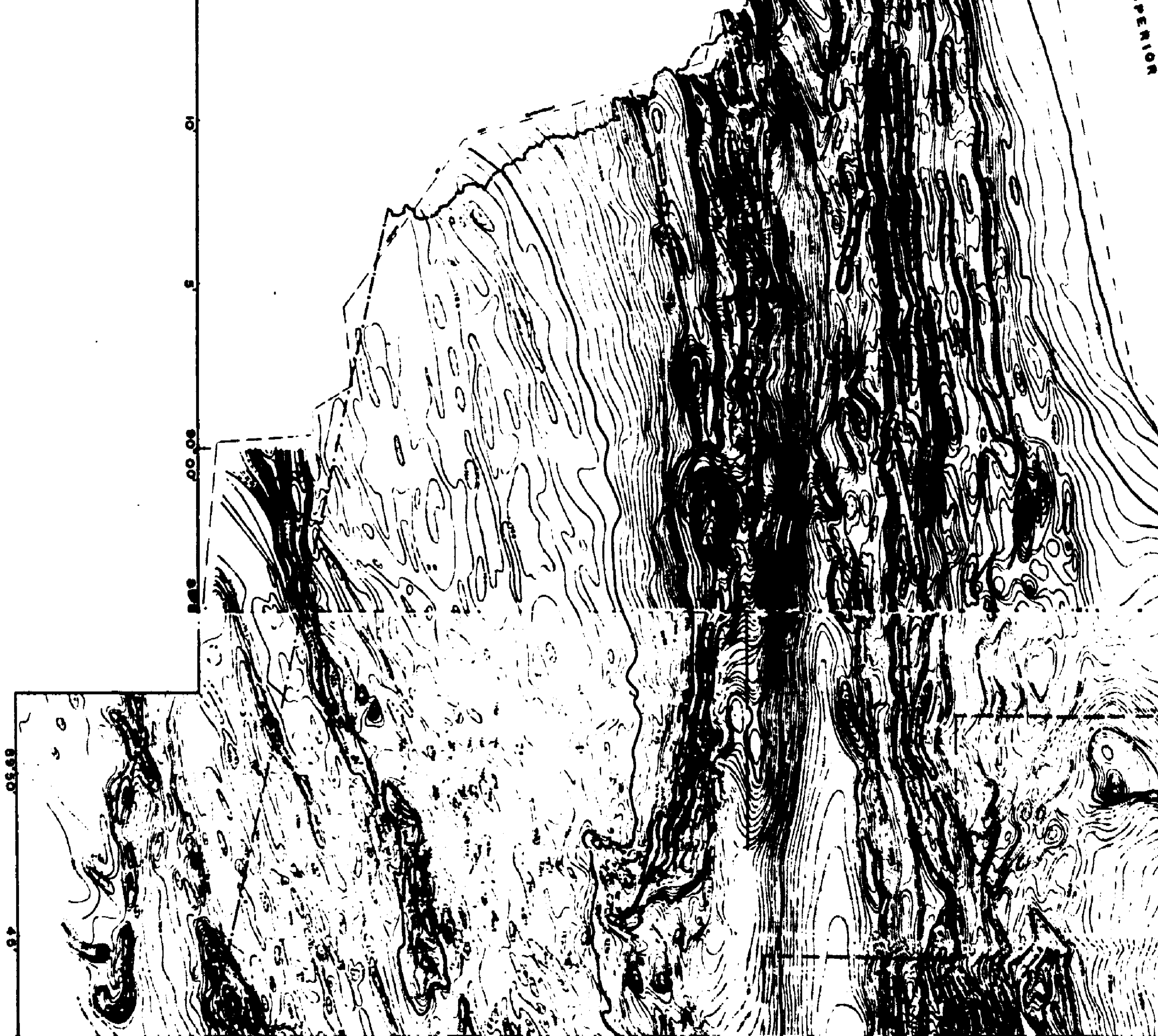
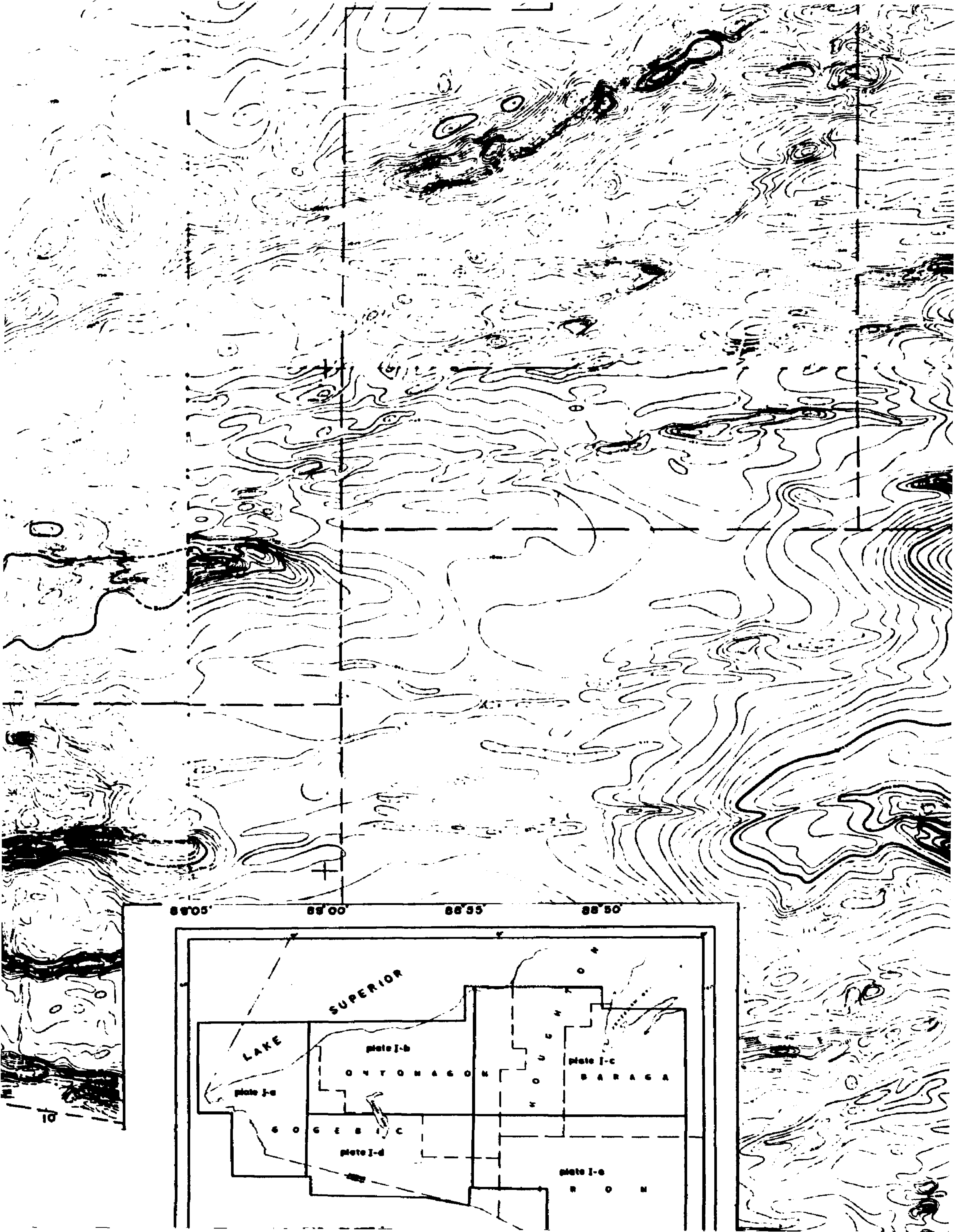


PLATE I-4



89°05'
89°00'
88°55'
88°50'
LAKE SUPERIOR
plate I-a
plate I-b
plate I-c
plate I-d
plate I-e
ONTONAGON
HOUGHTON
BARAGA
GOGEBIC
IRON
10

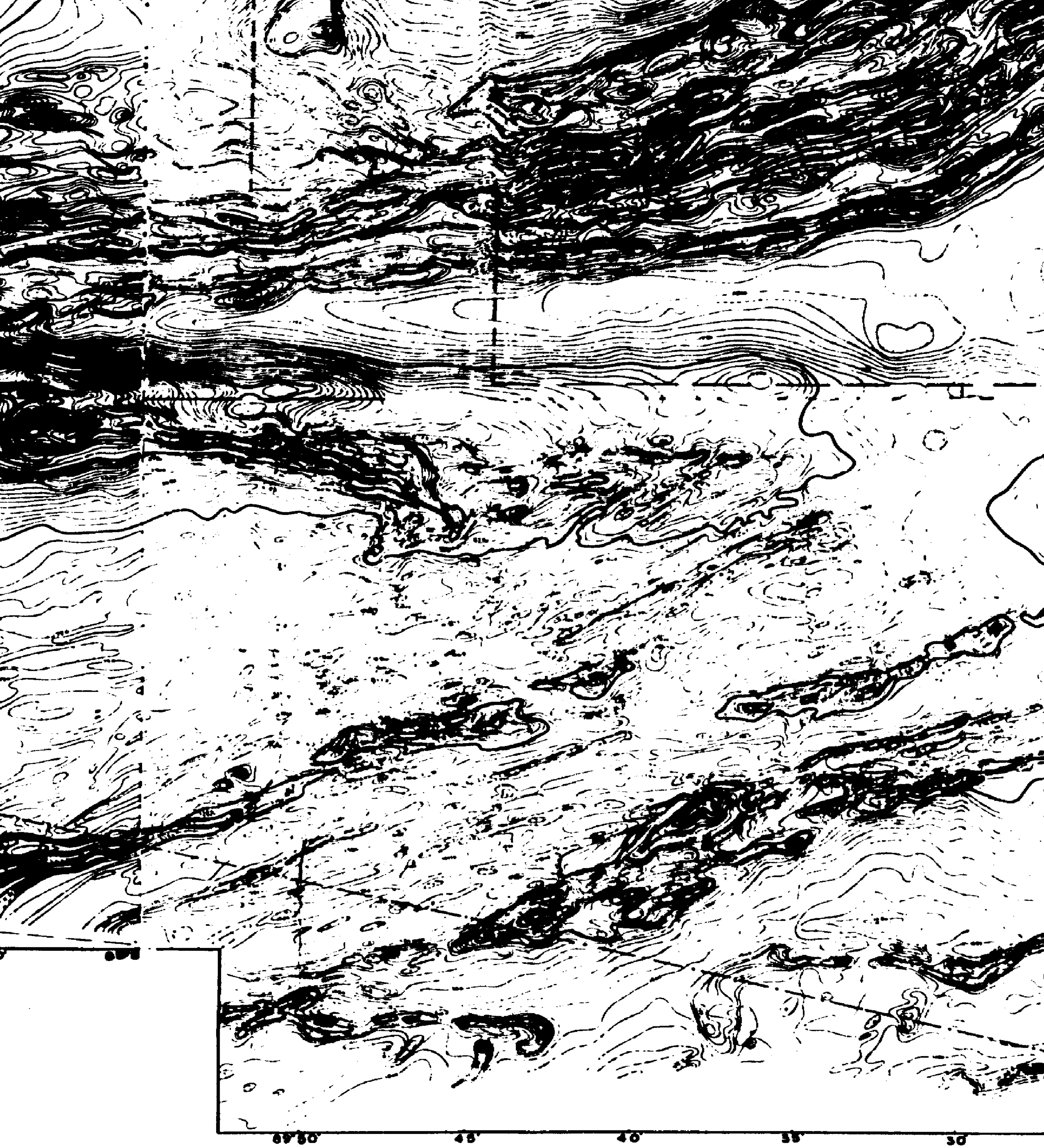
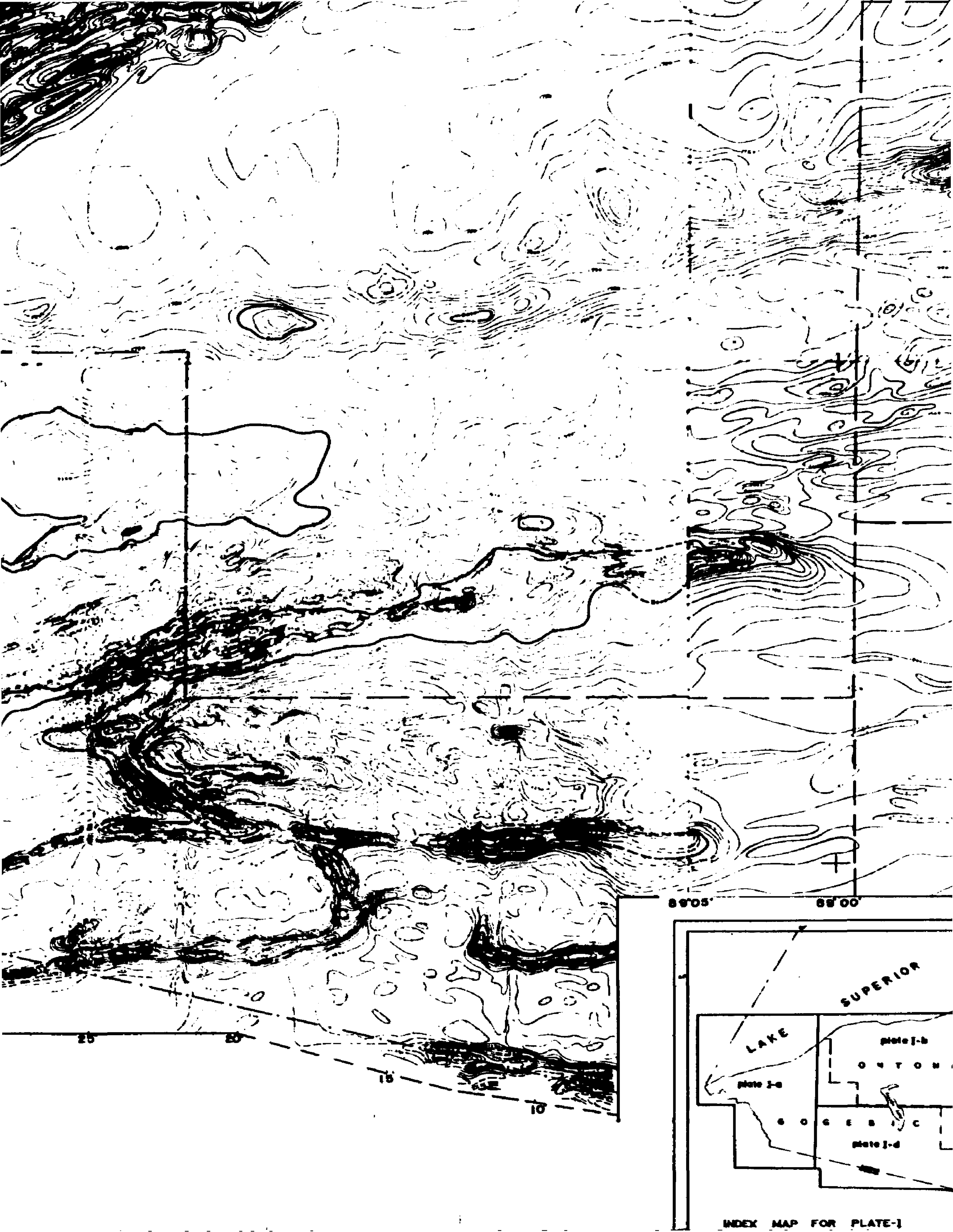
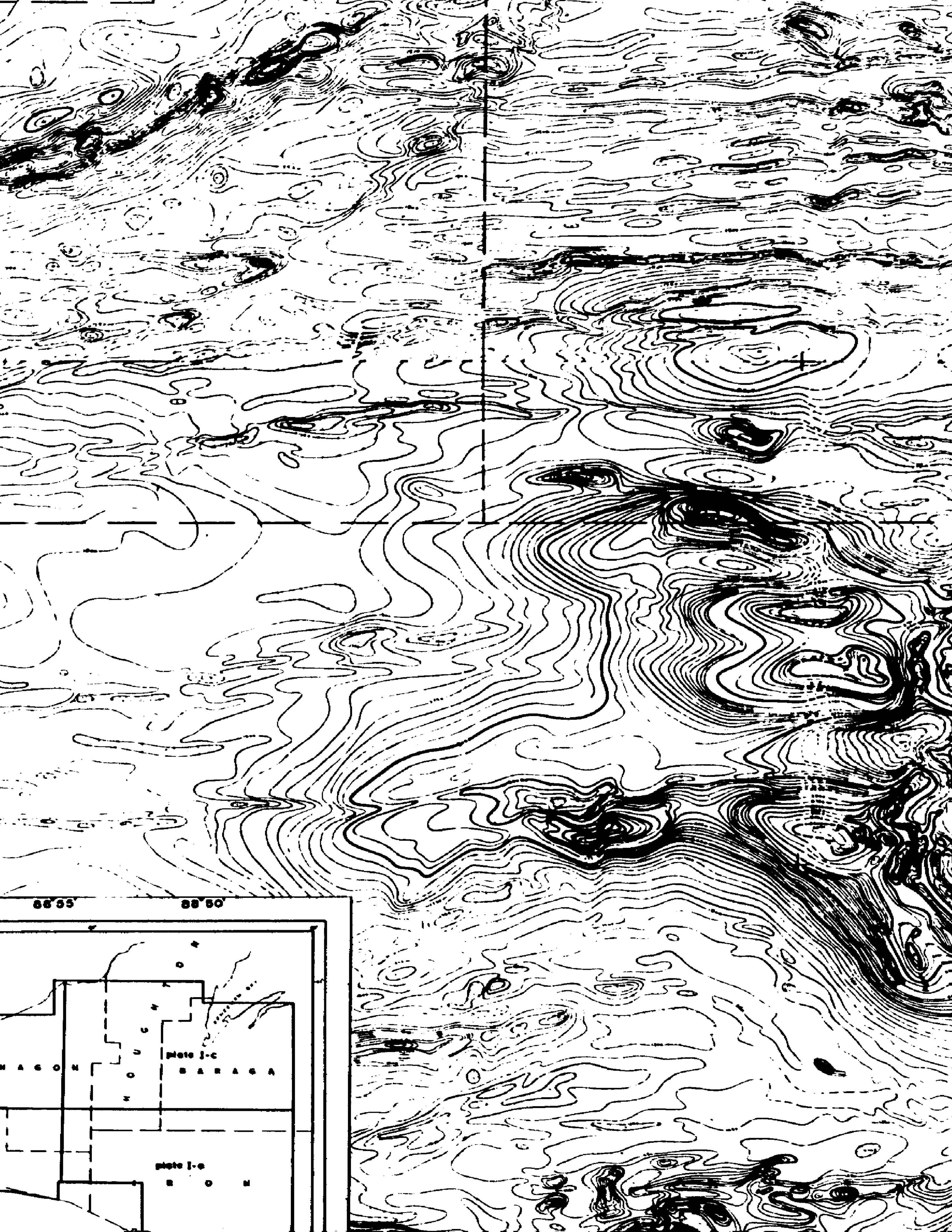


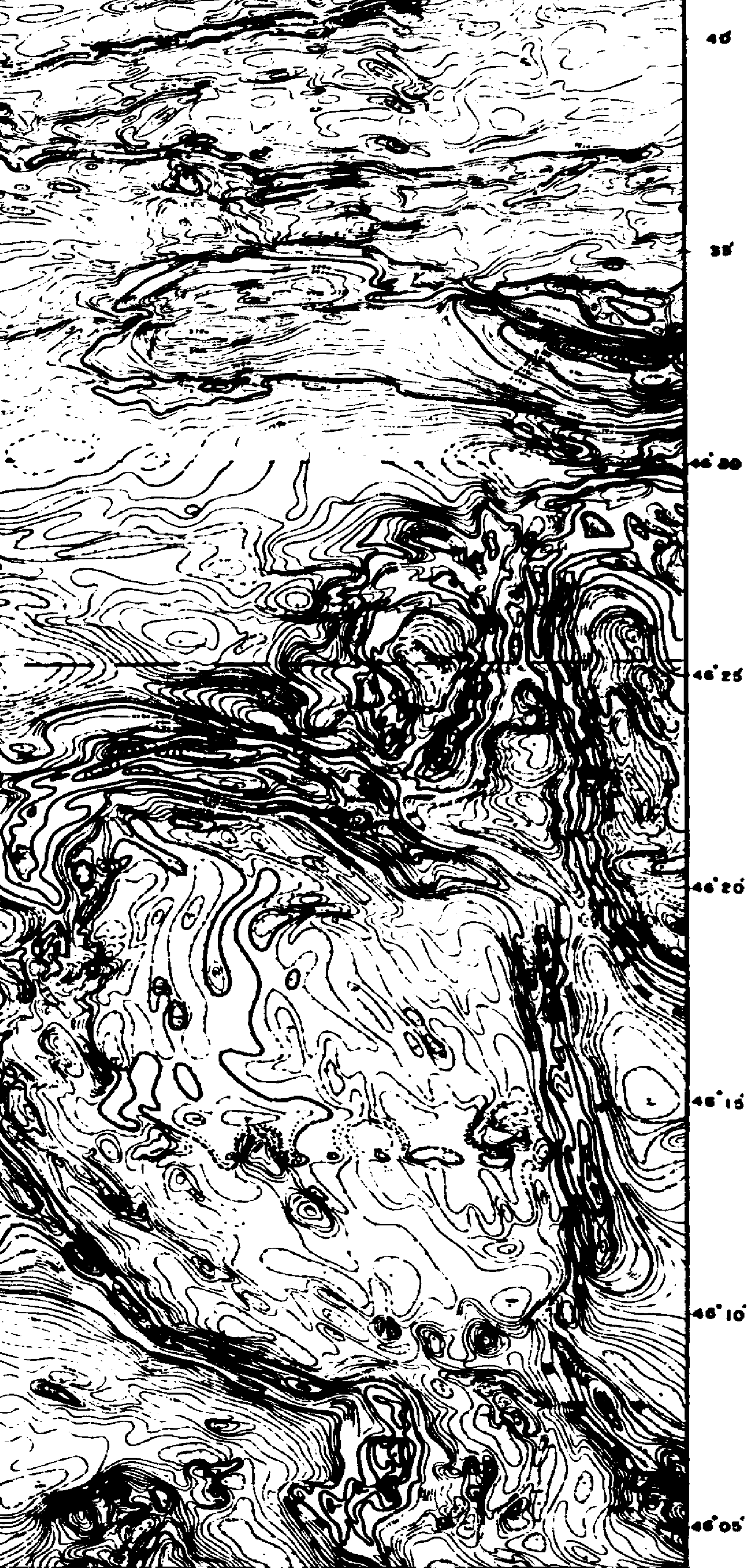
PLATE I-d

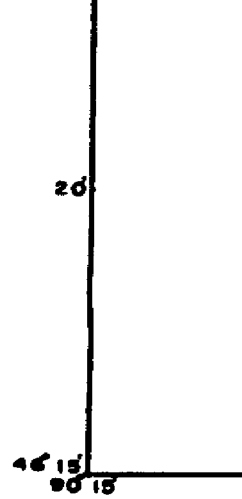


25
20
15
10
89°05'
89°00'
LAKE
SUPERIOR
plate 1-a
plate 1-b
plate 1-d
O N T O N
G O G E B I C
INDEX MAP FOR PLATE-1

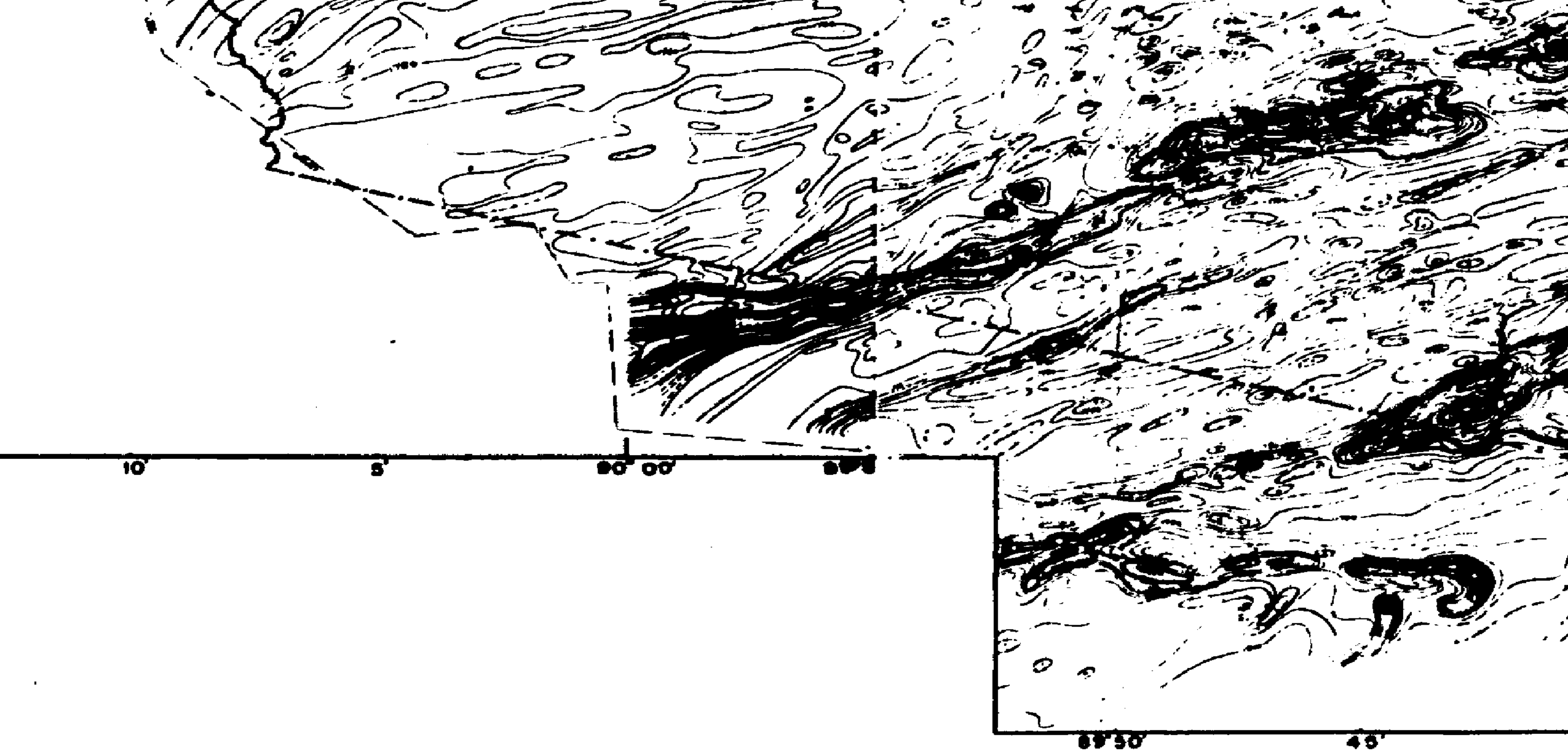


88°55'
88°50'
plate I-c
BARAGA
plate I-e
RON


40'
35'
46°30'
46°25'
46°20'
46°15'
46°10'
46°05'



20'
46°15'
90°15'


10'
5'
90°00'
89°50'
45'

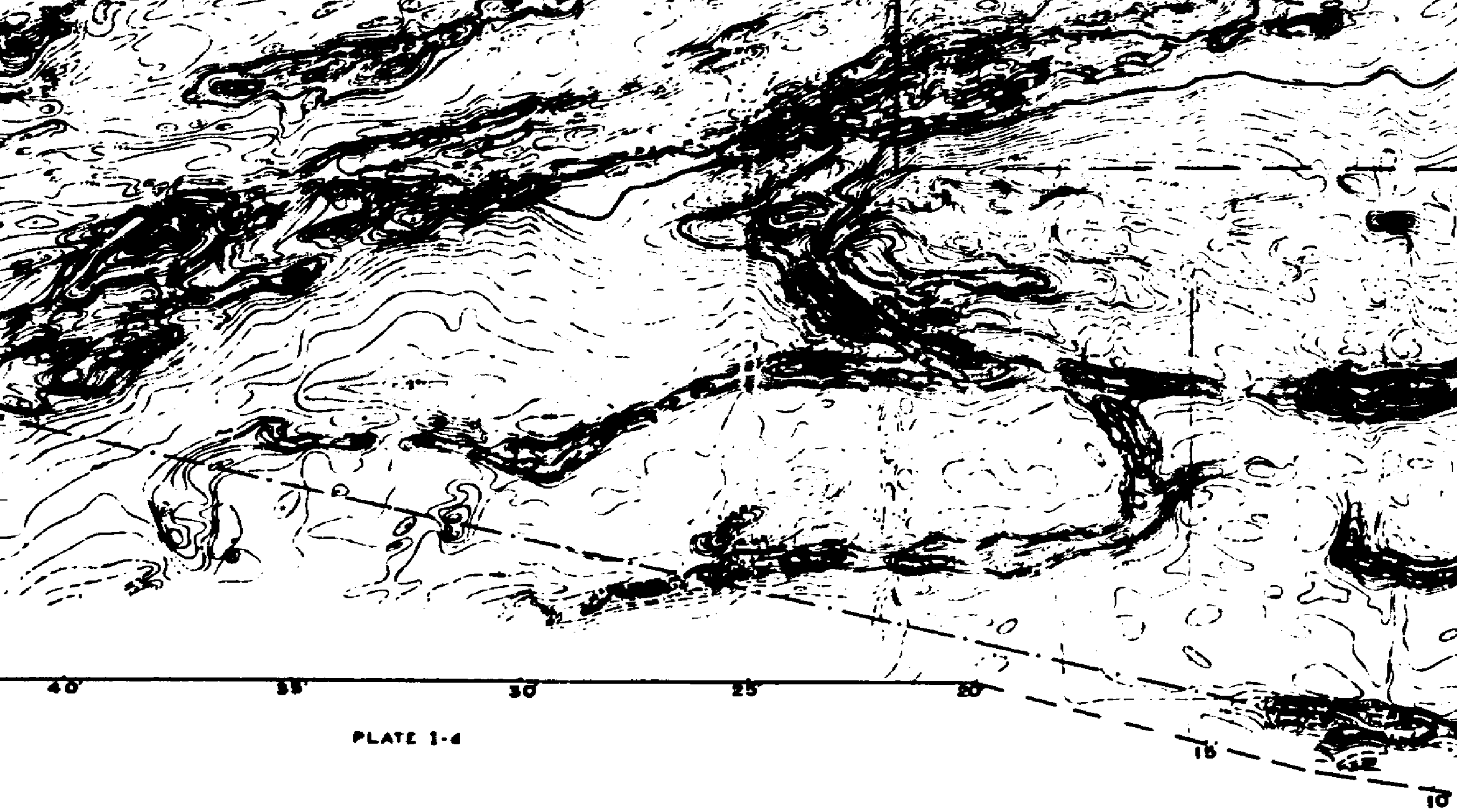
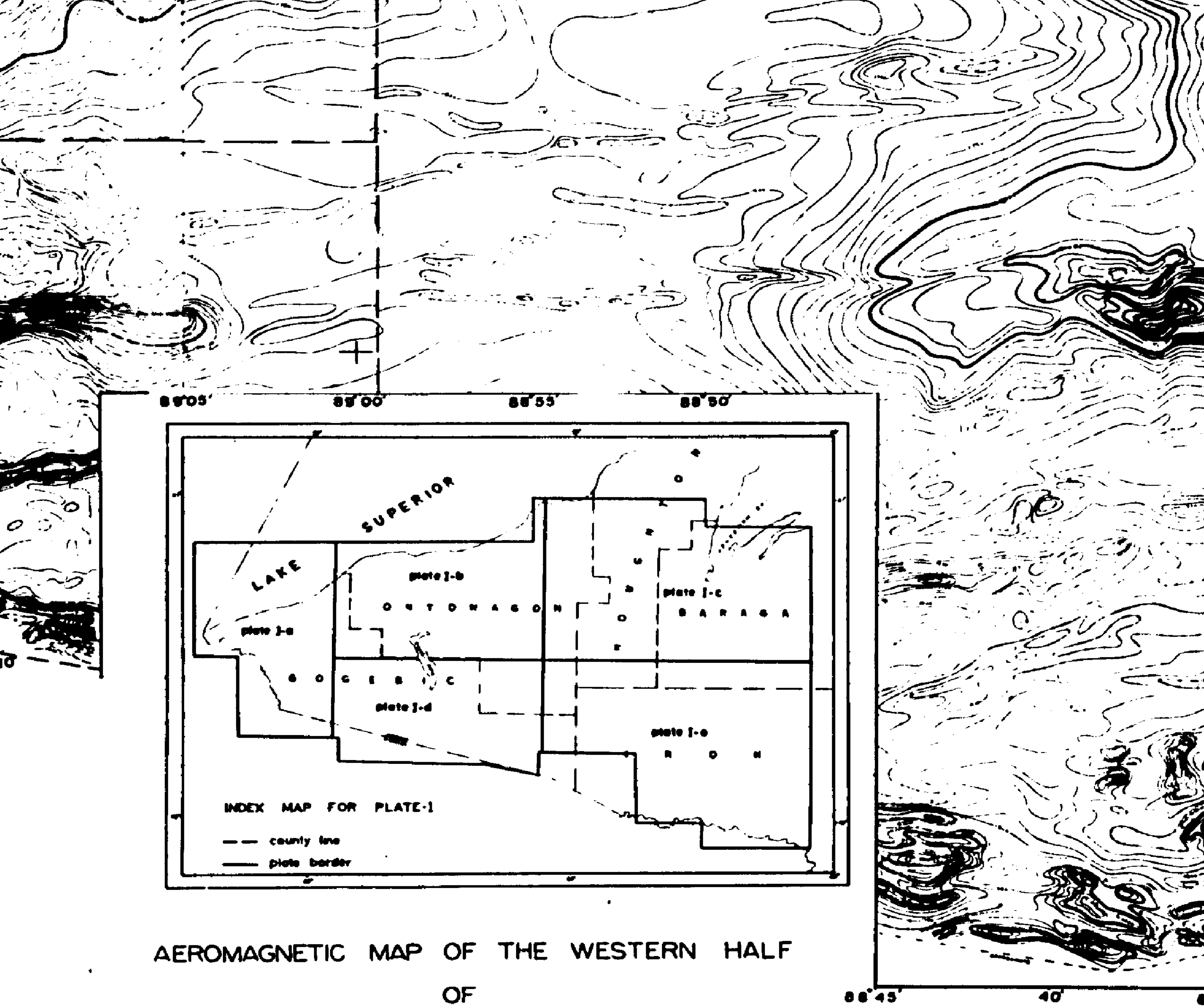


PLATE V



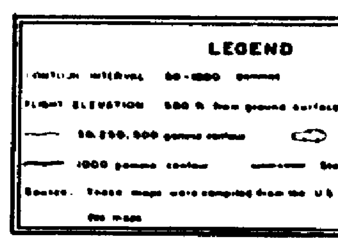
AEROMAGNETIC MAP OF THE WESTERN HALF

OF

THE NORTHERN PENINSULA OF MICHIGAN

SCALE

PLATE I-e



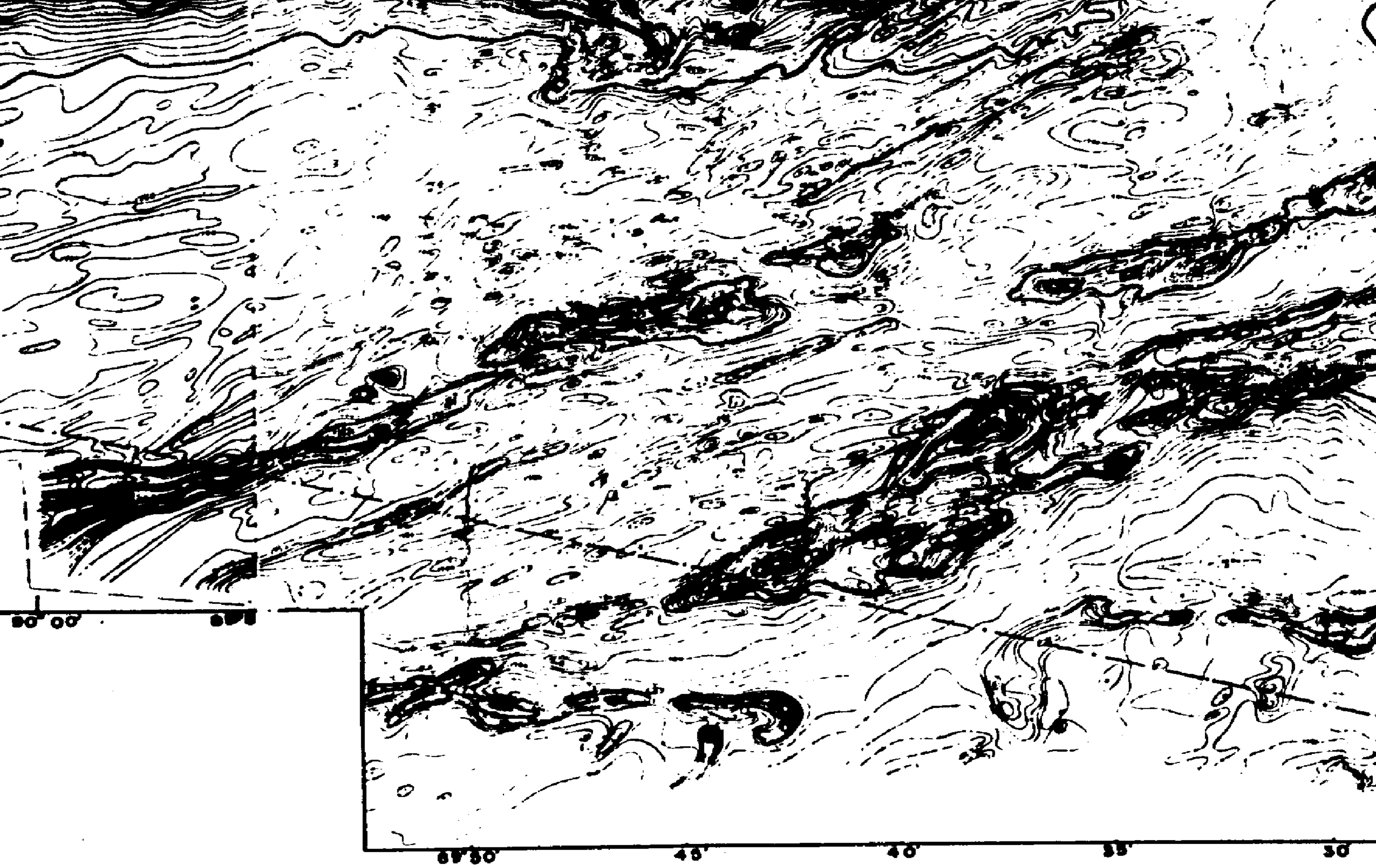
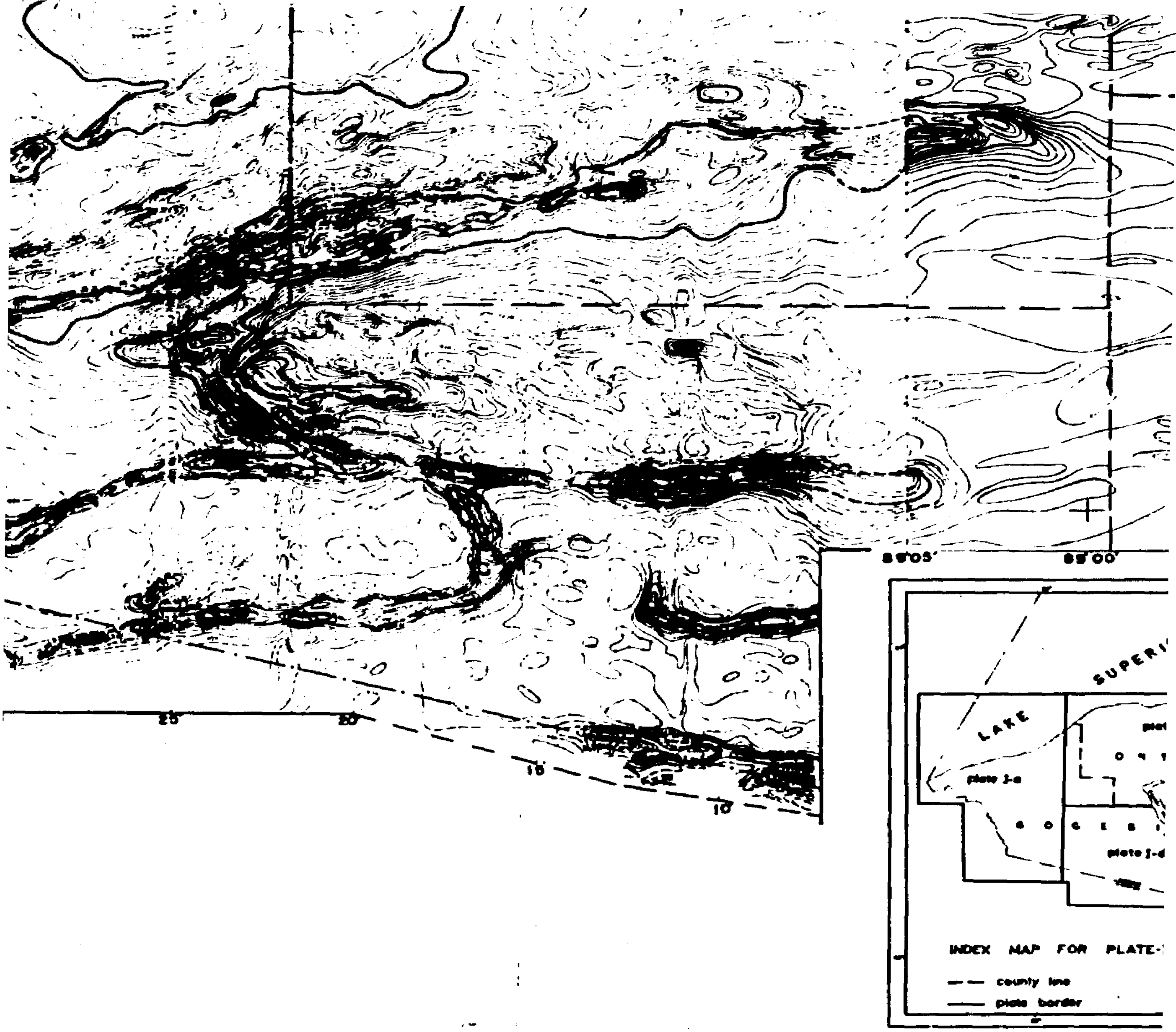


PLATE I-4

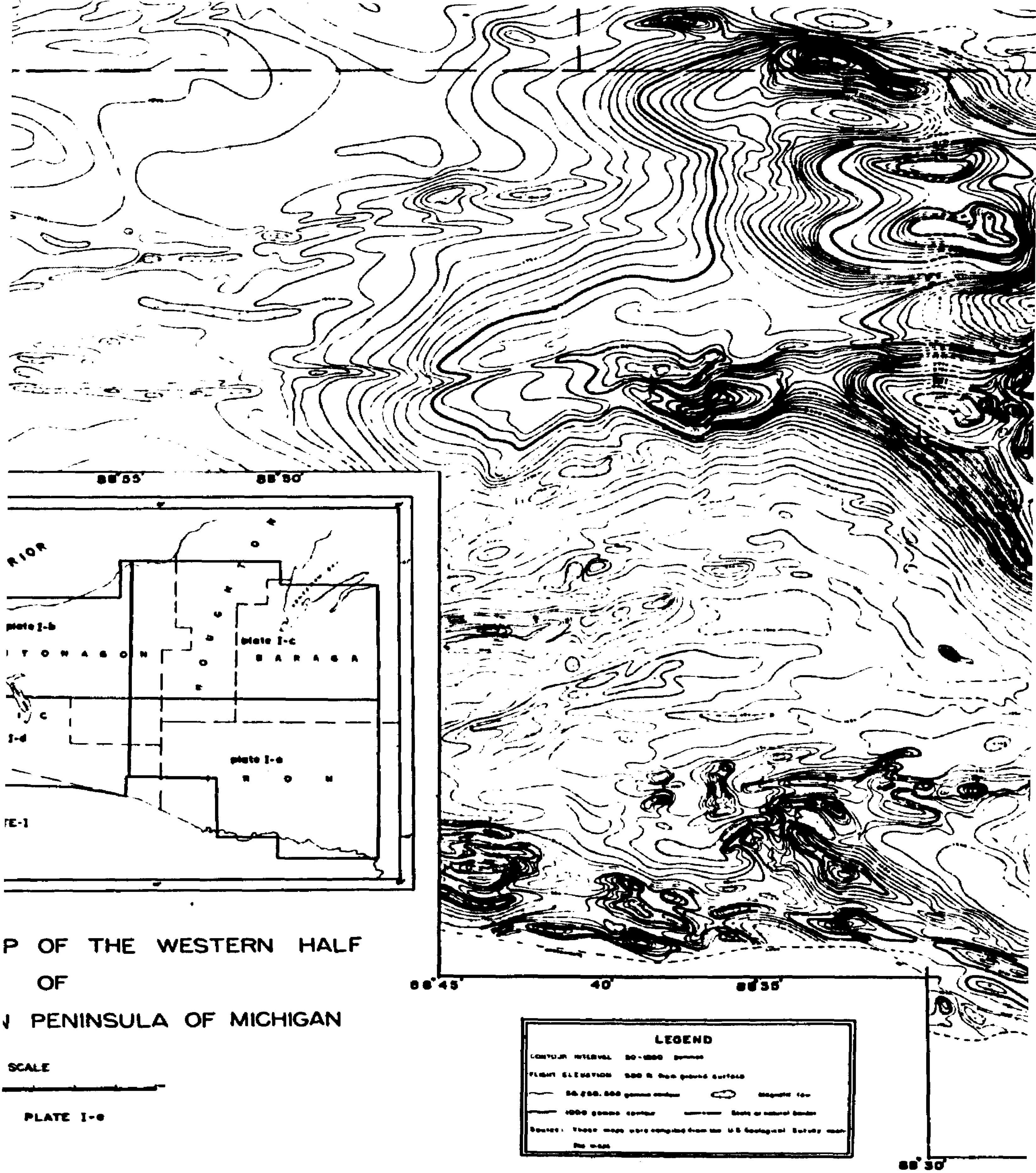
PLATE V



AEROMAGNETIC MAP

THE NORTHERN

SC



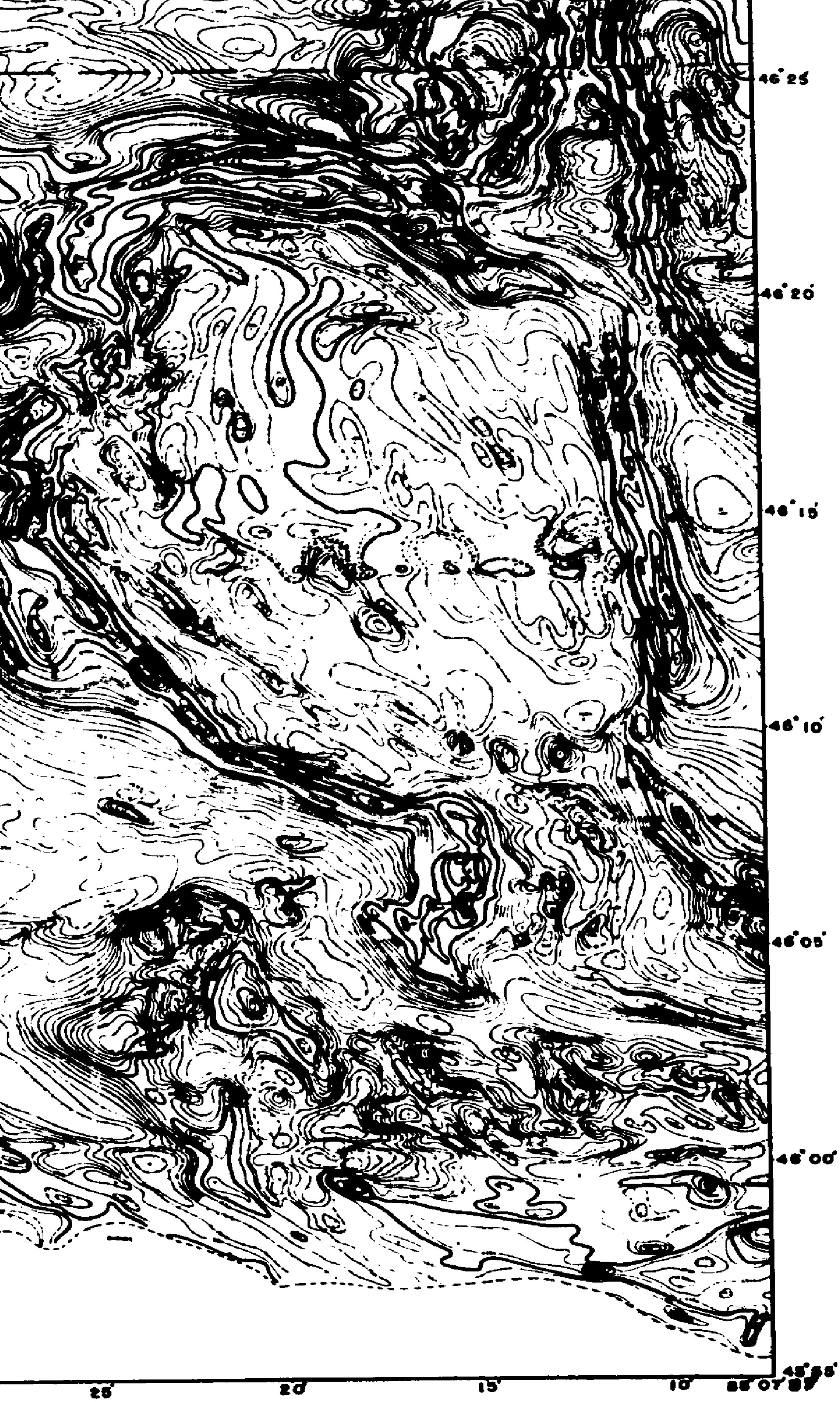
P OF THE WESTERN HALF

OF

N PENINSULA OF MICHIGAN

SCALE

PLATE I-e


46°25′
46°20′
46°15′
46°10′
46°05′
46°00′
45°55′
25′
20′
15′
10′
85°07′


90°25'
46°50'
20'
R 49 W
46°45'
T 50 N
40'
35'

PLATE II-4

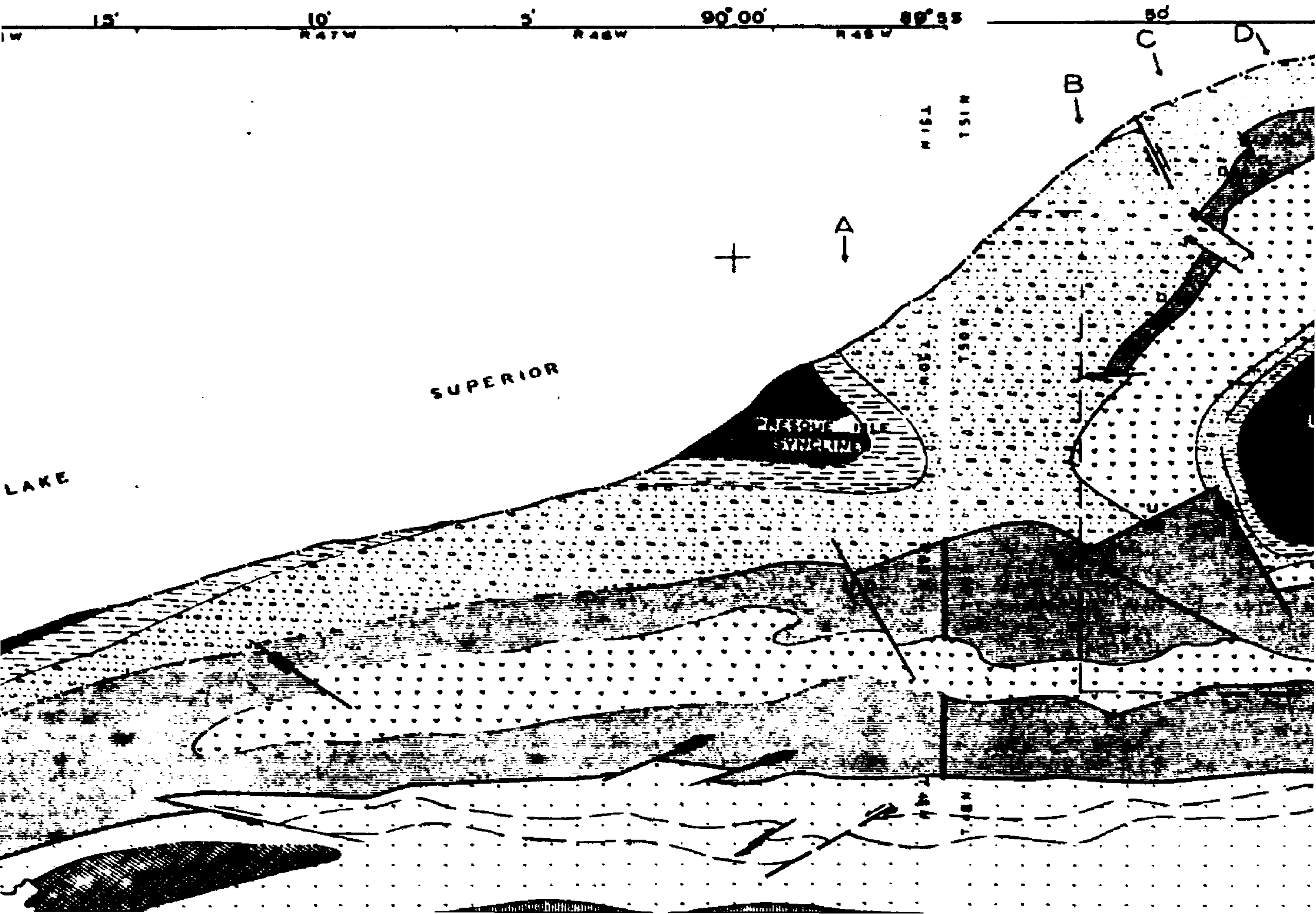
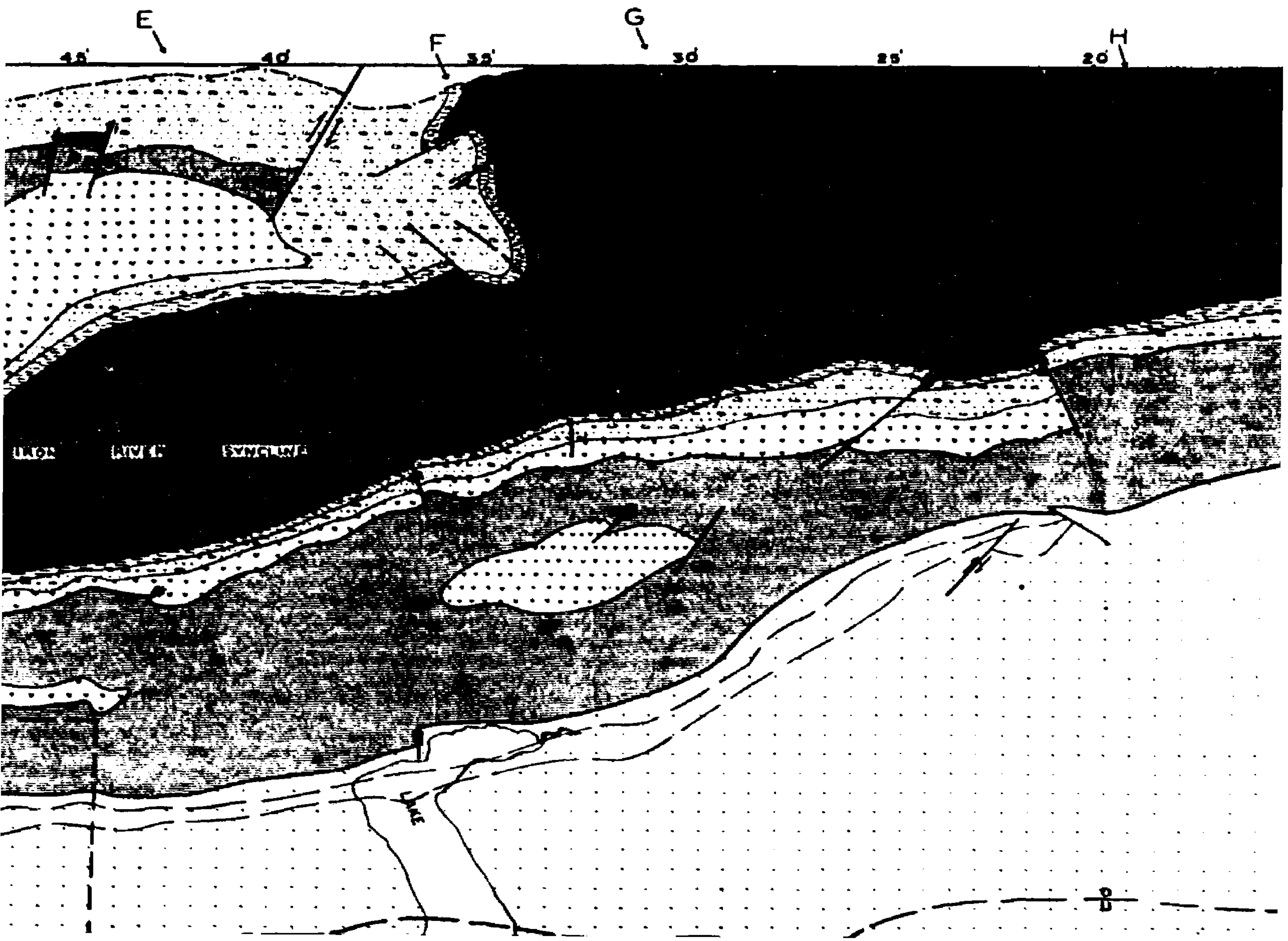
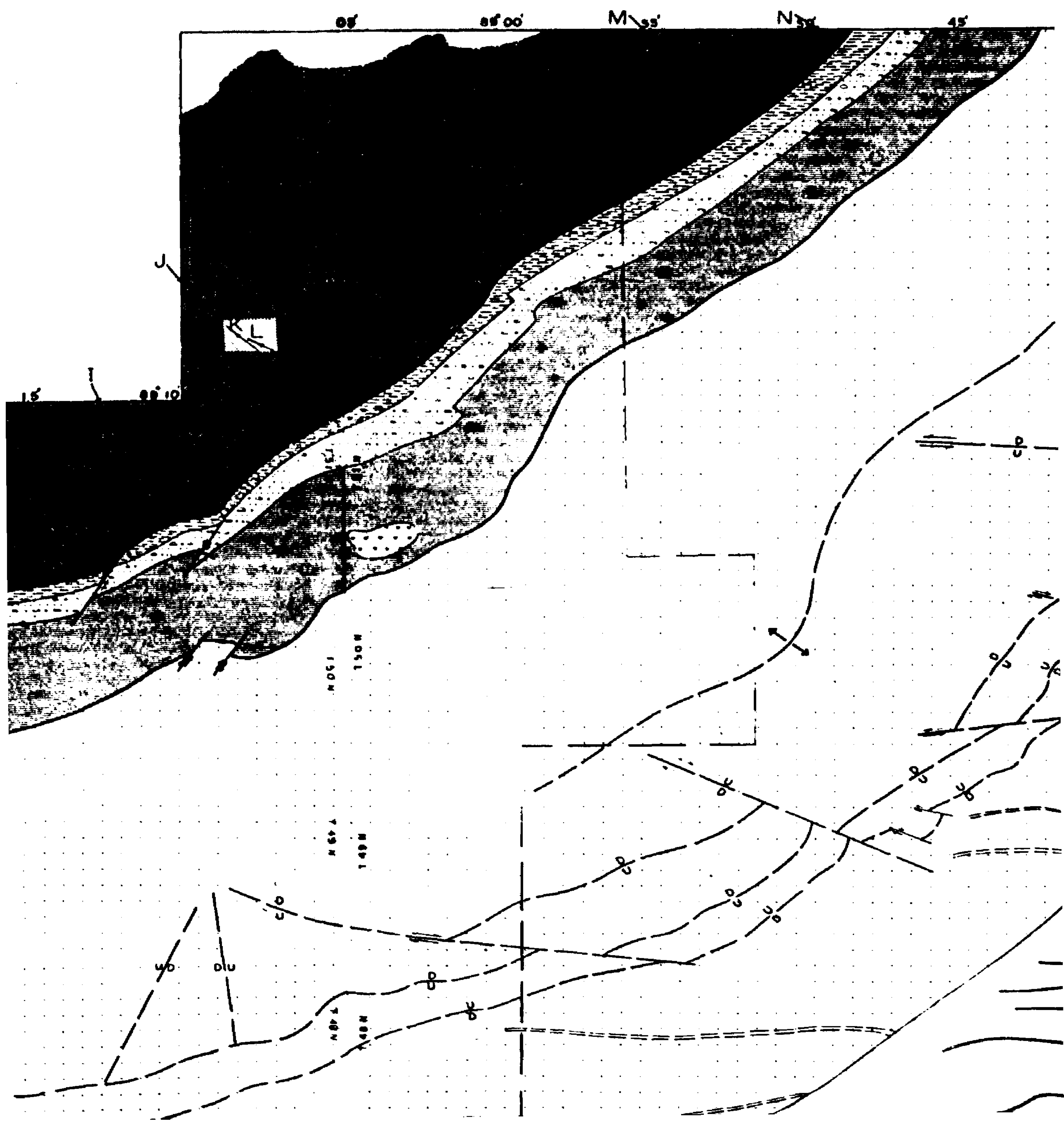

15'
10'
R47W
5'
R46W
90°00'
R45W
89°55'
50'
LAKE
SUPERIOR
PRESQUE ISLE SYNCLINE
A
B
C
D
T51N
T50N
T49N
T48N

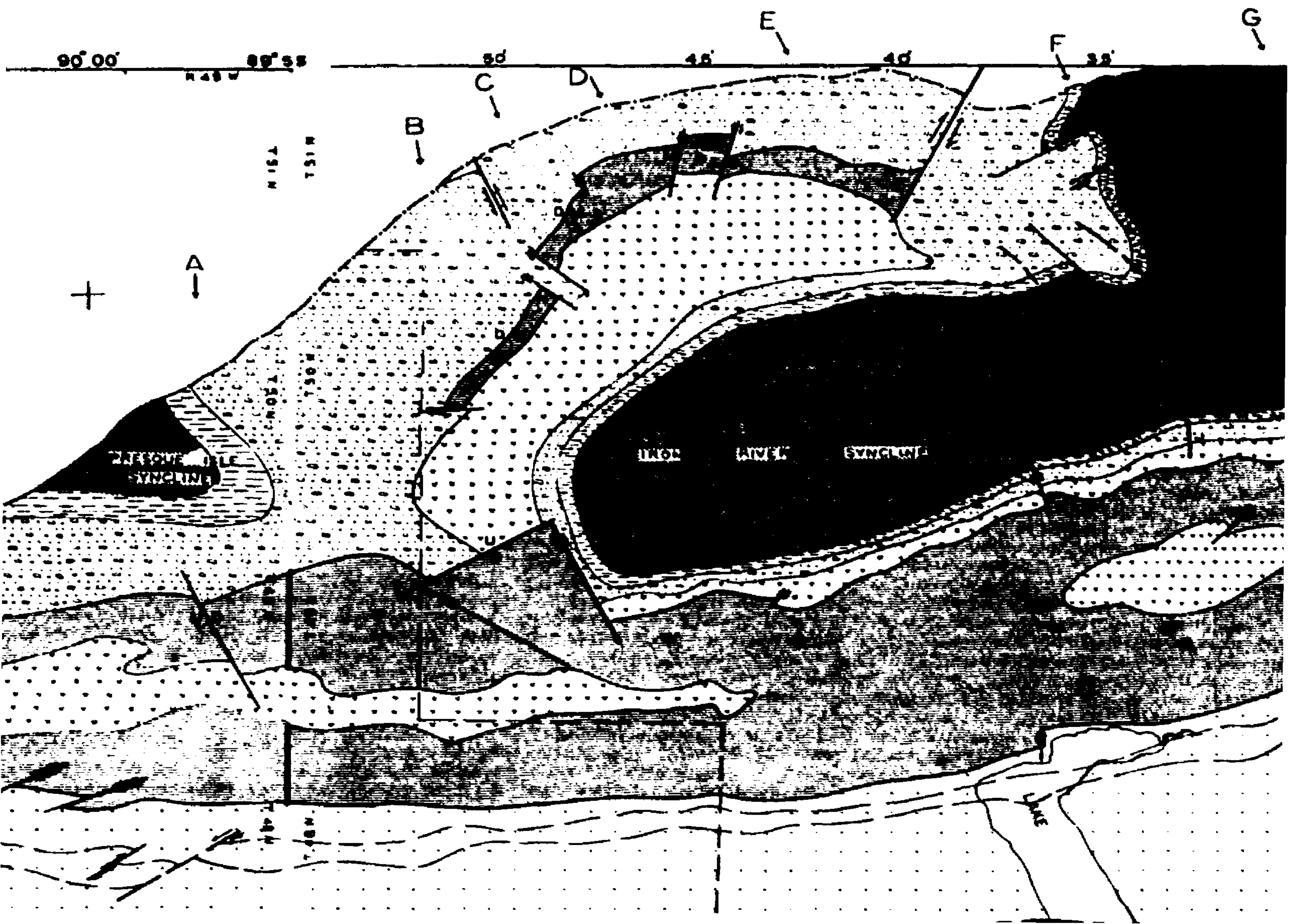
PLATE III-b



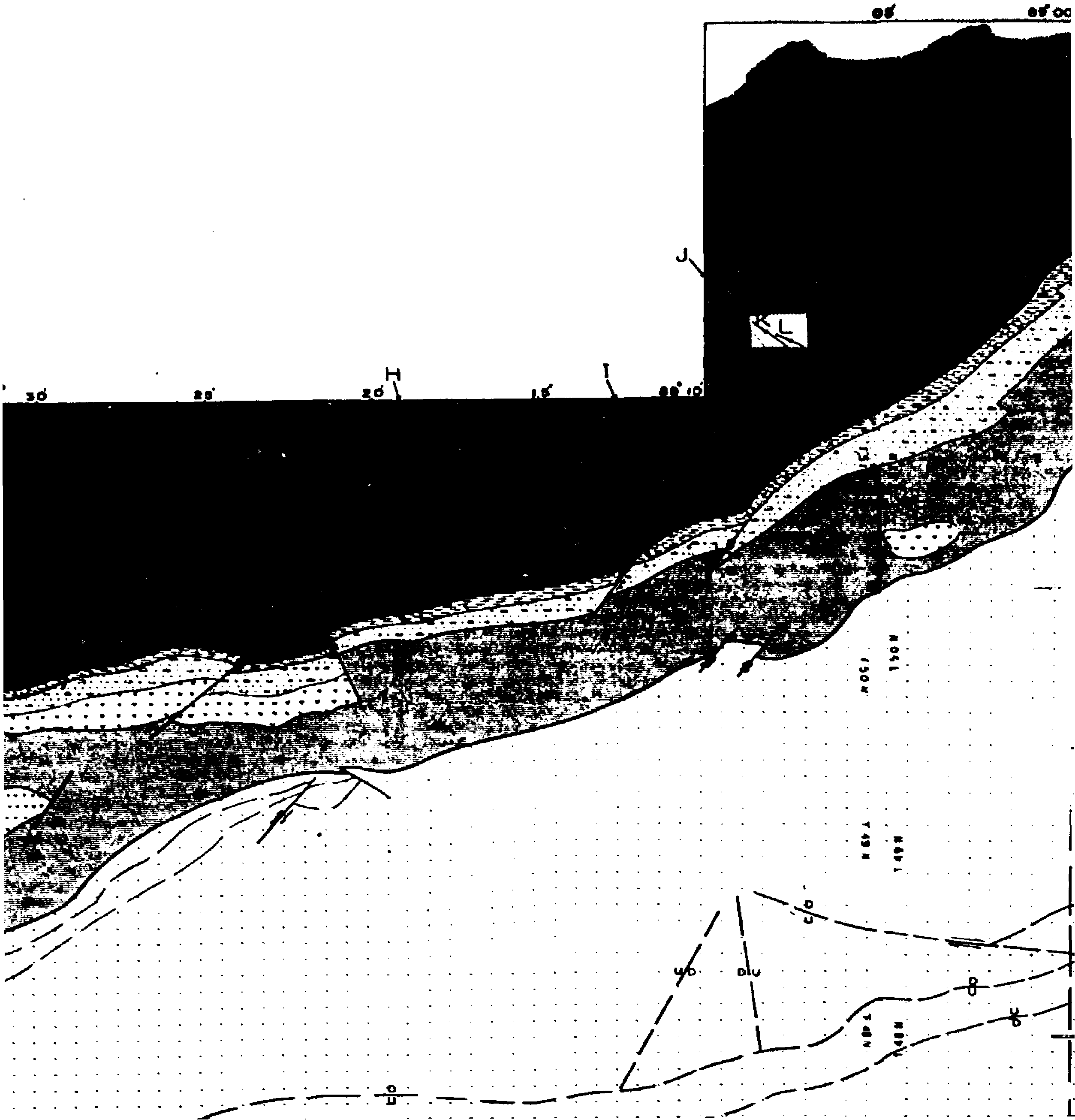


05'
88°00'
M
55'
N
50'
45'
J
K
L
I
15'
88°10'
T 50N
T 49N
T 48N
T 40N
T 49N
D/U
U/D
D
U

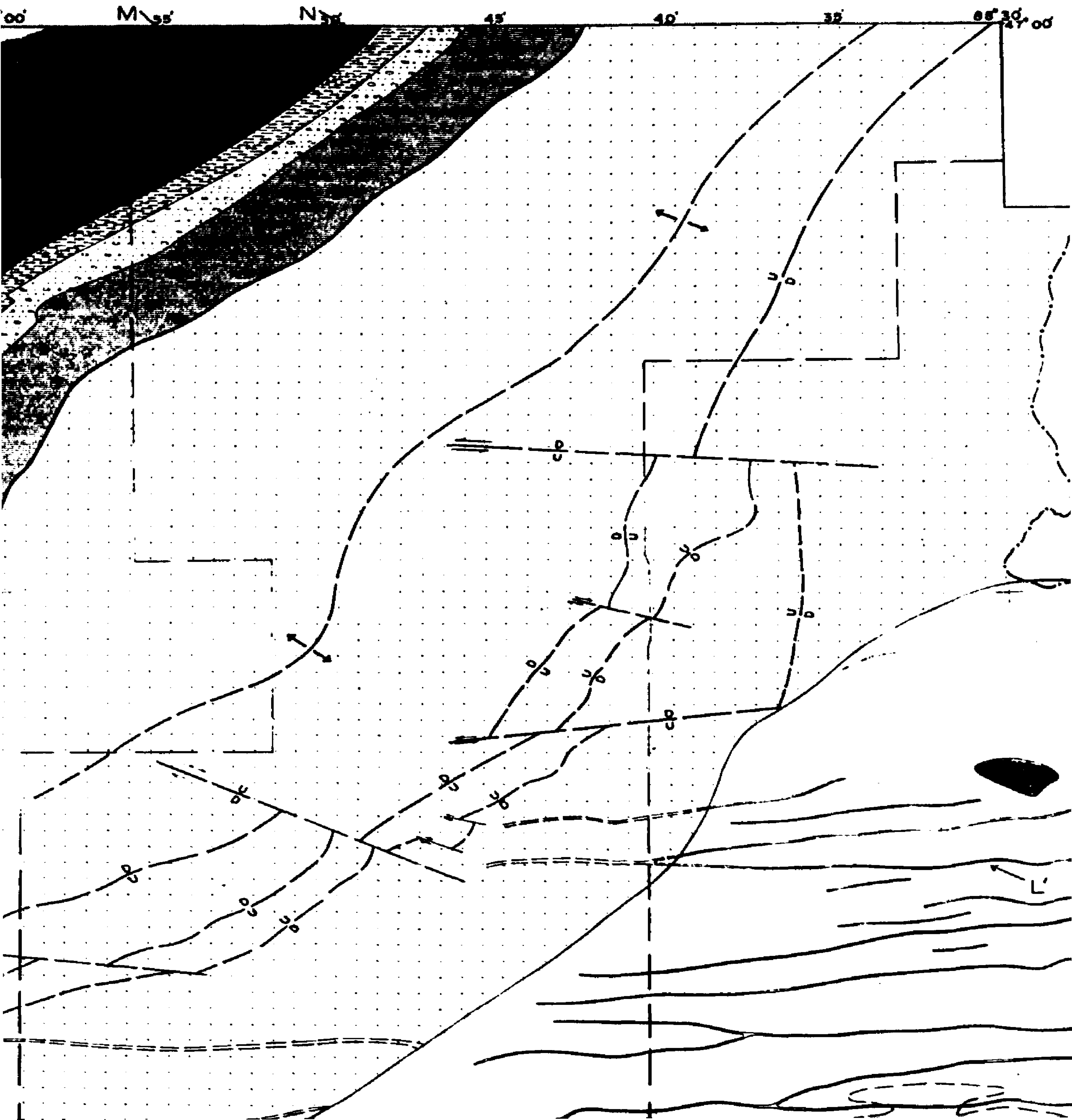
PLATE III-6



A
B
C
D
E
F
G
90°00'
89°55'
50'
45'
40'
35'
R 43 W
T 51 N
T 50 N
T 49 N
PRESQUE ISLE SYNCLINE
IRON RIVER SYNCLINE
LAKE

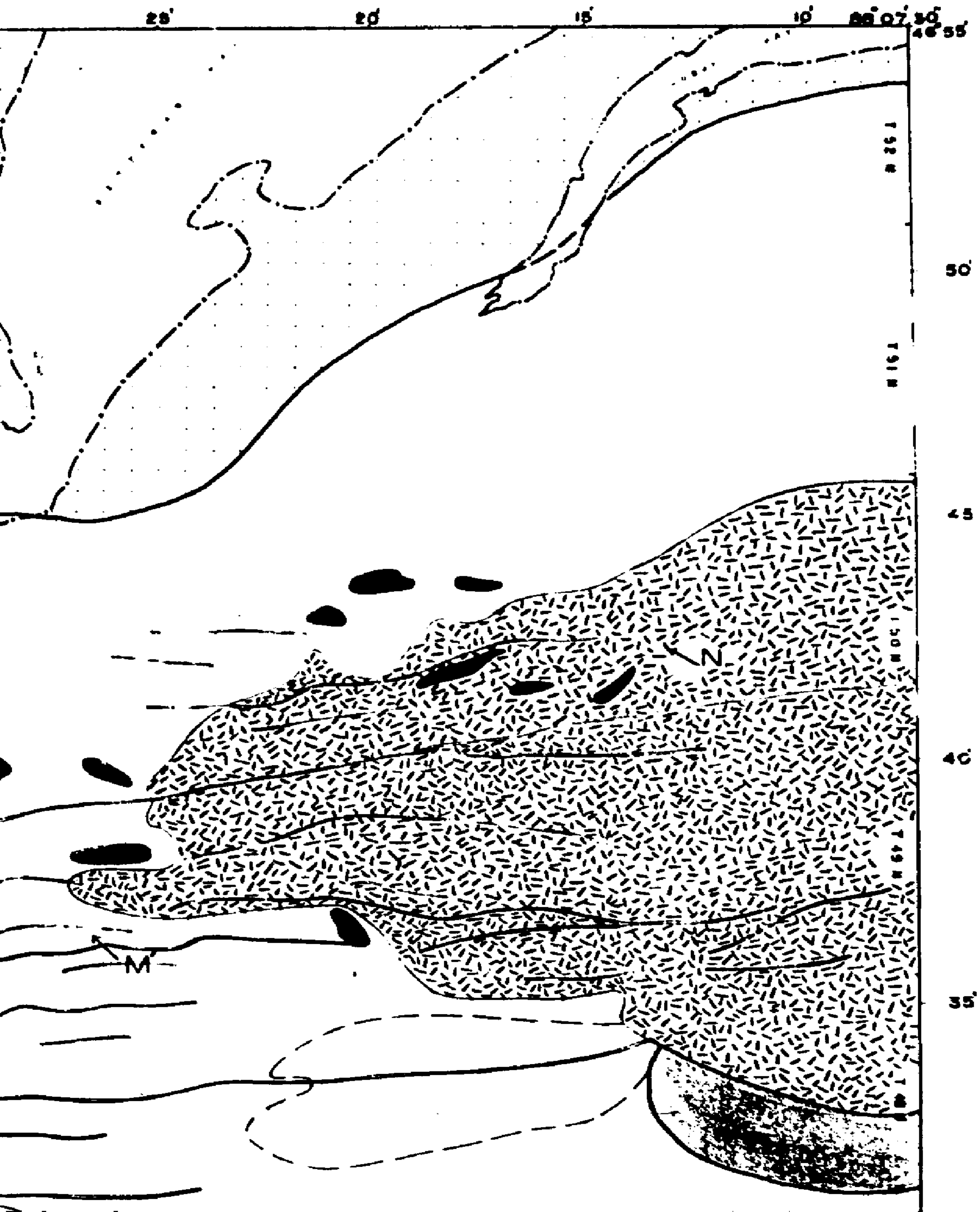


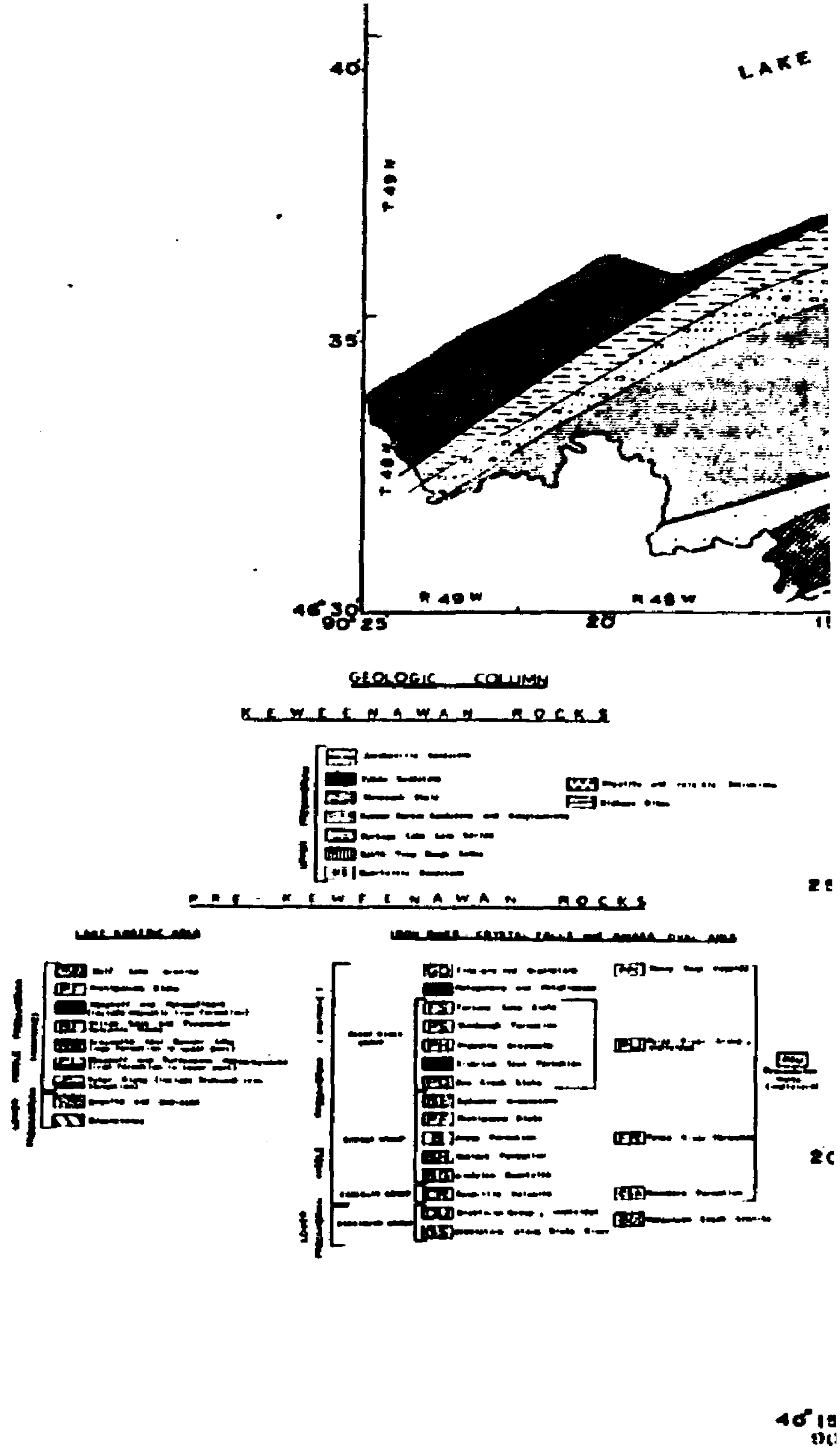
05'
J
K
L
H
I
30'
25'
20'
15'
U/D
D/U

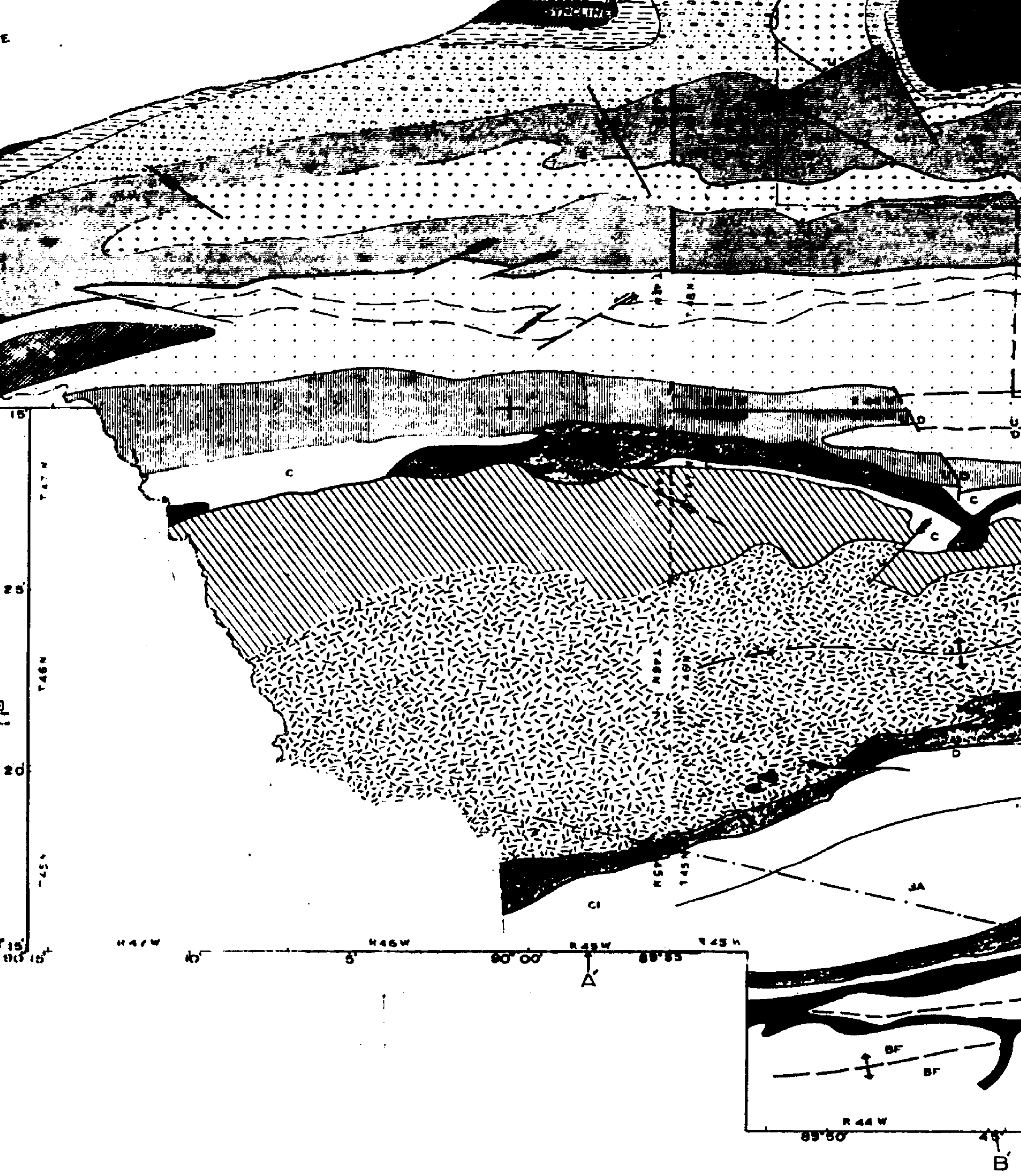


00'
M
55'
N
50'
45'
40'
35'
88°30'
47°00'
L'

PLATE III-c




LAKE
40'
T 49 N
35'
T 48 N
46°30'
90°25'
R 49 W
R 48 W
20
GEOLOGIC COLUMN
KEWEENAWAN ROCKS
PRE - KEWEENAWAN ROCKS
46°15'


SYNCLINE
15'
25'
20'
15'
T 47 N
T 46 N
T 45 N
C
C
C
D
D
D
U
CI
JA
BF
BF
R 47 W
R 46 W
R 45 W
R 44 W
10'
5'
90°00'
89°55'
89°50'
45'
A'
B'


LAKE
BOSEBIC
R 43 W
R 42 W
R 41 W
R 40 W
C
CL
BA
BF
D
PF
40
35
30
25
20
B'
C'
D'
E'
F'

PLATE III-d

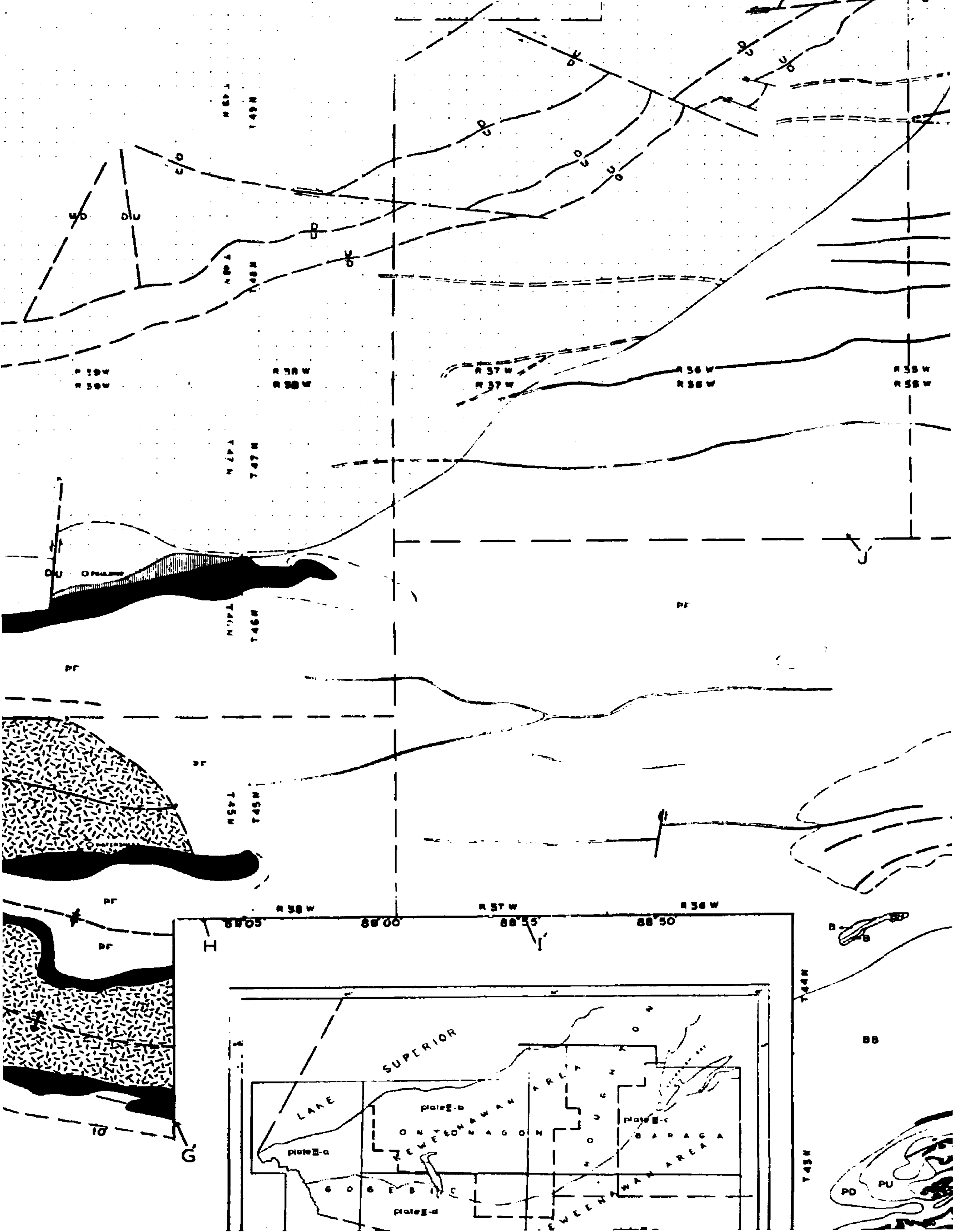
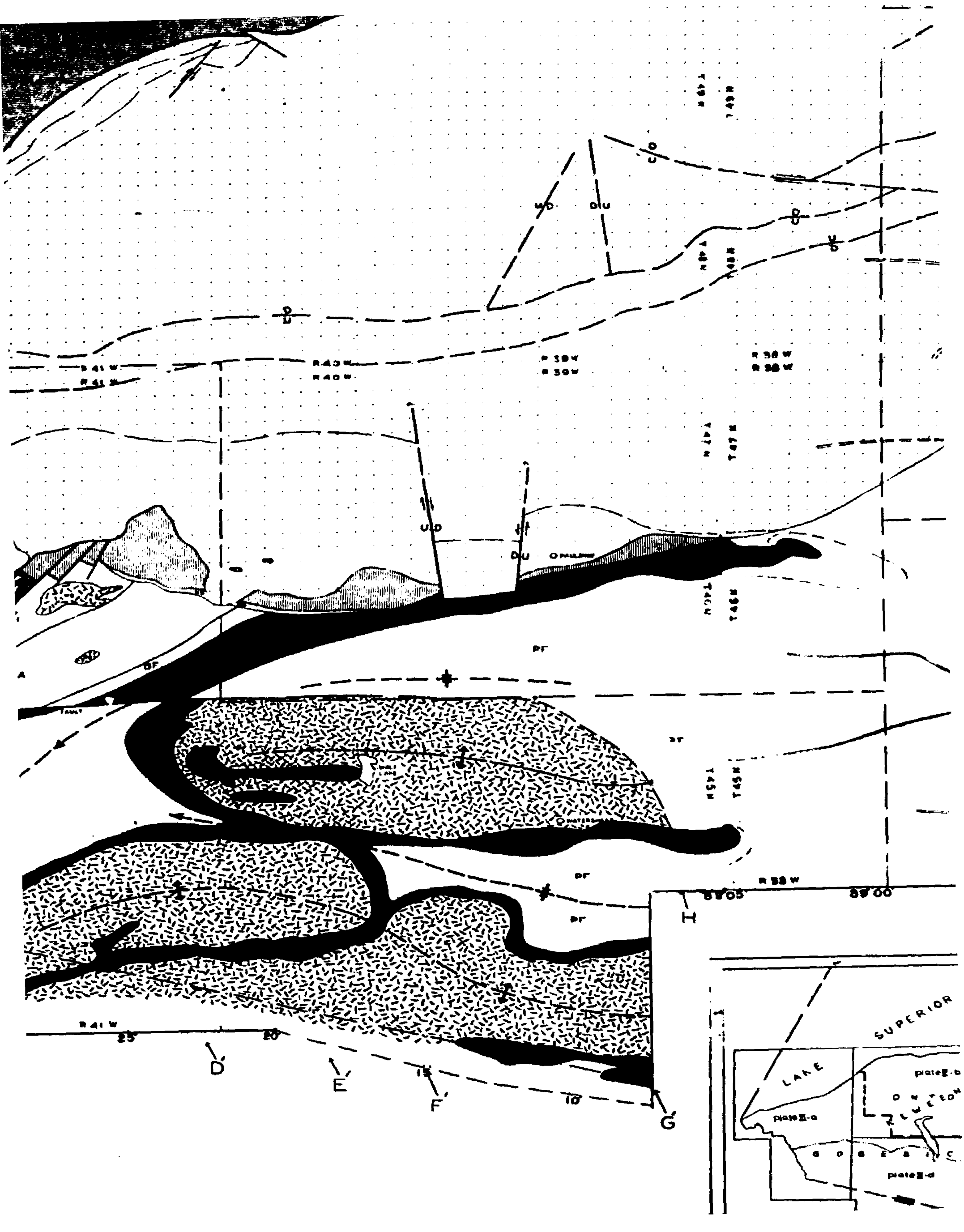
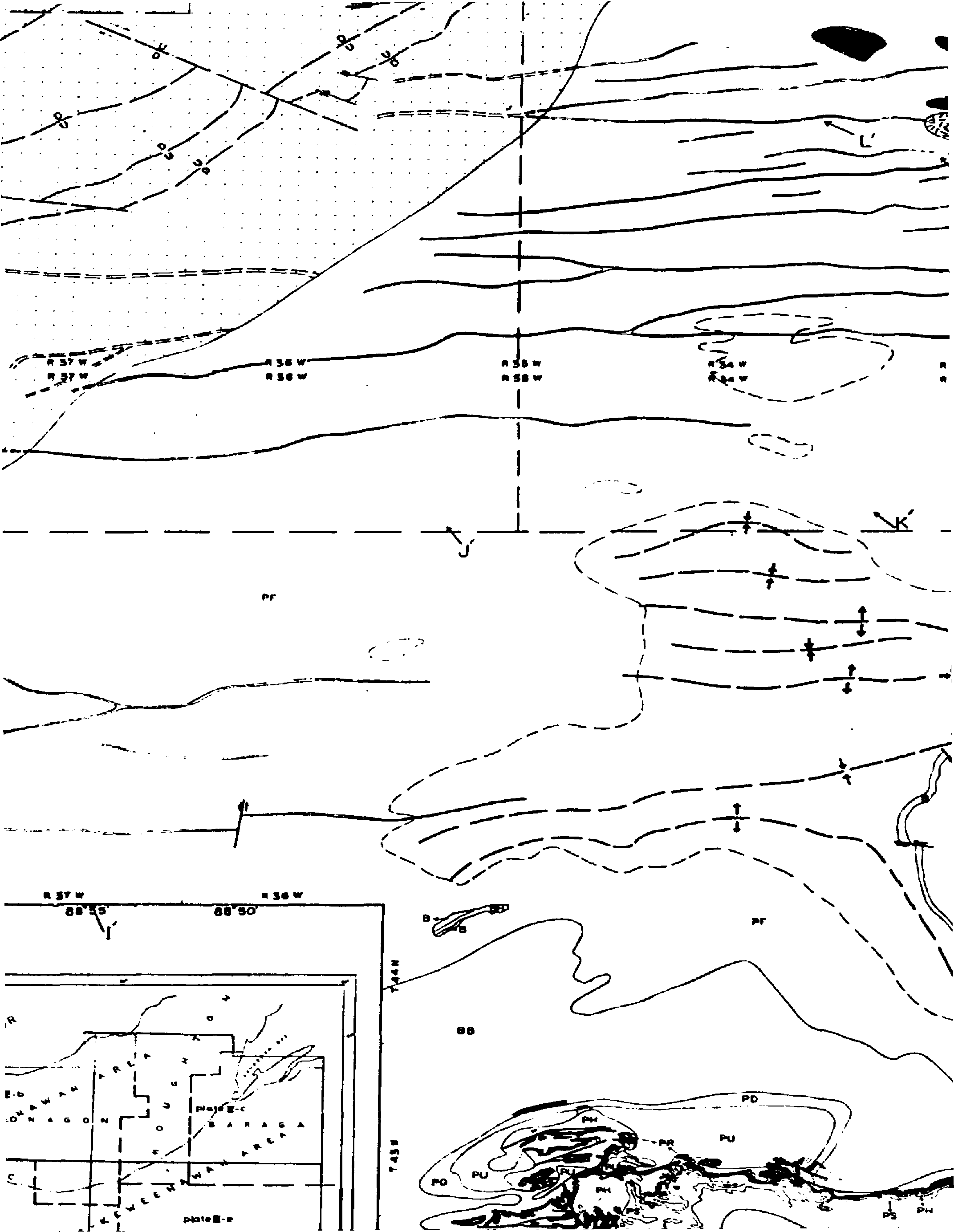

T 49 N
T 49 N
D U
D U
D U
T 48 N
T 48 N
R 39 W
R 39 W
R 38 W
R 38 W
R 37 W
R 37 W
R 36 W
R 36 W
R 35 W
R 35 W
T 47 N
T 47 N
D U
J'
PF
T 46 N
T 46 N
PF
T 45 N
T 45 N
PF
PF
R 38 W
R 37 W
R 36 W
88°05'
89°00'
88°55'
88°50'
H
I'
G'
B
BB
T 44 N
T 43 N
PD
PU
LAKE
SUPERIOR
plate III-a
plate III-b
plate III-c
plate III-d
ONTONAGON
BARAGA
GOGEBIC
HOUGHTON
KEWEENAWAN AREA

PLATE VI

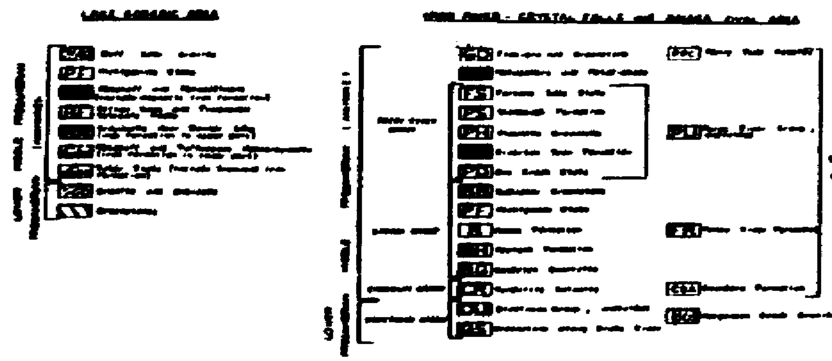

R 41 W
R 40 W
R 39 W
R 38 W
PF
DF
A
U D
D U
89 05
89 00
H
D
E
F
G
25
20
15
10
LAKE
SUPERIOR
plate III-a
plate III-b
plate III-d
GOGEBIC

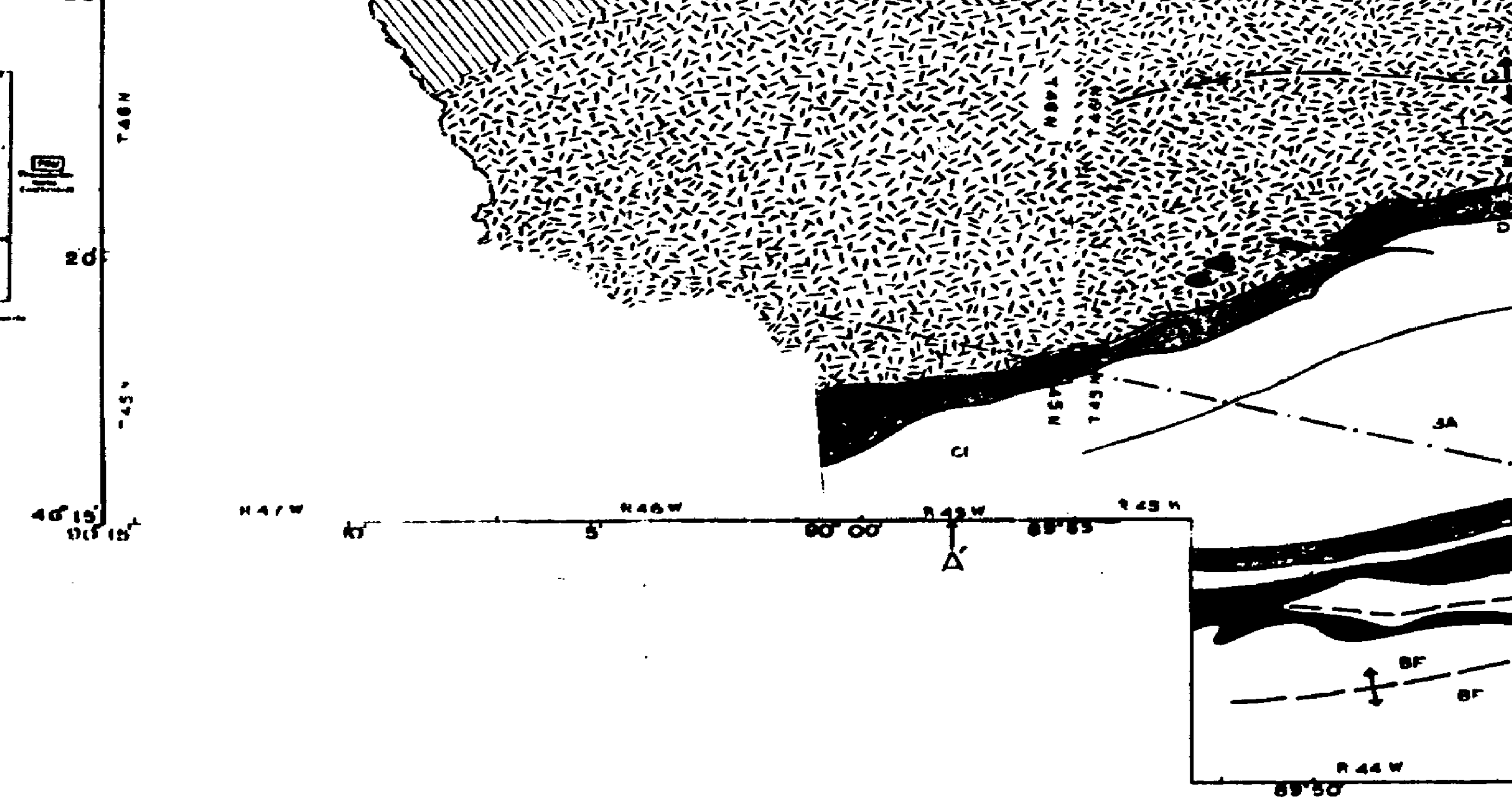


L'
R 57 W
R 56 W
R 55 W
R 54 W
K'
J'
PF
R 57 W
R 56 W
88°55'
88°50'
I'
T 44 N
T 43 N
BB
PD
PH
PU
PR
PS
plate III-c
plate III-e
B A R A G A

40'
35'
R 33 W
R 33 W
R 32 W
R 32 W
R 31 W
R 31 W
46°30'
46°25'
46°20'
46°15'
46°10'
46°05'
T 47 N
T 46 N
T 45 N
T 44 N
PF
B
CR
BH
BB
PD
BS
CU

PRE-KEWEENAWAN ROCKS





T 46 N
20'
T 45 N
40°15'
R 47 W
R 46 W
R 45 W
R 44 W
10'
5'
90°00'
89°55'
89°50'
A'
CI
3A
BF

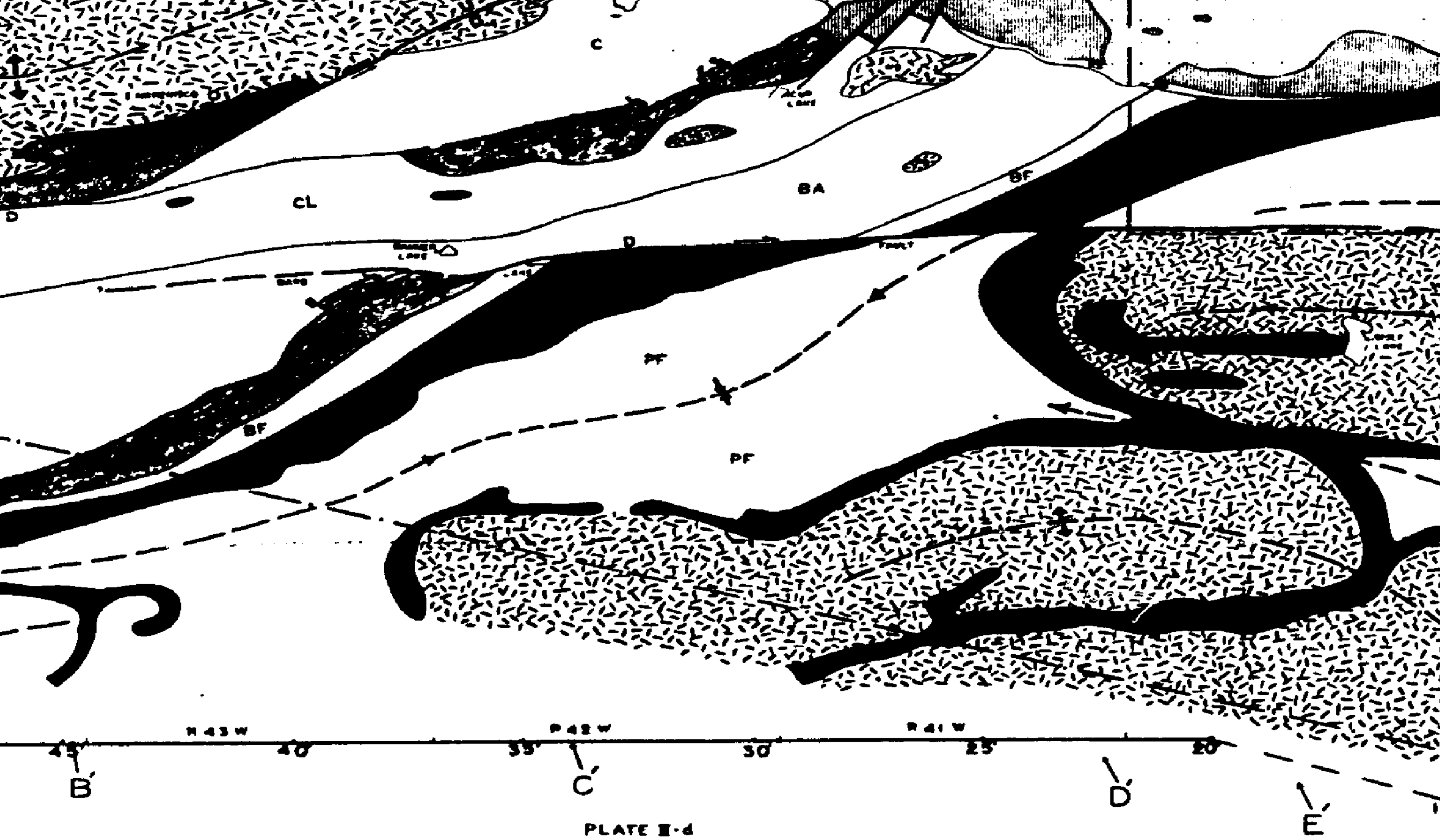
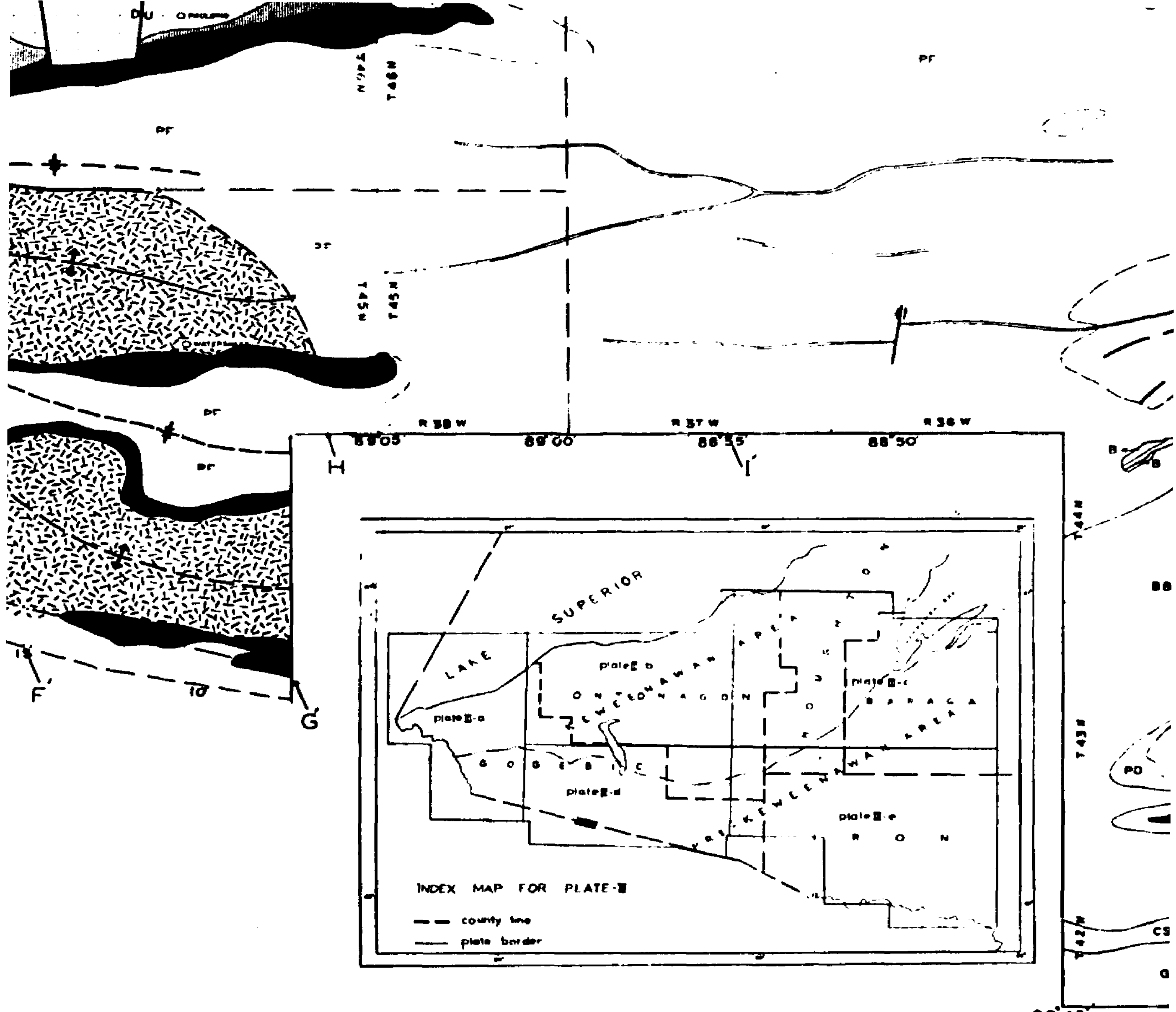


PLATE VI



BEDROCK GEOLOGY MAP

SCALE

PLATE III-a

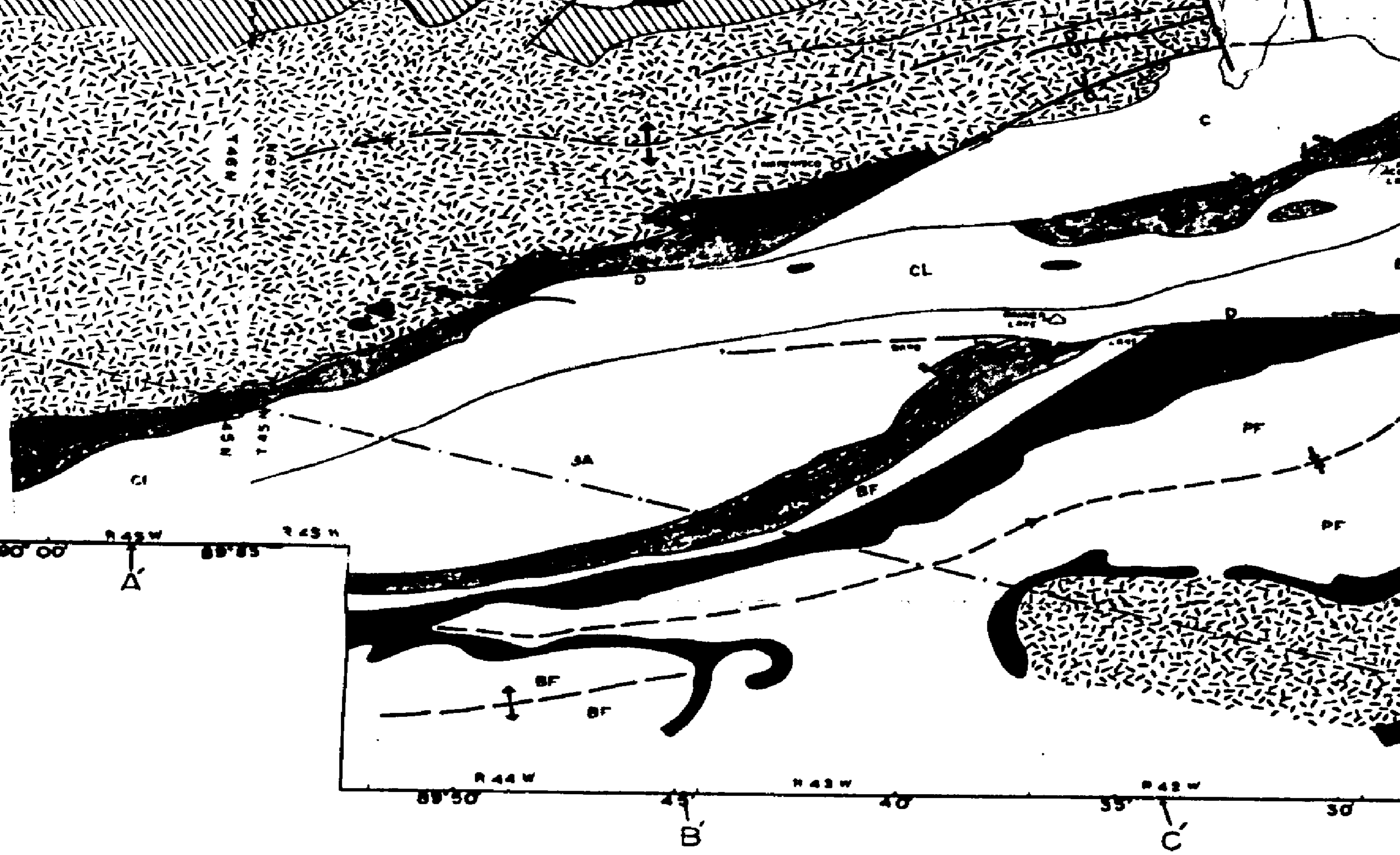
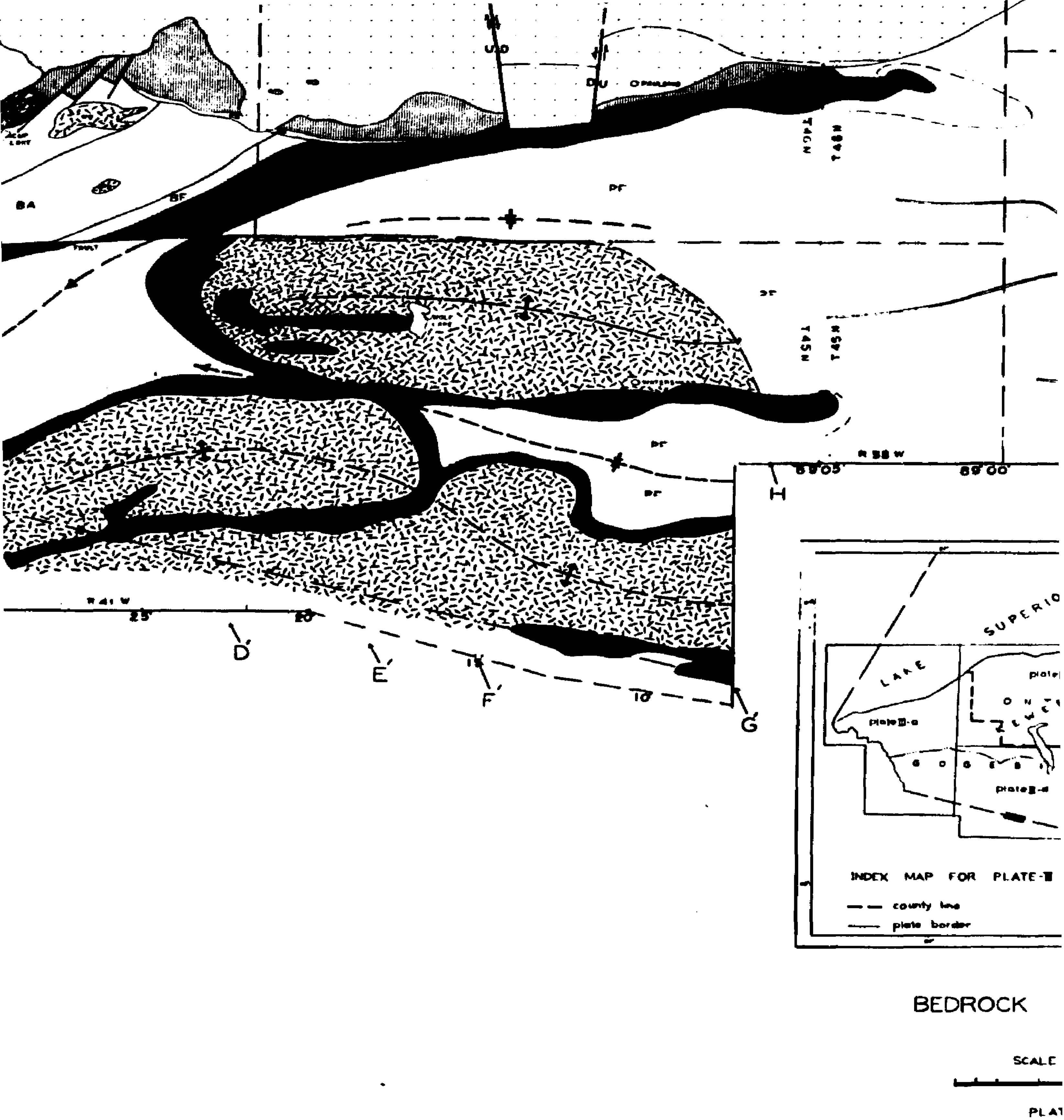
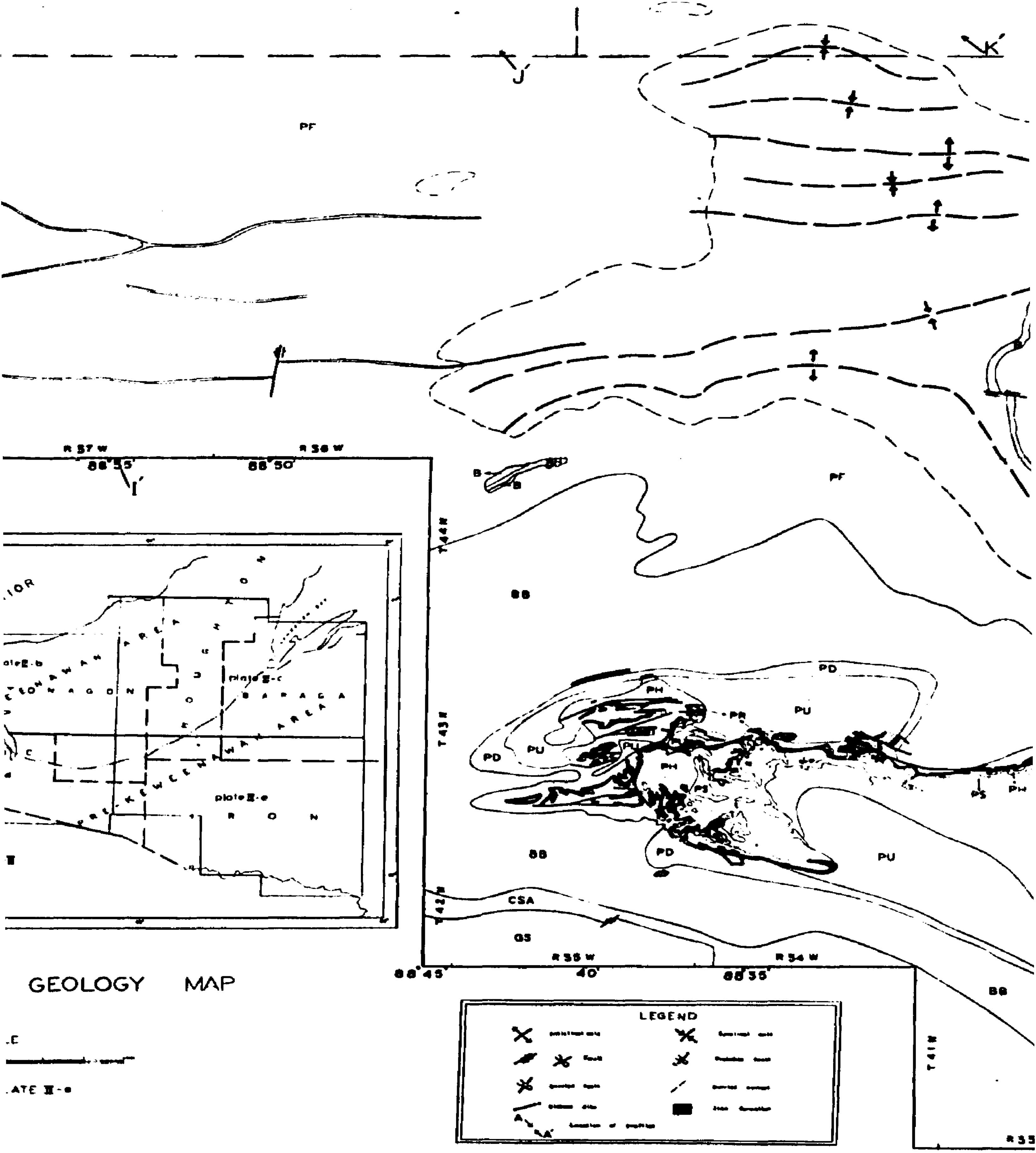


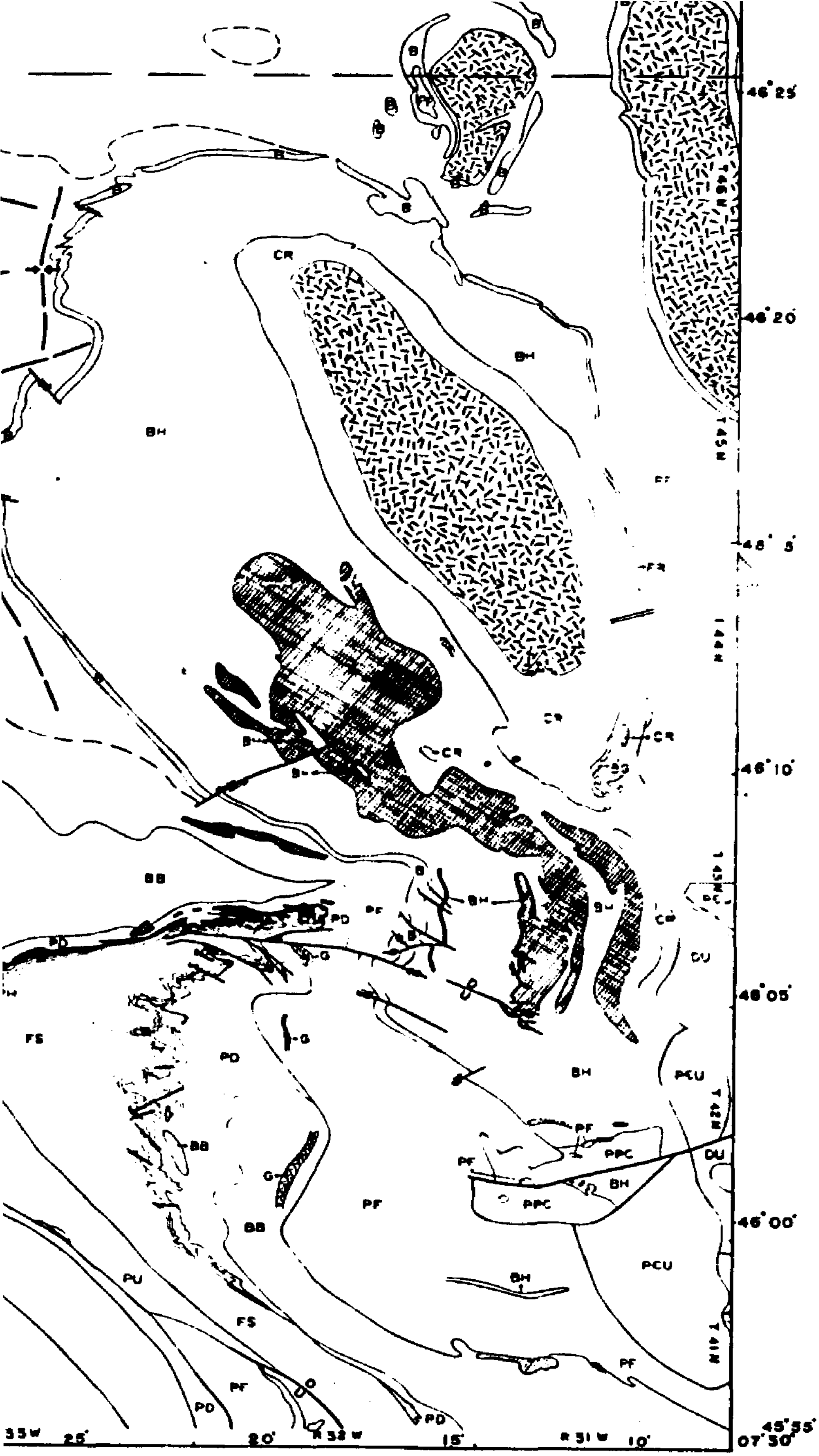
PLATE VI



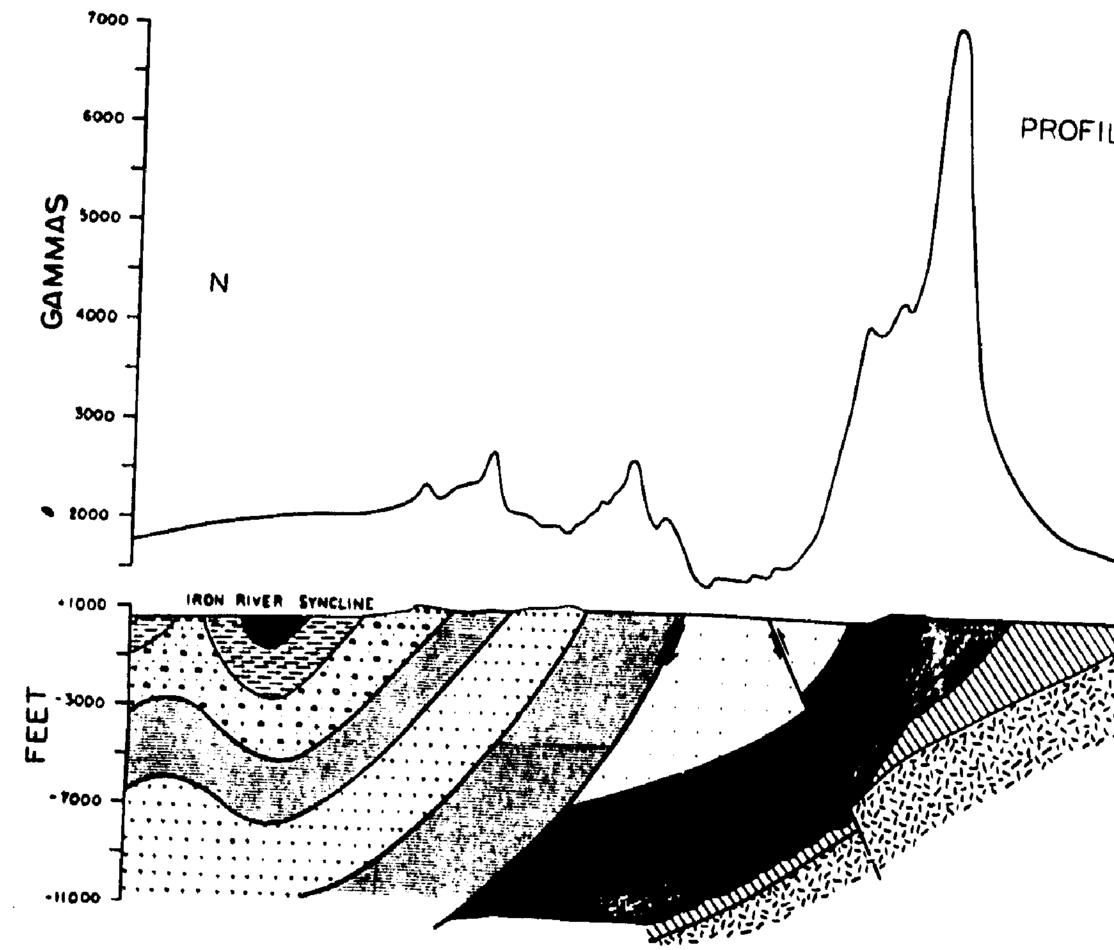
BA
BF
PF
FAULT
U D
D U
T46N
T46N
T45N
T45N
R 38 W
R 41 W
25
20
15
10
89°05'
89°00'
D
D'
E
E'
F
F'
G
G'
H
SUPERIO
LAKE
plate III-a
plate III-d
INDEX MAP FOR PLATE-III
county line
plate border
BEDROCK
SCALE
PLAT

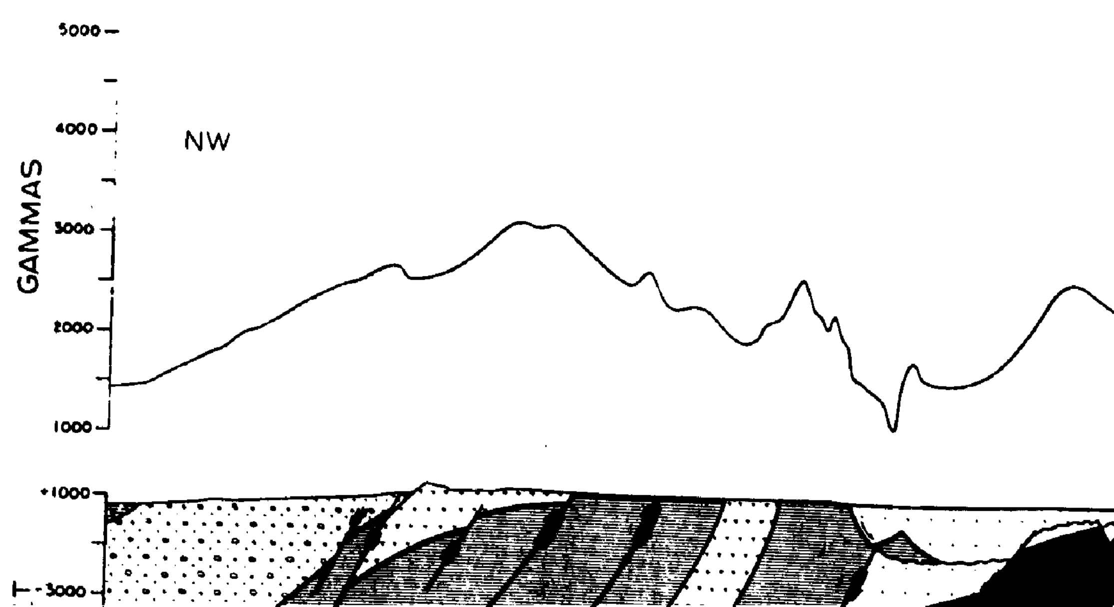


J'
K'
PF
R 57 W
R 56 W
88°55'
88°50'
I'
B
T 44 N
PF
BB
PD
PH
PR
PU
T 43 N
PD
PU
PH
PS
PS
PH
BB
PD
PU
T 42 N
CSA
GS
R 55 W
R 54 W
88°45'
40'
88°35'
BB
T 41 N
plate II-c
plate II-e
GEOLOGY MAP
LEGEND

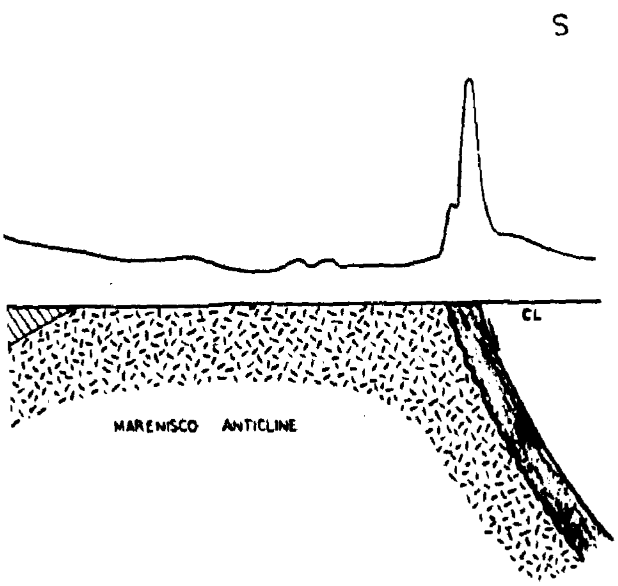


46°25'
46°20'
46°10'
46°05'
46°00'
45°55'
07'30"
T 45 N
T 44 N
T 42 N
T 41 N
25'
20'
R 32 W
15'
R 31 W
10'
CR
BH
BB
PD
PF
FS
PU
PPC
PCU
DU
G
B

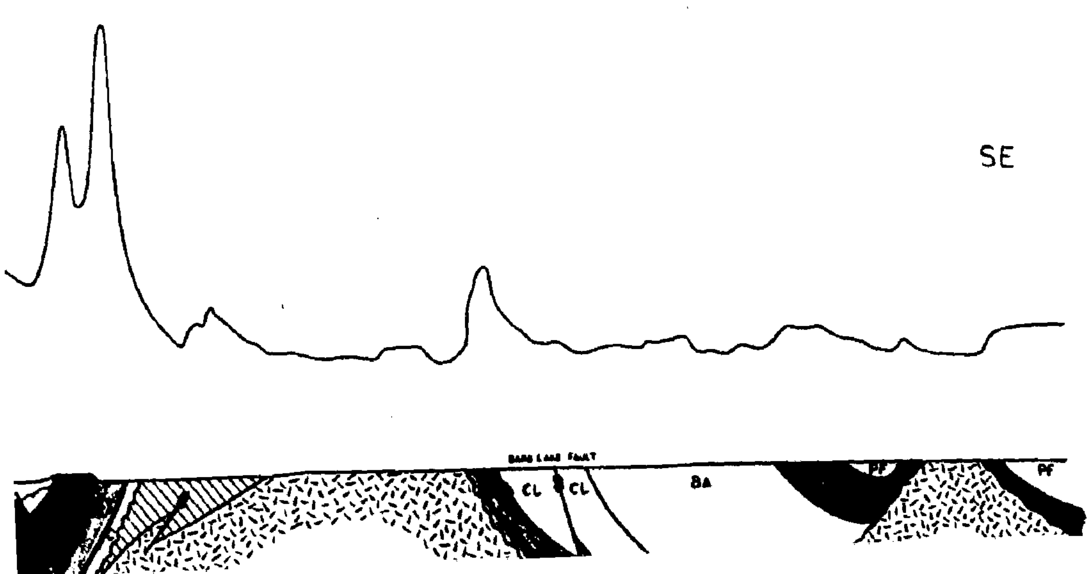

PROFIL
GAMMAS
7000
6000
5000
4000
3000
2000
N
FEET
+1000
-3000
-7000
-11000
IRON RIVER SYNCLINE

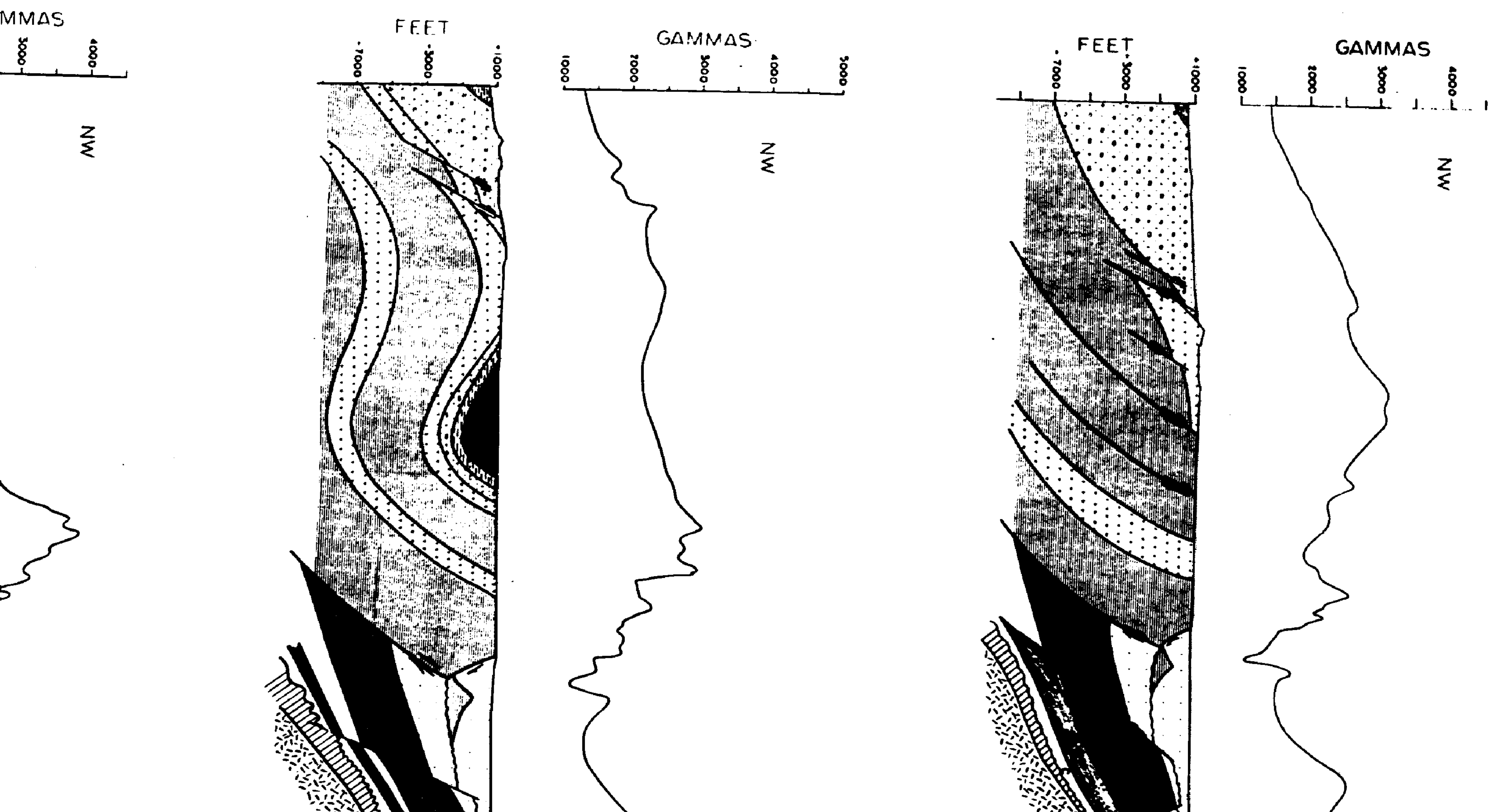

GAMMAS
5000
4000
3000
2000
1000
NW
+1000
-3000

ILE A - A'

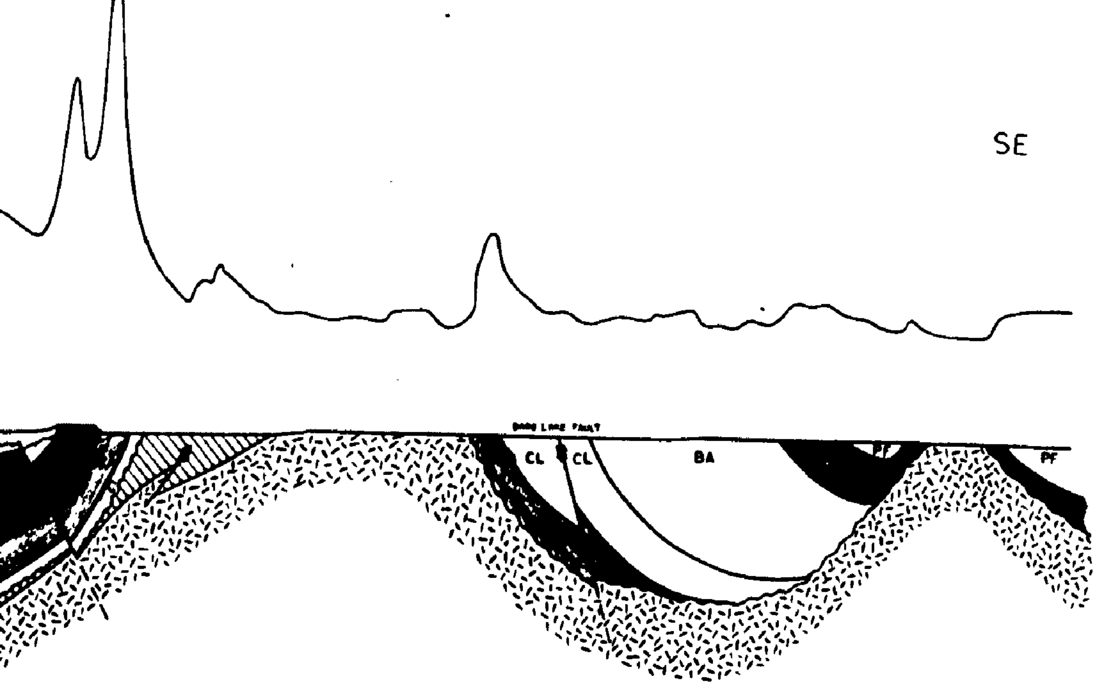


PROFILE B - B'

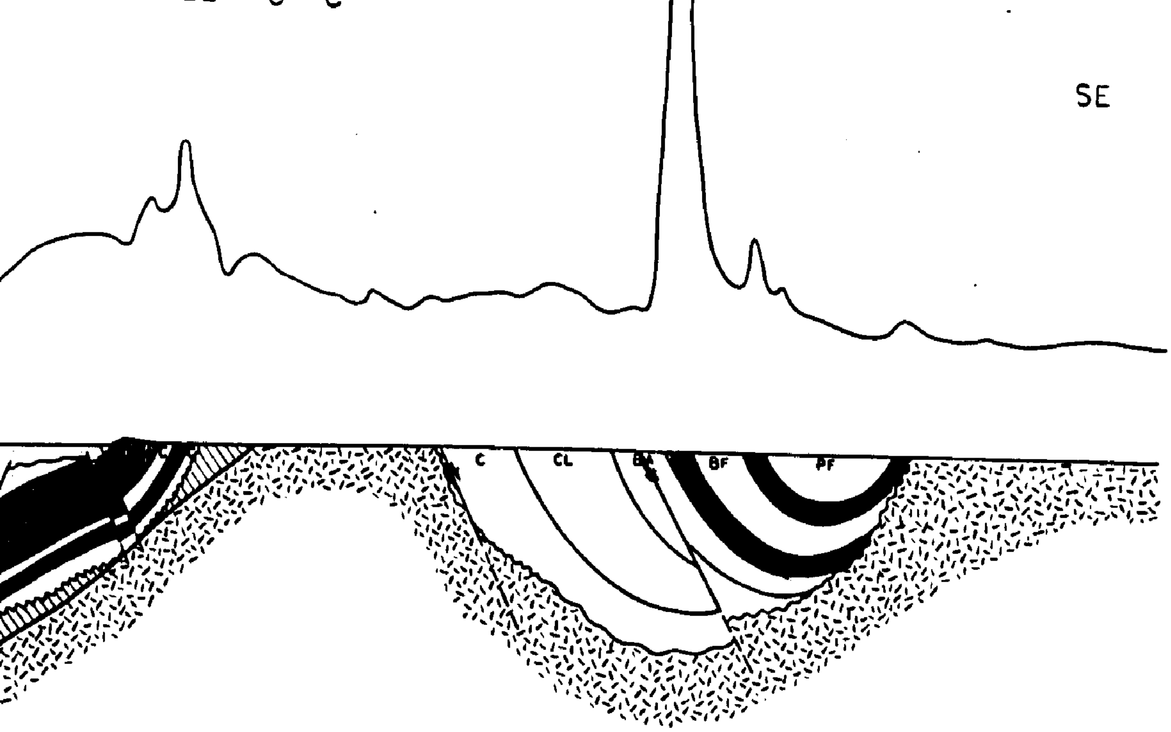




FEET
GAMMAS
FEET
GAMMAS

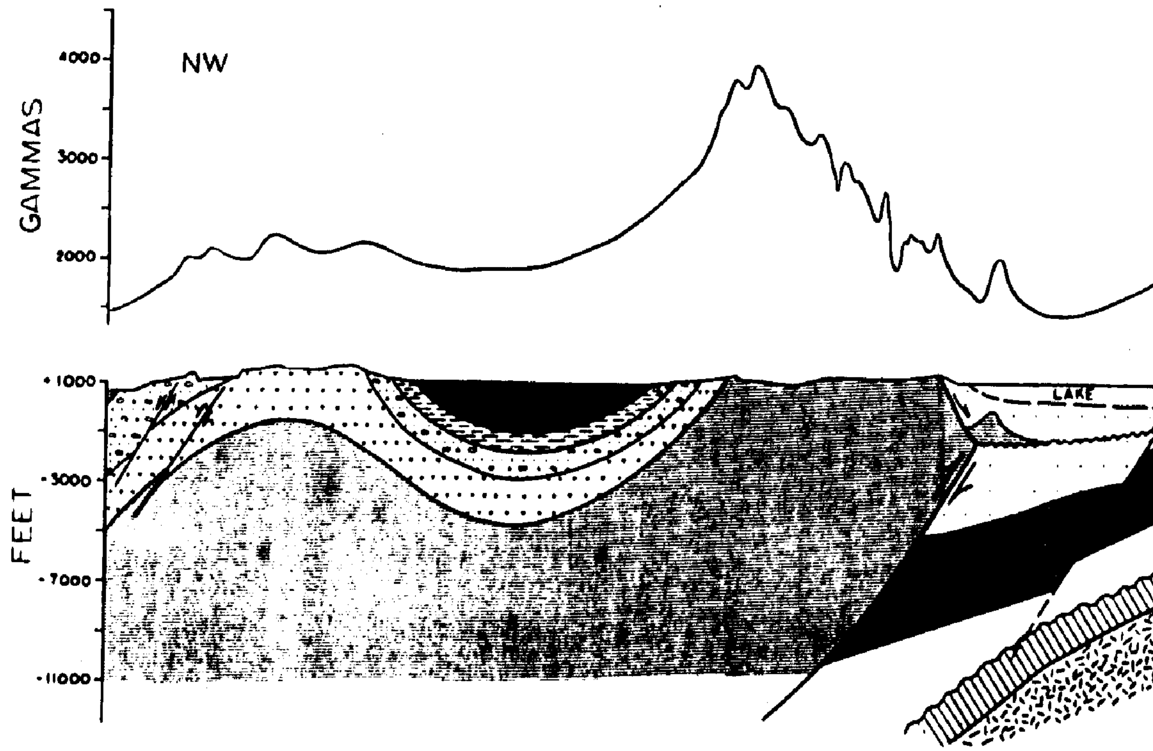


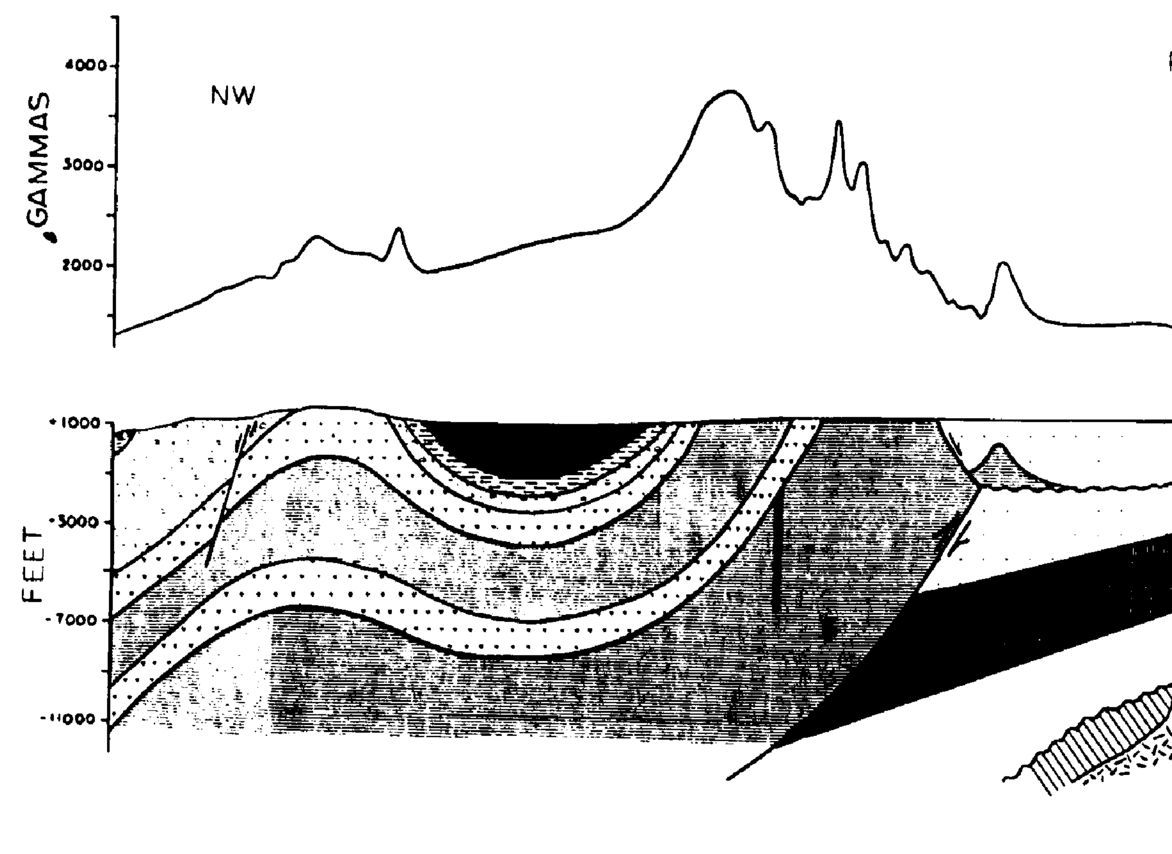
PROFILE C - C'

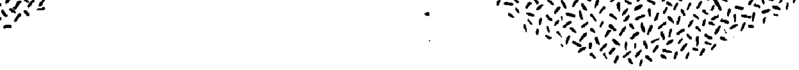


PROFILE D - D'

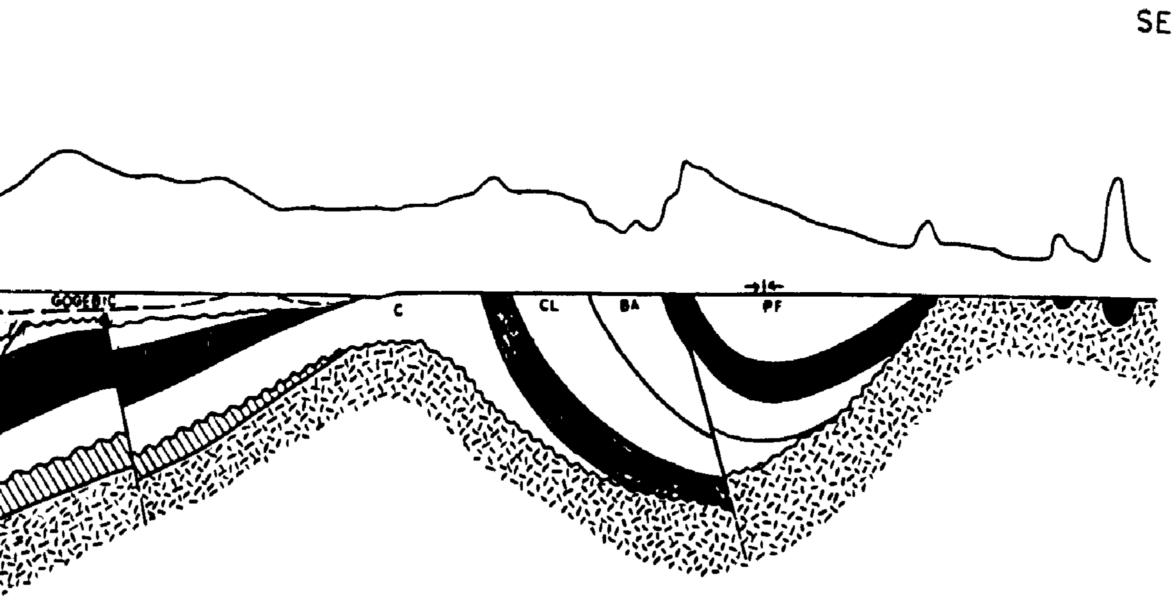
SE


NW
GAMMAS
4000
3000
2000
FEET
+1000
-3000
-7000
-11000
LAKE

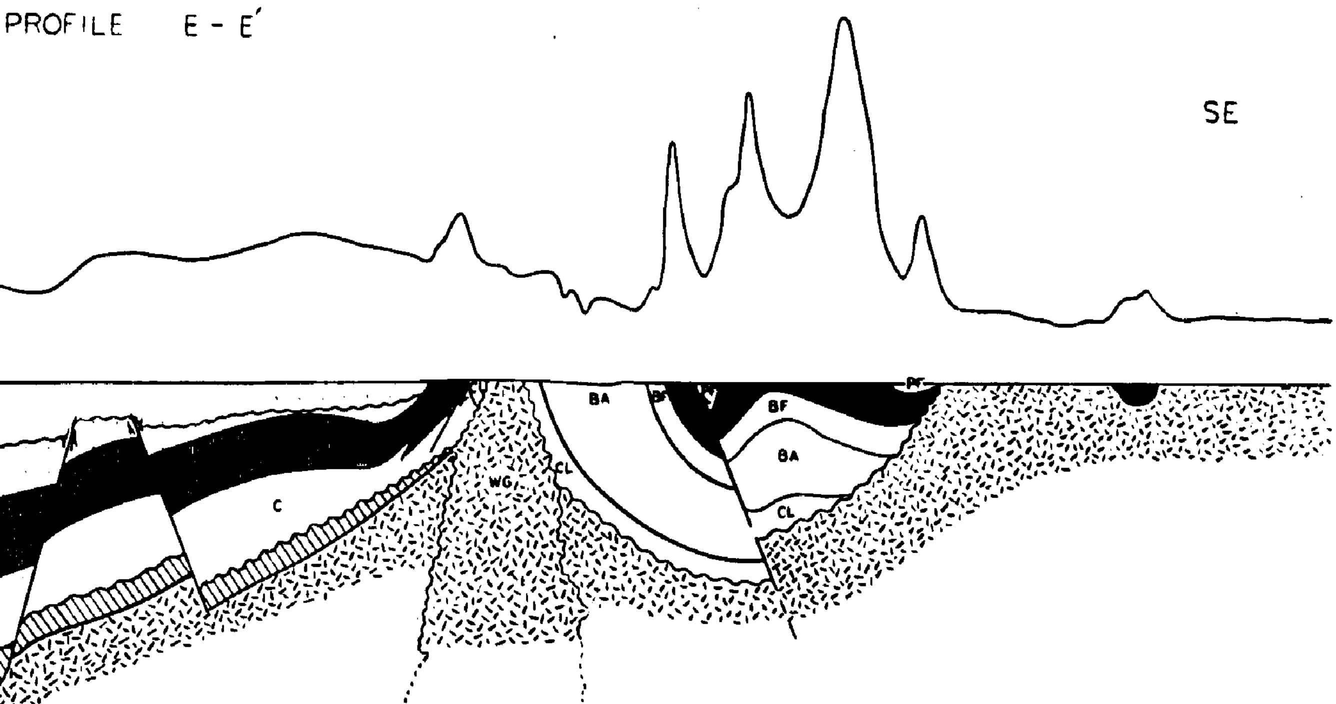

NW
GAMMAS
4000
3000
2000
FEET
+1000
-3000
-7000
-11000

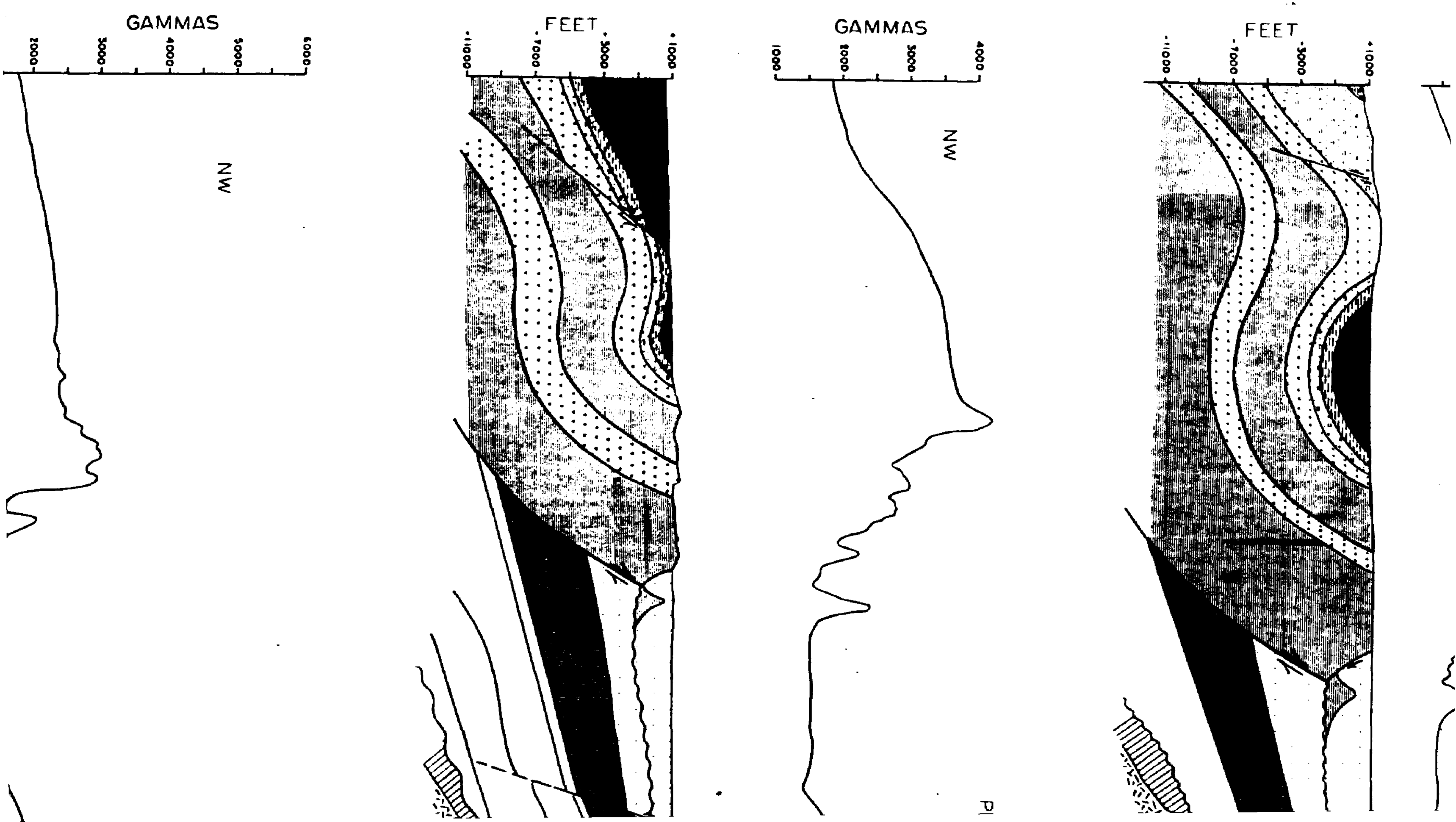


PROFILE D – D′



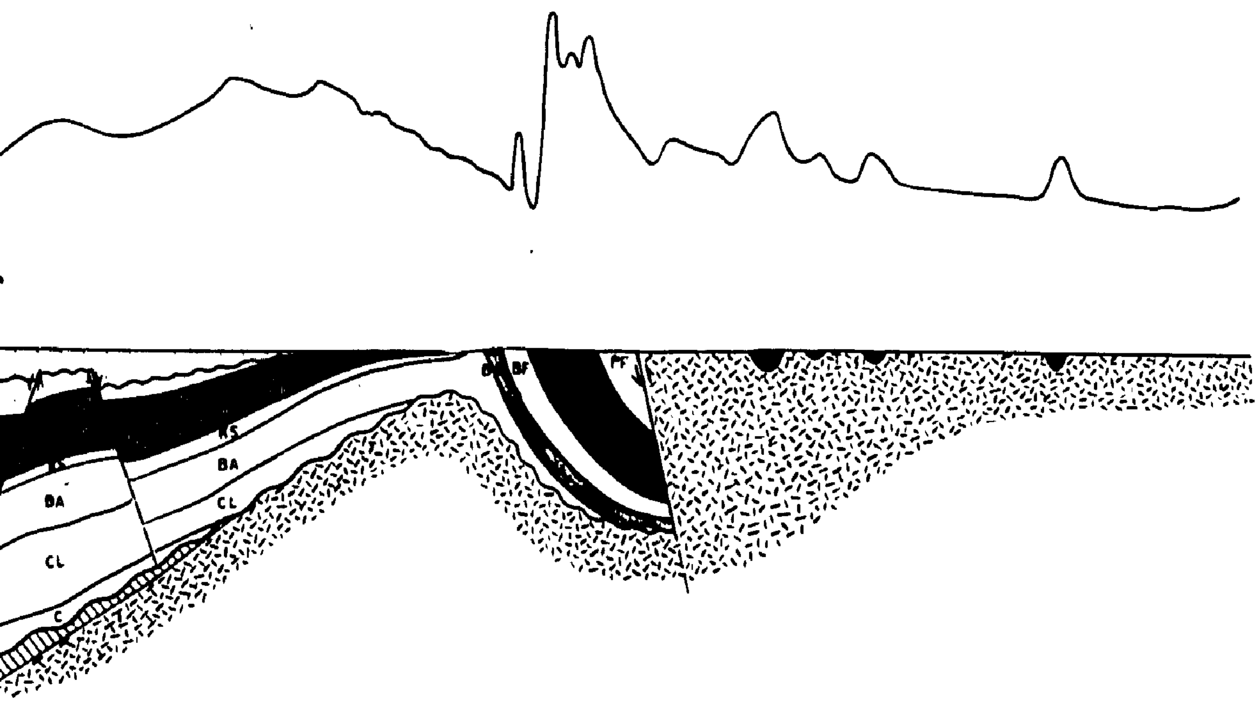
PROFILE E – E′




GAMMAS
2000
3000
4000
5000
6000
NW
FEET
GAMMAS
1000
2000
3000
4000
NW
FEET

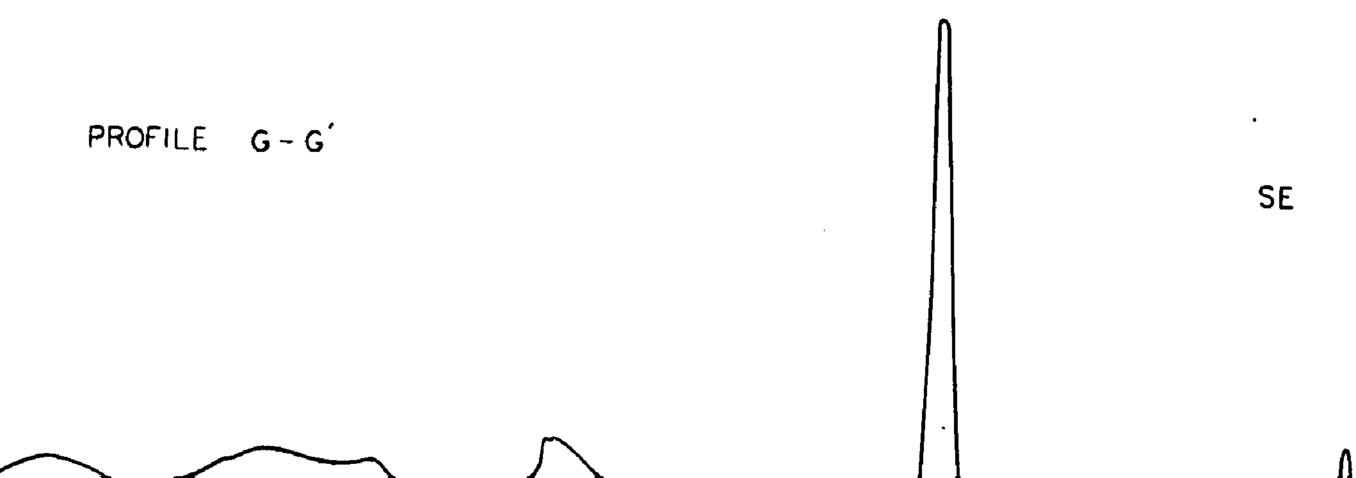
PROFILE F - F′

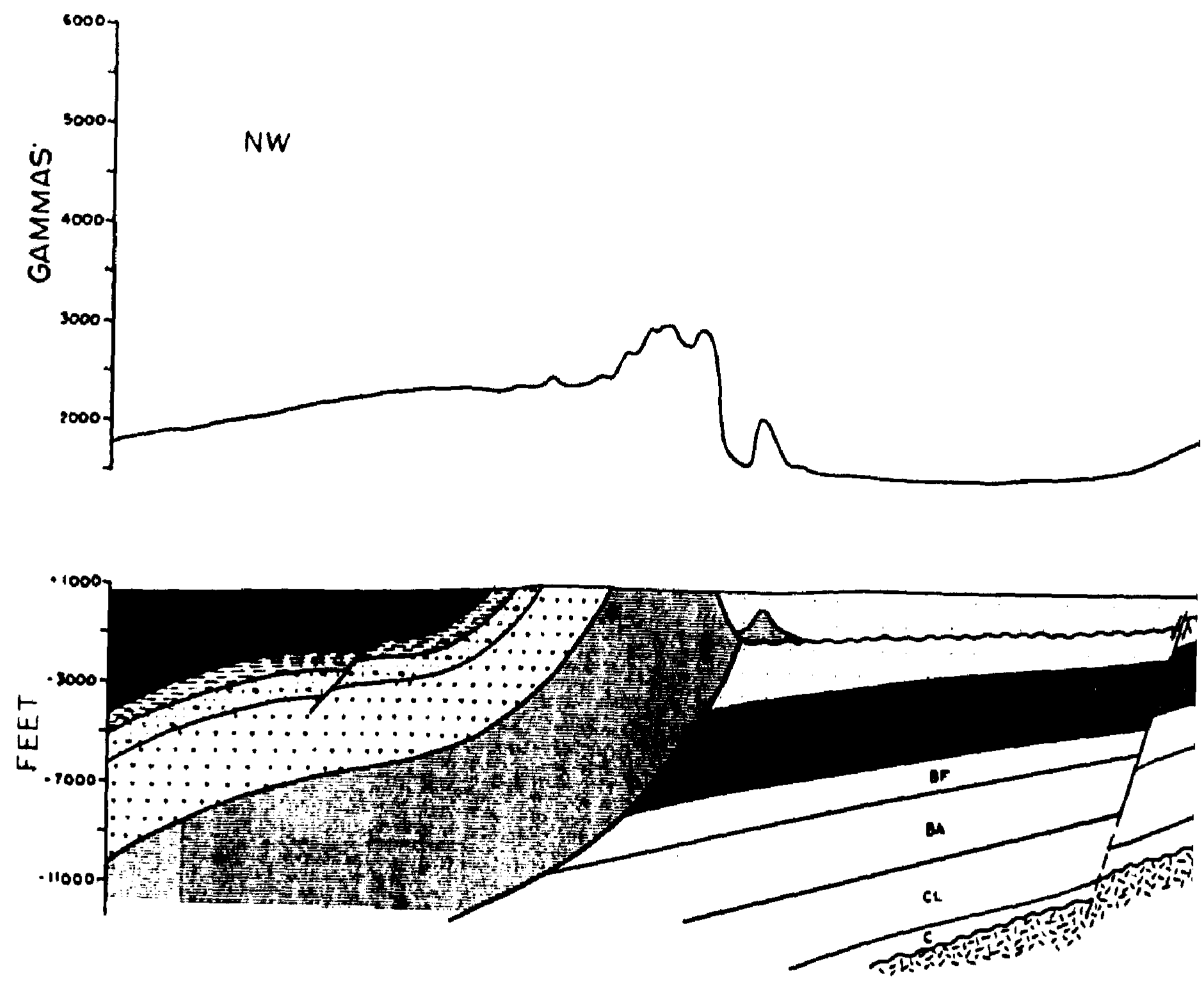
SE

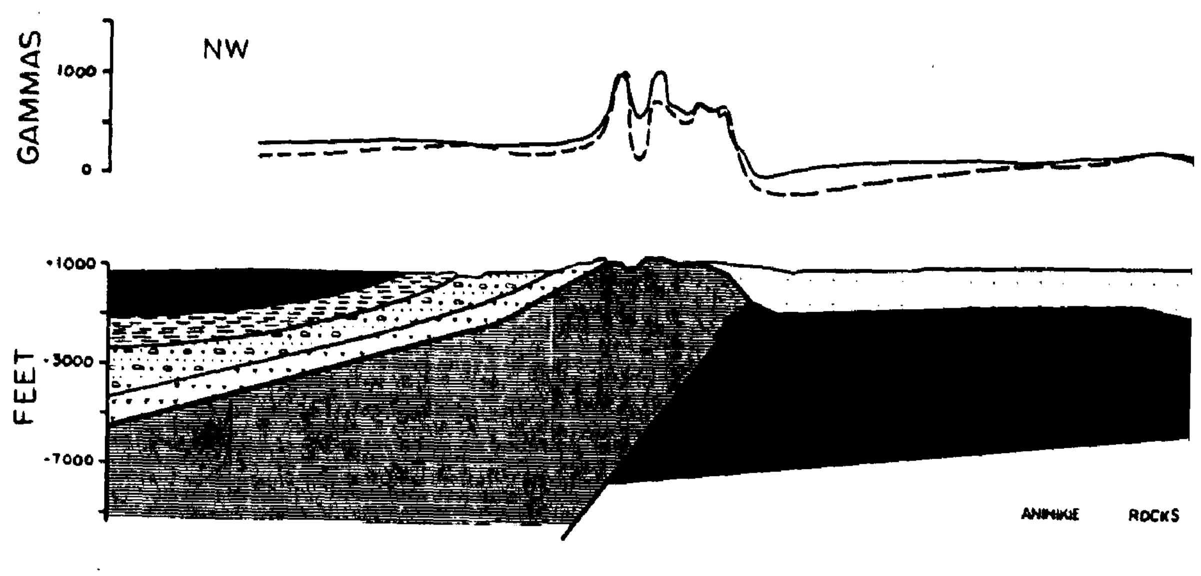


PROFILE G - G′

SE



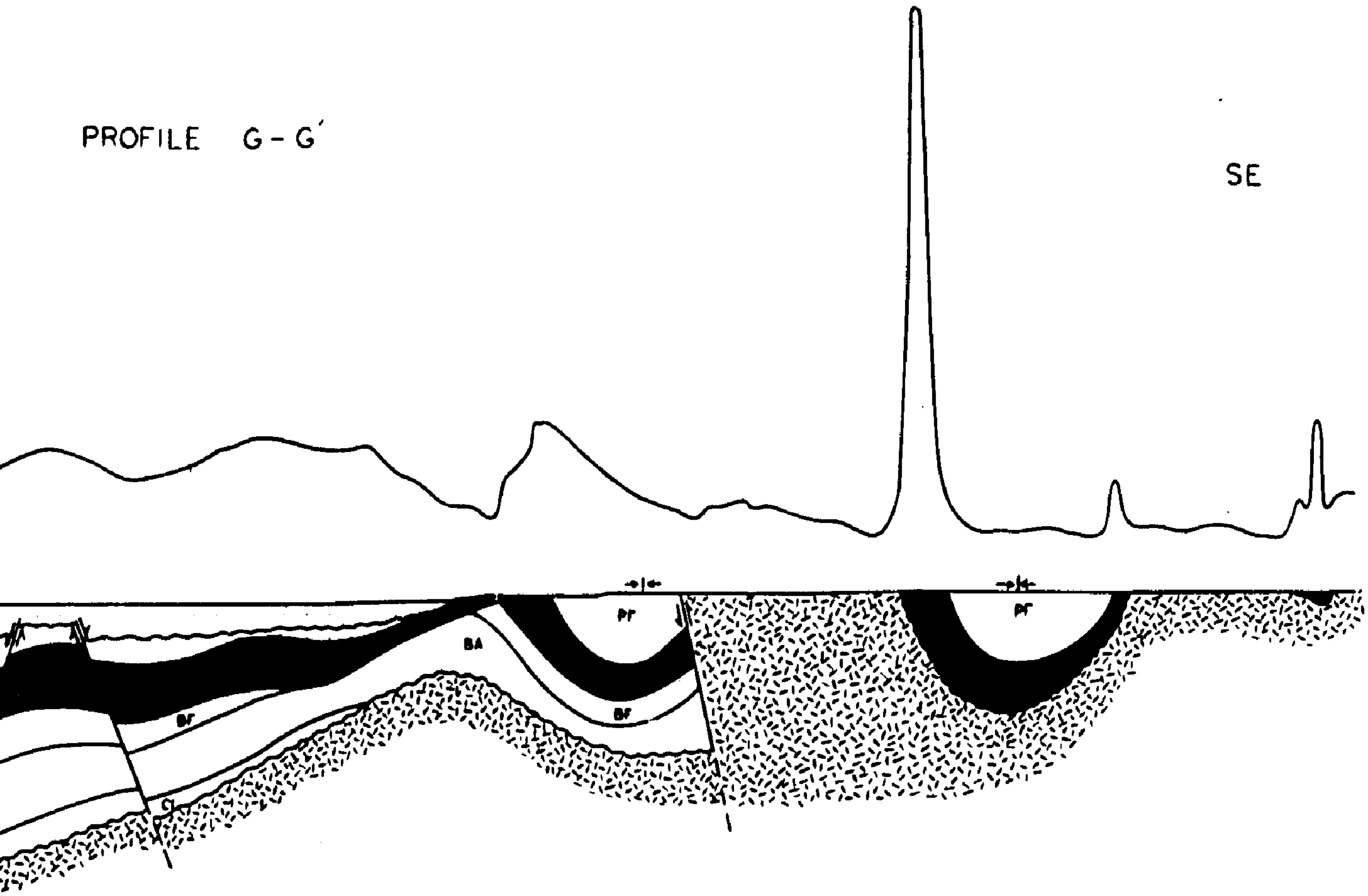

GAMMAS
6000
5000
4000
3000
2000
NW
FEET
+1000
-3000
-7000
-11000
BF
BA
CL
C


GAMMAS
1000
0
NW
FEET
+1000
-3000
-7000
ANIMIKIE
ROCKS

AS 3000 NW

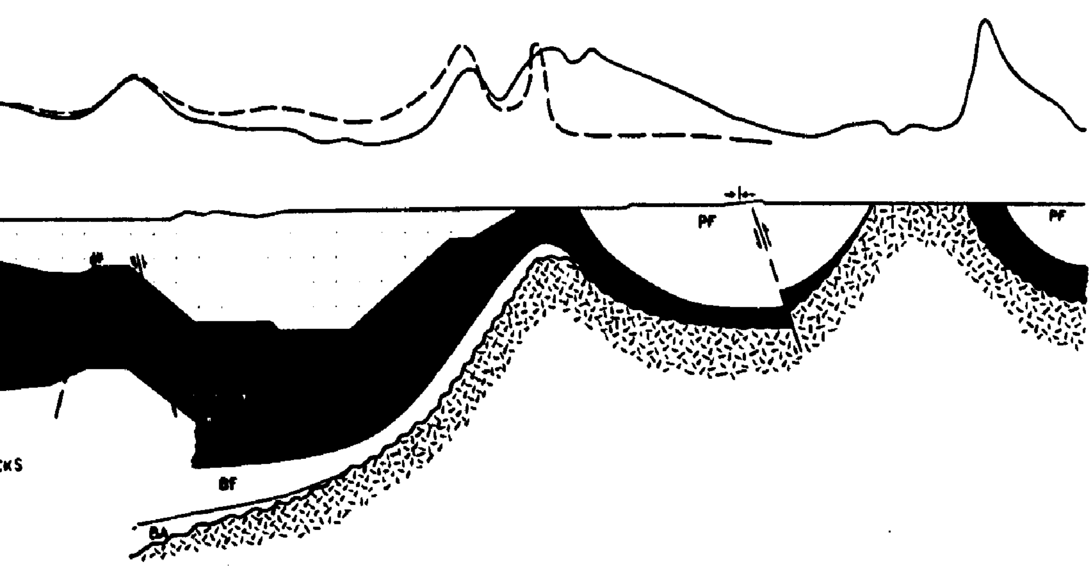
PROFILE G - G'

SE

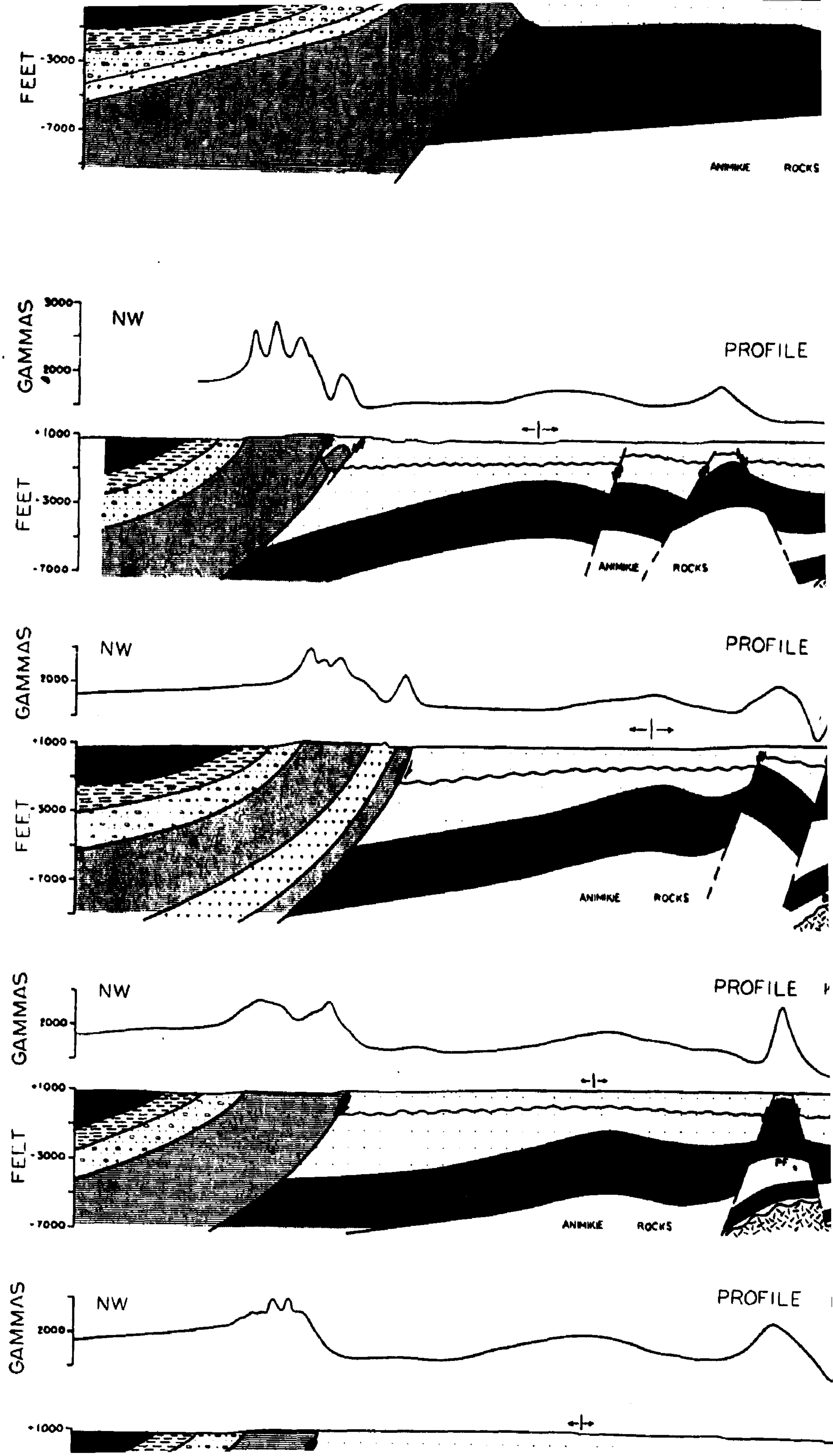


SE

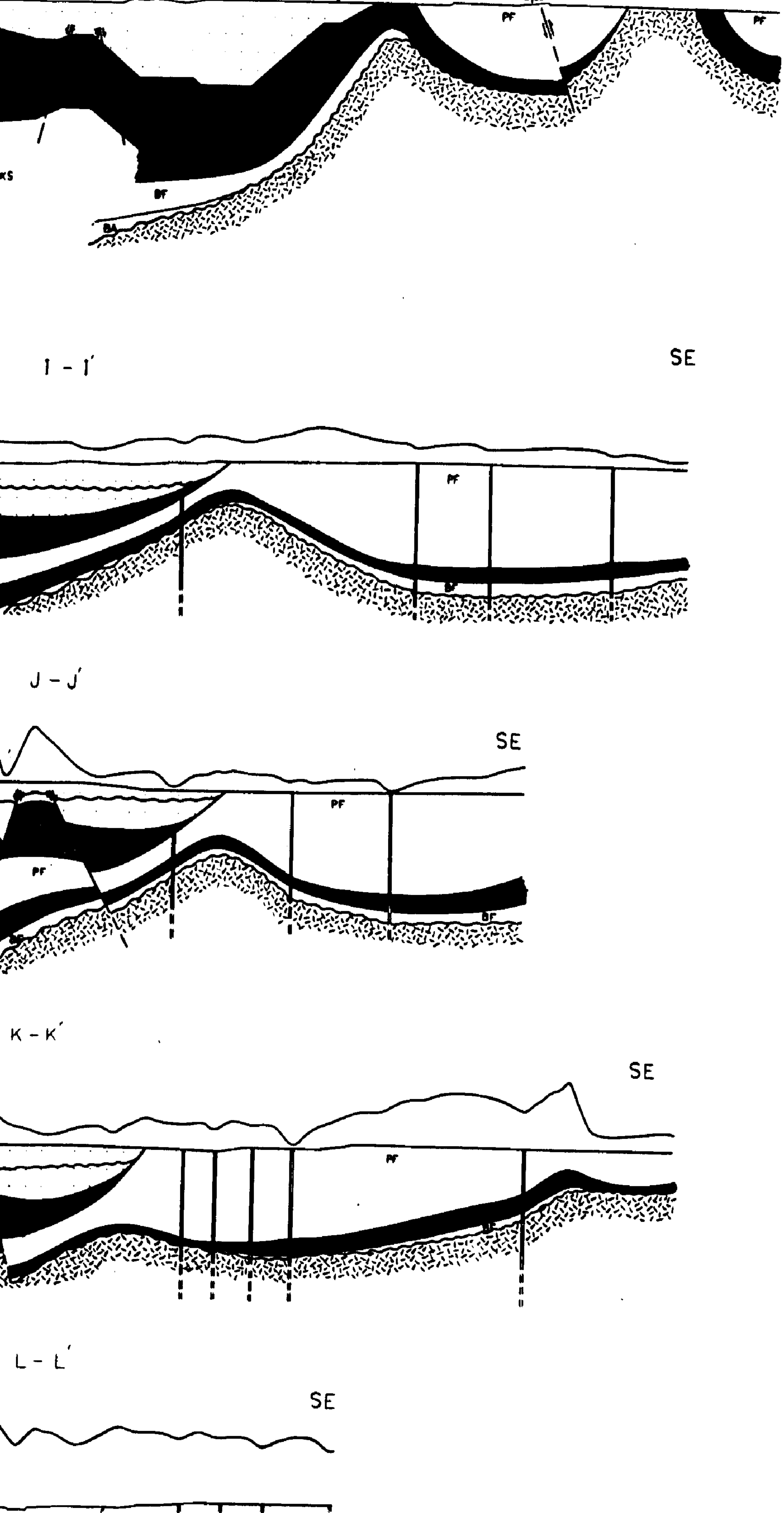
PROFILE H - H'

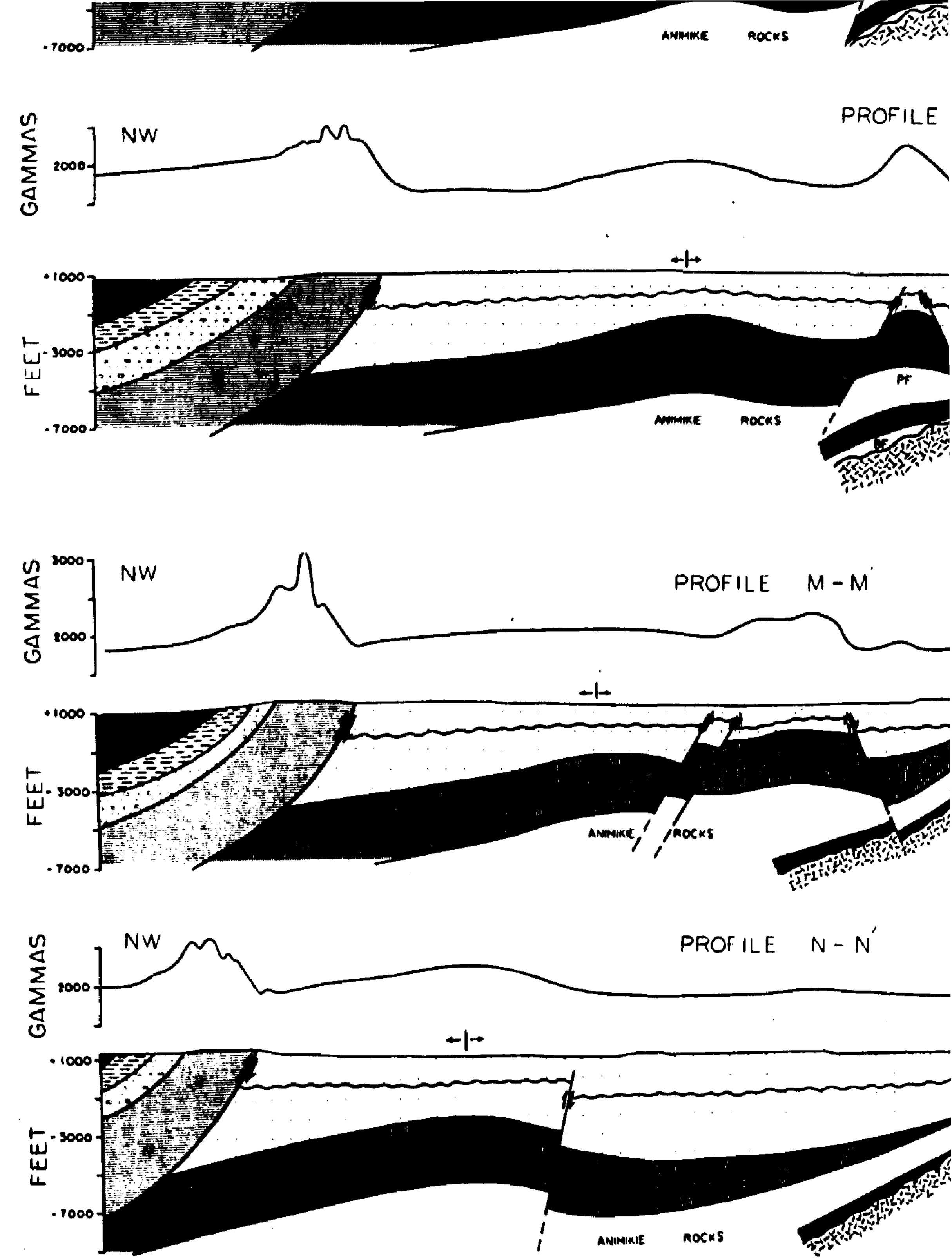


SE



FEET
-3000
-7000
ANIMIKIE ROCKS
GAMMAS
3000
2000
NW
PROFILE
FEET
+1000
-3000
-7000
ANIMIKIE ROCKS
GAMMAS
2000
NW
PROFILE
FEET
+1000
-3000
-7000
ANIMIKIE ROCKS
GAMMAS
2000
NW
PROFILE
FEET
+1000
-3000
-7000
ANIMIKIE ROCKS
GAMMAS
2000
NW
PROFILE
+1000


PF
PF
KS
BF
BA
I - I'
SE
PF
BF
J - J'
SE
PF
PF
BF
K - K'
SE
PF
L - L'
SE



INDEX FOR PLATE IV

PLATE IV-A	PROFILES	A-A', B-B'
IV-B		C-C', D-D'
IV-C		E-E', F-F'
IV-D		G-G', H-H'
IV-E		I-I', J-J', K-K', L-L'
IV-F		M-M', N-N'

VERTICAL SCALE 1 INCH=2000 FEET

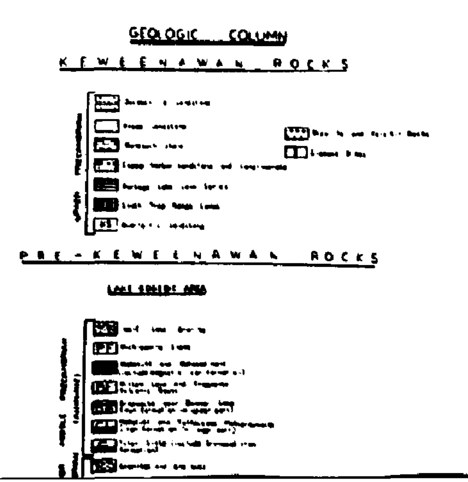
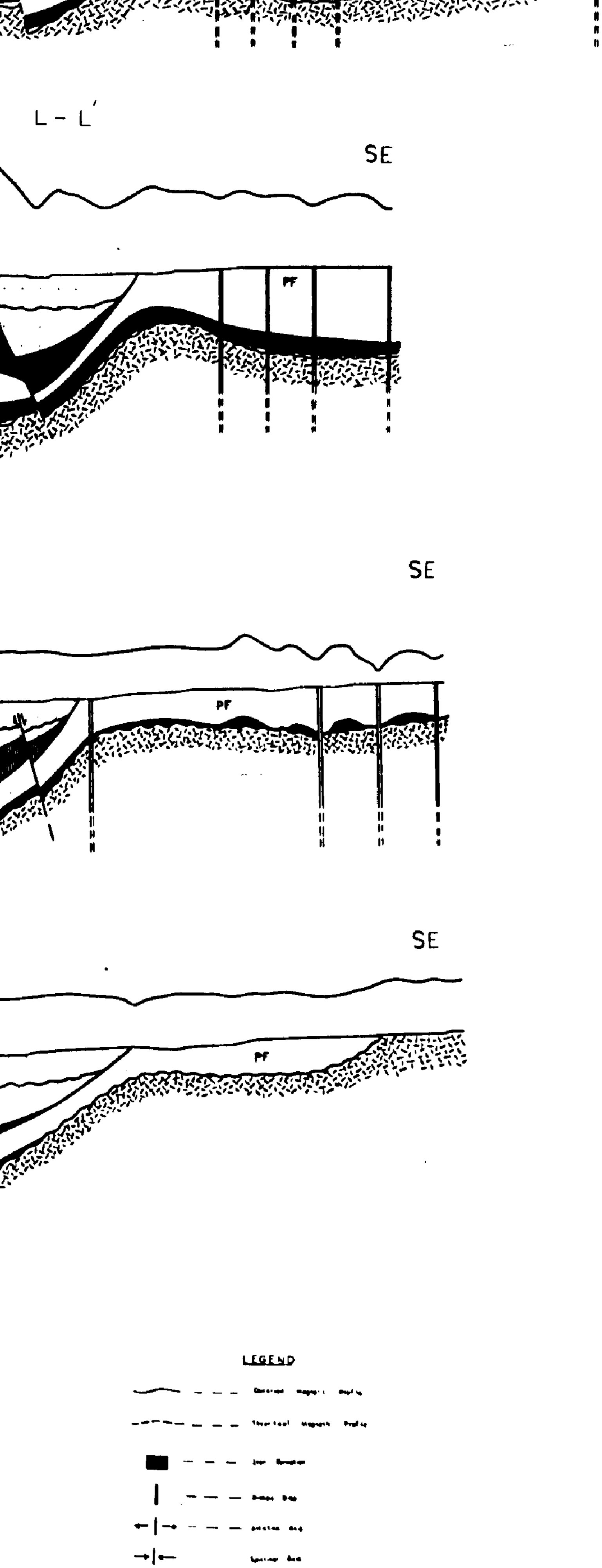
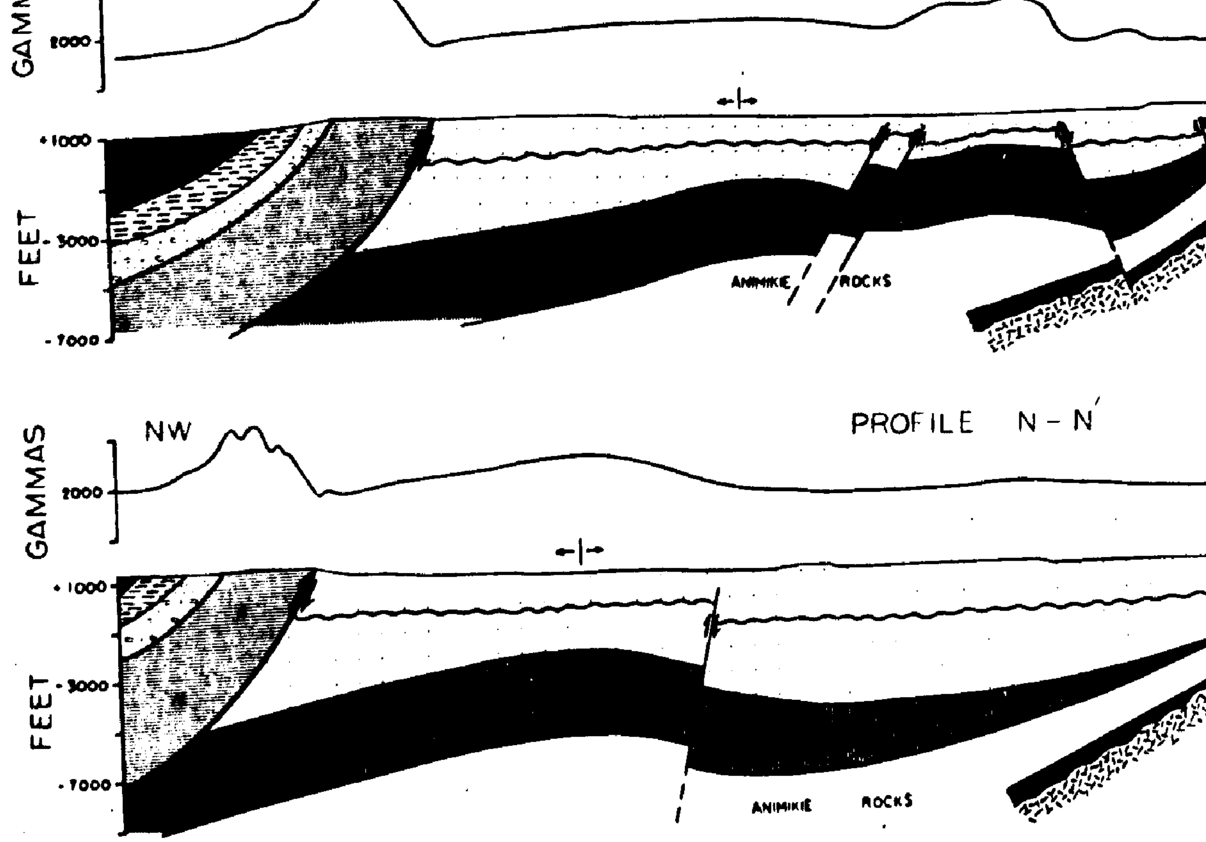


PLATE VII


L - L′
SE
PF
SE
PF
SE
PF
LEGEND



INDEX FOR PLATE IV

PLATE IV-A	PROFILES	A-A', B-B'
IV-B		C-C', D-D'
IV-C		E-E', F-F'
IV-D		G-G', H-H'
IV-E		I-I', J-J', K-K', L-L'
IV-F		M-M', N-N'

VERTICAL SCALE 1 INCH=2000 FEET

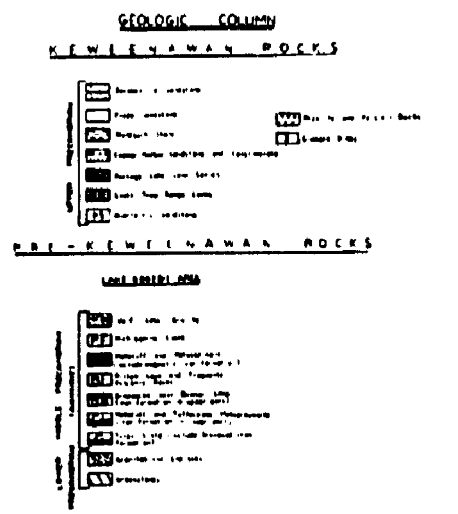
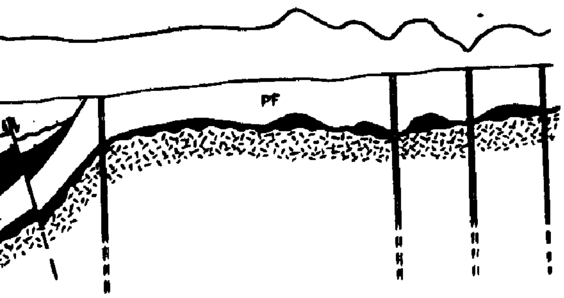
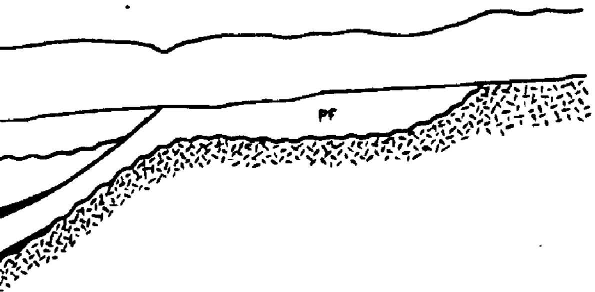
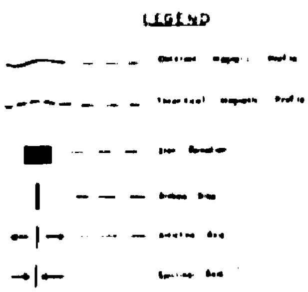


PLATE VII

PLATE IV - AEROMAGNETIC AND GEOLOGIC







C PROFILES