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THE APPLICATION OF THE GRAVITY METHOD TO
MAPPING BEDROCK TOPOGRAPHY IN
KALAMAZOO COUNTY, MICHIGAN

by

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ABSTRACT

The gravity method has been widely used to delineate buried bedrock valleys in glaciated areas. The method is based on mapping spatial perturbations in the gravity field associated with bedrock topography which causes horizontal variations in density between the bedrock and the generally less dense, overlying glacial drift. It is desirable, however, in both ground water, geomorphic, and engineering investigations to map not only the buried bedrock valleys, but to prepare a bedrock topography map from the gravity observations. A method of mapping bedrock topography using gravity measurements in conjunction with well log information has been developed and successfully applied to Kalamazoo County, Michigan. Depth to bedrock and gravity observations at well sites are used to calculate a regional gravity anomaly map which excludes the effect of bedrock above a datum. This map is subtracted from the Bouguer gravity anomaly values to obtain a residual gravity anomaly map reflecting primarily bedrock topography. The residual gravity anomalies obtained by this method show a significantly improved correlation with bedrock topography over residuals obtained by the conventional graphical and statistical methods. The residual gravity anomalies are converted to bedrock elevation using the assumed density contrast between the glacial sediments and the bedrock.

The bedrock topography map of Kalamazoo County shows a prevailing westward slope with a superimposed, complex bedrock channel system. The principal channels generally trend east-west or north-south. The map is used to discuss the preglacial and periglacial drainage and the ground water potential of the County.

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CHAPTER I

INTRODUCTION

Purpose and Method

The search for potable water is one of the oldest endeavors of man. Ancient civilizations thrived where ample quantities of surface water were available. The first recorded use of ground water dates back more than five thousand years (Tolman, 1937). Ground water was needed then, even as it is today, to supplement surface supplies of water for human consumption and irrigation. Therefore, the art of prospecting and developing ground water resources is as old as the earliest civilization known to man. Today, the exploration and development of ground water supplies has become an important and complex science.

During the last several decades industrialization, while demanding more water, has resulted in extensive pollution of surface, and to a certain extent, ground water, through irresponsible waste disposal practices. The increasing rate of surface water pollution and the expanding use of water have increased the demand for the development of new ground water resources. Therefore, present techniques of ground water prospecting must be revised and new methods perfected.

The application of geophysical techniques to ground water exploration is a comparatively new field with considerable potential. This branch of natural science is being used, not only in prospecting for ground water aquifers, but also in their evaluation and development. Accordingly, as in all developing fields, the effectiveness of the geophysical methods in solving diversified hydro-geologic problems must be examined. This will eventually lead to the modification of present methods and the development of new techniques for the analysis and interpretation of field data.

In formerly glaciated areas, glacial sediments are often the only available source for ground water because bedrock formations are either impermeable or contain polluted or saline water. Glacial sediments are known for their extreme heterogeneity. Both lateral and vertical variations of their physical properties are common. Glacial sediments in bedrock channels, however, have proven to be favorable sites for locating ground water aquifers. The reason for this are as follows: 1) Bedrock valleys have a greater probability of containing thicker sections of sand and gravel because of the increased thickness of glacial drift from the latest glaciation; 2) Bedrock valleys often are the loci of preserved or buried outwash deposits from earlier glaciation; 3) Outwash deposits on bedrock highs are more likely to be eroded (Horberg, 1950).

In most geologic situations, the bedrock formations have higher

densities than the overlying sediments. As a result, depressions in the bedrock surface produce lower gravity readings than these bedrock areas, which are topographically high. This correlation between bedrock topography and gravity renders the method suitable for mapping bedrock topographic features particularly in cases of significant relief on bedrock surface or a well developed hydromorphic pattern. Buried bedrock channels can be identified by the unique sinuous pattern which they commonly display on a Bouguer gravity map. In few cases, buried bedrock channels are difficult to delineate because glacial deposits have densities equal to or slightly exceeding that of bedrock (McGinnis et al, 1963). Lennox and Carlson (1967) conducted laboratory density measurements on a limited number of samples of silt, sandstone, sand, shale and till. They concluded that the densities of the first four materials are essentially the same. The till, on the other hand, showed appreciably higher densities. In this case, thickening of the till as encountered in buried channels could produce a high gravity trend along the valley axis. Hall and Hajnel (1962) have found both high and low gravity anomalies associated with the trends of known buried channels.

The gravity method has been applied in delineating buried bedrock channels and defining the cross section of these channels through model studies at locations where well control is available. The present study aims at expanding the scope of the gravity method by developing a technique of computing bedrock topography from gravity observations

and well control. A bedrock topography map is valuable, not only in ground water studies, but also in engineering and geomorphic investigations. The study was carried out in Kalamazoo County, Michigan because of the strong dependence of the area upon ground water sources, and also because of the availability of ample well data.

Correlative Investigations

Kalamazoo County has previously been studied, possibly more than once, by regional gravity and magnetic studies. These investigations were carried out by oil companies for the purpose of locating oil and gas fields in the buried Paleozoic bedrock. No major geophysical investigations, however, have been previously undertaken to study the ground water resources of the glacial sediments. The only geophysical studies carried out for the purpose of locating ground water aquifers were in the form of scattered, and rather limited resistivity measurements conducted by consulting firms on behalf of the City of Kalamazoo Water Department or local industry.

The Department of Natural Resources of the Michigan Geological Survey, in cooperation with the United States Geological Survey and the City of Kalamazoo, released Report Number 23 concerning the "Ground Water Hydrology and Glacial Geology of the Kalamazoo Area." This report is based on an investigation which started in

1946 and dealt with the availability and quality of ground water in the Kalamazoo area (Deutsch, Vanlier, and Giroux, 1960). The investigation involved the collection and compilation of data pertaining to the source, occurrence, and chemical quality of ground water. The United States Geological Survey, in addition, is conducting a hydrological program in Kalamazoo County which is based on well data, pumping tests, and a drilling program. The expected outcome of this study will be the delineation of aquifers, compilation of transmissibility coefficient and aquifer thickness contour maps. A report concerning the findings of this investigation will be released in the near future.

The Michigan Highway Commission is conducting a shallow coring program aimed at classifying and delineating surface glacial deposits in Kalamazoo County. The purpose of this investigation is to locate sand and gravel deposits suitable for road construction

General descriptions of the geology of the Southern Peninsula of Michigan including Kalamazoo County can be found in papers by Lane (1895), Leverett (1912, 1917) and Leverett and Taylor (1915).

Martin (1955) compiled an areal geology map of the Southern Peninsula of Michigan and prepared a special report on the glacial history of Kalamazoo County (Martin, 1957).

Reports containing ground water data on the Kalamazoo area were also made by Lane (1899) and Leverett (1906, a, b).

Area of Study

The area covered by this investigation is Kalamazoo County, Michigan. Located in the southwestern corner of the Southern Peninsula (Fig. 1), Kalamazoo County lies between latitudes $42^{\circ} 05' N$ and $41^{\circ} 25' N$ and longitudes $85^{\circ} 25' W$ and $85^{\circ} 45' W$. The County is divided into sixteen townships covering T1S to T4S and R9W to R12 W.

The major river in Kalamazoo County is the Kalamazoo. It flows from east to west in the eastern part of the County. At the City of Kalamazoo it changes direction and flows northward. There are several small creeks, the largest of which is Portage Creek. It joins the Kalamazoo River where it changes direction and flows northward. There are numerous lakes, mostly interconnected, the largest of which is Gull Lake, located in the northeastern corner of the County.

Most of the area is generally flat with a maximum relief of fifty feet. Surface relief in the northwestern part of the County, however, is appreciably higher due to the Kalamazoo moraines. The maximum elevation of the moraines is about 1050 feet above sea level, and the relief is about 150 feet.

The largest municipality is the City of Kalamazoo which has a population of about 200,000. Industry includes paper manufacturing, pharmaceutical products, and transportation equipment. These

industries make a considerable demand upon the local ground water sources.

The surface waters of the County, especially the Kalamazoo River, have become polluted through waste disposal of the paper companies and other industries. Thus, ground water is the main source of usable water.

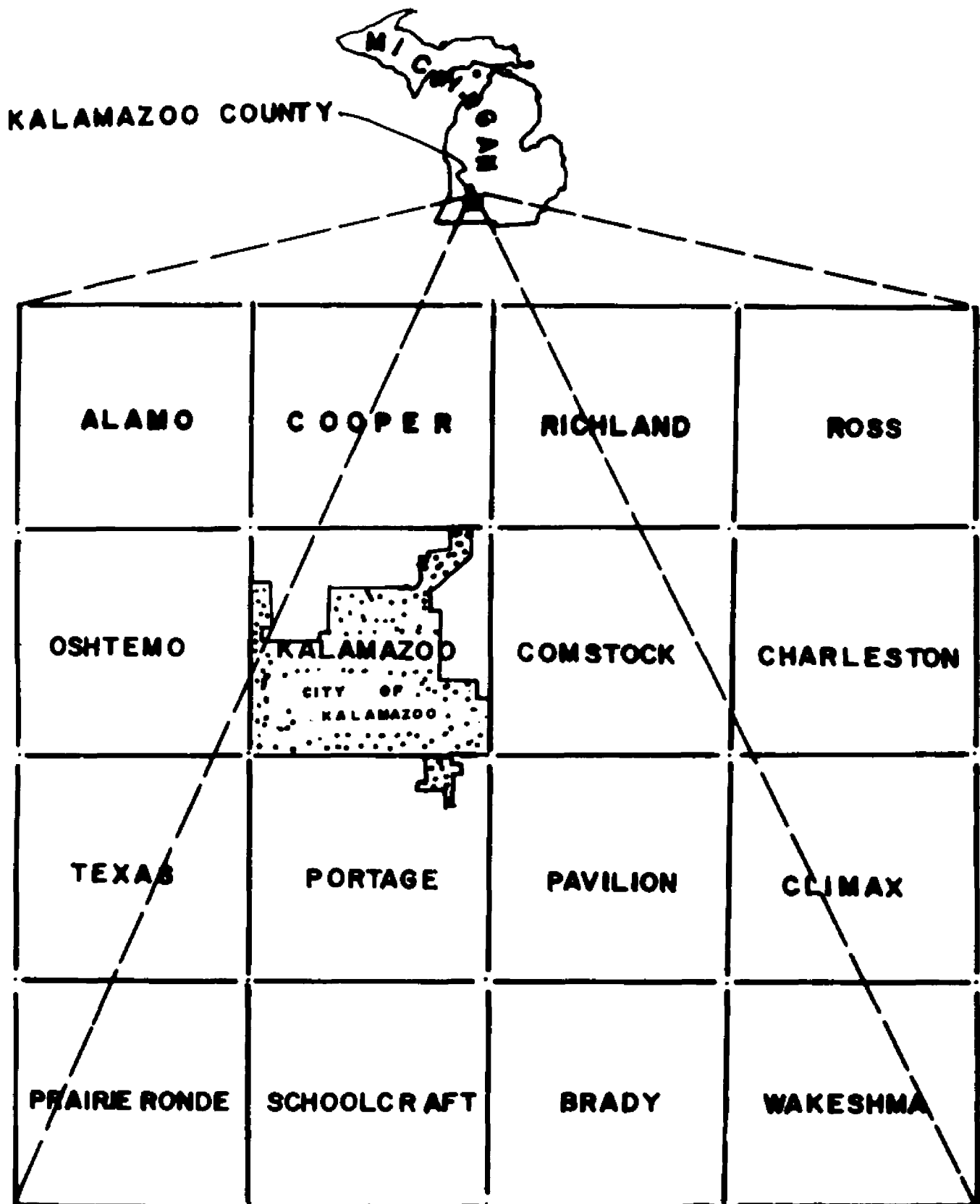


FIGURE 1 AREA OF STUDY

CHAPTER II

THE GEOLOGY OF KALAMAZOO COUNTY

Kalamazoo County is completely covered with glacial sediments ranging in thickness from less than 50 to 650 feet. The thickest section lies to the west where the Kalamazoo moraines overlies bed-rock channels. Throughout the area the glacial sediments are variable, ranging from well-sorted lenticular outwash deposits to completely unsorted, and mostly compact till.

The area was subject to two periods of Pleistocene glaciation; Illinoian, and Wisconsinan which deposited the main body of glacial sediments. Whether the Nebraskan and Kansan glaciation was active in Kalamazoo County is uncertain. Drilling logs reveal the presence of a soil profile which very often contains tree logs, brush stems, muck or peat beds. This soil profile is not present everywhere, but it is found in a sufficient number of places to establish the fact that the glacial sediments in Kalamazoo County were deposited during more than one glacial age. Older glacial deposits are more indurated and cemented than the younger and may be separated from them by well developed soil profiles or outwash deposits.

The Wisconsin drift sheet is the youngest and best preserved of the Pleistocene glacial deposits. Its moraines have a very distinct pattern reflecting the lobate nature of the ice sheets. The pattern reveals three Wisconsin lobes which invaded the Southern Peninsula of Michigan. The course of each lobe was controlled by the lowlands. The dominant one, the Lake Michigan lobe, followed the Lake Michigan basin and pressed into Kalamazoo County in a southeasterly direction. This lobe was responsible for the present surface topography of most of Kalamazoo County. It formed all the morainic ridges except for the northeastern part of the Tekonsha moraine which was deposited by the Saginaw lobe (Plate 1).

The retreat of Lake Michigan lobe was not uniform. There were at least four main intervals during which the ice front was stationary. This is evident from the areal distribution of the morainic ridges. The Tekonsha moraines were formed during the first and earliest halt of the Lake Michigan ice front. The second recessional halt deposited the Battle Creek moraines. Part of this discontinuous system lies in Ross, Pavilion, and Brady Townships. The third halt formed the morainic bodies located in Richland, Cooper and Prairie Ronde Townships. The fourth, and perhaps the longest still-stand of ice, formed the Kalamazoo moraines which are one of the most highly developed morainic ridges in the Southern Peninsula of Michigan (Martin, 1957). This one is composed of two well-defined

ridges separated by a narrow, yet nearly continuous outwash apron. The width of each ridge varies between one and four miles.

The Saginaw lobe followed the Saginaw Bay lowland and invaded Kalamazoo County from the northeast. This ice produced the easternmost part of the Tekonsha moraine and retreated faster than the other two lobes. The third main lobe was the Erie-Huron lobe, which came in along the Erie-Huron lowland and did not affect the present topography in the County (Mazola, 1962).

Besides the Kalamazoo and Tekonsha moraines, Kalamazoo County is covered with outwash deposits and ground moraines. The southeastern corner is characterized by drumlins and is dissected by several small creeks and unoccupied stream valleys trending northeast-southwest. These channels relate to the Kankakee torrent which in early middle Wisconsin time drained all three ice lobes in the area of southern Michigan and northern Indiana (Zumberg, 1960).

The bedrock in Kalamazoo County is immediately overlain by a relatively continuous layer of dense plastic blue clay with almost no grains larger than fine sand. This deposit is generally thicker at locations of low bedrock topography and contains blocks of Coldwater shale. It was probably deposited by turbid ice-dammed and semi-stagnant water.

The Paleozoic bedrock formations underlying the glacial drift are formed of two units. The oldest, the Coldwater shale of Mississippian

age, is the bedrock formation in most of the County. The Marshall sandstone overlies the Coldwater shale in the northeastern corner of the County though it has not been well delineated. The Coldwater shale is light colored, greenish to bluish black, becoming sandier toward the top and gradually passing upward into the Marshall sandstone. It occasionally contains limestone bands or lenses of Marshall-type sandstone. The shale is relatively impermeable and is not known to supply useable water in Kalamazoo County. The Marshall sandstone is quite fractured and permeable and is used as a ground water aquifer in Kalamazoo County and elsewhere in Michigan.

topography and followed major bedrock valleys. Broad and shallow bedrock valleys were more effective in controlling the directions of ice movement than narrower and deeper valleys (Chamerlin, 1888). Preglacial valleys trending in almost the same direction as the ice movement were more effective in the channeling flow than those trending at angles to it. The effectiveness of bedrock topography in controlling glacial movement also depends on the thickness of the ice mass. Thick ice sheets are less affected by bedrock topography than thin ones. Also, theoretically ice masses of more temperate glacio-thermal character are more mobile and their movements subsequently more controlled by bedrock topography than ice masses of more polar geophysical character.

Ice action greatly modified the pre-pleistocene bedrock landscape in the region of the study. Differential glacial scouring affected some areas more than others. Soft or jointed bedrock areas are gouged by ice to a greater degree than hard unjointed rocks. Also, in periglacial conditions wedging activated by freezing of water in exposed bedrock joints can promote future glacial plucking or mass wastage along valley flanks.

Preglacial valleys undergo the most severe geomorphic modification as a result of glacial action. In areas of continental glaciation tributary valleys trending normal to the ice front are overridden, truncated and often destroyed. Those parallel are gouged, widened,

interior. The bedrock is mostly shale, sandstone, and carbonate. These lithologies are folded and locally faulted. Their deformation was caused by regional stresses, vertical compaction over buried hills in the basement, faulting of Precambrian basement and strains due to solution of underlying weaker and more soluble beds (Newcomb, 1933; Cohee, 1965). Folding in the bedrock formations occurs along axial trends, the most prominent of which shows a prevailing north-west-southeast direction.

The preglacial drainage pattern in the Southern Peninsula and surrounding areas is not fully understood. Two hypotheses proposed regarding preglacial drainage have been summarized by Fenneman (1938), Spencer (1891), and Horberg and Anderson (1956). They suggest that the preglacial drainage in the Great Lakes was eastward and emptied into the St. Lawrence River. In Contrast, Grabau (1901) proposed a general southwesterly drainage discharging into the Mississippi probably by way of the preglacial Teays valley.

The former drainage pattern implies that streams were flowing into the southward advancing ice front. This would result in damming of drainage and the development of large periglacial lakes, with allied cross drainage zones and many drainage reversals. Mazola (1962) indicated that the presence of a deeply buried, clean, pebble-free clay in the glacial deposits of this area is possibly an evidence of the drainage blockage. Leverett (1899), Arey (1909),

and Udden, (1900) suggested that similar clays in Iowa represent quiet water deposits formed after submergence of the region, a view which supports damming of the streams. Bain (1897) believes that these clays are closely associated to loess deposits and probably related to it. Alden and Leighton (1919) and Kay (1916) believe that these clays resulted from chemical leaching and weathering of Kansan and Illinoian tills.

Drilling in Kalamazoo County reveals the presence of an almost continuous layer of blue clay directly above the bedrock surface. There is no evidence of varving or stratification in this clay layer. However it contains lenses of sand and/or gravel and includes blocks of bedrock material. In some bedrock valleys, this clay deposit may reach a thickness of 50 feet or more. Even in places where the clay is comparatively thick, a gradual change of clay to till has not been observed. This information, plus the fact that the clay layer is notably thicker in bedrock depressions, suggests that it may have been deposited under stagnant ice conditions due to glacial damming or drainage and not due to leaching of older till deposits. The clay may also be outwash deposit formed during a long interval of still stand in the initial phase of Wisconsinan glaciation. In this case the clay may be eroded rock flour produced during the early glacial advance.

Bedrock Channel Deposits as Ground Water Aquifers

As previously stated, many bedrock channels in other areas contain exceptionally thick sand and gravel deposits which can be developed into ground water aquifers. Some bedrock valleys, however, offer a better chance of containing sorted glacial sediments than others. Generally, the quality of glacial sediments in a buried bedrock channel depends on the following:

1. Age of glacial sediments. Older glacial deposits are more compact and cemented than younger sediments.
2. Direction of flow in the channel relative to ice advances.
 - a. Bedrock channels which slope in the same direction as the ice advance served as sluiceways for melt water. In this situation, the glacial debris tends to have been sorted resulting in excellent ground water aquifers (Wayne, 1956). The extent of sorting and quantity of outwash deposits in these valleys depend on the duration of the period during which the channel was active and the sediment load carried by melt water (Horberg, 1945).
 - b. When the direction of stream flow was toward the ice front, the stream channel became dammed and glacial lakes developed. In this situation the stream channel is mostly filled with clay silt, and mud, thus forming

a poor waterbearing material (Mazola, 1962; McGrain, 1948; Wayne, 1956).

- c. Periglacial or preglacial bedrock channels, developed parallel to the ice front while the ice front was stationary, may remain as active drainage channels for a long time. Accordingly, these channels may contain appreciable thicknesses of well-sorted outwash.

of the gravity readings agreed to within 0.2 scale divisions (about 0.02 mgals). The observed gravity reading was obtained by averaging the consistent readings.

The meter drift was estimated by reoccupying a selected base station every hour. In addition, gravity readings at two previously occupied stations were repeated during each hour to add extra precision to the drift correction. A base station (at the intersection of Texas Drive and 8th Street in Kalamazoo County) and fourteen sub-bases were established for the survey.

Reduction of Field Data

The observed gravity readings are not absolute, but rather are related to an arbitrarily chosen value. These relative readings must be corrected for various influencing factors which have no relation with subsurface geology. The values of these corrections can be accurately calculated and applied to the observed reading. The corrections are: (1) latitude correction, (2) free-air correction, (3) Bouguer or mass correction, and (4) terrain correction. The corrected gravity readings are known as the Bouguer gravity anomaly which is calculated by the following equation:

$$G_b = G_o + G_f - G_{bc} + G_t - G_e$$

where

G_b is the Bouguer gravity anomaly

G_o is the observed gravity reading corrected for meter drift

G_e is the latitude correction

G_{bc} is the mass correction

G_f is the free-air correction

G_t is the terrain correction

Latitude Correction

The Earth's gravity field increases from the equator to the poles. This increase is caused by a gradual decrease of the Earth's radius and the centrifugal force which opposes the Earth's gravitational field from the equator to the poles. The rate of the gravity field increase is $1.307 \sin 2 \theta$ mgals/mile, where θ is the latitude. The area under investigation lies between latitudes $42^\circ 05'$ and $42^\circ 25'N$. The corresponding rates of increase in the gravitational attraction are 1.3017 and 1.3002 mgals/mile respectively. The difference between the two rates is very small, and their average of 1.301 mgals/mile or 0.0002464 mgals/foot was assumed for the entire area.

The gravity stations were placed on the Michigan coordinate system established by the U. S. Coast and Geodetic Survey. A base latitude was selected at the southern border of Kalamazoo County and the latitudes of the stations were related to it.

Mass Correction

The mass or Bouguer correction compensates for the gravitational effect of the mass existing between the ground surface and

the datum. The datum was chosen to be 700 feet above sea level which is the lowest surface elevation in the County. The mass correction is computed from the equation:

$$G_{bc} = 2 \gamma \rho dh'$$

where γ is the universal gravitational constant, ρ is the overburden density and dh' is the difference between the datum and station elevation. A density of 2.15 gm/cc was assumed for the overburden material. The rationale behind this selection will be discussed in detail in the section concerning density calculations.

Free-Air Correction

The free-air correction compensates for the effect on the observed gravity readings of the variation of surface elevation at observation points. The rate of vertical gravity variation can be written as:

$$\frac{\partial g}{\partial h} = -0.09406 - 0.0007 \cos 2\phi \text{ mgals/ft.}; \text{ where}$$

ϕ is the latitude

and $\frac{\partial g}{\partial h}$ is the rate of vertical gravity variation.

The effect of latitude variation on $\frac{\partial g}{\partial h}$ is small and can be neglected; accordingly

$$\Delta g = 0.09406 \Delta h' \text{ mgals; where}$$

Δg is the free-air correction and

$\Delta h'$ is the difference between station and datum elevation.

Terrain Correction

In areas where topography in the vicinity of gravity stations is reasonably flat, the application of the infinite slab formula to estimate the mass correction is adequate. However, in areas where the topographic relief is great, local topography can introduce errors in the calculations of these corrections. In these areas the terrain correction is needed to compensate for local topographic effects.

The expected maximum value for the terrain correction is negligible because surveyed roads were selected to avoid rough topography. This value was estimated not to exceed 0.02 mgals in the western part of Kalamazoo County where the topography is rather complex. As only very few gravity stations are expected to have terrain effects requiring this correction, the terrain correction is neglected.

After applying the above discussed corrections to the observed gravity readings, the resulting Bouguer gravity values were contoured. Plates 3a and 3b show the resulting contour maps for both the northern and southern half of Kalamazoo County.

Sources of Errors and Accuracy

The accuracy of reduced gravity observations depends on the magnitude of errors introduced in surface elevation, and in the

gravity and latitude measurements. Accuracy is also affected by the magnitude of the terrain effect which has been assumed to be negligible, and by any significant error in the assumed density for the glacial sediments forming topography.

To examine the accuracy of the gravity observations, thirteen gravity stations, each occupied twice, were selected so that the two gravity observations at each location correspond to different drift curves. The standard deviation for these repeated stations was calculated to be 0.023 mgals.

Surface elevation errors introduce subsequent errors in the calculations of free air and mass corrections. In areas of detailed survey, surface elevations were tied to bench marks to within ± 0.01 feet. Assuming no error in elevations of bench marks, the above error in surface elevation introduces a subsequent error of 0.0066 mgals in the calculation of free air and mass corrections. In the reconnaissance part of the survey, surface elevations are accurate to ± 0.1 of the contour interval of the United States Geological Survey Topographic Sheets. The contour interval in these sheets is either 10 or 20 feet. Therefore, the elevations are considered accurate within to ± 2.0 feet, which corresponds to an error of ± 0.132 mgals in the calculations of free-air and mass-corrections.

Latitude measurements were performed on a base map having a scale of 1:24,000. Station locations are accurate to ± 50 feet. The

Factors Controlling Densities

Density measurements on samples taken at different locations in a geologic formation often reveal that the density of individual formations varies significantly both laterally and vertically. Variations in physical properties such as mineralogy, porosity, composition, degree of saturation, texture, and degree of cementation, are all reflected in density variations. In relatively homogeneous formations, the range of density variations is usually small and an average density can be easily adopted. But other formations may be extremely heterogeneous. Thus, the use of an average density in gravity reductions can distort anomalies and lead to appreciable errors in interpretation. The extent of formation heterogeneity is especially critical where the geologically interesting gravity anomalies are of low amplitude, i. e., generally less than a few milligals.

Glacial sediments are a typical example of formations which may exhibit a wide spectrum of density. The pattern of this variation can be very complex and difficult to predict. A typical glacial deposit may be composed of a poorly sorted, inhomogeneous till which is made up of particles varying from a clay to boulder size. The boulders are usually randomly dispersed in a matrix of a smaller size particles. As a result of this conglomeration of different sizes, composition and textures, the density of till material usually varies within a rather wide range in contrast to glacial outwash deposits

which are more sorted and homogeneous. Therefore, glacial outwash is expected to show a more uniform density. Outwash deposits, however, are usually lenticular and seldom have great lateral or vertical dimensions.

Also, the effect of water table depth can be significant on the lateral density variation in glacial sediments. The thickness of glacial sediments lying above water table in Kalamazoo County varies between zero and one hundred feet. Since the density of porous sediments increases with the degree of water saturation, lateral variation in thickness of the glacial sedimentary section above the water table is expected to cause corresponding lateral variation in density. The order of magnitude of density variation as a result of saturation can be realized by noting that dry sands with twenty percent porosity upon saturation show 0.2 gm/cc increase in density.

Published Densities

A review of literature concerning density ranges of different rock types gives a quantitative perspective to the preceding discussion (Manger, 1963; Birch, 1942). For example, in Figure 2, which is adapted from Birch (1942) by Grant and West (1965), indicates that density of soil and alluvial material ranges from 1.6 to 2.2; sandstones from 2.0 to 2.7 and shales from 1.90 to 2.8 gm/cc. This

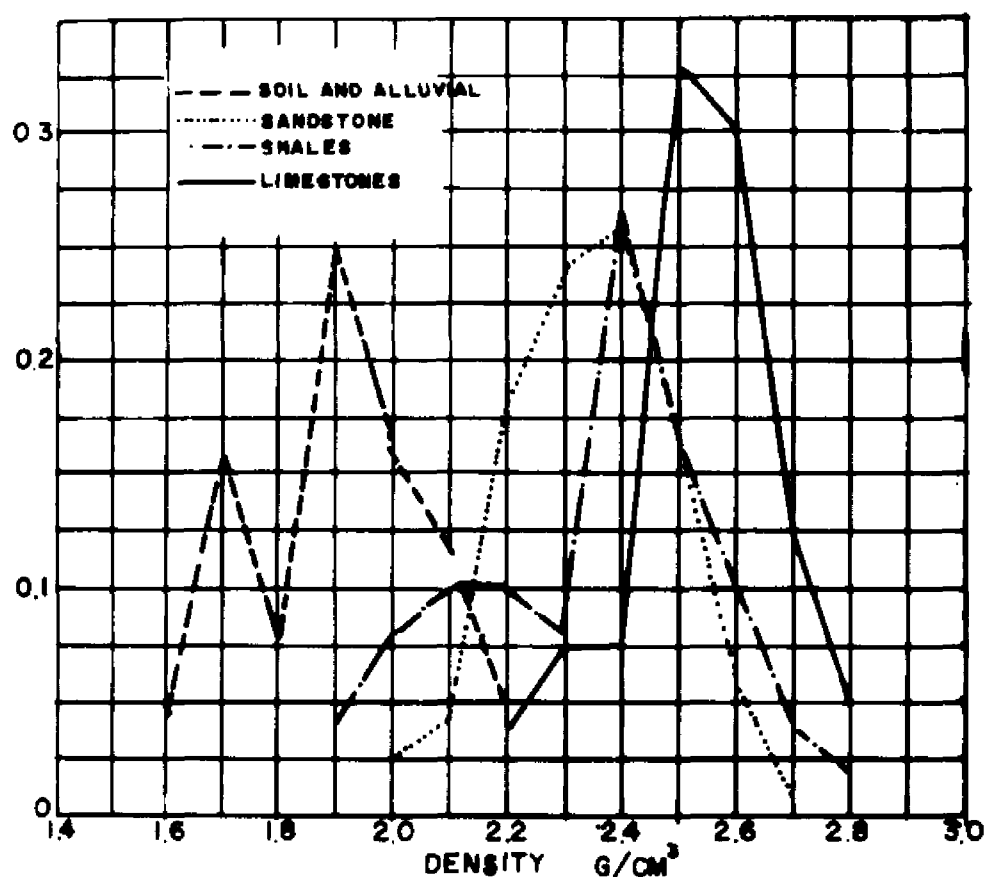


FIGURE 2 HISTOGRAM OF SMALL SPECIMEN BULK DENSITIES OF VARIOUS KINDS OF SEDIMENTARY ROCKS. [FROM BIRCH(1942) BY GRANT AND WEST (1965)]

figure also suggests an extensive density overlap among all the sedimentary groups. Part of this overlap probably results from the fact that these rock densities are plotted without regard to age or depth of burial.

Glacial sediments exhibit a similar density distribution. A typical section of glacial sediments may be formed of outwash or till deposits, or both. The outwash or till sections are usually formed of thin layers or lenses of intercalated sand, silt, clay, gravel, or mixtures of each apparently arranged at random. The density variation produced by such random distribution together with the possible density variation within the individual sediments themselves produce a complex lateral density variation pattern in the glacial sediments. To illustrate, Hall and Hajnal (1962) conducted laboratory density measurements on drill core samples of glacial sediments obtained from two test holes located near Kindersley, Saskatchewan, Canada. The results of their measurements are shown in Table 1.

Table 2 shows a tabulation of densities obtained from samples collected from eighteen drill cores taken from test drilling near Two Hills, Alberta, Canada, and in the neighborhood of Saskatchewan River (Lennex and Carlson, 1967). The densities of silt, sand, sandstone, and shale are nearly the same. The density of till seems to be appreciable higher. However, these densities are based

<u>Material</u>	<u>Density</u> gm/cc
clay	2.0
till	2.10-2.20
silt	1.80
sand	1.90-2.15

Table 1. Density of glacial sediments near Kindersley, Saskatchewan, Canada (after Hall and Hajnal, 1962).

<u>Material</u>	<u>Average Saturated Density</u> gm/cc	<u>No. of Samples</u>
silt	1.99	3
sandstone	2.00	6
sand	2.04	2
shale	2.05	2
till	2.25	5

Table 2. Density of Sediments near Two Hills, Alberta (after Lennox and Carlson, 1967)

on a very limited number of samples and may not be representative of the sedimentary rock types and glacial deposits in the cited areas, nor indeed in the area of the present concern.

Methods of Density Determination

Introduction

The reduction and quantitative interpretation of gravity observations requires prior knowledge of densities of various

subsurface formations. The reliability of gravity findings is largely dependent on the accuracy with which these densities are determined. Definitely, in situ density calculations give the best results because the measurements are carried out on rock samples in their natural situation. Such methods as borehole density logging, Nettleton's profile, variable density, together with a suggested method presented below and referred to as the gravity-geologic method, are examples of available techniques for in situ rock density calculation.

Laboratory Procedures for Measuring Densities

Laboratory density measurements consist of calculating the volume and weight of rock samples obtained by an appropriate sampling technique. The procedure is not well suited to unconsolidated rocks since the acquisition, handling, and transportation of samples often disturb them and lead to changes in their physical properties. In some cases, density measurements are preformed on samples taken at regular intervals in a formation. The resulting densities are then used to calculate a weighted average density or a smoothed depth-density function.

Commonly, the laboratory methods are used to determine an average density for overburden from samples restricted to surface

outcrops of the formation. However, in glacial and glacio-fluvial material differential compaction, cementation and saturation can lead to an increase of density with depth (Athy, 1930). To obtain a representative density of overburden this method requires a considerable amount of sampling, a large number of measurements, and a sampling technique which minimizes sample disturbance.

Density Profile Methods

Nettleton's profile method involves calculating an overburden density from gravity readings. The estimated density represents the density of material constituting the topographic feature. The procedure consists of taking closely-spaced gravity readings over a selected topographic feature. Then the gravity readings are reduced using different possible density values for the material forming topography. The average density of the overburden is selected to be the one which gives the least correlation between the Bouguer gravity and topography.

The topographic features employed in Nettleton's method should not be associated with a structural feature. In other words, the topographic feature used in this computation should not be one which is anomalous in its physical properties. Also, the relief of the feature should be appreciable so that accurate density calculations can be achieved. Moreover, the regional gravity

surface must be simple. The gravity stations should be located along a relatively straight line across the feature, their elevations should be measured accurately, and terrain corrections performed.

Although this method determines the average density of the material forming the topographic relief, it does not give information as to the density of rocks below the level of the lowest point of topography (Vajk, 1956).

Obviously, the Nettleton method requires much labor and relies on personal judgement to determine the density empirically. To circumvent the drawbacks of the profile method, Siegert (1942) suggested a least square method of calculating overburden densities. He assumed that the observed gravity reading along a relatively short segment of the profile vary linearly with distance. This assumed linearity permits the determination of interpolated gravity and surface elevation at a station from the straight lines drawn through the observed gravity and surface elevations of two stations on either side of the designated station. The same process of interpolation is performed on each station of the profile. If g_i and h_i are the differences between the interpolated and measured values of observed gravity and elevation at station i then $g_i = -k h_i$ where k is the combined free air and mass factor. The above mathematical formulation

demands that k is chosen so as to make $\sum_{i=1}^n (g_i - k h_i)^2$ a minimum, where n is the number of gravity stations along the profile. The least square procedure is applied to determine the value of k which makes the gravity profile as smooth as possible. This value of k is readily then converted to the overburden density.

Variable Density Approach

The application of an average density is justified in situations where the expected error due to variability of density is negligible when compared with the amplitude of the anomalies of interest. In many applications, the anomalies under investigation have a low amplitude, thus errors introduced because of abnormally high density variations may be of sufficient amplitude to severely distort or even mask the actual anomalies. The search for Niagaran reefs in Michigan by gravity provides an example of such a situation. Some of the most oil-prolific reefs do not exceed several tens of feet in thickness. They are buried under an overburden of a few thousand feet. The gravity anomalies associated with these reefs seldom exceed an amplitude of 0.3 mgals. In these cases if the density of the material forming the topography varies 0.1 gm/cc from the selected average, the actual anomalies will be distorted by 0.13 mgals in areas where a surface topographic relief of 100 feet exists. This is an appreciable error compared

to the expected anomaly.

The approach of using a variable density in the reduction of gravity data has not received as much attention as it really deserves. Only three papers dealing with the subject are known to the author. Vajk (1956) demonstrated the necessity of using a variable density under certain conditions, however he did not suggest a definite procedure for calculating the variable density. Grant and Elsharty (1962) calculated the variable density by minimizing the correlations between surface elevation and Bouguer gravity residuals which were extracted from the Bouguer gravity and elevation surfaces by approximating the regional trends by polynomials using the method of least squares. Density residuals at individual stations were calculated to reduce the correlation between surface elevation and Bouguer gravity residuals. These density residuals were added to an assumed average density to obtain the variable densities.

This method of calculating a variable density may produce erroneous density values due to the ambiguity of the potential field used in the calculation. The errors in calculated densities are expected to be relatively high when deeply buried masses produce gravity anomalies of identical width to those produced by lateral density changes in surface sediments. It is also obvious that the gravitational effect produced by lateral variations

in density of surface sediments, and the surface elevation residuals are determined by approximating the regional effects by polynomials; a method which takes objectivity. Human judgement and experience greatly influence the outcome of the computations.

Merritt (1968) suggested a method of calculating a variable density of overburden material by utilizing observed gravity and elevation readings. All stations located within a predetermined radius of a center station were used to calculate the overburden density at the station. The coordinates of all the stations in each station group were calculated relative to the coordinates of the center station. The observed gravity values of stations surrounding and including the center station were approximated with a polynomial equation. The polynomial is a first degree function of the station elevation, and a first, third, or fifth degree function of the station coordinates. For example, the first degree polynomial equation is expressed as:

$$g_p = a_0 + a_1 \sum x_i + a_2 \sum y_i + a_3 \sum h_i$$

where

g_p is the predicted observed gravity.

a_i is the polynomial coefficient.

x_i and y_i relative station coordinates.

and h_i is the station elevation with reference to the datum. The

function g_p is chosen such that $\sum [g_o - g_p]^2$ is a minimum, where g_o is the measured observed gravity. The least square coefficient associated with the elevation term is utilized to calculate the overburden density at the center station. The densities obtained by applying this method greatly depend on the grid radius employed. If a unique density pattern is to be chosen, a method must be devised to determine the optimum grid radius.

Geophysical-Geological Method

The method presented here for calculating rock densities is similar to the approach suggested by Legge (1944). He noted that the Bouguer gravity anomaly can be represented by

$$G_i = \sum_{j=0}^n \sum_{l=0}^m a_{jl} x_i^j y_i^l$$

where G_i is the Bouguer gravity anomaly at station i

a_{jl} is the polynomial coefficient

x_j and y_l are the x and y coordinates of station i .

The Bouguer gravity anomaly also can be written as follows:

$$g_{Bi} = g_i + k h_i'$$

where

h_i' is the difference between the station elevation and datum

g_{Bi} is the Bouguer gravity anomaly

k is the combined mass and free-air factor

g_i is the latitude corrected observed gravity.

The least square principle demands that:

$$\sum_{i=1}^N [(g_i + k'hi) - \sum_{j=0}^n \sum_{\ell=0}^m a_{j\ell} x_i^j y_i^\ell] = \text{a minimum.}$$

Legge's method is modified here so that the available geologic information could be utilized as additional control in calculating an average density for both the glacial sediments and bedrock. The geologic information consists of the thicknesses of glacial and bedrock sediments at 256 test hole locations assuming a datum of 300 feet above sea level. For each well location, assume that h_i is the thickness of glacial sediments, while H_i represents the thickness of bedrock material above the chosen datum. Let us assume, also, that the Bouguer gravity anomaly can be written as:

$$G_i = \sum_{j=0}^n \sum_{\ell=0}^m a_{j\ell} x_i^j y_i^\ell$$

where G_i is the Bouguer gravity anomaly at test hole i

$a_{j\ell}$ is a polynomial coefficient

x_i and y_i are the location coordinates of test hole i .

The mass or Bouguer correction which should be added to the free-air anomaly to obtain the Bouguer gravity anomaly can be written as:

$$K(\rho_1 h + \rho_2 H)$$

where $K = \text{constant}$

ρ_1 and ρ_2 are the densities of glacial and bedrock sediments, respectively.

Accordingly, we can write

$$g_{Bi} = g_{oi} - K (\rho_1 h_i + \rho_2 H_i)$$

where g_{oi} is the free-air anomaly at test hole i . The least square principle demands that:

$$\sum_{i=1}^N [g_{oi} - K (\rho_1 h_i + \rho_2 H_i) - \sum_{j=0}^m \sum_{l=0}^m a_{jl} x_i^j y_i^l]^2 = \text{a minimum}$$

where N represents the total number of test holes. This equation is a first degree function of the thickness of the glacial and bedrock sediments above the datum. Dividing each term of the equation by K , the least square coefficient of h_i and H_i yield the glacial and bedrock average densities directly. Density values were computed for up to fourth degree function of the station coordinates.

The elevation datum was chosen to be the lowest known bedrock elevation. Free-air anomalies at test holes where direct gravity observations were not made were calculated by interpolation from a previously compiled Bouguer gravity contour map using an arbitrarily chosen density of 2.15 gm/cc.

This method was applied to all existing test holes which reached or penetrated the bedrock surface and the results are shown in Table 3. this table shows the densities of glacial and bedrock sediments corresponding to a regional trend representation of up to the fourth degree polynomial. Also shown are the

sums of the squared residuals.

Degree of Polynomial	1st	2nd	3rd	4th
ρ_1 gm/cc (glacial sediments)	1.90	1.95	2.15	2.09
ρ_2 gm/cc (bedrock sediments)	2.08	1.95	2.43	2.30
Sum of squared residuals	435	248	156	130

Table 3. Density values resulting from applying the geophysical-geological method to all test holes in Kalamazoo County.

It is apparent from Table 3 that fairly reasonable density values were obtained by using a third degree function of the x and y coordinates. The fourth degree function representation resulted in an abnormally low bedrock density while the sum of the residuals is the lowest.

Table 4 shows that the results which were obtained when calculations were stricted to 25 test holes chosen in areas covered with till type glacial sediments. Most of these wells are located in the Kalamazoo Moraine.

Degree of Polynomial	1st	2nd	3rd	4th
ρ_1 gm/cc (glacial sediments)	2.44	2.16	1.95	2.10
ρ_2 gm/cc (bedrock sediments)	2.95	2.29	1.38	2.08
Sums of squared residuals	0.56	0.26	0.06	0.02

Table 4. Density values obtained by applying the geophysical-geological method to test holes located in areas covered with till deposits.

The first degree representation in x and y of the Bouguer gravity produced density estimates which appear to be in best agreement with values anticipated from previous studies. However, the sum of the squared residuals is larger than that obtained from the higher degree equations. To further investigate the extent of density dependence on the type of glacial sediment, Kalamazoo County was divided into several overlapping areas depending on the nature of surface glacial deposits. The areas were also delineated to insure that enough relief on the bedrock surface existed within each area (minimum of 50 feet) to allow a reliable estimate of densities. The results, however, did not show a coherent relationship between the densities obtained and the type of glacial deposit.

The failure of the method may be accounted for by the limited data and the interpolation process employed to obtain gravity values at test hole locations where direct gravity observations were not available. Also, the polynomial representation of the Bouguer gravity anomaly may not eliminate the regional effects quantitatively.

The assumption that $K_1 (\rho_1 h_1 + \rho_2 H_1)$ represent the gravitational effect of both the bedrock and glacial sediments above the datum implies that topography of the ground and bedrock surfaces are sufficiently horizontal that glacial and bedrock sediments

above the datum can be represented by infinite slabs. However, in cases where the bedrock and surface topography exhibit considerable relief the infinite slab assumption may lead to erroneous results. In these situations, an alternative procedure is suggested based on a method devised by Talwani, et al (1959) for the calculation of the gravitational effect of irregular two dimensional bodies. The cross section of the drift and bedrock layers are approximated by polygons as shown in Figure 3. The combined gravitational effect of the glacial and bedrock material above the datum can be written as:

$$f_1(X, Z) \rho_1 + f_2(X, Z) \rho_2$$

where $f_1(X, Z)$ and $f_2(X, Z)$ are the gravitational effects of glacial and bedrock layers respectively assuming a density of 1.0 gm/cc.

They can be expressed as: $f(X, Z) = 2\gamma \sum_{p=1}^I \int_{Z_p}^{Z_{p+1}} \left(a_p + \frac{b_p}{Z''} \right) dZ''$

$$\text{where } a_p = \frac{X_{p+1} - X_p}{Z_{p+1} - Z_p} \quad b_p = \frac{X_p Z_{p+1} - X_{p+1} Z_p}{Z_{p+1} - Z_p}$$

In these equations (Figure 3) p represents the polygon side number, X and Z are the coordinates of polygon corners. The summation is carried over the I sides of the Polygon. Accordingly, the least square principle demands that:

$$\sum_{i=1}^{i=N} [g_{oi} - \{f_1(X, Z) \rho_1 + f_2(X, Z) \rho_2\} \sum_{j=0}^n \sum_{k=0}^m a_{jk} x_i^j y_i^k]^2 =$$

a minimum where g_{oi} is the free-air gravity anomaly at well

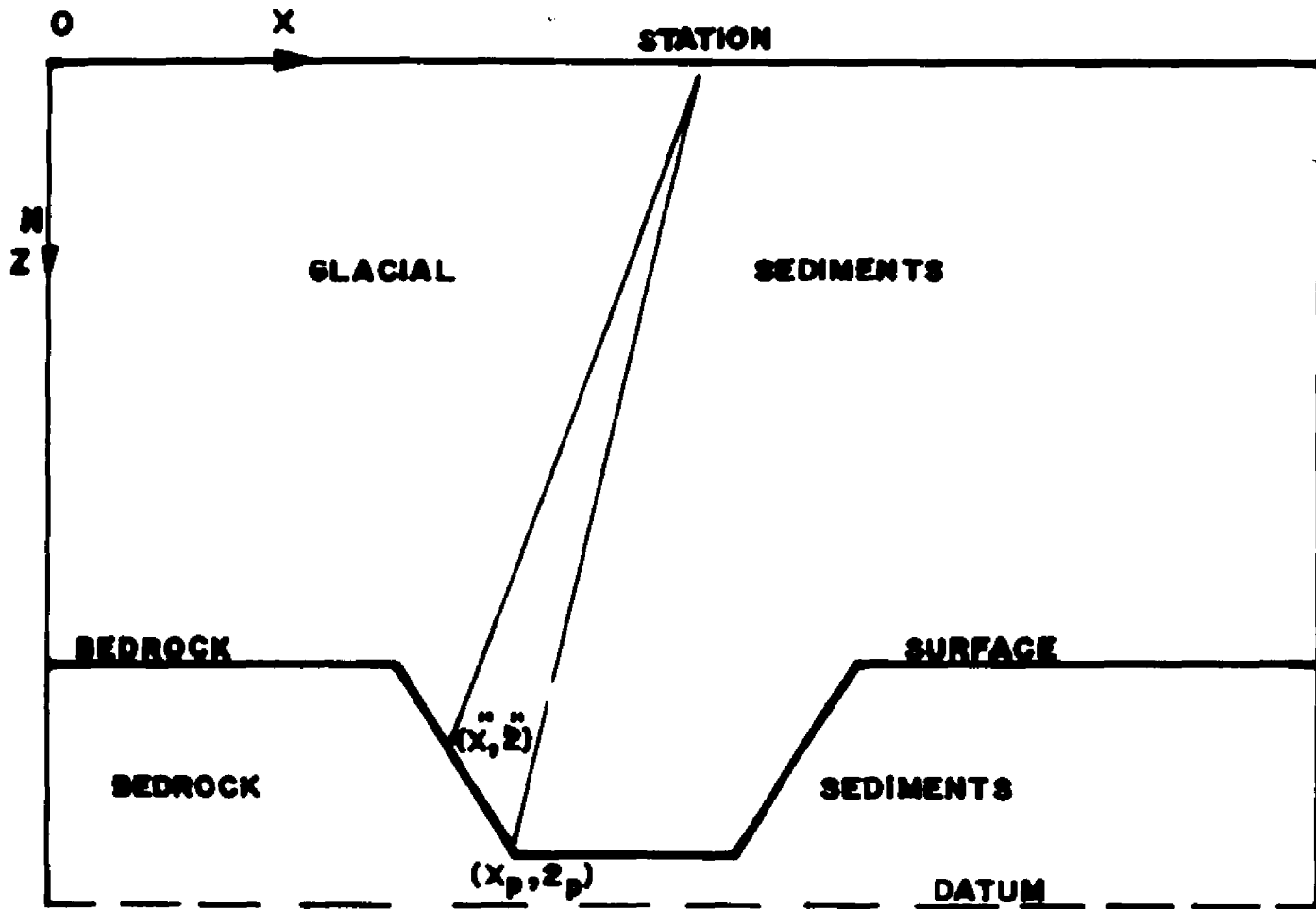


FIGURE 3 POLYGON REPRESENTATION OF GLACIAL
AND BEDROCK SEDIMENTS

number i and other symbols are as defined above. The choice of a density of unity for the density of both the glacial and bedrock sediments in calculating $f_1(X, Z)$ and $f_2(X, Z)$ makes their least square coefficients equal the density of the glacial and bedrock sediments. This modified approach has been applied to profile P shown in Plate 2a which is established by six wells. The profile is located in Comstock and Kalamazoo Townships where the surface sediments are mostly outwash glacial deposits. Table 5 shows the densities calculated by fitting polynomials of up to the fourth degree to the Bouguer gravity anomaly.

Degree of polynomial	1st	2nd	3rd	4th
ρ_1 gm/cc (glacial sediments)	1.80	1.90	2.27	1.43
ρ_2 gm/cc (bedrock sediments)	1.70	2.16	2.60	1.76
Sum of squares of residuals	10.50	1.94	0.95	0.55

Table 5. Densities of bedrock and glacial sediments obtained by approximating the two dimensional glacial and bedrock masses by polygons.

The third degree polynomial is shown to yield the best density values. It is also clear that the fourth degree polynomial, while showing the smallest sums of the square of the residuals, does not yield realistic densities.

Attempting to assign an average density to the glacial and bedrock sediments using the above listed results appears to be

a risky venture. The sum of the squares of the residuals cannot be used as criterion for selecting the most suitable equation to represent the regional effect. The density values corresponding to the smallest sum of the squares of the residuals in most cases do not fall within the known range of density variation. Accordingly, a reasonable average density was selected for the glacial and bed-rock materials, based on published data. Unconsolidated sand, gravel, and clay deposits usually have a density ranging between 1.9 and 2.1 gm/cc depending on compaction, cementation and the degree of saturation. Till materials, on the other hand, have generally higher densities which vary between 2.1 to 2.3 gm/cc. An average density of 2.15 gm/cc was assumed for the glacial sediments because sediments could be till or outwash type deposits or a combination of both. This value lays midway between the normal density of the till material and that of sand, gravel, and clay deposits. This density value also was determined by Klasner (1963) using Nettleton's profile method in the New Haven, Michigan area which is immediately to the west of Kalamazoo County. The use of two separate density values in the reduction of gravity data depending on whether we are dealing with areas covered with till or outwash deposits appears very appealing. However, glacial deposits often change nature at depths, and unless proven otherwise, the use of an average density seems to be safest.

The density of the Coldwater shale was assumed to be 2.55 gm/cc. This value was obtained by laboratory measurements at the Department of Geology of Michigan State University and appears to be a reasonable estimate.

CHAPTER VI

REGIONAL AND RESIDUALS

Introduction

One of the most unfortunate facts about geophysical methods of exploration is that the measurements are not very selective in nature. Consequently they portray not only the distribution and physical characteristics of features of interest, but also anomalous bodies creating measureable effects at the point of measurement. Surface inhomogeneities and random reading errors often add to the complexity of the situation. The extraction of the anomaly of interest from this complex spectrum of overlapping effects is, therefore, a critical and certainly frustrating task entrusted to the geophysicist. Much of this frustration has been laid upon the ambiguity inherent in the mathematical representation of the potential field. This fact has been pointed out several times in literature (Skeels, 1947; Nettleton, 1954).

Conventional Methods of Isolation Residuals

The development of techniques for extracting residual gravity effects from the total effects has been the subject of intensive study for the last several decades. Several methods have been suggested

for this purpose. In this connection, two complementary terms have been introduced in literature; the "regional" and "residual". The "regional" or trend (Grant, 1954) is defined as the Bouguer gravity value which would have been obtained had the anomalies of interest been absent. The anomalies of interest are called "residuals" and are obtained by subtracting the regional from the Bouguer gravity. Therefore, depending on what we define as residual, numerous regional values can be obtained, and vice versa. The term "regional" by itself has no meaning unless the expected anomalies are completely defined.

From the practical point of view, the regional is often recognized as those smooth broad variations which have low curvature, suggesting deep-seated disturbances. Admittedly, this definition of the regional could be misleading.

The earliest method of regional elimination was by contour or profile smoothing. The justification of this procedure is that the smooth variations are attributed to anomalous masses which are considered to be too deep or broad to be of interest for exploration. This is the most empirical approach of defining the regional. This method may be useful in particular cases when the regional is simple and has a uniform gradient. However, in areas where the regional is complex, the method becomes very difficult to apply (Nettleton, 1954).

A more refined version of the above method is often called "cross profiling". This involves plotting gravity profiles in a network of intersecting lines. The spacing of these lines and their orientation depends on the degree of complexity and trend of the regional. The advantage of the cross profiling method is that the regional values at each point of intersection have to be the same for the two intersecting profiles by adjusting and modifying the regional curves. This method is still empirical and can lead to erroneous results. It is similar to the method of direct contour or profile smoothing except that the cross profiling method is done along two sets of profiles. This extra dimension may improve the accuracy of estimating the regional, especially in cases where the regional is rather complicated.

To evaluate cross profiling as a method of eliminating the regional gravity trend and producing gravity residuals indicative of bedrock topography, the method was applied to the Bouguer gravity map of Kalamazoo County (Plates 3a, 3b). One set of parallel profiles was established in the northeast-southwest direction parallel to the general Bouguer gravity gradient. The second set of parallel profiles was taken normal to the first, with the spacing between lines established at about three miles in both set of lines. After the cross profile routines were completed, the residual gravity values at 39 randomly chosen test holes were plotted versus bedrock

elevation (Figure 4). The selection of the 39 test holes was performed by drawing at random, ten percent of the test holes of each township with a minimum of two holes from each Township. Figure 4 shows that the scatter of points on either side of the least square line is appreciable. A value of 0.21 was obtained for the correlation coefficient, resulting in a coefficient of determination of 0.04 indicating that only 4 percent of the observed variations of the gravity residuals obtained by cross profiling is attributed to bedrock topography. A test of significance at the 5% and 1% levels indicates that the above correlation coefficient does not differ from zero. The points in Figure 4 which are enclosed in squares represent maximum negative deviation from the least square lines. Most of these points correspond to test holes located over very prominent, broad, relatively low Bouguer gravity anomalies which are caused by deep seated mass distributions. Obviously, the cross profile method did not remove these anomalies completely and the residuals were accordingly lower than expected. Similarly, the circled points of Figure 4 show anomalously higher values of residuals. These points correspond to test holes located over a prominent broad gravity high which was not completely eliminated as a regional effect. Accordingly, most of the scatter of points in Figure 4 indicates that the cross profile method can produce distorted gravity residuals in terms of this analysis. To produce meaningful residuals by applying

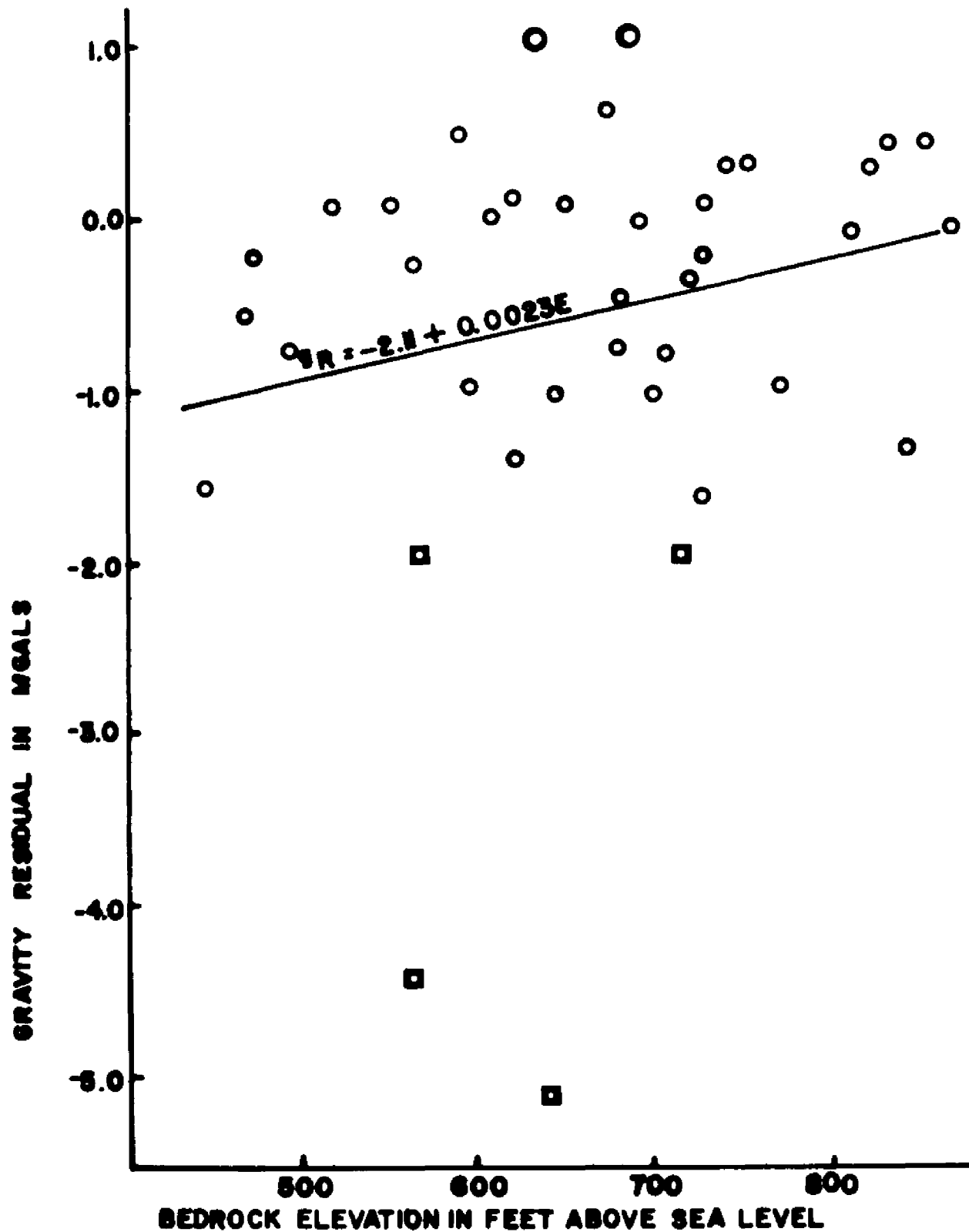


FIGURE 4 — RELATION BETWEEN CROSS PROFILE RESIDUALS (g_R) AND BEDROCK ELEVATION (E)

the cross profile method, the interpreter must be familiar with the geology of the area. Also, he should know the approximate amplitude, width and shape of gravity anomalies which are to be defined as residuals.

All the methods of contour or profile smoothing depend on the experience and judgement of the interpreter. In extremely complicated situations, different interpreters might arrive at totally different regional maps.

The apparent inadequacy of the smoothing technique has led various workers to the other approaches for regional evaluation. These techniques were designed in such a way that the interpreter's judgement is removed, as much as possible, from affecting the outcome of the regional calculations. Griffin (1949) suggested defining the regional as the weighted mean of the observed values at a number of points in the surrounding area. Using cylindrical coordinates he defined the regional according to the following equation:

$$G = \frac{1}{2\pi} \int_0^{2\pi} g(r, \theta) d\theta$$

where G is the regional and $g(r, \theta)$ is a gravity value at a point on a circle of radius r centered at the data point. He pointed out that this approach eliminates human bias. Peters (1949) and Elkins (1951) indicated that the residual obtained by applying this method could be equivalent to the second derivative. Nettleton (1954),

Swartz (1954) Dean (1959), and Ray and Jain (1961) indicated that the approach leads to different results depending on the grid spacing and the formula used. It is apparent that human judgement is not completely eliminated because the choice of the grid configuration and dimension is not based on any theoretical consideration.

In addition to the smoothing and gridding methods of calculating the regional, a group of analytical methods has been introduced in the geophysical literature. These methods commanded a great deal of popularity in recent years. The polynomial approximation of the regional by the method of least squares has proved to be one of the most popular of analytical methods. The earliest version was employed by Numerov (1929) on gravity data obtained over a lake. He assumed the regional to be a first degree polynomial of the form $a + bh + dy + cx$; where x and y are Cartesian coordinates, h is the depth of water in the lake, and the constants, a , b , c , and d are determined by the least square method. Agocs (1951) demonstrated the applicability of the method for the removal of a plane regional superimposed on the gravitational effect of a sphere. He remarked that the method can be used to approximate a more complicated regional by using a higher order polynomial. Simpson (1954) used a higher order polynomial. He conceded that large amplitude local anomalies or blunders in observations could lead to local unrealistic estimates of the regional.

While the idea of using polynomials seems to keep human bias at a minimum, some assumptions have to be made as to the properties or behavior of the raw data. These assumptions are usually employed to establish checks and controls through which the equation that best fits the data can be selected. It is usually assumed that the residuals occur at random and that positive and negative local disturbances have about equal probability of occurrence. Therefore, the sum of residuals should be a minimum.

In the traditional way of executing the least square fitting of a polynomial, a low order polynomial equation is initially used, and the least square method is applied to calculate the coefficients. More terms are then added to produce a higher order equation which is subjected again to the least square analysis. This process of adding more terms and calculating coefficients is usually repeated until a polynomial equation which produces a minimum sum of the squared values of residuals is obtained. Obviously, certain terms are common to several polynomial equations. The coefficient of each one of these terms is determined once for each equation in which it exists because the coefficient of a certain term may depend on the polynomial equation in which it exists. To avoid the added labor of calculating the coefficient of some terms several times, the approach can be modified in such a way that the effect of any term in the polynomial can be separately investigated so that, step by step, a check of the goodness

of fit can be achieved. This approach was described by Oldham and Sutherland (1955), and Grant (1957), who assumed a regional equation of the form:

$$G = b_0 p_0 + b_1 p_1 + \dots + b_n p_n$$

where the p_j 's are polynomials in x and y , the b 's are coefficients, and p_j being of degree j . The polynomials are determined so that

$\sum (p_j p_k) = 0$ when $j \neq k$. The summation is taken over all the occupied values of x and y . This modified version is superior to the conventional polynomial approximation because the coefficients and the standard error are independent of the degree of the polynomial fitted. The computations can be carried out faster and with less labor. This is especially advantageous in case of high degree polynomials.

The residuals obtained by fitting a polynomial to the regional are not particularly suited for quantitative interpretation. The statistical basis behind the method assumes that the average value of the residual is zero. In other words, the probability of occurrence of positive and negative residuals is equal. In the majority of actual cases, this assumption seems to be hardly tenable. When we, for example, wish to delineate preglacial valleys or locate salt domes, we are expecting to compute a regional which will yield predominately negative residuals.

The extraction of gravity residuals by approximating the regional gravity trend by a polynomial applying the method of least squares

was performed on the Bouguer gravity map of Kalamazoo County. The gravity residuals corresponding to the fifth and seventh degree polynomial representation of the regional were calculated at the 39 test hole locations described in the discussion of the cross profile method. These residual values plotted versus bedrock elevations and the results are shown in Figures 5 and 6 which correspond respectively to the fifth and seventh degree polynomial regional. It is apparent that Figure 5 displays less scatter of points than Figure 6. This is also apparent from the values of the correlation coefficients of 0.44 for the fifth and 0.34 for the seventh degree polynomial representation of the regional. The corresponding coefficients of determinations are 0.19 and 0.12 respectively. These values of the coefficient of determinations also indicate that, in this study, the gravity residuals obtained by approximating the regional trend by polynomials is superior to those from cross profiling in reflecting bedrock topography. Tests of significance of the correlation at the 5% level indicates that the correlation between bedrock elevations and polynomial residuals is significant. At the 1% level the correlation between fifth degree polynomial residuals and bedrock elevations is significant while the seventh degree polynomial residuals are not significantly correlated to bedrock elevations. The deviations of the residuals from the least square lines in Figures 5 and 6 indicates that the method of representing the regional trend by polynomial analysis often results in distorted

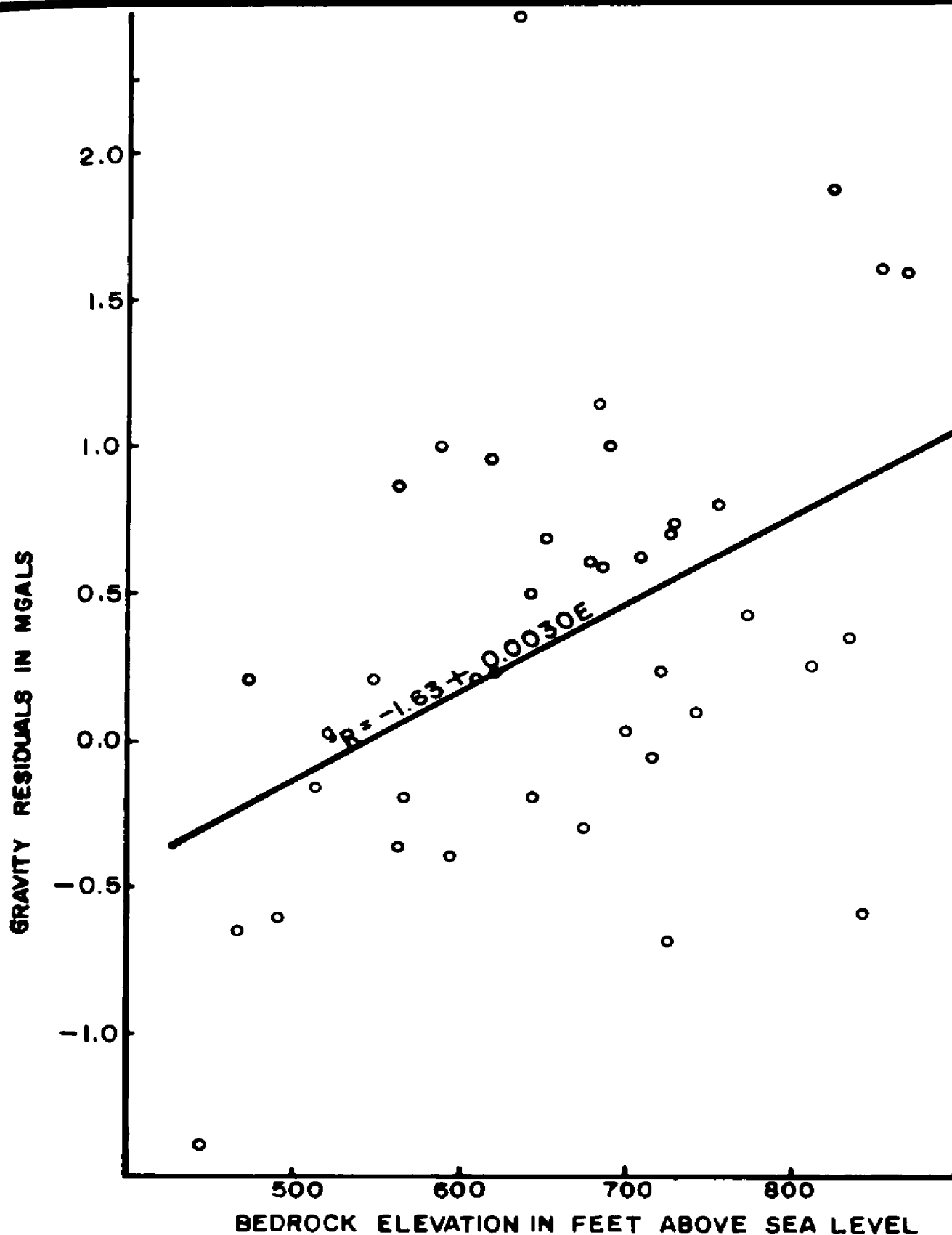


FIGURE 5 — RELATION BETWEEN FIFTH DEGREE POLYNOMIAL RESIDUALS (gR) AND BEDROCK ELEVATION (E).

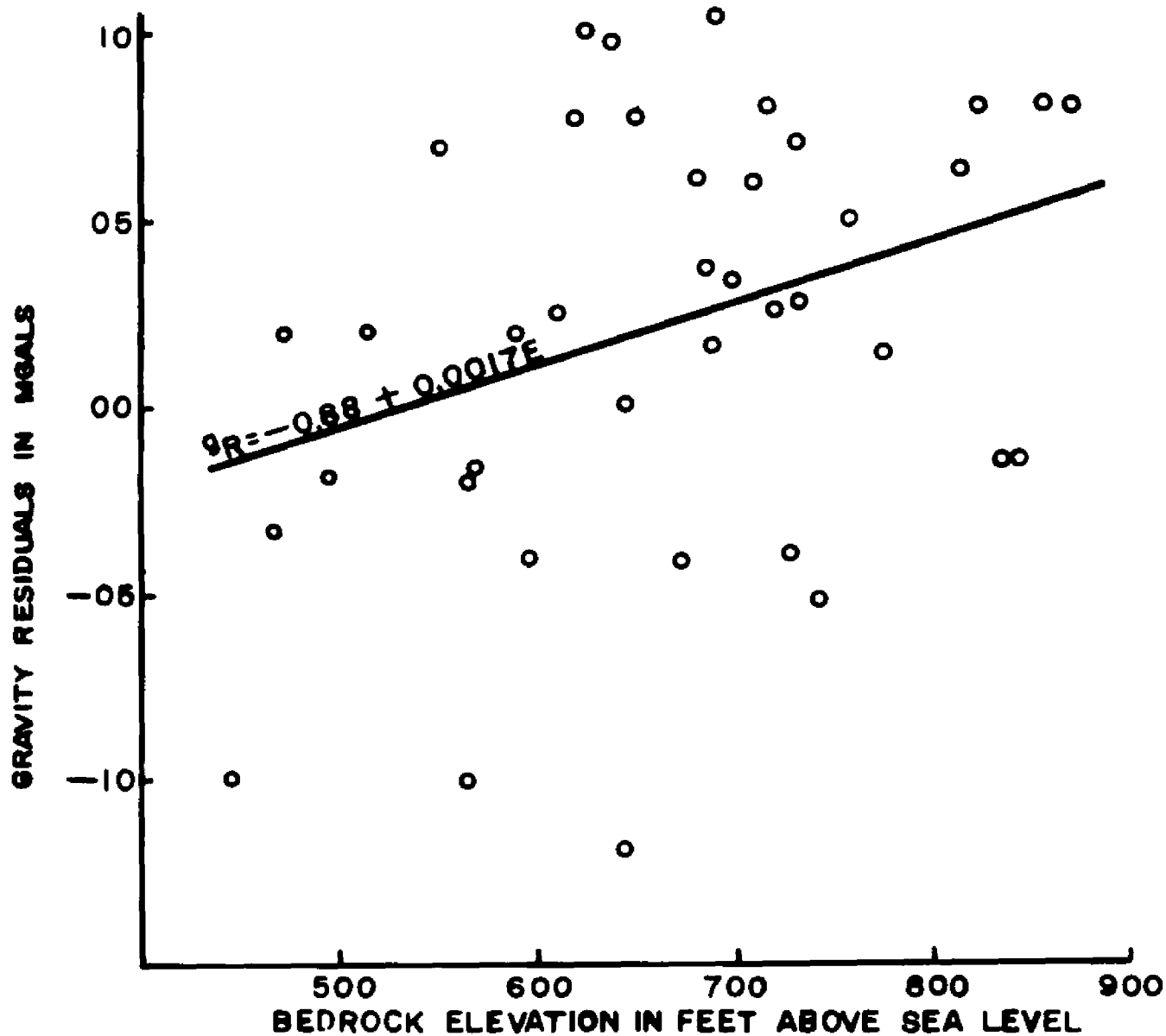


FIGURE 6 — RELATION BETWEEN SEVENTH DEGREE POLYNOMIAL RESIDUALS (gR) AND BEDROCK ELEVATION (E).

residuals as in the case of the cross profile residual.

The above discussion concerning the available methods for the extraction of the residual anomaly from the observed potential field, point out that, although the methods are numerous and diversified, none of them seems to offer a totally objective residuals. However, some are more objective than others. The grid methods are subjective and empirical. The labeling of their results as residuals is questionable.

The polynomial approximation of the regional may lead to a more realistic evaluation of the regional than the grid methods, especially in situations where the regional is simple and can be represented by a low degree polynomial. In most cases, however, the residual pattern obtained is only suited for locating trends rather than for quantitative interpretation.

The cross-profiling method is generally favored in producing the most realistic residuals, especially when the interpreter has a fairly thorough knowledge of the subsurface geology of the area, and particularly, of the structure he is exploring.

Geologic Residual Gravity Anomaly

The above discussion demonstrates the fact that gravity residuals obtained by employing any of the described methods can be extremely inaccurate in defining the bedrock topography. The application of these residuals in calculating the dimensions and depths of mass

distributions characterized by small amplitude anomalies in areas of complex regional gravity may lead to erroneous results. The accuracy of the results is certain to be enhanced when known geology is incorporated. It is the goal of this suggested method to apply the geologic information available in Kalamazoo County, and the observed Bouguer gravity in calculating gravity regional and residual effects. The available geologic information consists of 256 test holes reaching or penetrating the bedrock surface together with 50 additional test holes which penetrated a considerable thickness of glacial sediments.

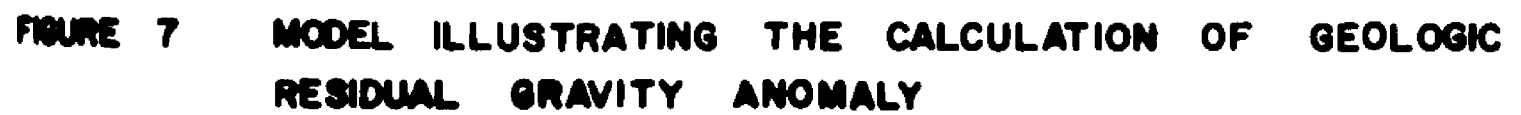
To apply this method, it is essential to assume that the regional gravity effect is broad, and the test holes are located so that the interpolation of calculated regional gravity at test hole locations completely defines the regional gravity effect. The assumption that the regional effect is simple and regional anomalies rather broad is justified because the regional anomalies are caused by deeper, and generally broader density variations in the Paleozoic section and underlying rocks.

The regional gravity effect at a specific location is here defined as the observed Bouguer gravity which would be obtained had the bedrock material, above a datum, been replaced by glacial sediments. The datum was chosen to be the lowest elevation point on the bedrock surface in Kalamazoo County, and is 300 feet above sea level. Accordingly, the residual Bouguer gravity anomaly is defined as the gravitational effect of the surplus mass due to the existence of

denser bedrock above datum elevation rather than glacial sediments.

To illustrate the method, let us assume that at a specific test hole location ρ_1 , ρ_2 and h , H are the densities and thicknesses of glacial and bedrock sediments respectively (Figure 7). At this location the surplus mass caused by the presence of H feet of bedrock material instead of glacial sediments contributes $g = 2\pi\gamma H (\rho_2 - \rho_1)$ milligals to the gravity reading. This effect here defined as the residual Bouguer gravity. For a constant density contrast, the residual Bouguer gravity is directly proportional to the thickness of the bedrock section above the assumed datum elevation. The regional Bouguer gravity at the location is obtained by subtracting the residual Bouguer gravity from the observed Bouguer gravity. It must be emphasized here that the surplus mass effect or residual Bouguer gravity is always positive as long as H is positive. However, in locations where bedrock surface is below the assumed datum elevation, H is negative and the residual Bouguer gravity also is negative.

A density contrast of 0.4 gm/cc was assumed for the density contrast ($\rho_2 - \rho_1$) and the regional gravity effect at each test hole location was calculated as described above. The regional values which were computed at well locations were interpolated to define the regional surface. A suitable approach would be to fit a polynomial using the method of least square to the regional values or to contour them directly. Direct contouring was selected because



**FIGURE 7 MODEL ILLUSTRATING THE CALCULATION OF GEOLOGIC
RESIDUAL GRAVITY ANOMALY**

many test holes, not reaching bedrock, have been employed as extra control in the contouring process. The maximum depth of penetration of these test holes was used in the same manner to calculate a minimum value of the regional which was used as a regional contouring guide. The Bouguer gravity values at the test hole locations were computed from direct gravimetric readings or interpolated from the Bouguer gravity contour map. The gravity regional contour map was employed to estimate the gravity regional at every gravity station. The gravity regional value was subtracted from the Bouguer gravity anomaly value at each gravity station to produce the residual gravity anomaly value. These were contoured to produce the residual gravity contour map shown in Plates 4a and 4b. A contour interval of 0.2 mgals was selected. The conversion of residual gravity to bedrock elevation can be achieved using the following equation:

$$E_B = g_R / [2\pi\gamma(\rho_2 - \rho_1)] + D$$

where

g_R is the value of the residual gravity at a gravity station

γ is the universal gravitational constant

D is the chosen datum elevation (300 feet above sea level)

$\rho_2 - \rho_1$ is the density contrast between bedrock and glacial sediments (0.4 gm/cc)

E_B is bedrock elevation relative to sea level.

It is apparent from this equation that a residual value of zero represents a bedrock elevation of 300 feet above sea level. Positive and

negative residual values represent bedrock elevations greater or less respectively. Bedrock elevations were calculated at each gravity station and contoured to obtain the bedrock topography map (Plates 5, 6a and 6b).

Because of the density of the glacial drift in particular may vary considerably, the expression ($\rho_2 - \rho_1$) is also expected to vary. The effect of this variation on the accuracy of the method of calculating gravity residuals depends on the range of density variation. In areas where local density contrasts are more than the assumed 0.4 gm/cc, the calculated bedrock elevations are expected to be higher than true values, and vice versa.

The assumption that the bedrock upper surface is a gently undulating surface to justify the approximation of bedrock masses by infinite slabs, is another possible source of error. Glacial erosion certainly smoothed and reduced the relief on the bedrock surface; yet, some glaciated valleys may have sufficiently steep sides to impair the validity of the assumption. To evaluate the effect of an irregular complex bedrock surface on the accuracy of our calculations, let us assume a situation as shown in Figure 7.

The glacial drift is shown to overlay a flat bedrock surface except for the presence of a bedrock channel. Suppose that the elevation of the bedrock surface is to be calculated at points A, B, C, D, and E employing the residual gravity values at each location. The errors

introduced in the calculations of the regional, residual, and bedrock elevations at any point between A and E can be explained as follows:

(1) At point A located at a large distance from the edge of the valley, the errors introduced are insignificant. (2) At B, directly above the edge of the valley, the error is expected to be maximum. Its magnitude depends on the depth, and the steepness of the valley sides. The application of the infinite slab formula to the residuals in this location to calculate bedrock elevation implies that the valley is neglected.

The presence of the valley renders the value of the residual gravity at location B less than what it would be in the absence of the valley.

Therefore, the application of the infinite slab formula to calculate the bedrock elevations at B from the residual gravity value results in bedrock elevation which are less than the true values. (3) At D,

the error is also maximum. The infinite slab assumption implies the absence of the bedrock material above the valley floor. The presence of such material renders the residual gravity at location D more than its value if the bedrock material above the valley floor was absent. Therefore, at location D, the calculated bedrock ele-

vation is expected to be higher than the actual values. (4) As we move towards E, the errors decrease until they reach a minimum at the center of the valley. (5) At location C between B and D, the absolute value of the error is less than that at either point, B or D.

In this region applying the infinite slab formula implies that we are

adding the bedrock mass labeled 1 and at the same time, ignoring the presence of the mass labeled 2 (dotted). The two errors reduce each others effect, and the net result is a smaller error. At a certain location C, between B and D, the gravitational effect of the added mass is equal to that of the ignored mass, and the net error is zero. Because the number two mass is always closer to the surface than mass number one, point C is always closer to B than D.

The magnitude of errors introduced in the calculations of bedrock topography by applying the infinite slab formula in areas of complex bedrock topography can be visualized by a model study. The model employed is shown in the upper right hand side of Figure 8. The model indicates a flat-lying bedrock surface modified by a steep-sided bedrock channel. The slope of the bedrock valley sides was assumed to be 10° and its floor width 1000 feet. The glacial sediments were assumed to be 100 feet thick and the valley depth was varied between 25 and 125 feet, at 25 feet intervals. For each valley depth, the gravitational effect resulting from the excess mass produced by the presence of bedrock sediments instead of glacial sediments above the datum was calculated at several surface stations using the method suggested by Talwani, et al (1959). Using a density contrast of 0.40 gm/cc, these gravitational values correspond to what has been defined earlier as the residual Bouguer anomaly. The suggested approach for calculating

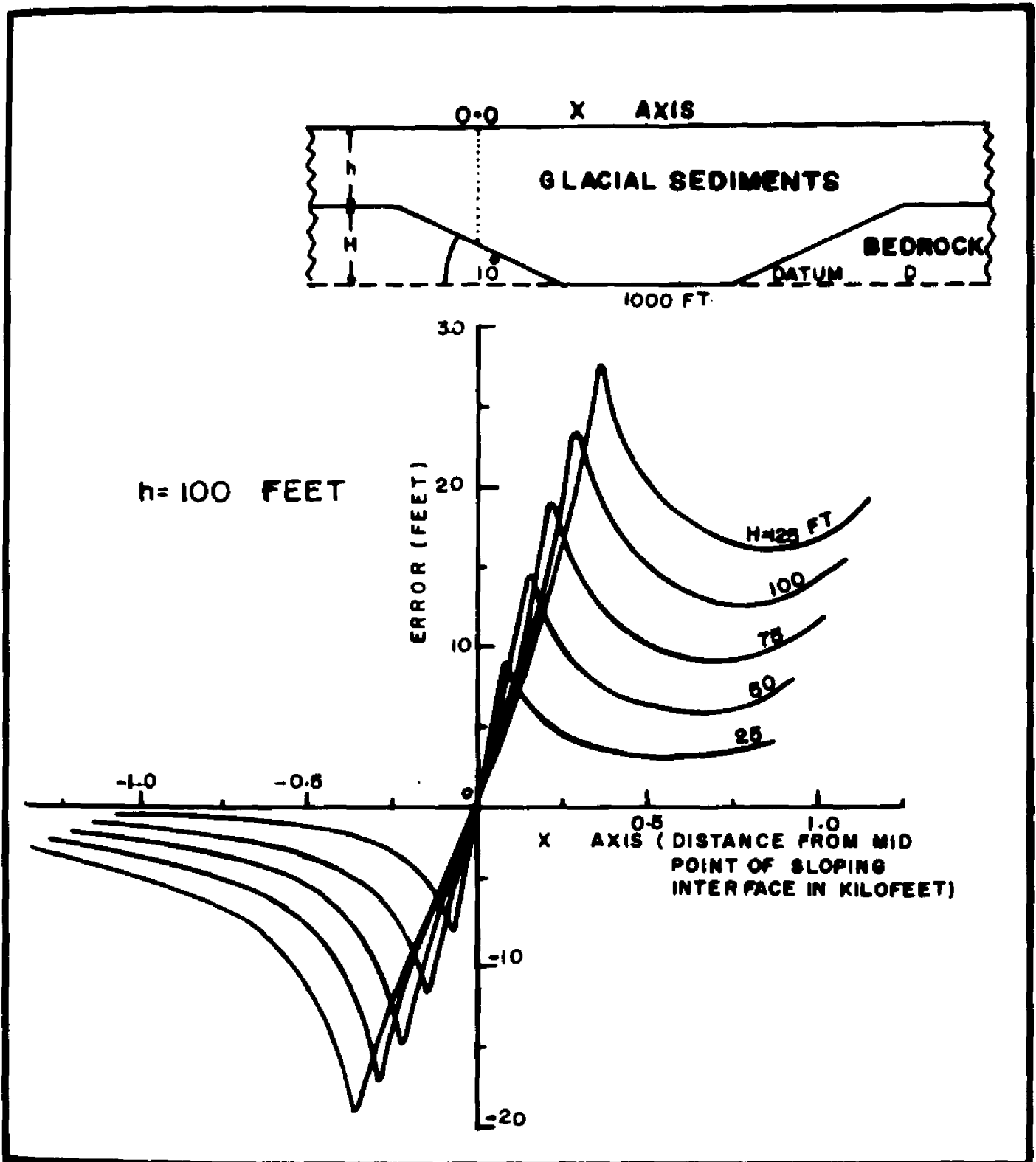


FIGURE 8 ERRORS IN CALCULATING THE THICKNESS OF BEDROCK SEDIMENTS ABOVE DATUM USING THE INFINITE SLAB FORMULA

the bedrock elevation from the residuals was then applied to each residual value at each surface station. The errors introduced in the calculations of bedrock elevations from the gravity residuals by applying the infinite slab formula was obtained at each surface station by subtracting the known bedrock elevations at each surface station (relative to datum D) from the calculated values. Figure 8 shows the magnitudes of the errors in terms of distance from midpoint on the side of the bedrock channel. As discussed above, the graphs show that the errors in calculating bedrock elevations from the residual gravity values are minimum at great distance from the edge of the valley and approximately half way down its sides. Errors are, however, maximum at the upper and lower points on the valley sides.

To demonstrate the superiority of this geologic method of isolating gravity residuals reflecting bedrock topography, the 39 test holes previously used to evaluate the residual maps were assumed nonexistent. The regional gravity values at each one of those test holes was estimated by interpolating the regional gravity values obtained by the geologic method at the surrounding test holes. The interpolated regional gravity value at each test hole was subtracted from the corresponding Bouguer gravity values to obtain residual gravity values. These residual gravity values are plotted versus bedrock elevation in Figure 9. This figure shows that the points in

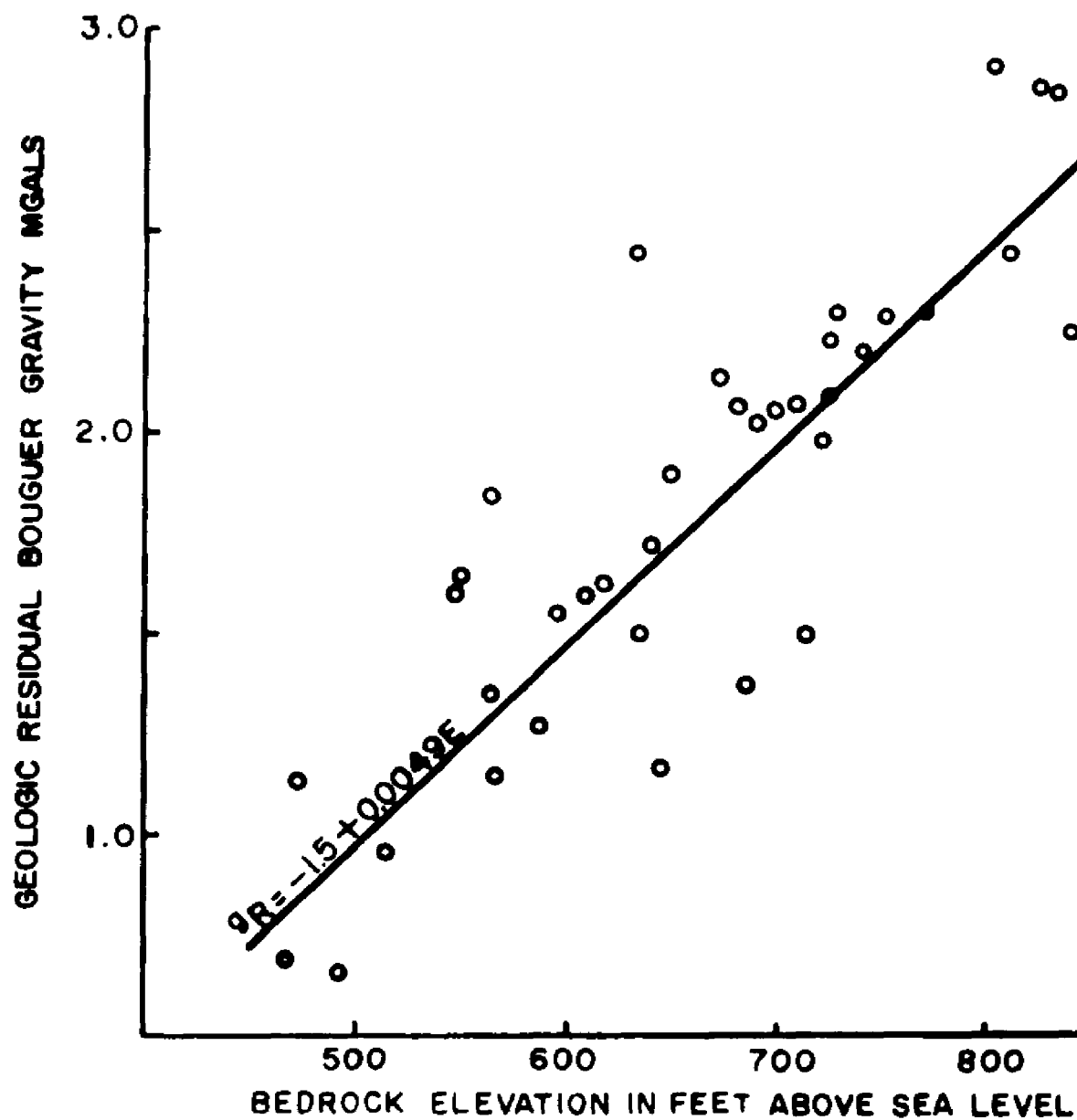


FIGURE 9 - RELATION BETWEEN GEOLOGIC RESIDUAL BOUGUER GRAVITY (g_R) AND BEDROCK ELEVATION (E).

the graph exhibit appreciably less scatter around the least squares line than those in Figures 4, 5 and 6. A coefficient of determination of 0.83 was calculated for the points of Figure 9. The correlation between bedrock elevations and geologic residual Bouguer gravity is highly significant at the 1% level. This shows that the geologic method is far superior to the methods of cross profiling and polynomial approximation of regionals by the method of least square in producing residual gravity values which reflect bedrock topography. Most of the points in Figure 9 which show appreciable deviation from the least squares line correspond to test holes located in areas where additional bedrock control is very scarce. The regional values at these test holes were thus obtained by interpolating from regional gravity values located at large distances from the test hole sites.

CHAPTER VII

DISCUSSION OF RESULTS

Bouguer Gravity Anomaly

The Bouguer gravity anomaly contour map of Kalamazoo County is shown in Plates 3a and 3b. As mentioned previously, a density of 2.15 gm/cc was assumed for the glacial sediment and an elevation of 700 feet above sea level was taken as the datum. The Bouguer gravity contour map represents the gravitational effect of all disturbing masses beneath the ground surface. These effects include lateral density variation and the local thickening and thinning within the glacial sediments, and the effect of structure and density variations in the Paleozoic section and basement complex.

The Bouguer gravity anomaly maps exhibit the following broad features:

1. A general northeast-southwest gradient of roughly 0.8 magls/mile is apparent, with value increasing to the south.
2. A gravity high is centered in the southwestern corner of Comstock Township. It extends eastward across central Charleston Township to the eastern border of the county. This gravity high seems to disappear towards the west in

west central Kalamazoo Township, due to the presence of a bedrock channel. It becomes noticeable again in section 22 and broadens in Osthemo and Alama Townships.

3. A prominent gravity high covers Prairie Ronde, Schoolcraft, and the southern half of Portage and Texas Townships. This gravity high trends north-northwest and displays its strongest expression in Northwest Schoolcraft Township.
4. A gravity high is located at the southeastern corner of the County and appears to extend southeastward into Calhoun and St. Joseph Counties.
5. A prominent area where the general Bouguer gravity gradient is very low trends northwest-southeast from the northern boundaries of Richland and Cooper to central Richland and Charleston Townships. It crosses the Kalamazoo County line at the southeastern corner of Charleston Township. In this area a broad low anomaly seems to be responsible for cancelling or greatly reducing the local gravity gradient. This feature coincides with a very prominent low in the total magnetic field.
6. A gravity low centered in east-central Climax Township extends eastward across south Pavilion and swings to the northwest in Portage Township. From there, it extends westward crossing the county line in west Texas Township.

Most of the anomalies discussed above generally have corresponding magnetic anomalies (Hinze, 1963). This correlation is very important in identifying the causative bodies of these anomalies and the isolation of gravity residuals. The glacial and Paleozoic sediments are known to have little or no magnetic effects. Therefore, we can conclude that these broad features in the Bouguer anomaly map are caused by structural and lithologic variations in the basement complex and hence should be eliminated as regional. This interpretation is substantiated by the generally low gradients of the gravity anomalies, which again indicate a deep source.

In addition to these broad features, the map also indicates the presence of local linear trends of relatively low Bouguer gravity values. These trends are caused by bedrock channels and will be described in detail in the section regarding the gravity residuals and bedrock topography.

Gravity Residuals

Bedrock Topography Residual Bouguer Gravity Anomaly Map

Plates 4a and 4b show the gravity residuals calculated by employing the well log information and the Bouguer gravity anomaly contour map. The residual values represent the gravitational effect of the excess mass resulting from the presence of denser bedrock sediments above the datum elevation (300 feet

above sea level) instead of glacial sediments. Defined in this manner, the residual gravity values are positive as long as the bedrock elevation is greater than the datum elevation. Negative residual gravity values indicate bedrock elevations less than the datum elevation.

Inspection of the residual contour map reveals the presence of several linear trends characterized by lower gravity residuals. These trends resemble a fluvial drainage pattern and are believed to be caused by bedrock channels. The most prominent linear low residual area is located just east of the western boundary of Kalamazoo County. Here it generally trends north-south. This trend enters the County at the northwestern corner and crosses the southern boundary at south-central Pararie Ronde Township. The lowest residual gravity values of zero mgals occur at two localities along the axis of the trend at the southwestern corner of Oshtemo and the west-central portion of Texas Townships.

Several additional low residual trends are apparent and have an east-west or northwest-southeast direction. The most prominent extends generally east-west across central Kalamazoo County. It enters the County at the northeastern corner of Charleston Township, continues northwestward to central Ross Township where it turns southward, then westward and continues

in this direction across Comstock, Kalamazoo, and Oshtemo Townships. This major trend is joined by several tributaries trending northwest-southeast and northeast-southwest. The drainage system of this trend appears to be very complex in and west of the City of Kalamazoo.

Other minor trends include an east-west bedrock channel and its two tributaries. This trend occupies the northwestern and north-central part of Kalamazoo County.

In addition to the above mentioned low residual gravity trends, several residual gravity highs also exist. The most prominent of these are located in northwestern Wakeshma, southwestern Climax, and southeastern Pavilion Townships. Several additional areas of high residuals are apparent in northwestern Kalamazoo, southeastern Oshtemo, northeastern Richland, and northwestern Rose Townships. These high gravity residuals reflect relatively high bedrock topography.

Gravity Residuals Obtained by Approximating the Regional by Polynomials

As mentioned previously, gravity residuals obtained by fitting a polynomial to the gravity data for the purpose of separating regional trends may not be suitable for quantitative interpretation. They are useful, however, for visual study of anomalous trends. With this in mind, gravity residuals were computed for gravity

regionals approximated by polynomials of fifth and seventh degrees. The County was divided into two parts by an east-west line in such a way as to permit areal overlap. The calculations were performed separately on these two halves. Residuals corresponding to the fifth and seventh degree polynomial regionals are illustrated in Plates 7a, 7b, and 8a, 8b.

Examination of the residual contour maps reveals the close similarity between the fifth and seventh degree residuals. However, as expected, the seventh degree residuals anomalies are generally of less amplitude than the fifth. Also, the seventh degree residuals show better resolution of anomalies than the fifth.

A careful comparison between residuals obtained by approximating the gravity regional by a seventh degree polynomial and the bedrock topography residual Bouguer gravity anomaly demonstrates the ability of the least square technique to outline anomalous areas. However, the method fails to define the regional quantitatively. The result is that gravitational effects of deeper bodies are not completely eliminated, thus causing distortions to the gravity residuals. For example, the gravity high located in southern Comstock is still very prominent in the fifth and seventh degree polynomial residuals. This anomaly is caused by basement effects and should be eliminated as a regional. The same situation is repeated in southern Texas and northern Paine Ronde Townships where a gravity high caused

by the basement is not completely eliminated as regional. Some negative gravity anomalies caused by anomalous features in the Paleozoic section or the basement are also apparent in the residual maps. These negative anomalies could give a false indication of a bedrock channel. This can be illustrated by an area in Wakeshma Township where it appears from the residuals obtained by a seventh degree polynomial regional that the "F" valley (plates 5) extends farther south into Brady and Wakeshma Townships, than suggested by geologic information.

Bedrock Contour Map

Plates 5, 6a and 6b show the bedrock topography map of Kalamazoo County. The contour lines are dashed in areas where bedrock control and gravity coverage is insufficient to permit accurate outlining of bedrock topography. The contour map indicates a prevailing westward slope of the bedrock surface. Bedrock elevations as high as 850 feet are encountered in the eastern part of the County while these at the western part are under 350 feet at certain locations. Superimposed on this general bedrock surface slope are several prominent high topographic features which are located in southwestern Schoolcraft, southeastern Oshtemo, northeastern Texas, northwestern Ross, and northeastern Comstock Townships. Local low elevations on

the bedrock surface exists along the axes of bedrock channels.

A close examination of the bedrock topography map indicates the presence of a very complicated bedrock channel system. The main bedrock channels seem to trend generally east-west or north-south. However, the tributaries of the main bedrock channels trend northwest-southeast. Bedrock channels are designated in plate 5 by alphabetic symbols for easy reference.

The "A" valley trends westward across Kalamazoo County. It possesses fairly steep sides and a rounded floor indicating the possible effect of glaciation, or indeed combined glacial and fluvial erosion. Its channel exhibits appreciable meandering indicating strong fluvial effects. Several contour closures along the axis of the channel and local reversals of slope are apparent, further suggesting glacial or glacio-fluvial influences.

The most prominent feature of the "A" channel is the fact that most of its tributaries in Kalamazoo County seem to join the river from the south. The largest of these tributaries is the "F" channel which originate in central Brady Township. The "F" channel has a very broad channel and a rather straight course. Its sides show very gentle slopes. The "G" channel is another tributary to the "A" bedrock channel. It seems to join the "A" channel near the same point at which the "A" and "F" channels meet. The "J" valley is another tributary to the "A" channel.

It has a narrower cross section and very steep sides.

The "E" channel joins the "A" channel at the center of Comstock Township and trends westward parallel to the "A" channel. Its channel coincides with the "G" channel for about a mile in southeastern Kalamazoo Township and swings westward to meet the "F" channel in southwestern Kalamazoo Township. It changes course to southwestward and meets the "K" channel in west-central Texas Township.

The "C'" and "C''" channels are tributaries to the "C" channel which was flowing westward in northern Alamo Township. Its direction of flow becomes northward in section 4 of the Township and crosses the Kalamazoo border into Allegan County. This channel and its tributaries are broad with gently sloping sides.

The "K" and "B" segments represent the deepest bedrock channels in Kalamazoo County. Their channels are narrow and have steep sides. The lowest bedrock elevation in Kalamazoo County exists along the axis of the "K" segment and occurs in west-central Texas and southeast Oshtemo Townships.

The "M" channel is the southernmost bedrock channel in Kalamazoo County. Its direction of flow was west-northwestward. This channel may not be very accurately delineated because of lack of accurate gravity and well log information in this part of

the County. However, its existence is established by the presence of a bedrock channel in Van Buren County which seems to be a continuation of the same drainage (Giroux, et al, 1964).

CHAPTER VIII

INTERPRETATION OF RESULTS

Correlation of Bedrock and Surface Topography

In areas covered with a thin glacial deposit, surface topography very often reflects bedrock topography. In Kalamazoo County, however, glacial sediments are sufficiently thick that much of the bedrock topography is masked by the glacial cover. Thus, while the bedrock surface generally slopes downward to the west, surface topography is highest at the west side of the county. Surface topography is greatly influenced by the areal distribution of terminal moraines in the County. The distribution does not seem to be related to bedrock topography.

Because a correlation between surface topography and bedrock topography is lacking, the correlation between surface drainage and the bedrock channel system is expected to be very poor. The available bedrock information in the southwestern part of the Southern Peninsula of Michigan indicates a prevailing westward slope of the bedrock surface. Assuming post-glacial rebound to be less than the relief difference in bedrock, the prevailing direction of preglacial

drainage in the area (which includes Kalamazoo County) would presumably have been westward towards the Lake Michigan Lowland. It is also apparent that present surface drainage is to the west, but little of it coincides with the preglacial drainage lines. Coincidence between the present surface drainage and bedrock channels exist only in areas where differential compaction of thick glacial deposits has occurred in bedrock channels, or where glacial deposits are insufficient to fill these channels.

There are several examples in Kalamazoo County where bedrock channels (as proven by drilling) have surface expression. These channels are shown in Plate 9. The most prominent example are the tributaries of Pine Creek in Kalamazoo County which seem to be flowing over the "C" and the northern part of the "B" bedrock channels. The "B" channel coincides with a tributary of Pine Creek which joins Rupert, Murry, Hipps, and Barbour Lakes to the main creek. Southward the surface expression of the "B" channel disappears beneath the glacial deposits of the Kalamazoo moraines which conceal its surface expression. Part of the "E" channel located between the "F" and "K" channel also coincides with the surface drainage lineation of the west fork of Portage Creek and Crooked, Duck, and Pretty Lakes. A third example of bedrock channel being reoccupied by surface streams is the bedrock "C" channel which generally coincides with Spring and Brook Creeks. The association of the present

Kalamazoo River to segments of the "A", "D", and "C" channels is also apparent. This suggests the possibility that the Kalamazoo River follows surface depressions along bedrock channels.

Relation Between Bedrock Channels and Surface Geology

Plate 1 shows the distribution of bedrock channels and surface geology in Kalamazoo County. It is apparent from the map, that the two distributions are totally independent and unrelated. This suggests that bedrock topography was not a major factor in controlling the movement of glaciers. Examination of the bedrock topography map (Plate 5) and Plate 1 also indicates no apparent relation between bedrock channel distribution and bedrock surface geology.

Reconstruction of the Drainage Pattern Before and During Glaciation

Before discussing the classification of bedrock channels in Kalamazoo County, a few pertinent facts are worth restating: (1) Preglacial bedrock channels flow in the general direction of the bedrock surface slope. Their courses, however may be controlled by structure and differential hardness of bedrock. (2) The bedrock surface of the southwestern part of the Southern Peninsula of Michigan, which includes Kalamazoo County, slopes westward towards Lake Michigan. The structural trend is, however, to the northwest. (3) Preglacial channels never cross drainage divides which may be formed of more resistant bedrock formations.

A careful study of Plate 5 indicates that water in bedrock channels "C" and its tributaries "C'" and "C''", as well as the "A" and "M" channels, generally flow in a prevailing westerly direction towards the Lake Michigan Basin. These channels appear to have relatively broad floors up to a mile wide and exhibit noticeable meandering. These facts suggest that the above mentioned bedrock channels may have represented the preglacial fluvial drainage in Kalamazoo County, Michigan. The "F", "G", and "J" channels appear to have been tributaries to the "A" channel and are believed to be preglacial as well.

In terms of these configurations the following sequence of events is postulated. When the ice front of the Lake Michigan lobe, which invaded Kalamazoo County from the northwest, covered the northwestern corner of the County, it blocked the westward flowing master "C" channel. The dammed water began to rise until it reached the elevation of the drainage barrier between the "A" and "C" channels. The dammed water then breached the drainage barrier in Kalamazoo Township to form the "D" segment of the bedrock drainage channels which was flowing southward. Thus, the preglacial drainage in the "C" and part of the "C'" was seemingly diverted to flow southward and join the "A" channel. This drainage pattern apparently did not last very long because the floor elevations of the "C", "C'" and "D" channels are appreciably higher than that of the "A" channel.

Apparently, the "B" channel was also formed as a cross drainage by the glacial melt water from the southward advancing and eastward spreading Lake Michigan ice front to the "A" channel. This channel is appreciably deeper than the "C" and "D" channels indicating that it was carrying a larger load of water southward.

The ice front seemingly advanced farther southward and continued to spread to the east; eventually blocking the "A" channel. The damming of the preglacial "A" channel probably created an alternative route for drainage farther south. This drainage is suggested on Plate 5 as the "E" channel which trended southwest. Small segments of the preglacial "G" and "F" tributaries of the "A" channel were incorporated in this new periglacial stream channel. As a result of this drainage diversion, drainage offsets occurred in the western part of the "A" channel, and in the northern parts of the "G" and "F" bedrock channels.

The "K" channel may also have been created by glacial melt waters flowing southward from the advancing Lake Michigan ice front towards the "M" preglacial channel which was not yet dammed by the advancing ice front. This segment "K", like the "B" channel, is appreciably deeper than the "A" or "C" channels and has steep sided valley walls accentuated probably by post-glacial down cutting. This evidence suggests that the "B" and "K" channels are periglacial. It is also possible that the "K" channel was the locus for a northwest

flowing water in preglacial time, then a reversal in drainage occurred during glaciation. As the ice front advanced further south and east, presumably the "E" channel drainage was dammed and the "I" and "H" channels were formed to carry the westward advancing drainage to the "K" and hence to the "M" channel.

CHAPTER IX

GROUND WATER POSSIBILITIES IN KALAMAZOO COUNTY, MICHIGAN

Introduction

The City of Kalamazoo's municipal water needs, in addition to industrial and domestic water consumption in Kalamazoo County, is totally dependent on ground water supplies. Most of this needed supply comes from aquifers in the glacial sediments. The remaining portion is supplied by wells completed in the Marshall sandstone aquifers and located in the northeastern corner of the County.

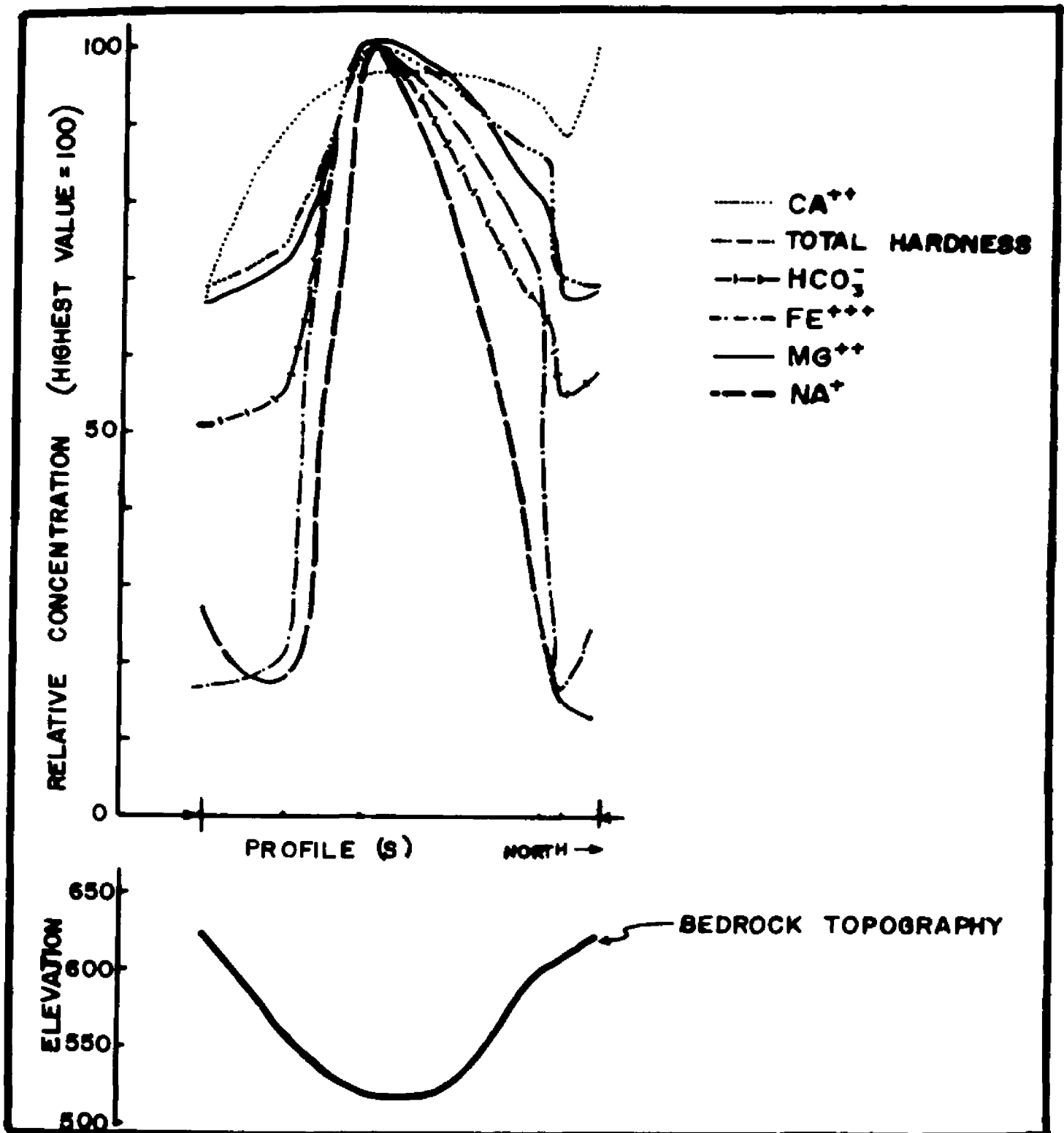
The chemical quality of the ground water produced from the glacial and sandstone aquifers is quite variable. The most common salts are the bicarbonates of calcium and magnesium. According to Deutch, Vanlier, and Giroux (1960), the bicarbonates are derived from particles of limestone and sandstone which are the major constituent of glacial sediments. In some areas, however, the most abundant dissolved material is calcium sulfate. The sulfates are more common in the ground water produced from wells completed in sand and gravel aquifers which are in contact with shale or basal till. It was noted by Deutch, Vanlier, and Giroux (1960) that lowering the water table results in an upward migration of the calcium

sulfate waters from the Coldwater shale to the aquifers in glacial sediments. Iron and manganese are also a common constituent in the ground water of Kalamazoo County. Their concentration is variable depending on the locality.

The author believes that the migration process is faster in areas occupied by bedrock channels especially where a local depression in the floor of the bedrock channels exists. Figure 10 shows the normalized concentration (highest concentration taken as 100) of several chemical compounds in the ground water pumped from five wells belonging to the Upjohn Company and located along profile "S" (Plate 6a) crossing the axis of the "F" channel in Portage Township. The graph has been constructed from water analysis data supplied by the Upjohn Company. It is obvious that ground waters obtained from wells located along the axis of the bedrock channel is the highest in salt content. The increased rate of upward migration of dissolved salts from bedrock sediments to glacial aquifers located in bedrock channels may be caused by the combined effect of these suggested factors: (1) The effective area through which saline water migration takes place is greater in areas of bedrock depressions than in flat areas. (2) Bedrock depressions are possible site for upward migration of waters of relatively higher salinity content because the salinity of bedrock sediments generally increases with depth. (3) Some of the bedrock channels in

Kalamazoo County may be established along the troughs of minor folds in the bedrock surface. It is also possible that some of them follow minor faults or fracture zones in the bedrock surface where the resistance to stream erosion is minimum. Whether the channels are established over fault zones, fractures, or minor folds, the rate of upward migration of saline waters from the bedrock to the glacial sediments is expected to be enhanced. The evidence of high salinity in ground waters produced from aquifers located at the center of bedrock channels is demonstrated in one location as seen in Figure 10. Whether this situation exists in other areas or not is unknown. More studies are warranted.

The glacial sediments in Kalamazoo County range in thickness between 50 feet, mostly in the vicinity of the Kalamazoo River, to 650 feet in the west side of the County where the Kalamazoo moraines are underlain by bedrock channels. The saturated thickness in areas where the glacial sediments are thin is very small and the possibility of developing aquifers suitable for satisfying the needs of municipalities or industries is minimal. Accordingly, areas underlain by a thick section of saturated glacial sediments are more favorable for locating aquifers of appreciable thickness and suitable yield. Areas which are covered with thick outwash and recent channel deposits are especially favorable for locating ground water aquifers. Besides having high permeabilities, aquifers developed in the channel deposits



of recent streams, very often, replenish the water lost to pumpage by direct recharge from surface waters. This is the reason why many of the pumping stations of the City of Kalamazoo Water Department are located along surface drainage. The waters of the Kalamazoo River, which is the largest surface drainage in Kalamazoo County, are highly polluted. Accordingly, no attempt was made to develop ground water aquifers in its channel deposits. Glacial till sediments in Kalamazoo County are mostly formed of red or blue compact and impervious sediments which are formed of particles having a wide range of sizes. However, in some areas, till deposits are formed of fine grained clay type sediments which are grey, brown, or greyish blue in color. Both varieties of till deposits are unsuitable as aquifers.

Exploration drilling in the spring of 1968 indicated that the outwash apron located between the outer and inner Kalamazoo Moraines is underlain by very thick, highly permeable sand and gravel deposits. An exploration test hole was attempted at the center of section 21 of Oshtemo Township where the mud circulation was lost at a depth of 260 feet after penetrating 50 feet of very coarse gravel and/or sand deposits. The drilling was discontinued because the circulation could not be restored and heaving of the outwash deposits made drilling impossible. The results indicate an upper aquifer of 90 feet of sand and/or gravel and a lower aquifer beginning at a depth of 207

feet below the surface. The total thickness of the lower aquifer could not be determined because of the termination of drilling at the site. The lower and upper aquifers are separated by 30 feet of till deposits.

The existence of this extraordinarily thick sequence of outwash deposits in the apron may be accounted for as follows: While the Lake Michigan ice front was stationary during the formations of the inner Kalamazoo moraines, the glacial melt water was confined between the ice front and the outer Kalamazoo moraine to the east, which was already present. This resulted in the confinement of deposition of the glacial outwash deposits to the area between the two Kalamazoo moraines. Thick outwash deposits may also exist directly to the east of the outer Kalamazoo moraine. The glacial sluiceway which was flowing eastward away from the ice front during the formation of these moraines is expected to have deposited the coarser detritus directly to the east of these outer moraines.

Bedrock Channels in Kalamazoo County as Loci for Ground Water Aquifers

Ground water exploration in bedrock channels in Ohio (Schaefer, White, and VanTyl, 1946), Illinois (Horberg, 1950; Piskin and Bergstrom, 1967; Stephen, 1967) and Indiana (Wayne, 1956) indicate that bedrock channels are especially favorable for locating ground water aquifers. However, in several instances, bedrock channels

were found to contain fine grained deposits such as clay, silt, and impervious sediments or till deposits (McGrain, 1948; Wayne, 1956). Fine grained glacial deposits may be formed under stagnant conditions due to damming of drainage by ice fronts. In some situations, it is also possible that pre-existing outwash deposits in bedrock channels were excavated and destroyed by the advancing ice, or associated torrential outwash waters, and then the channels refilled with poorly sorted till or even fine grained fluvial or lacustrine deposits. Under these circumstances, glacial sediments in bedrock channels usually possess low permeability and cannot be developed as aquifers.

The available well log information in Kalamazoo County is not sufficient to establish the nature of the glacial deposits in all bedrock channels. The City of Kalamazoo Water Department undertook a drilling program in 1968 and 1969 to investigate the nature of glacial deposits in selected locations. About 30 drill holes were completed during this period, mostly in Comstock, Richland, and Oshtemo Townships. However, few of these test holes were located over bedrock channels. Based on available drill log information, the following general conclusions are drawn regarding the nature of glacial deposits in the bedrock channels of Kalamazoo County: (1) The "A" channel (Plate 5) appears to be generally filled with till type deposits. This conclusion is based on scattered drill log information in Comstock, Kalamazoo, and Oshtemo Townships. It is

possible that the preglacial deposits in this channel have been excavated and destroyed by glacial action and then replaced by unsorted till or even relatively unsorted glacio-fluvial deposits. (2) The "F" and "G" bedrock channels appear to contain outwash deposits. East-central Portage Township is extensively drilled by the Upjohn Company. Several aquifers were developed along the segment of the "F" valley located in the area. The better aquifers in this area are located along the sides of the bedrock channel. A few inferior wells were developed along the axis where the glacial outwash deposits are fine-grained and less sorted. The water pumped from these wells shows a relatively higher percentage of dissolved salts. (3) The "E" bedrock channel is known to contain extensive outwash deposits. These deposits are especially thick in the segment of the channel to the southwest of the City of Kalamazoo where the bedrock channel coincides with the surface drainage lines of the west fork of Portage Creek, Crooked, Duck, and Pretty Lakes. The thick outwash deposits in this segment probably consists of both glacial outwash and recent post-glacial channel deposits. (4) Spring and Brook Creeks flow southwestward and over the "C" tributary of "C" bedrock channel. Flow gauges placed at selected locations along the creek indicate that during dry periods appreciable surface water flow is sustained by ground water. This suggests that the presence of permeable outwash and channel deposits in the area surrounding the Creek and in the "C" bedrock

channel. As a result, four exploration drill holes were completed along the sides of the channel in Richland Township in early spring of 1968. The results indicated the presence of up to 170 feet of outwash deposits underlain by clay and other lacustrine deposits. The "C" and "C'" tributaries of the "C" channel have not been drilled extensively. However, an exploration drill hole was completed in northwest Cooper Township about 1200 feet south of the axis of the "C" channel which encountered 90 feet of surface outwash deposits underlain by clay and lake type deposits. More drilling is need to define the nature of glacial deposits in the channel in other areas. (5) The glacial sediments in the "B" and "K" valleys are the thickest in Kalamazoo County. The nature of the deposits is not known in detail. Besides several oil test holes which do not indicate the nature of glacial deposits in the "B" valley, only one exploration test hole was drilled by the City of Kalamazoo Water Department. This test hole was drilled over the axis of the "B" valley in central Alamo Township. The results indicate the presence of 55 feet of outwash deposit in the form of thin layers of sand and/or gravel and clay. This section of outwash is underlain by till and lake type deposits. The thick glacial sediments in the "B" and "K" valleys are apt to contain thick outwash deposits and further exploration drilling is strongly recommended in these areas. (6) More study is also needed to accurately define the axis and nature of glacial sediments in the "M" valley.

CHAPTER X

CONCLUSIONS

Applicability of the Gravity Method in Outlining Bedrock Topography

The results of the gravity investigation in Kalamazoo County, Michigan, warrant the following conclusions: (1) The gravity method can be successfully employed in Kalamazoo County to outline bedrock topographic features and map the bedrock surface. The density of the glacial sediments in the area which was estimated to be 2.15 gm/cc, is appreciably lower than the reported 2.55 gm/cc value for the density of Coldwater shale. This large density contrast permitted the application of the gravity method to outline bedrock topography. (2) The procedure developed for isolating the residual gravity anomalies caused by buried bedrock topography has been successfully used to obtain a fairly detailed bedrock topography map of the County. (3) The detail in the compiled bedrock topography map made it possible to reconstruct the preglacial and periglacial drainage in Kalamazoo County. (4) The proposed approach of calculating the average density of the glacial and bedrock sediments using the free-air anomaly and well log information produced density estimates comparable to measured values. However, the results

are inconclusive because of the wide range of density values obtained and the lack of correlation between free-air anomaly values and various types of glacial sediments. The interpolation of the free-air anomaly values to well locations where direct gravity observations were not available and the difficulty of defining the polynomial equation which best approximates the regional trend were the main sources of inaccuracy. (5) The gravity residuals obtained by approximating the regional trend by a polynomial applying the method of least squares is useful in delineating bedrock channels. The method however, did not result in a quantitative definition of the residual Bouguer gravity anomalies. The residuals obtained by approximating the regional by a polynomial of up to the seventh degree appeared to be distorted by the gravitational effects of deep structures which should have been eliminated as part of the regional. Accordingly, these residuals were not suitable for quantitative interpretation.

Suggestions for Further Studies

Additional gravity observations and explorational drilling is desirable in Schoolcraft and Prairie Ronde Townships to define accurately the "M" valley and its tributaries. The "A" valley in Ross and Charleston Townships is defined on the basis of only a few gravity observations. Further gravity and exploration drilling in

This area is thus also justified for defining the axis of the valley and nature of its glacial sediments.

Very little is known about the glacial sediments in the "B" and "K" valleys and so more exploration drilling is desirable here as well.

The glacial deposits of the outwash apron located between the inner and outer Kalamazoo moraines appear to be formed mostly of thick, highly permeable sand and/or gravel horizons. Because of the commercial implications this area is highly recommended for further exploration drilling.

The implications for detailed glacial geological study in such areas using geophysical techniques are considerable. They are not only academically of interest, but can lead to locating further and better sources of uncontaminated water for future commercial and municipal use.

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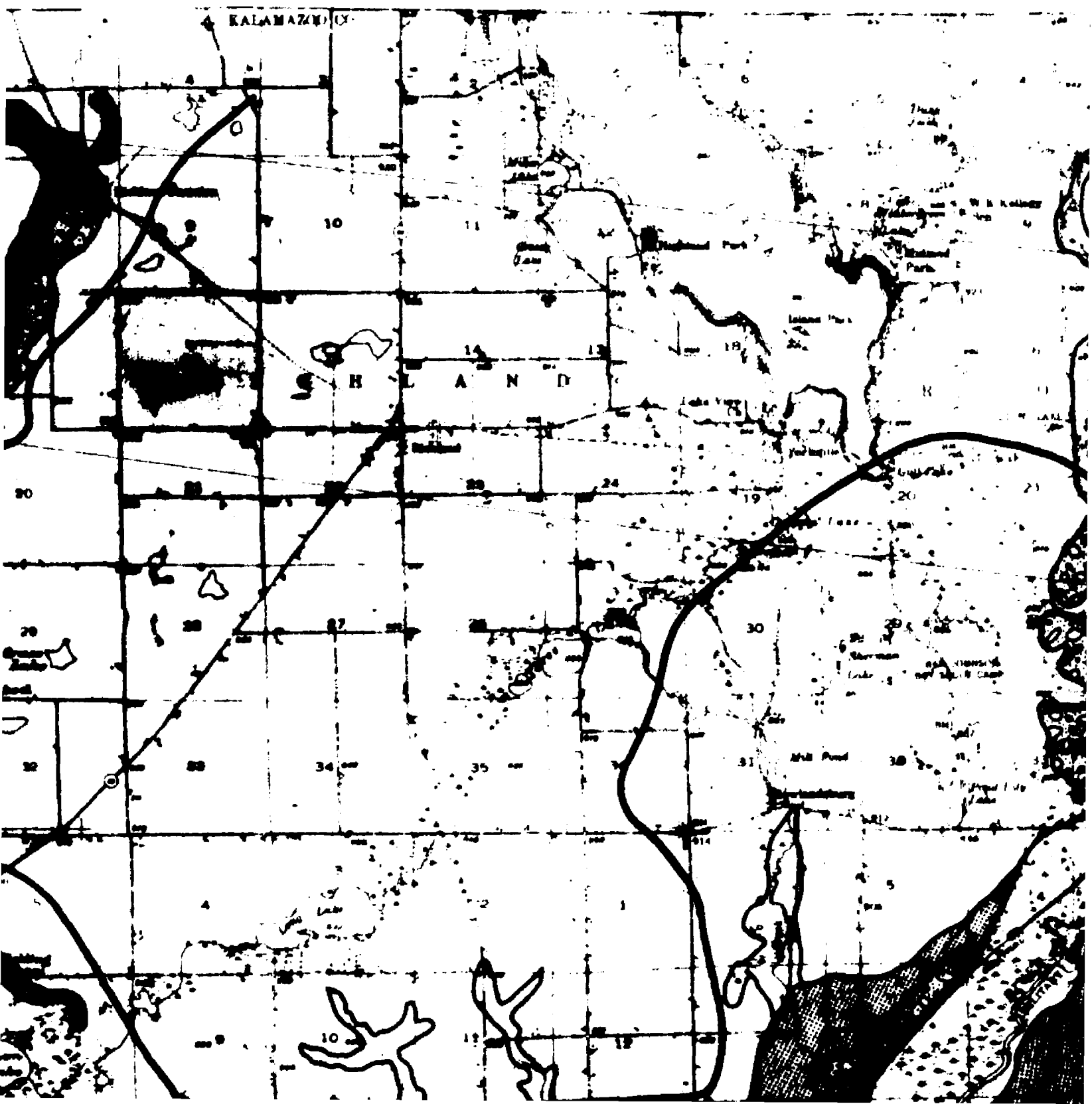
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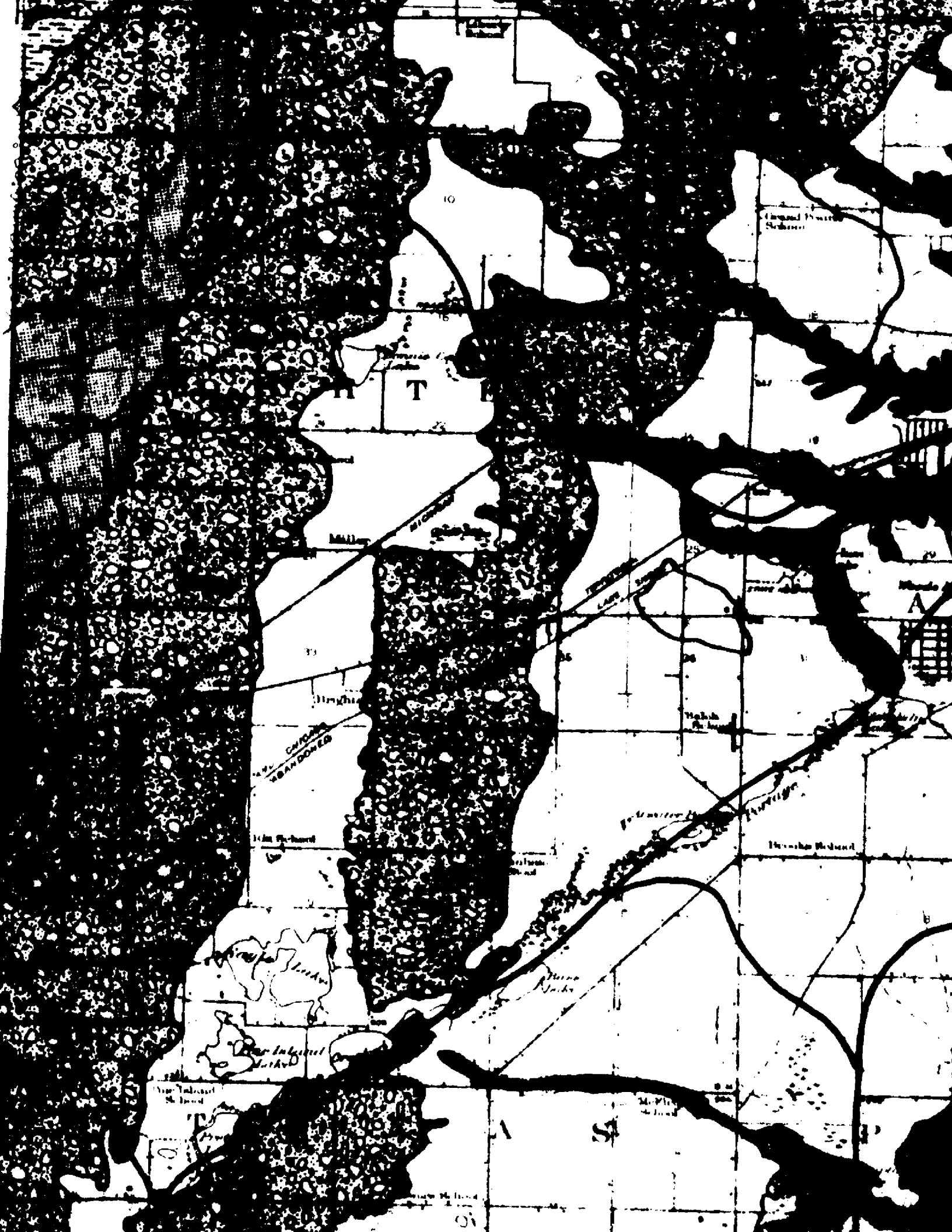
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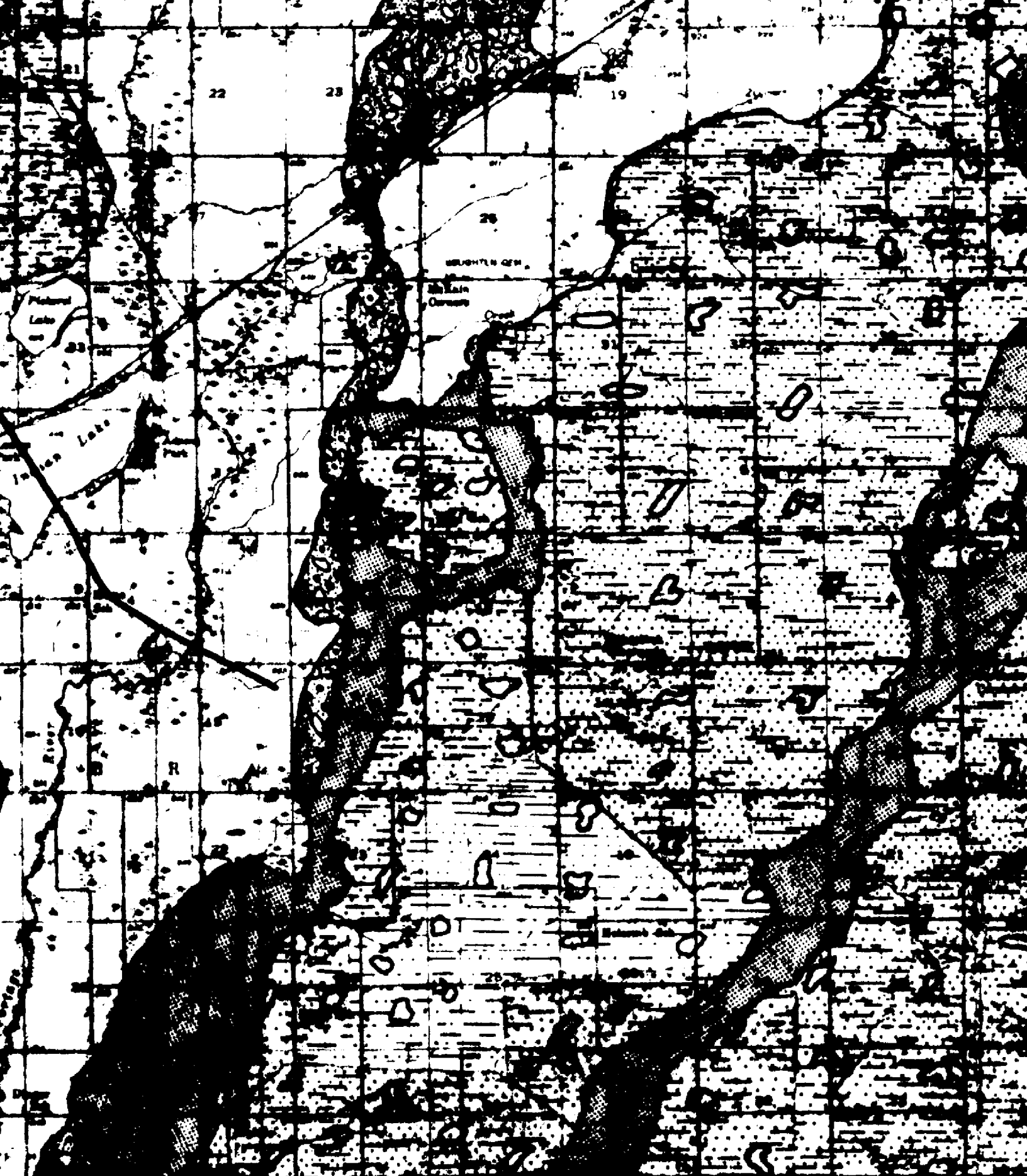








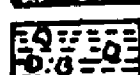




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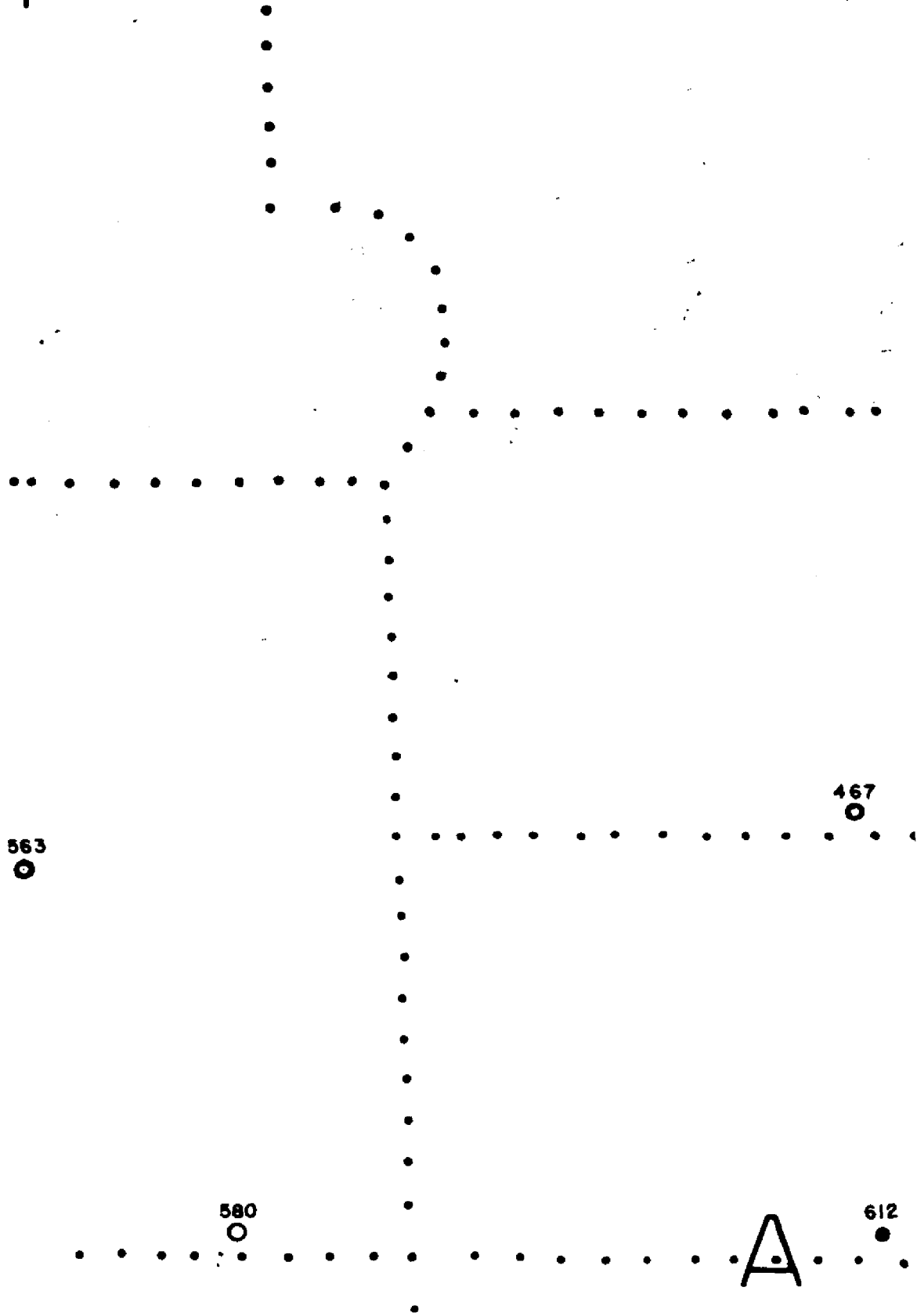
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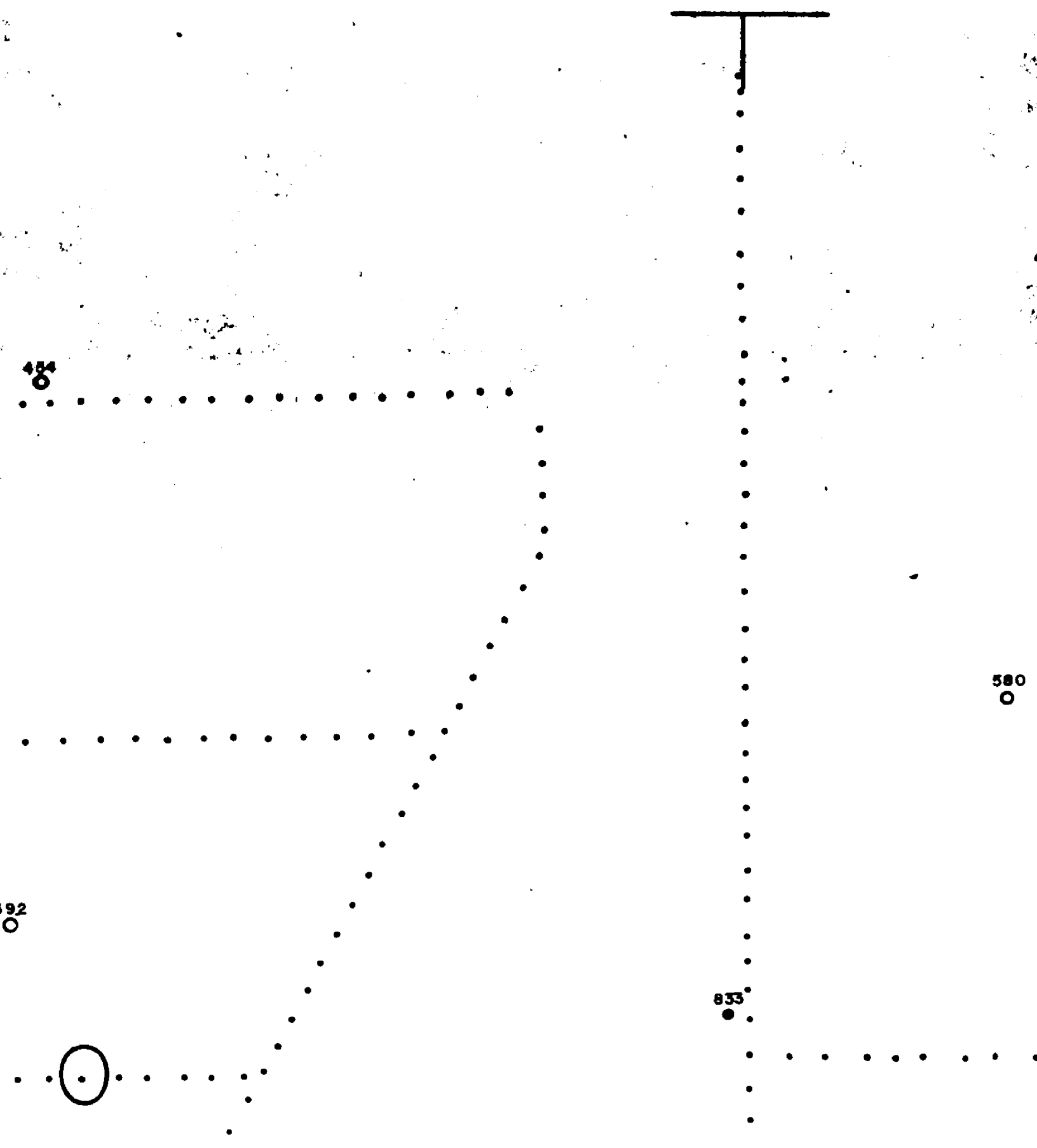
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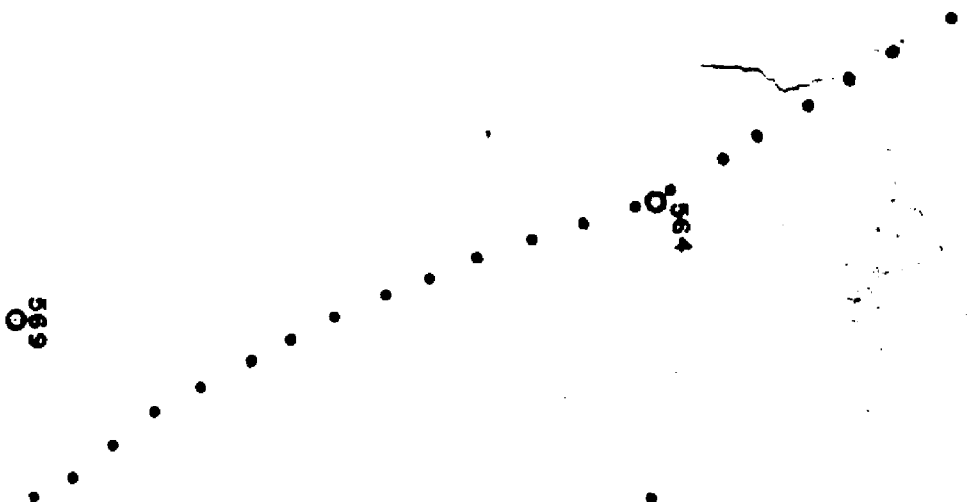
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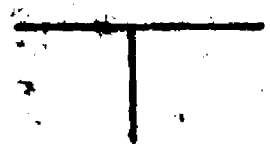
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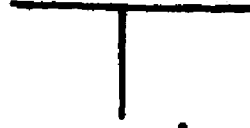
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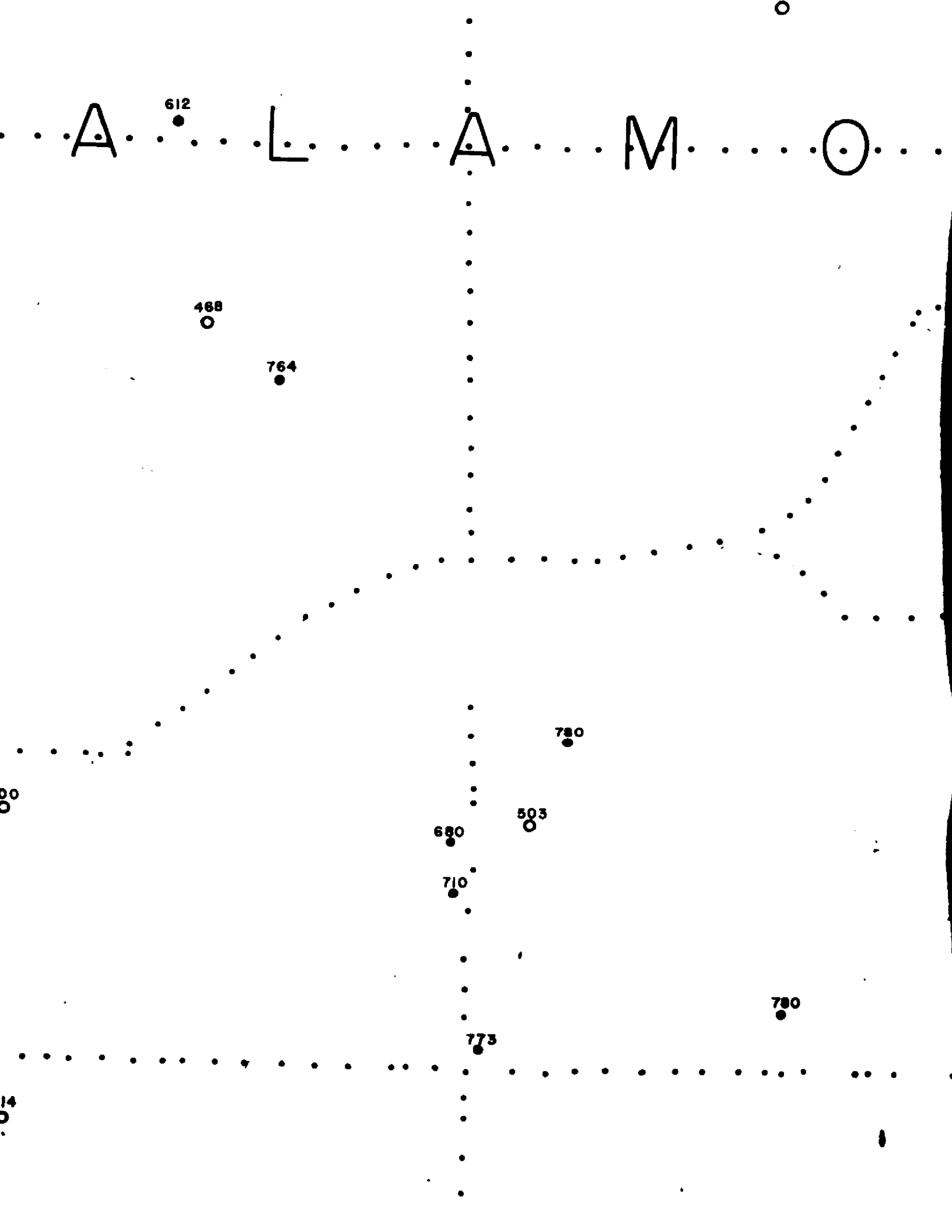
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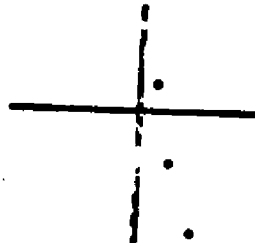
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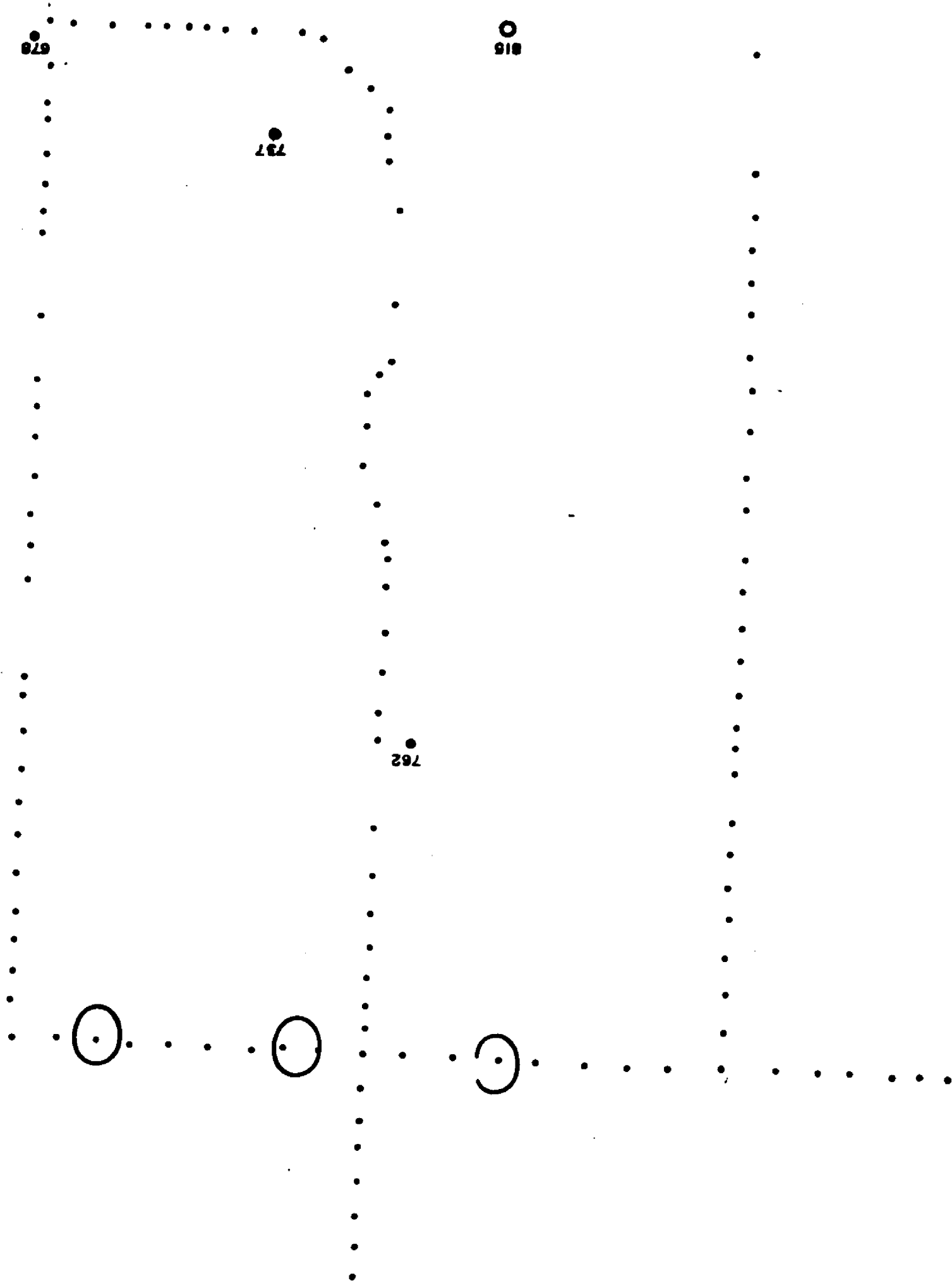
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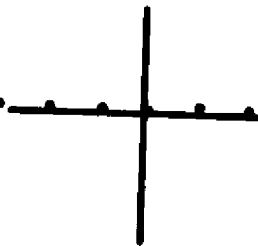
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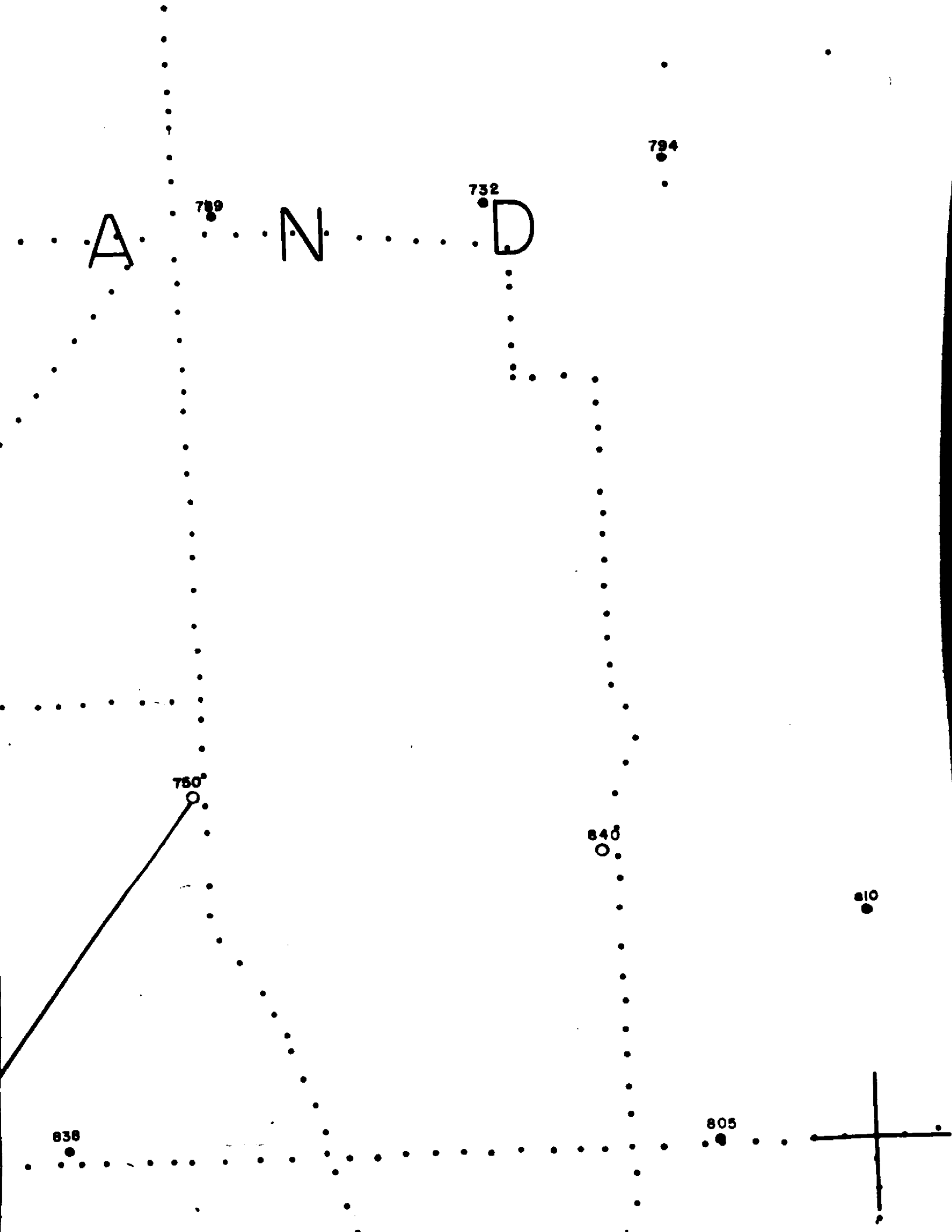
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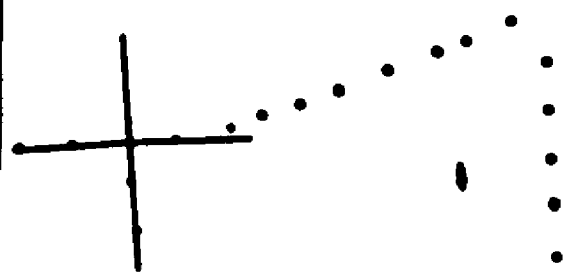
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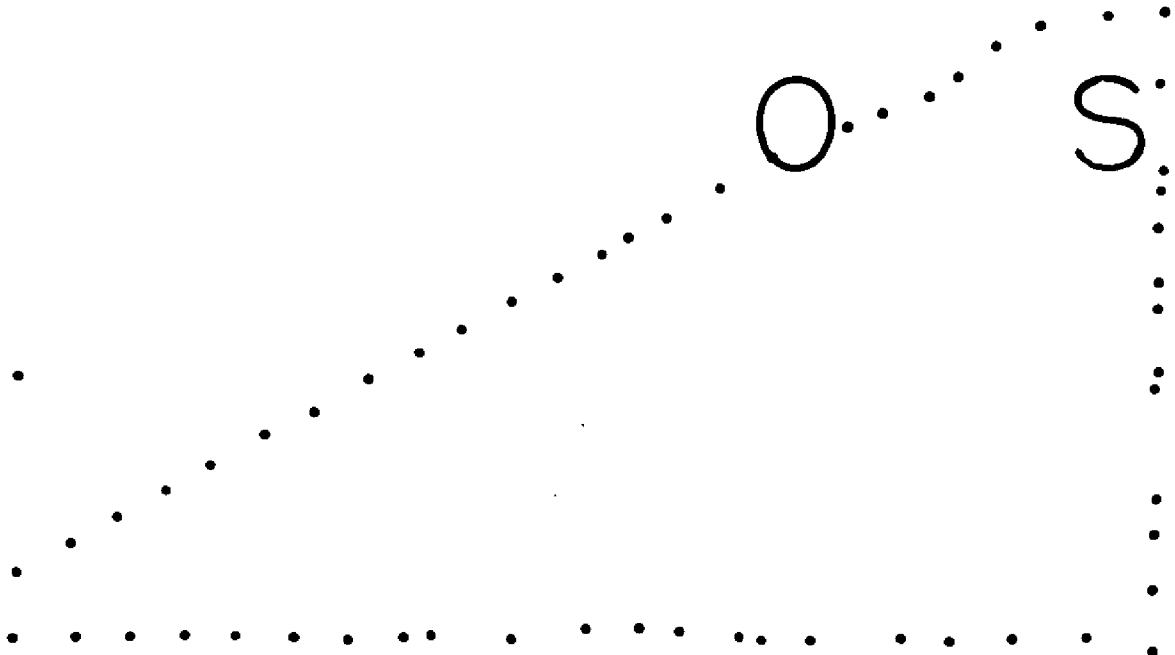
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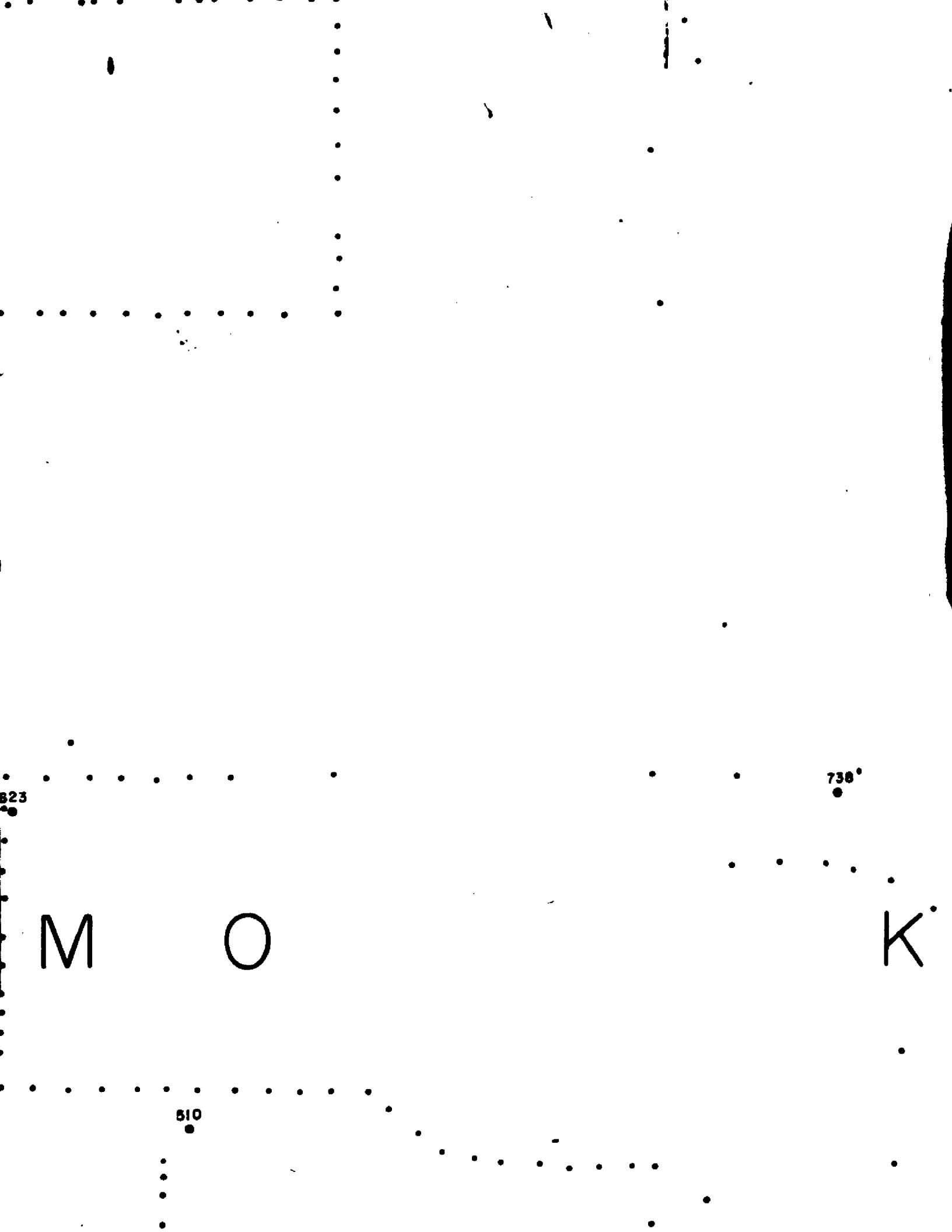
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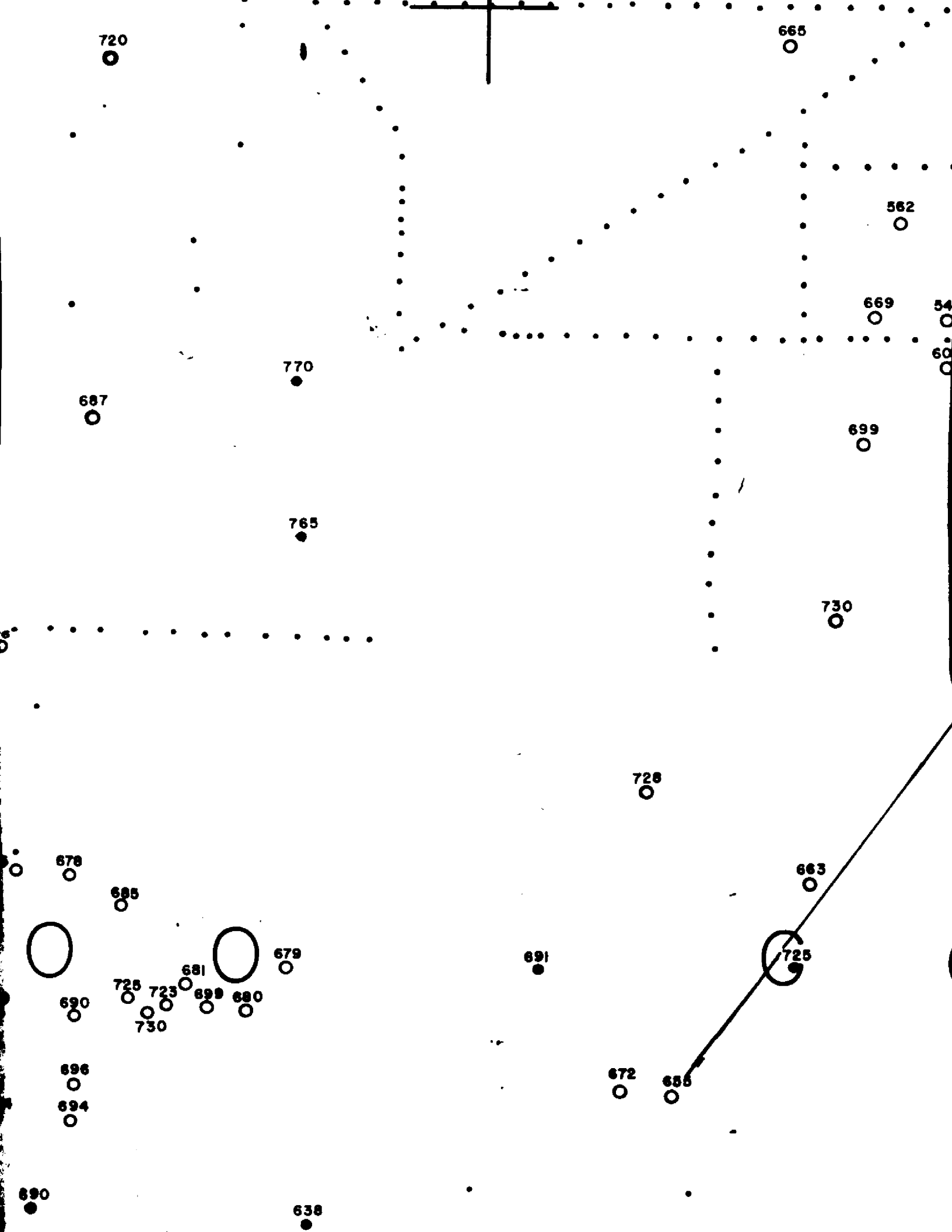
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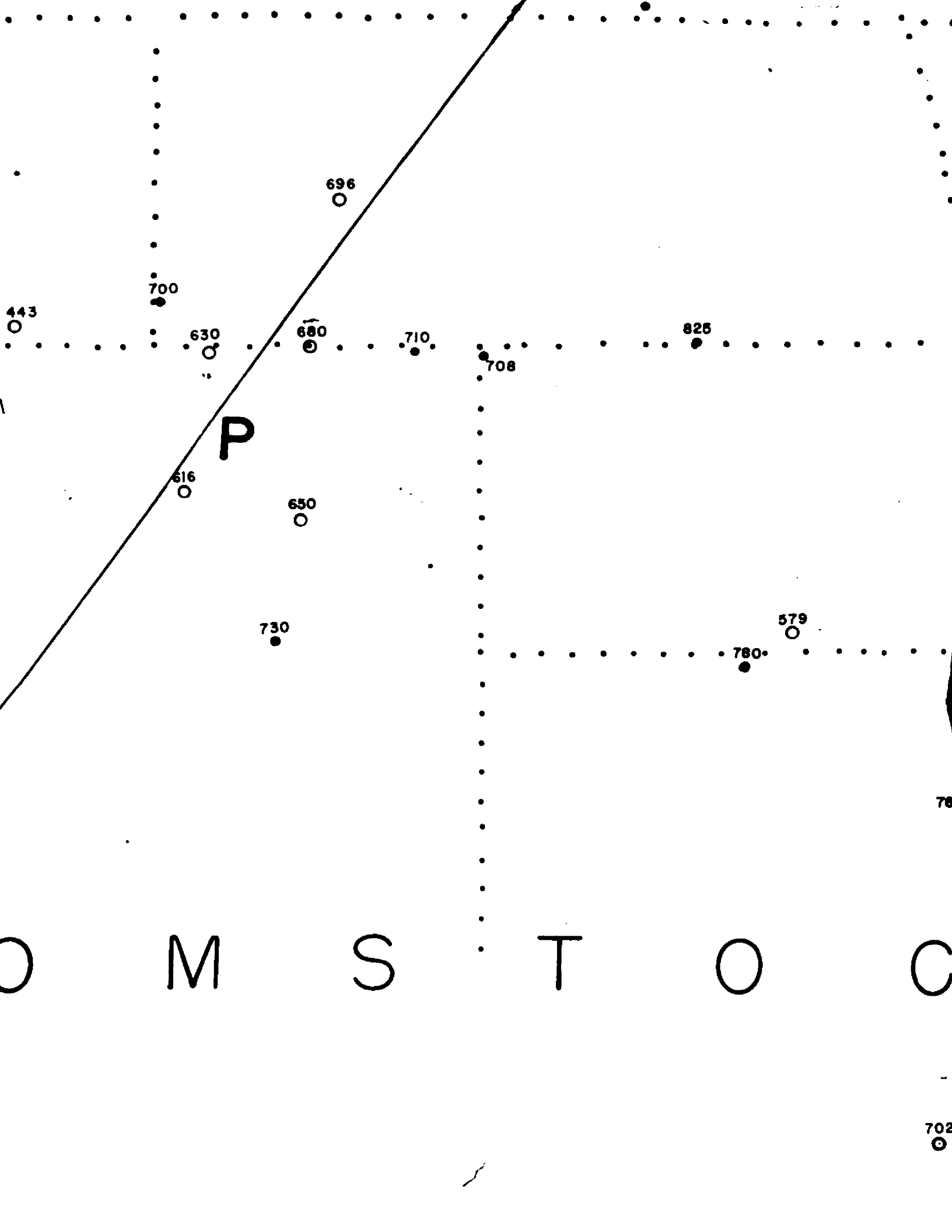
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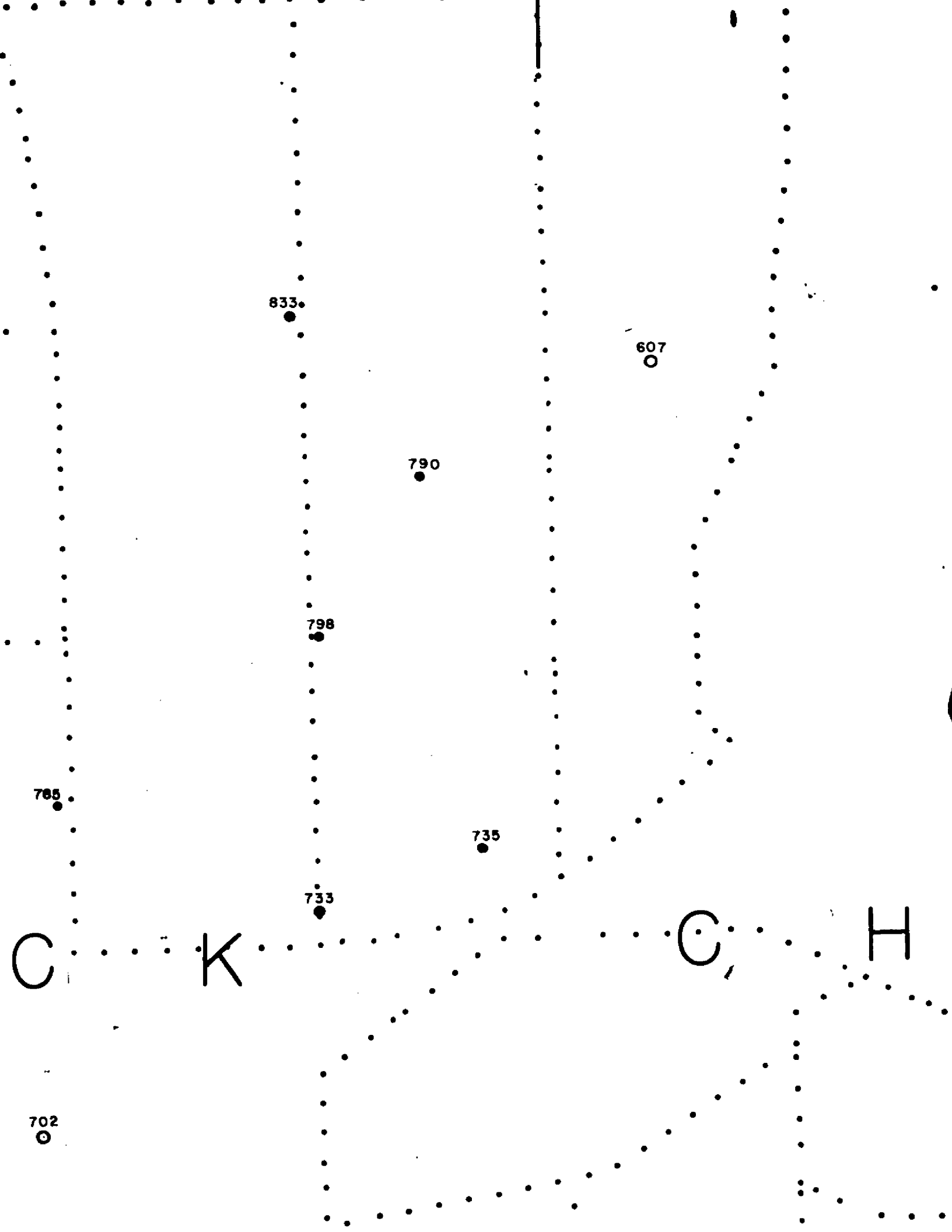
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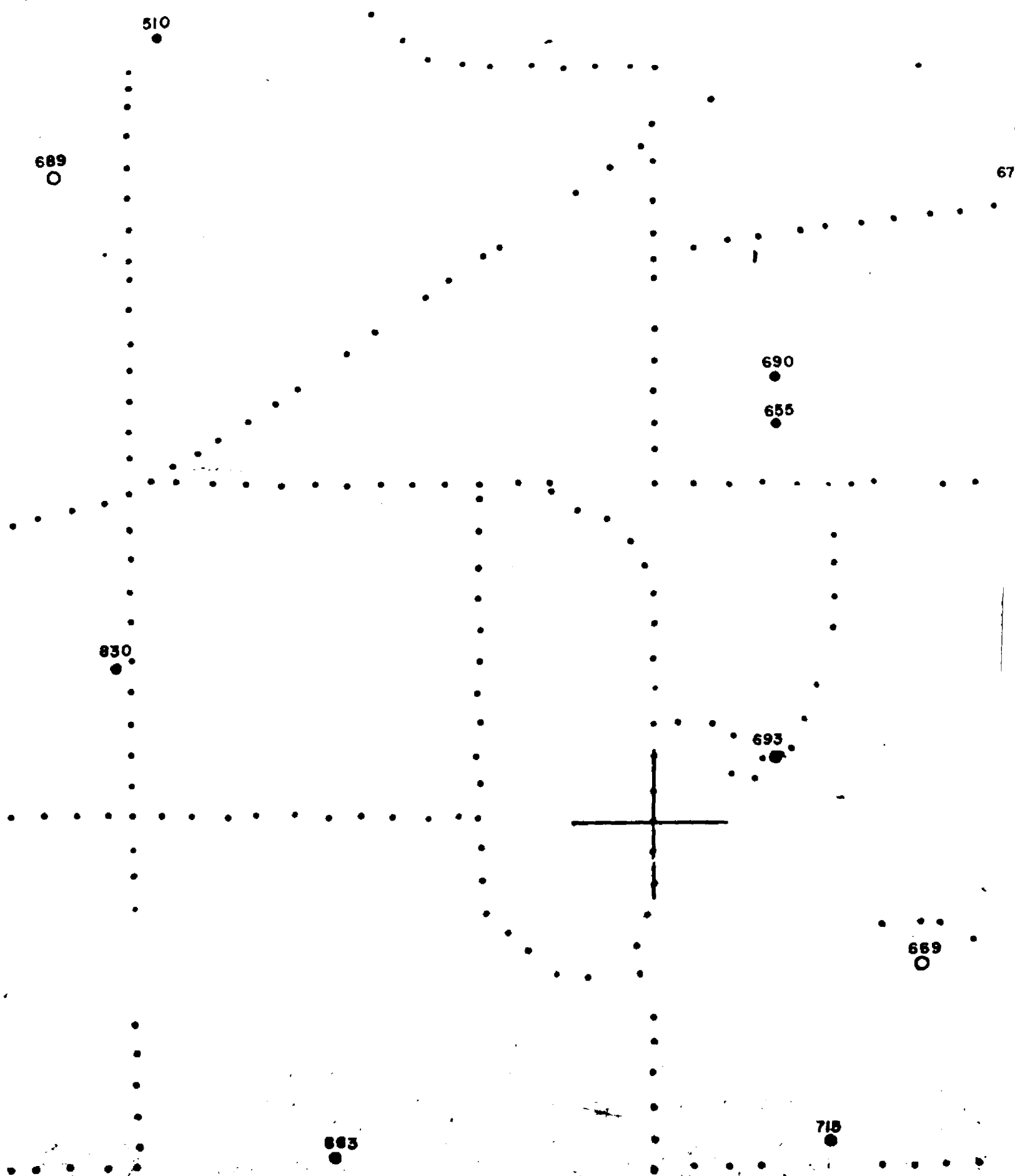


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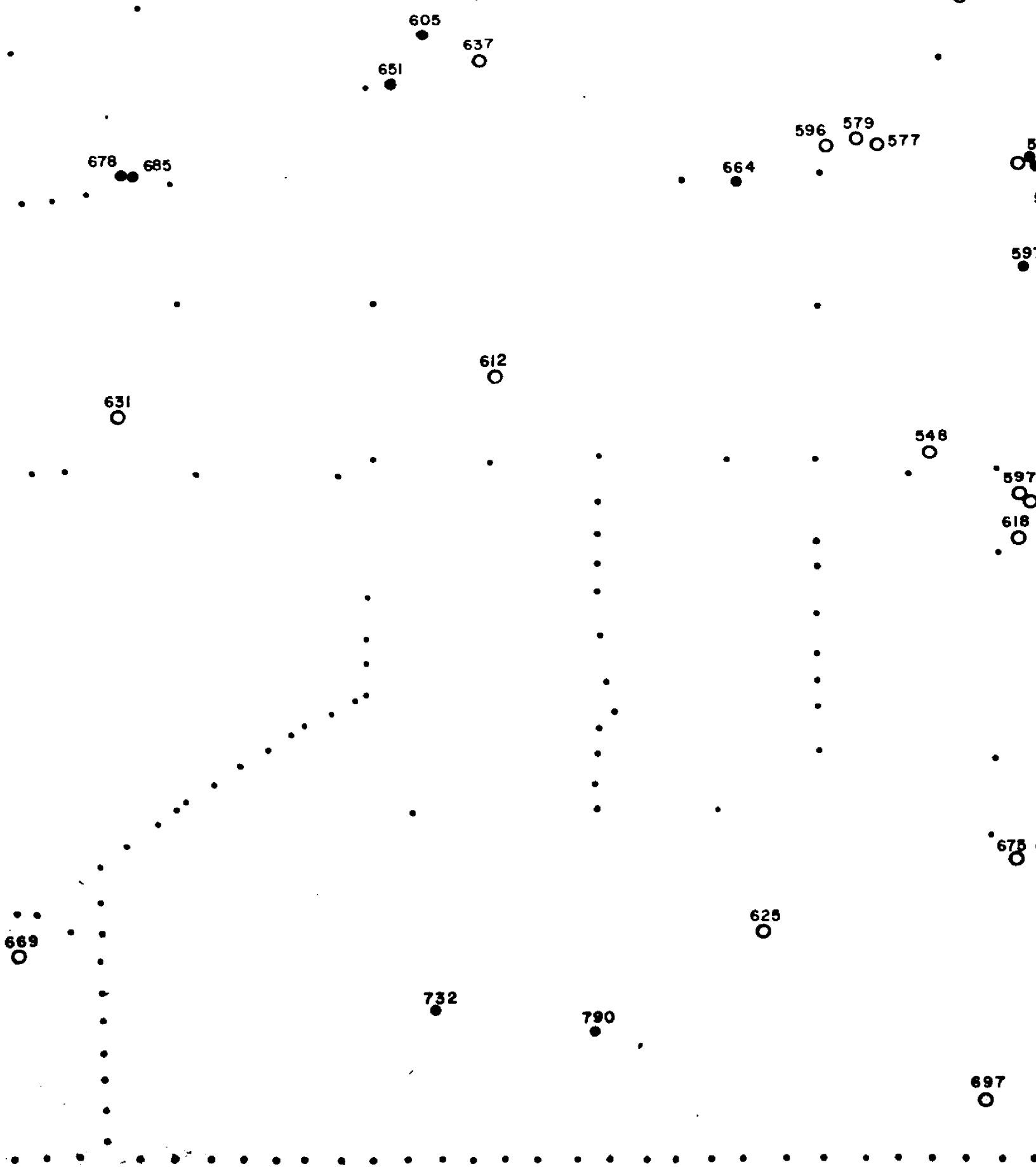
689
○

PLATE

2b

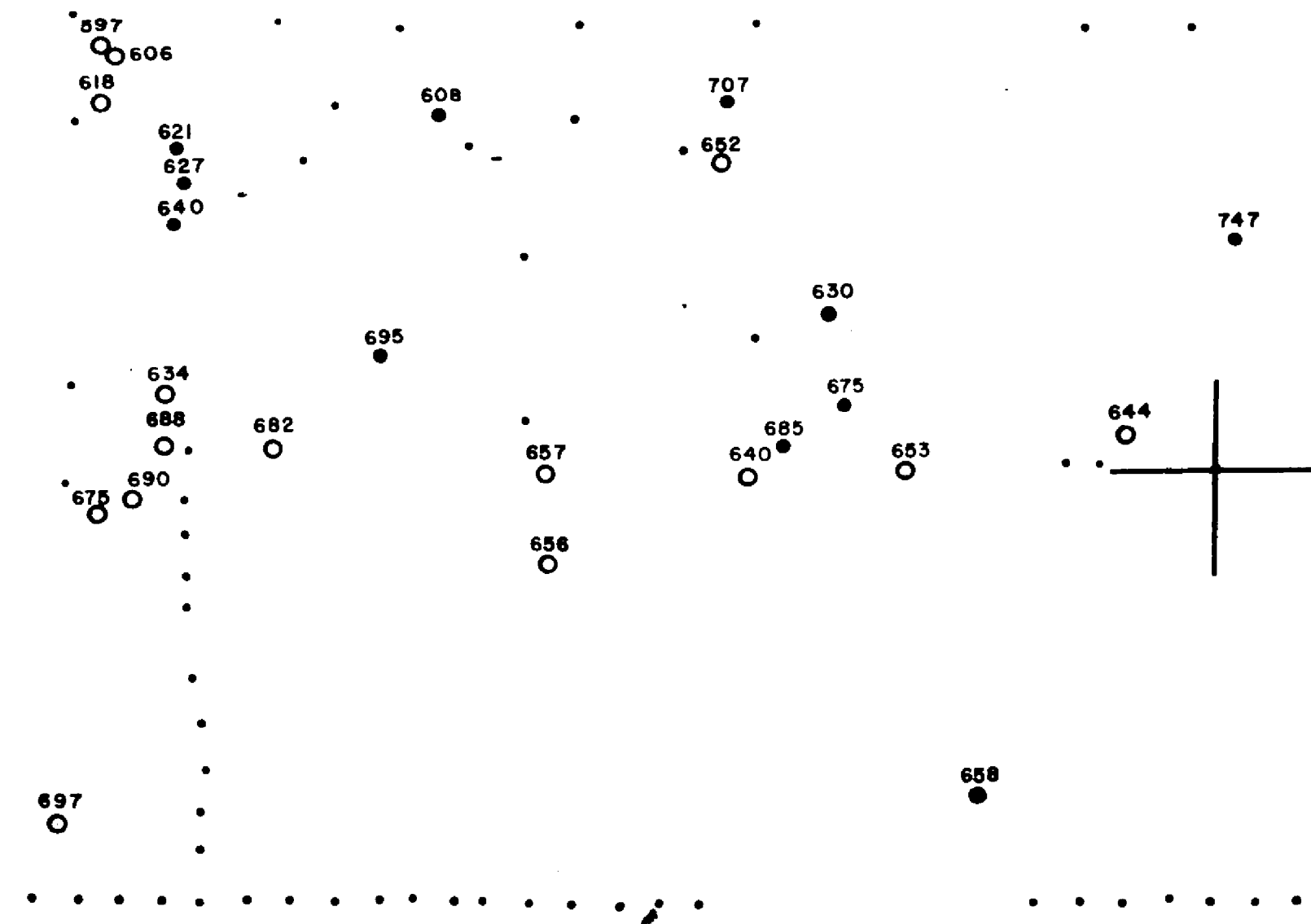


GRAVITY STATION



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8



HOLE

LOCATIONS

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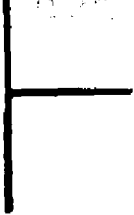
857

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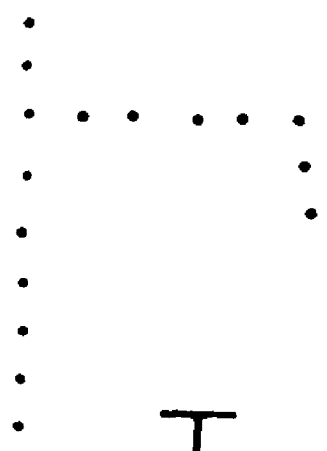
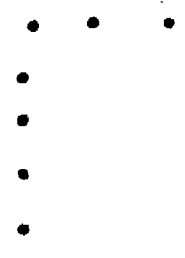
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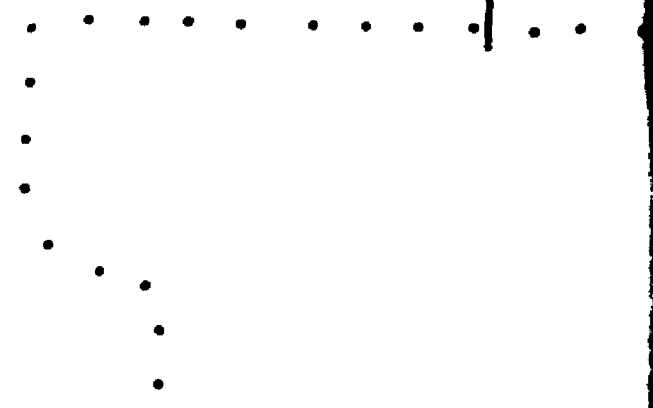
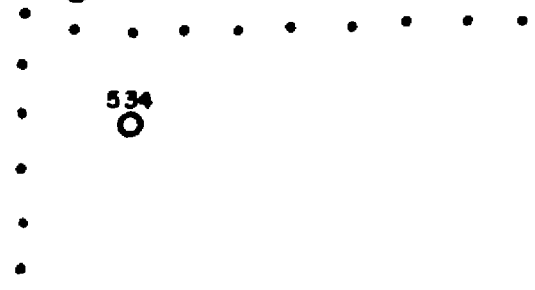
T3S

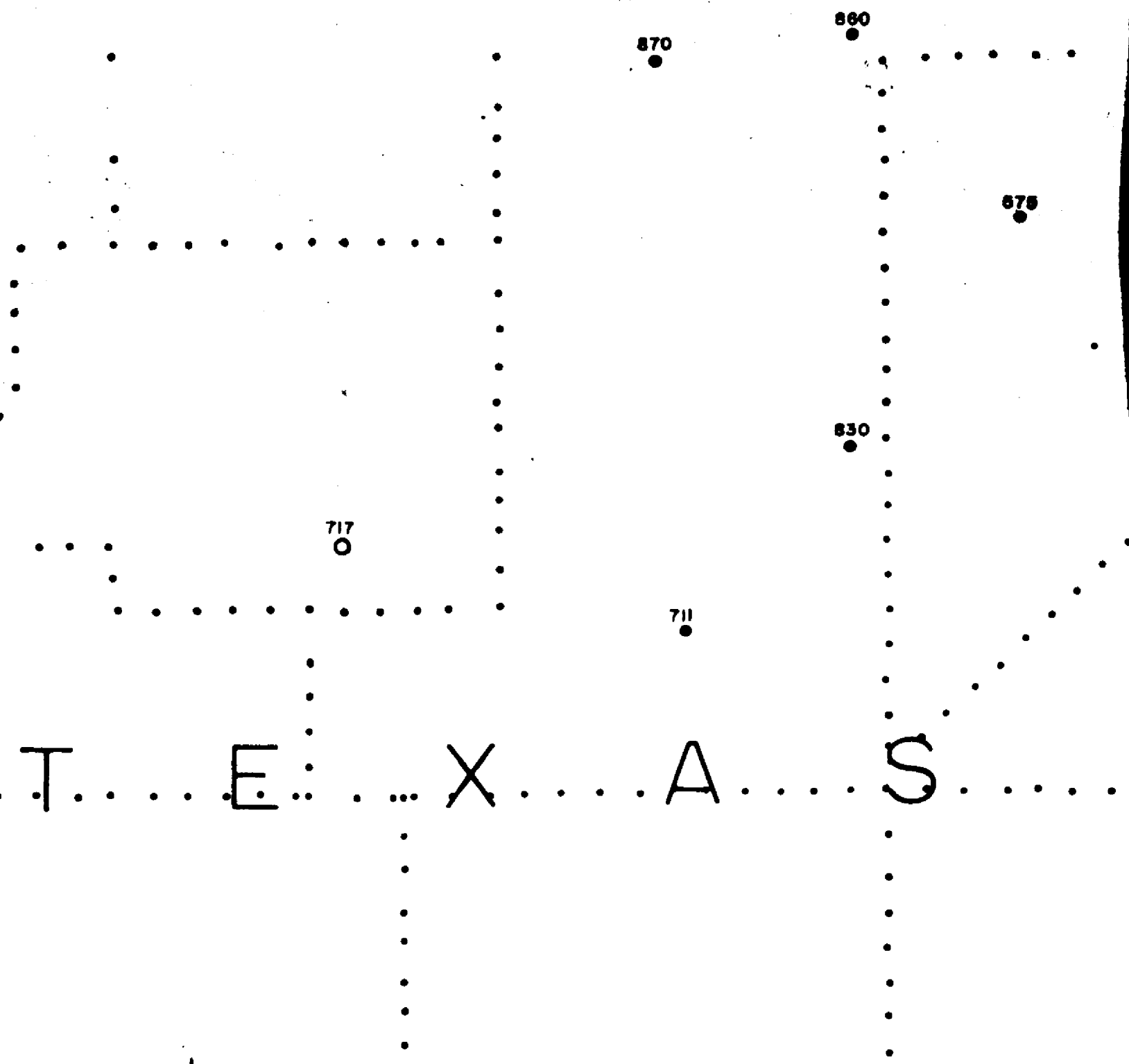
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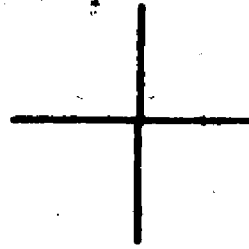
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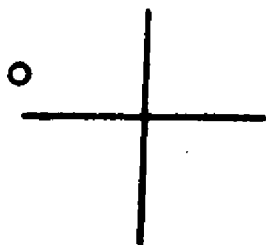
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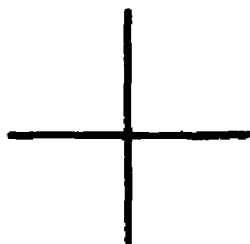
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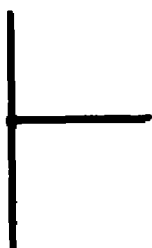
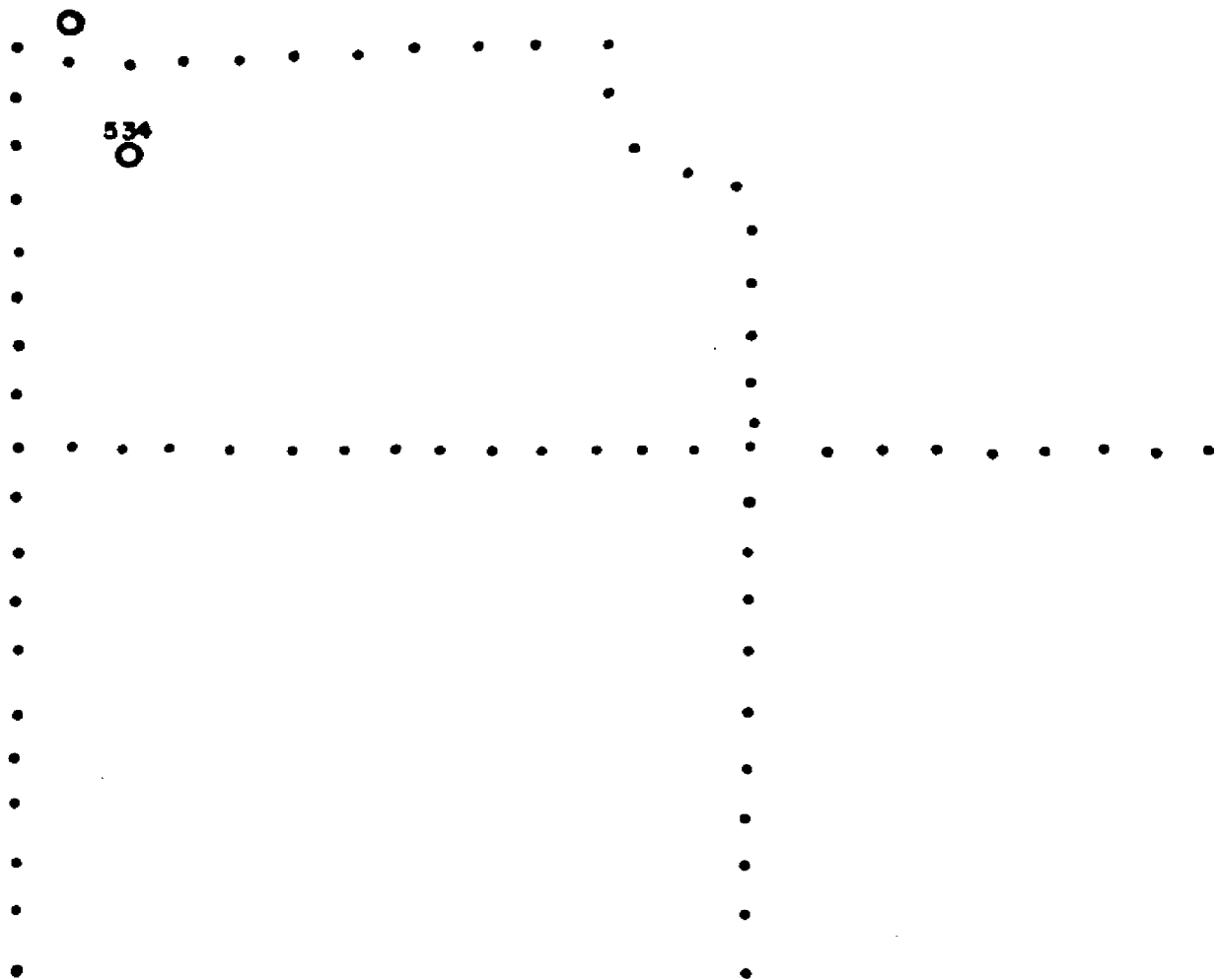
888
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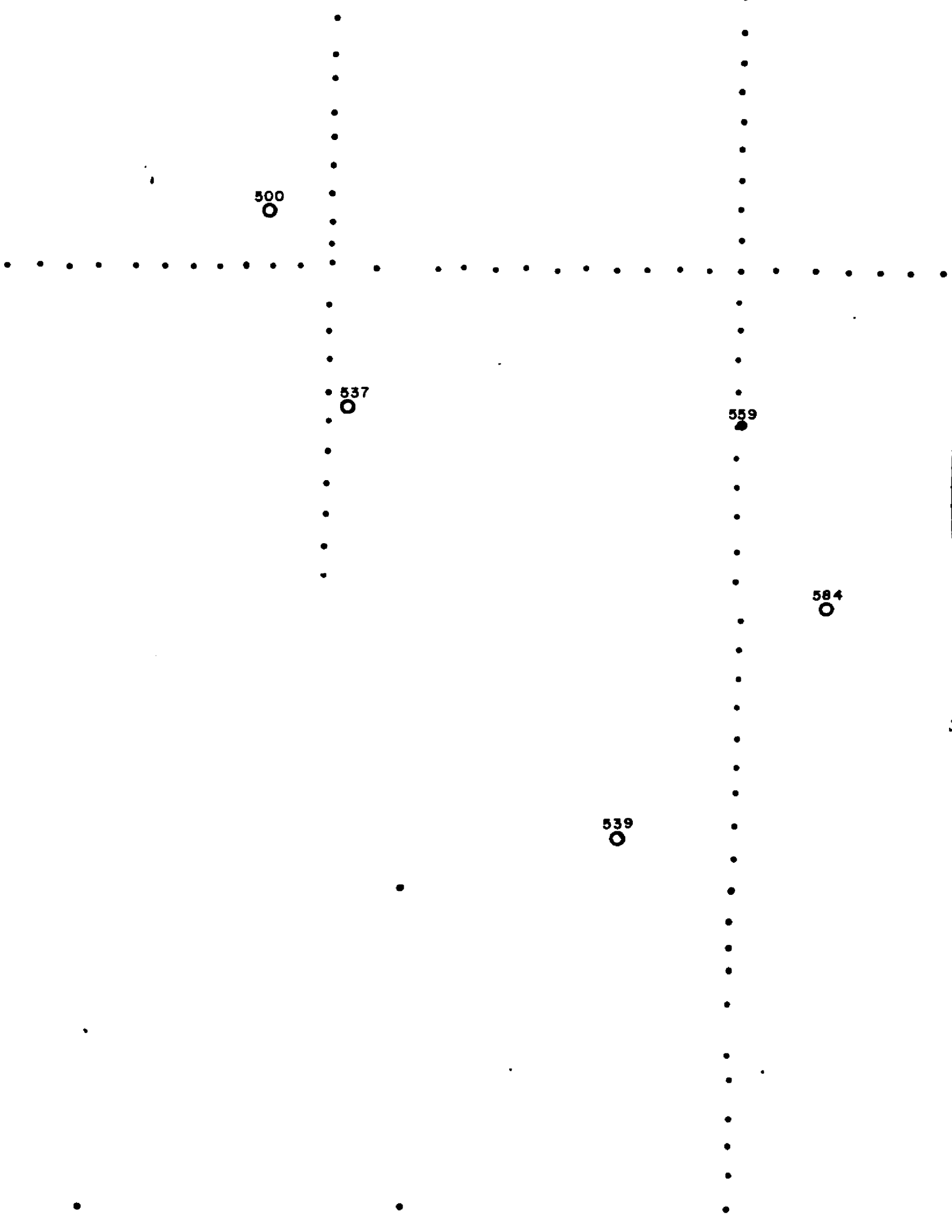
X

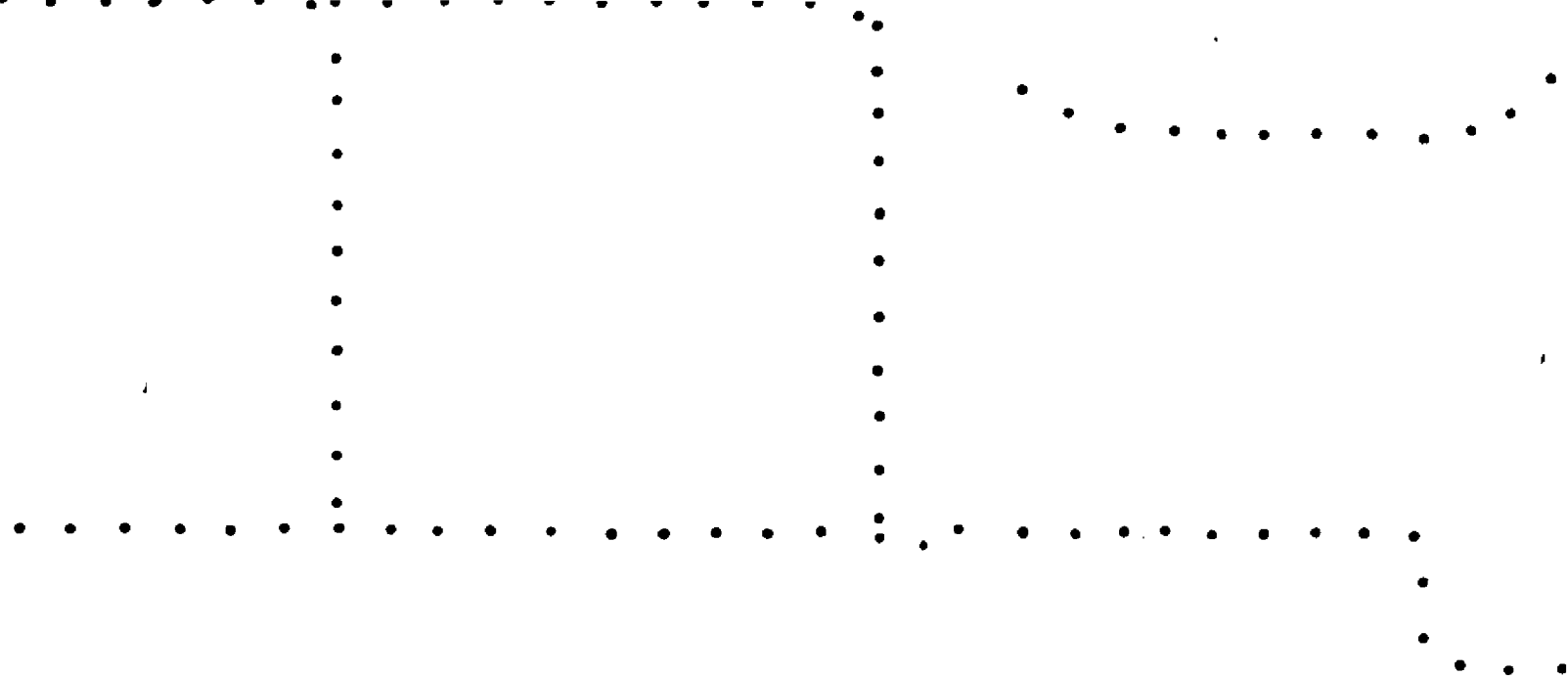
T3S

-10'



800



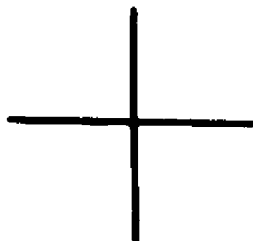


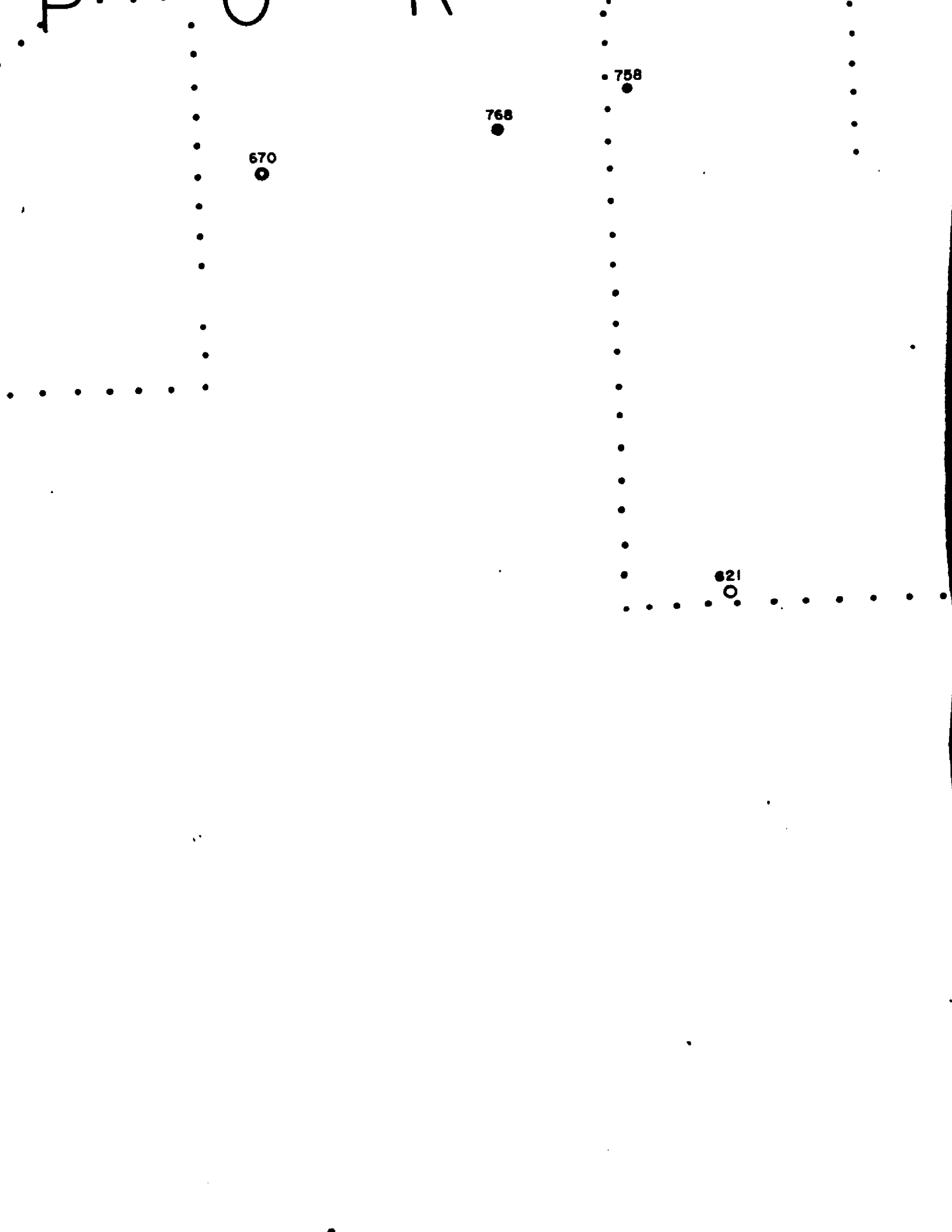
547
○

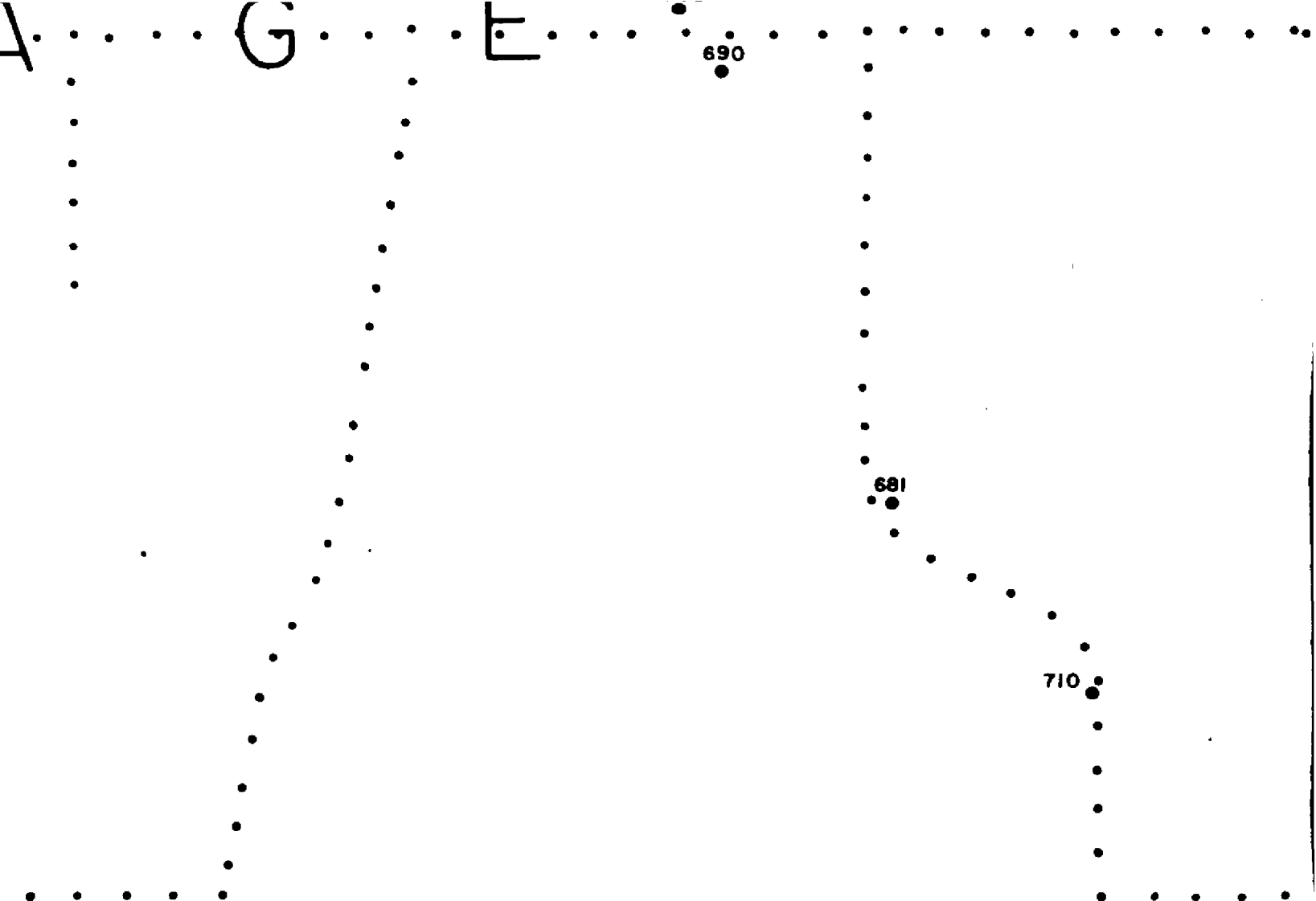
582
○

617
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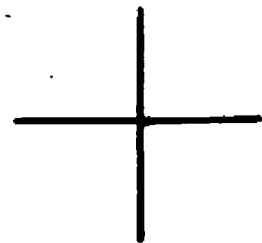
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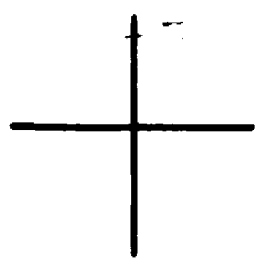
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PL

R12W

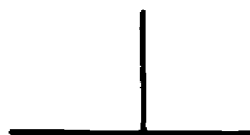
PLATE

2a

GRAVIT

609
○

603
○



40'

AVITY STATION AND

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636
O

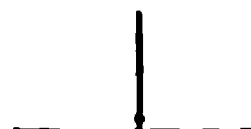
RIIW

35

D DRILL HOLE LC

668
○

683
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LOCATIONS

- N
○ DRILL HOLE REA
- N
● DRILL HOLE NO1
- GRAVITY STATION

R

30'

BOLE REACHING BEDROCK SURFACE , N IS BEDROCK SURFACE ELEVATION

BOLE NOT REACHING BEDROCK , N IS ELEVATION OF DEEPEST POINT

STATION

804
○

805
●

RIOW

E ELEVATION

EST POINT

836

855

25'

841

834

848

R9W

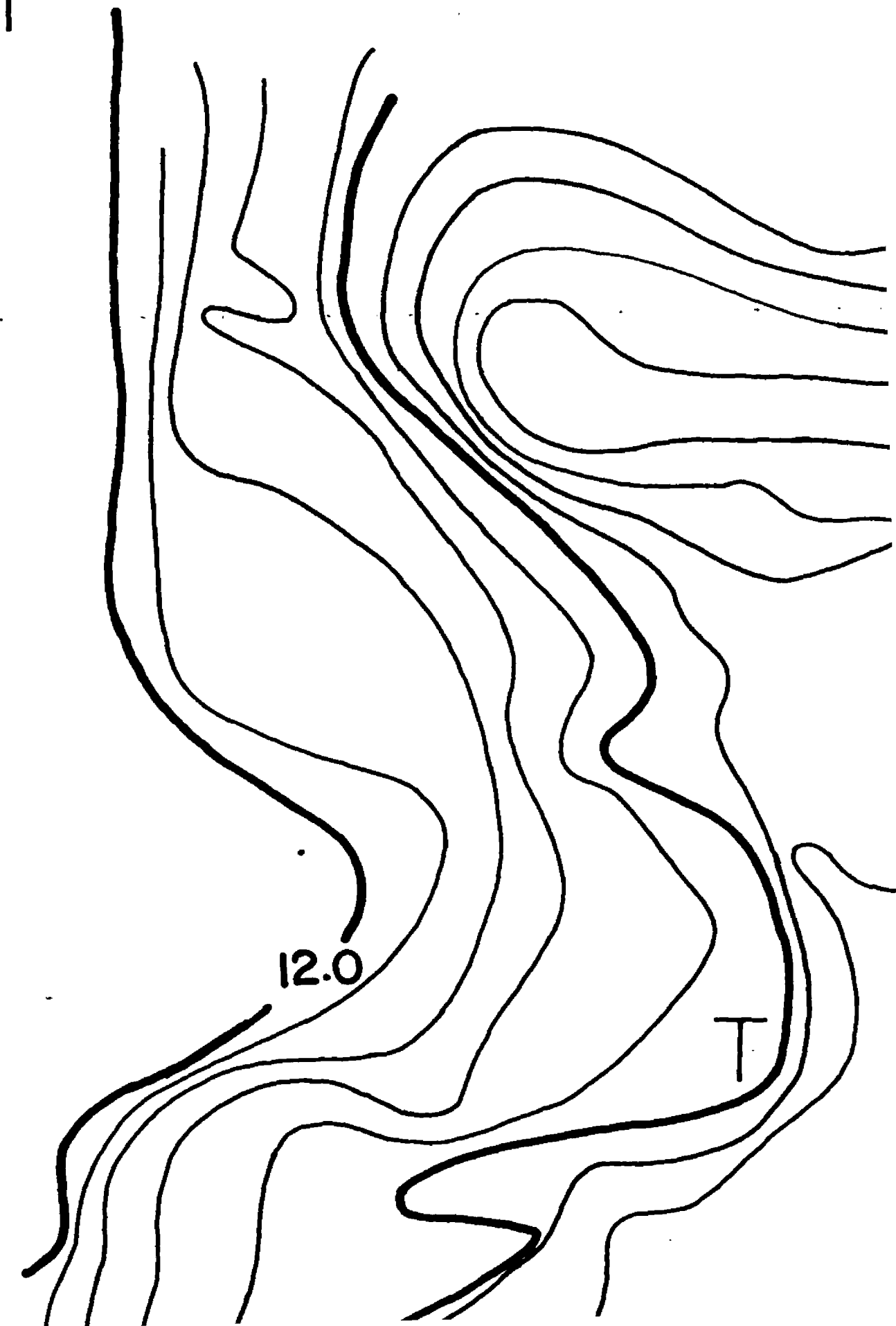
85° 20'

810
○

05.
42.



20'

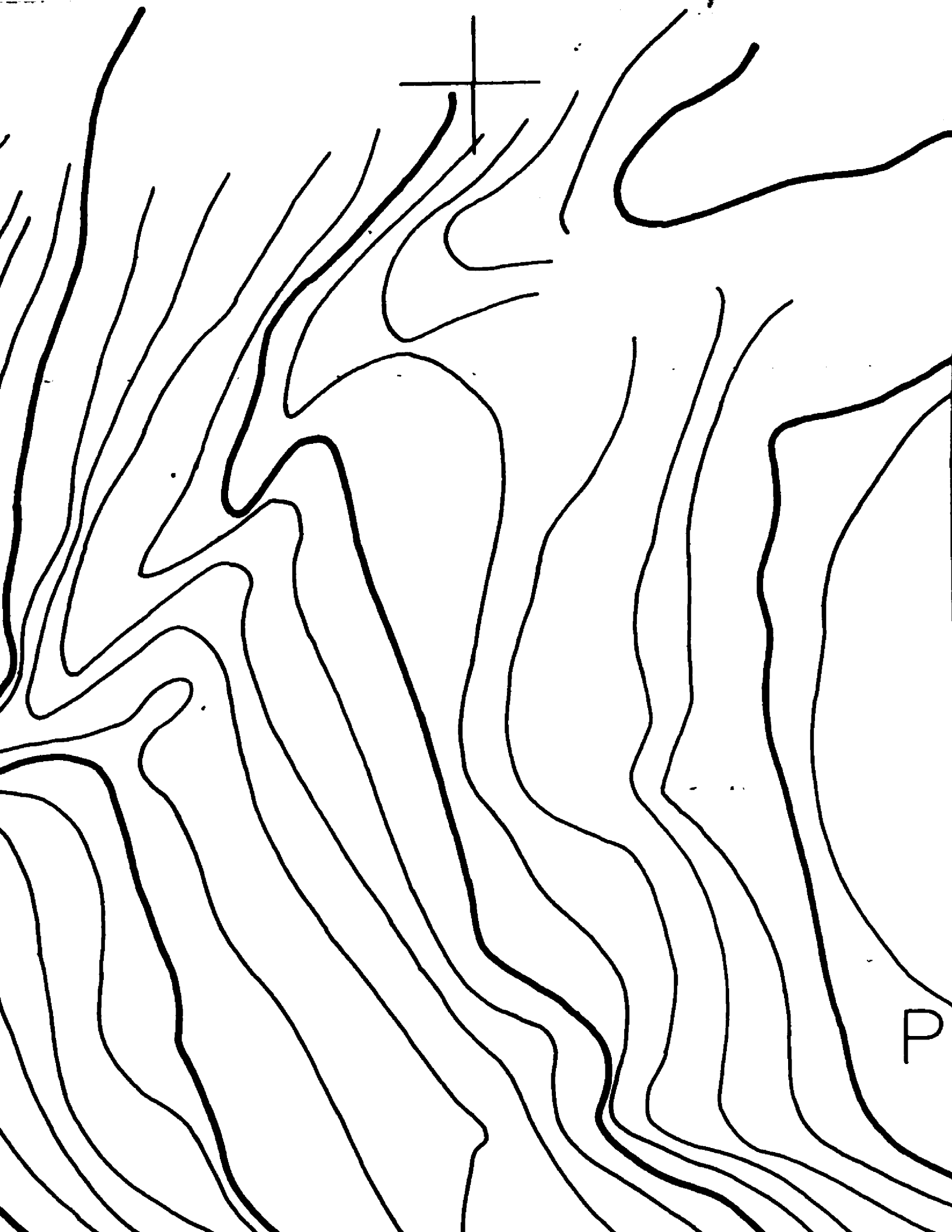


12.0

T3S

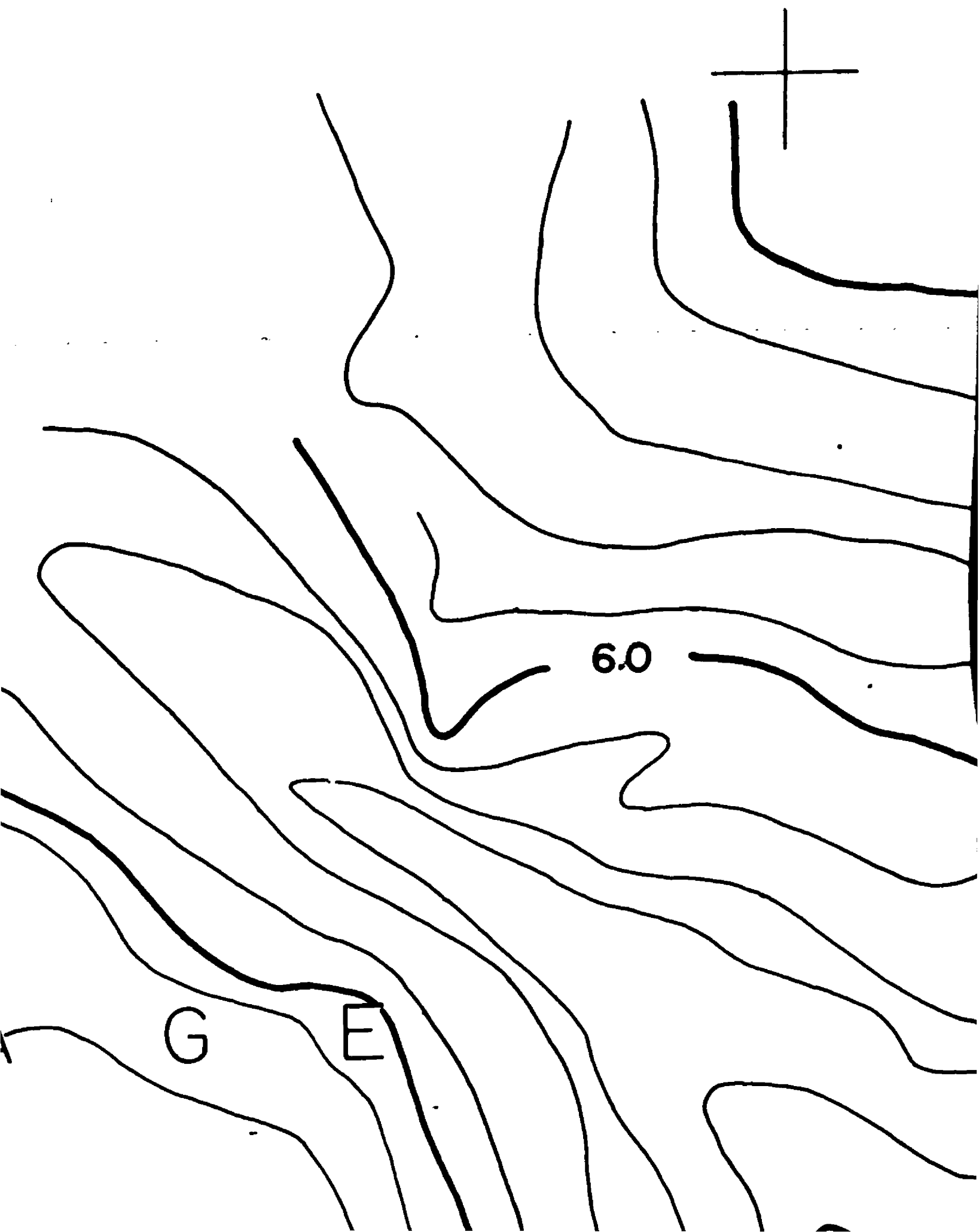
T

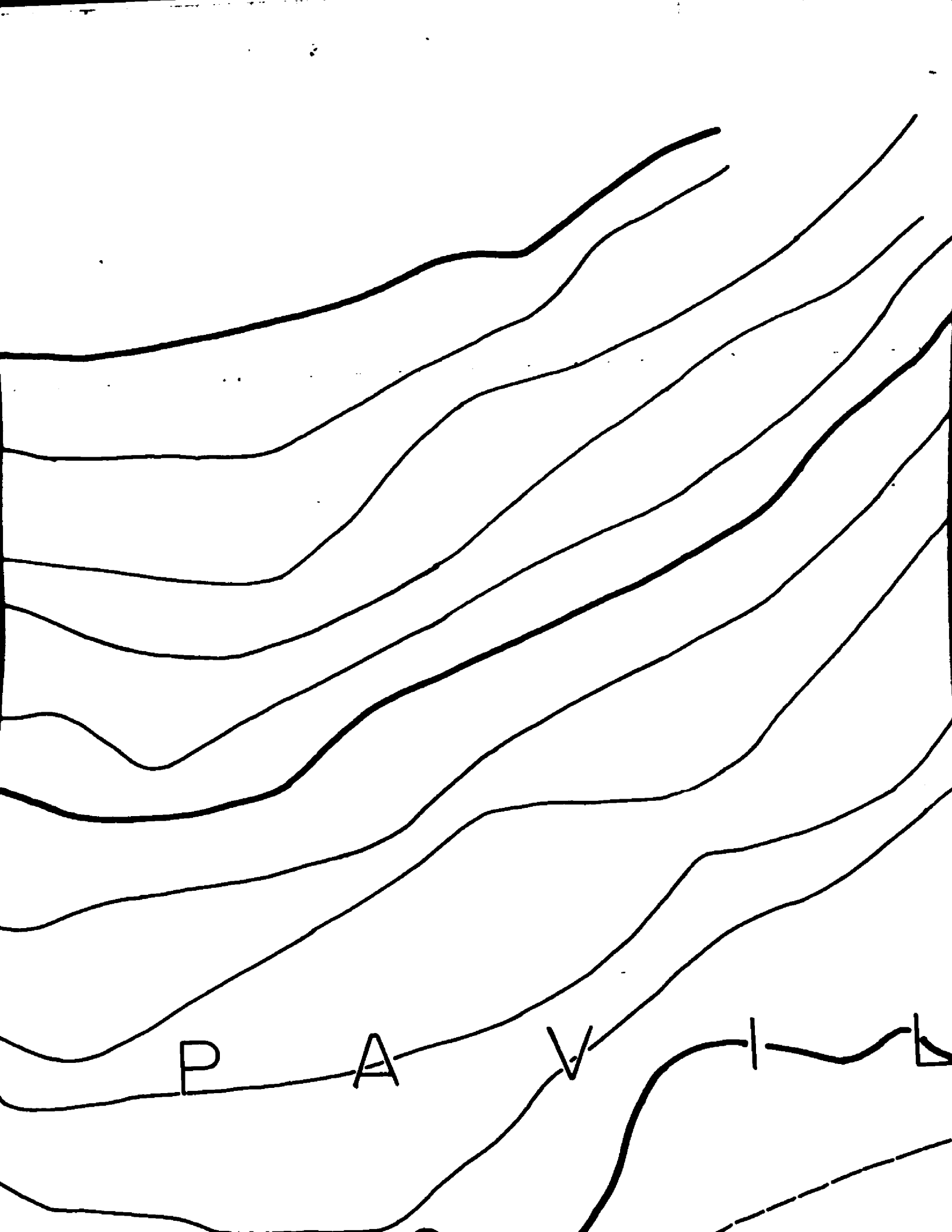




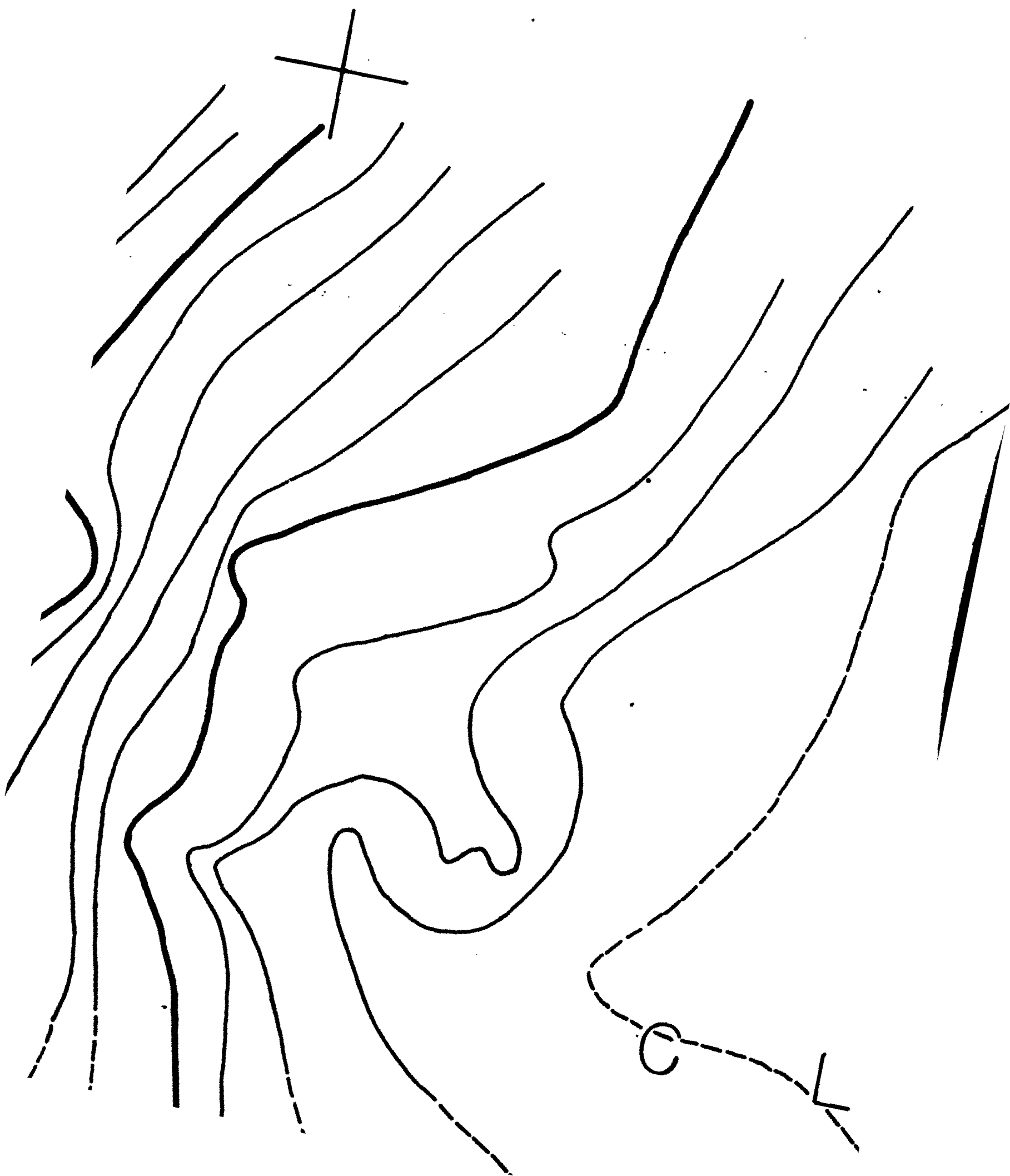


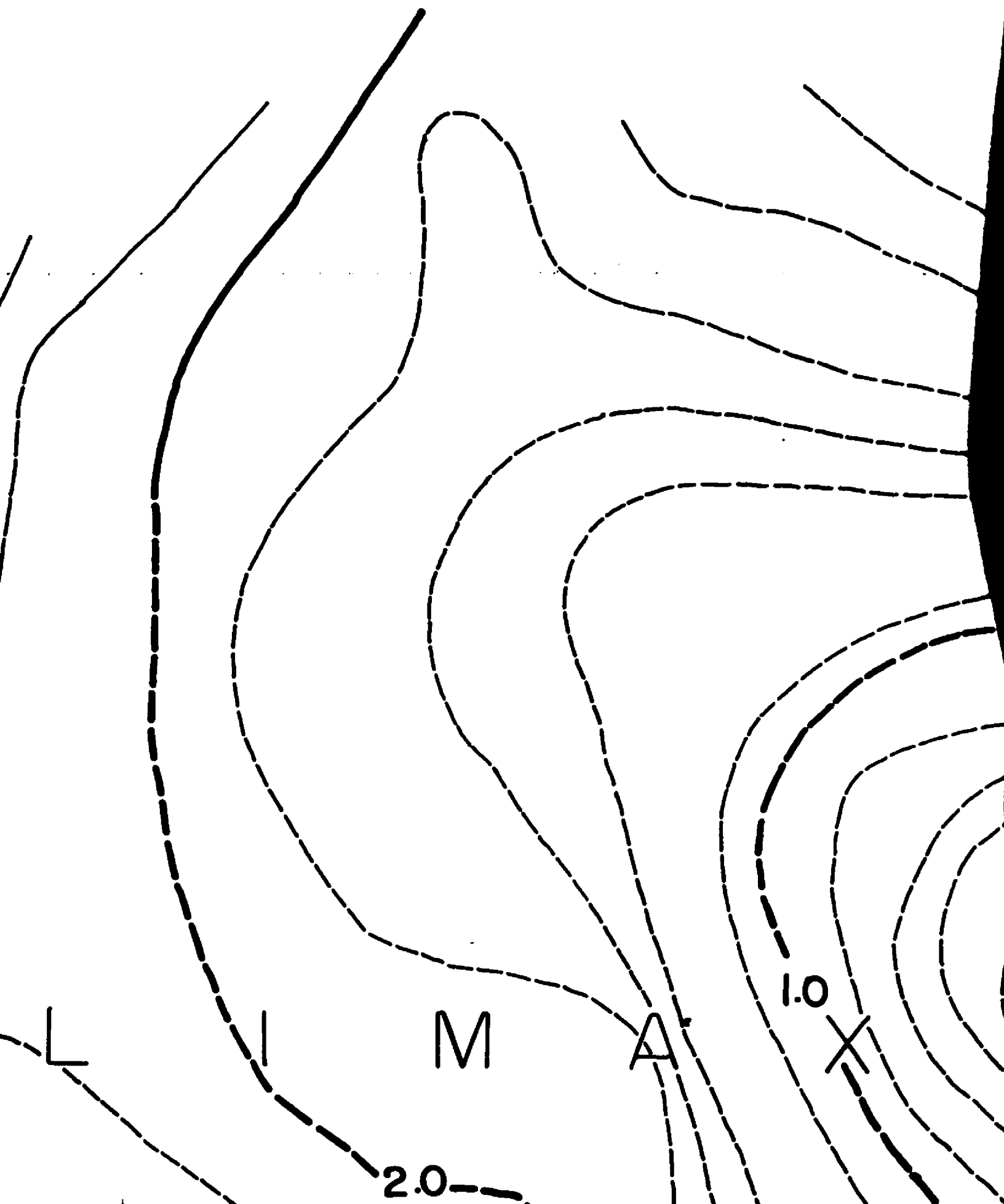
P O R T A

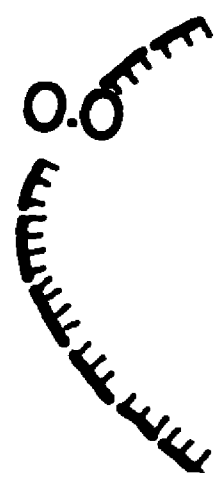
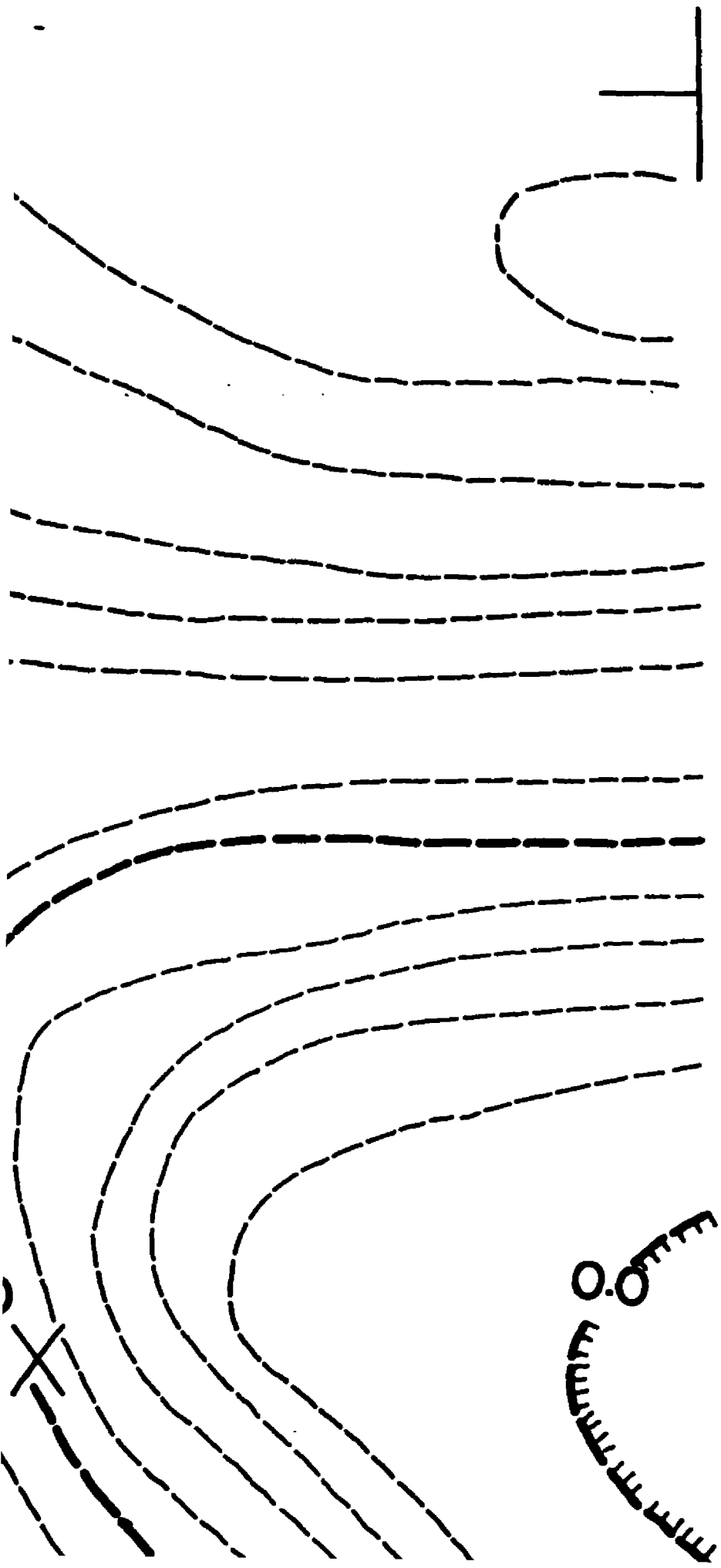








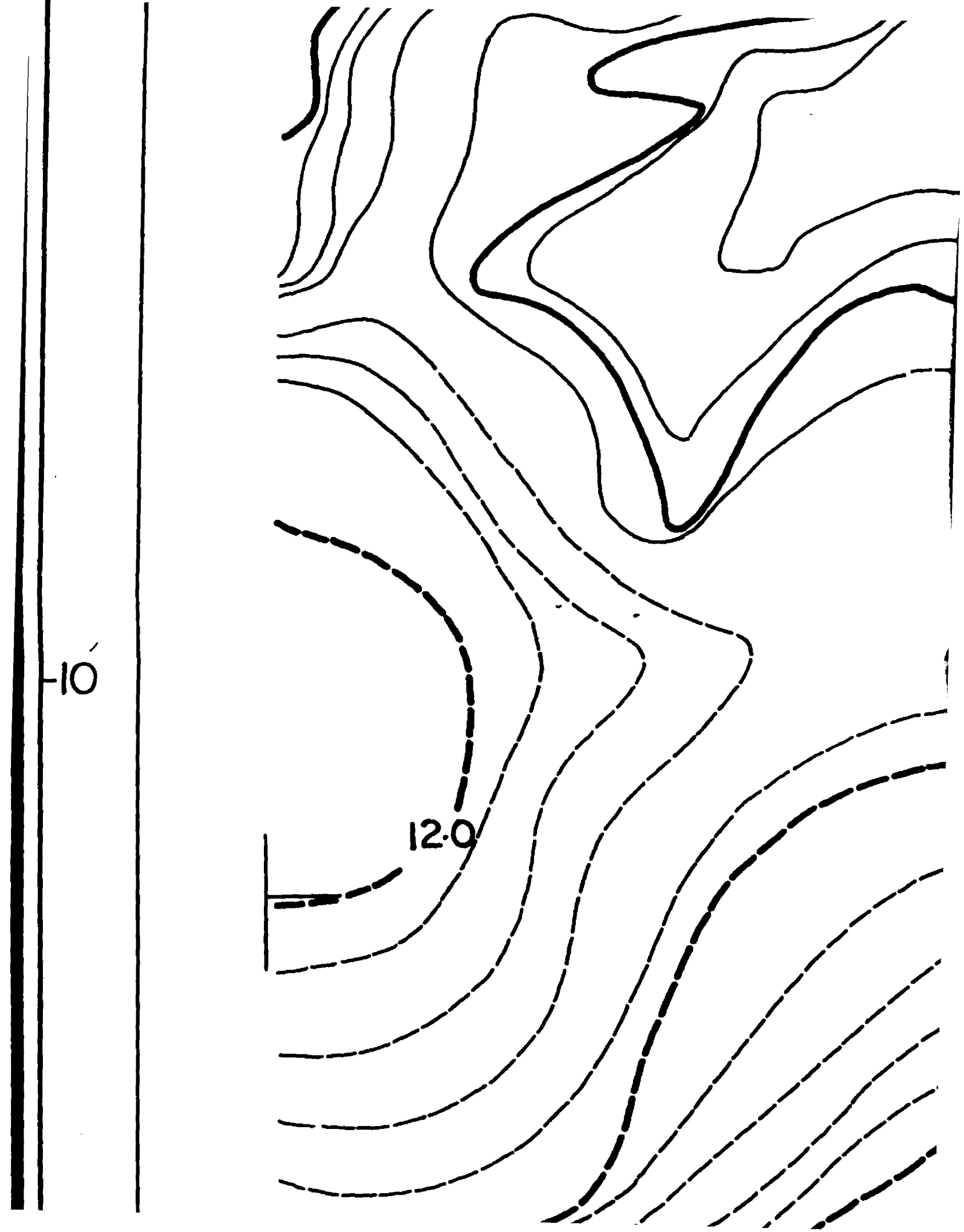




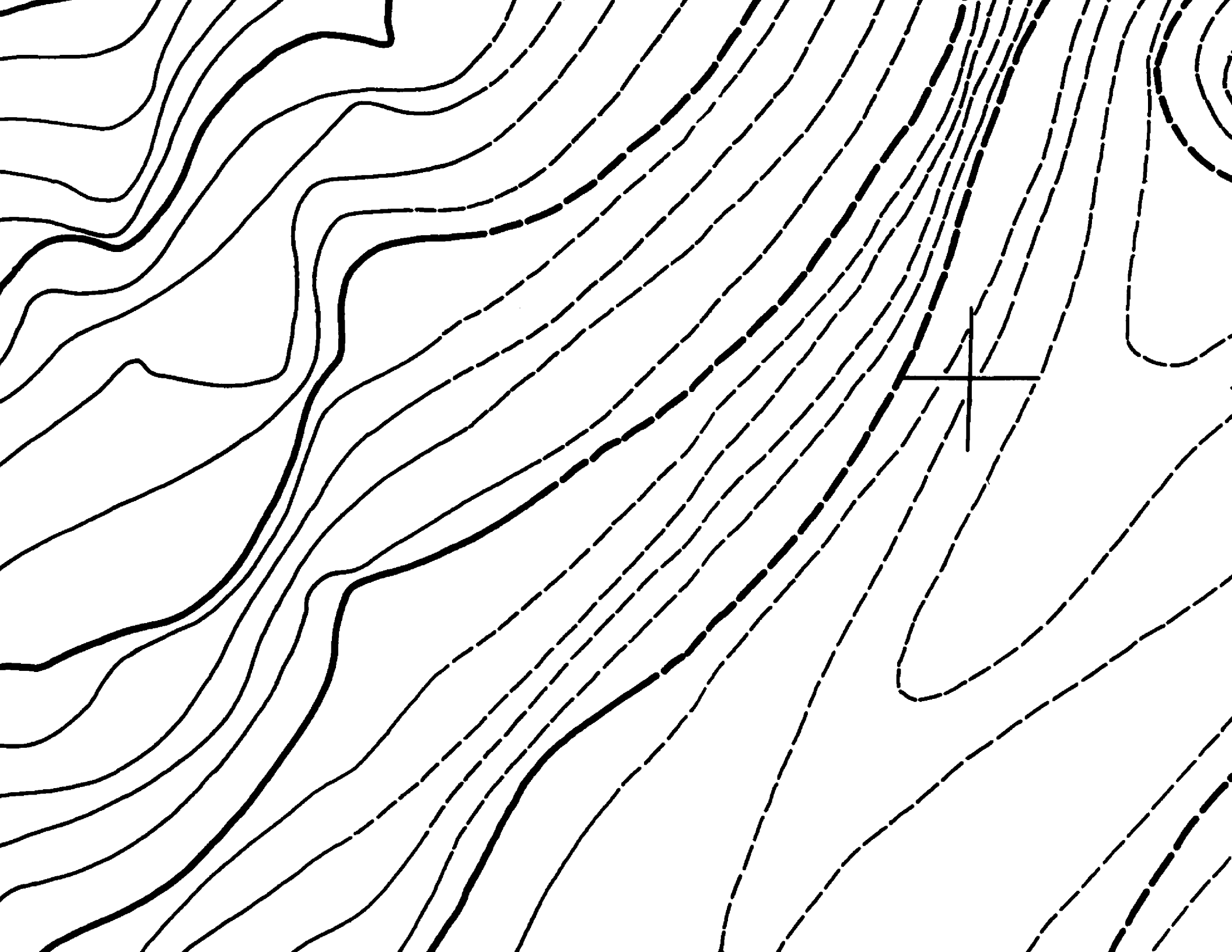
T3S

-10'

12.0

A topographic map showing contour lines. The map is oriented with a vertical line on the left side. The contour lines are drawn with varying line styles: solid, dashed, and dash-dot. The label '-10'' is located on the left side, and the label '12.0' is located in the center-left area. The contour lines represent different elevations, with the '12.0' contour being a prominent dashed line.





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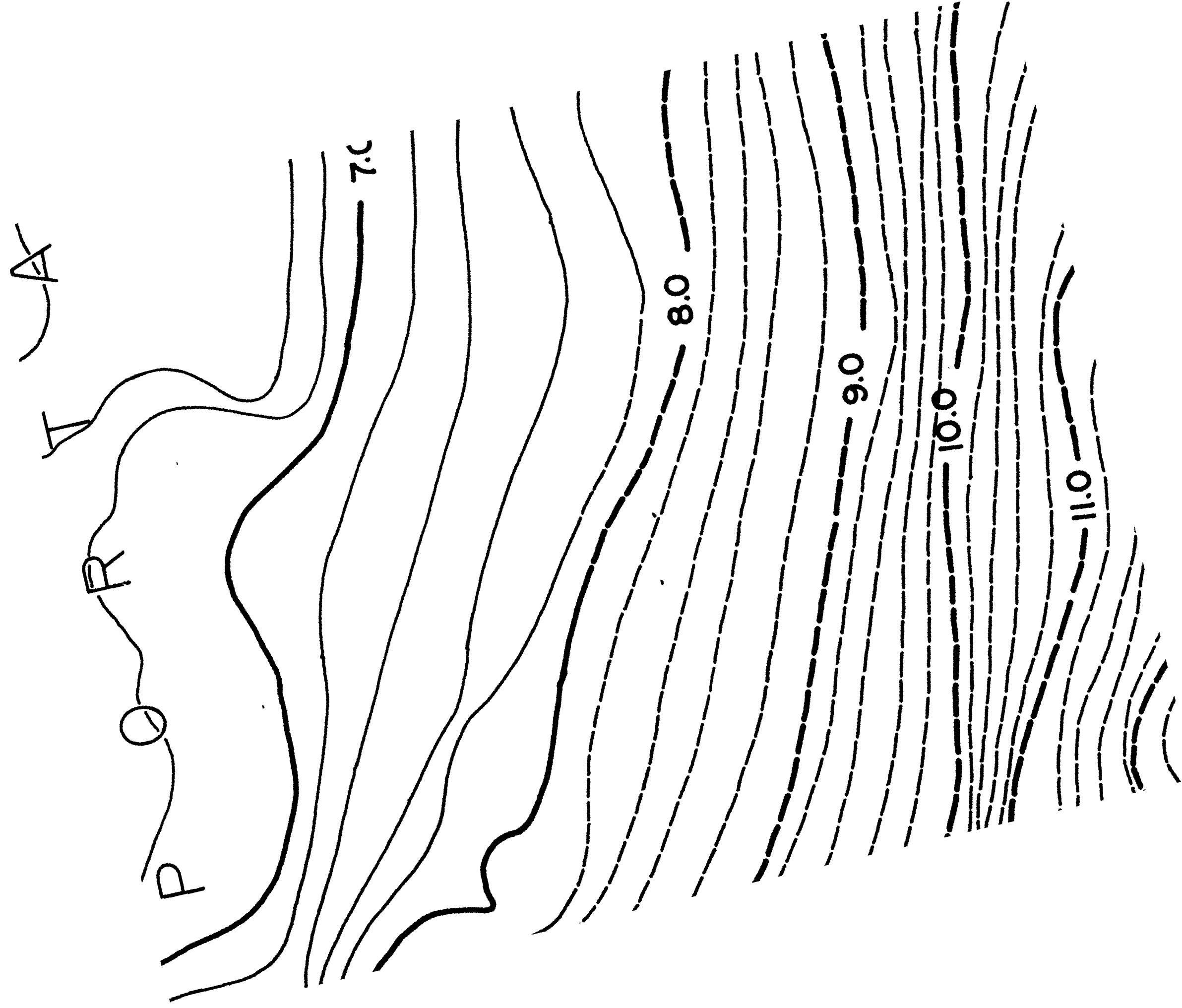
7.0

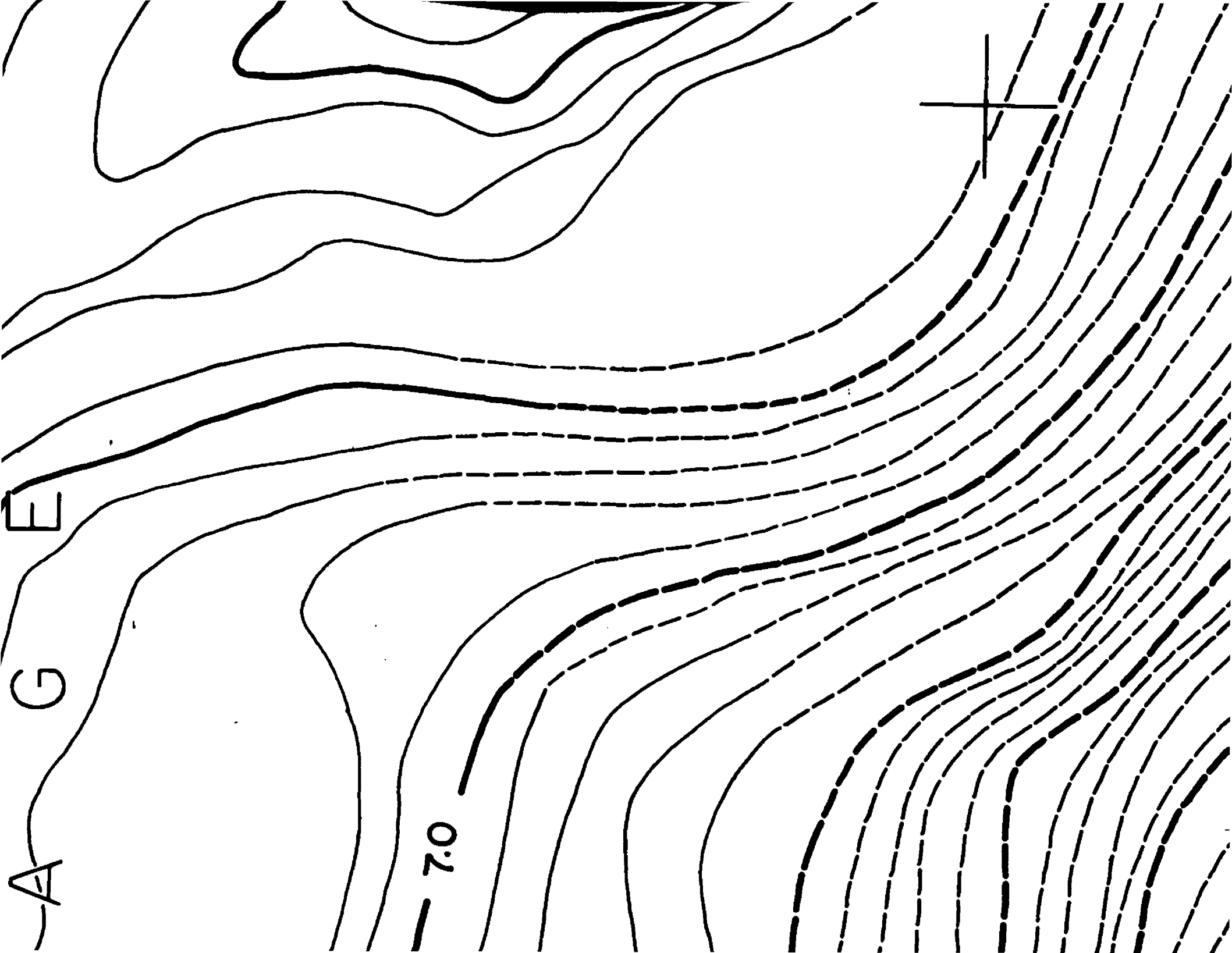
8.0

9.0

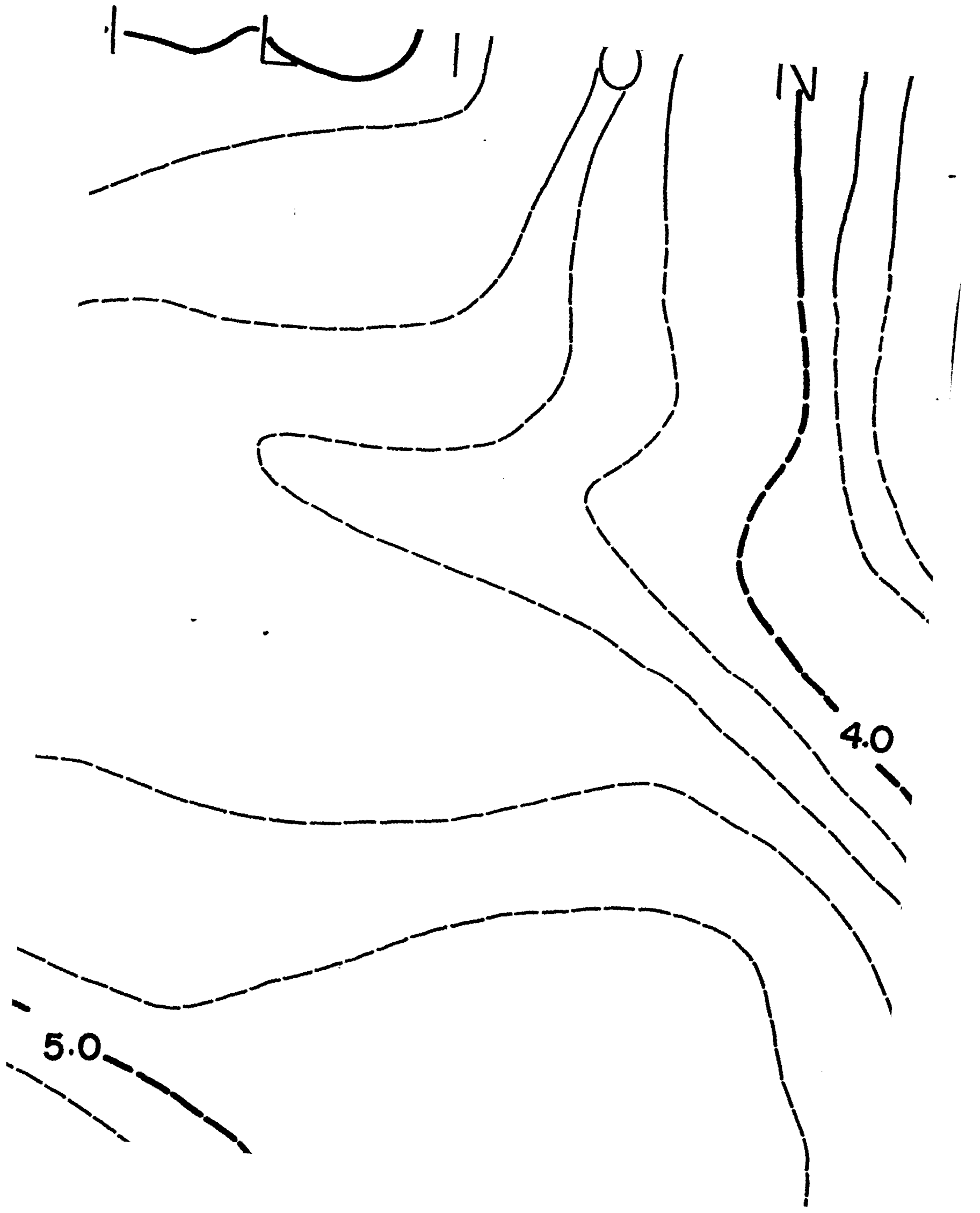
10.0

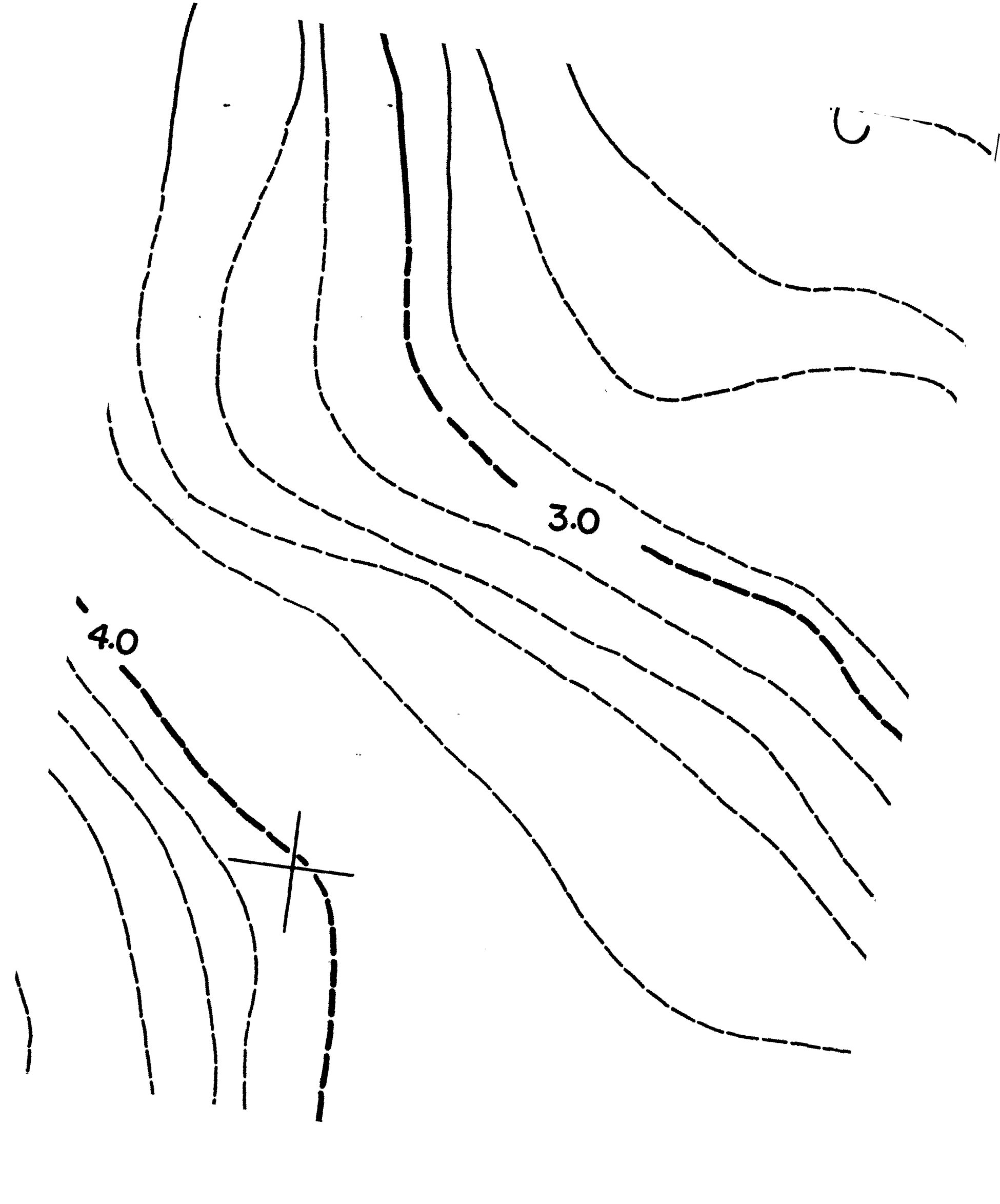
11.0

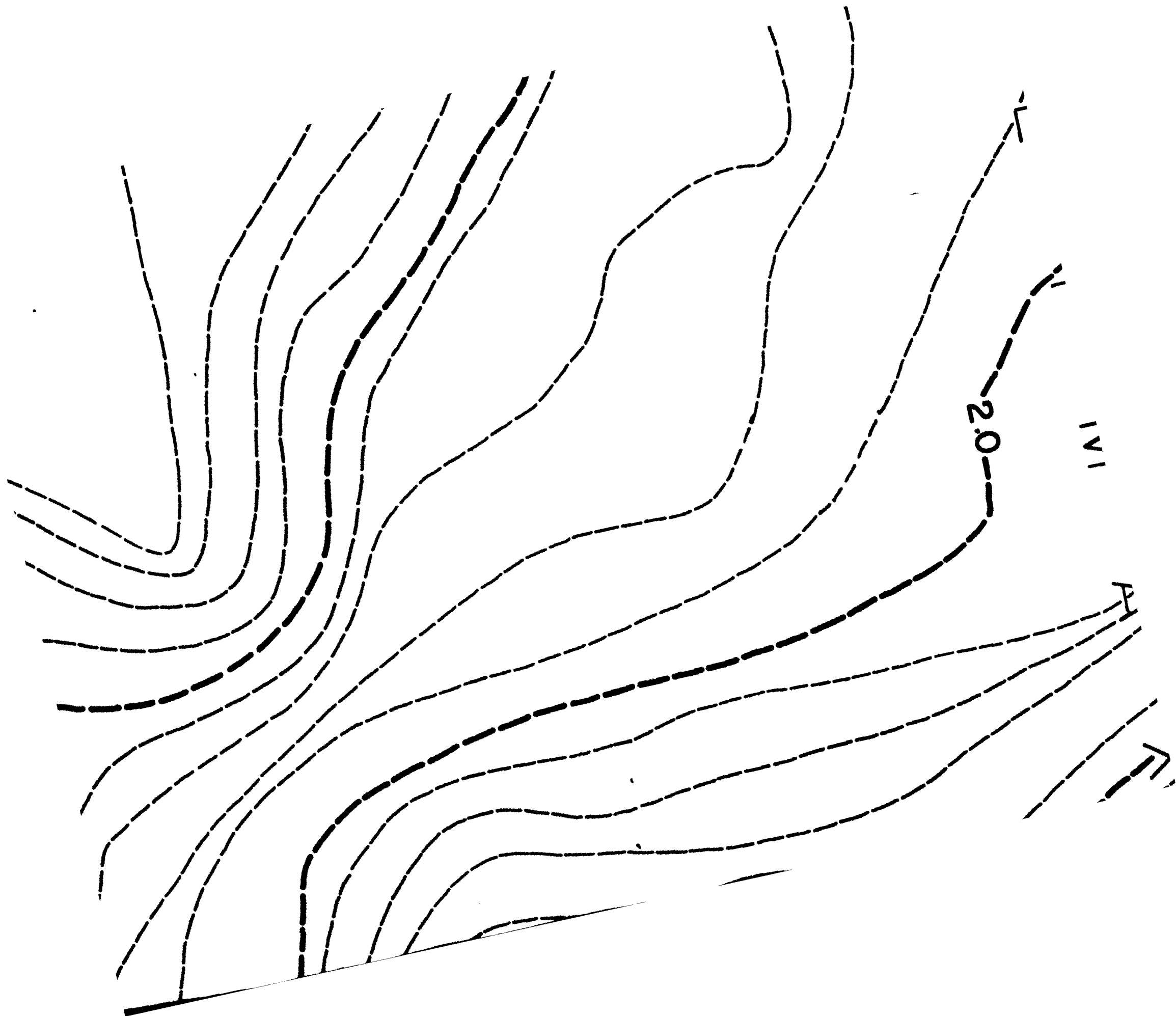


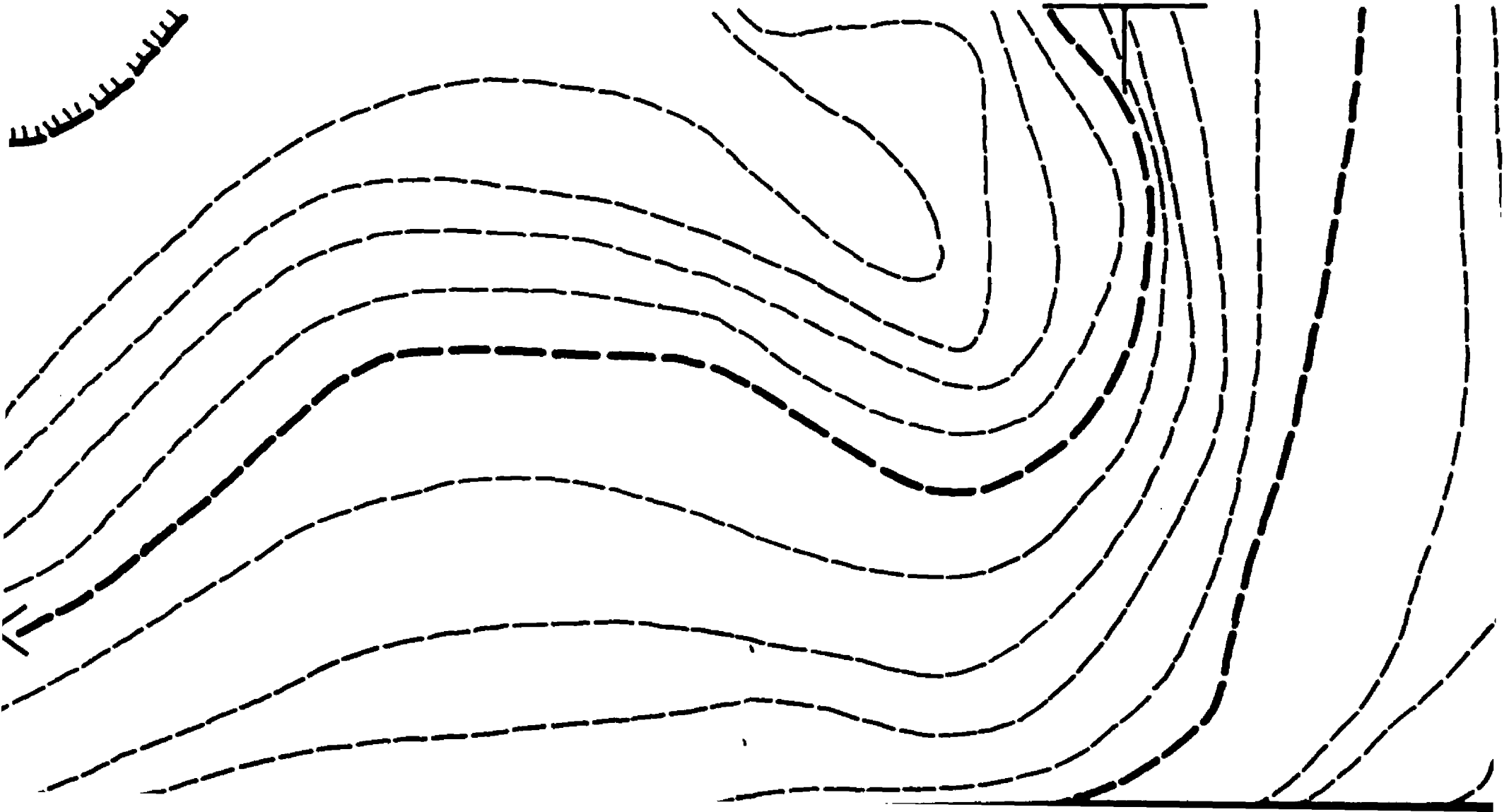










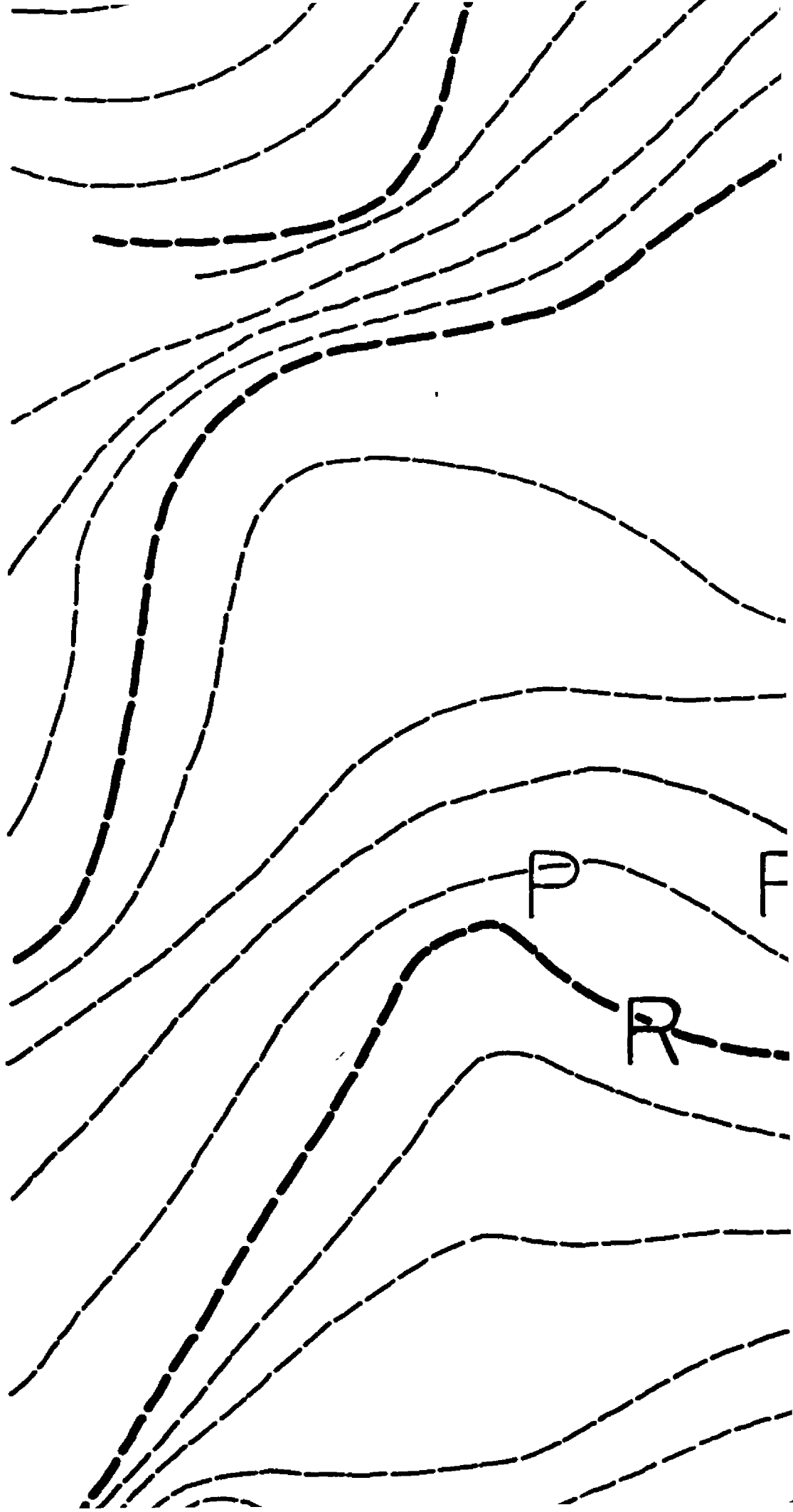


T4S

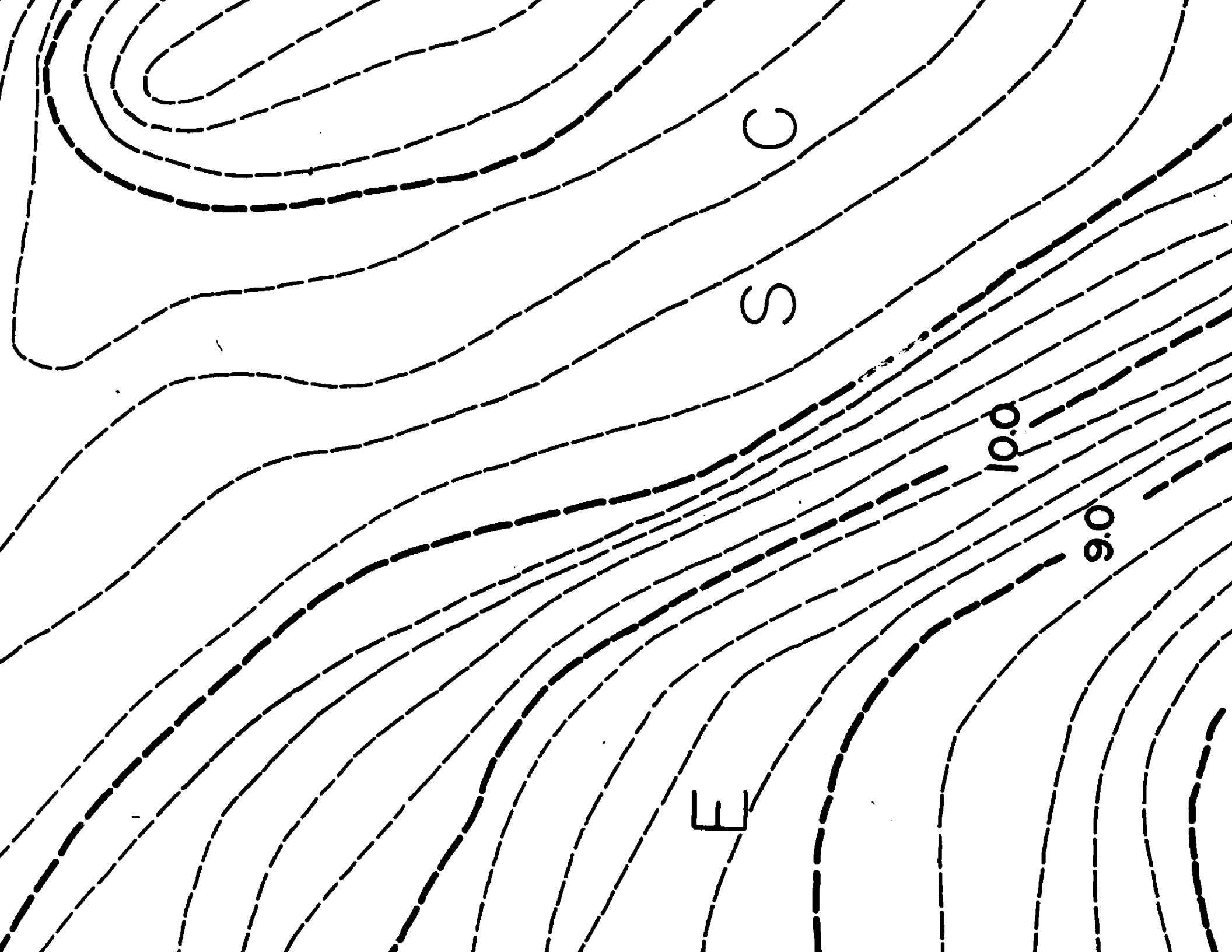
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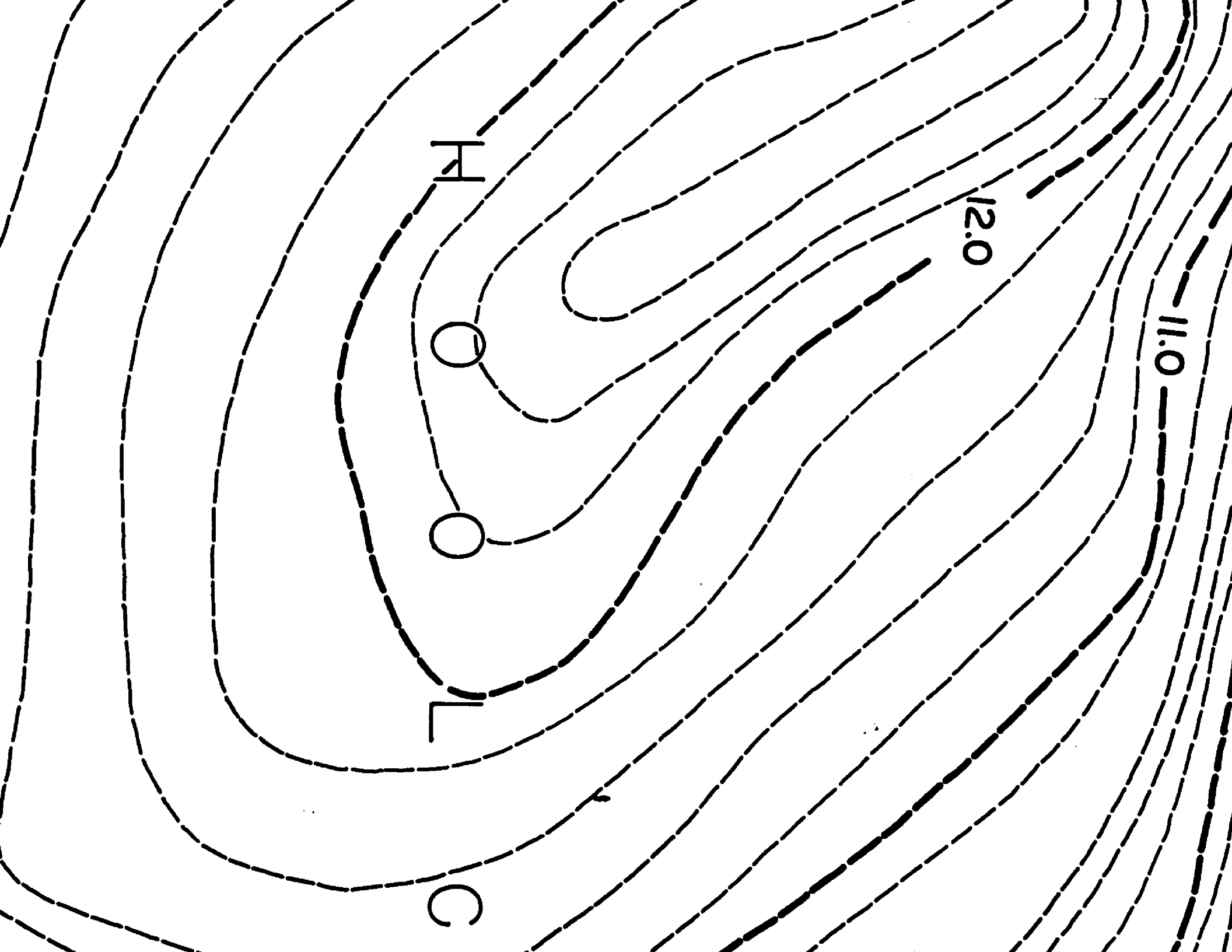
R

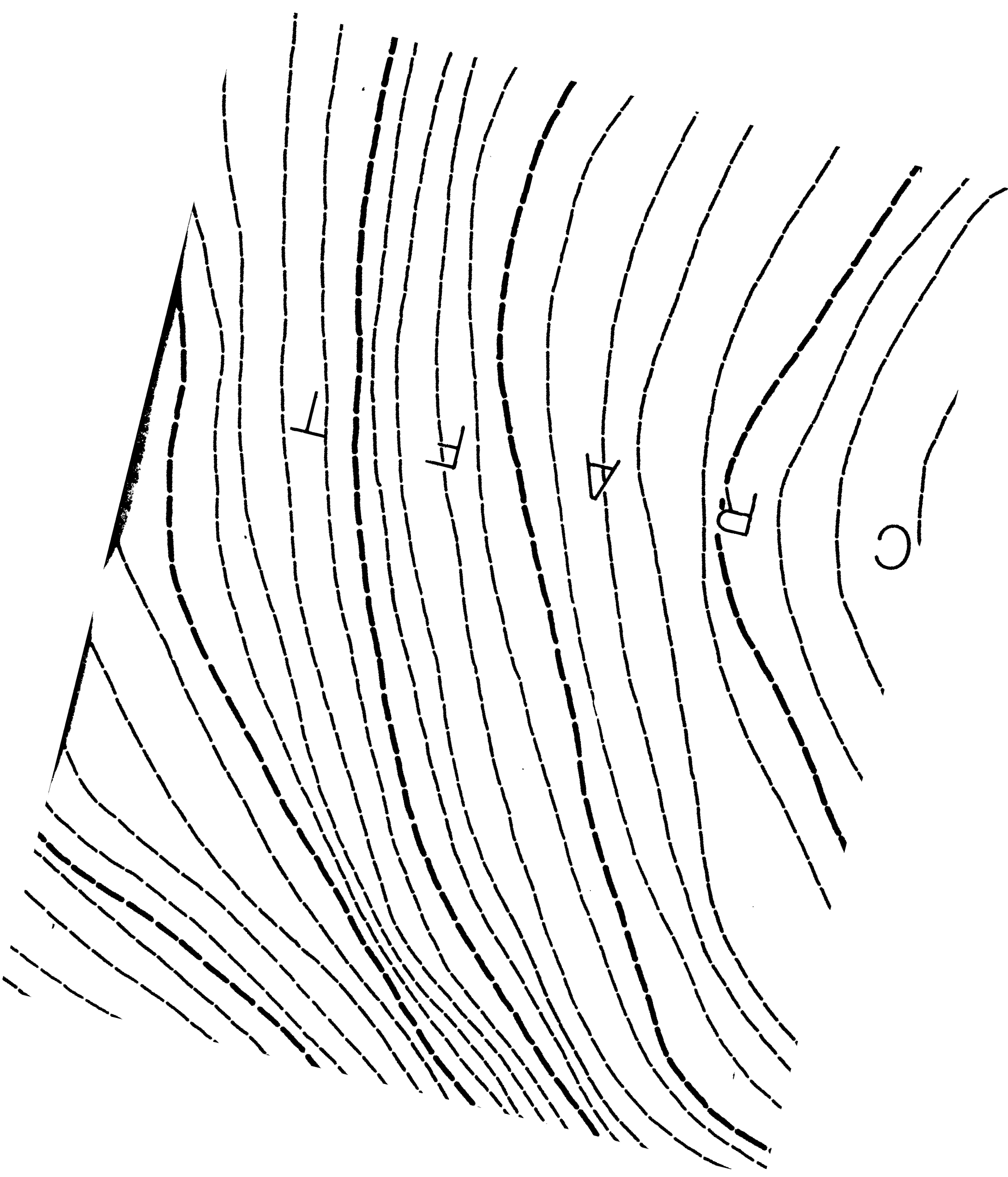
F

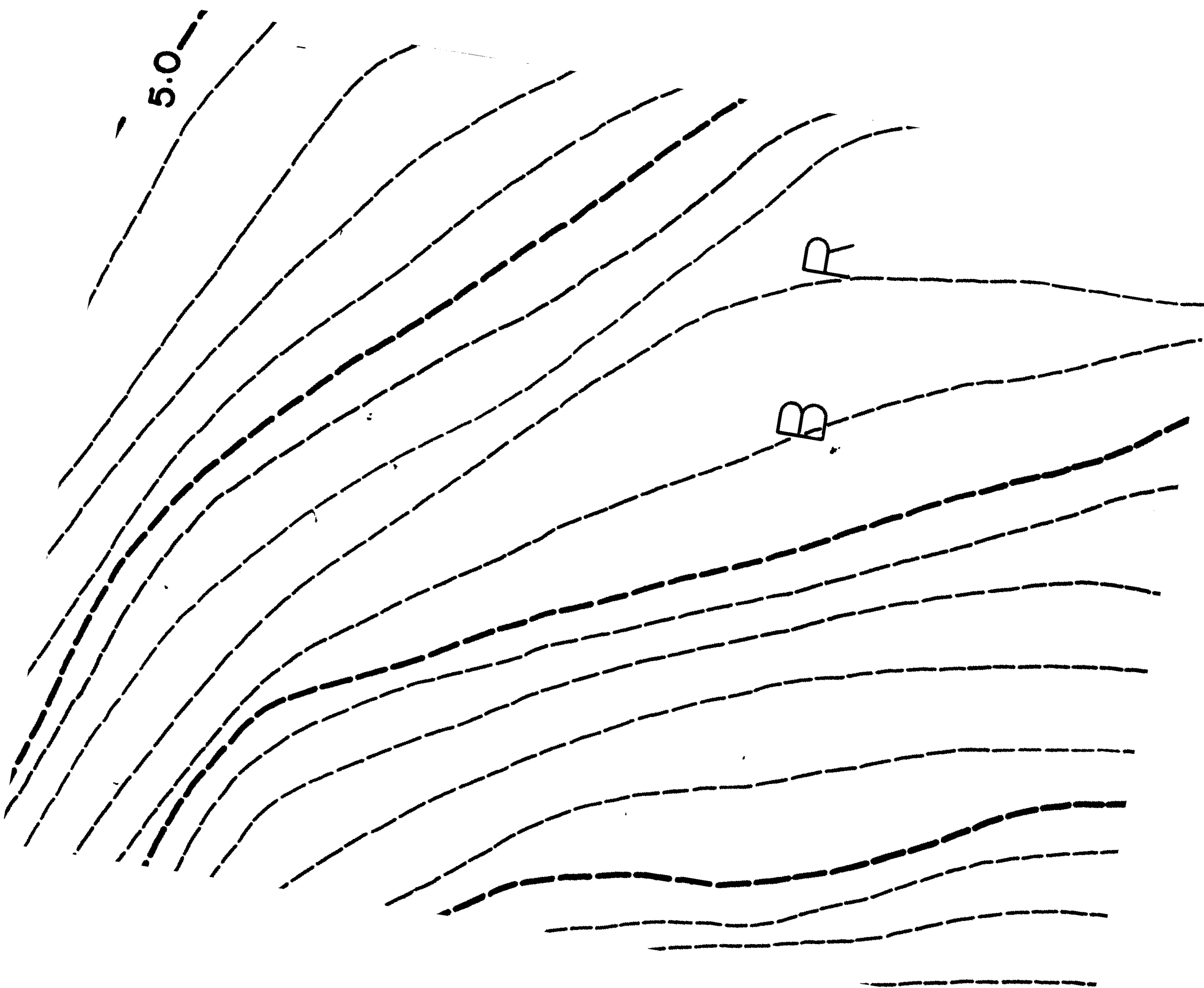


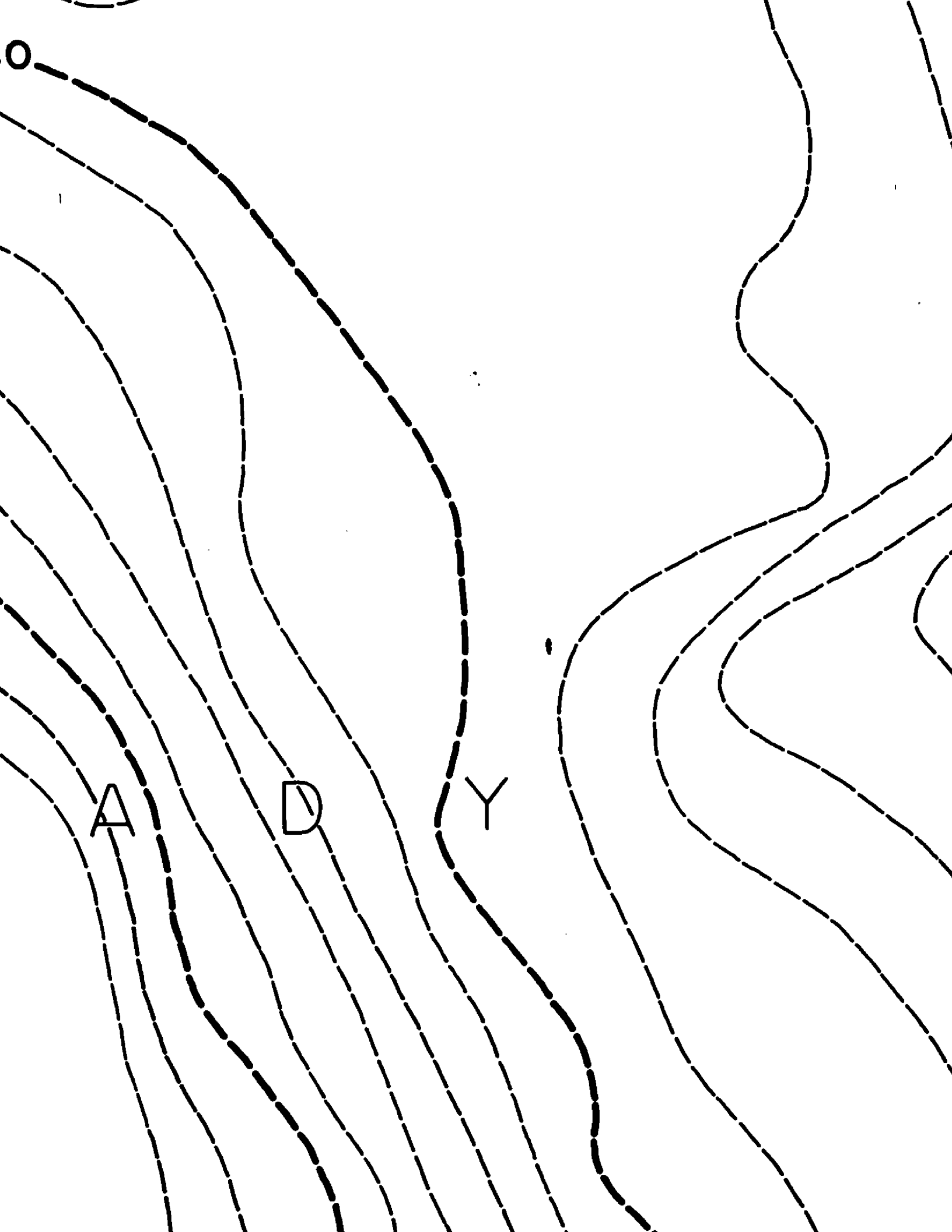
R A I R E
O N D E

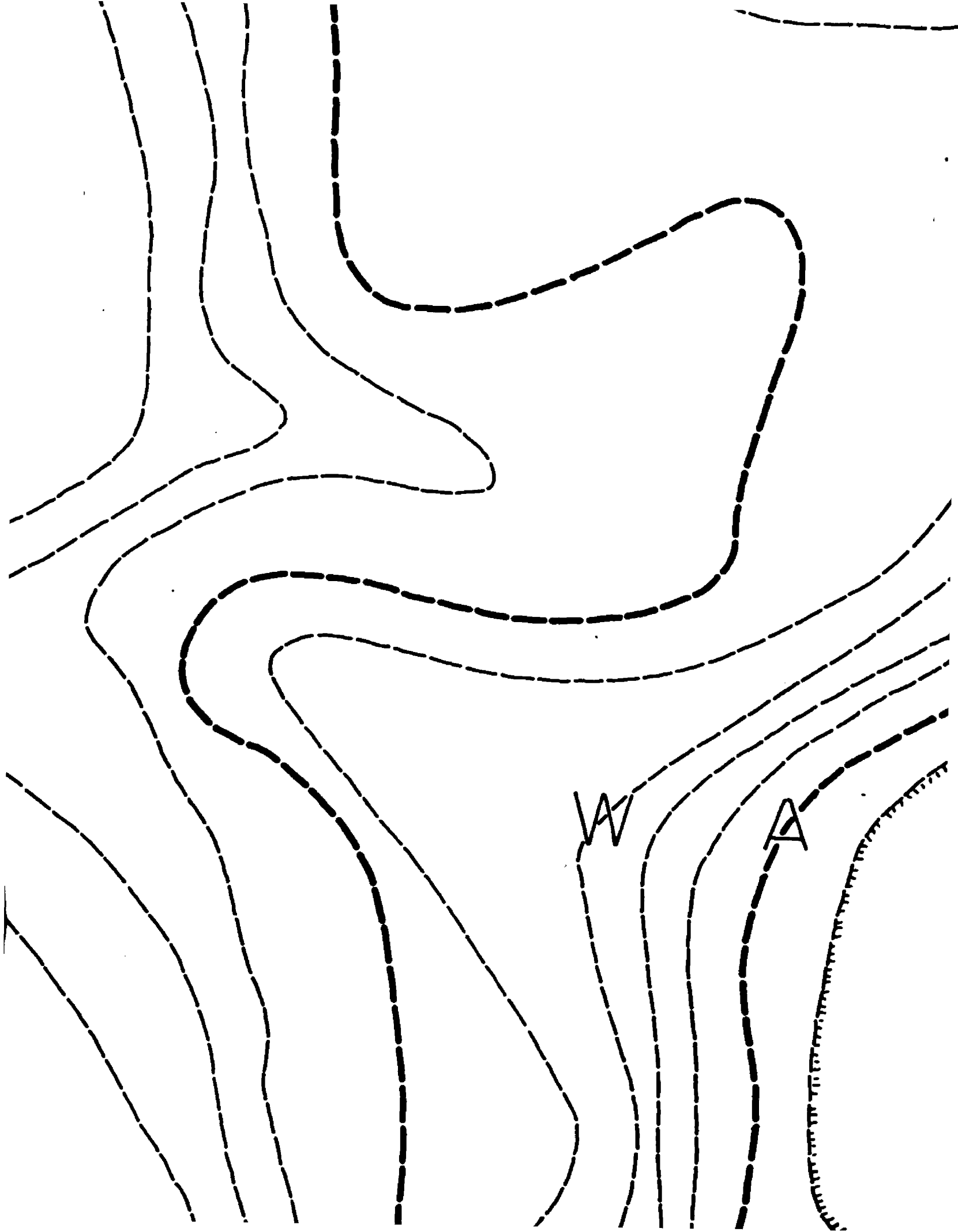


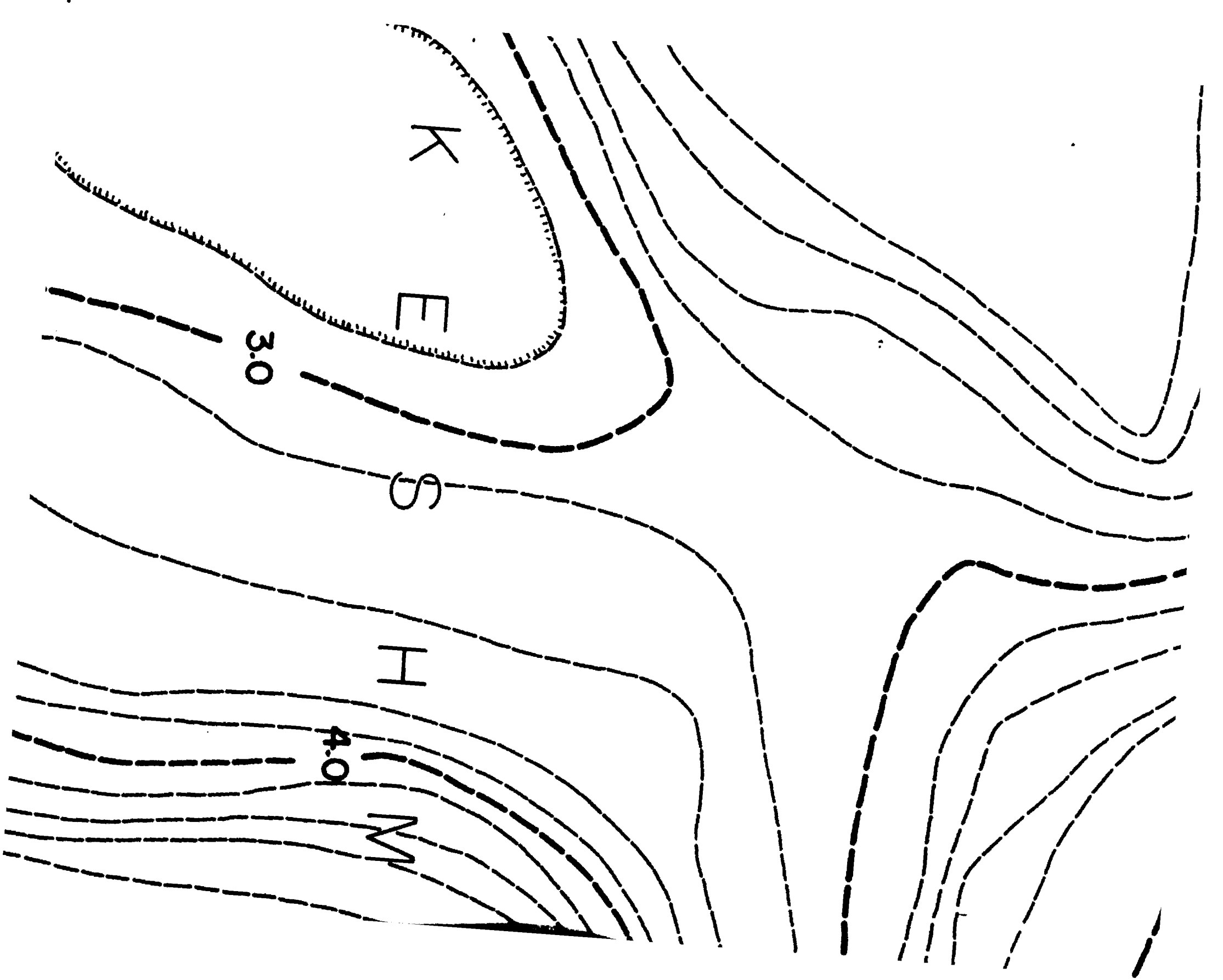


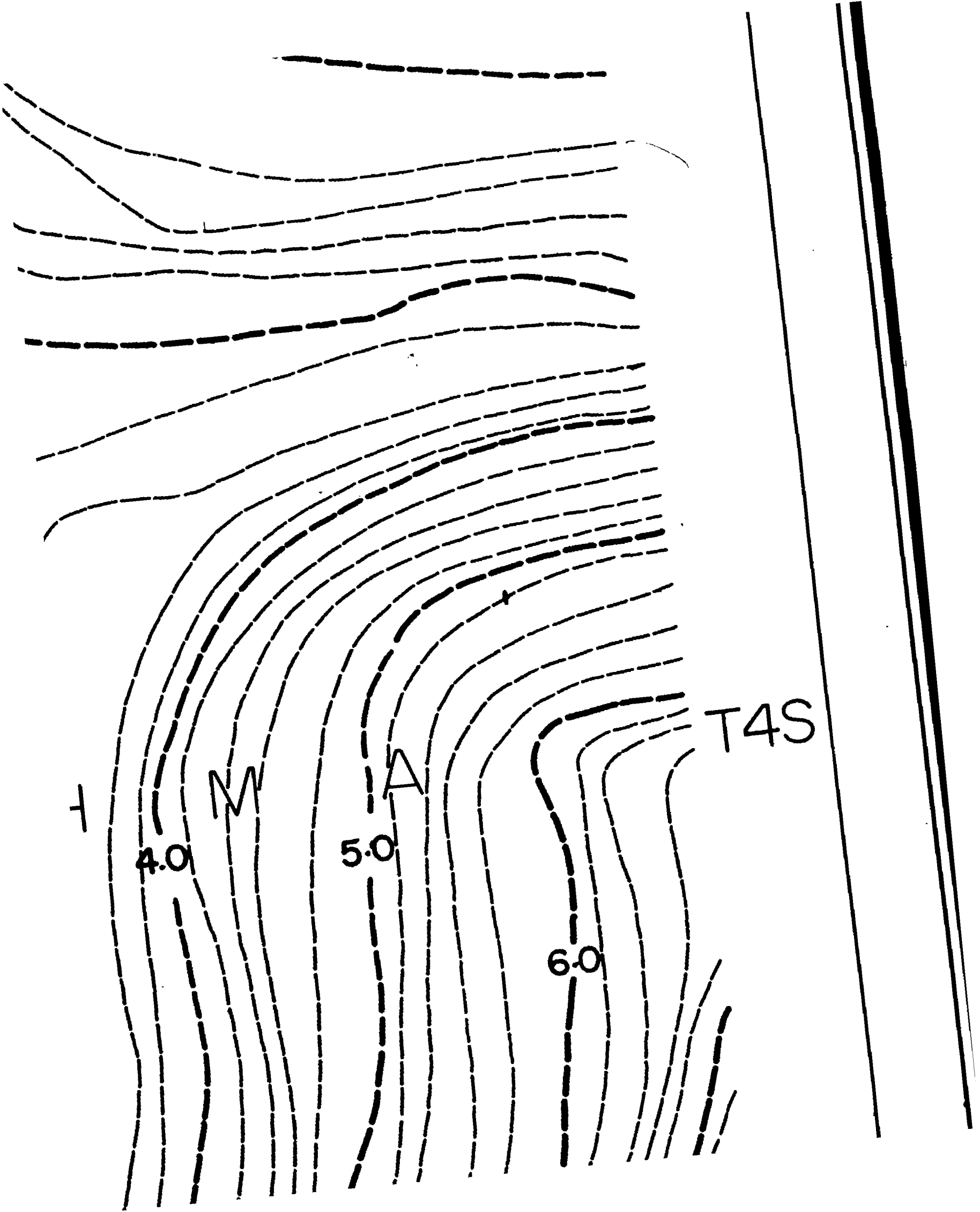




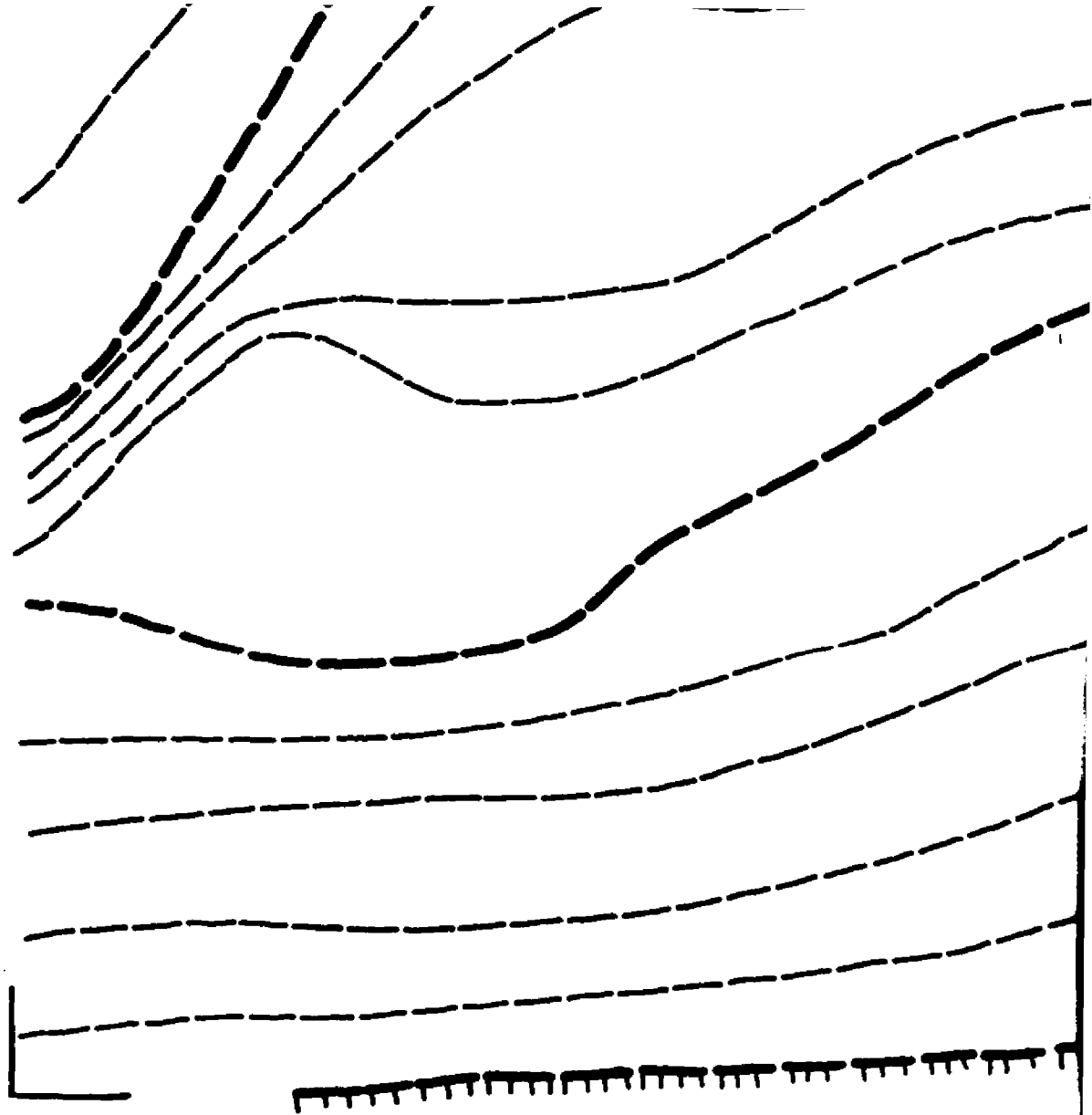




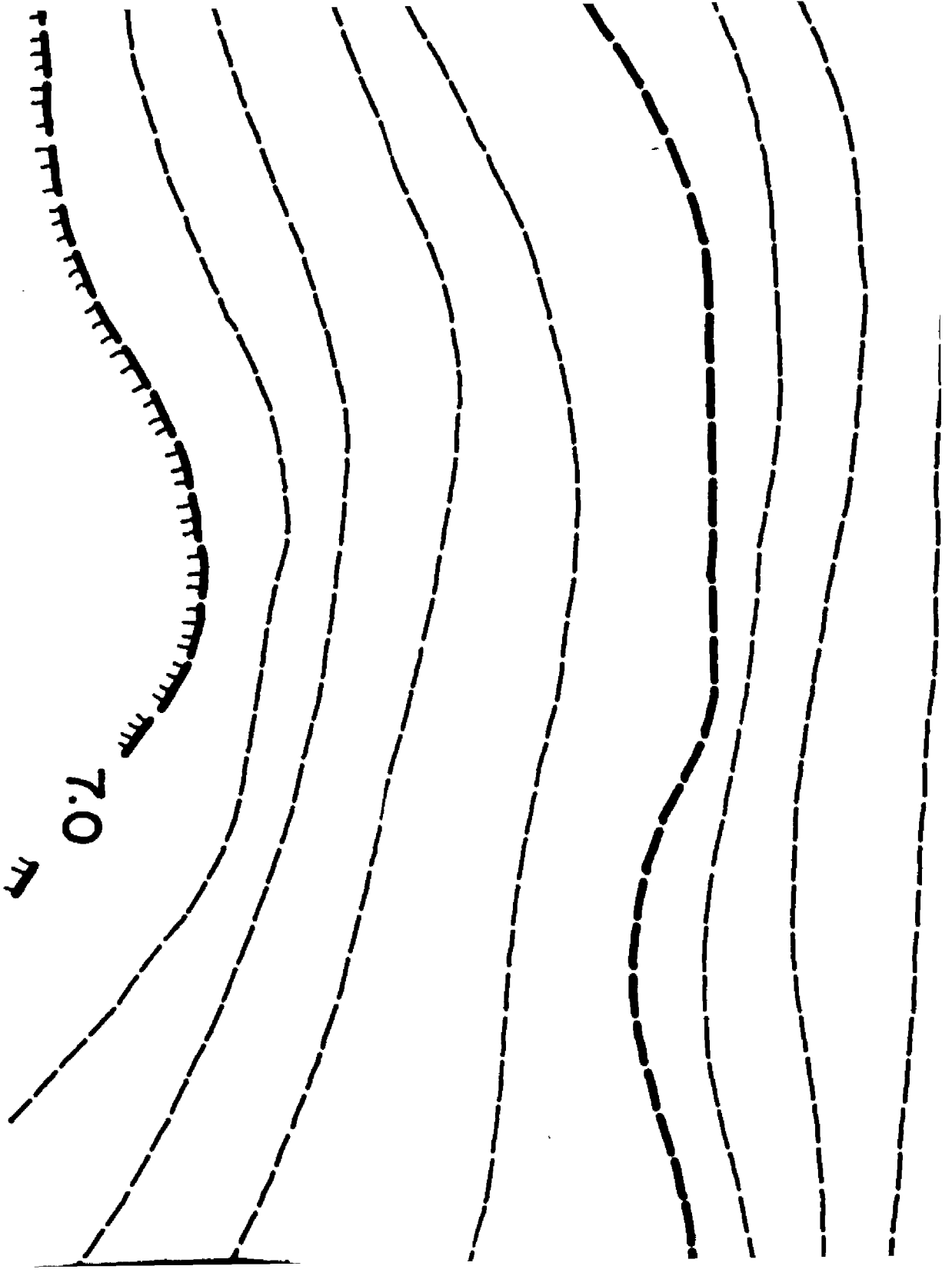




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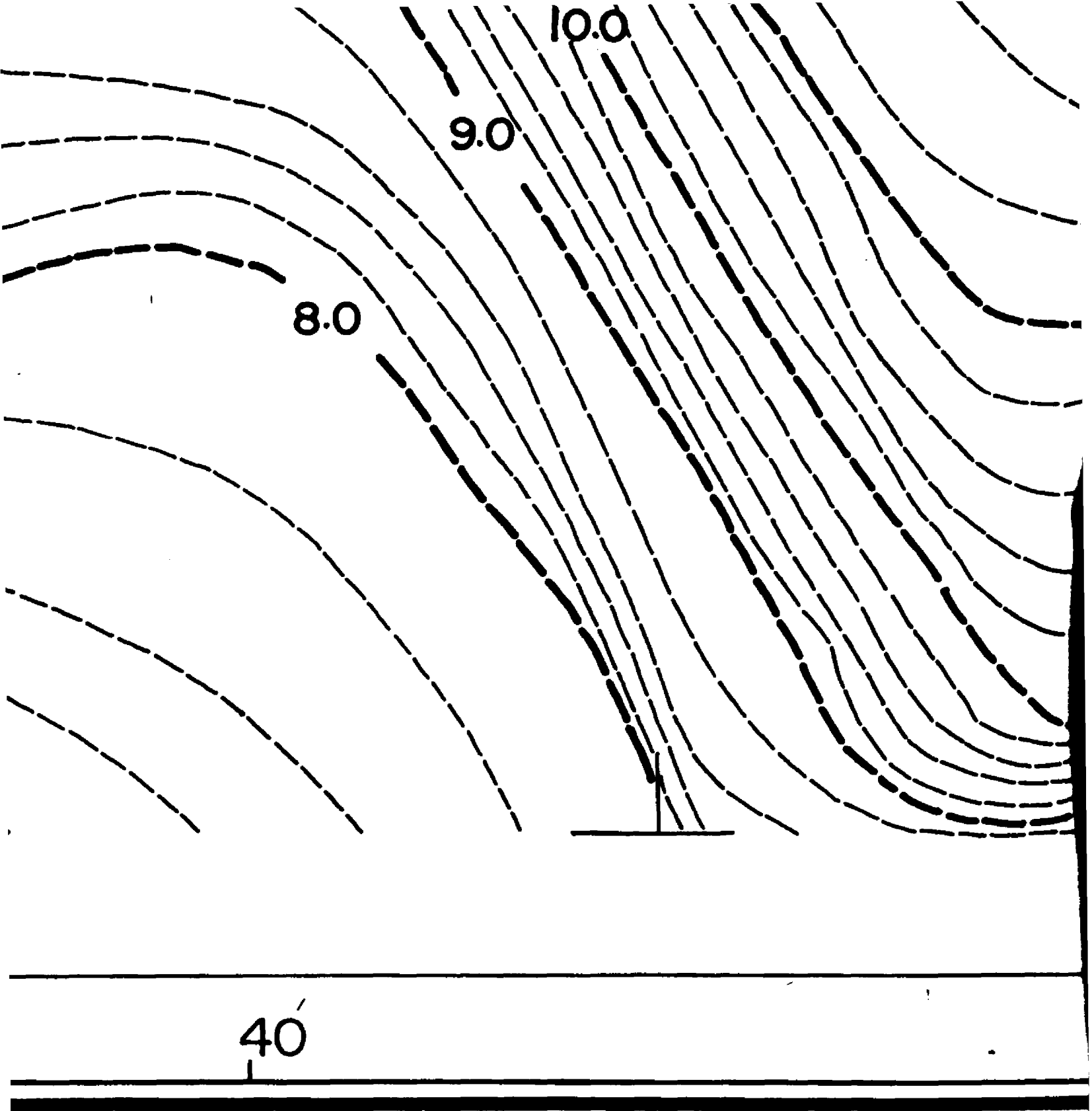
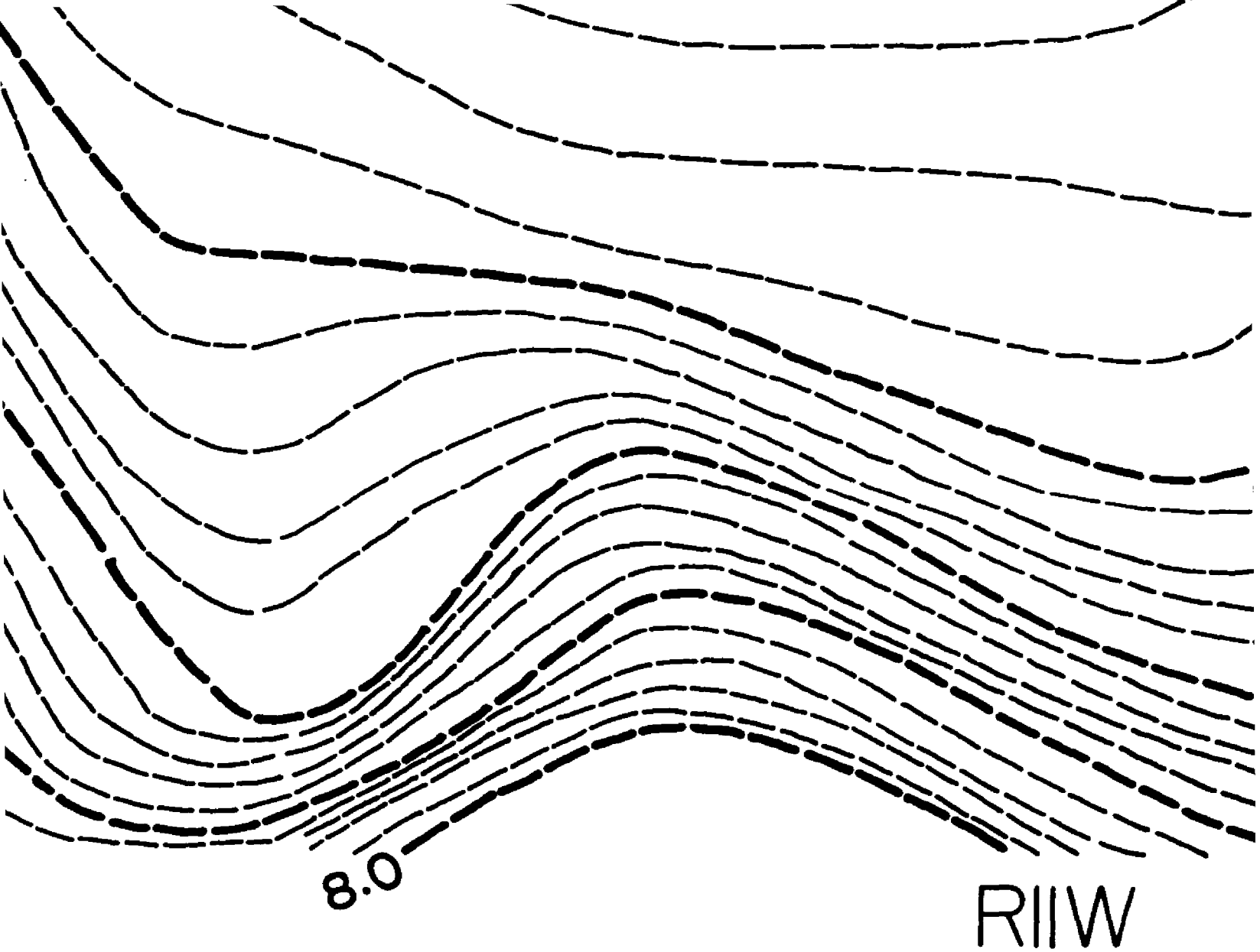


PLATE 3a.

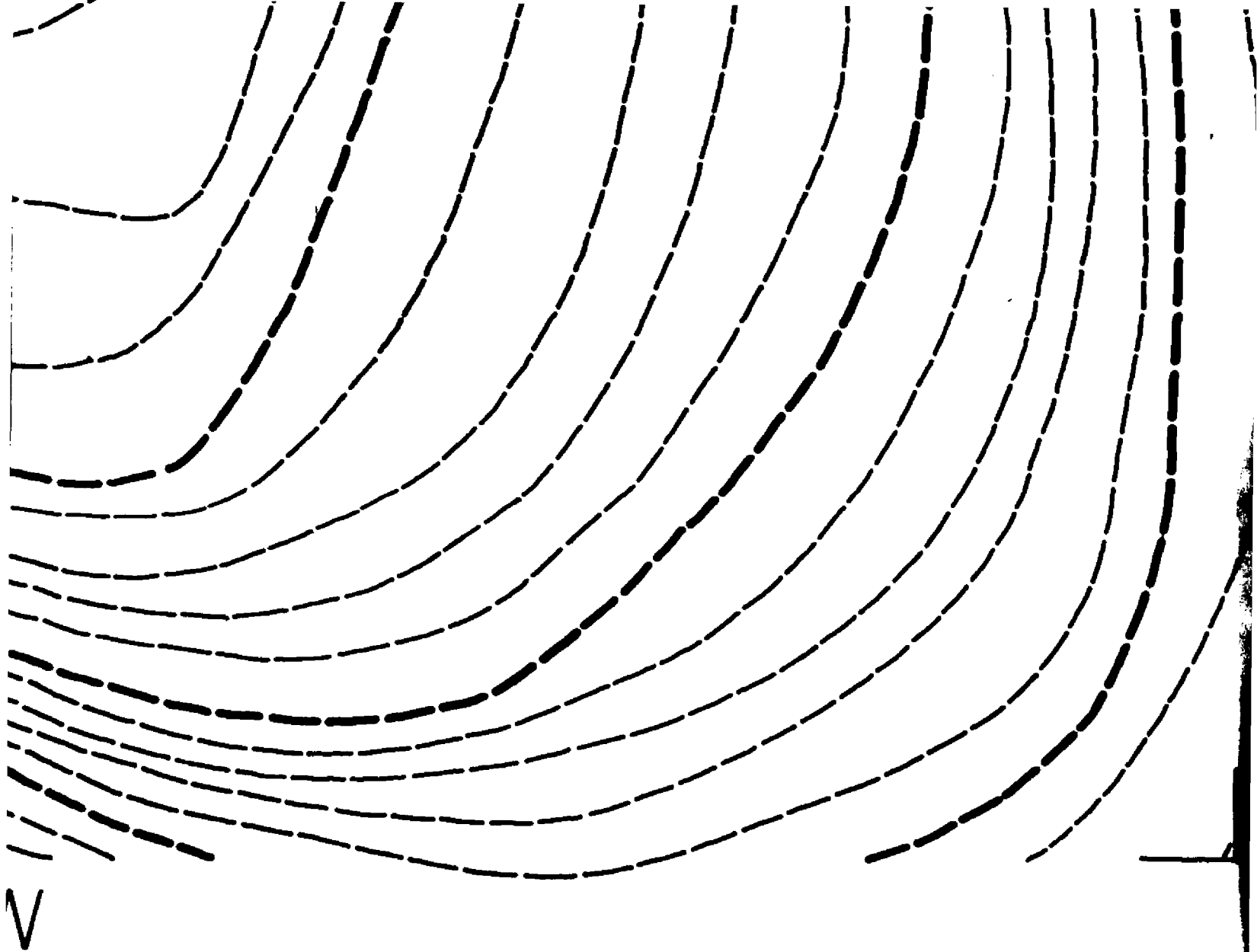
CONTOUR M

SOUTHERN H



OUR MAP OF THE BOUG
HERN HALF OF KALAMAZOO COUNTY

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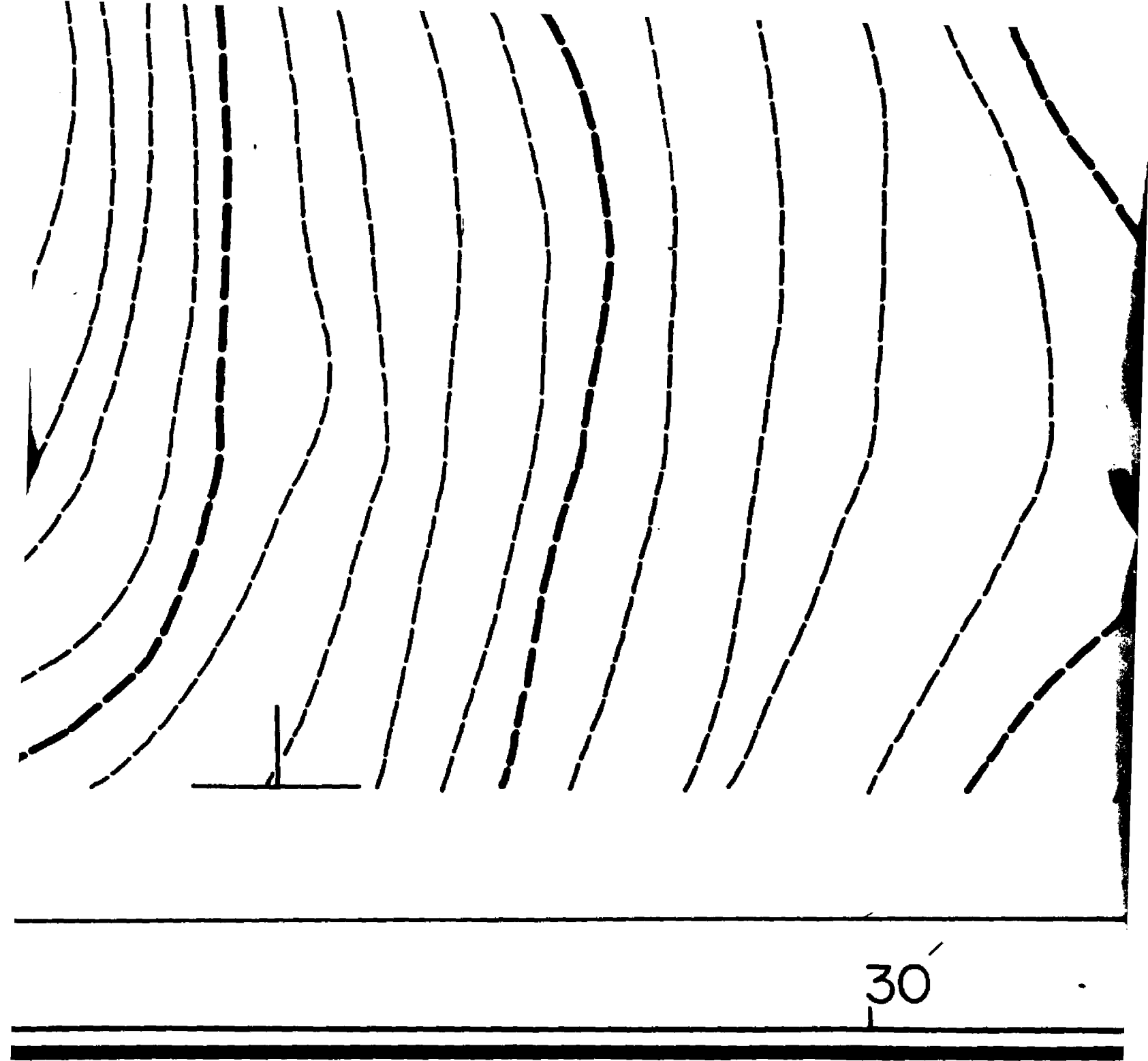
35

BOUGUER GRAVITY ANOM

COUNTY

CONTOUR INTE

SCALE 1 : 24000

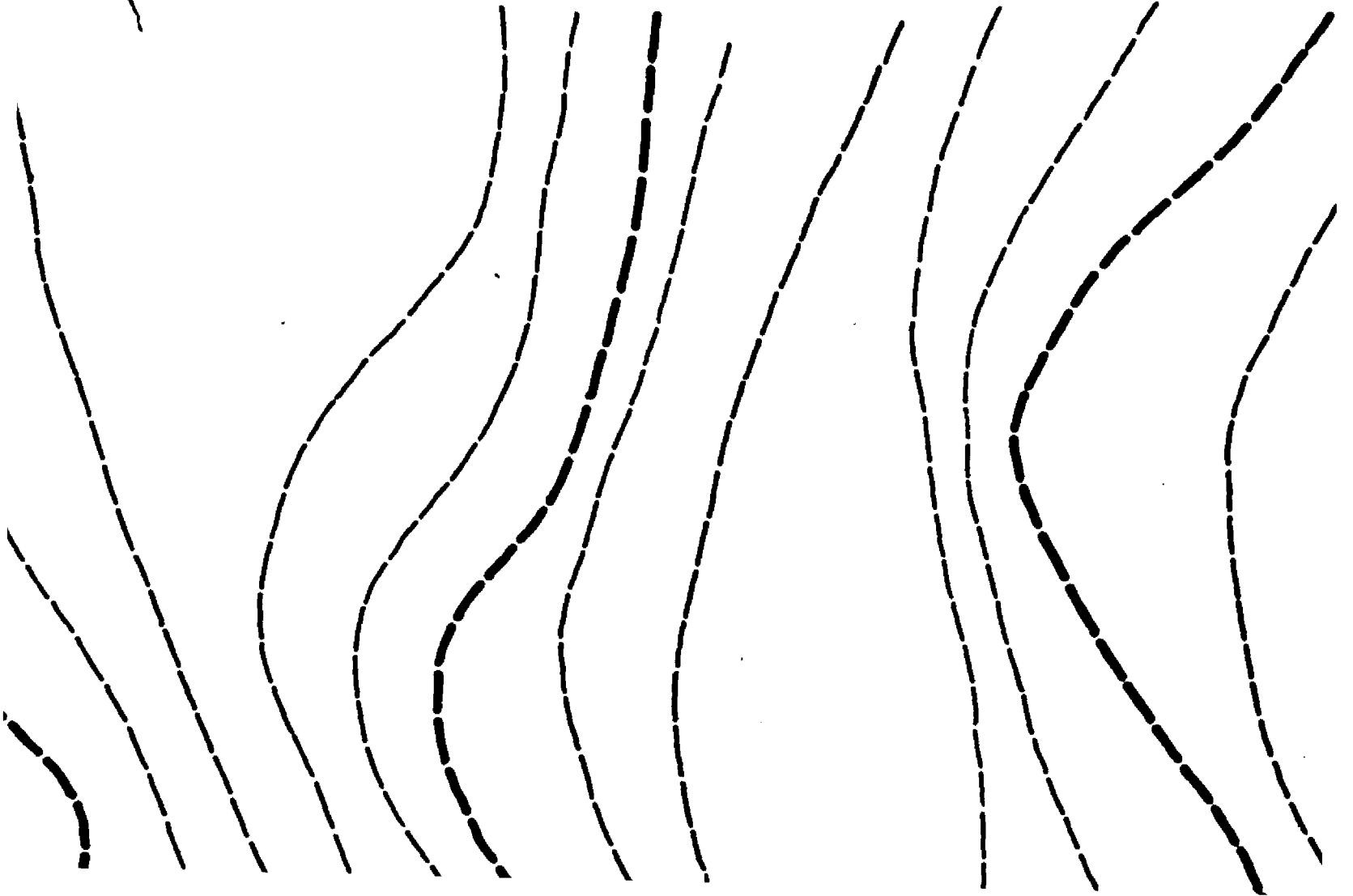


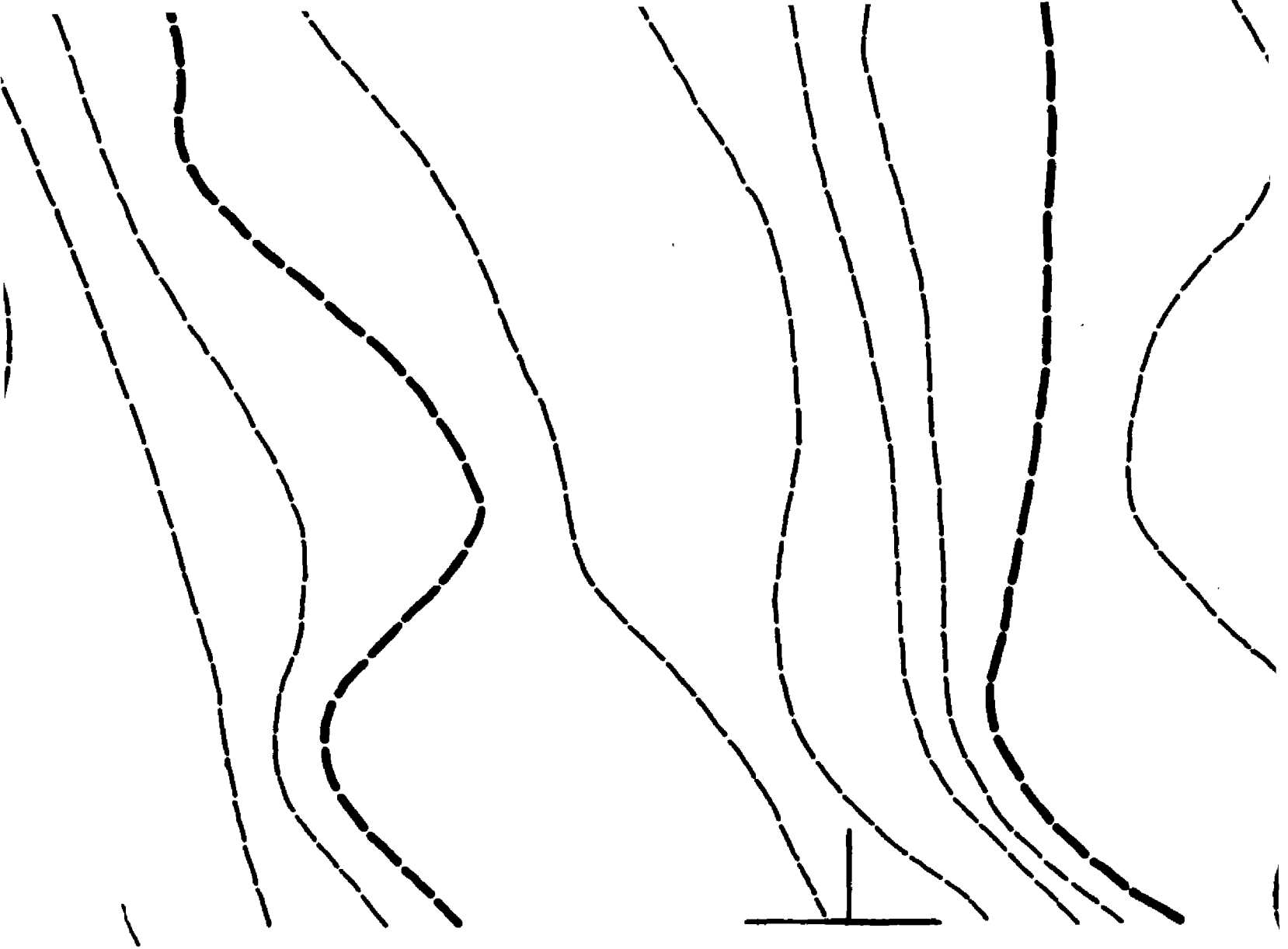
ANOMALY

OUR INTERVAL 0.20 MGALS

DENSITY = 2.15 GM/C.C.

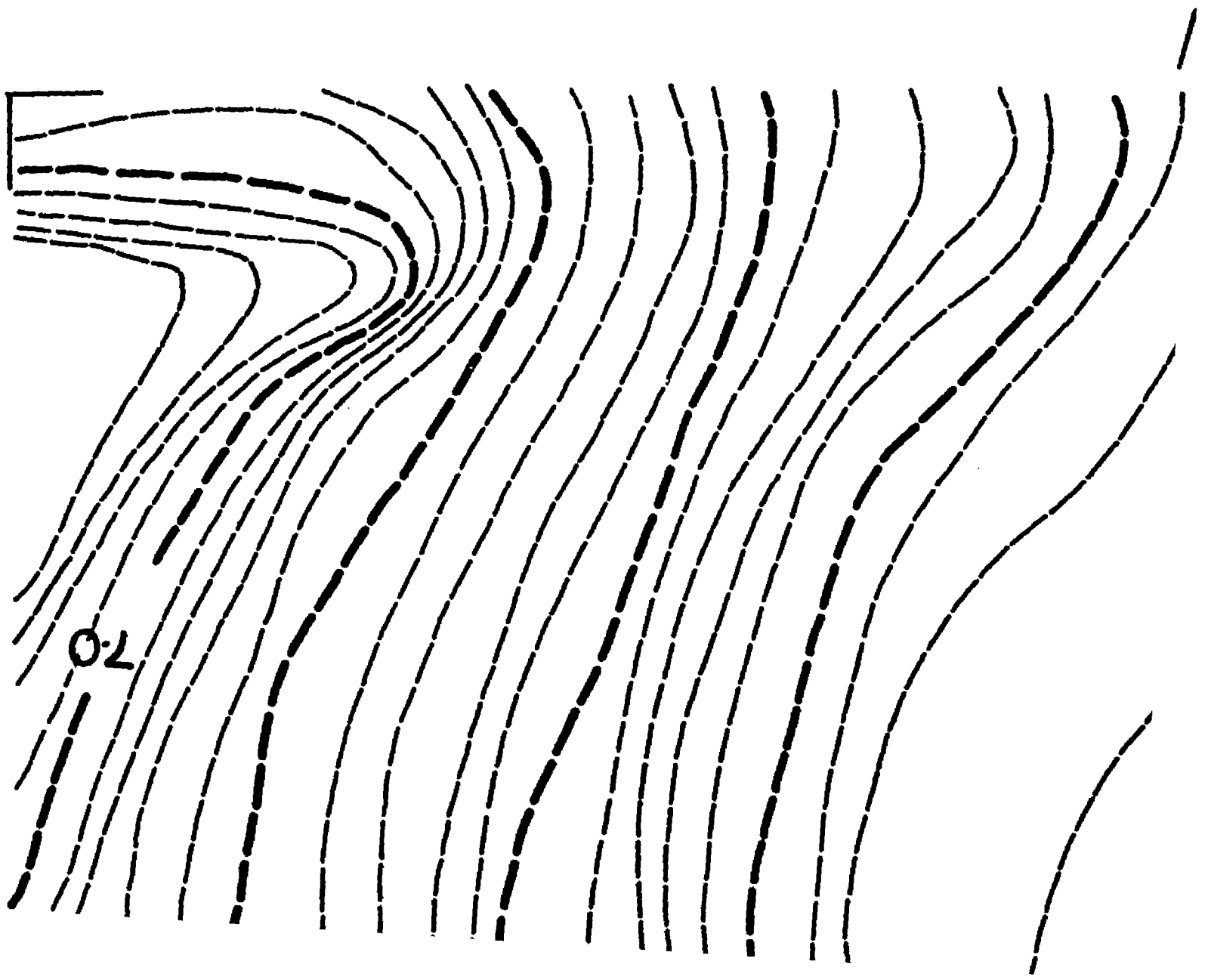
RIOW





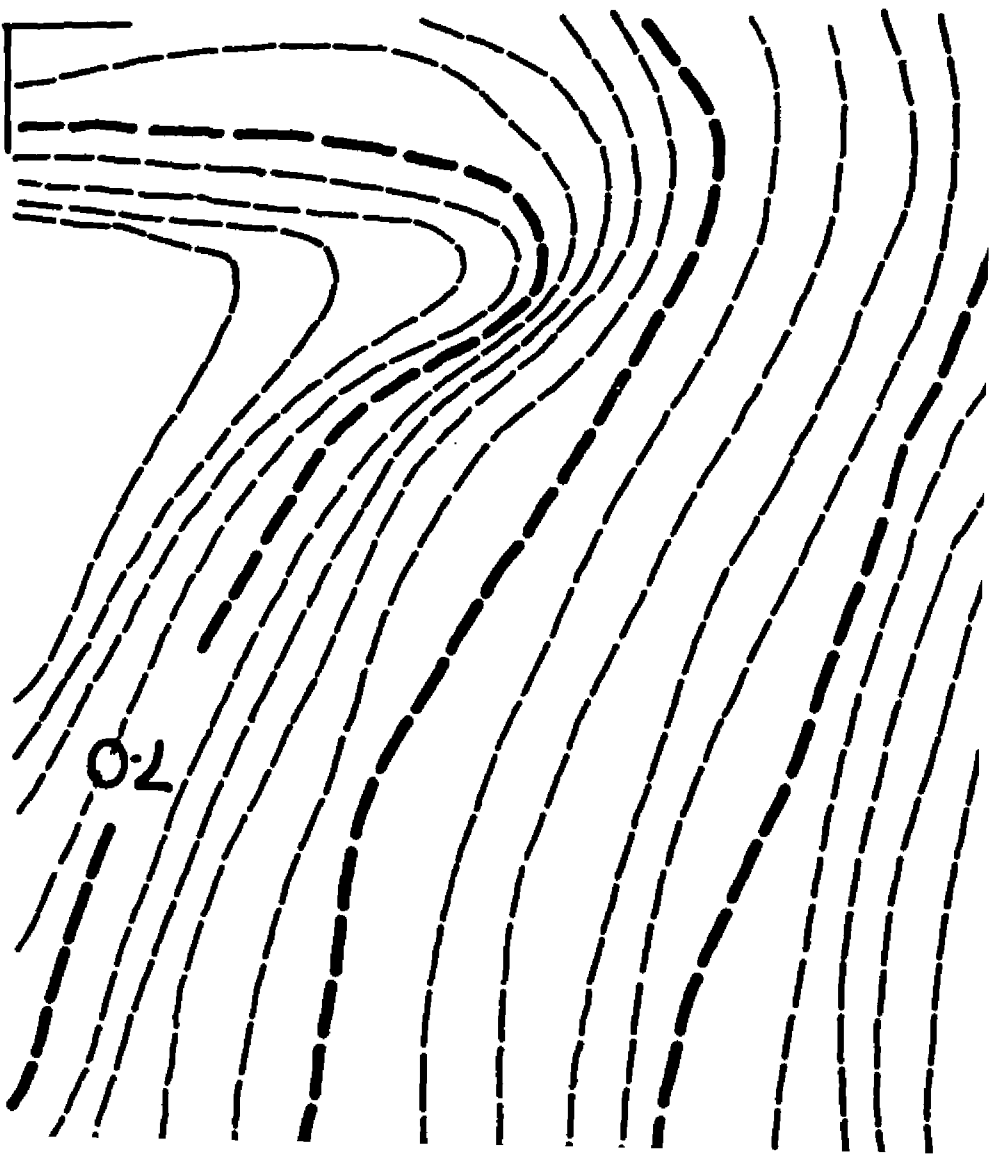
25'

85.20



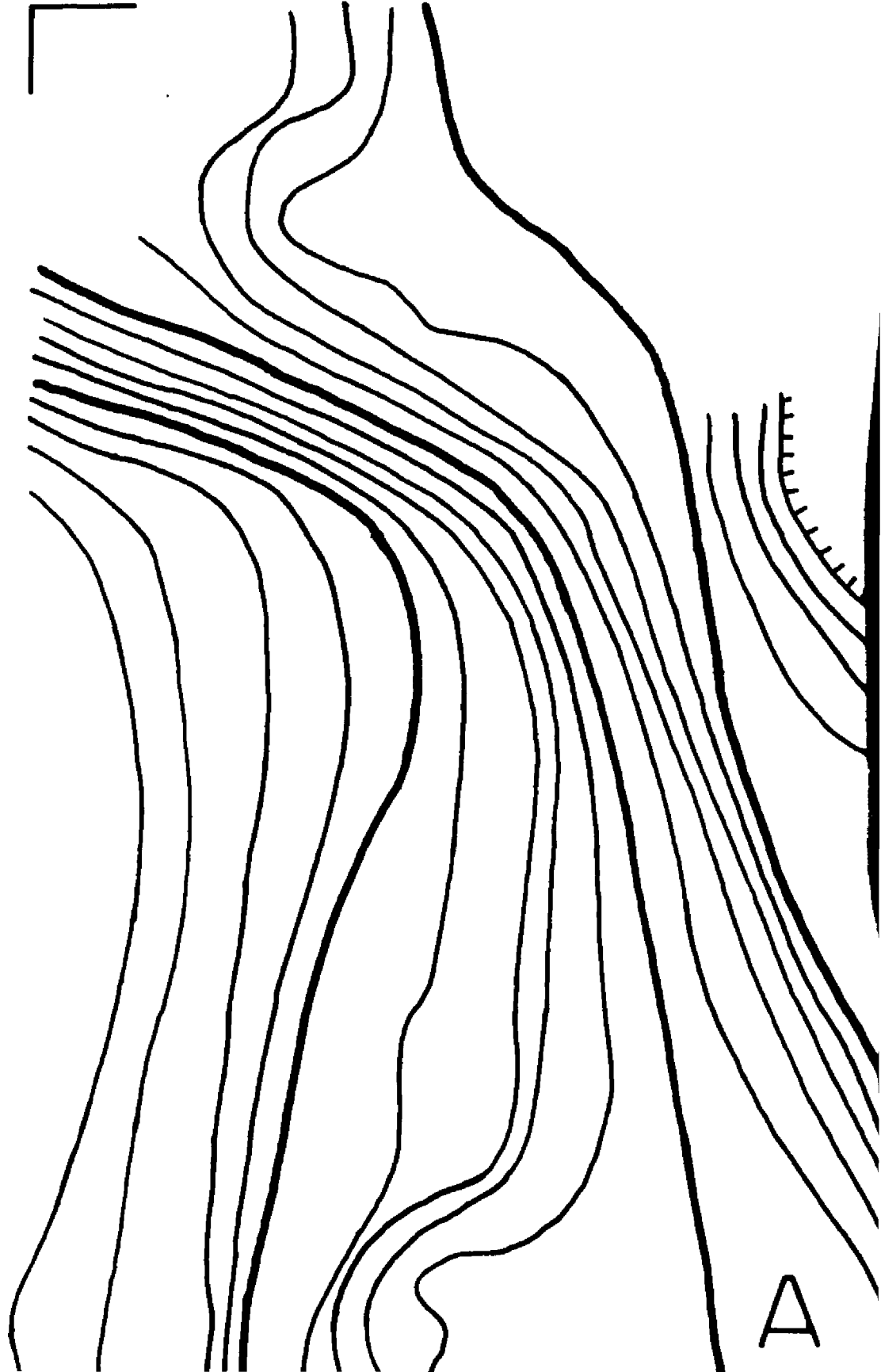
42.05

7.0



45'

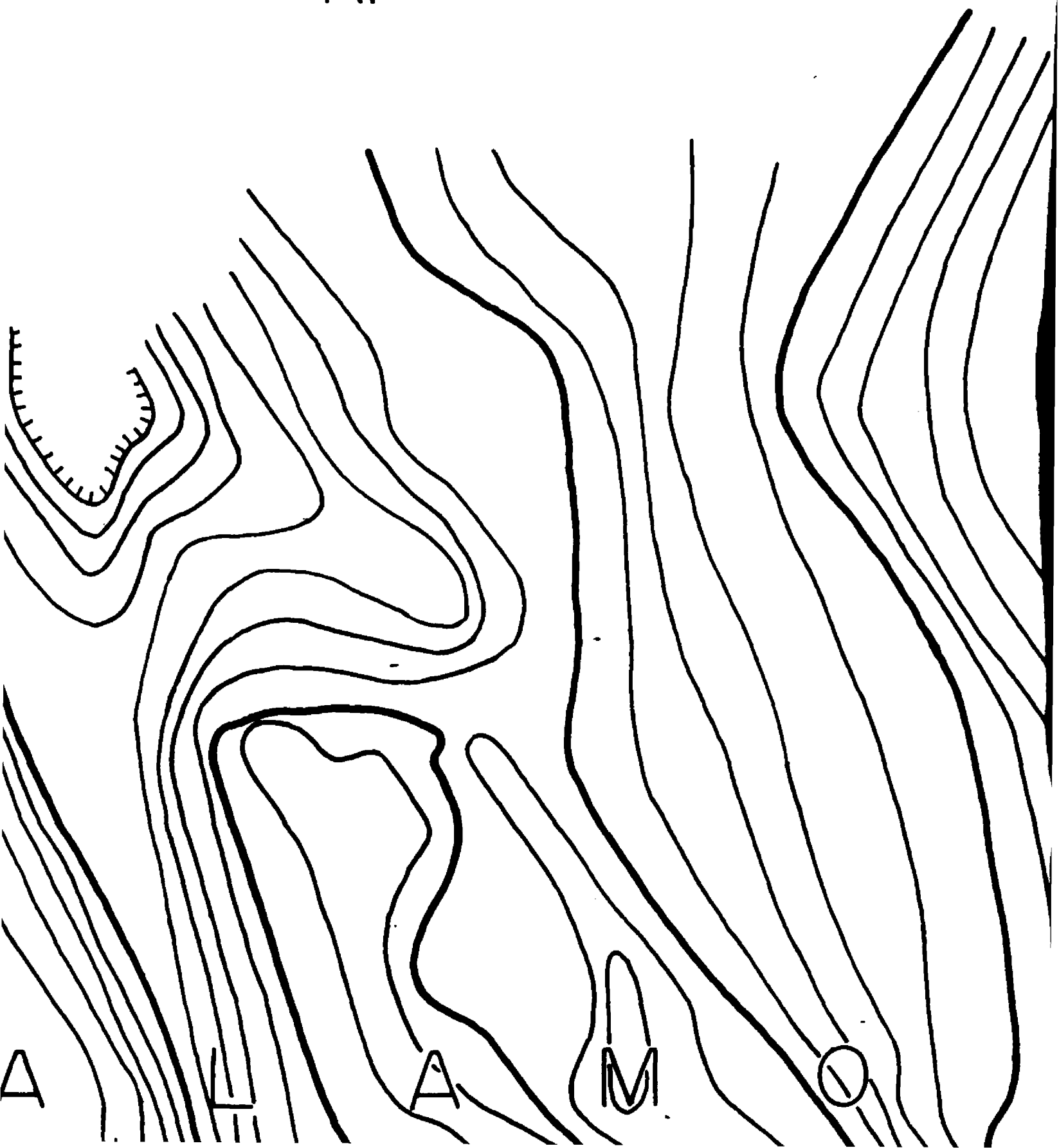
42°
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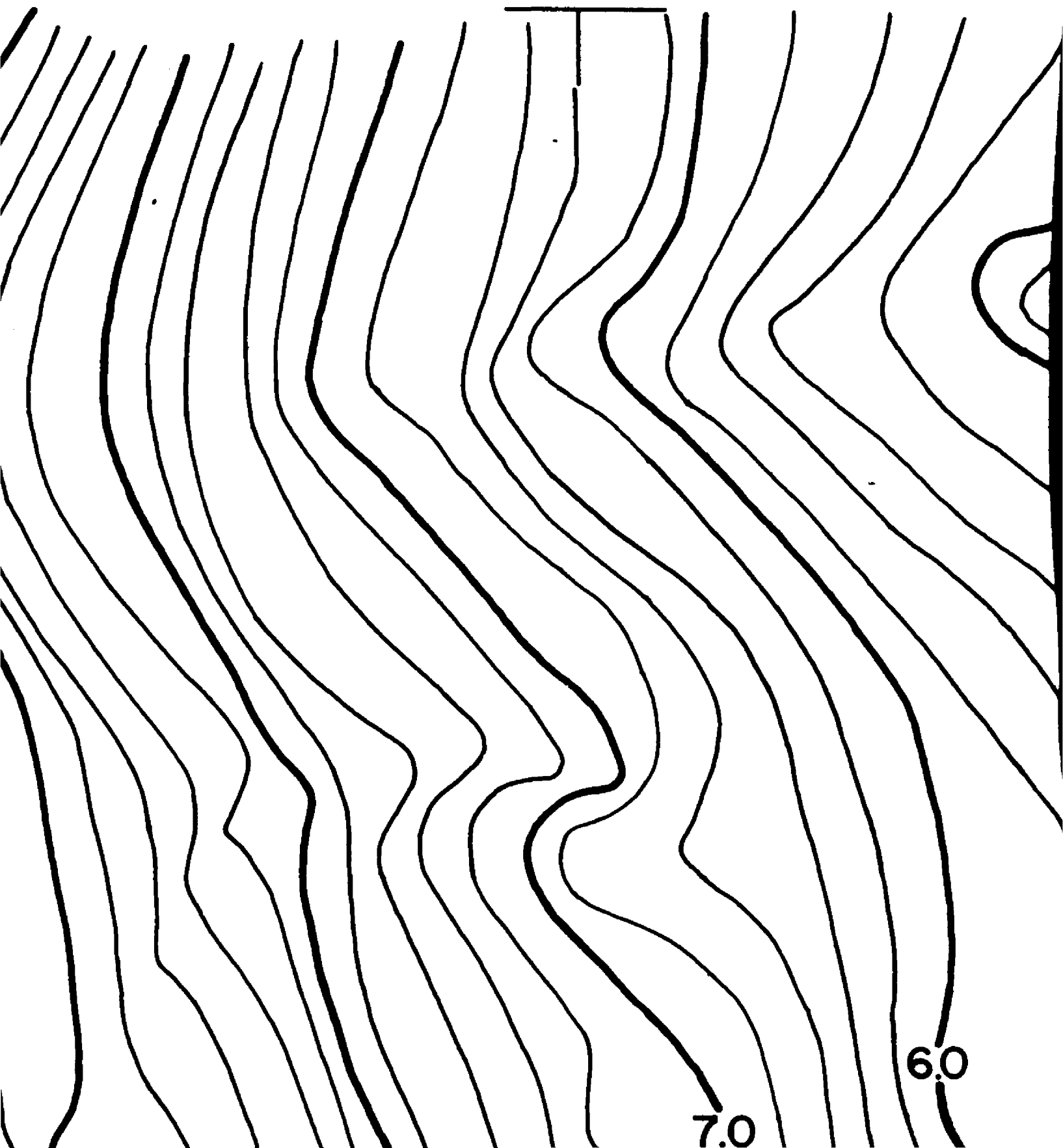
TIS

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R12W



40'



35'

RIIW

5.0

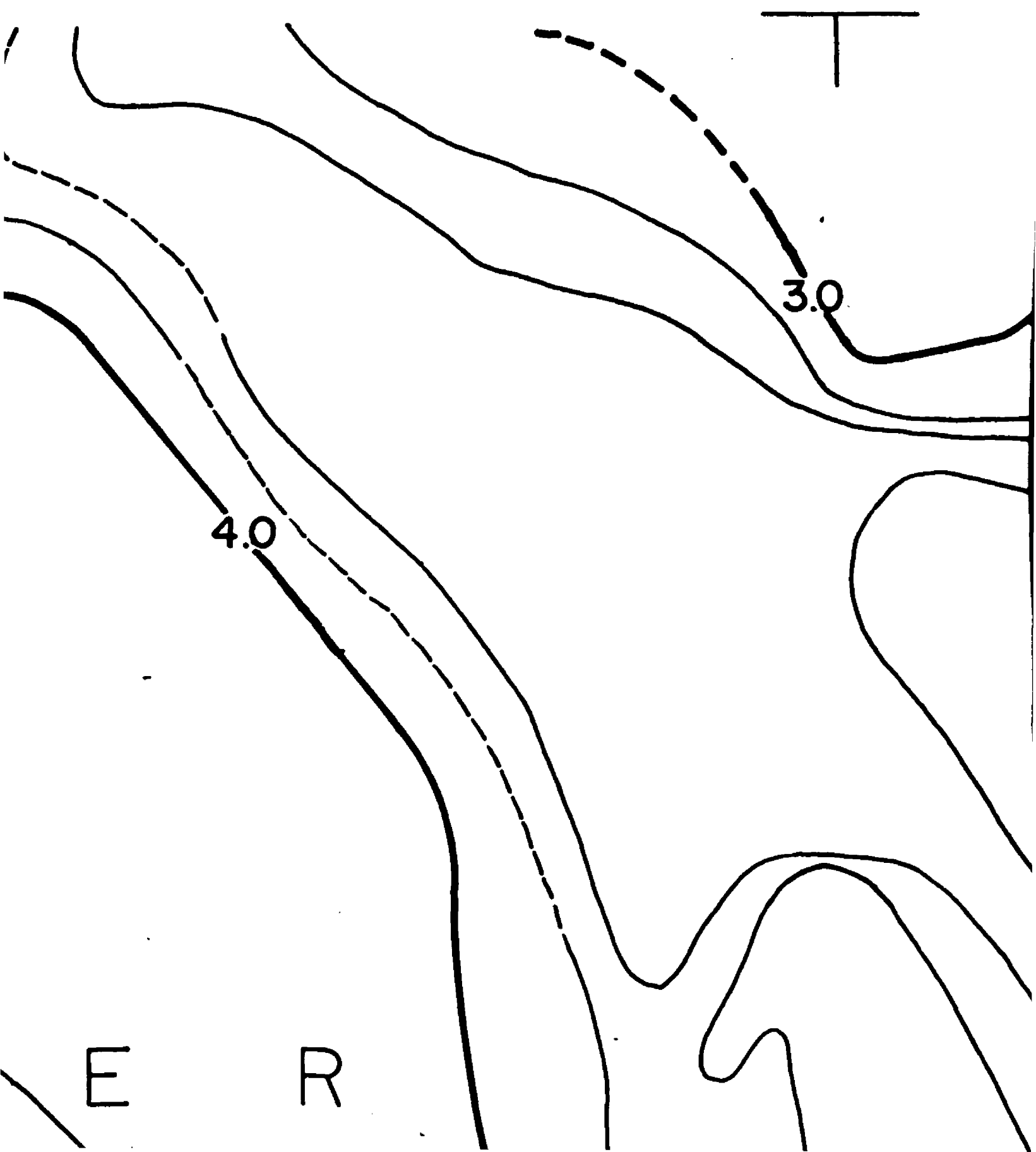
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30'

RIOW

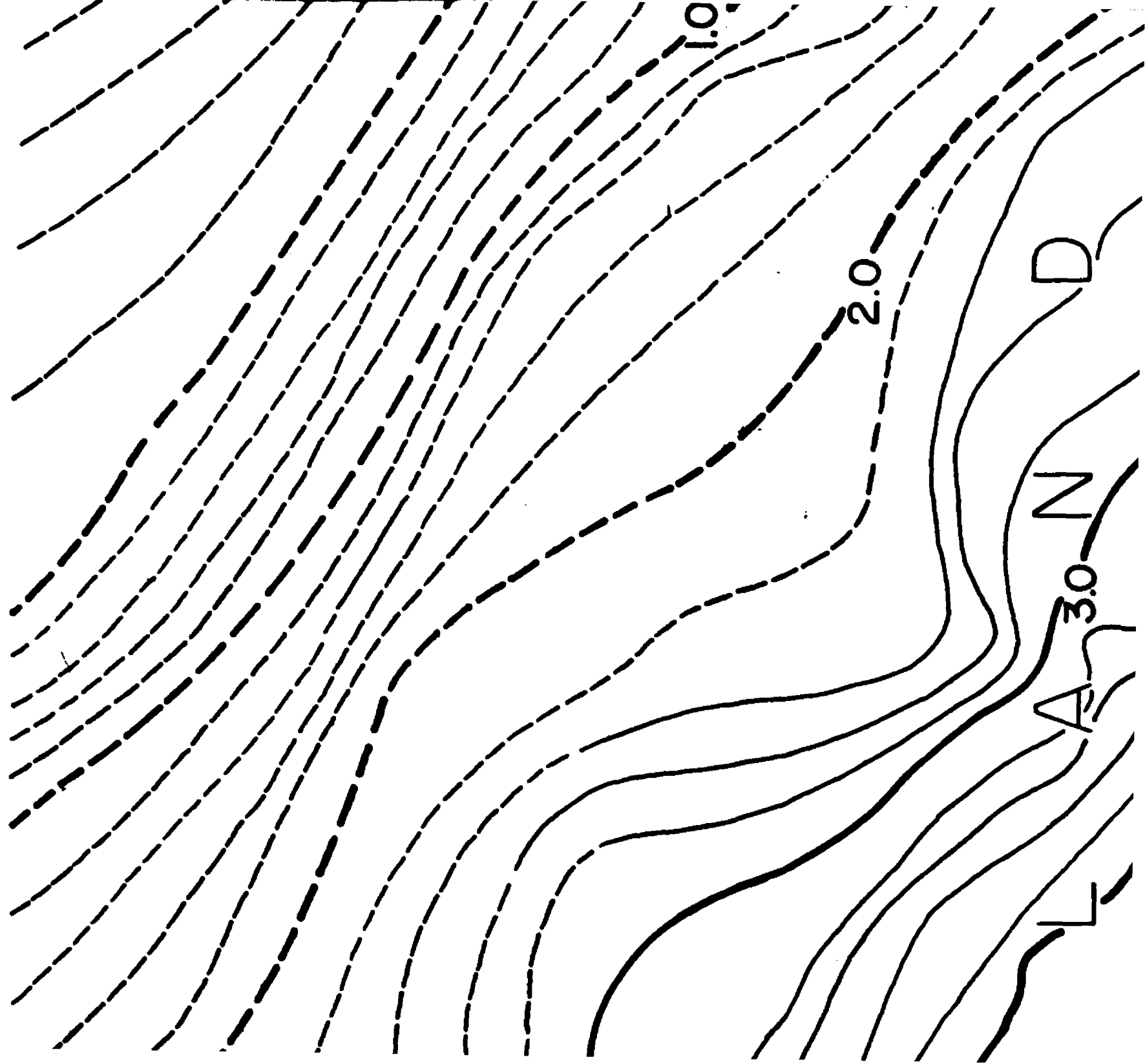
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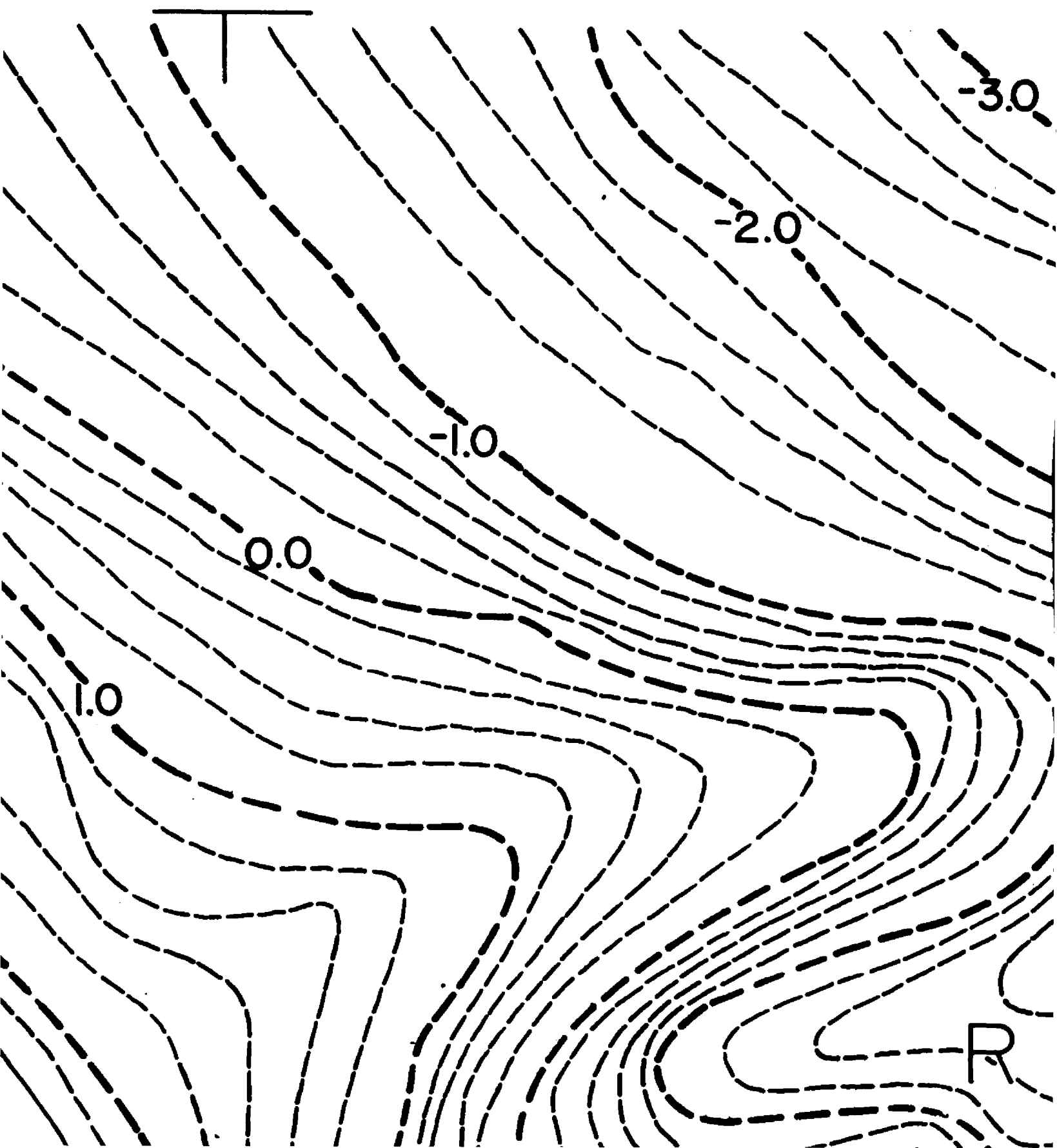
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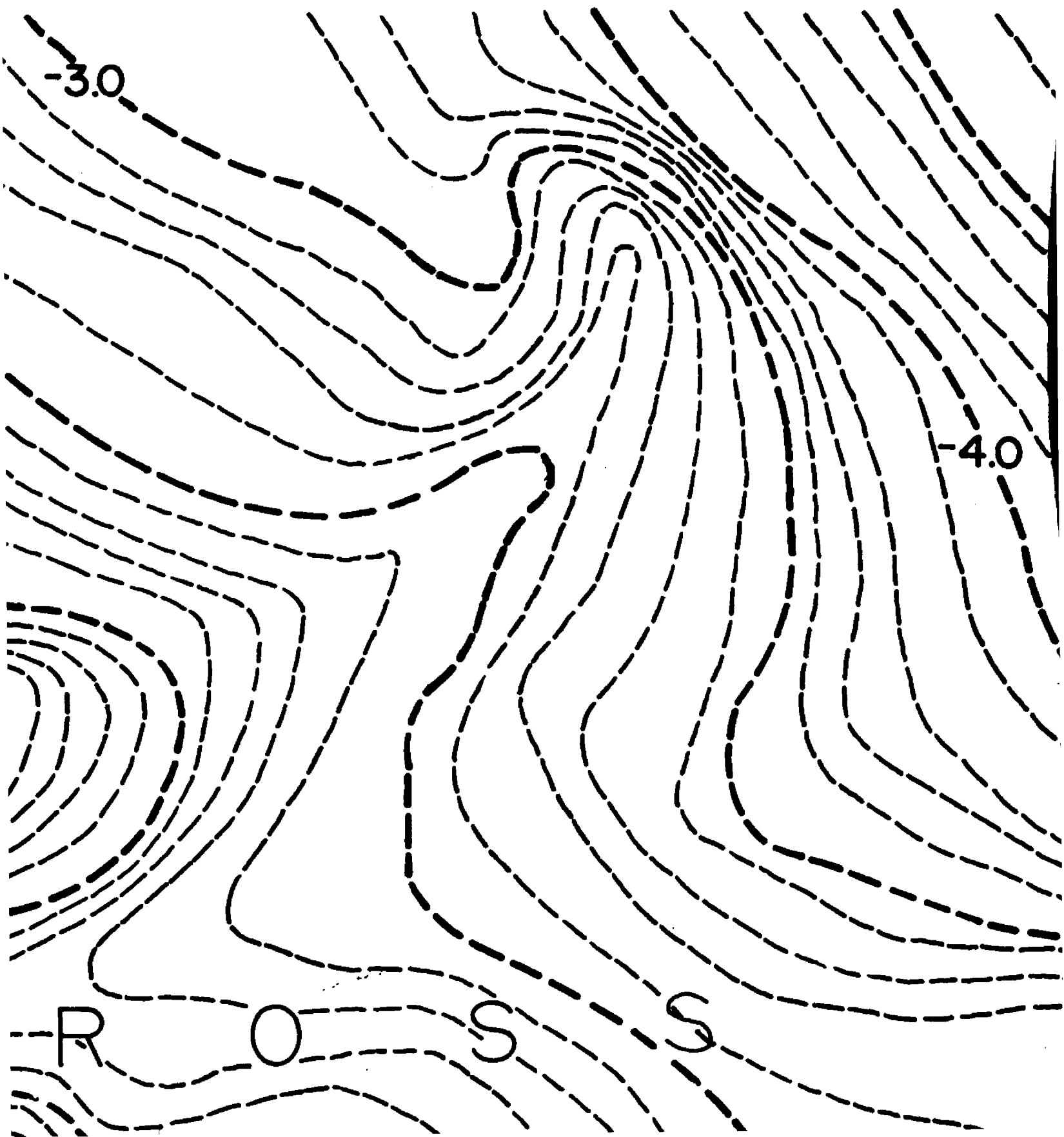


25



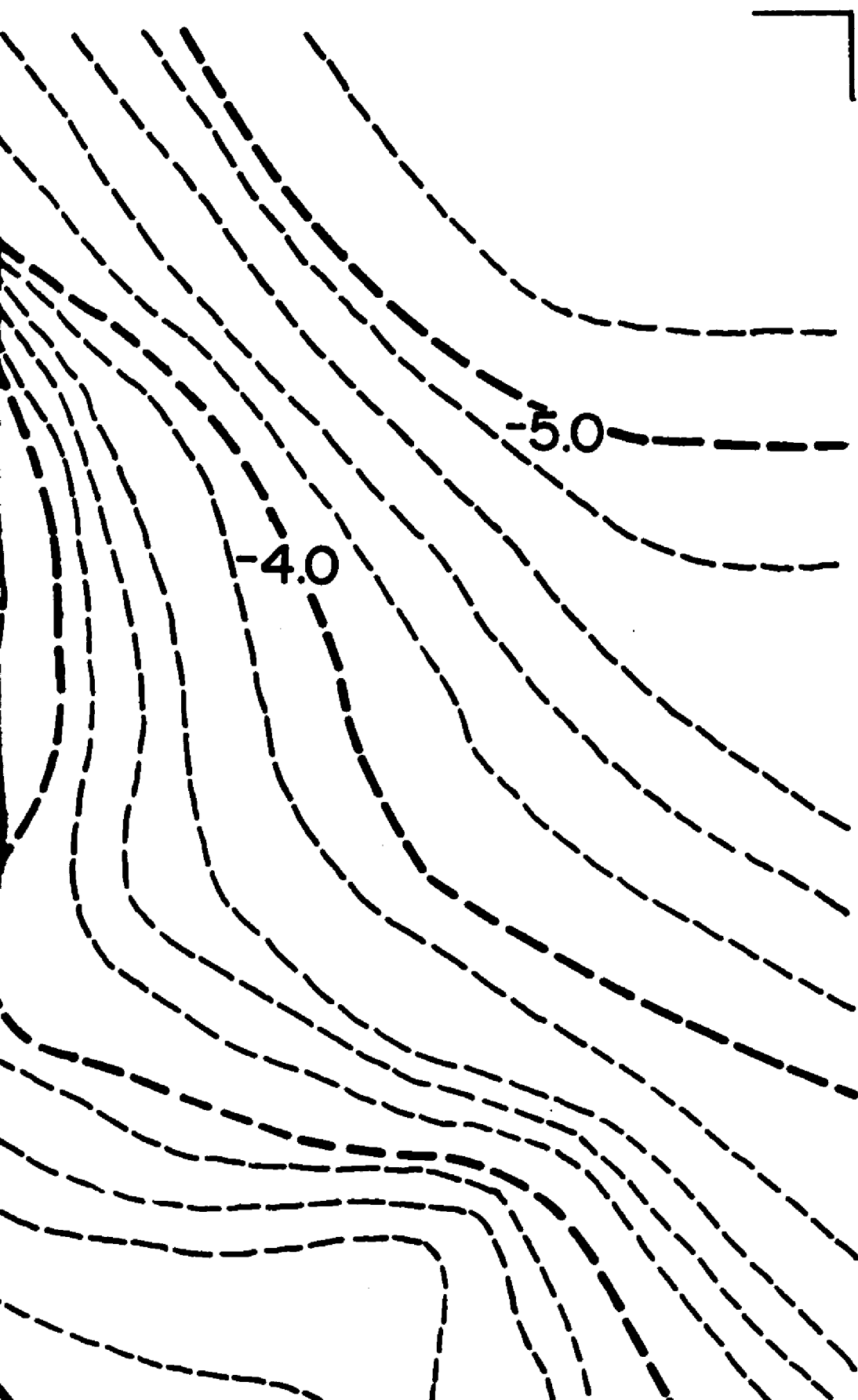
85°20'

R9W

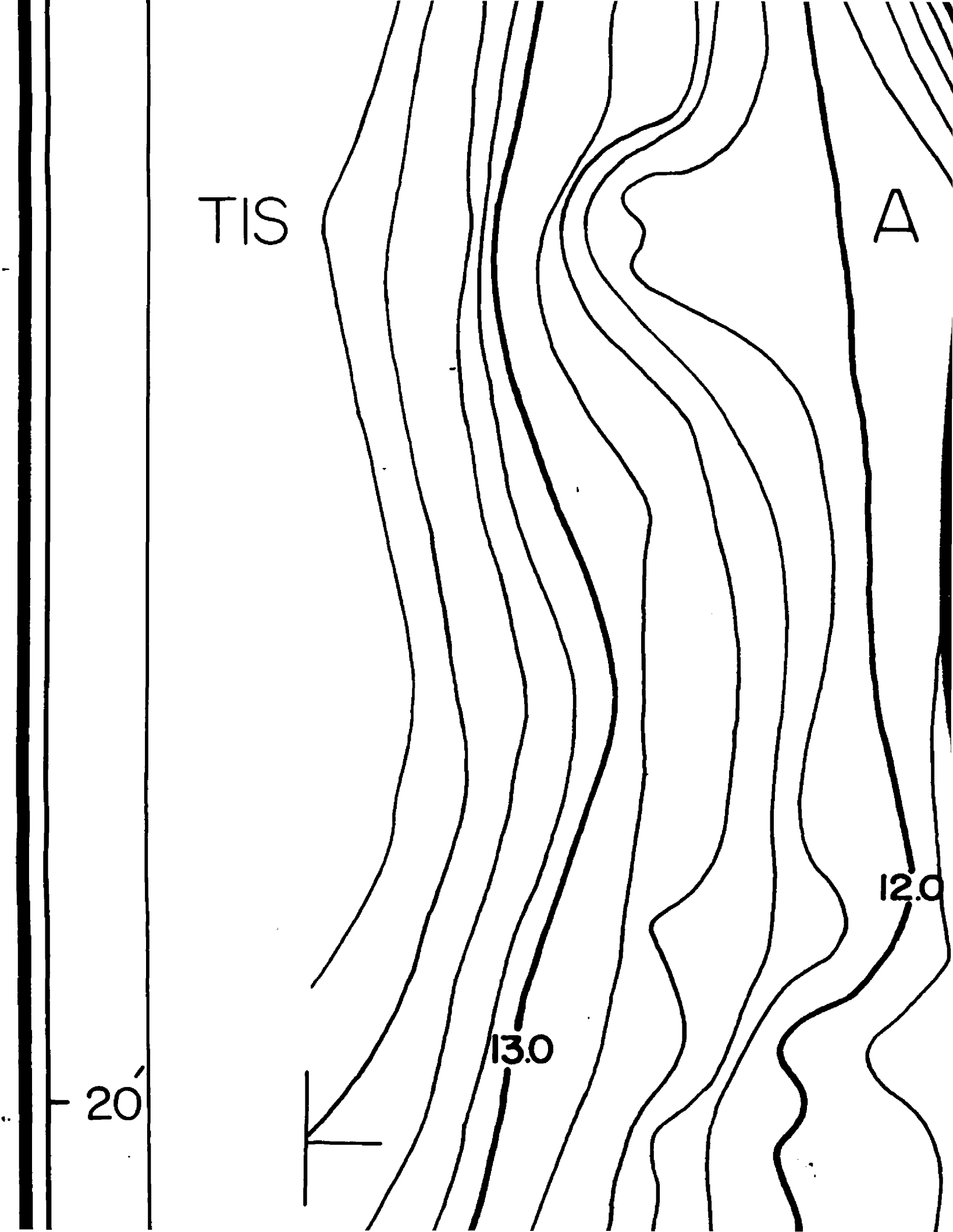


35° 20'

42°
25'



TIS



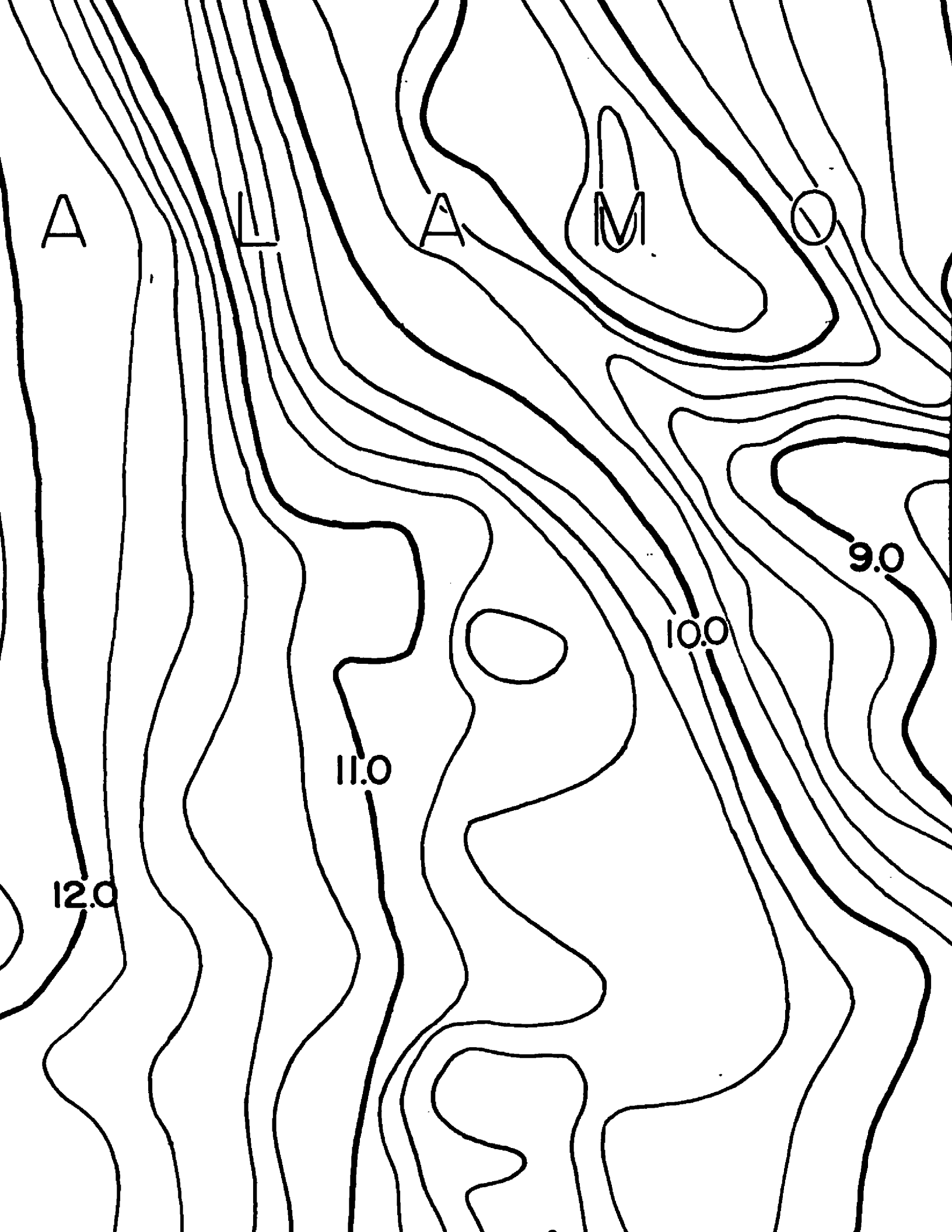
TIS

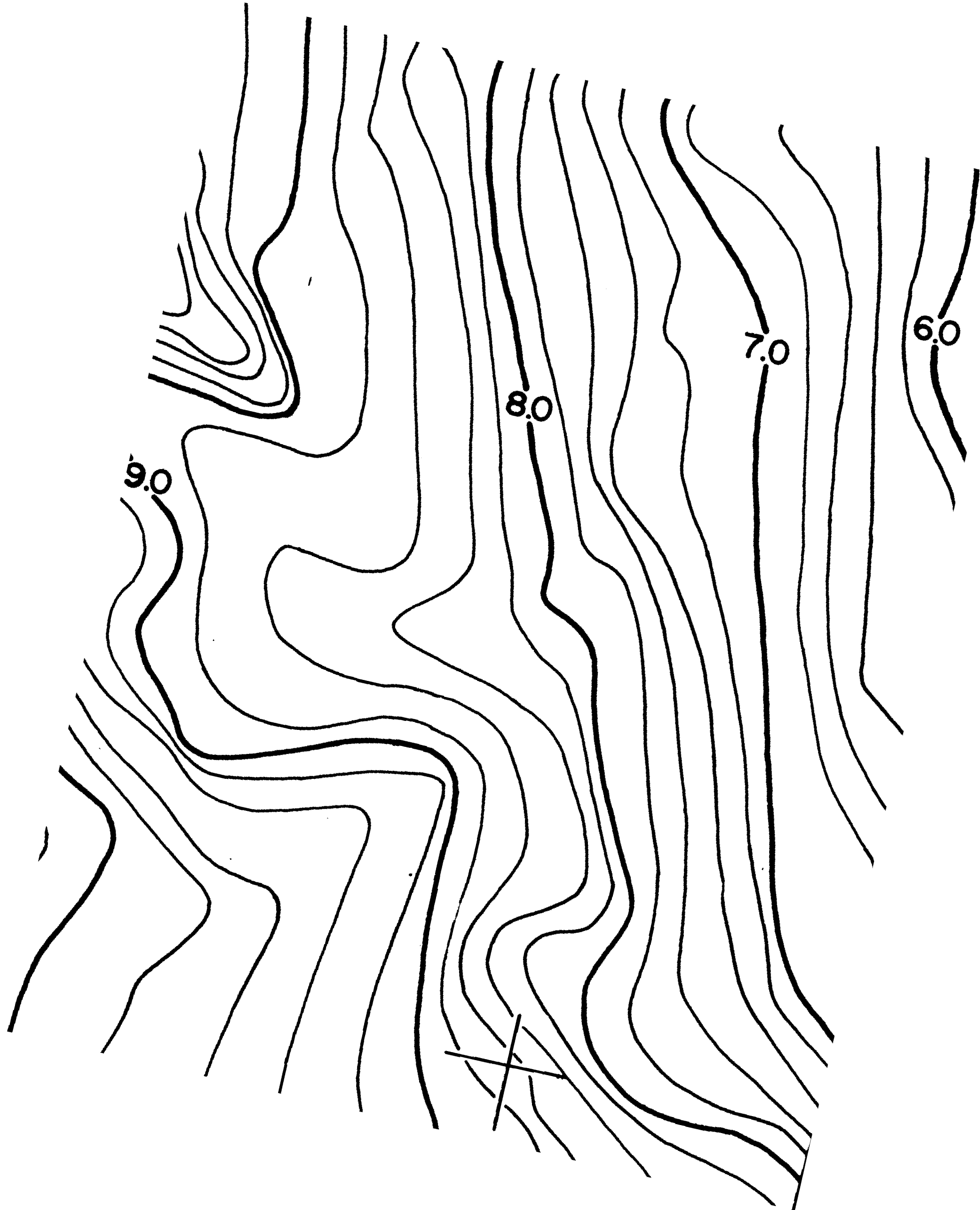
A

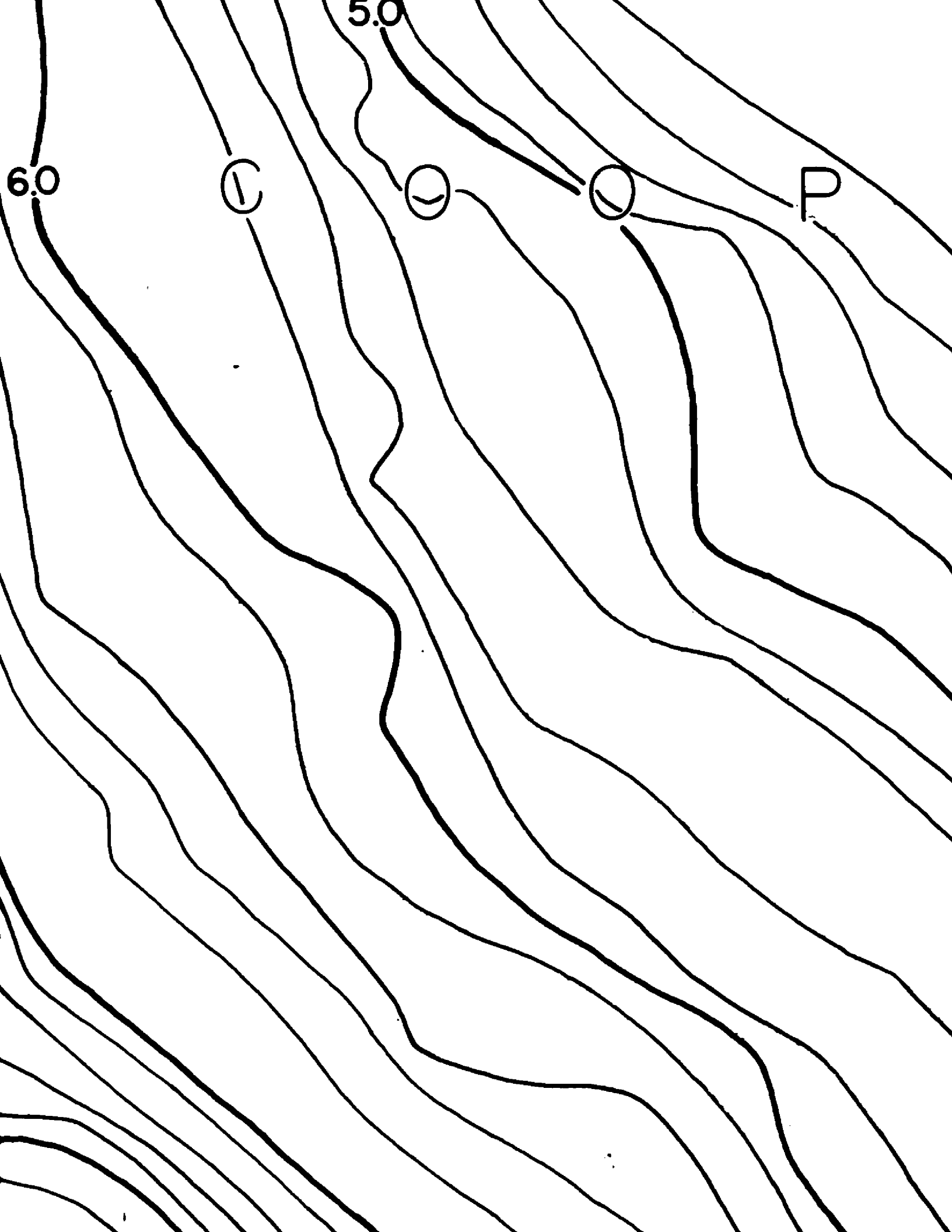
20'

13.0

12.0





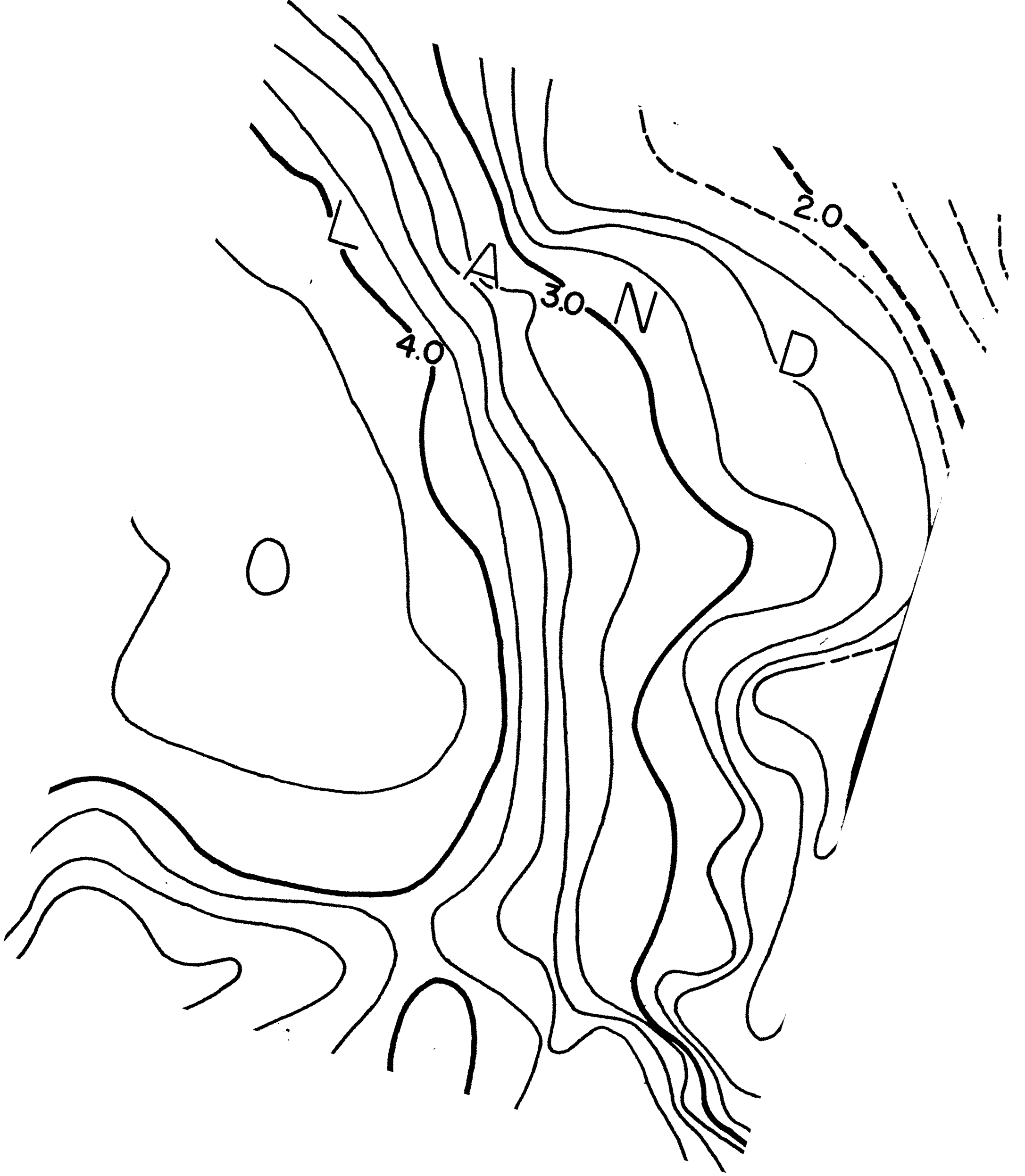


E

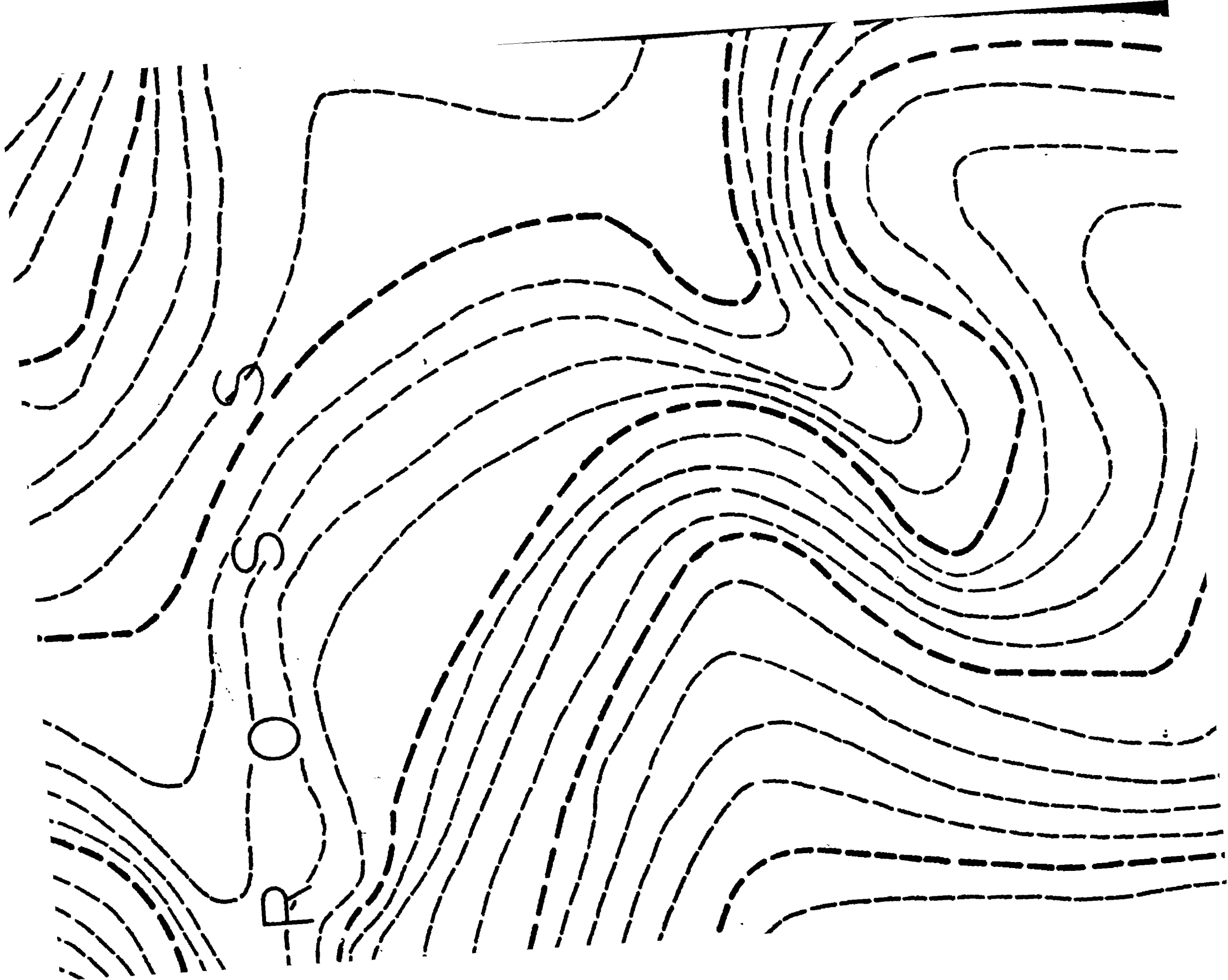
R

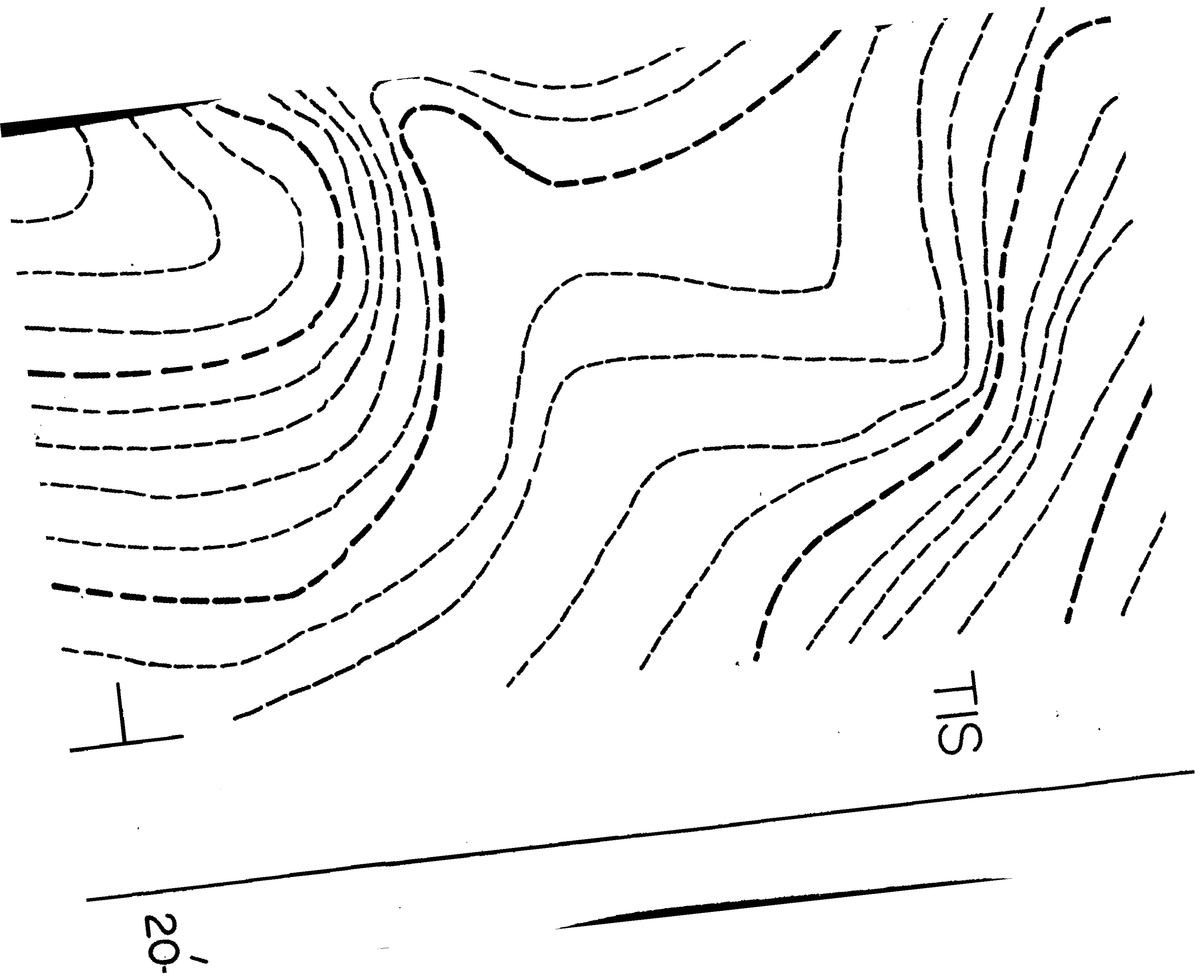


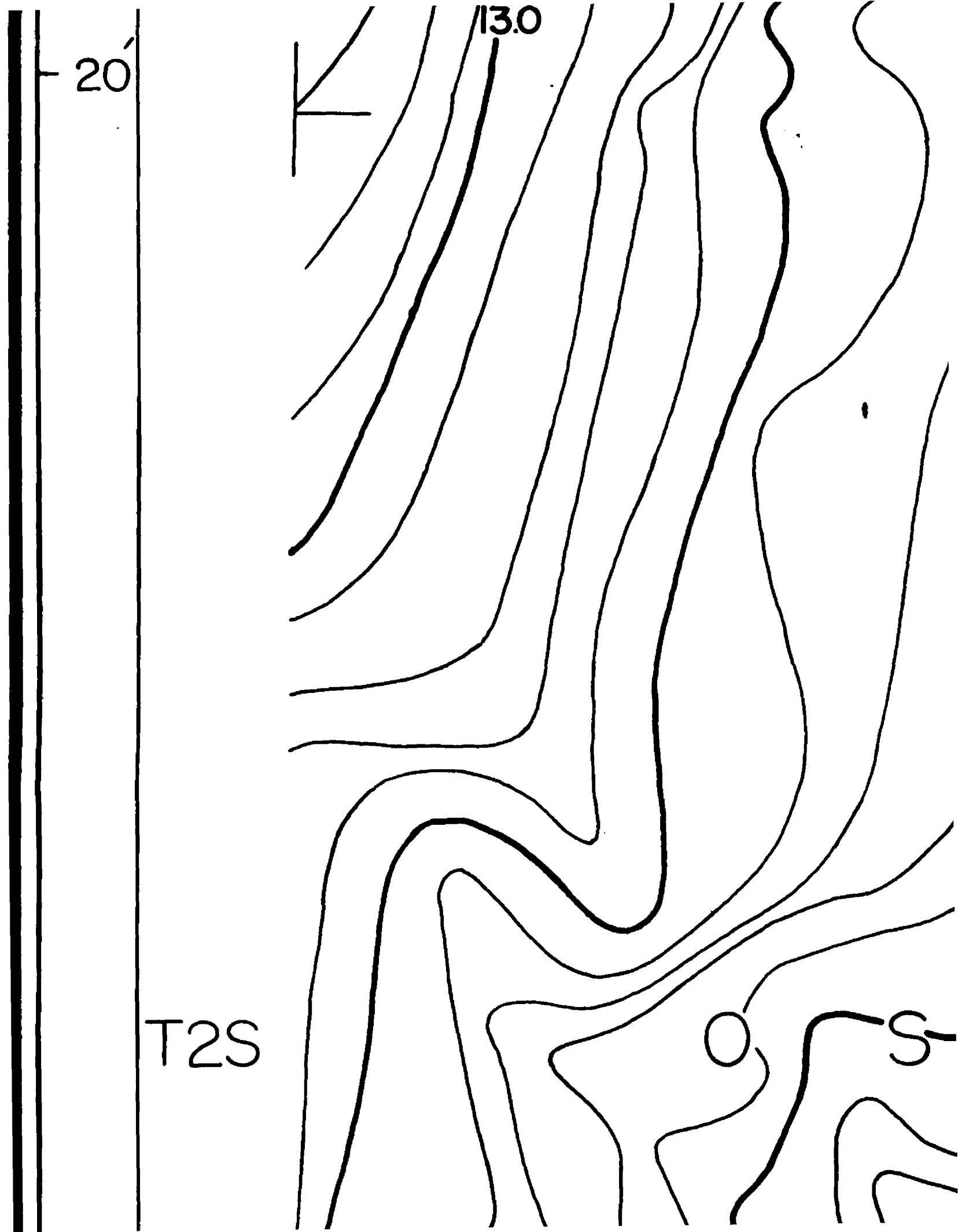






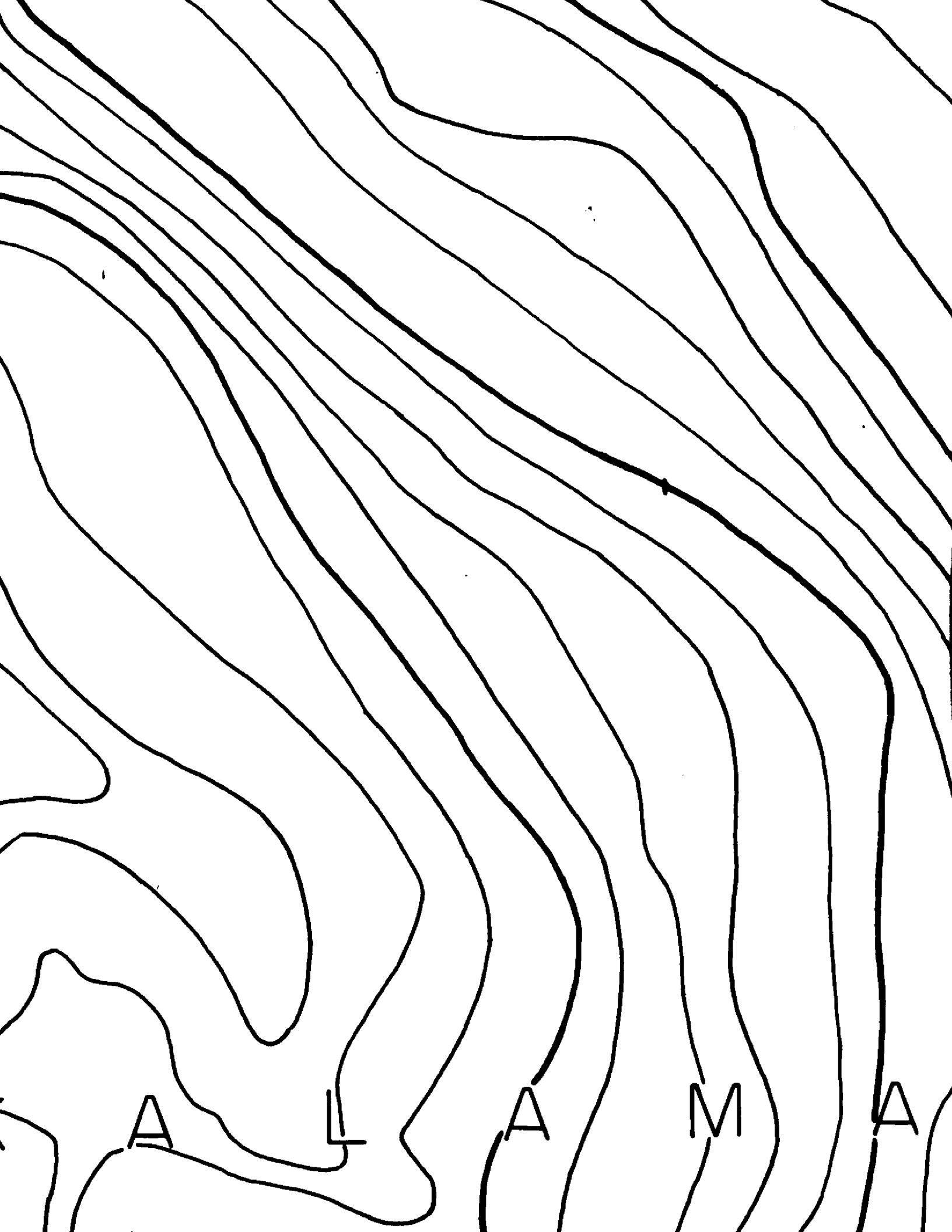












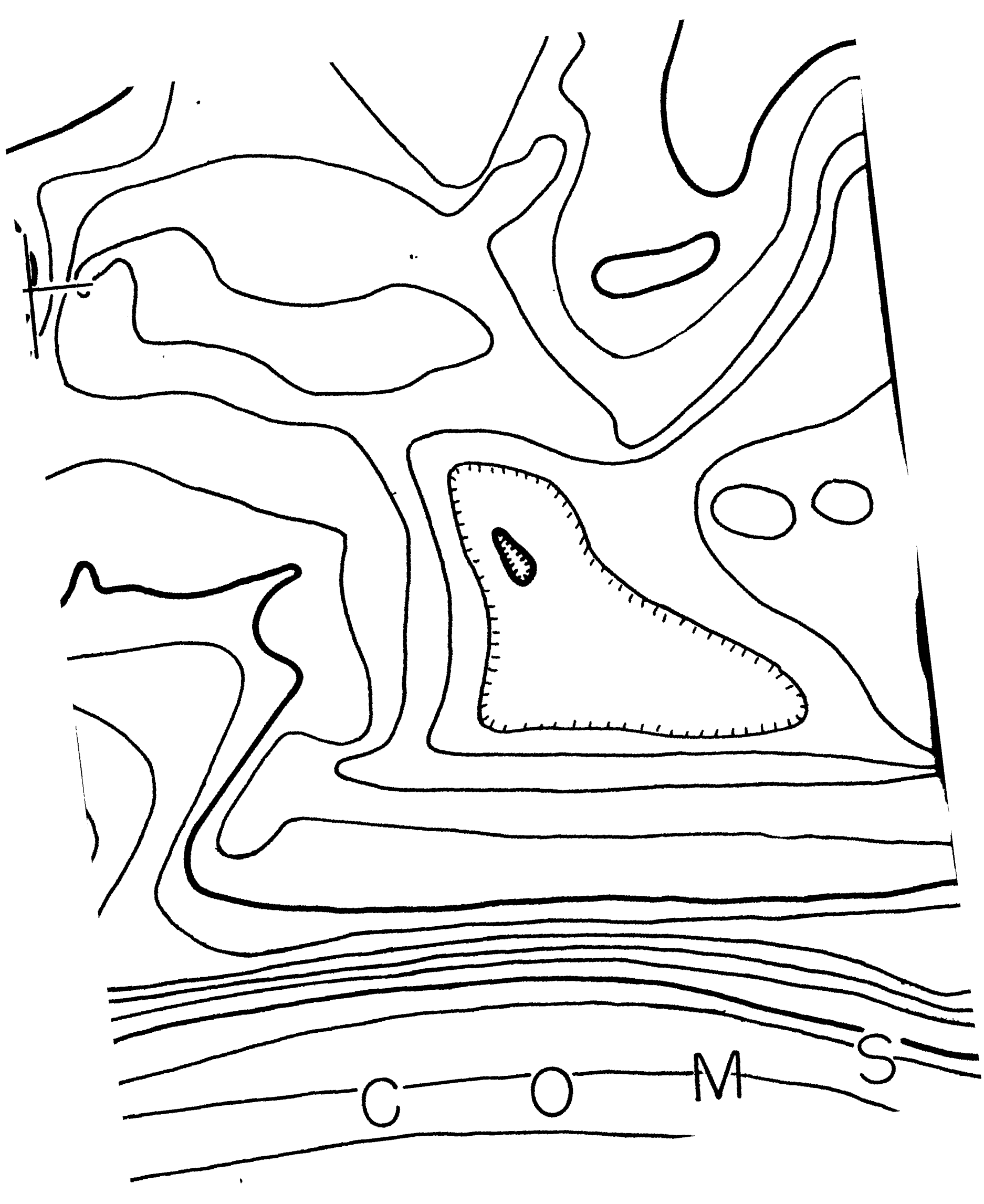


A

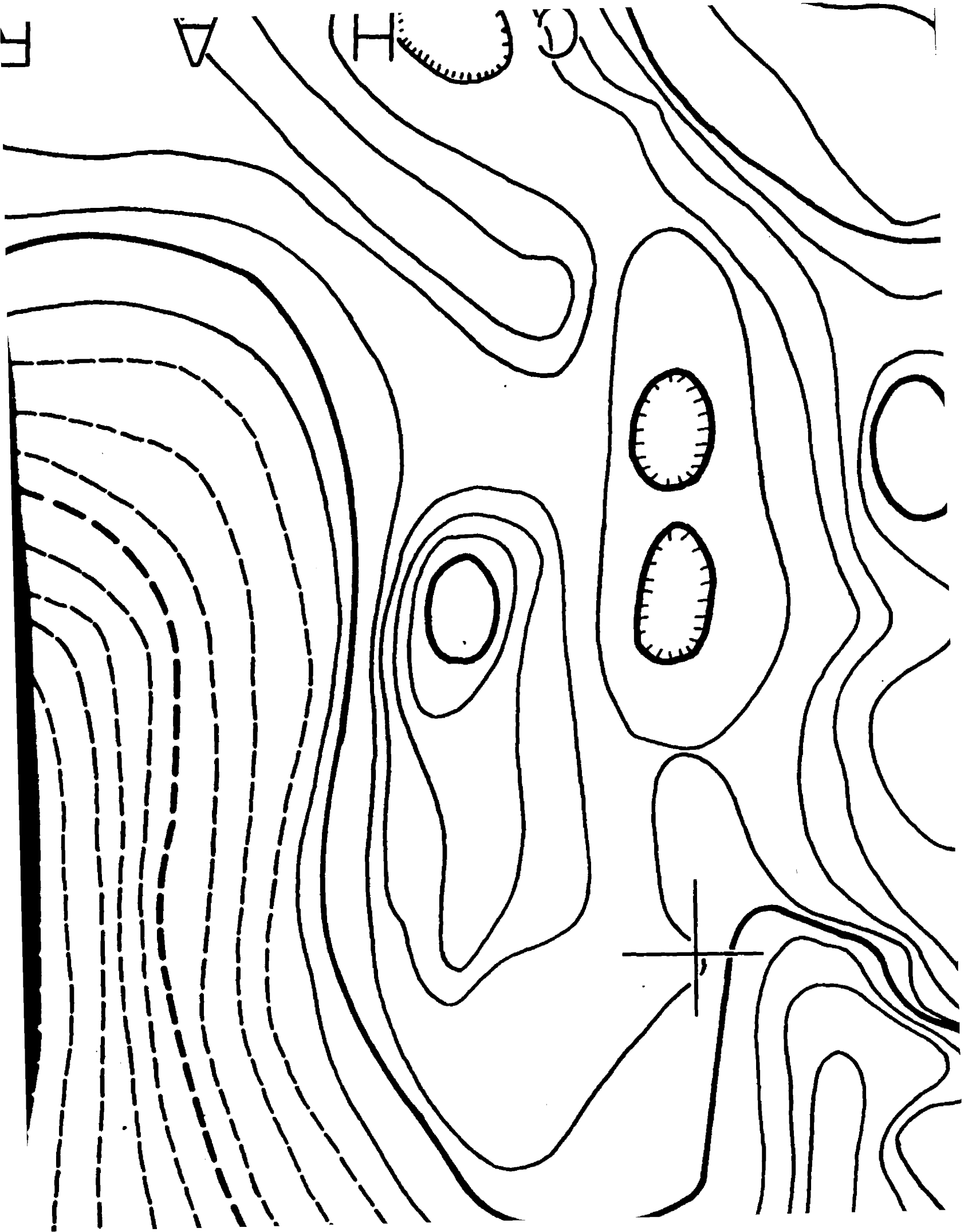
Z

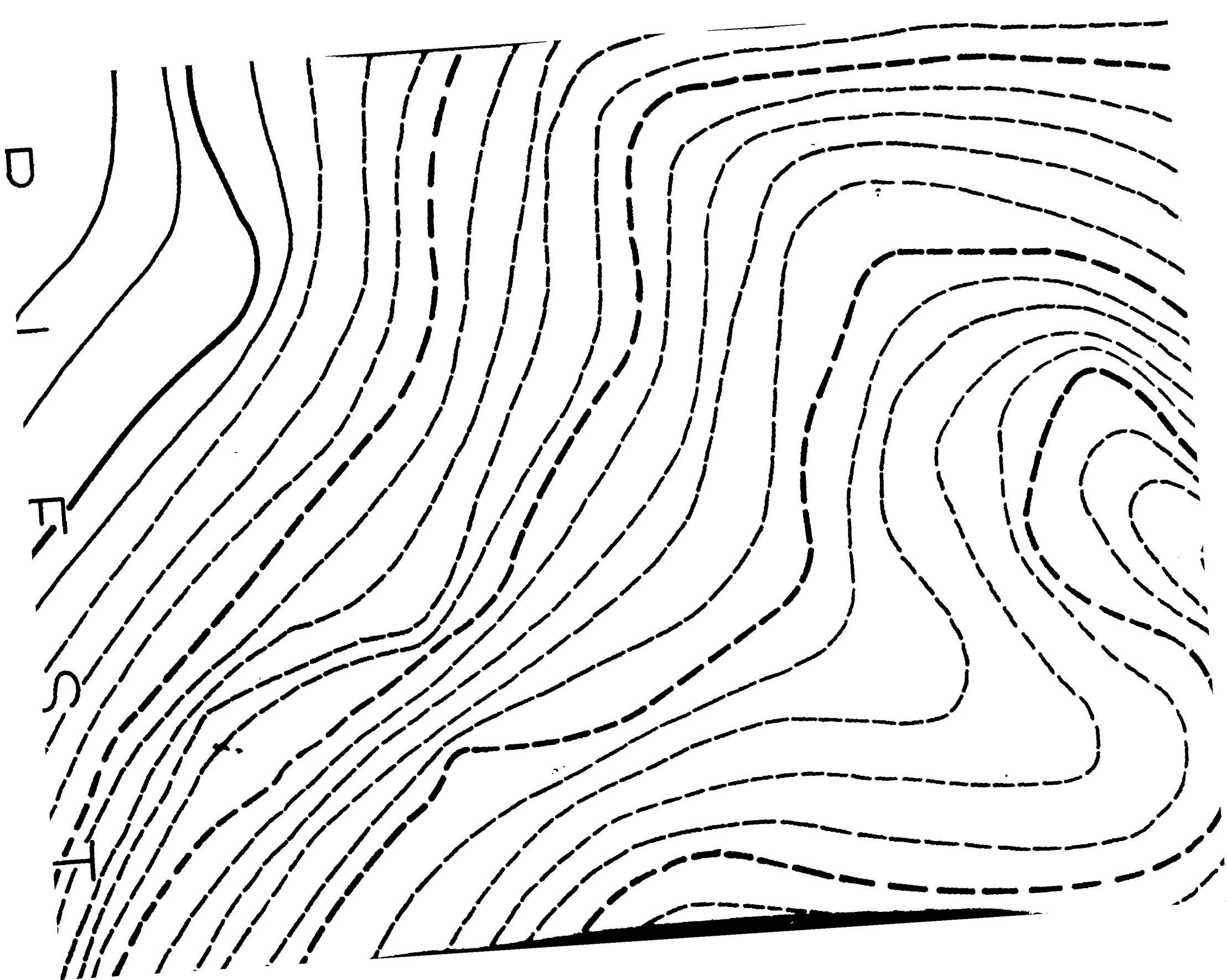
O

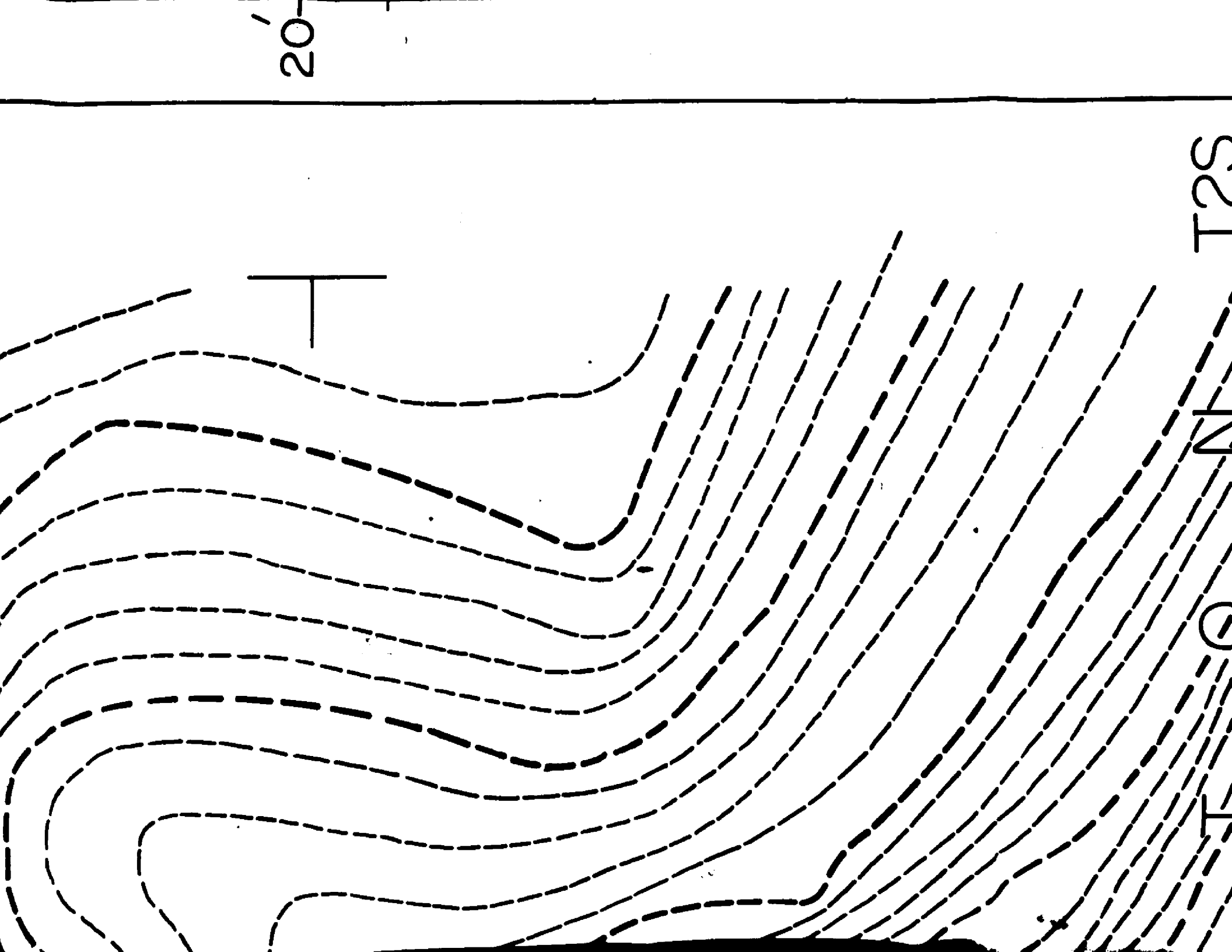
O











20'

T2S

N

①

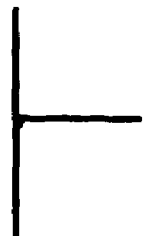
T

T2S

O

S

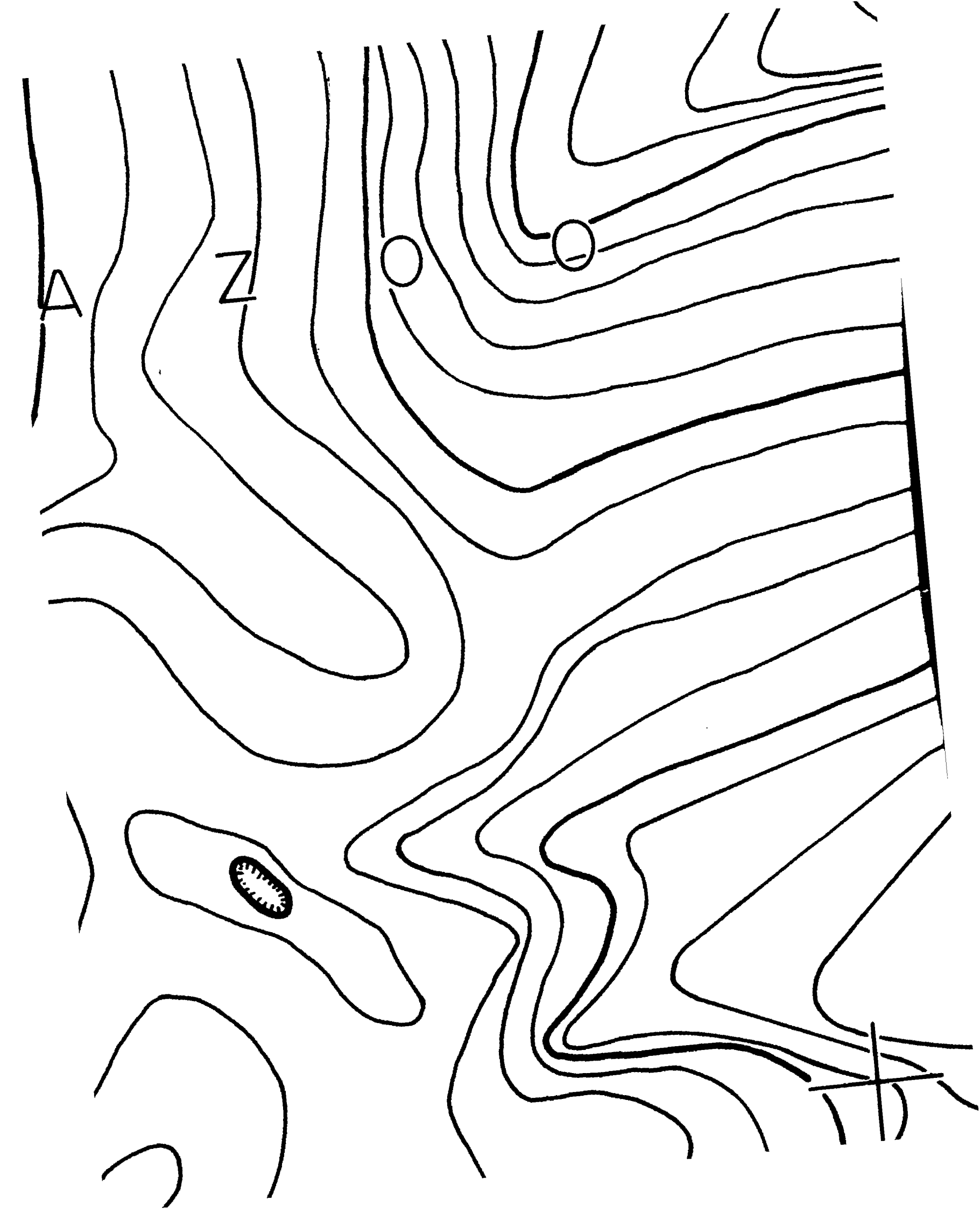
15'









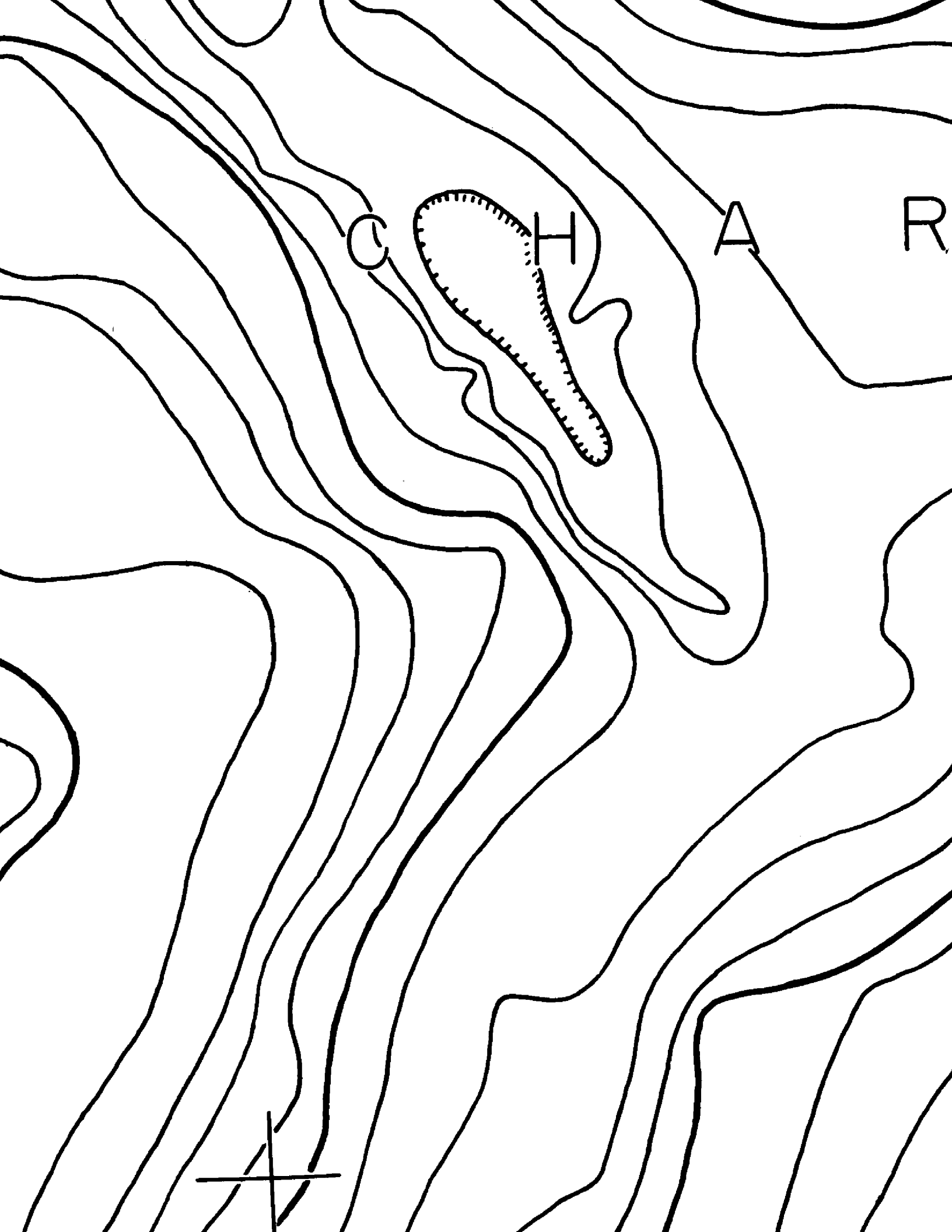


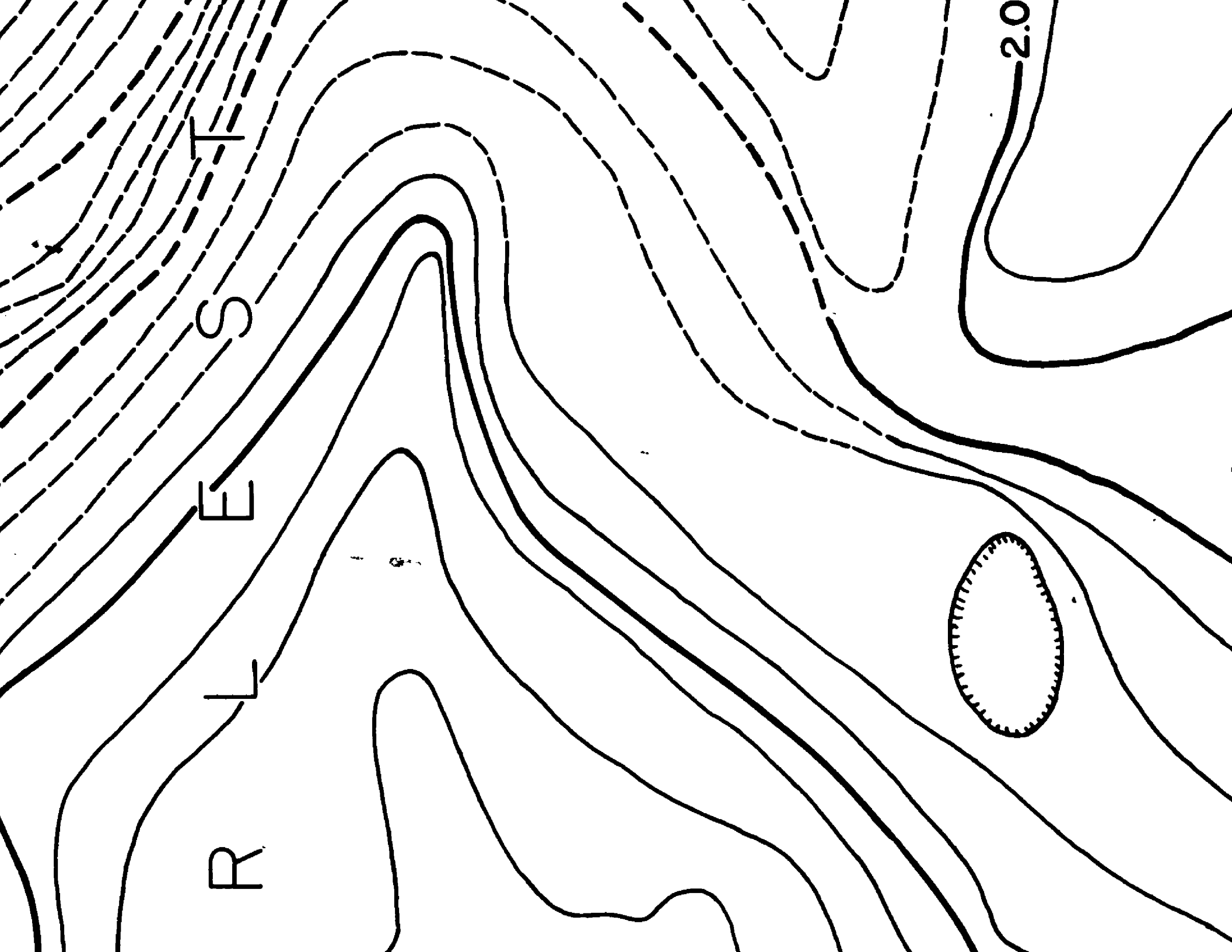
C — O — M — S

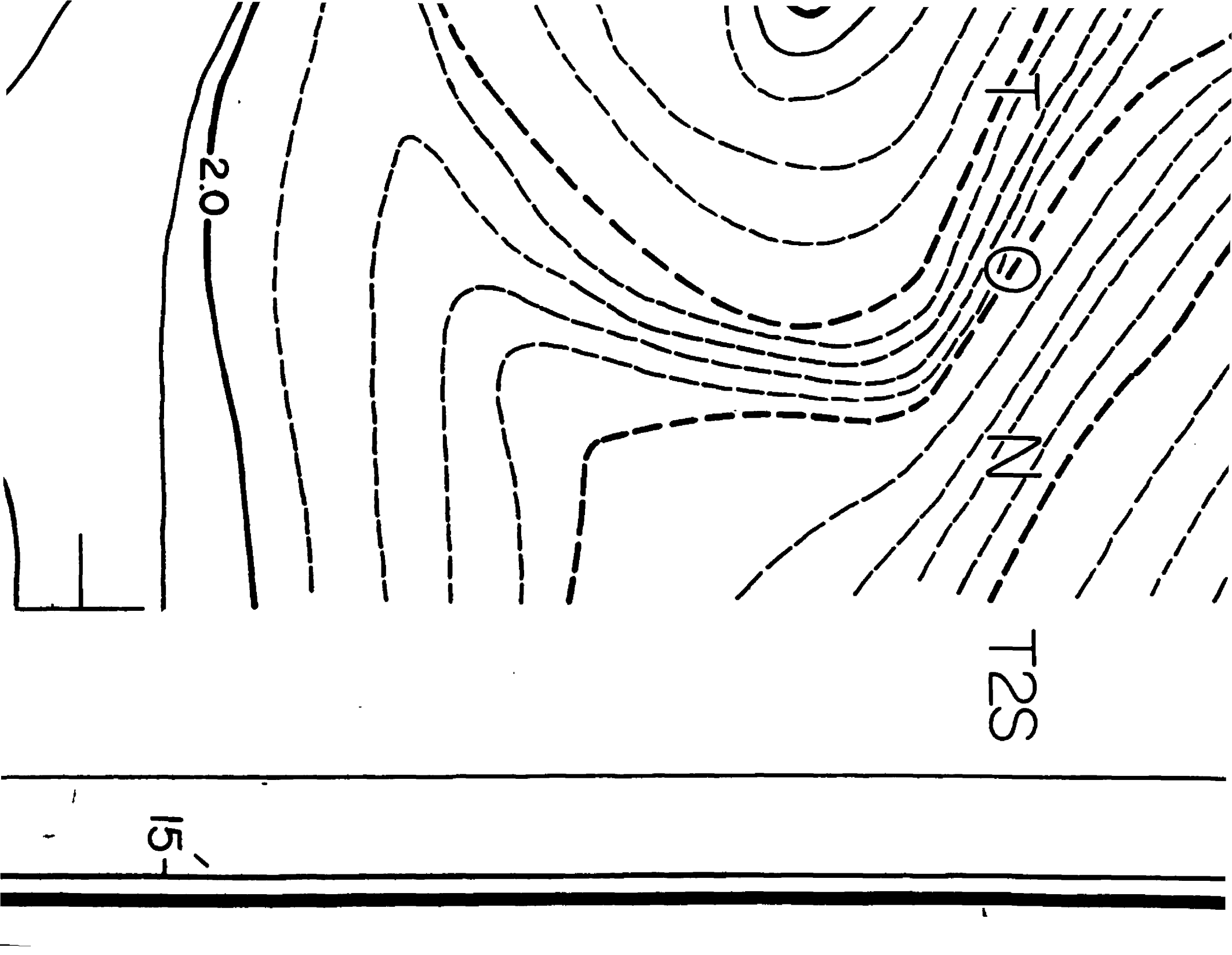
7.0

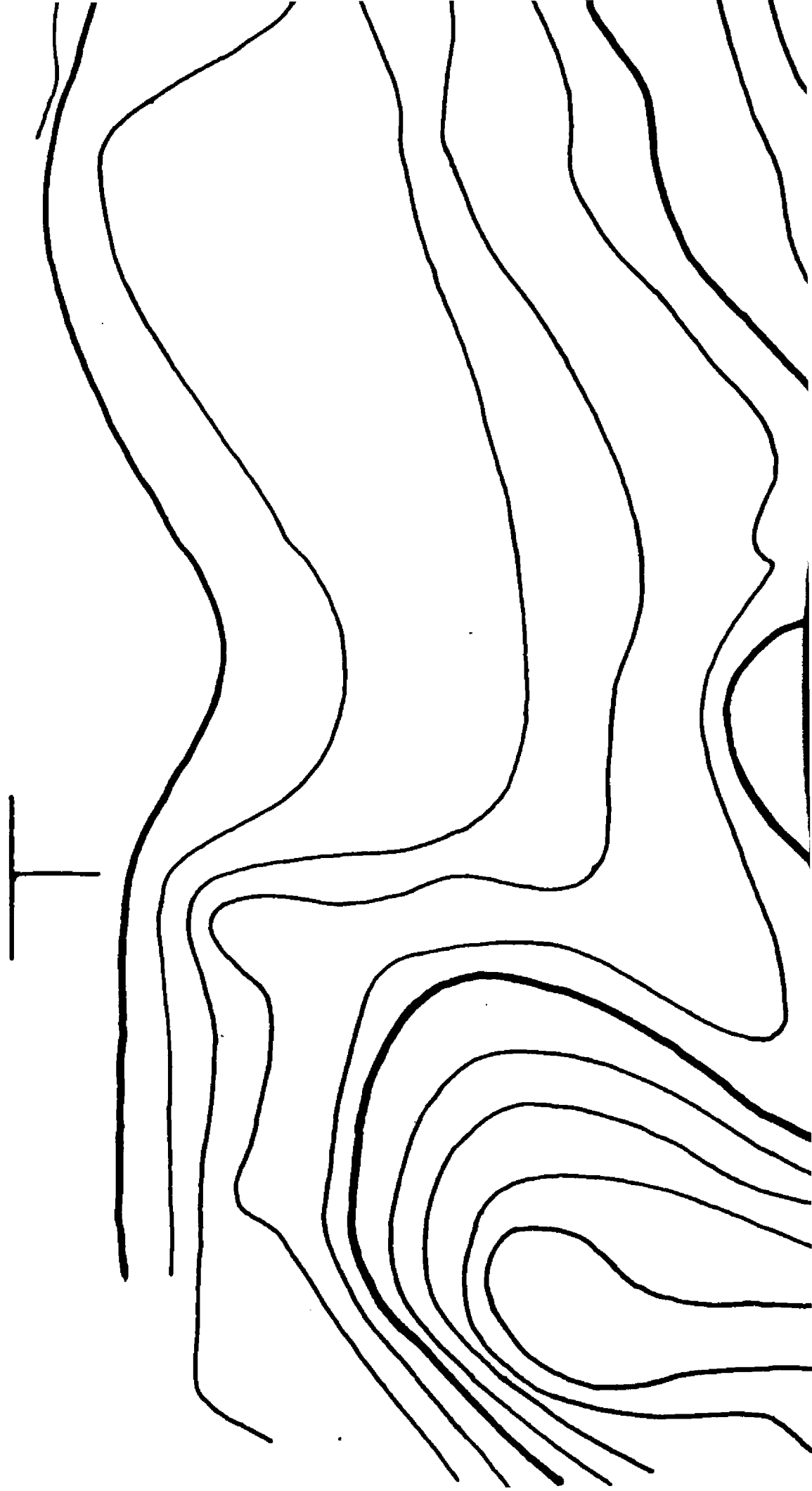
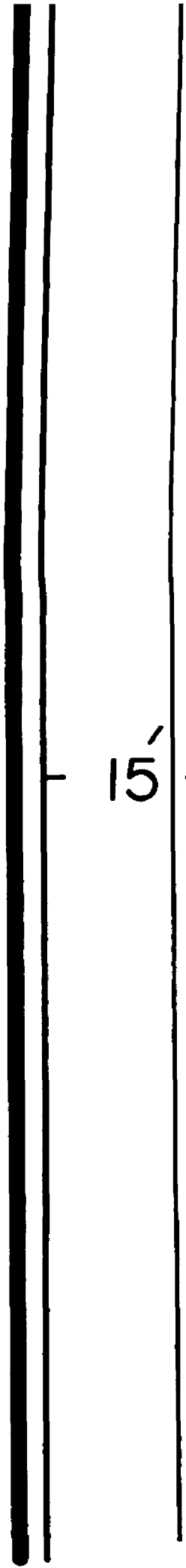
h

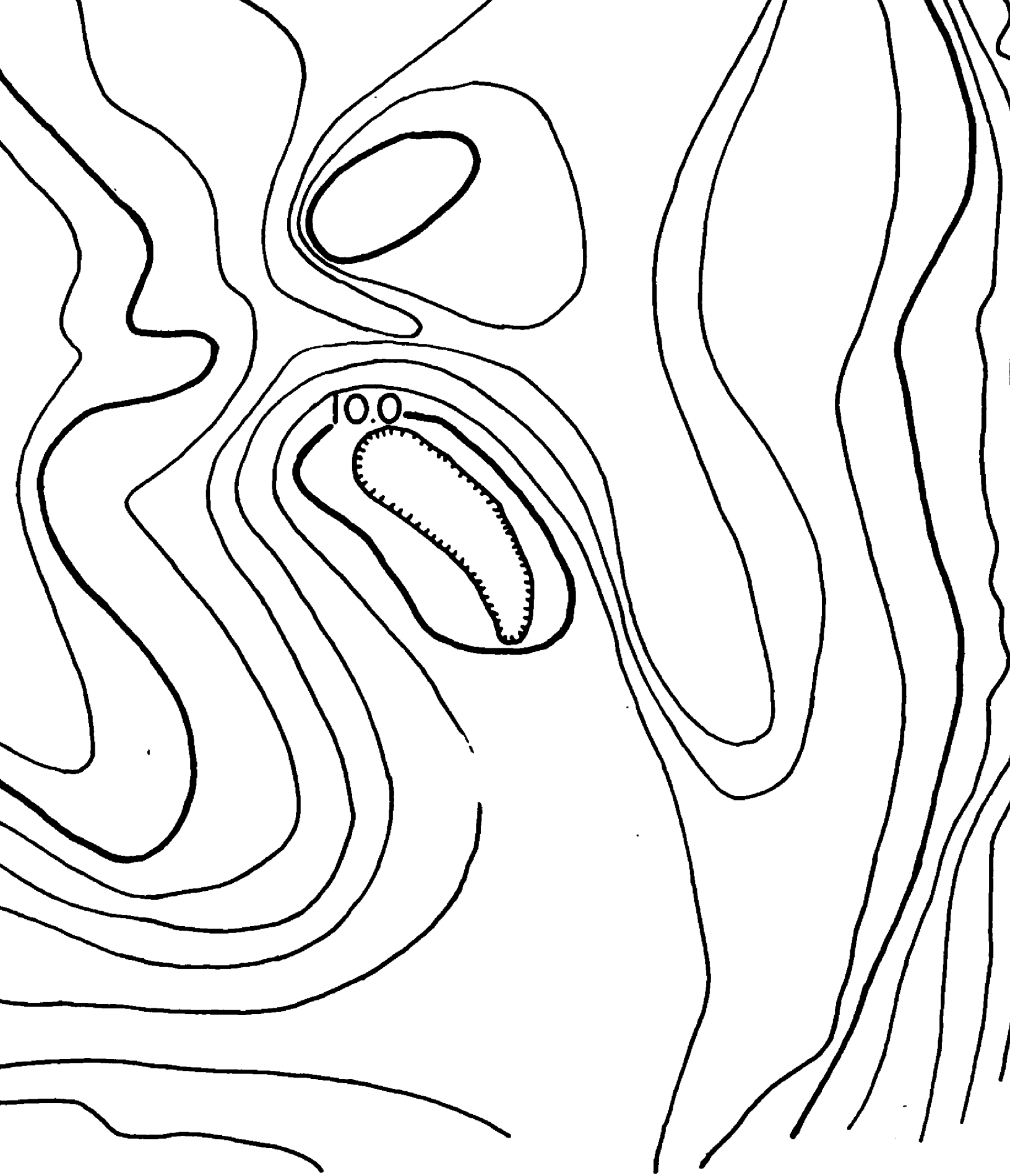










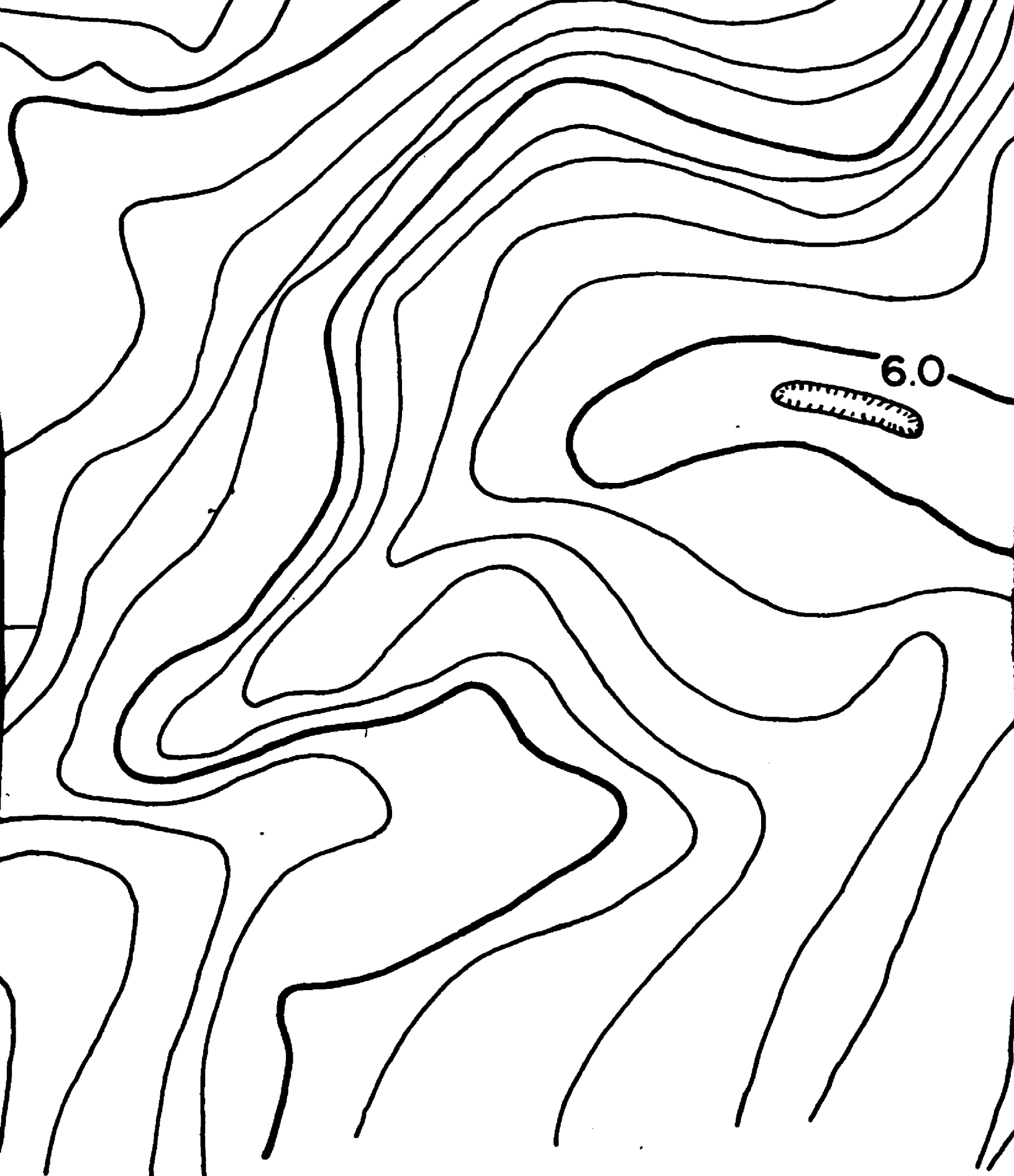


PLA



PLATE 3b

CONTO



CONTOUR MAP OF THE



THE BOUGUER GRAVIT



GRAVITY

ANOMALY

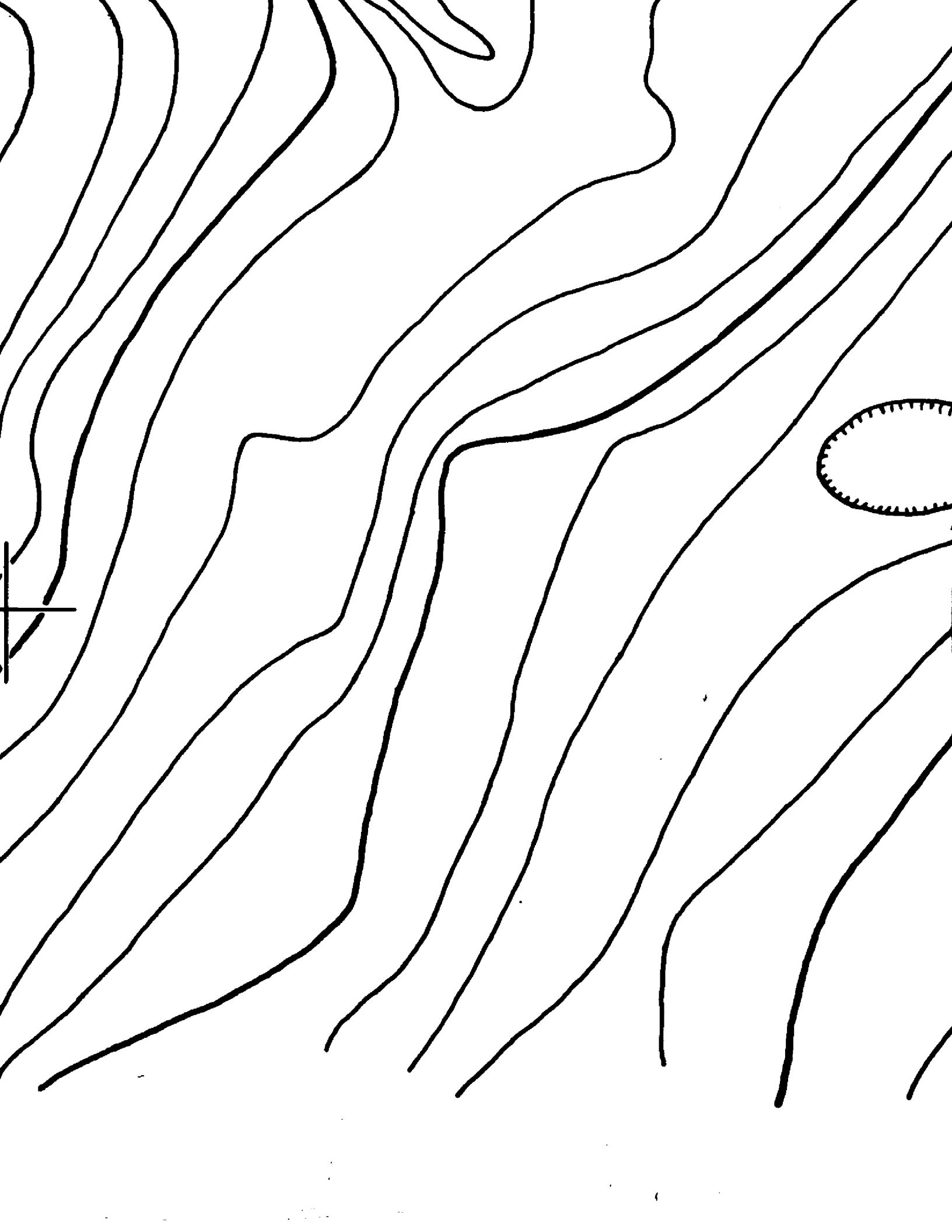
NO



NORTHERN HALF OF KALAMAZOO



LAMAZOO COUNTY







15'

T3S

0.0

T



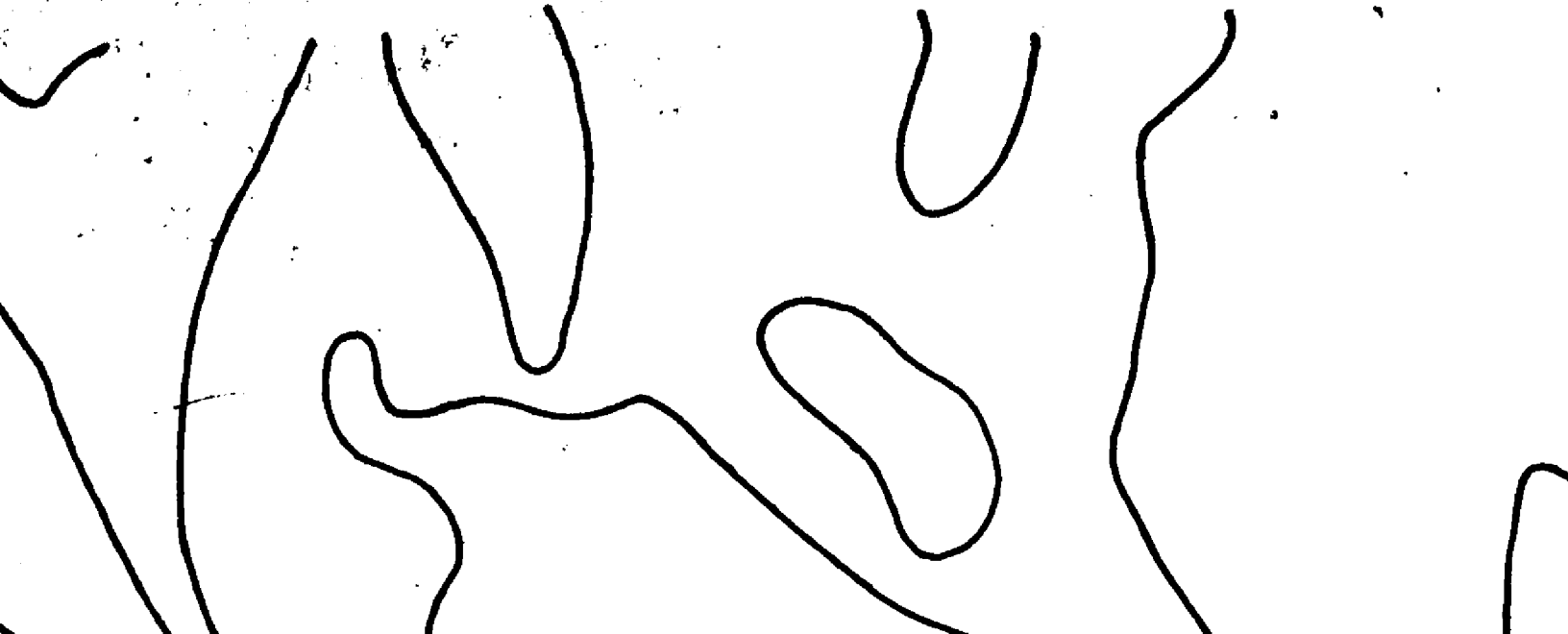
T

E

X

A

S



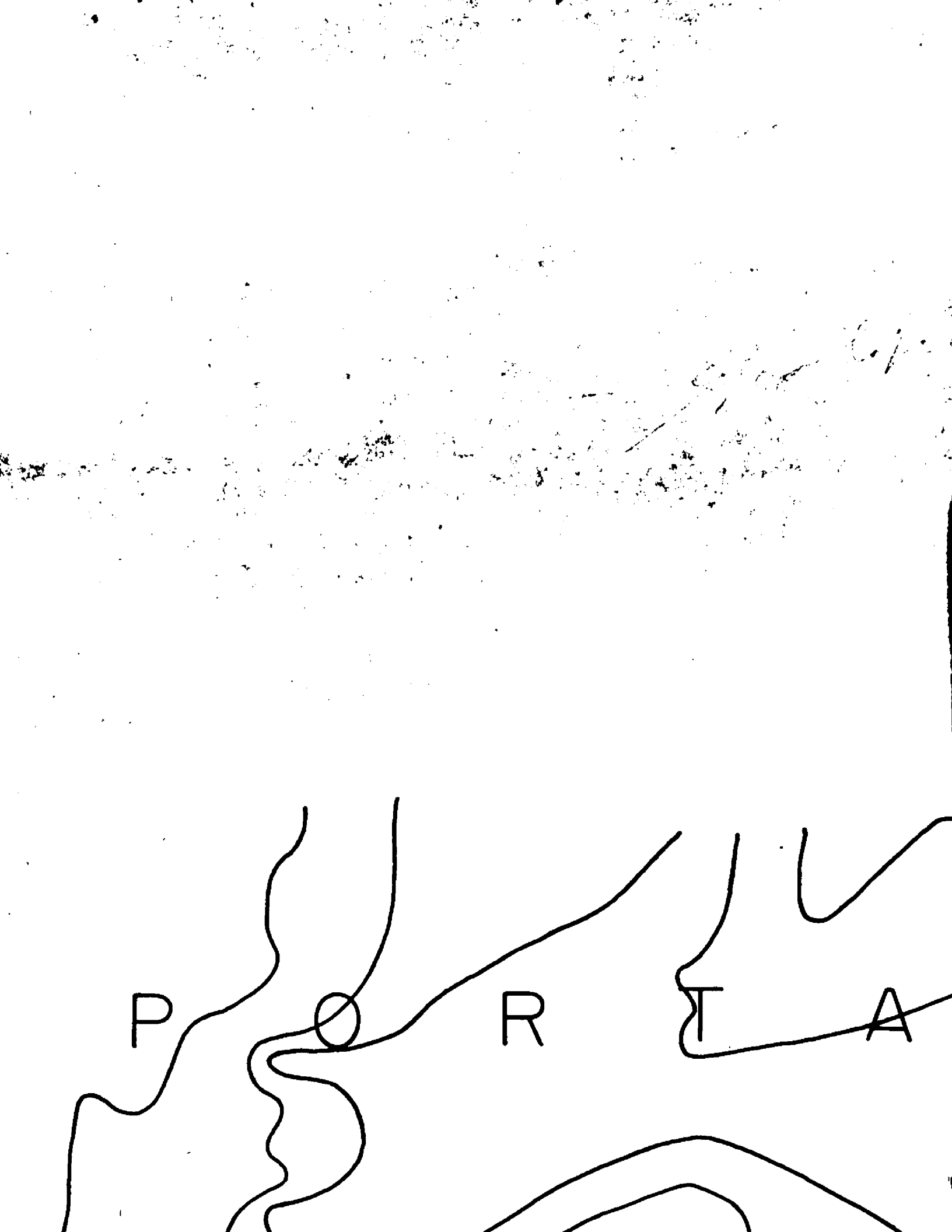
P

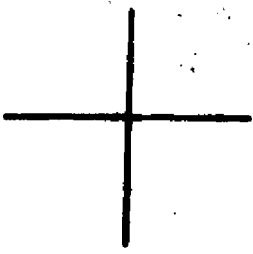
Q

R

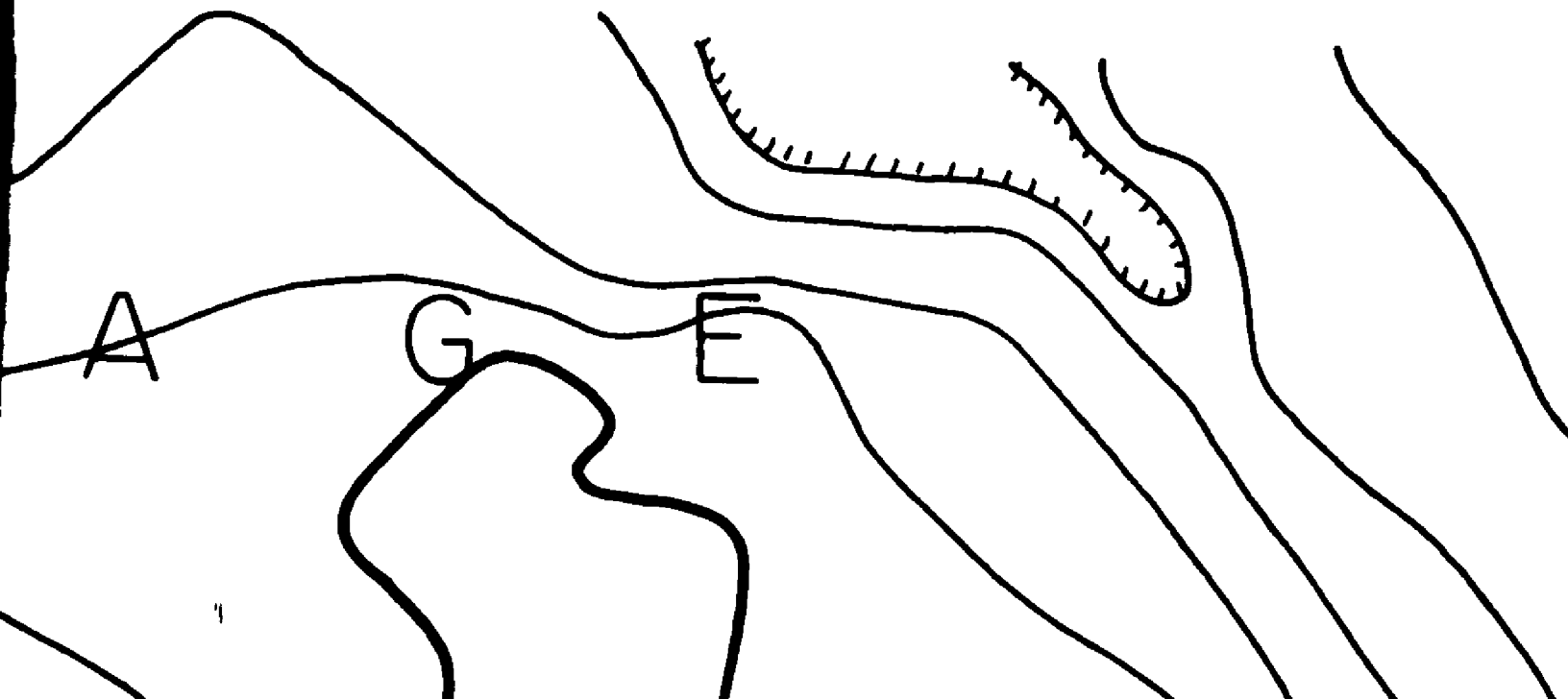
7

~~A~~





Handwritten text, possibly a signature or title, located in the upper left quadrant.





P

A

2.0

~~2.0~~

I







C

I

M

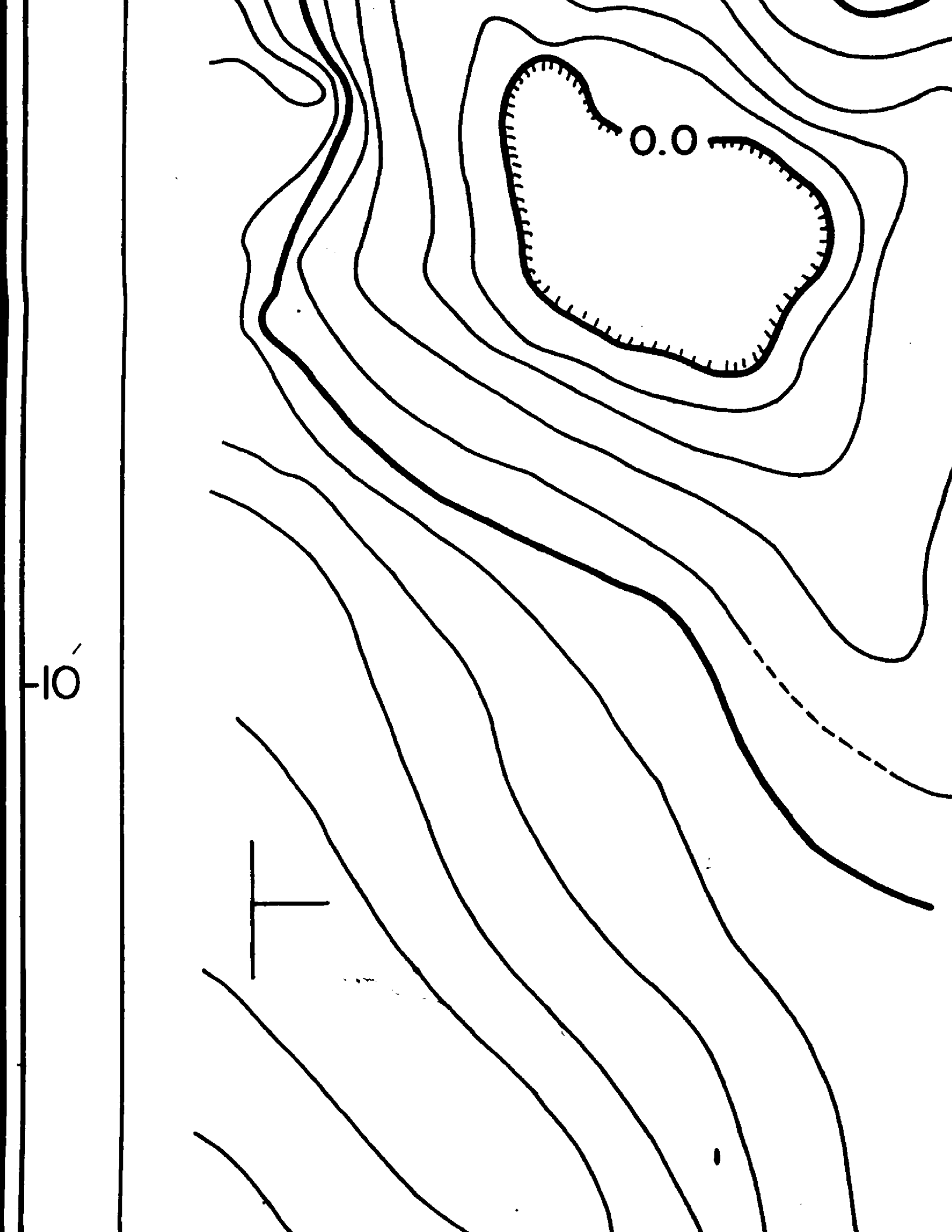
A



A

X

T3S

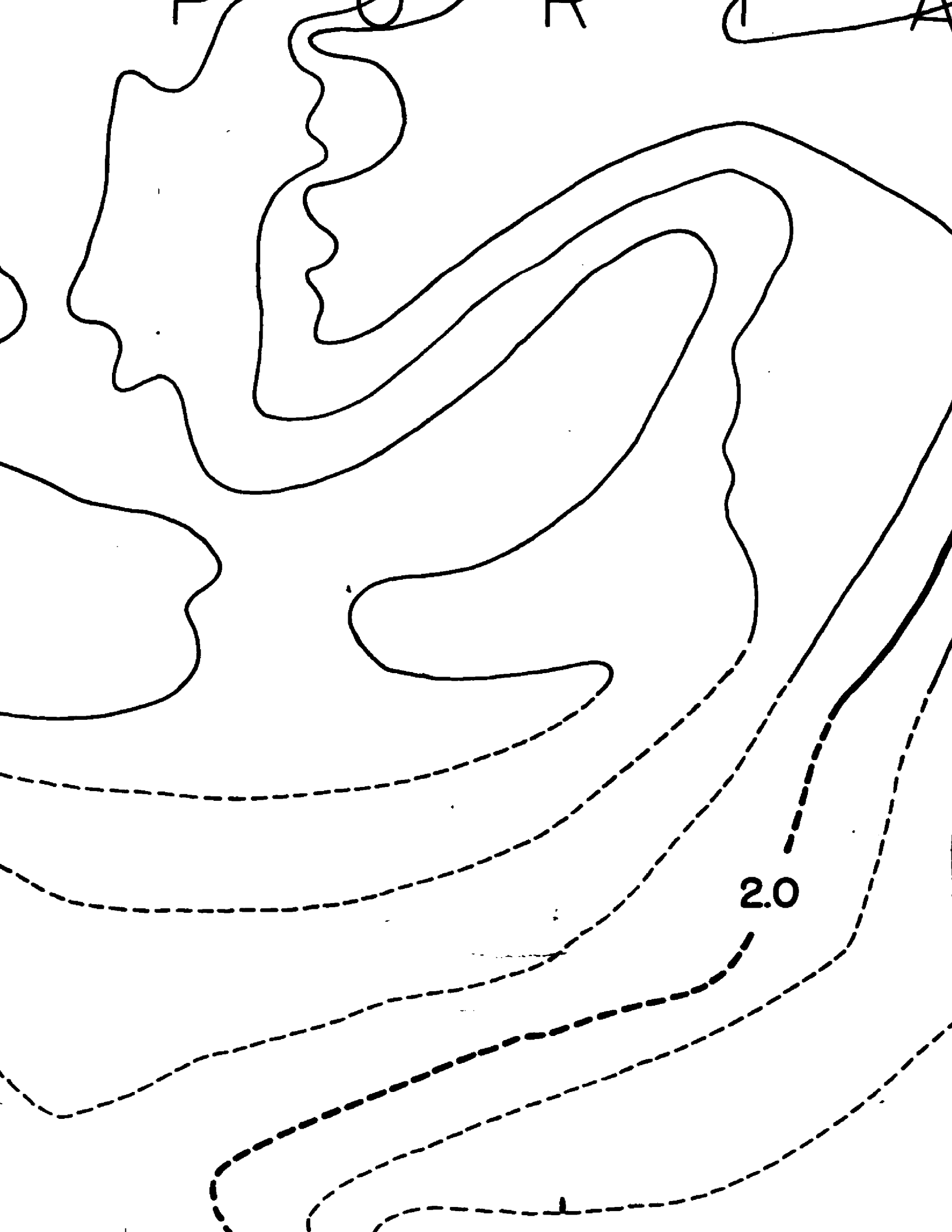


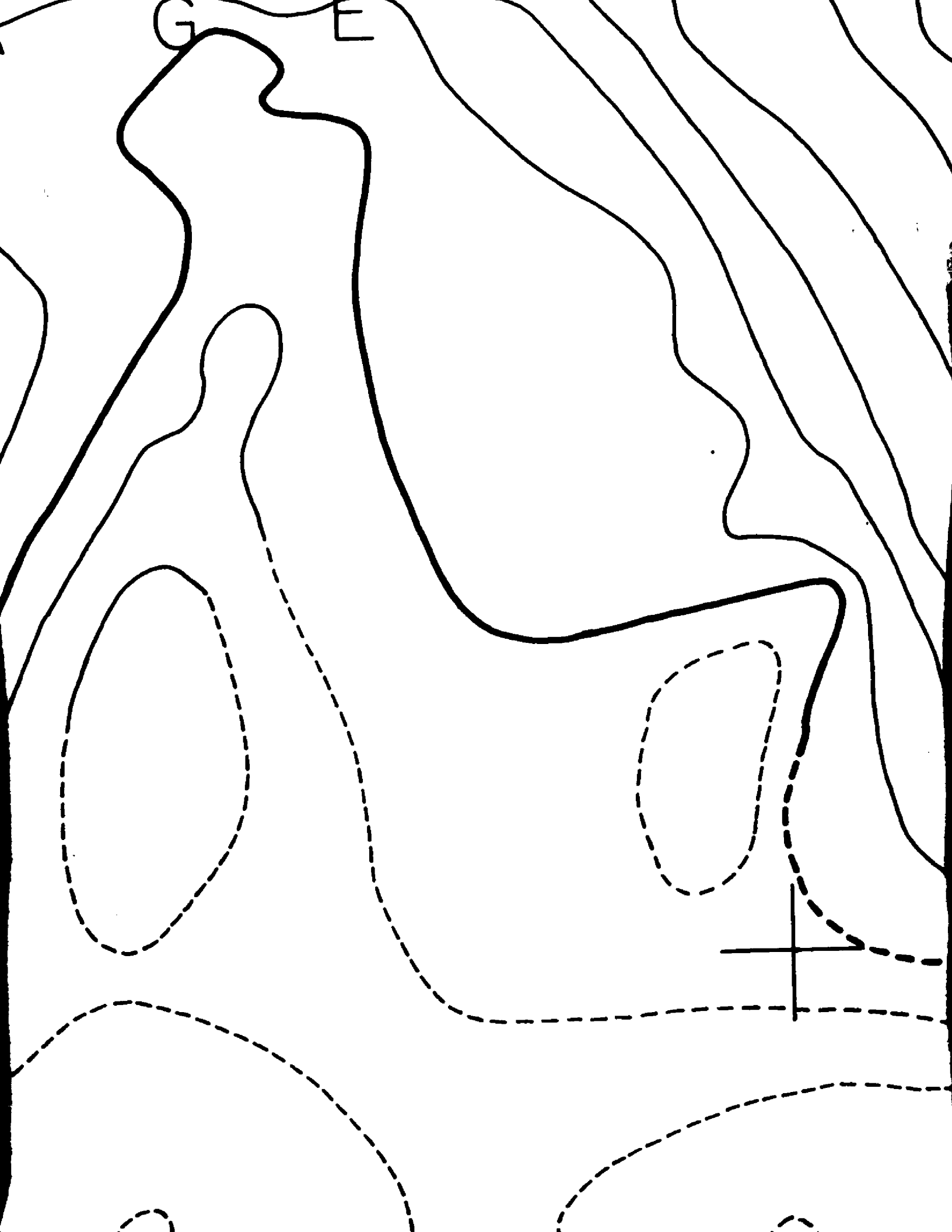


1.0

1.0

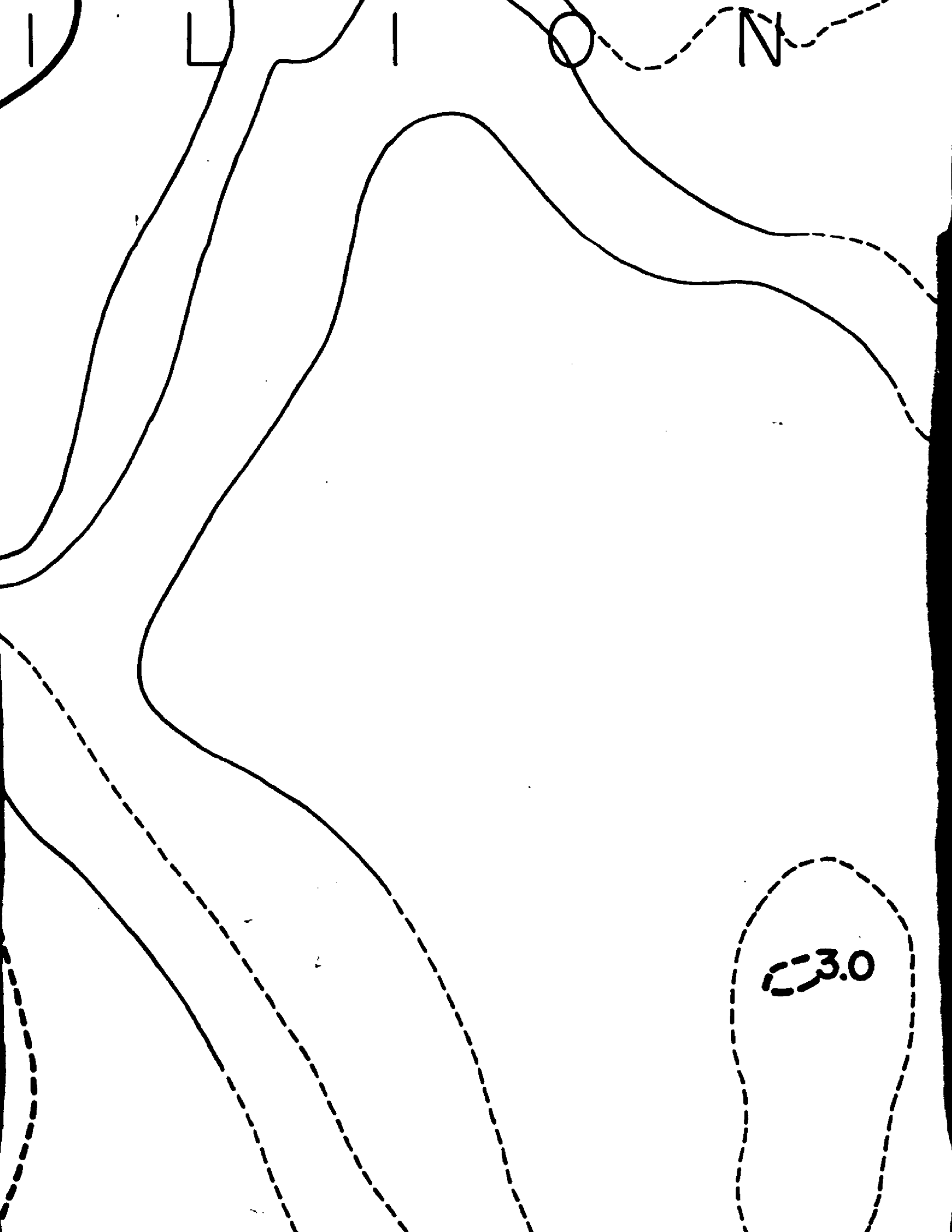


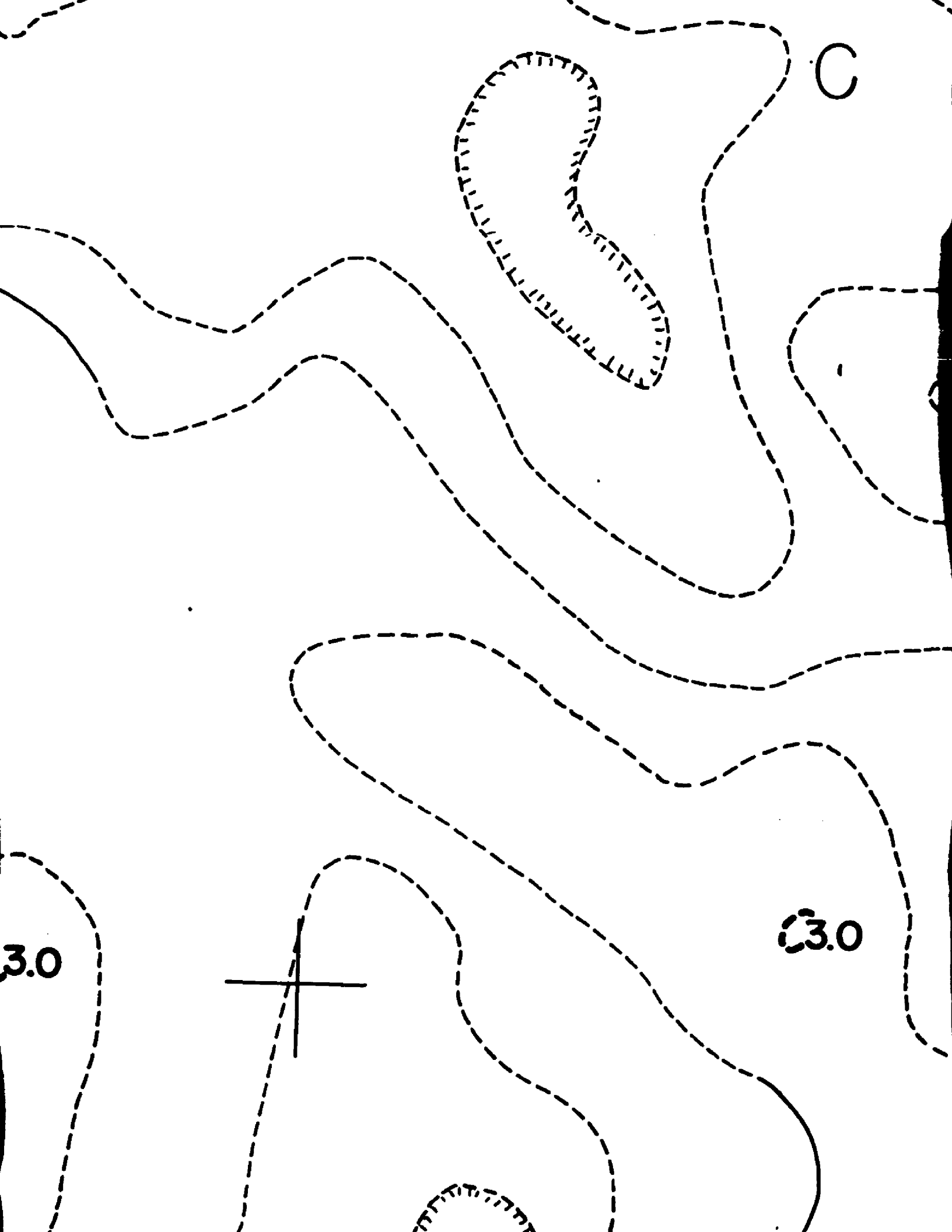




P A ~~Q~~2.0 I



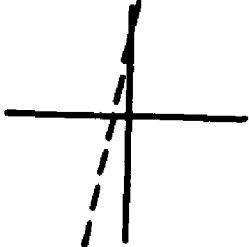


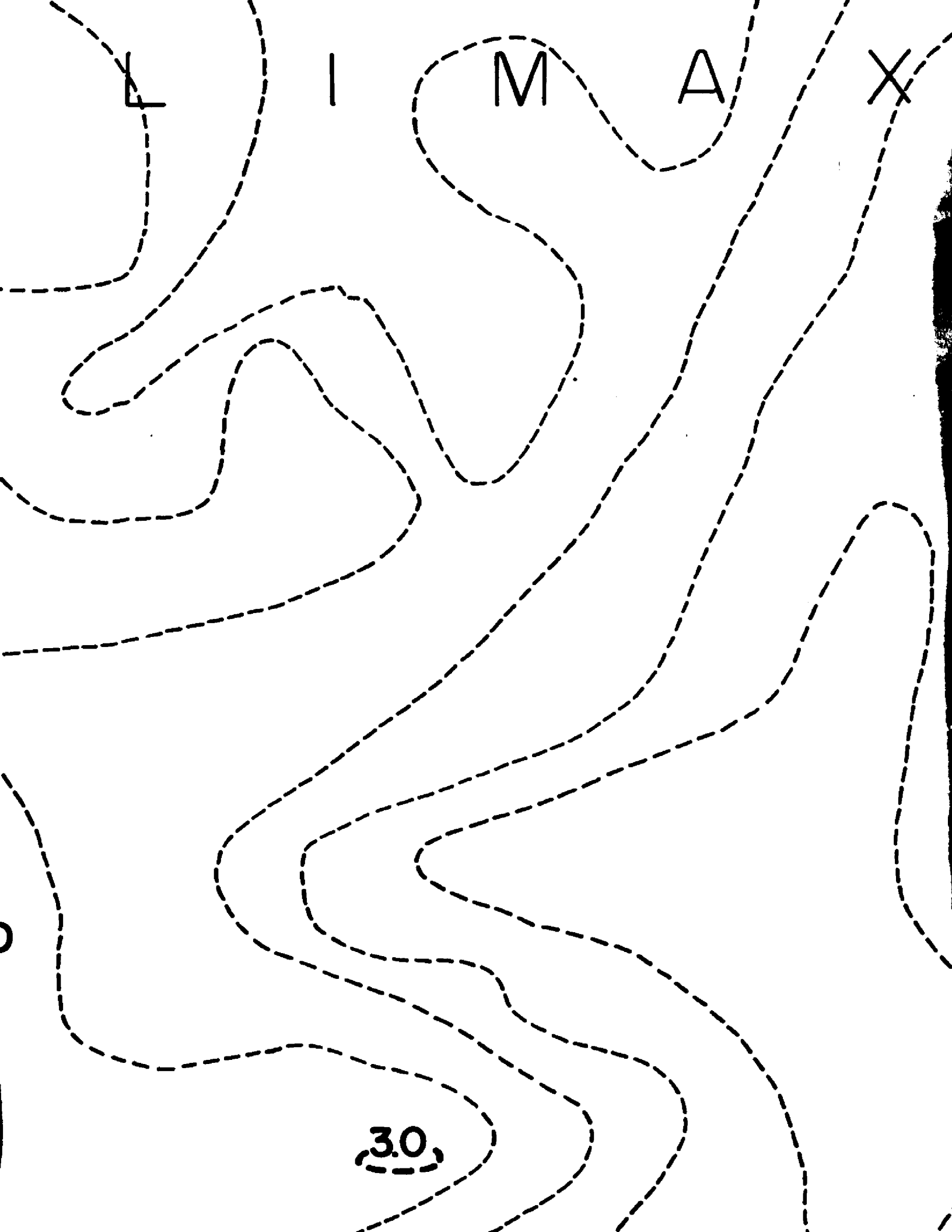


C

3.0

3.0





L

I

M

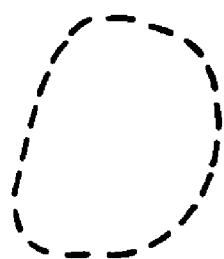
A

X

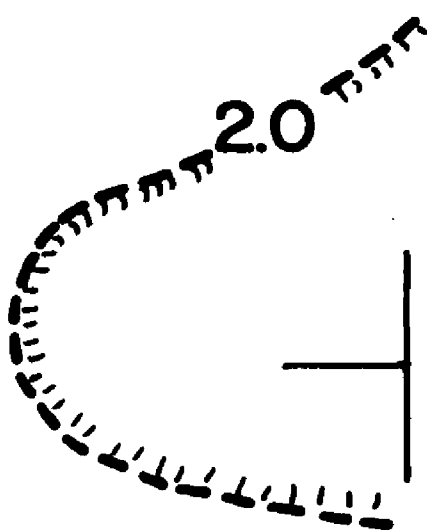
30,

T3S

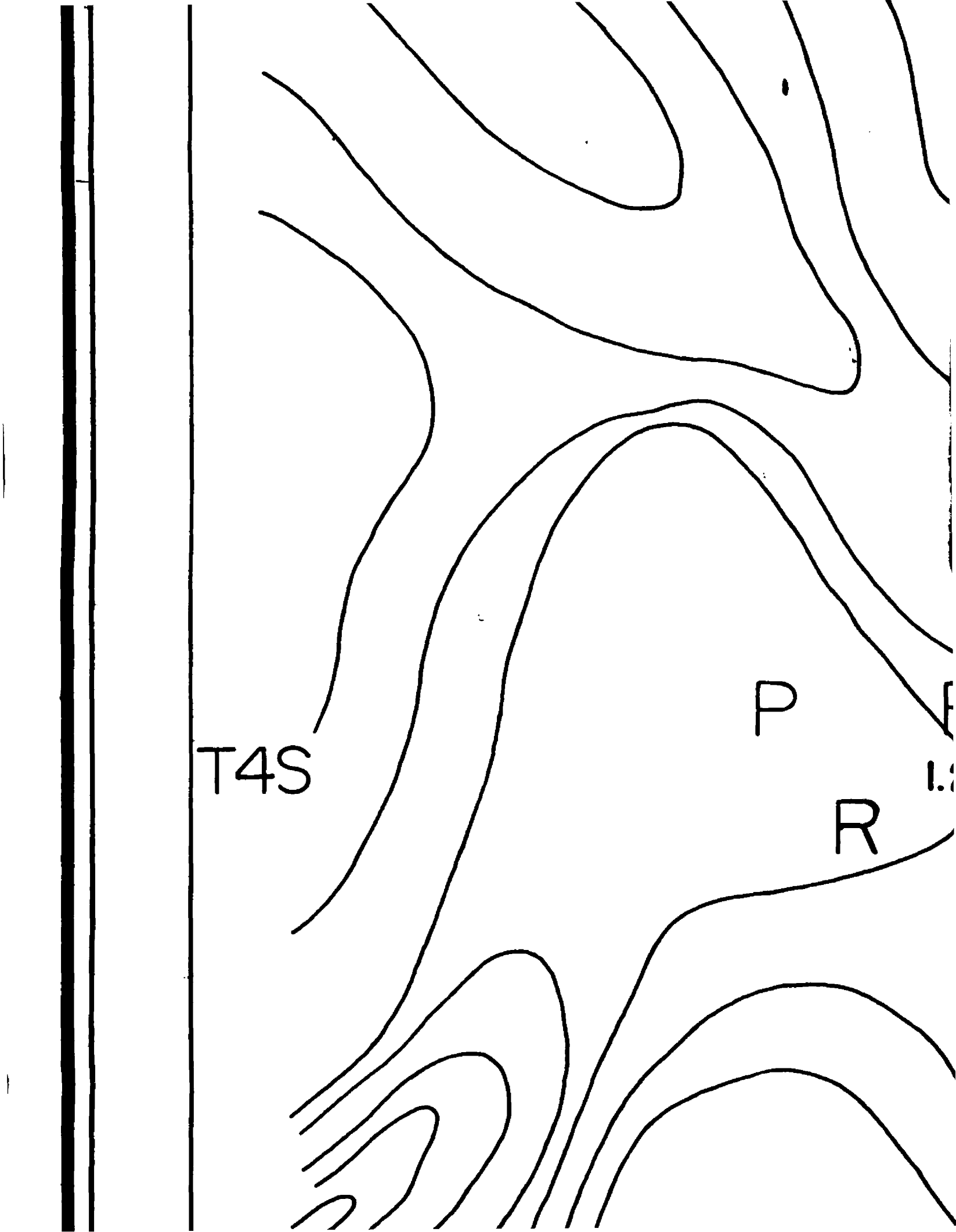
X



2.0



10'



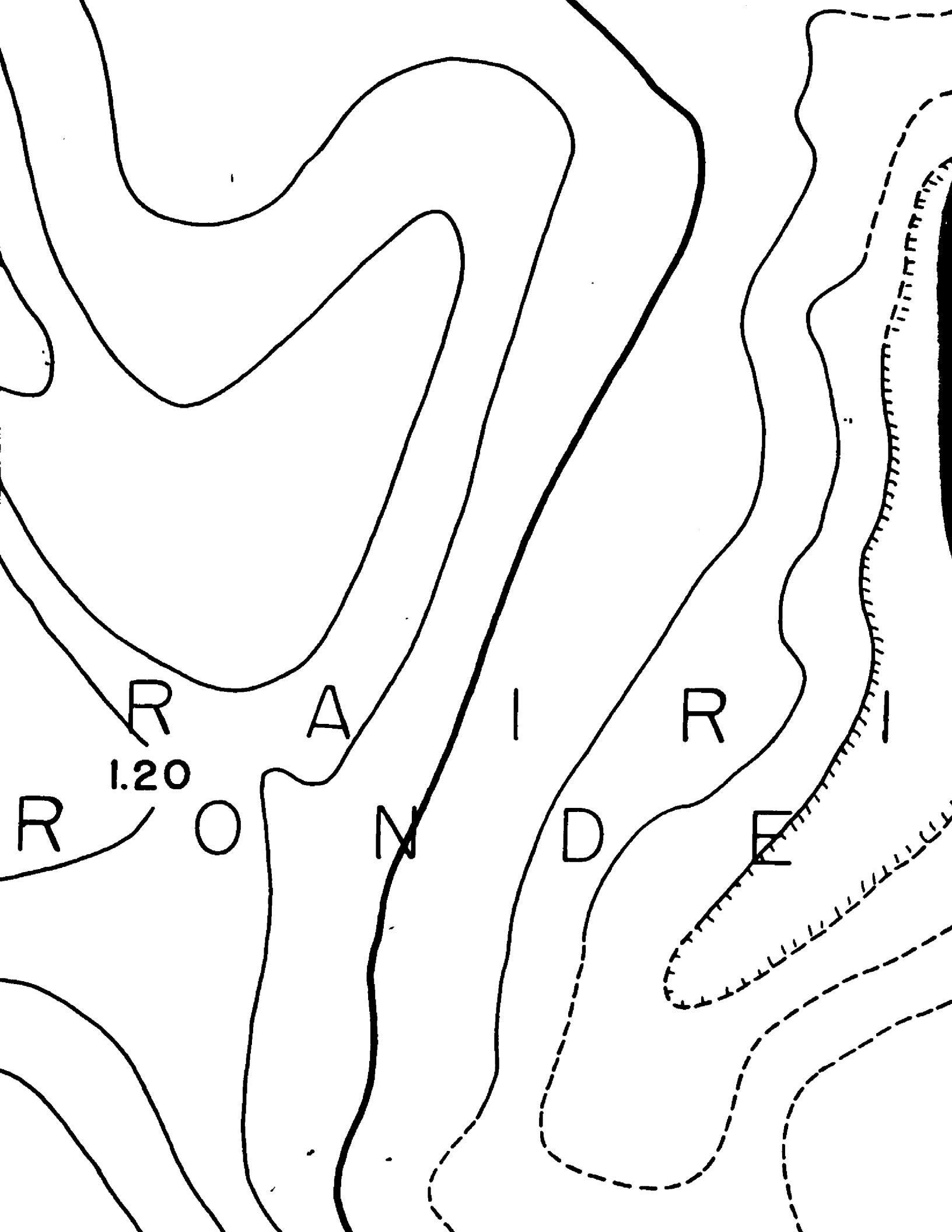
A hand-drawn contour map on a white background. The map features several curved lines representing contours. On the left side, there are two thick vertical lines. The map is labeled with 'T4S' on the left, 'P' in the center-right, 'R' in the lower right, and 'F' on the far right edge. A small '1.5' is also visible near the 'F' label. The contours are drawn with a single black line, and the overall style is that of a field sketch or a preliminary map.

T4S

P

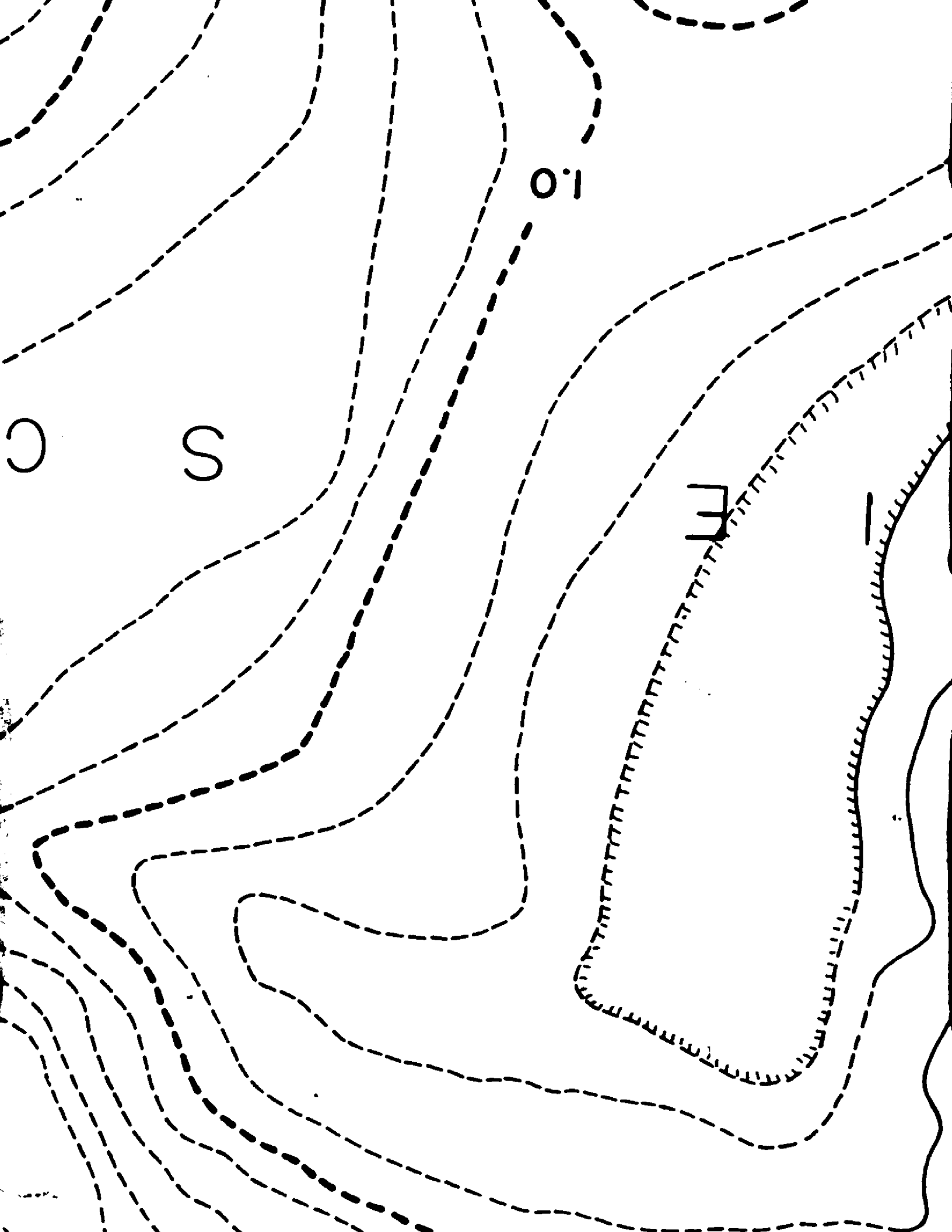
R

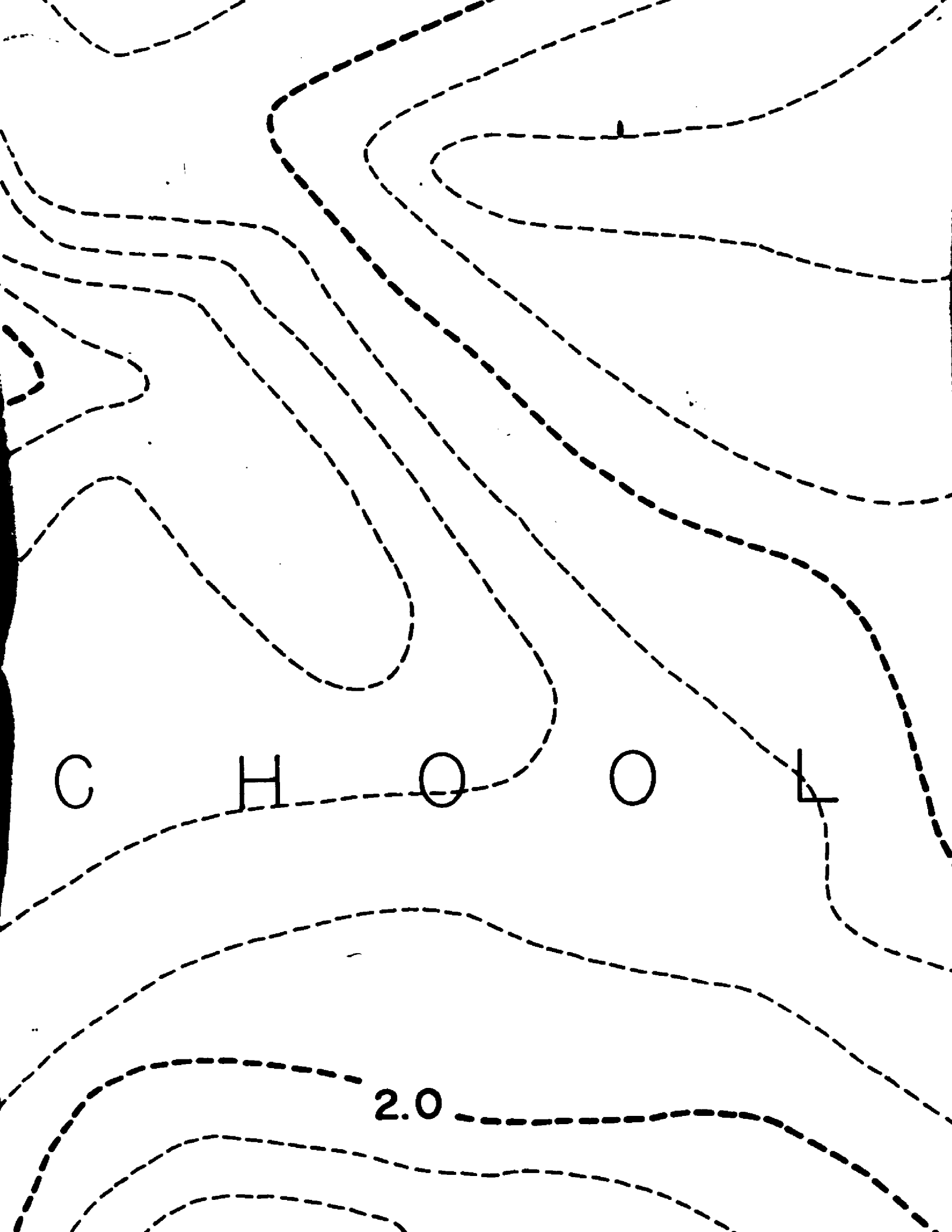
F
1.5

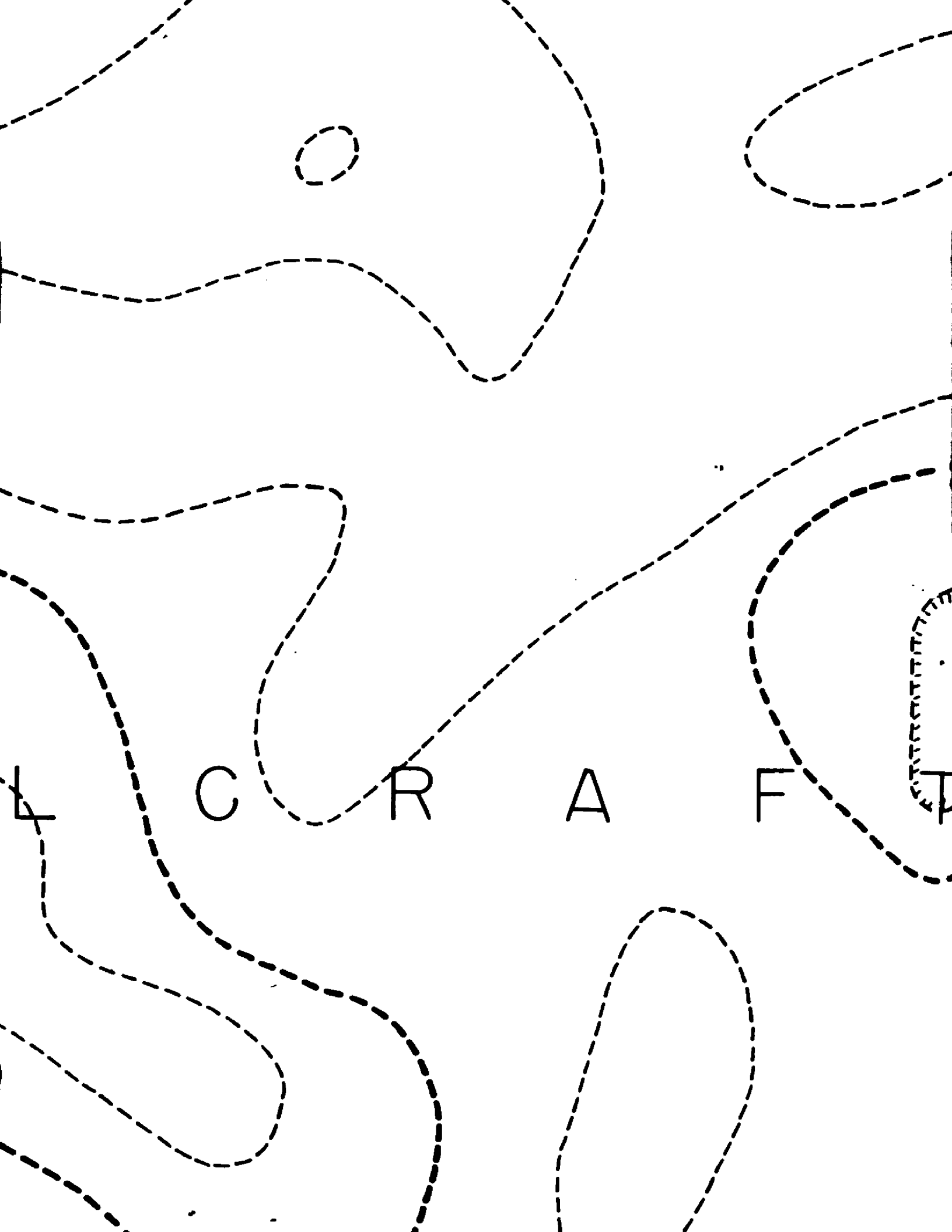


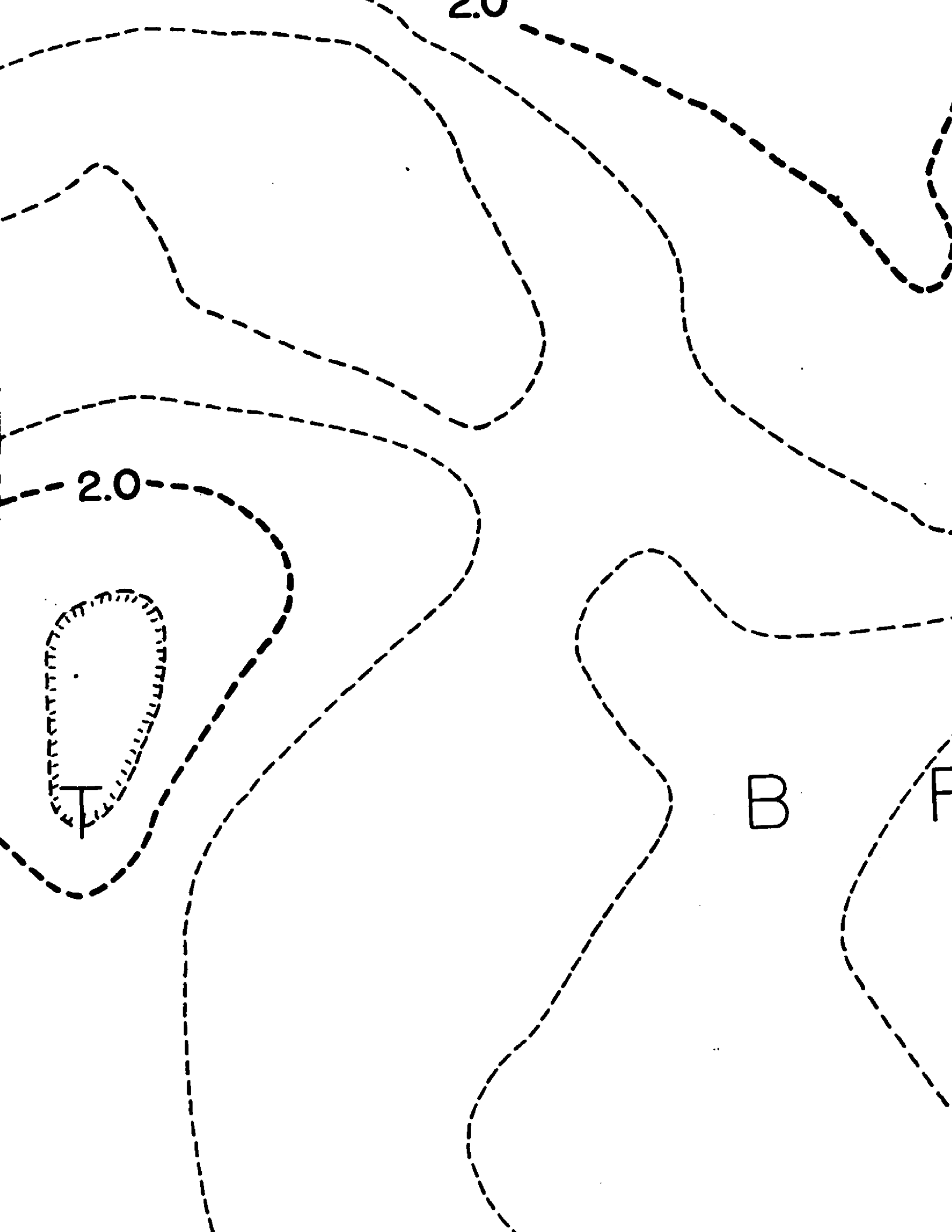
RAN I R
O N D E

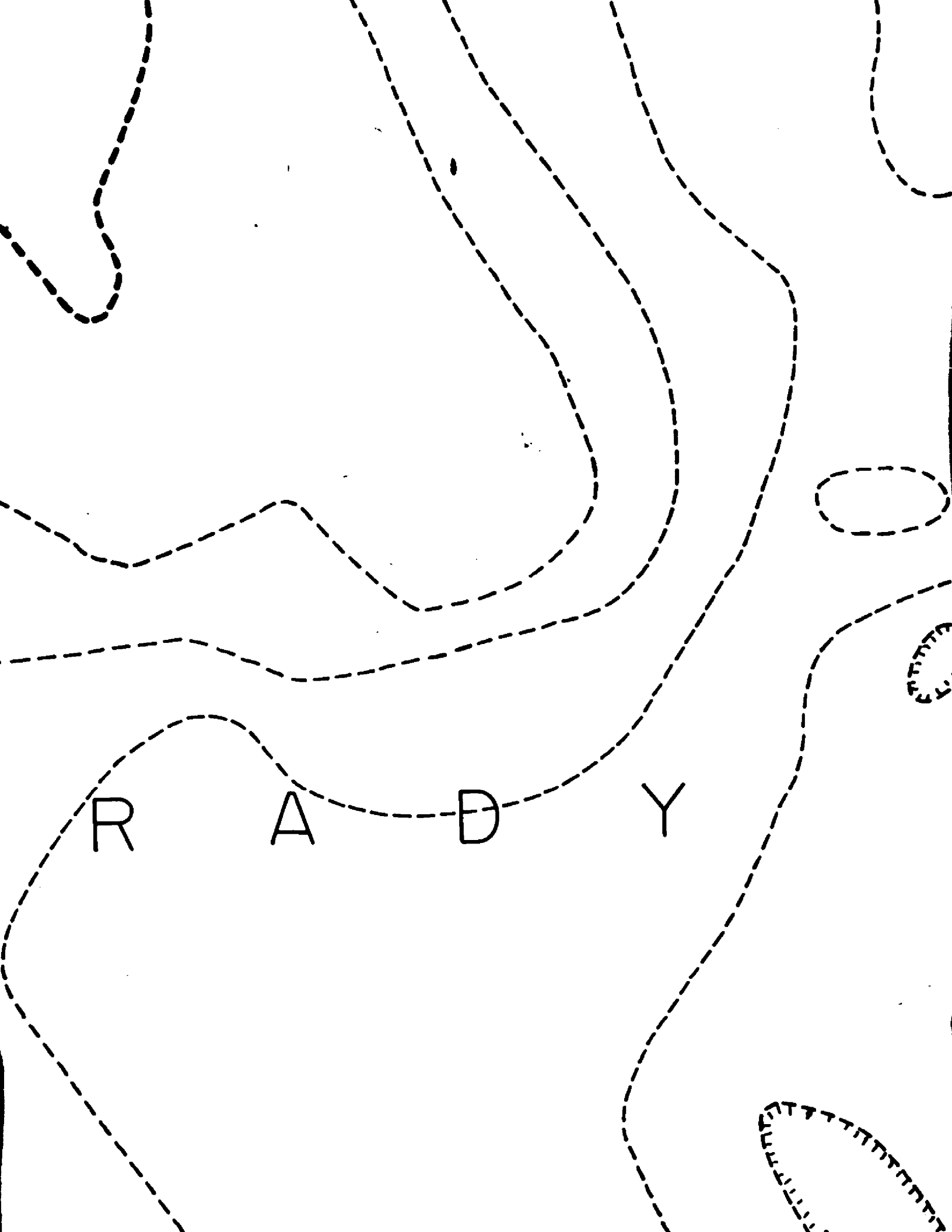
1.20

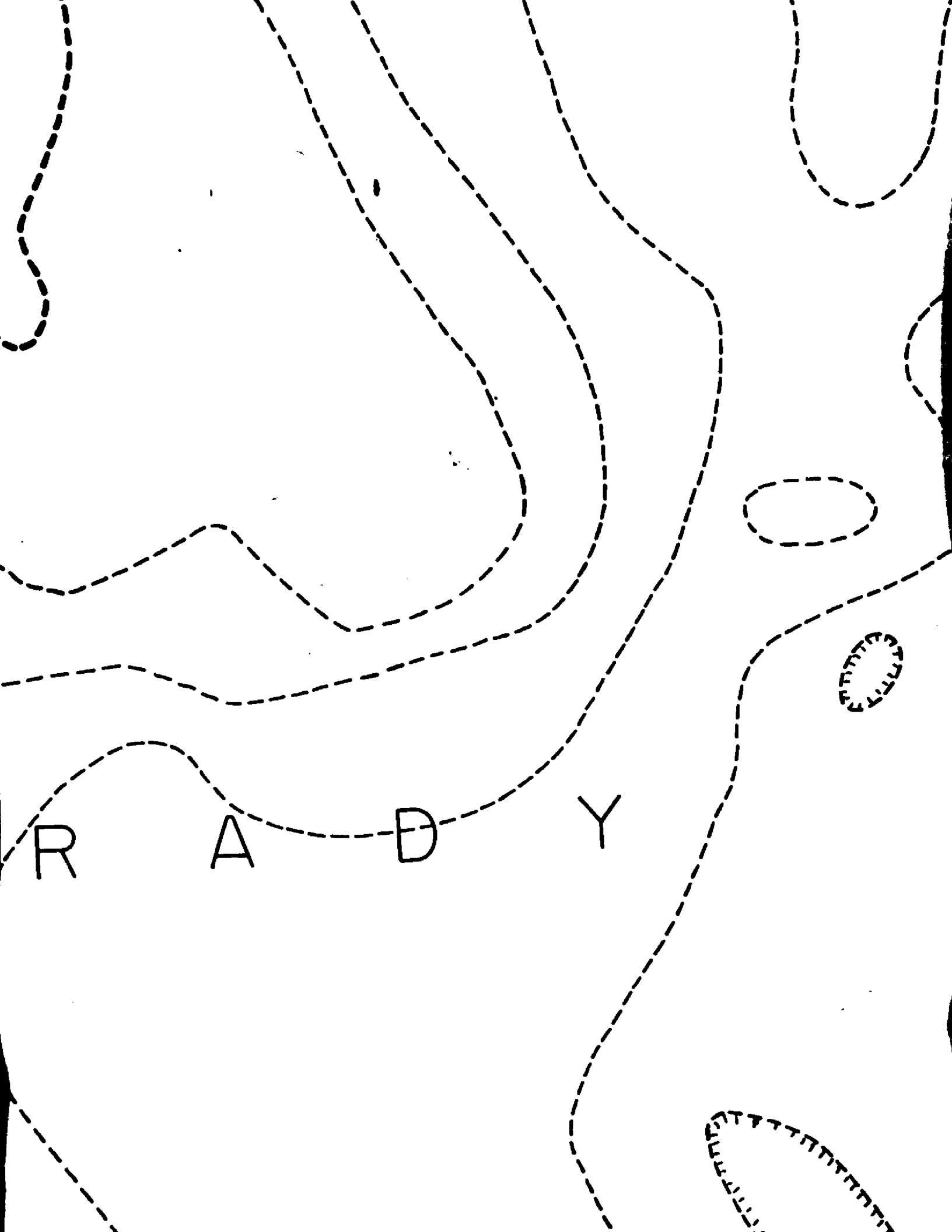














3.0,

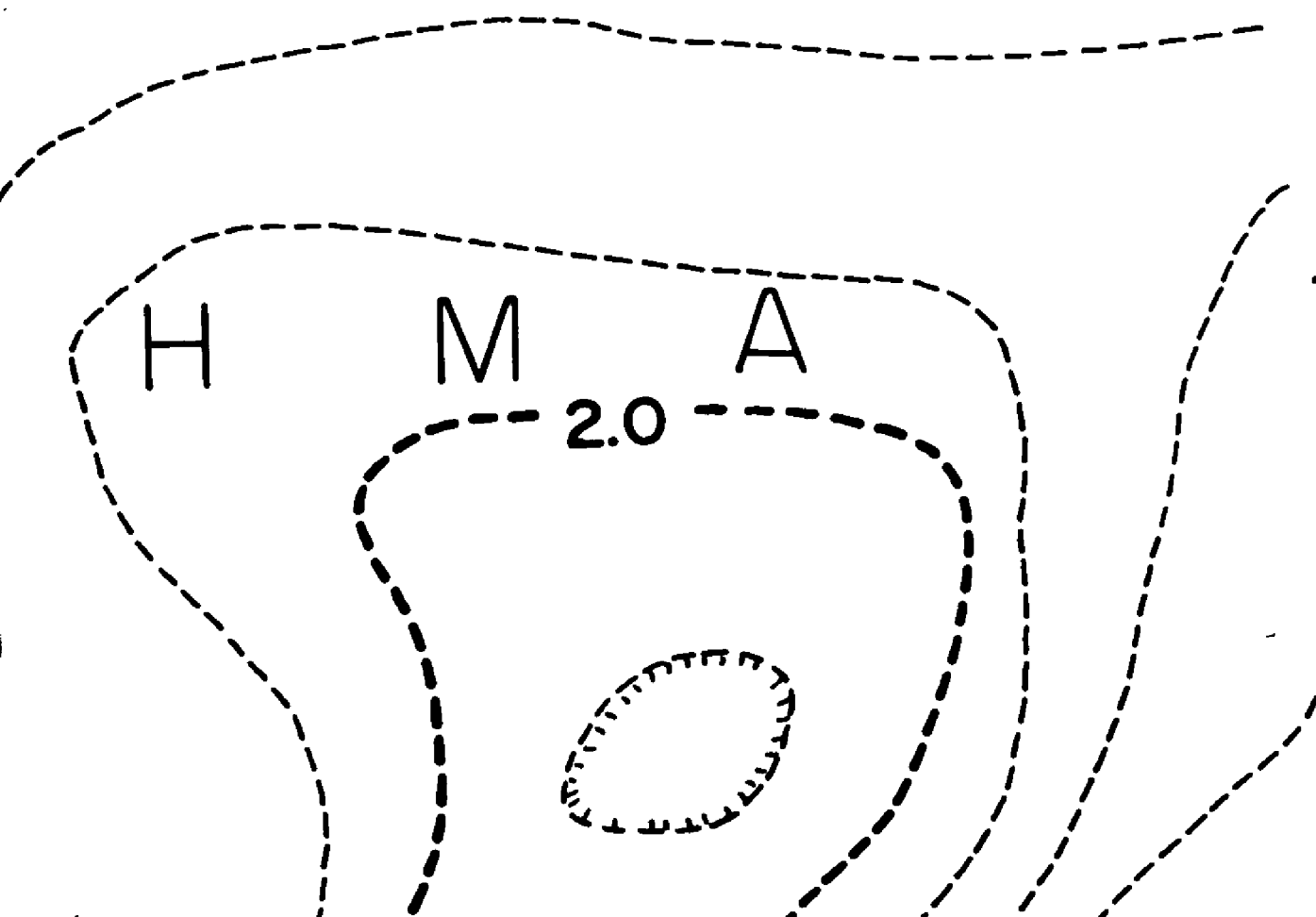
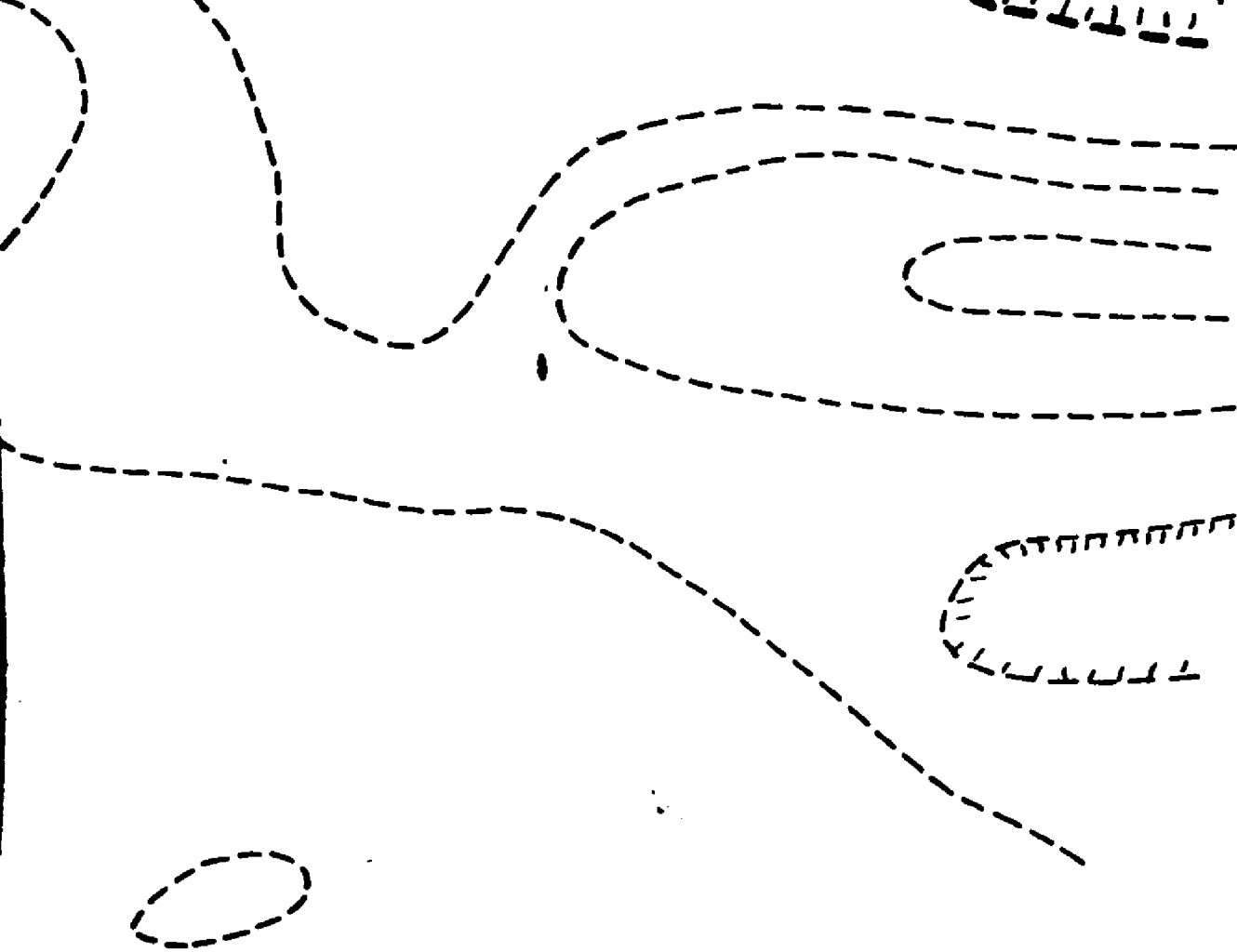
A

K

E

S

H



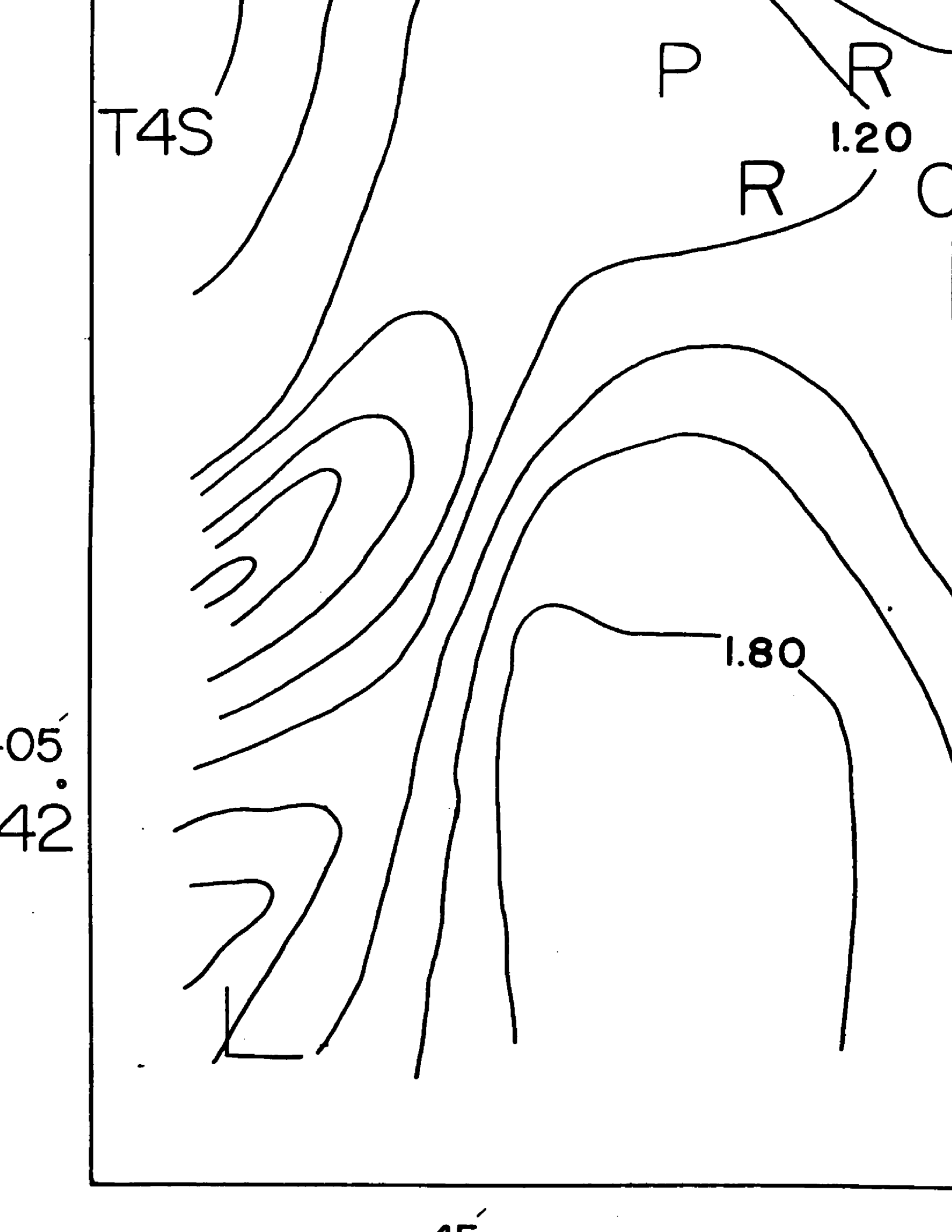
T4S

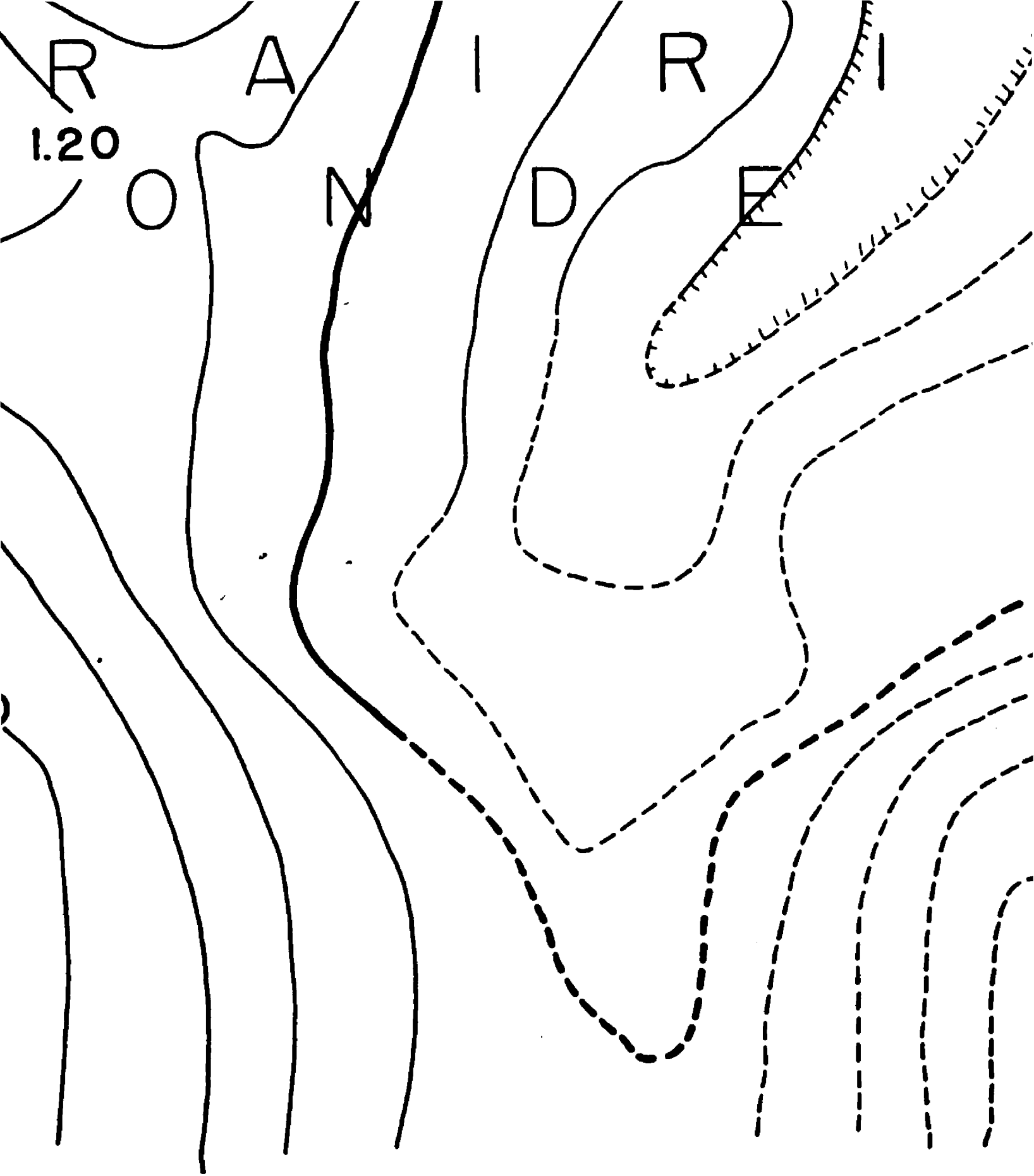
H

M

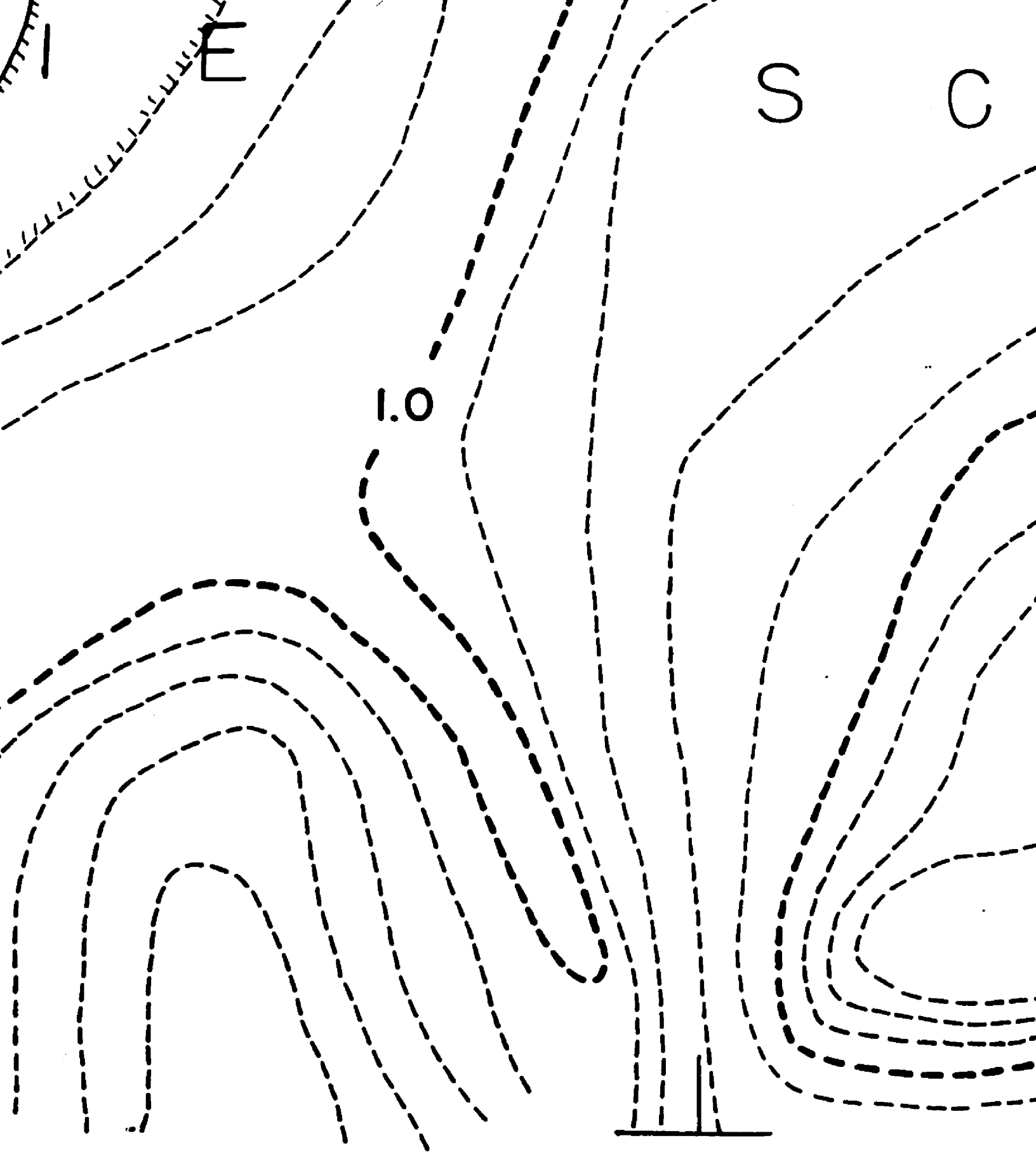
A

2.0





RI2W



C

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2.0

2.60

RIIW

RIIV



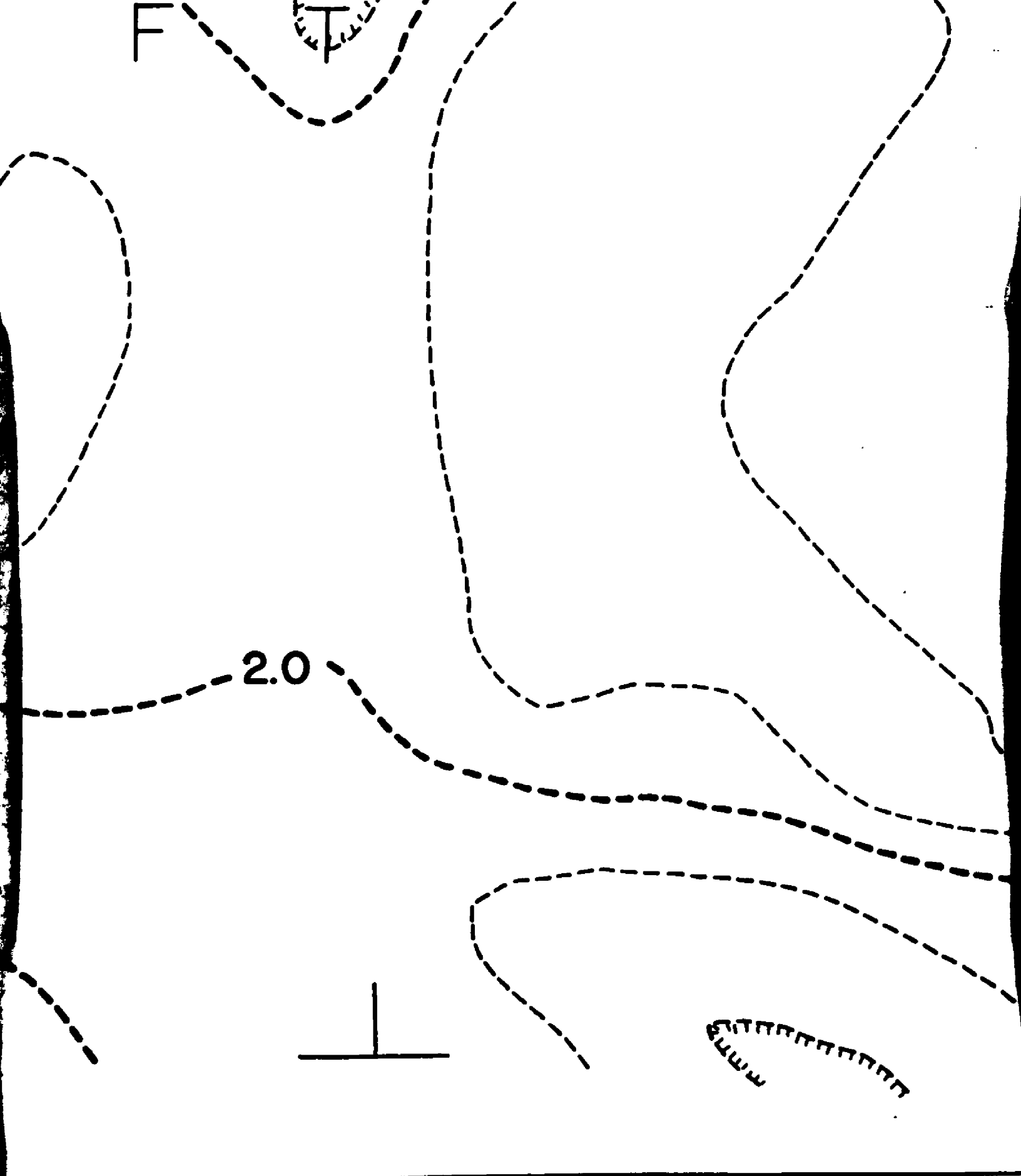
f

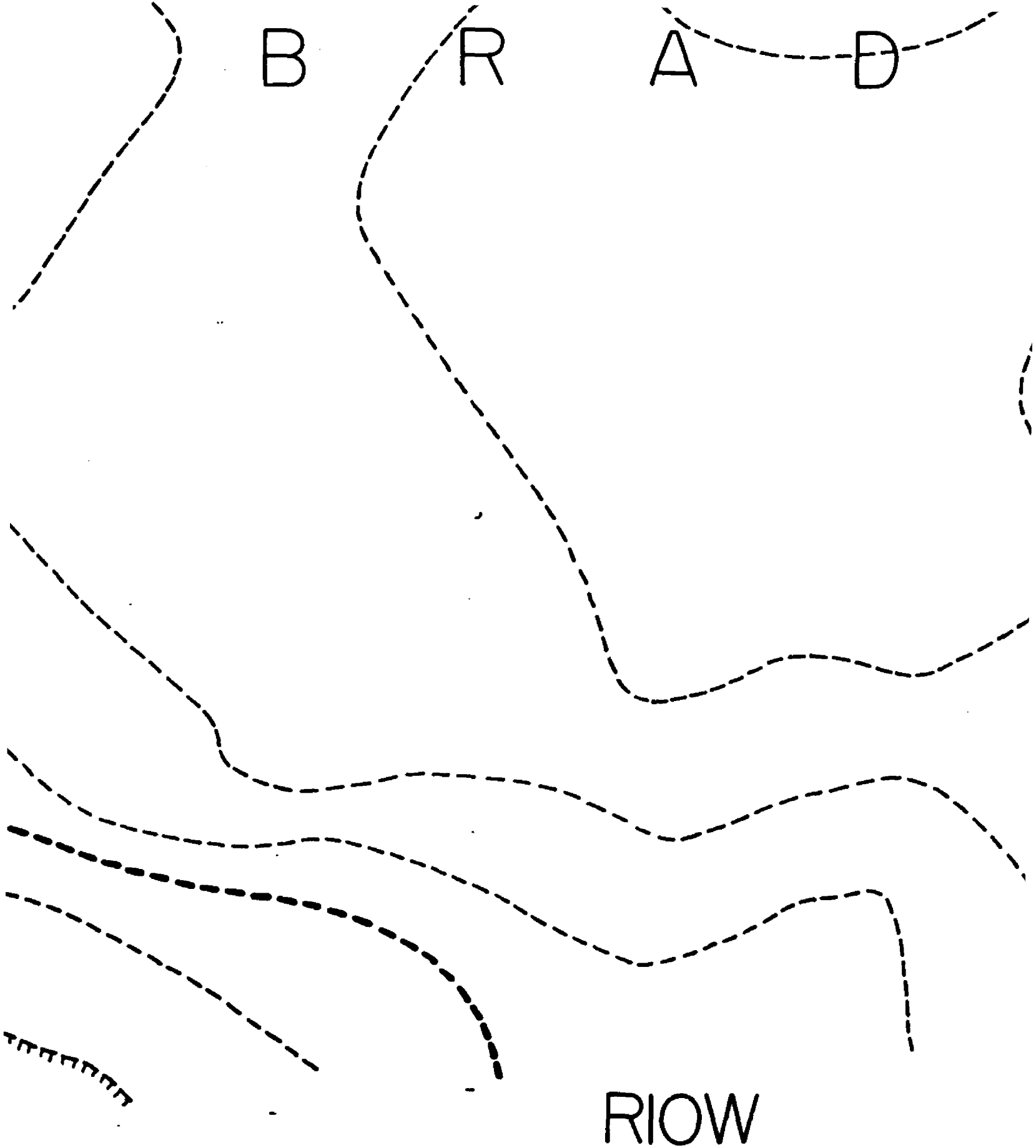
C

R

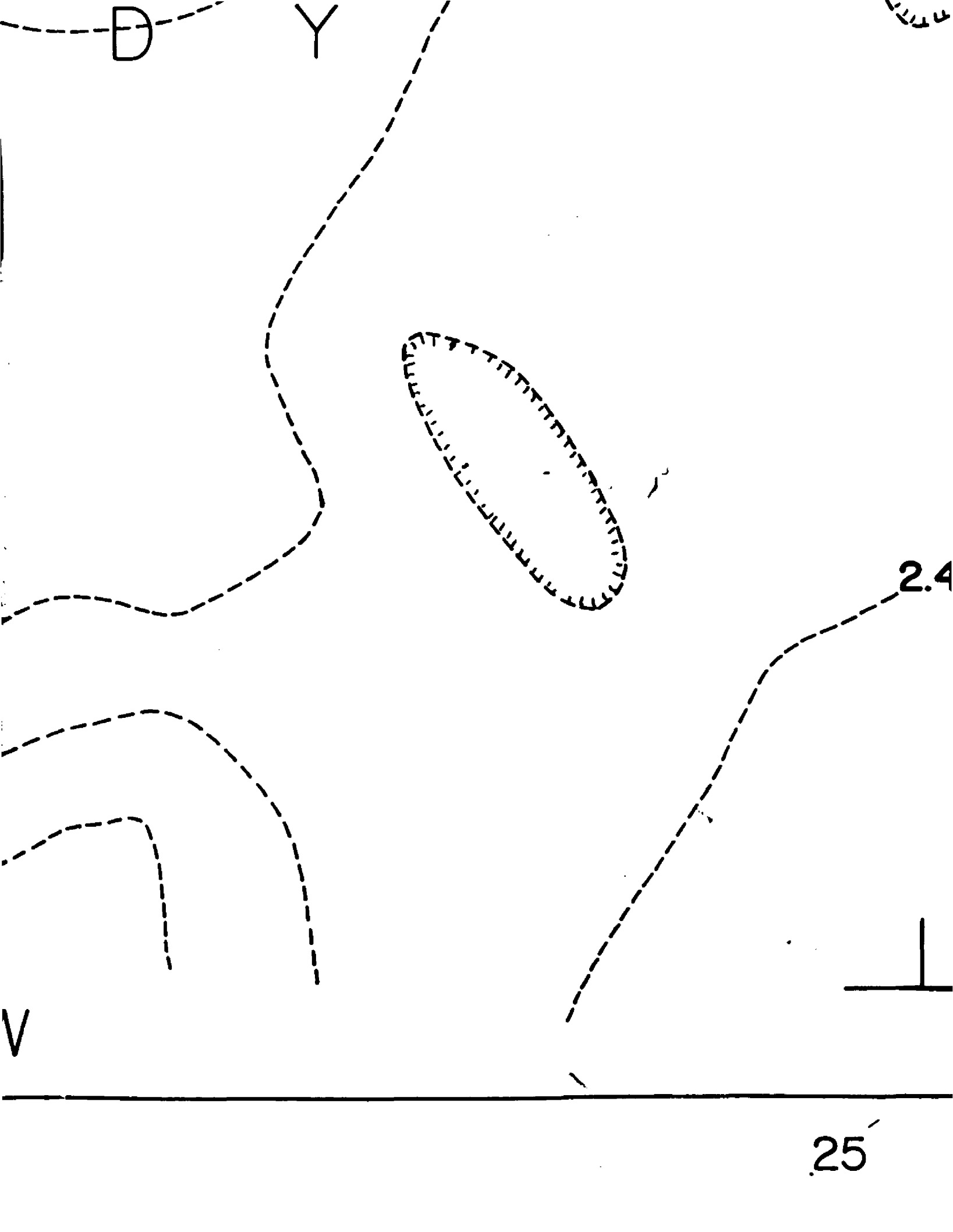
A

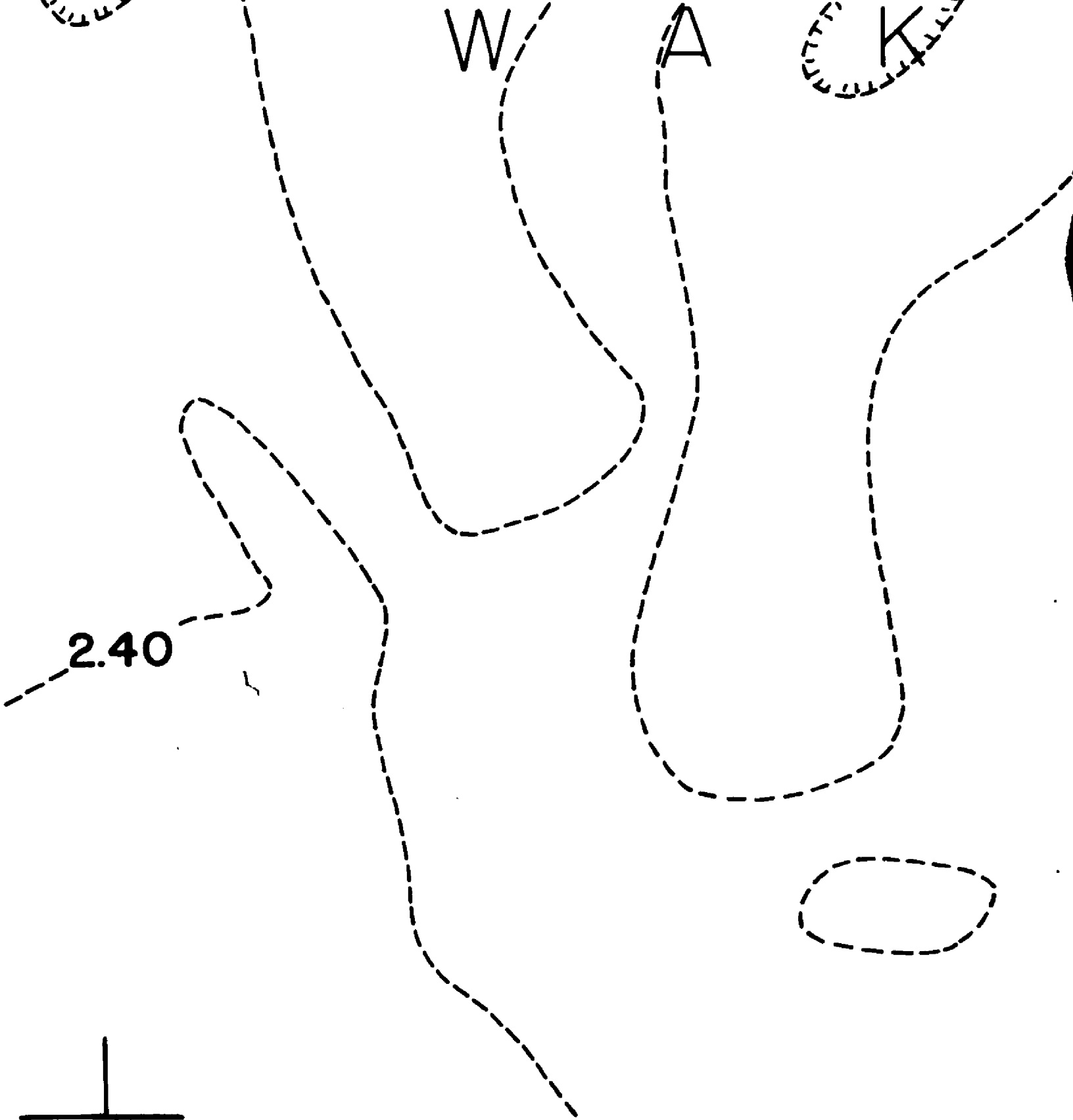
F

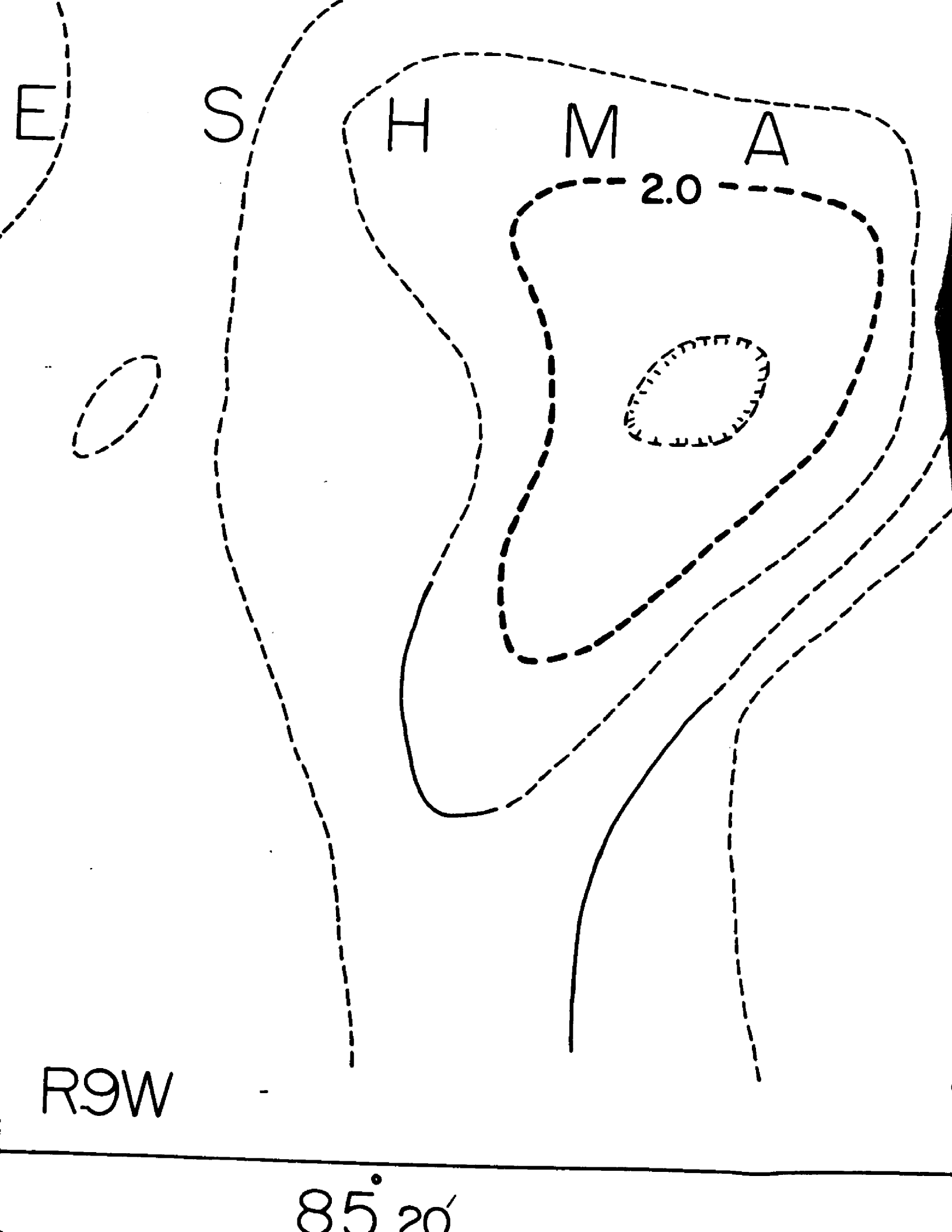


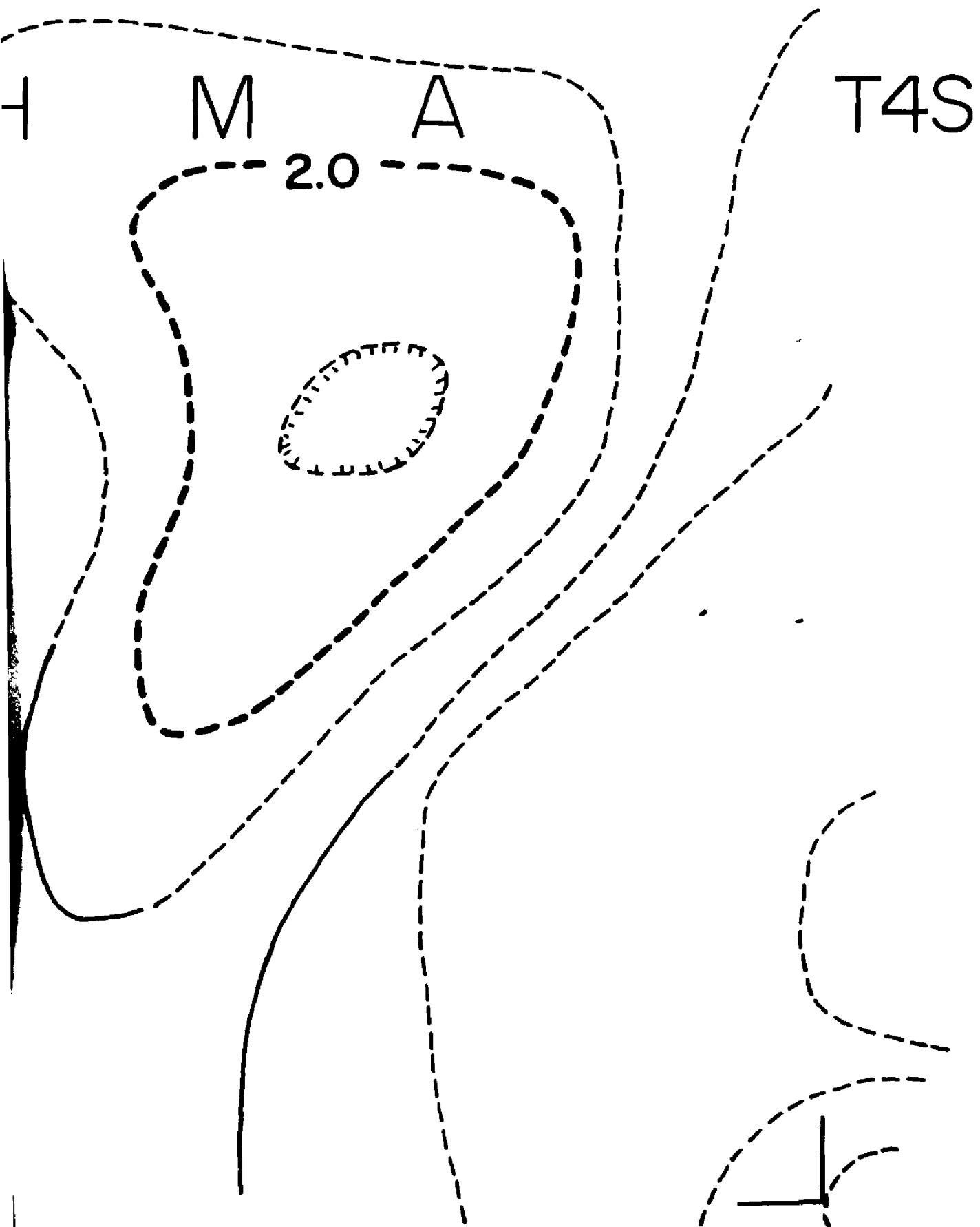


30'

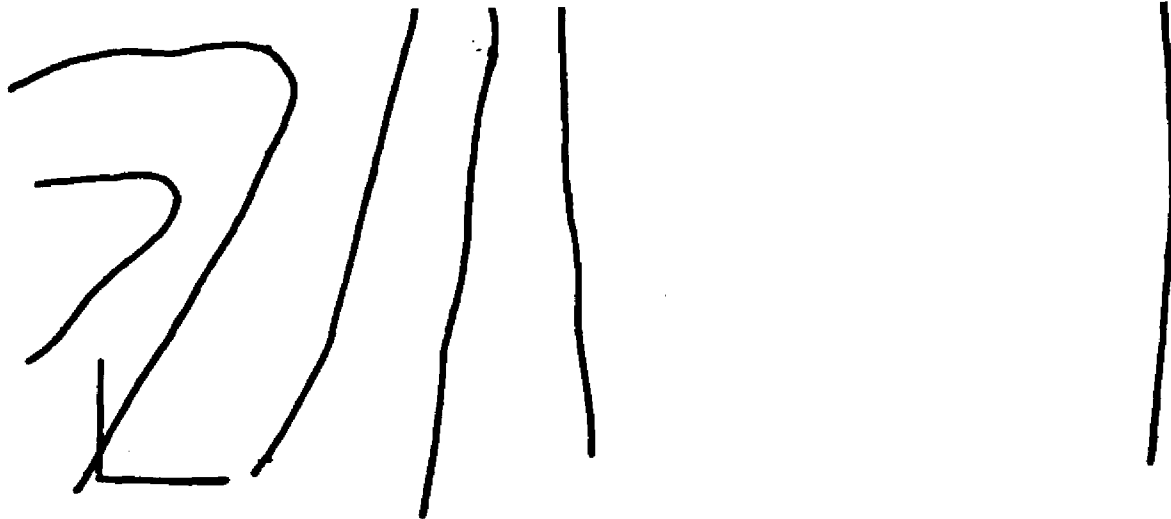




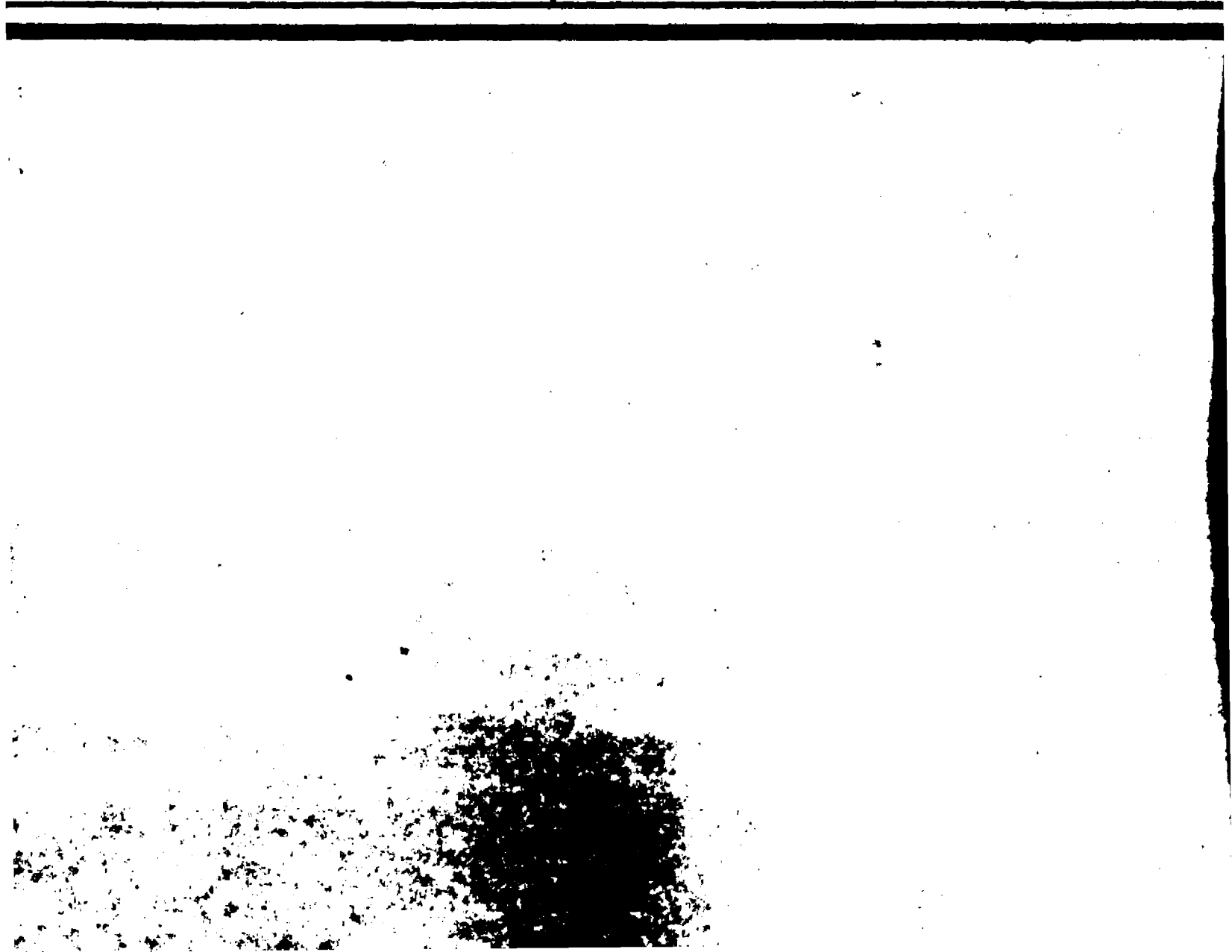


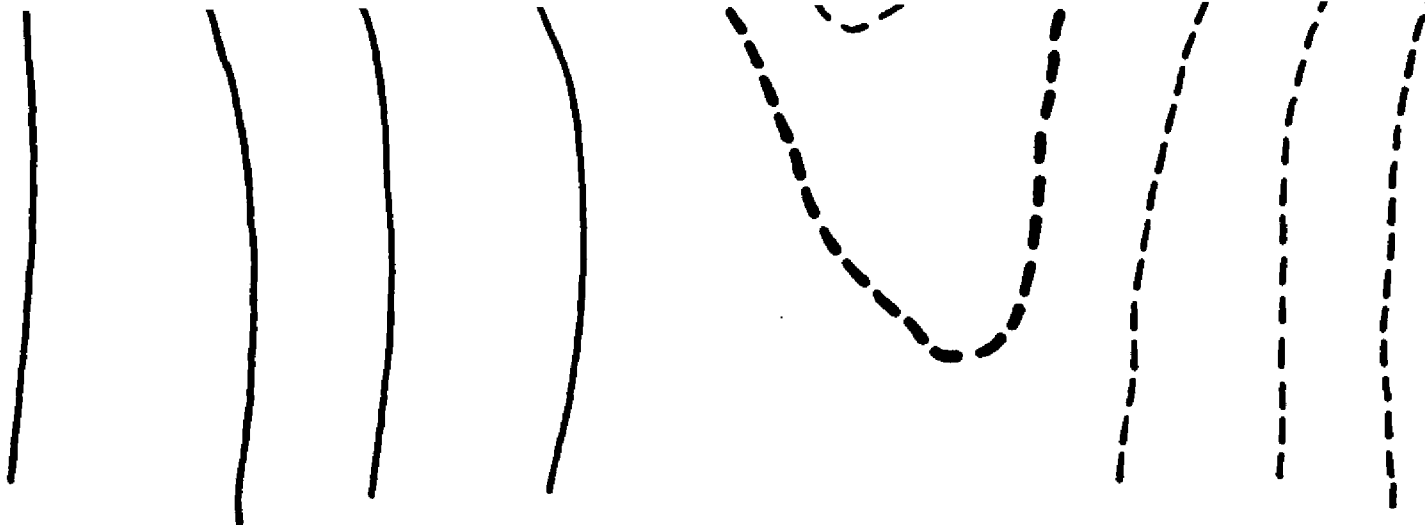


42



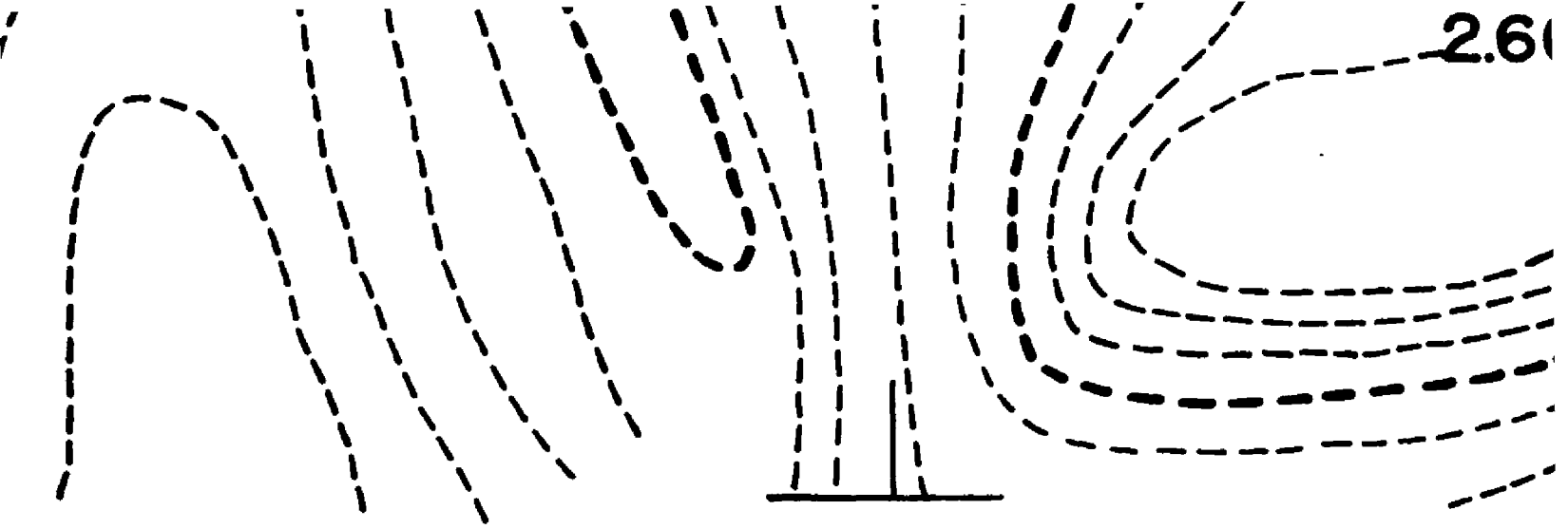
45





R12W

PL



LATE 4a

BEDROCK

SOUTHERN HALF

SCAL



RIIW

35

CK TOPOGRAPHY RESI

HALF OF KALAMAZOO COUNTY

SCALE 1 : 24000



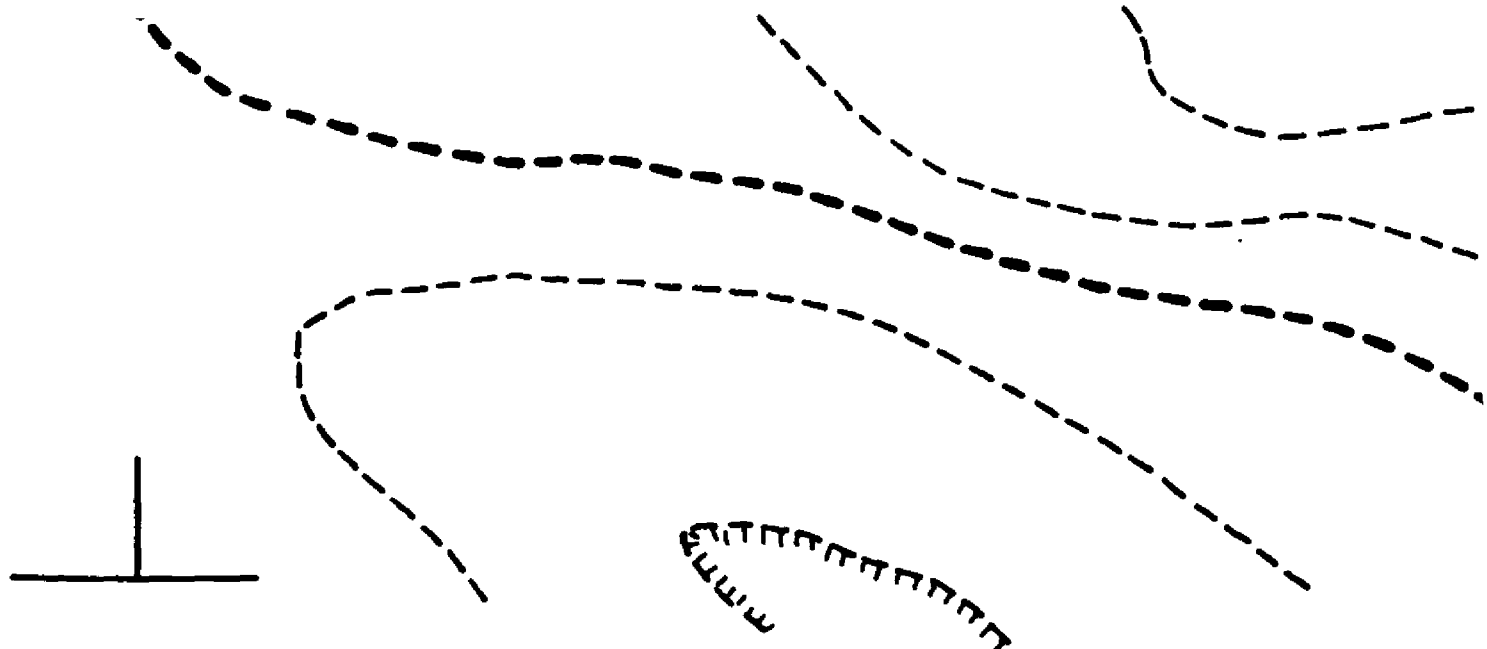
35

RESIDUAL BOUGUER

NTY

CONTOUR IN

DENSIT COM

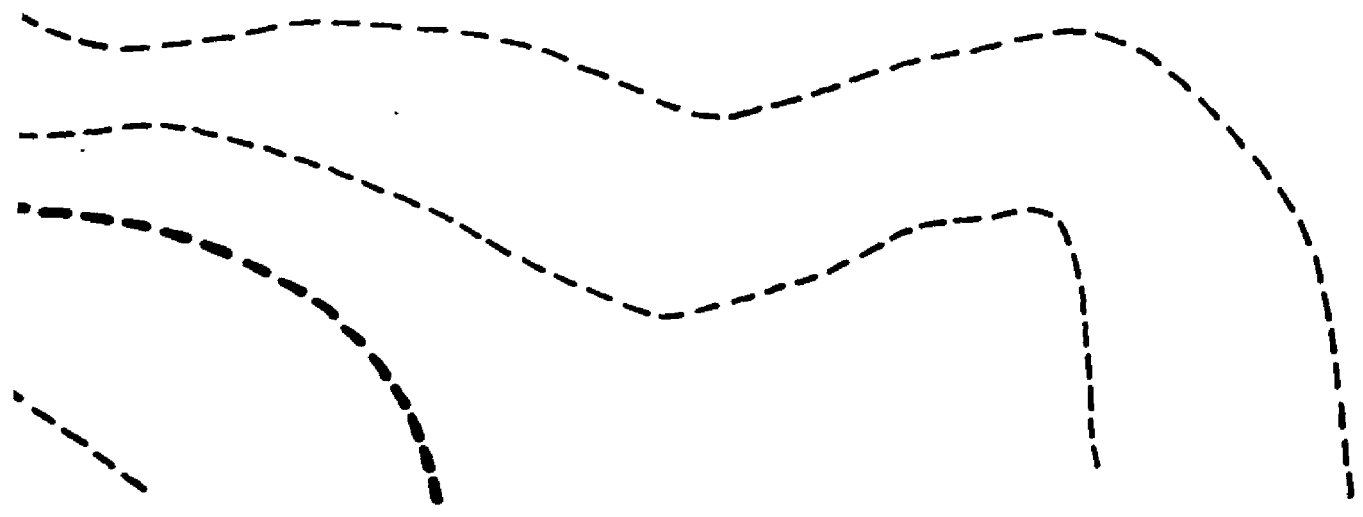


30'

R GRAVITY ANOMALY

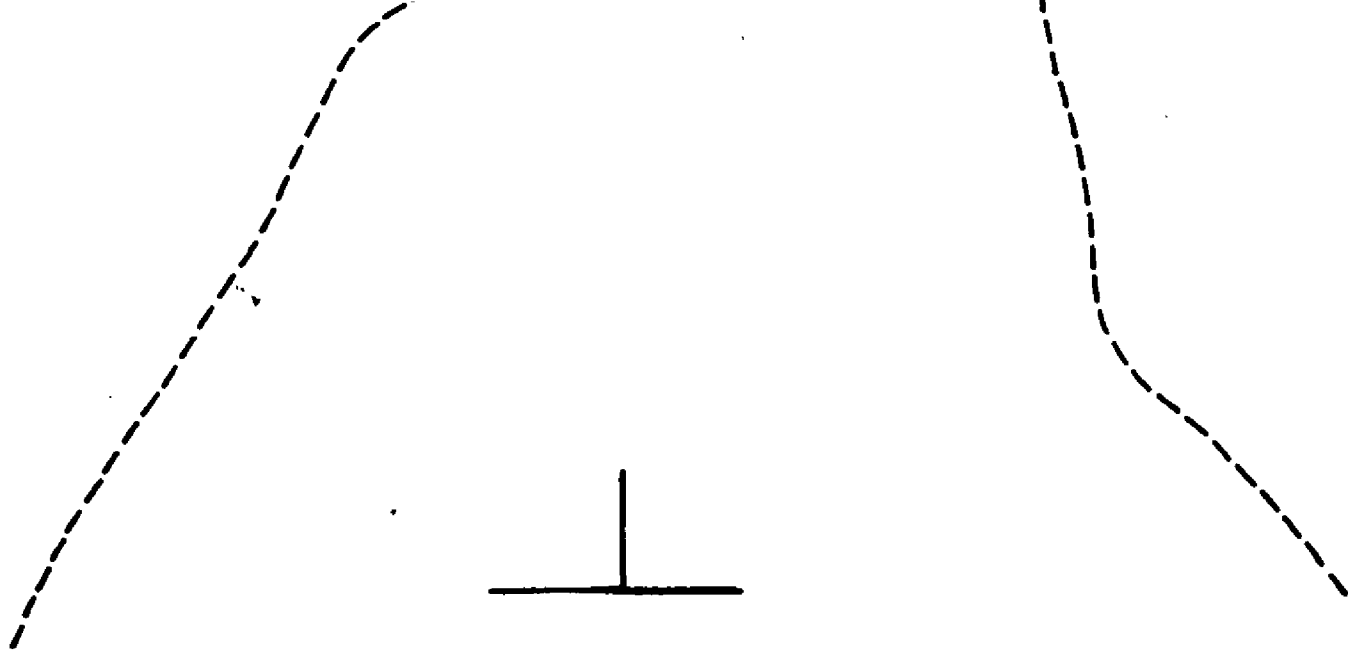
OUR INTERVAL, 0.20 MGALS

IT CONTRAST 0.40 GM/CC



RIOW

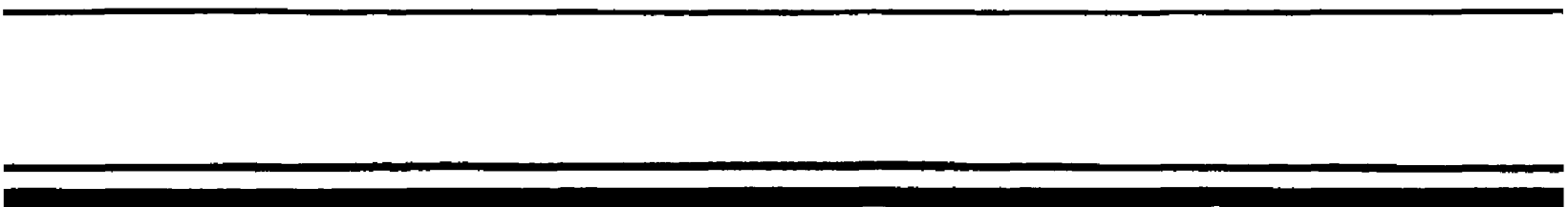
VIALY MAP

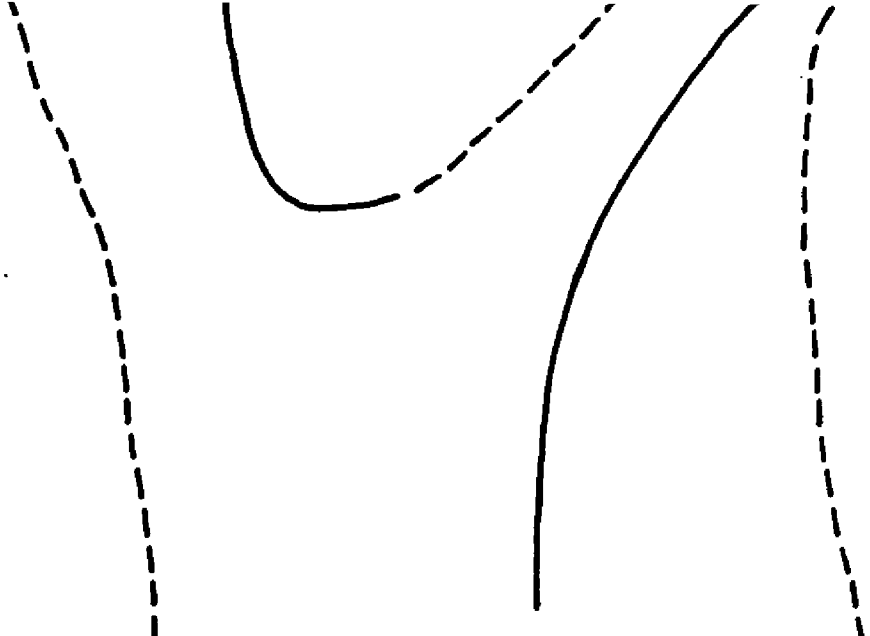


25



R9W

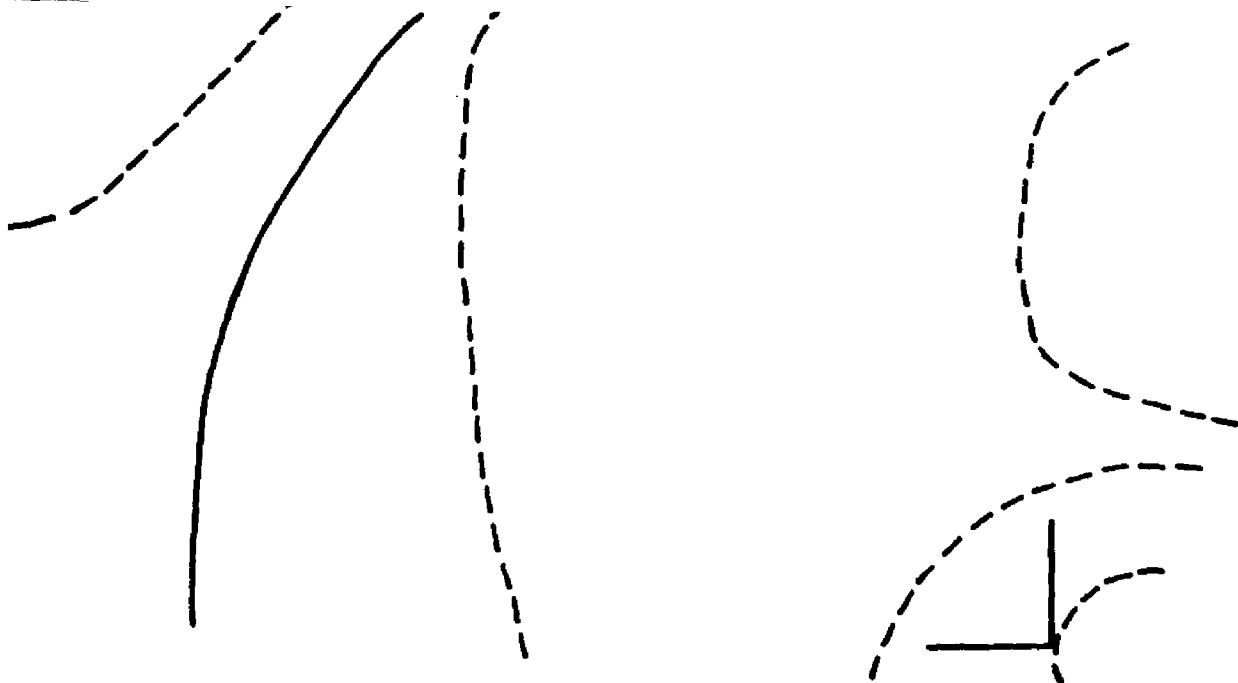




R9W

$85^{\circ} 20'$

05-
42



45

42
25



TIS

A

45

R12W

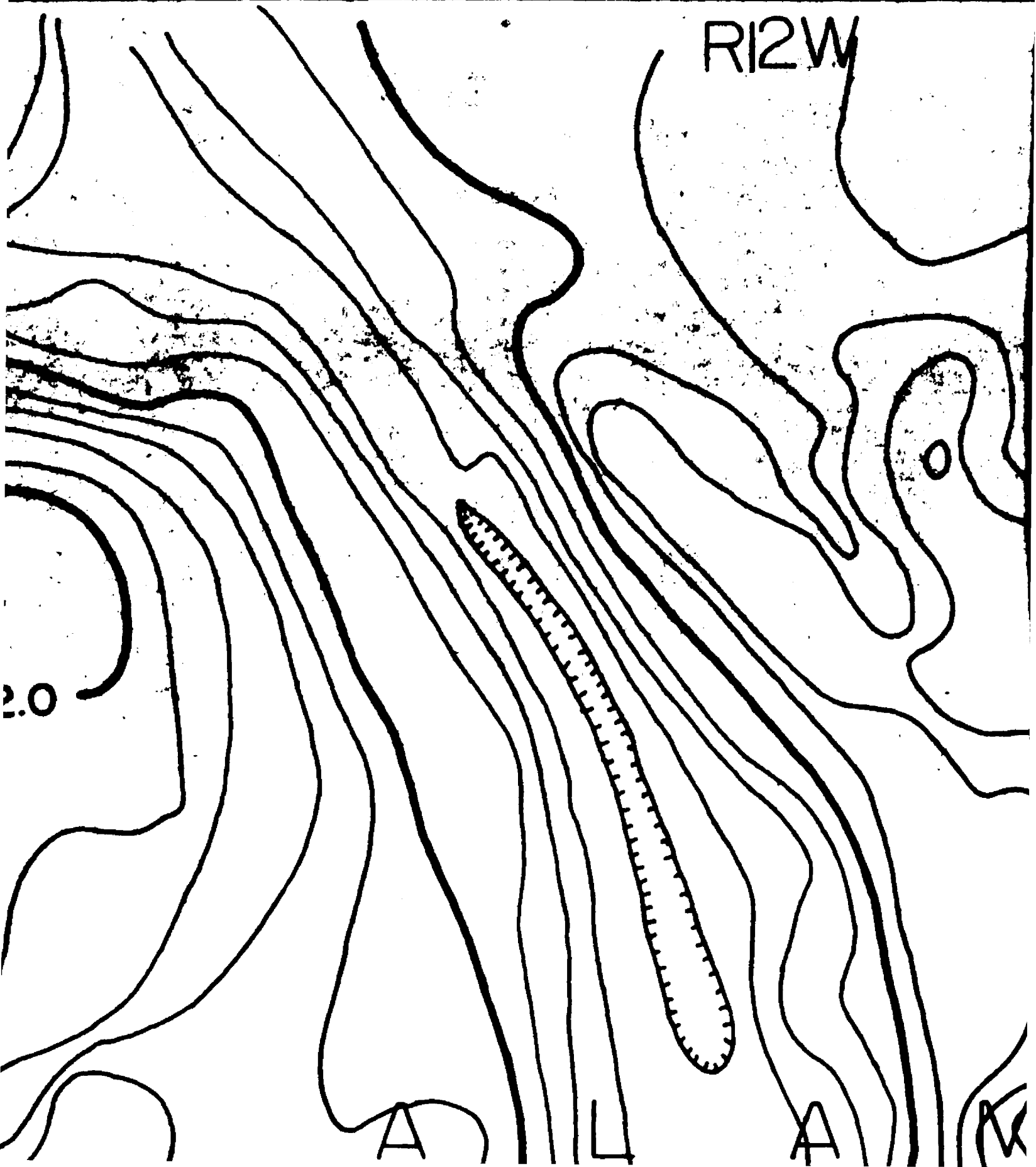
2.0

A

L

A

R



40'

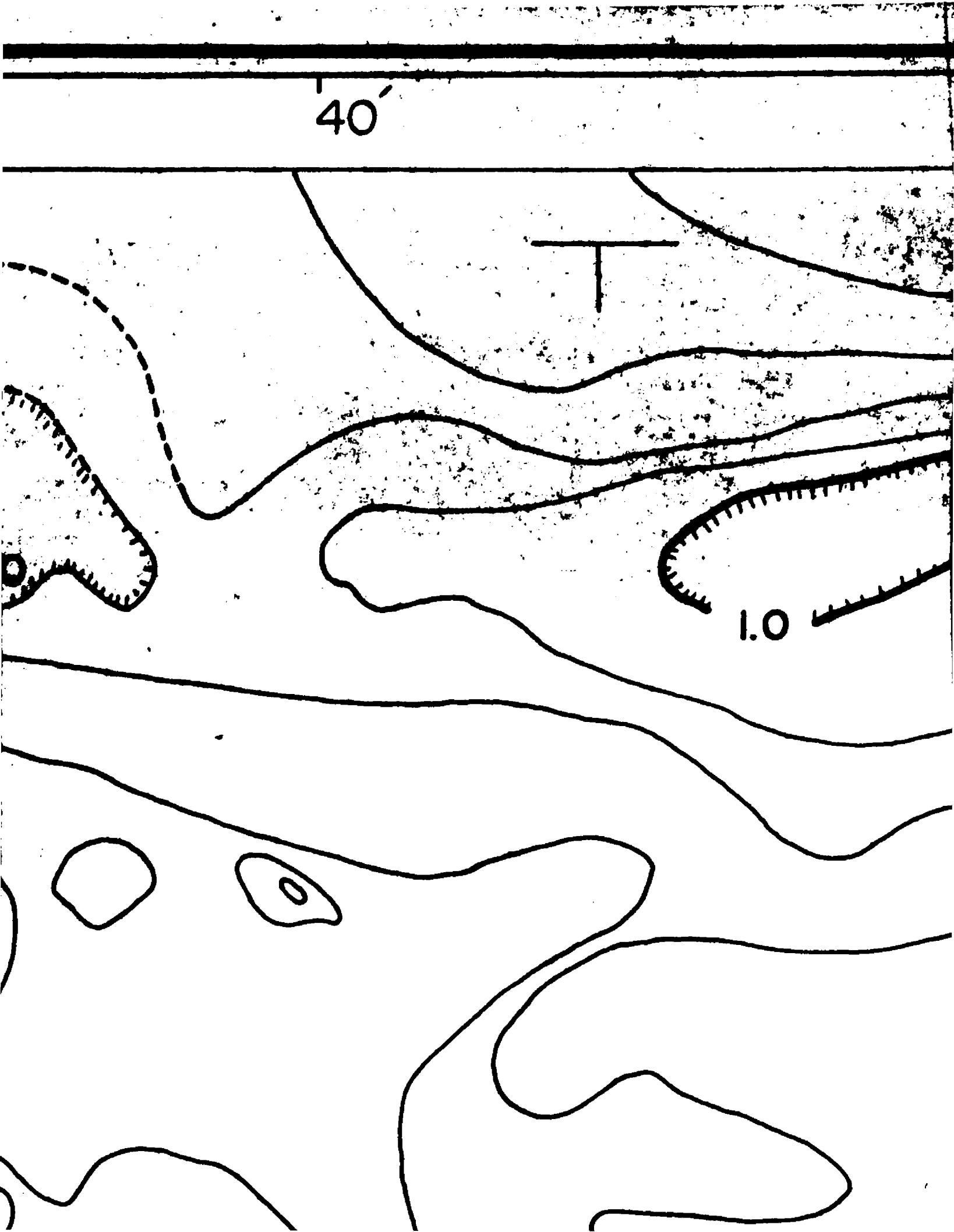
12W

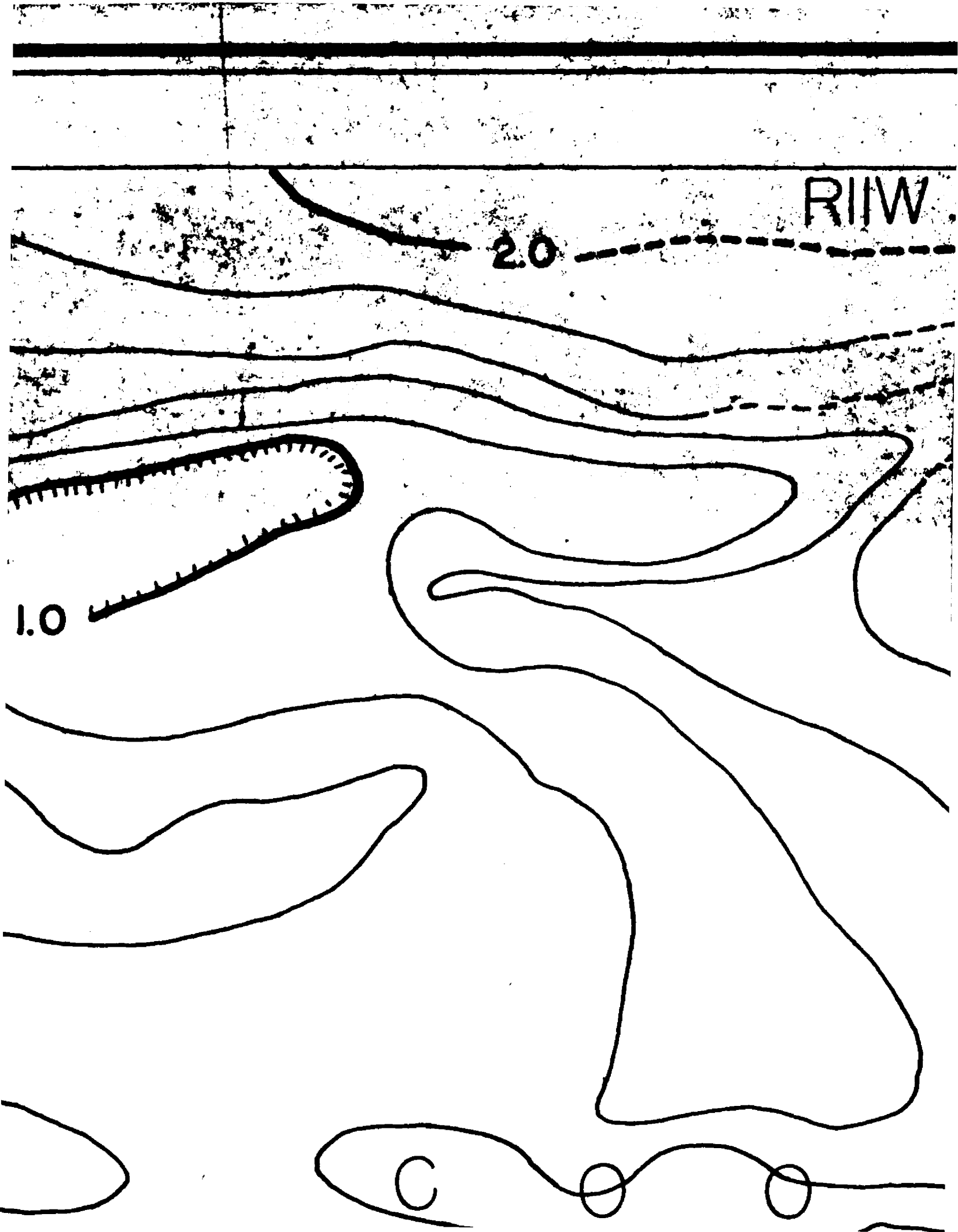


40'

T

1.0



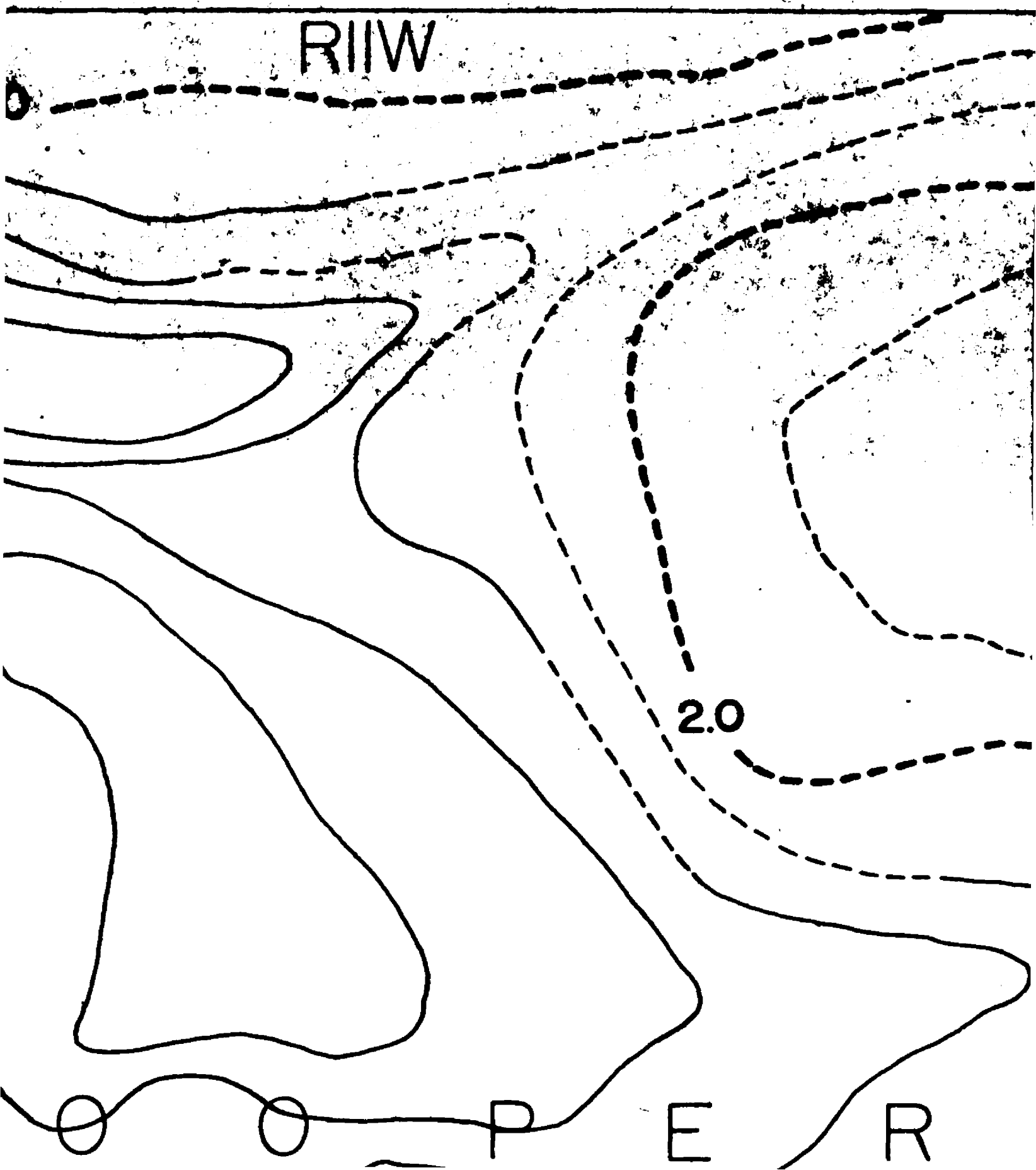


35

RIIW

2.0

O O P E R

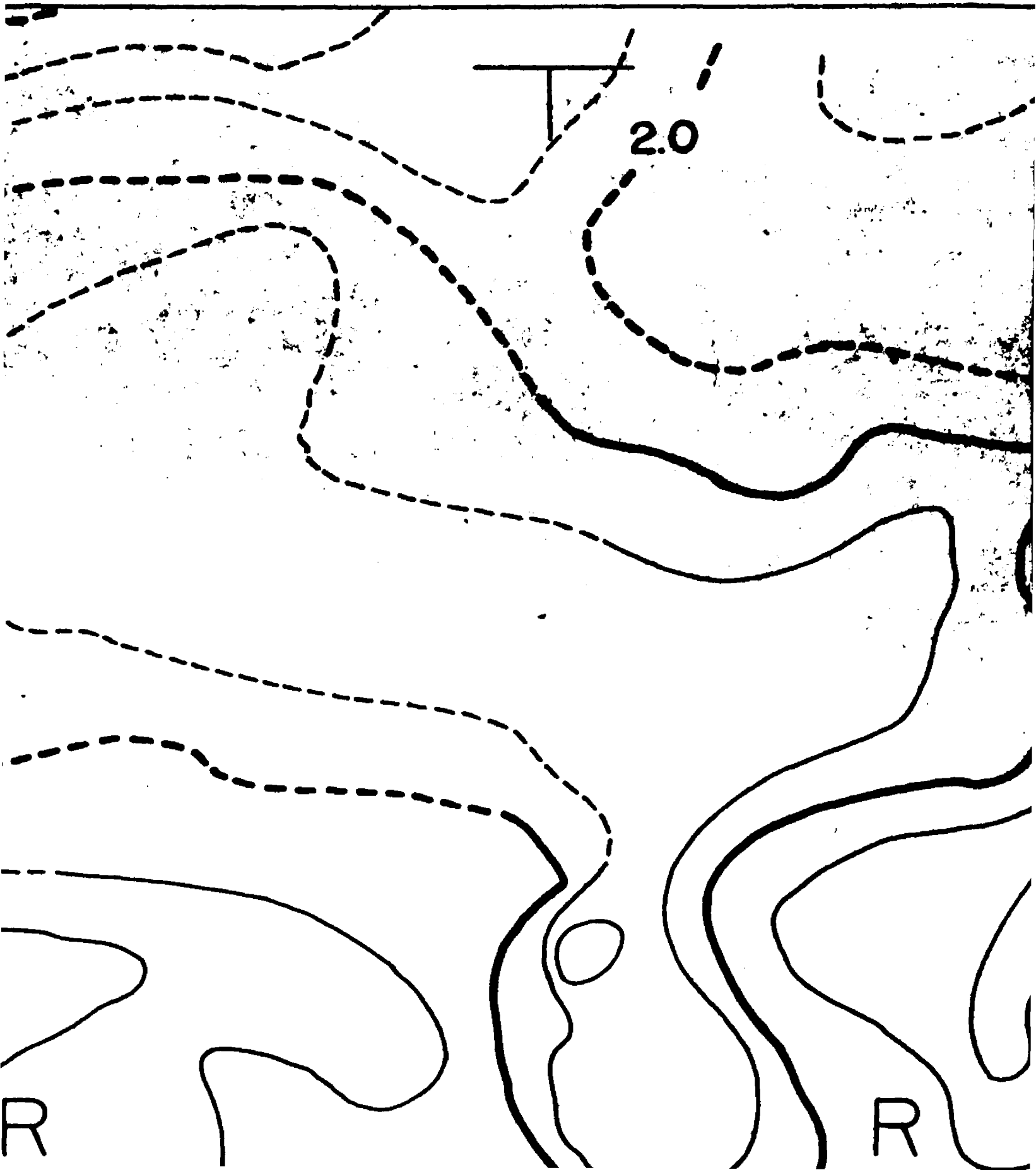


35

RIIW

2.0

O P E R



30'

RIO

2.0

1.40

2.

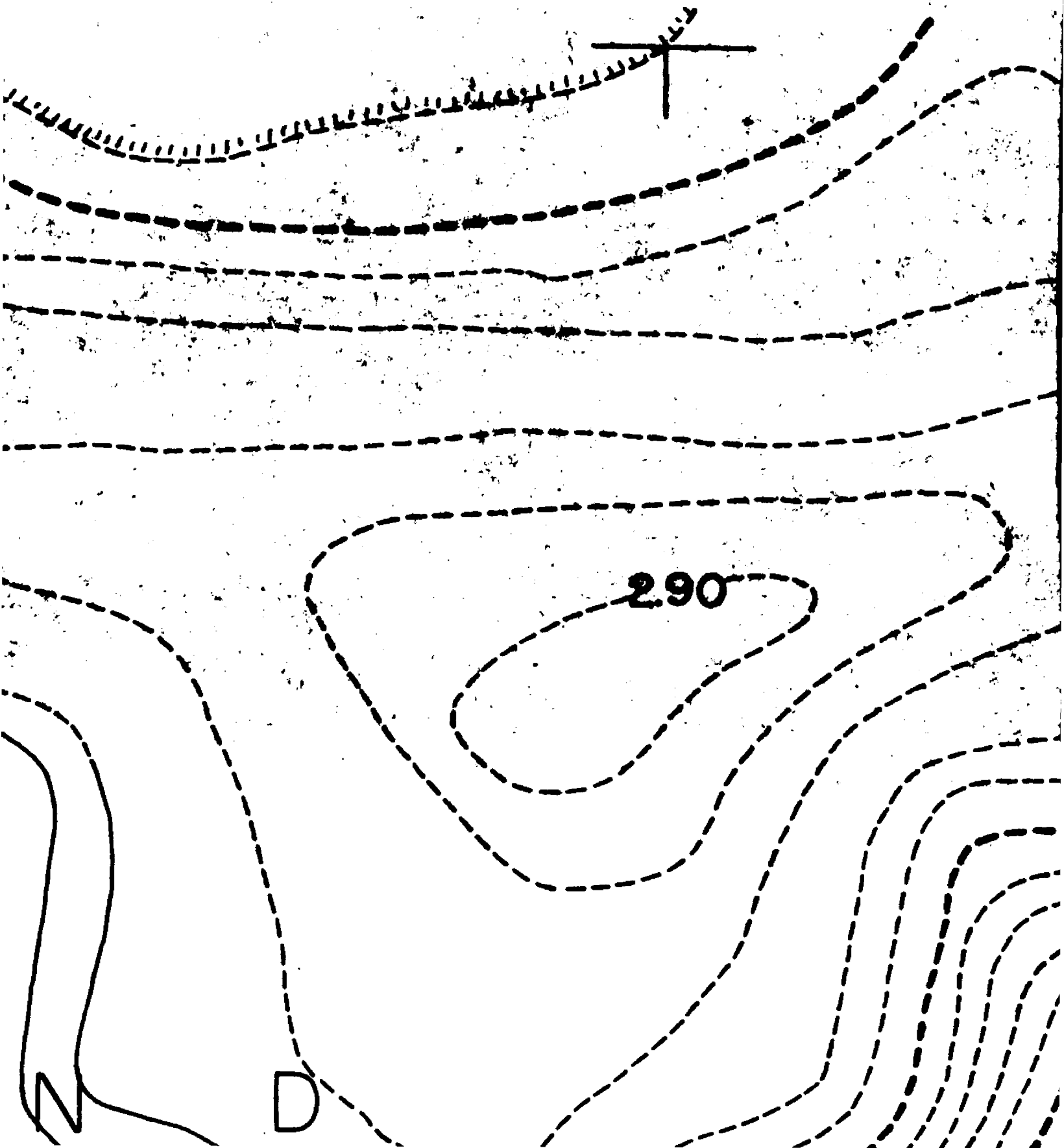
R

I

C

H

25

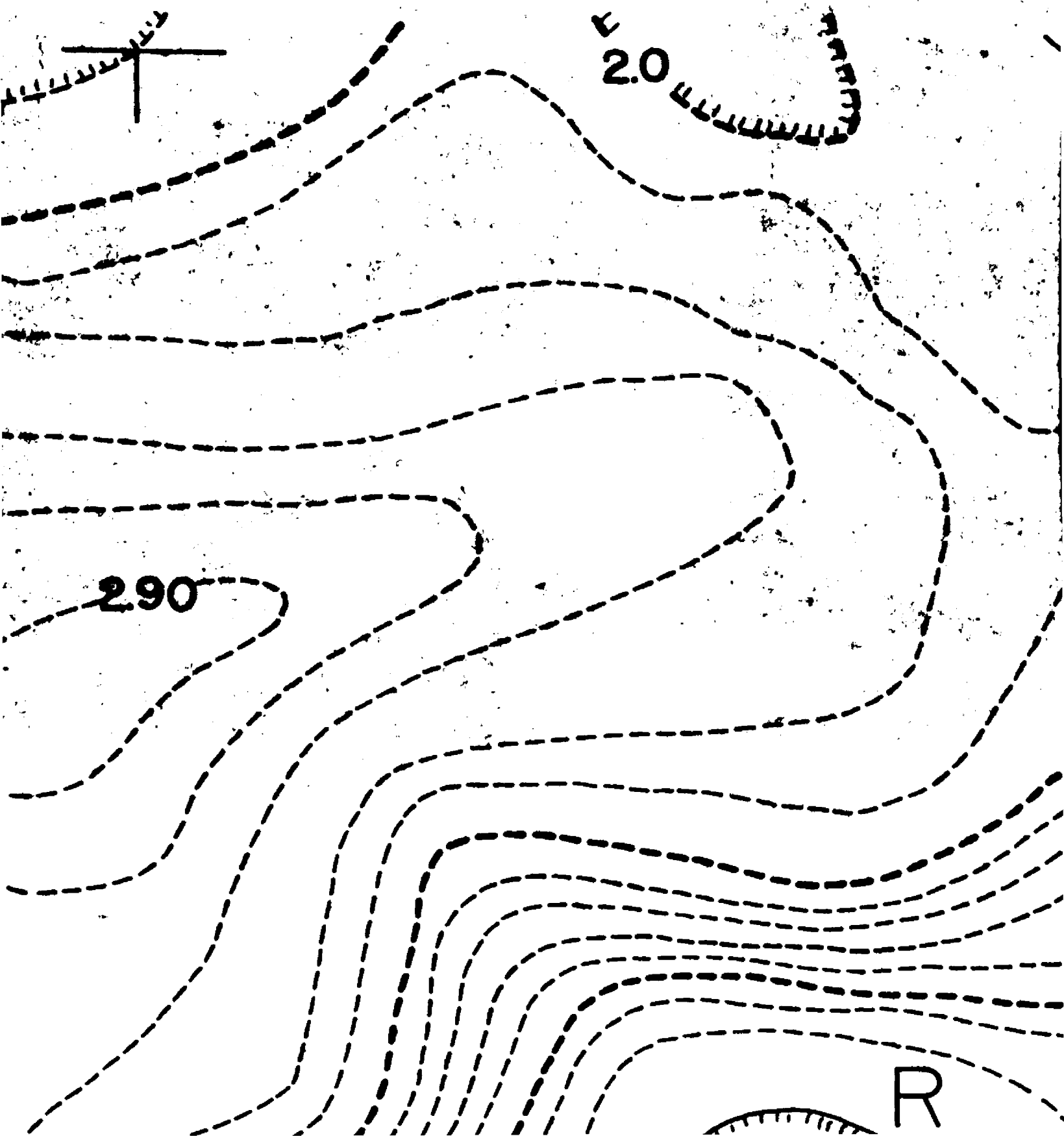


25

2.0

2.90

R



R9W

2.0



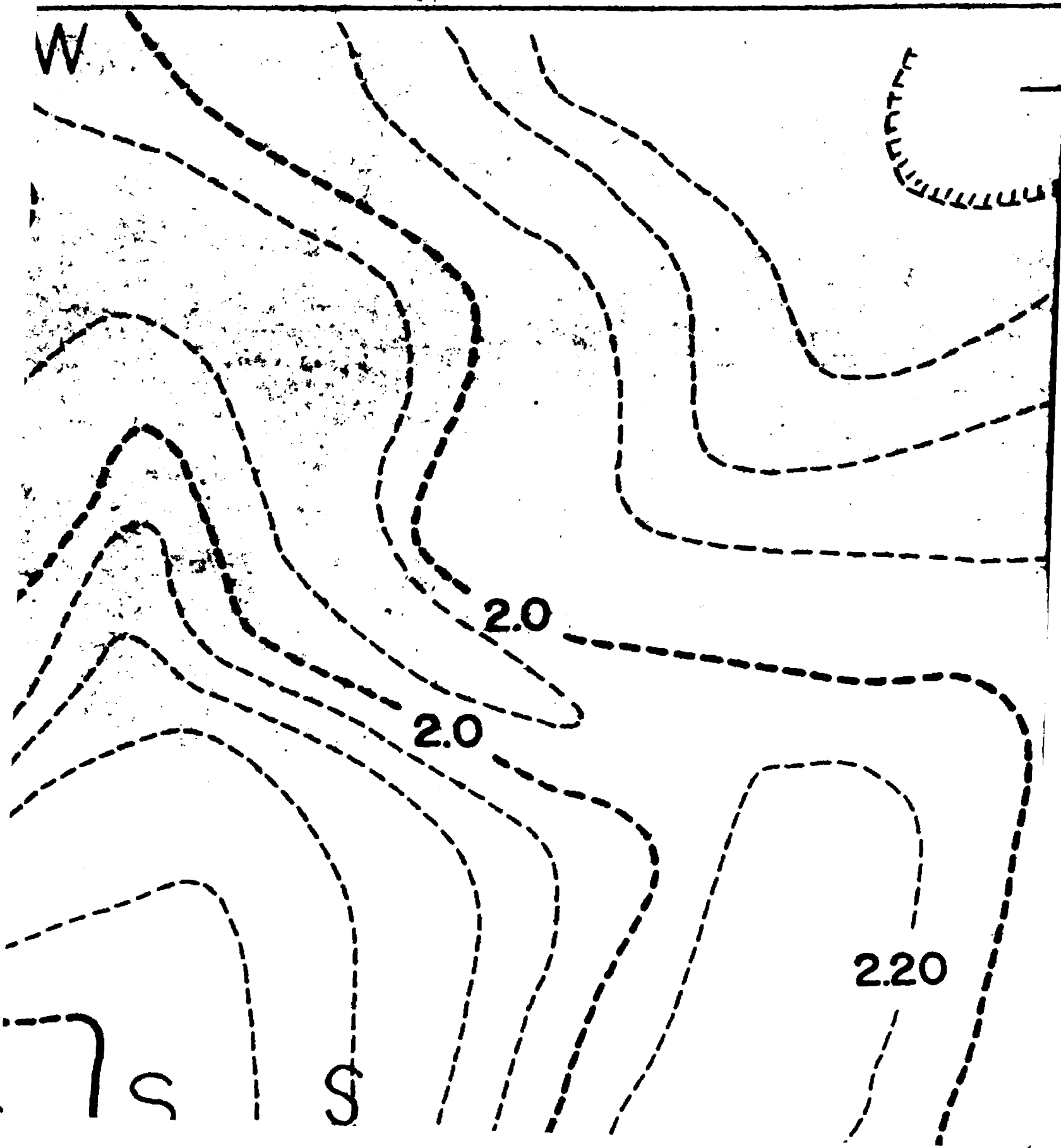
R

O

S

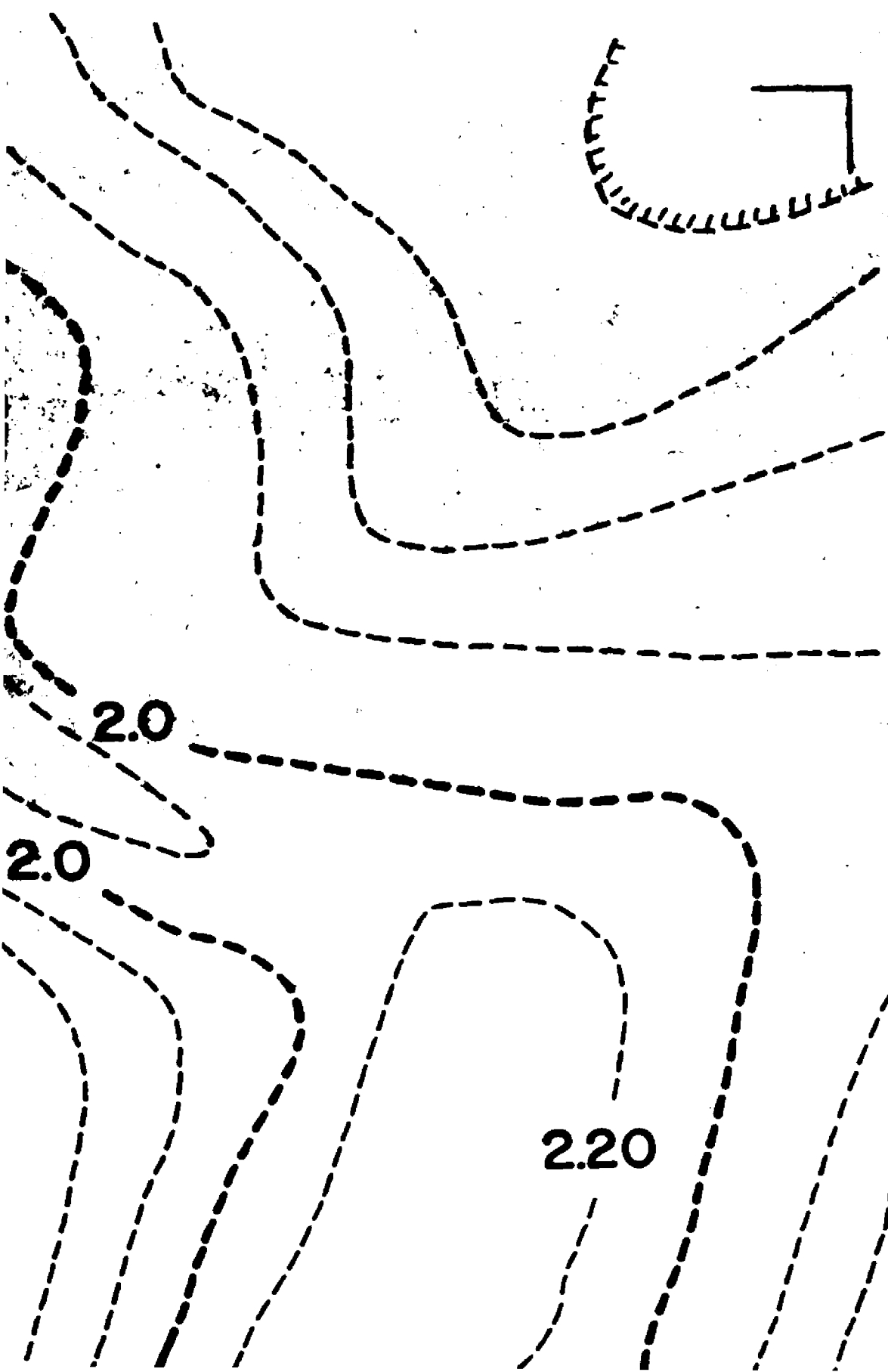
S

85° 20'

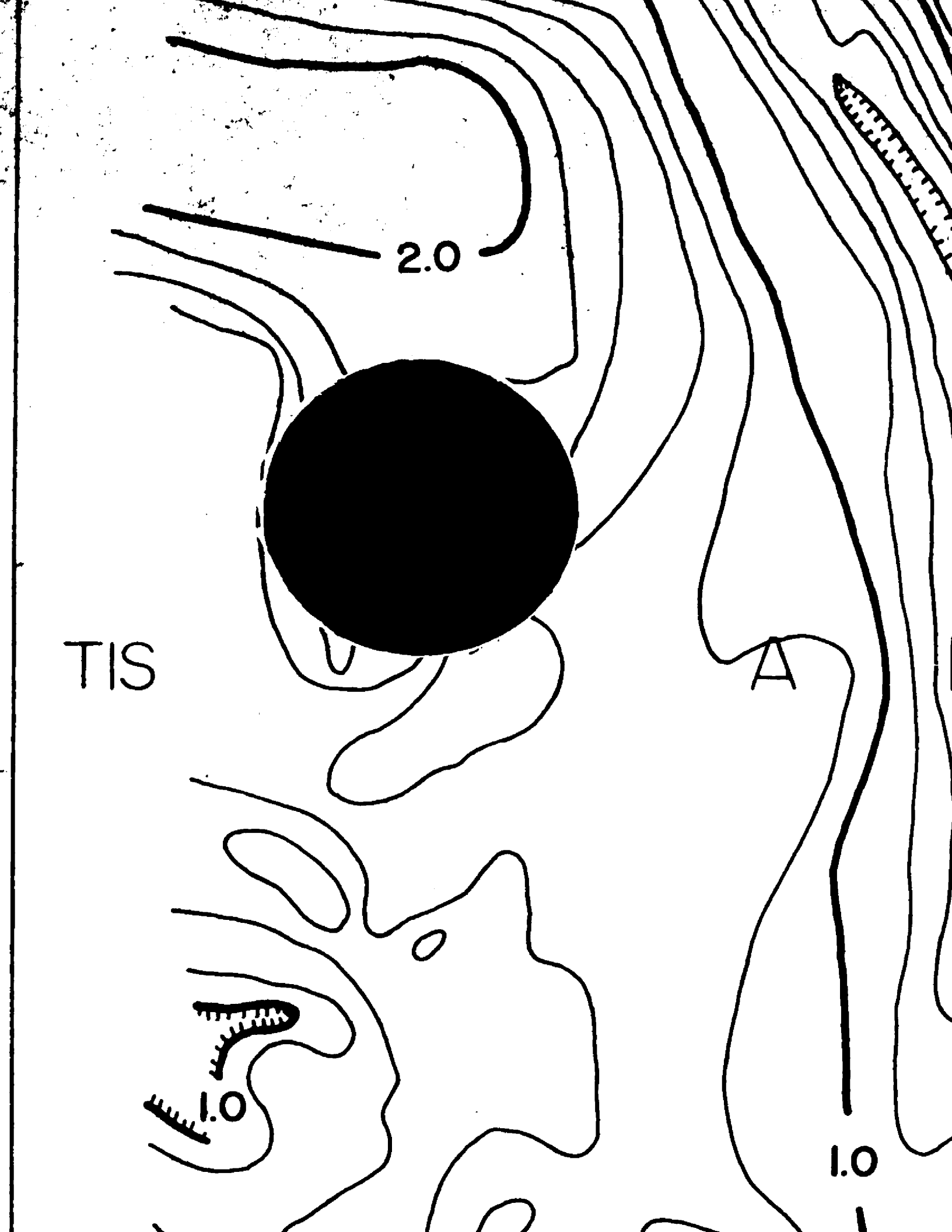


15° 20'

42°
25'

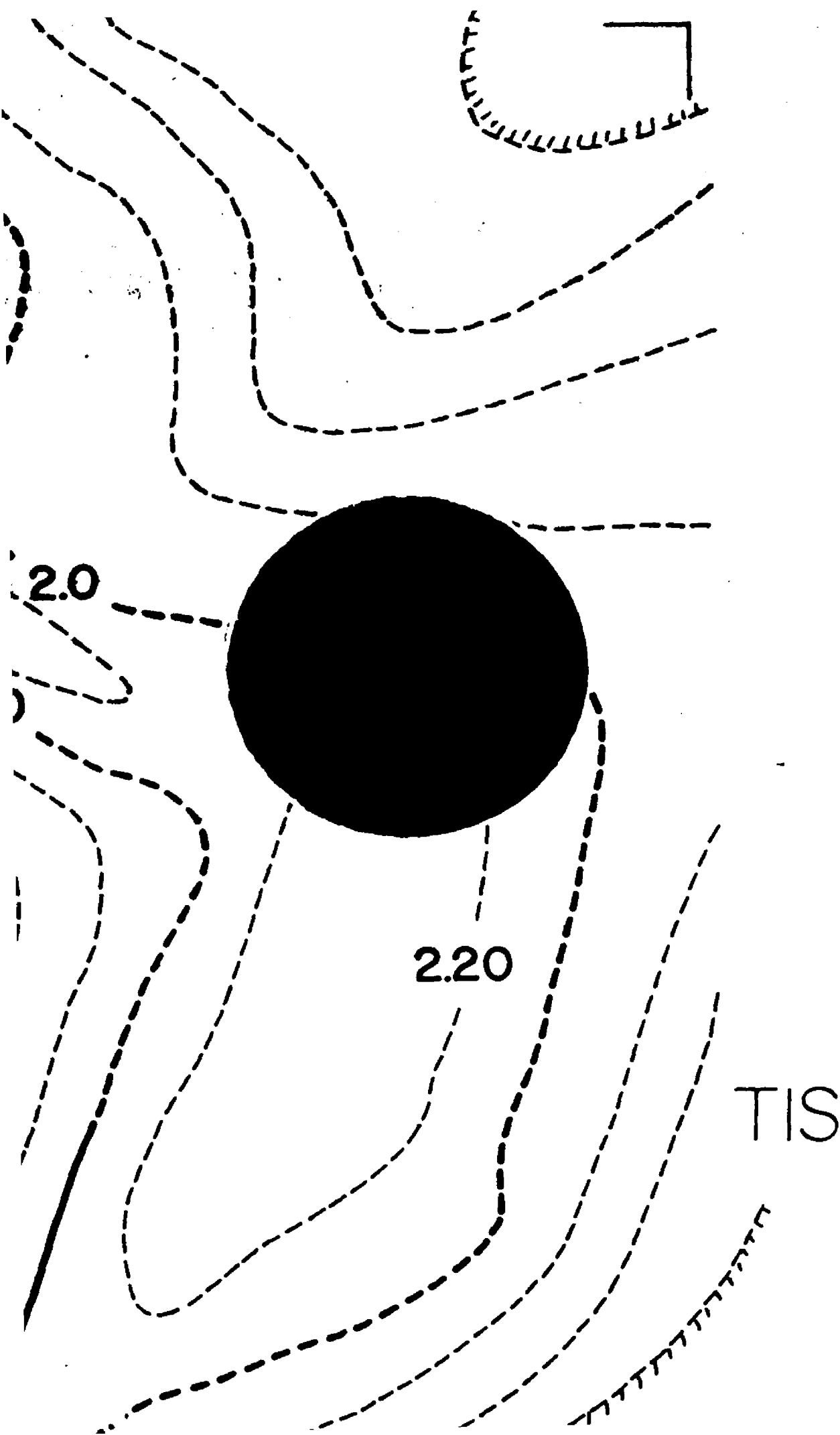


TIS





42
25



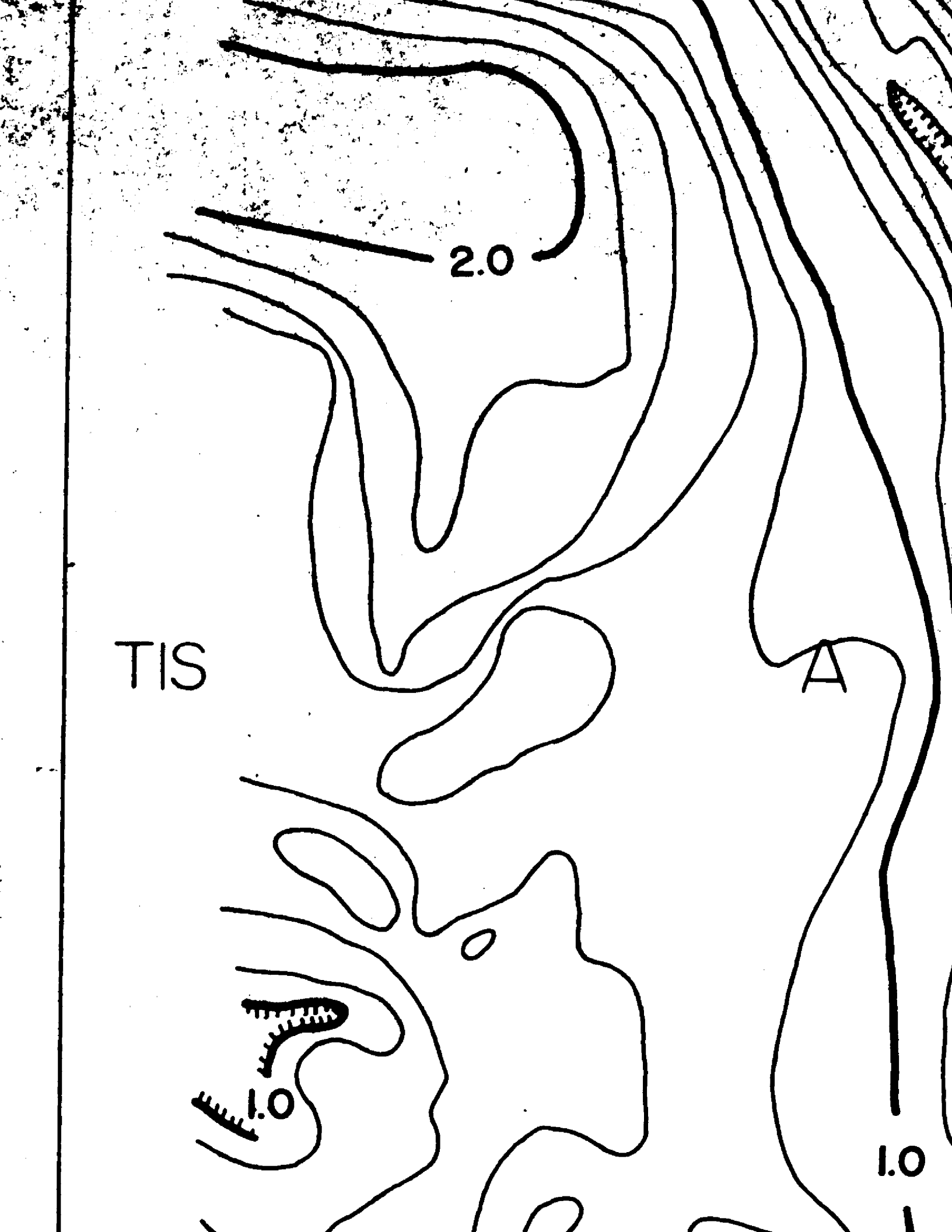
TIS

2.0

A

1.0

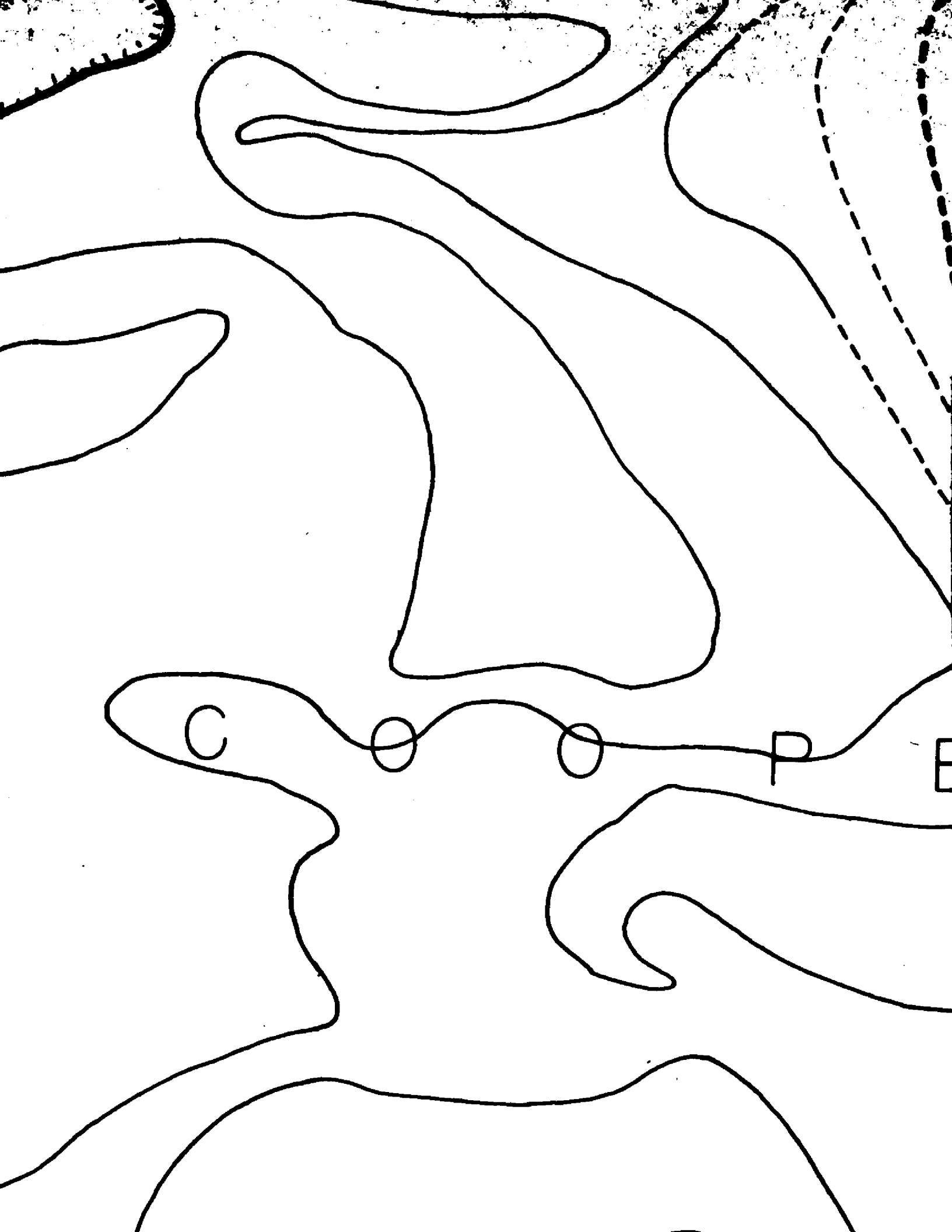
1.0

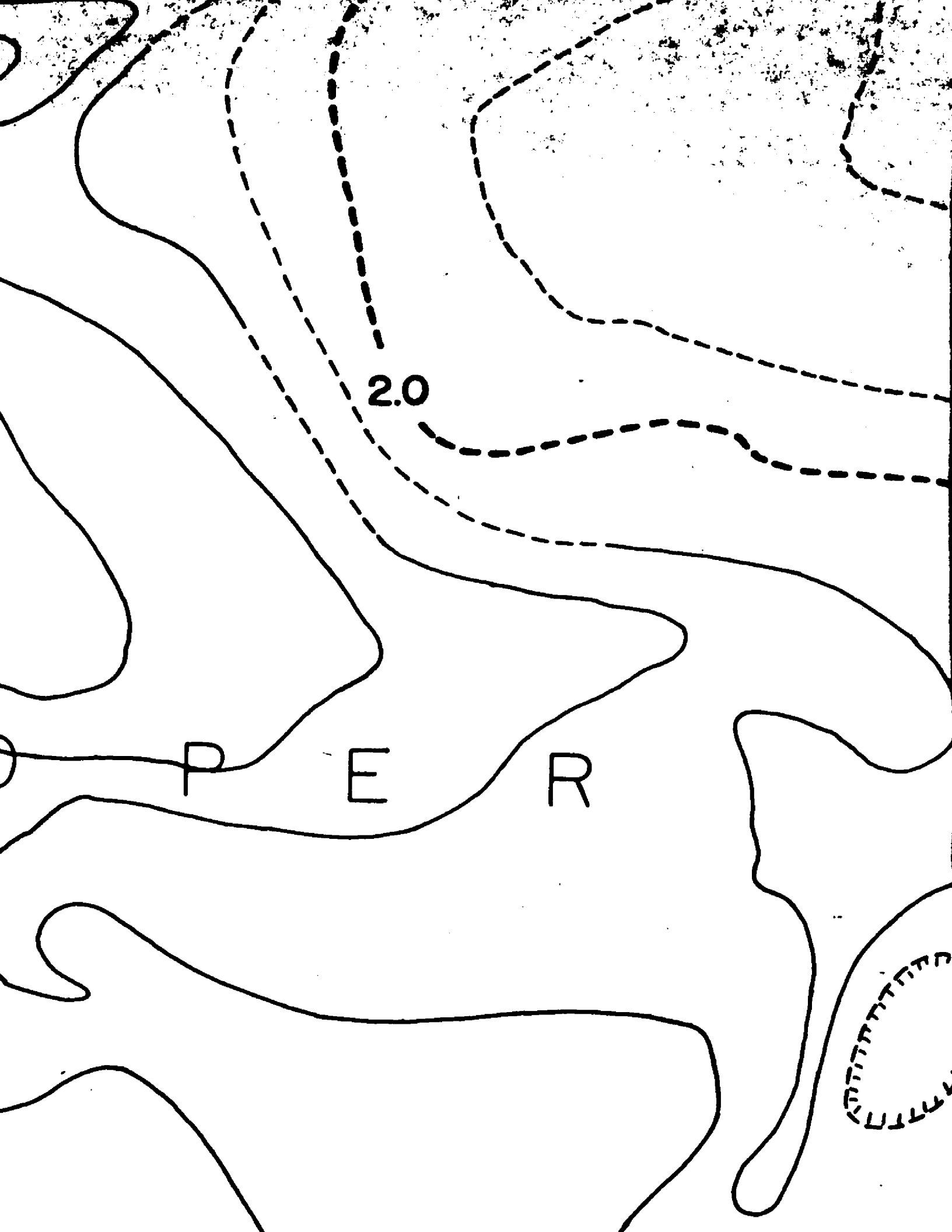












2.0

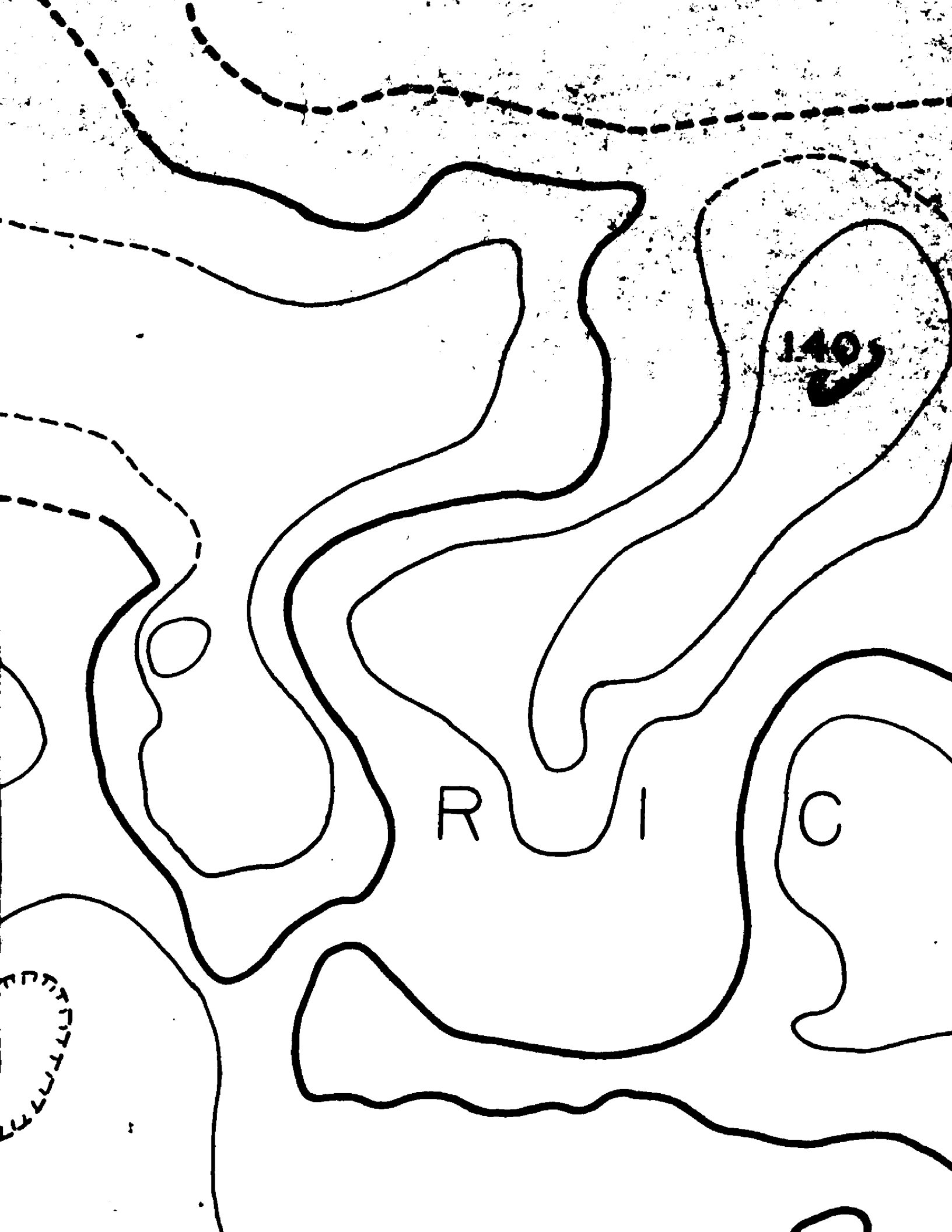
P

E

R

Handwritten scribble or signature in the bottom right corner.



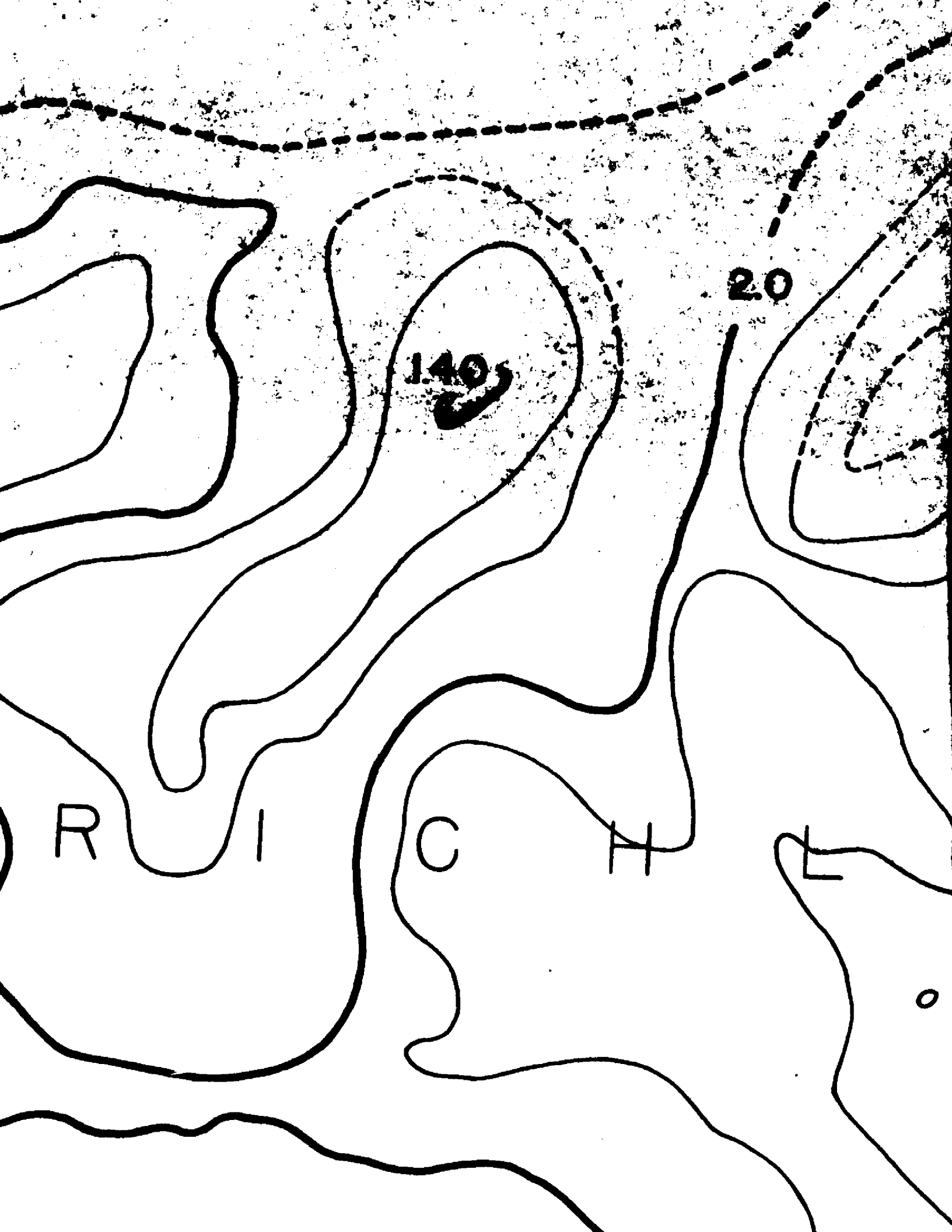


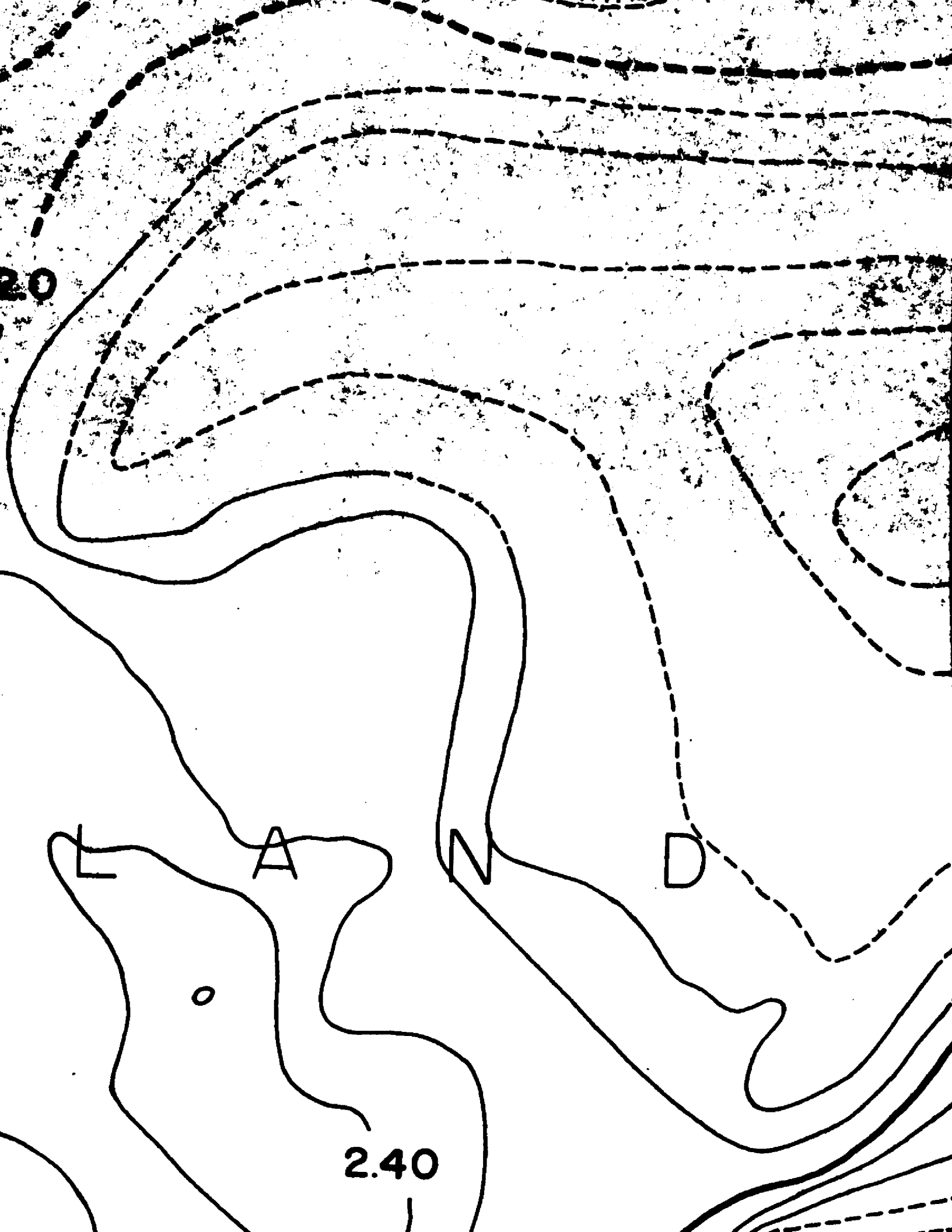
R

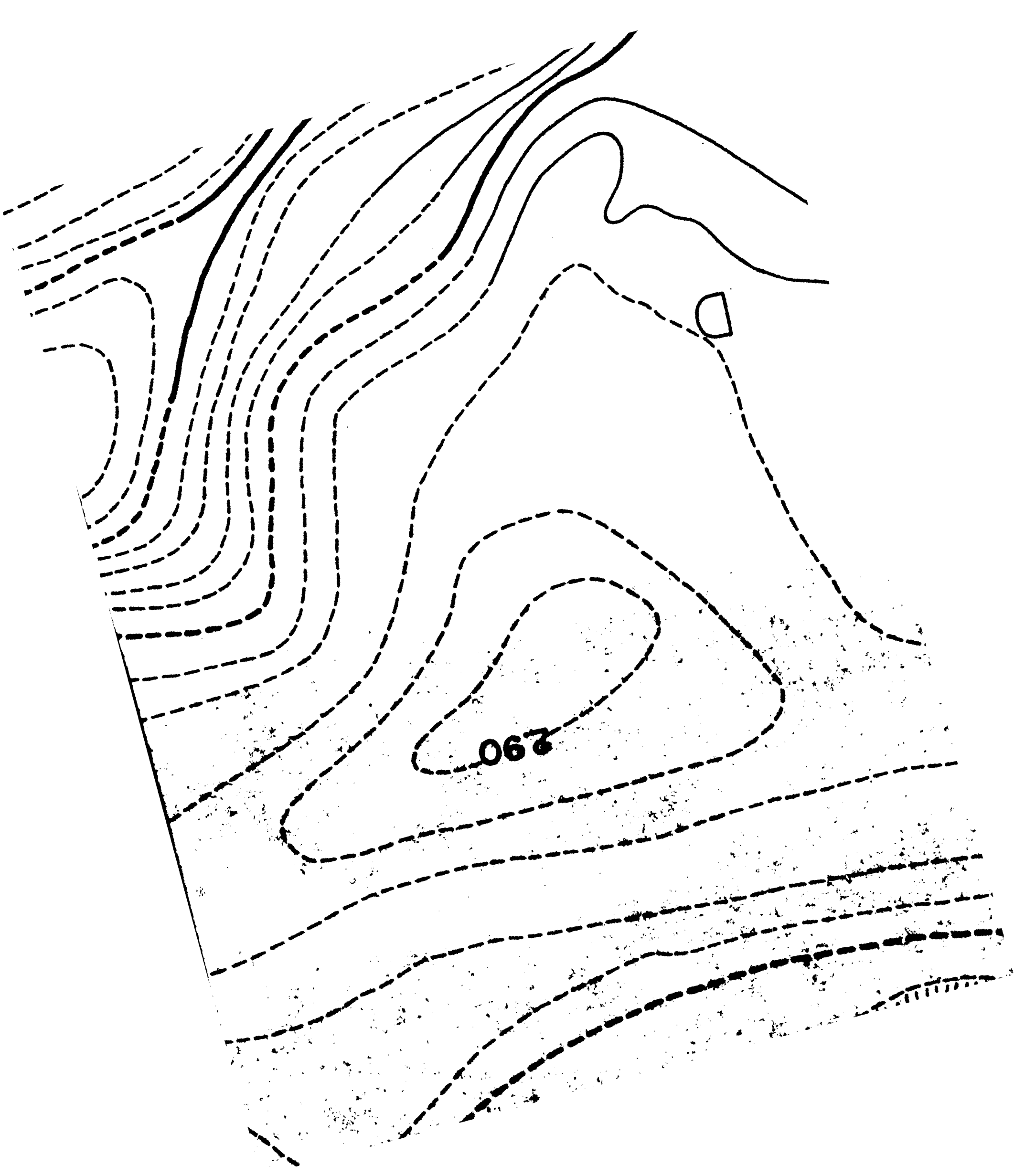
I

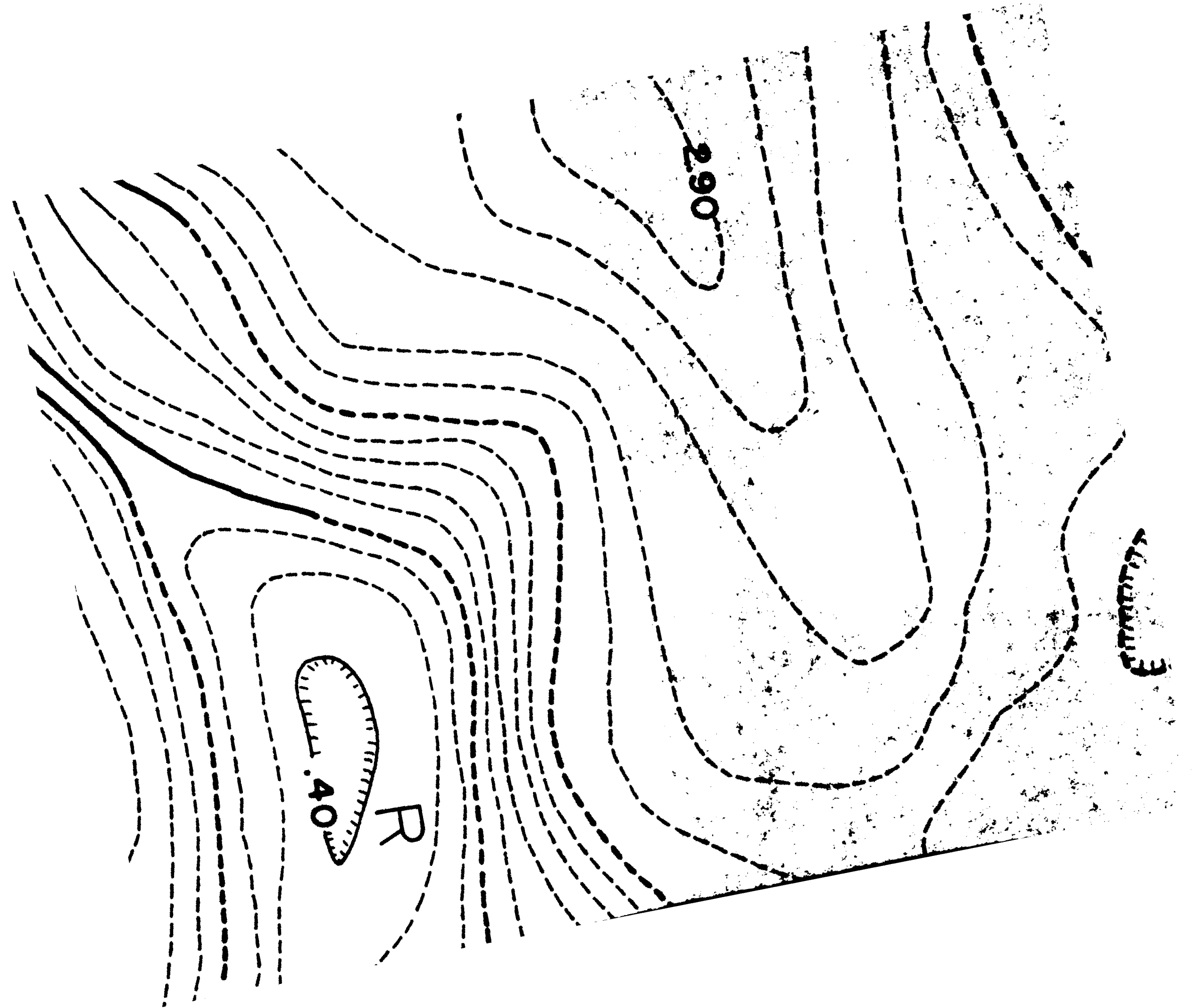
C

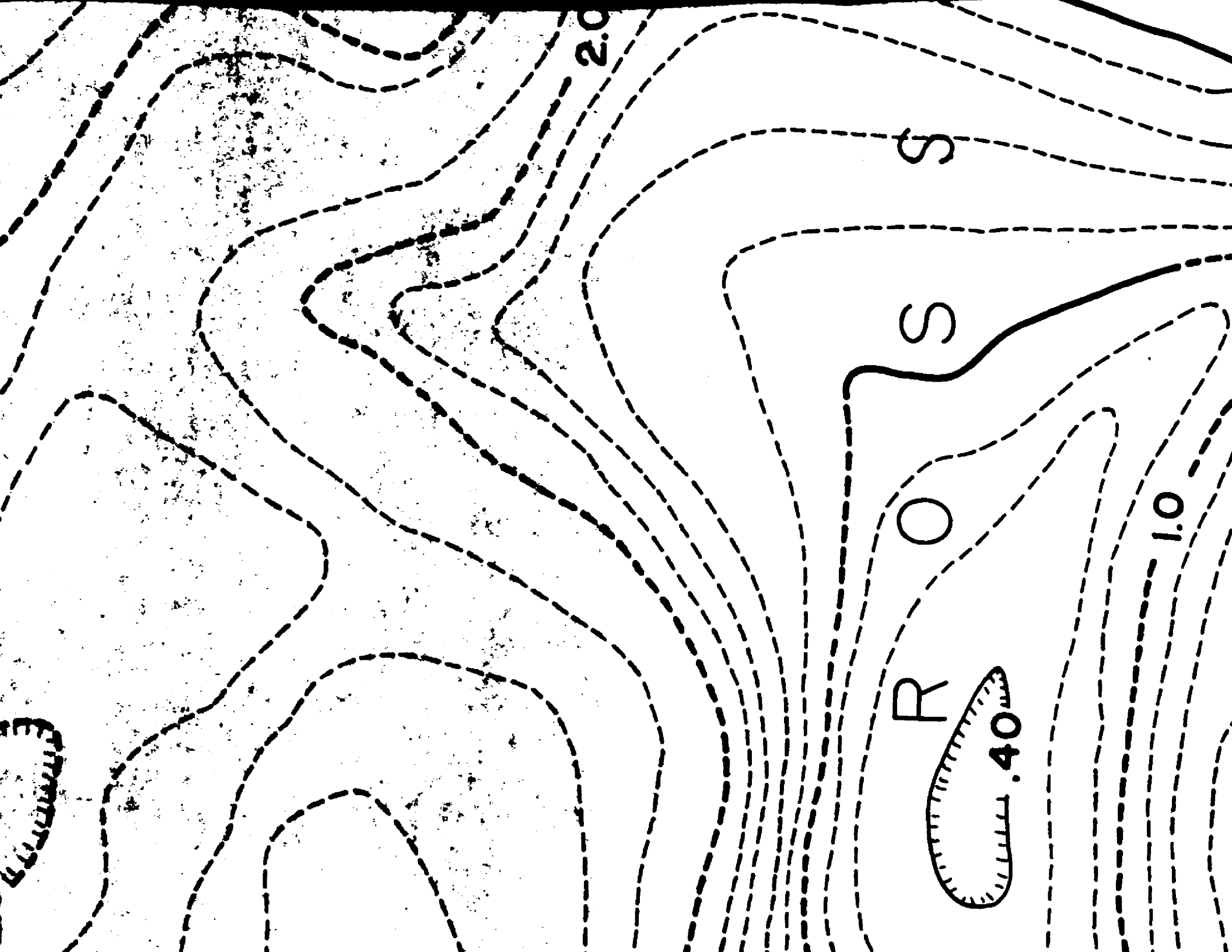
140





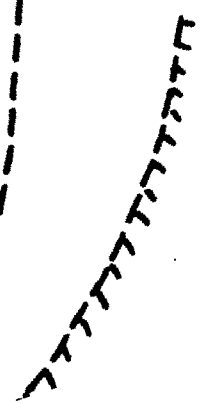
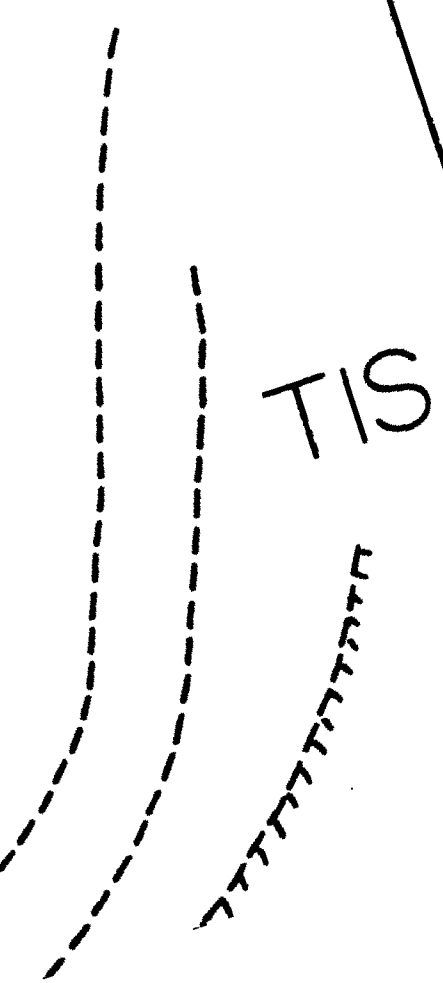
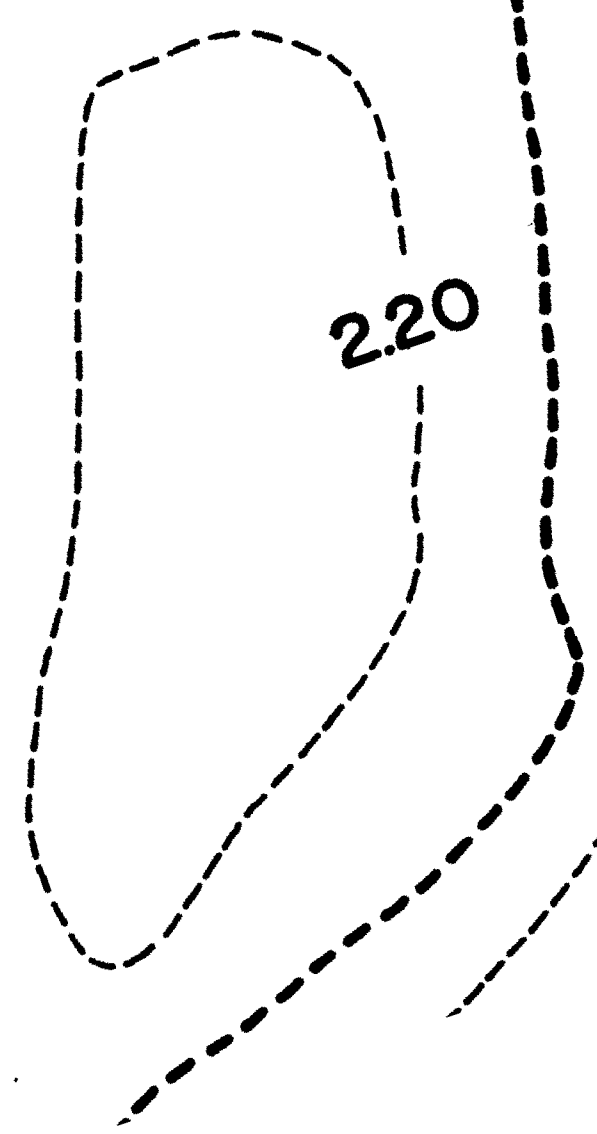
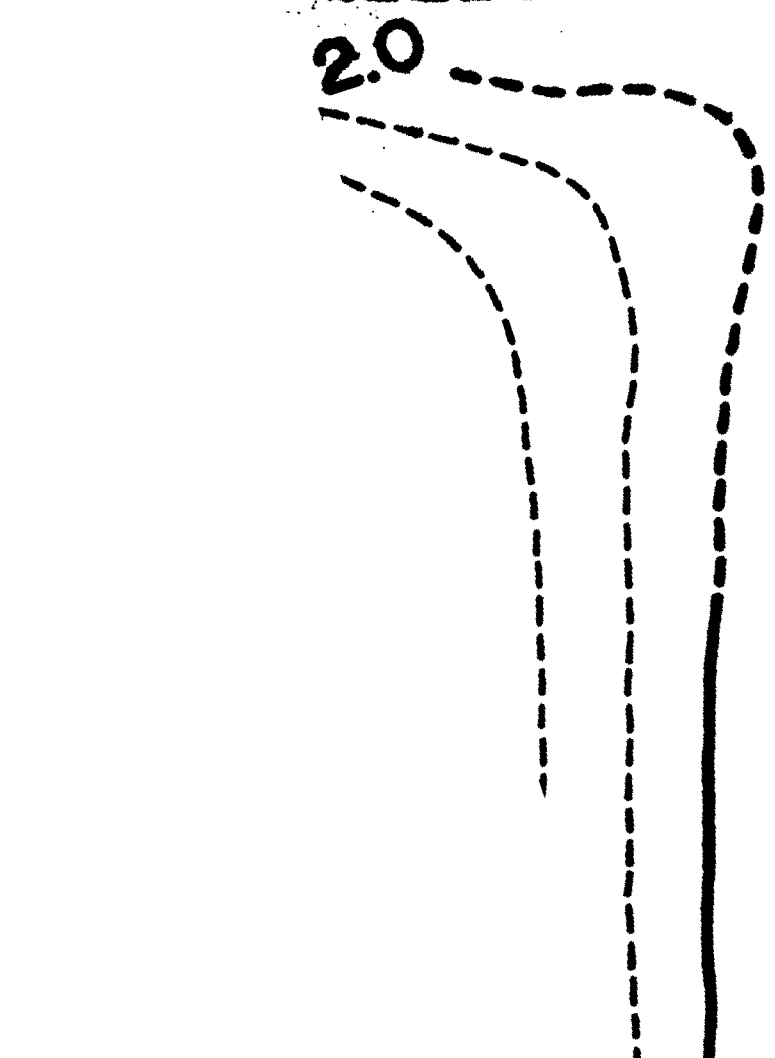
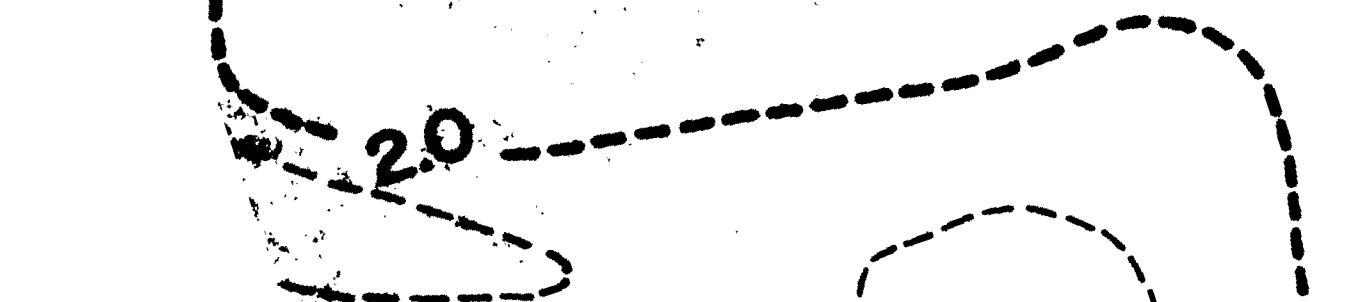
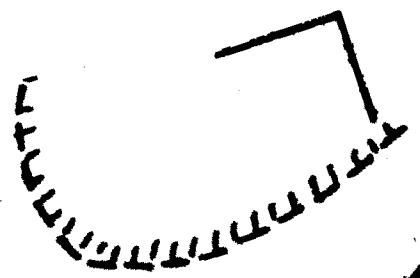






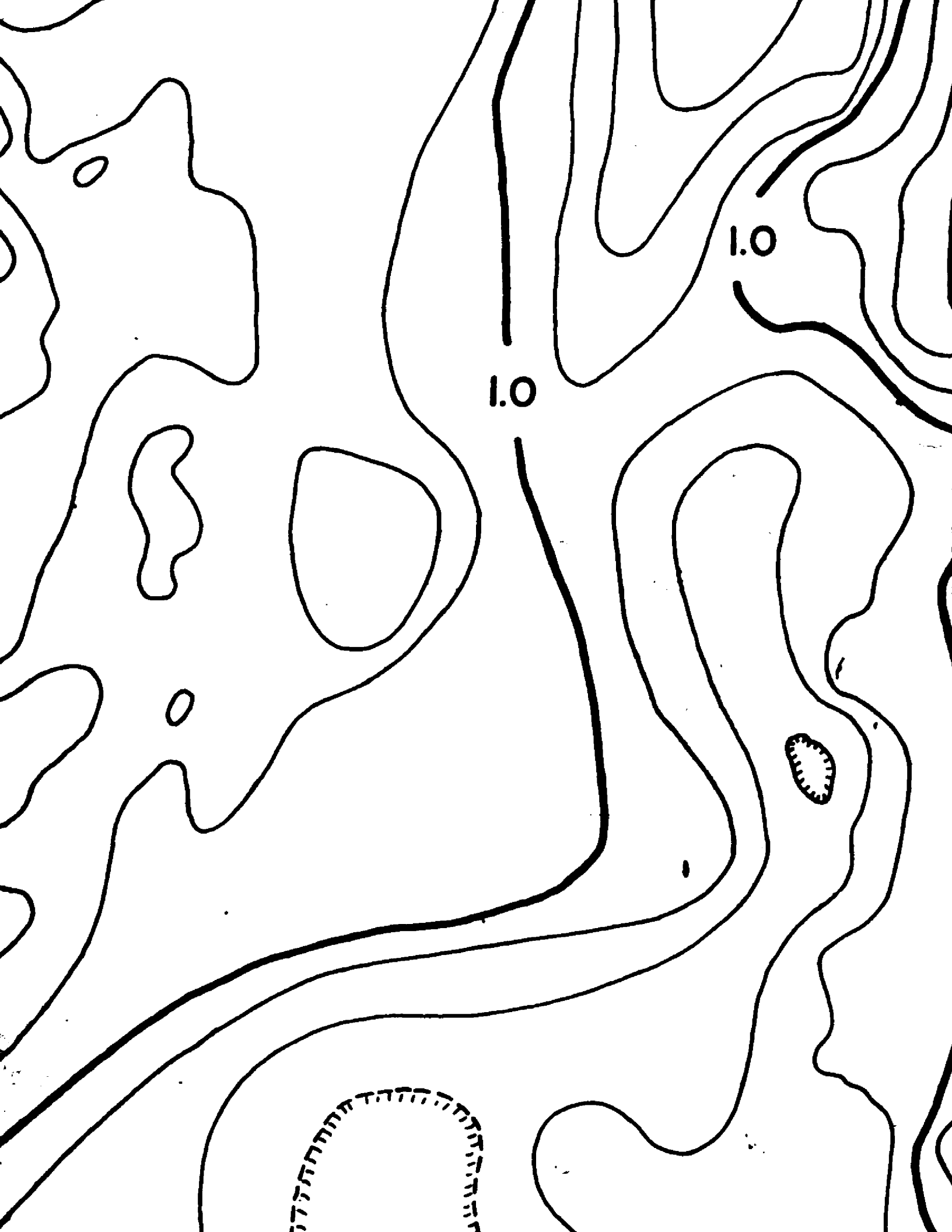


42
25-



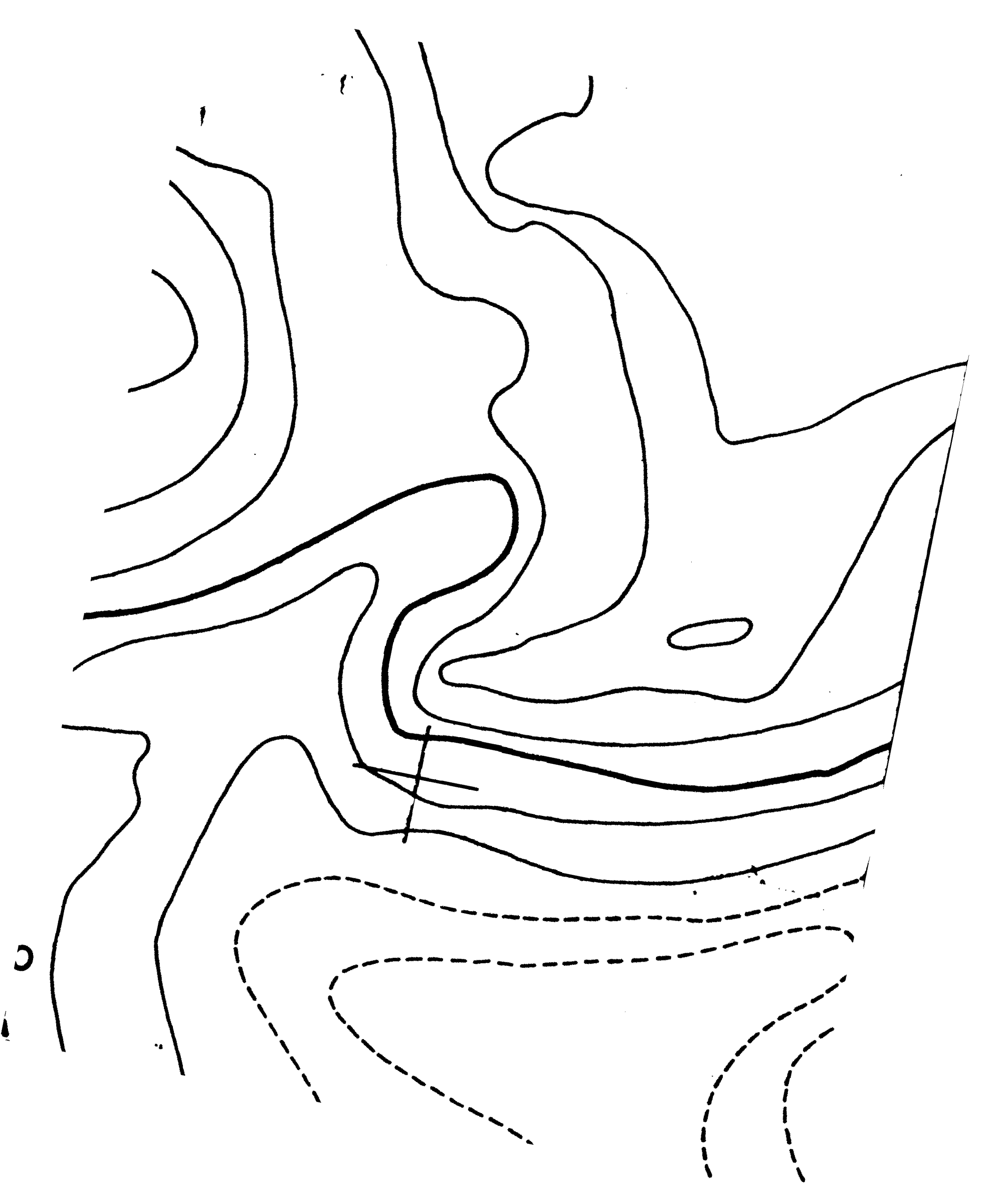
- 20'













2.0





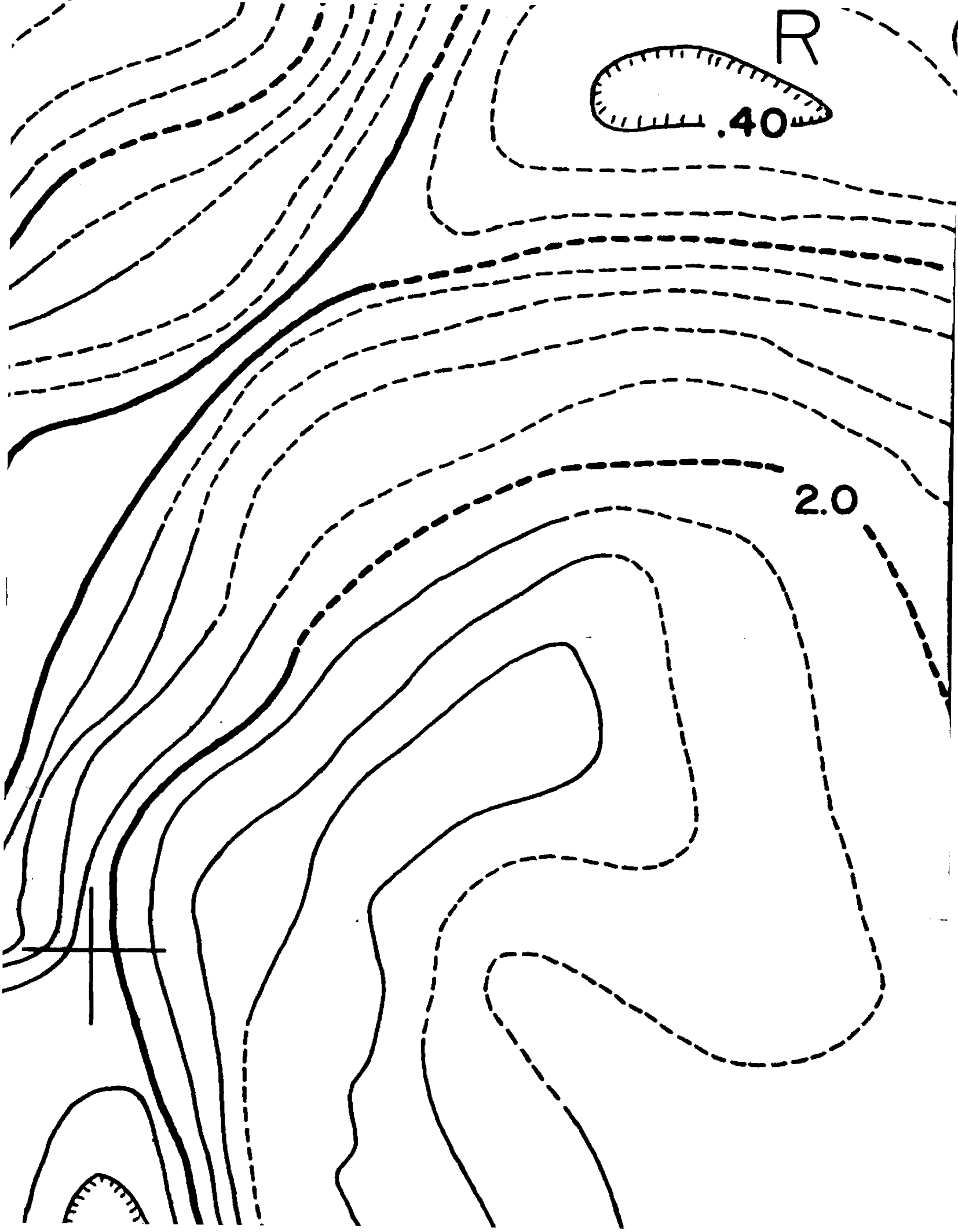


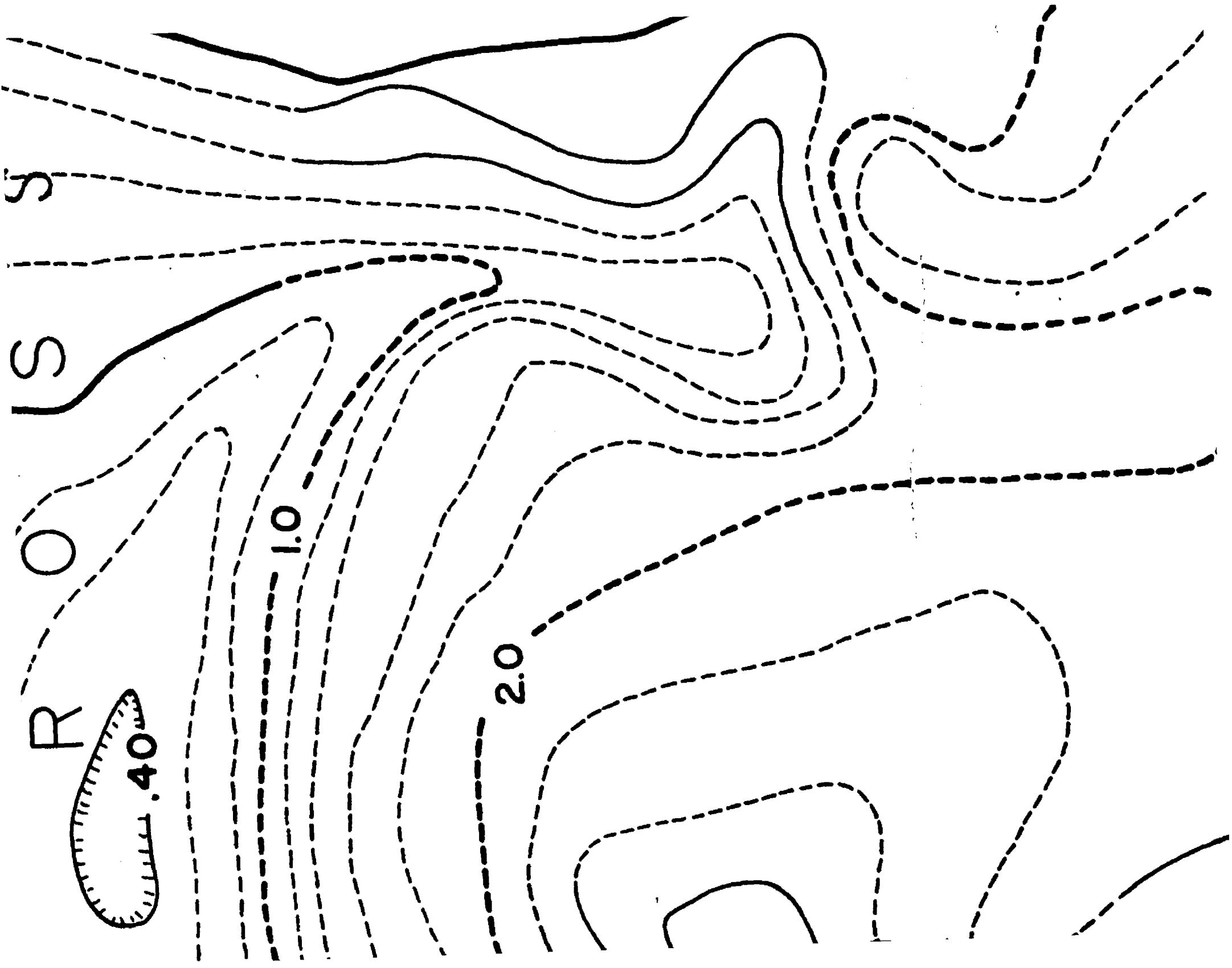


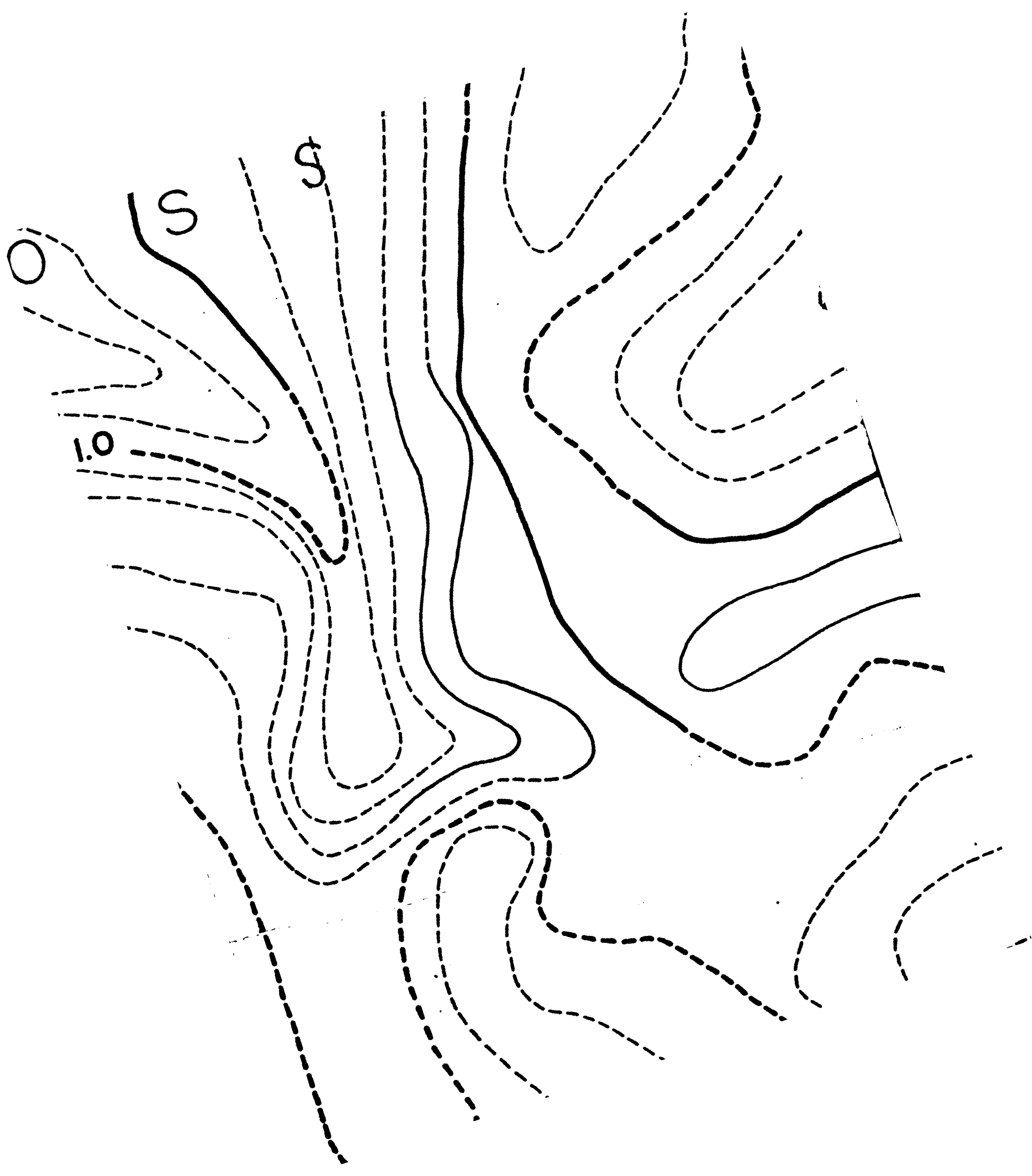




2.40



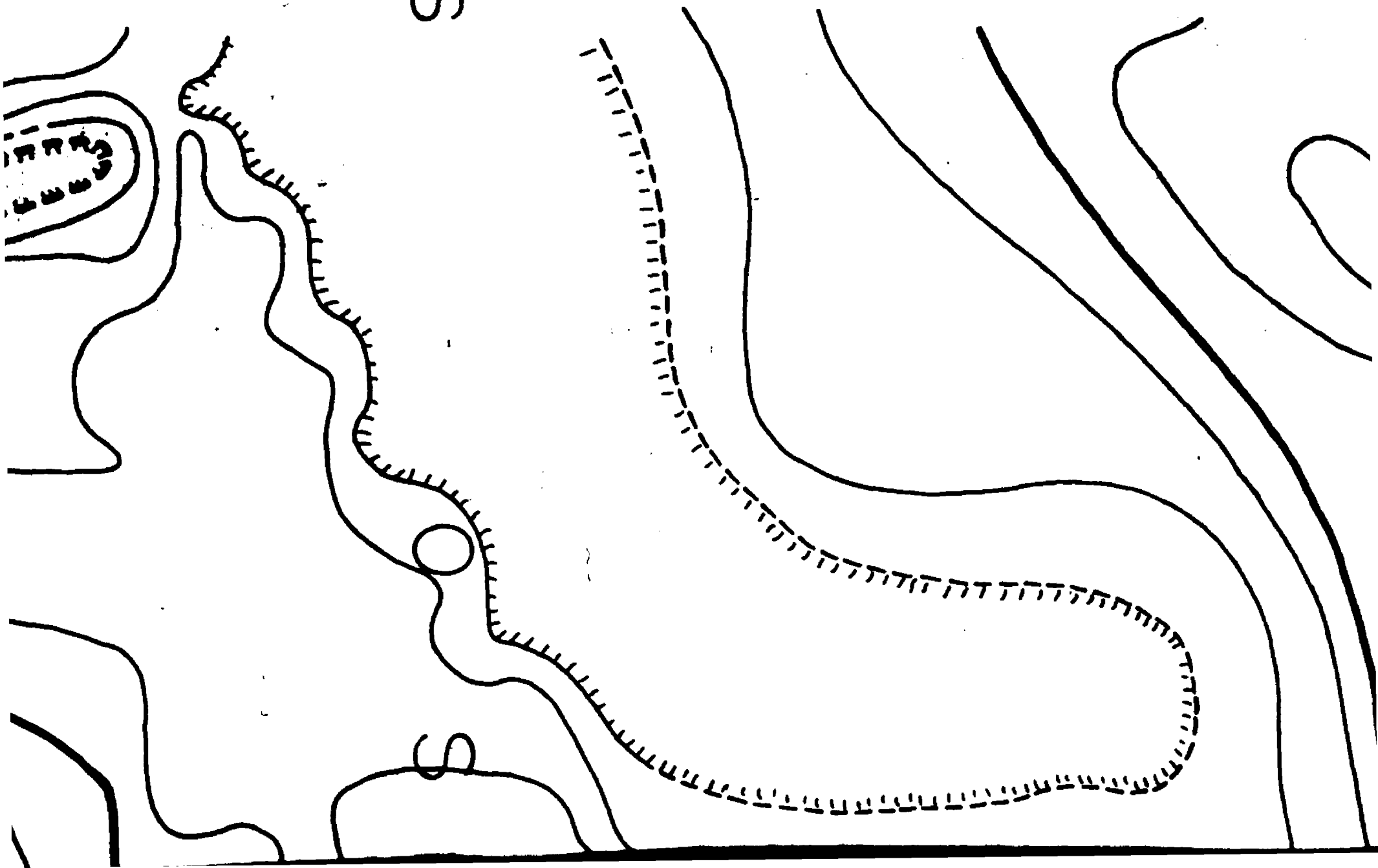




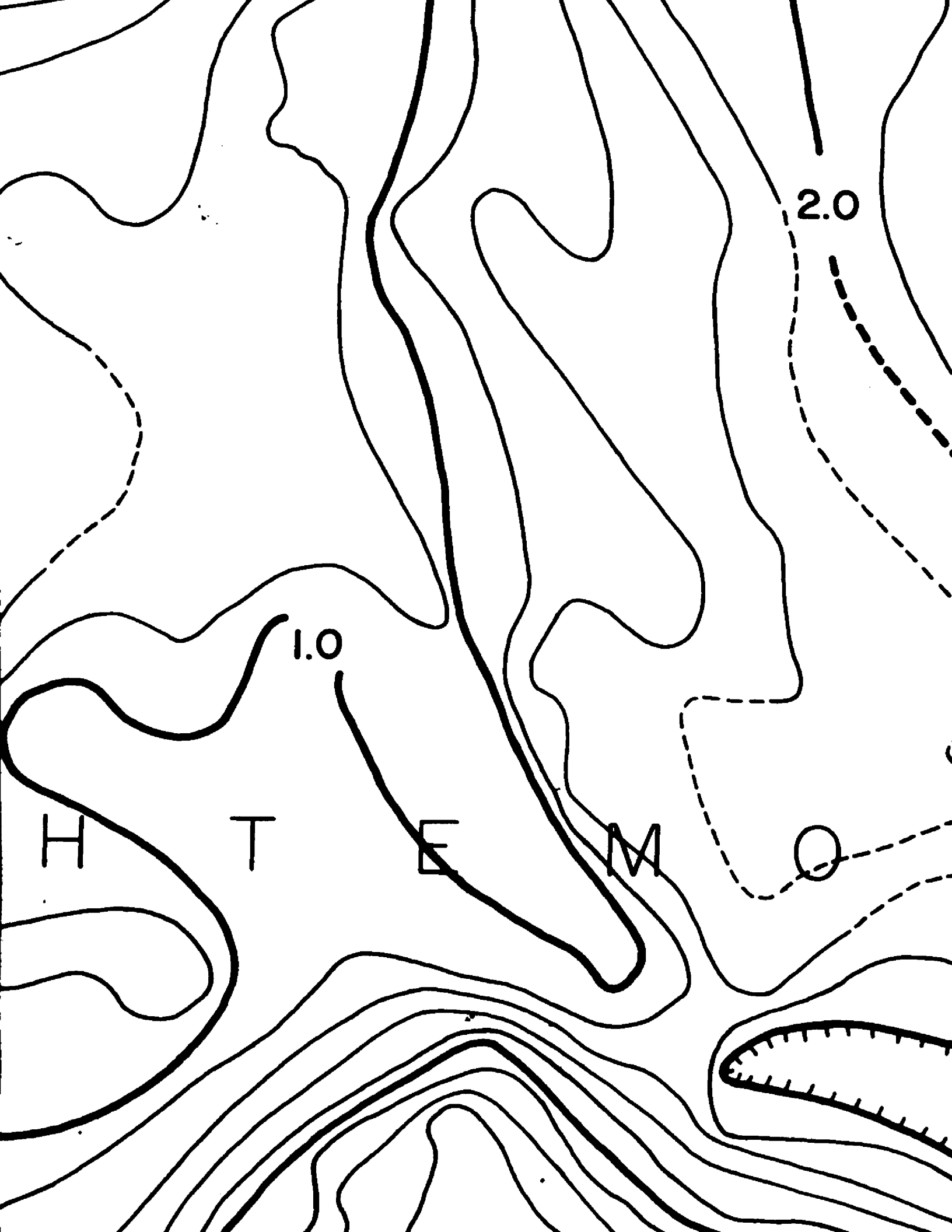
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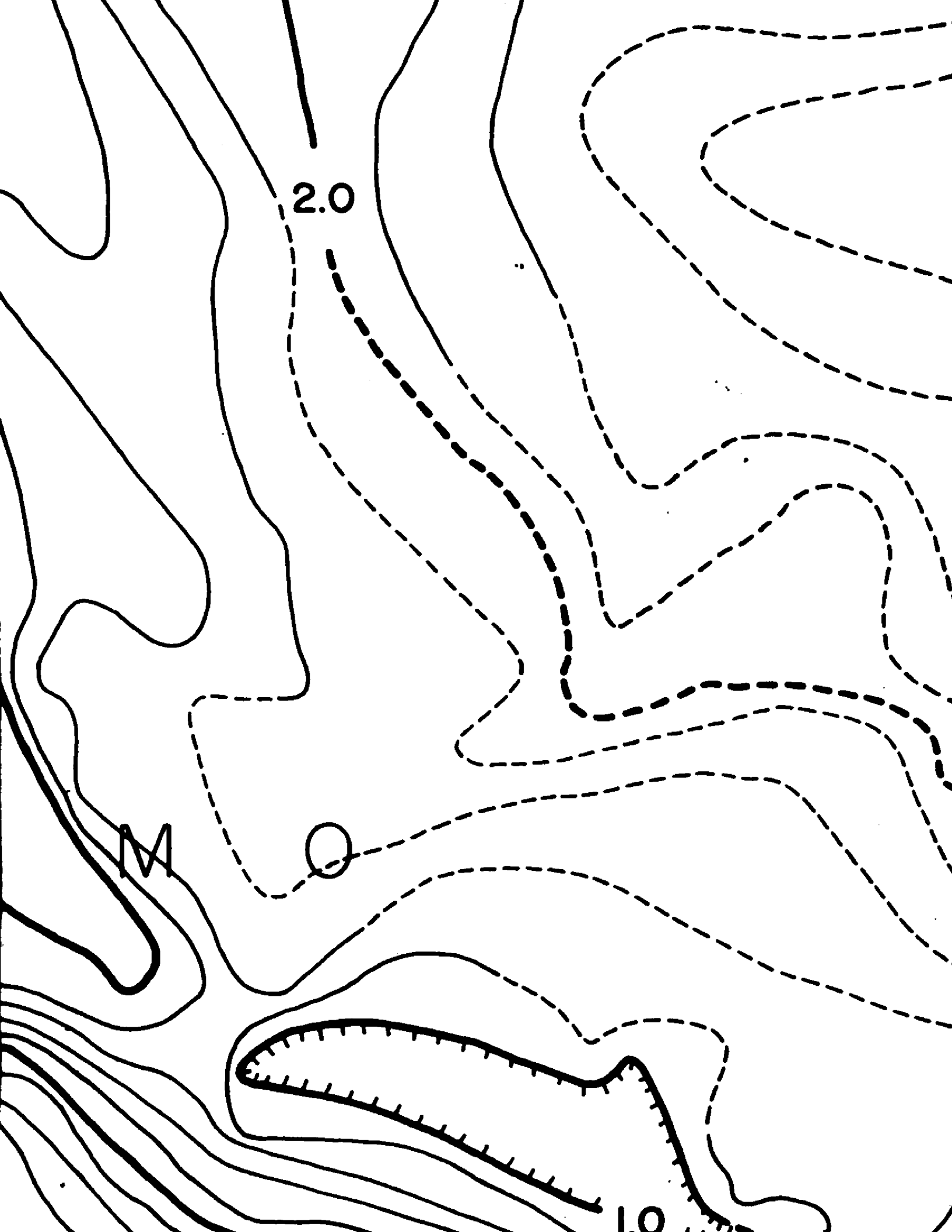
20'

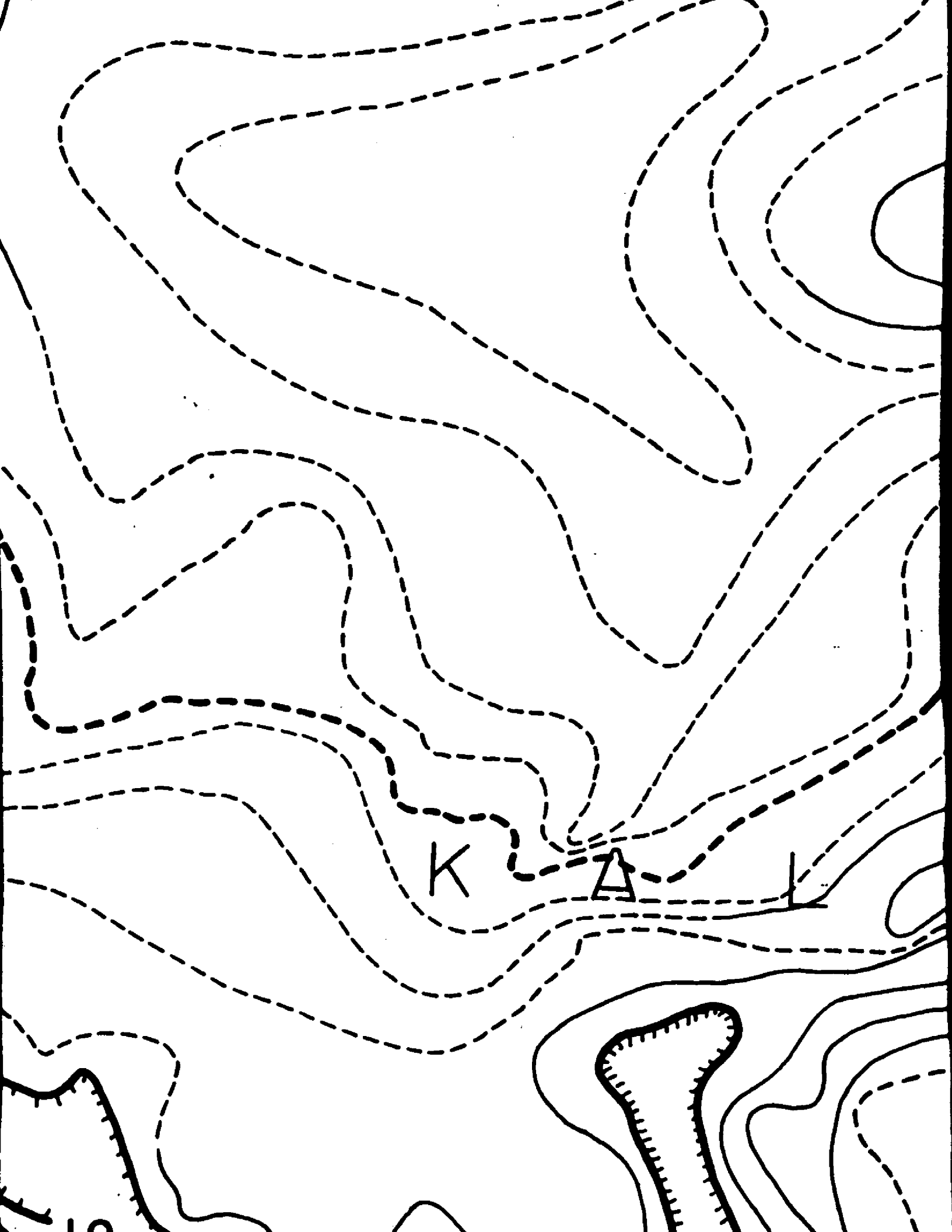
T2S

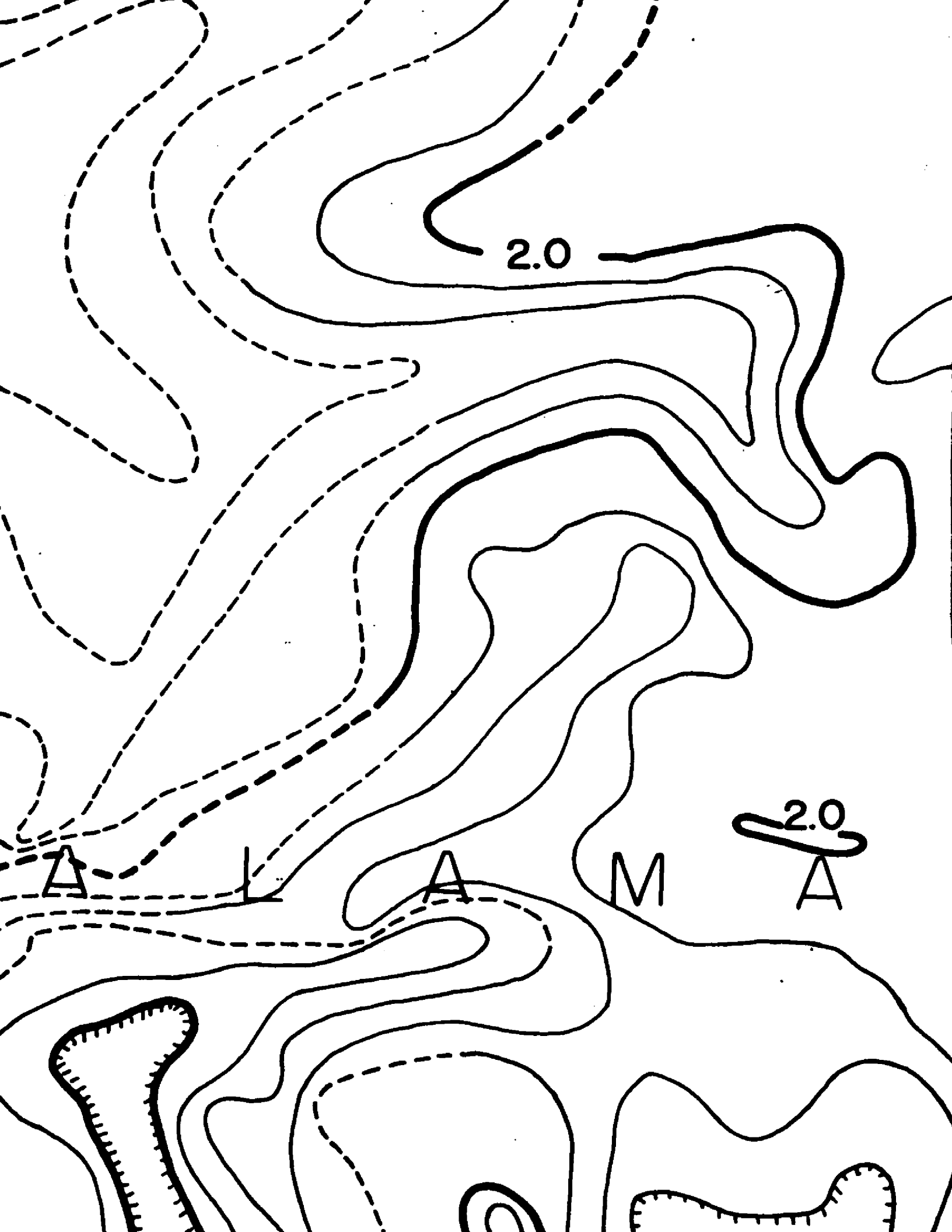


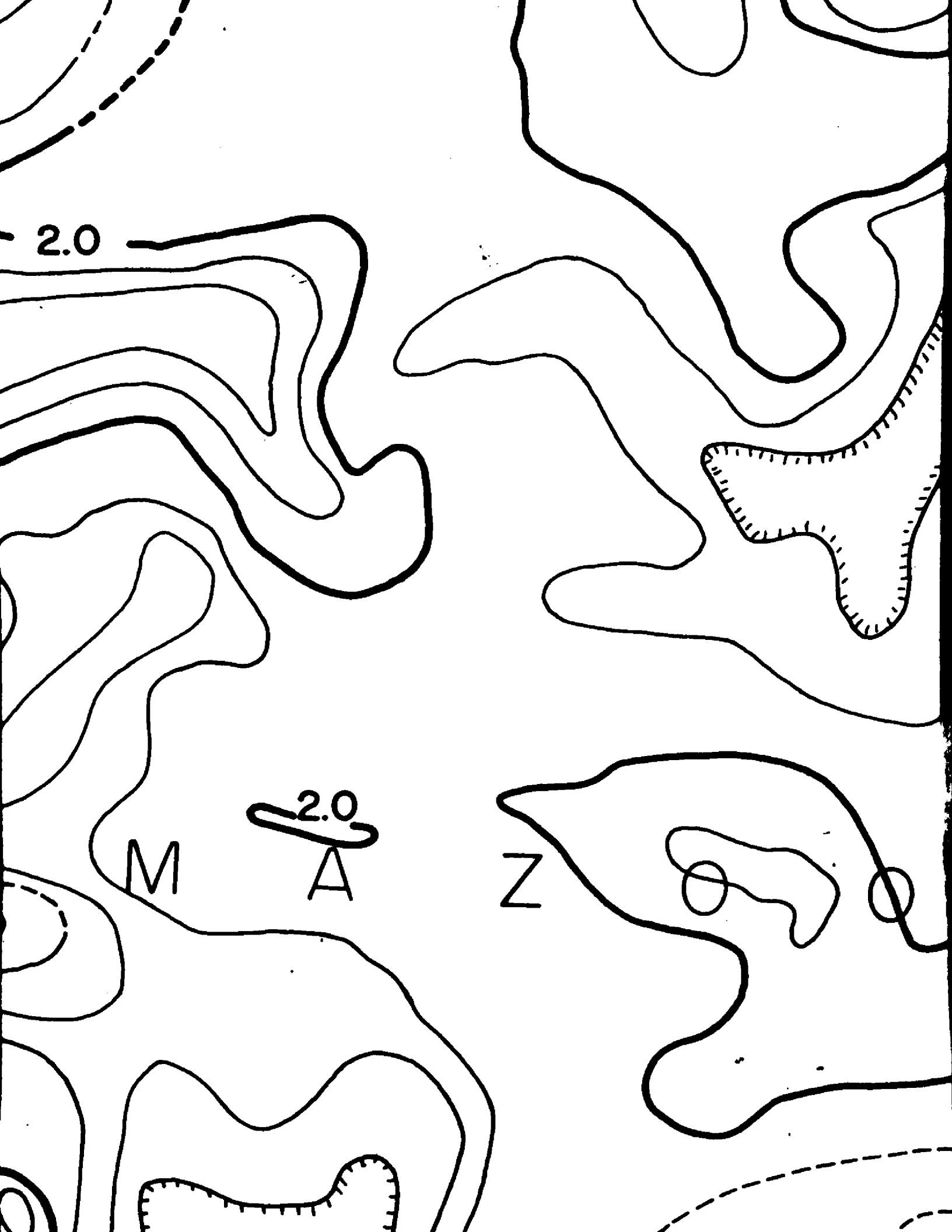


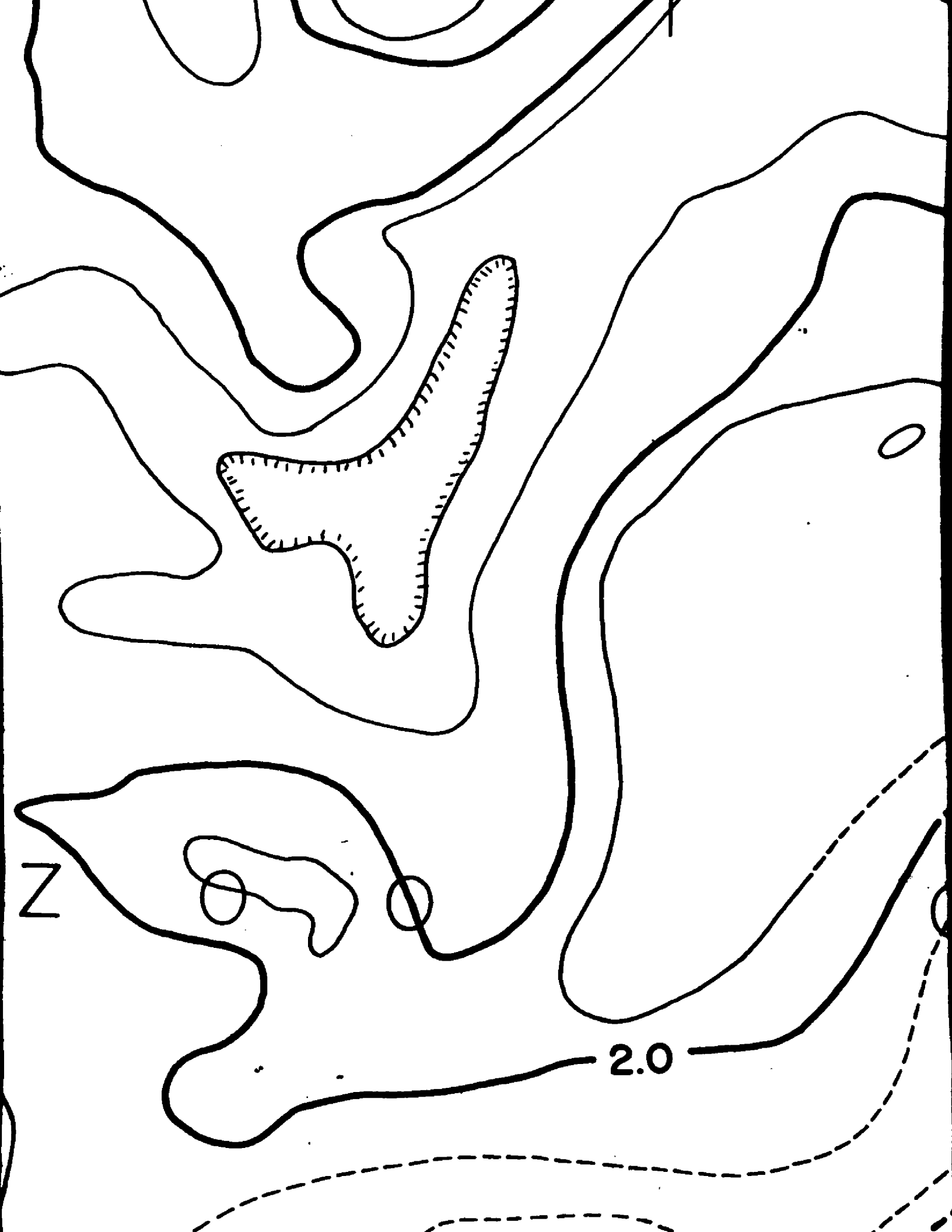


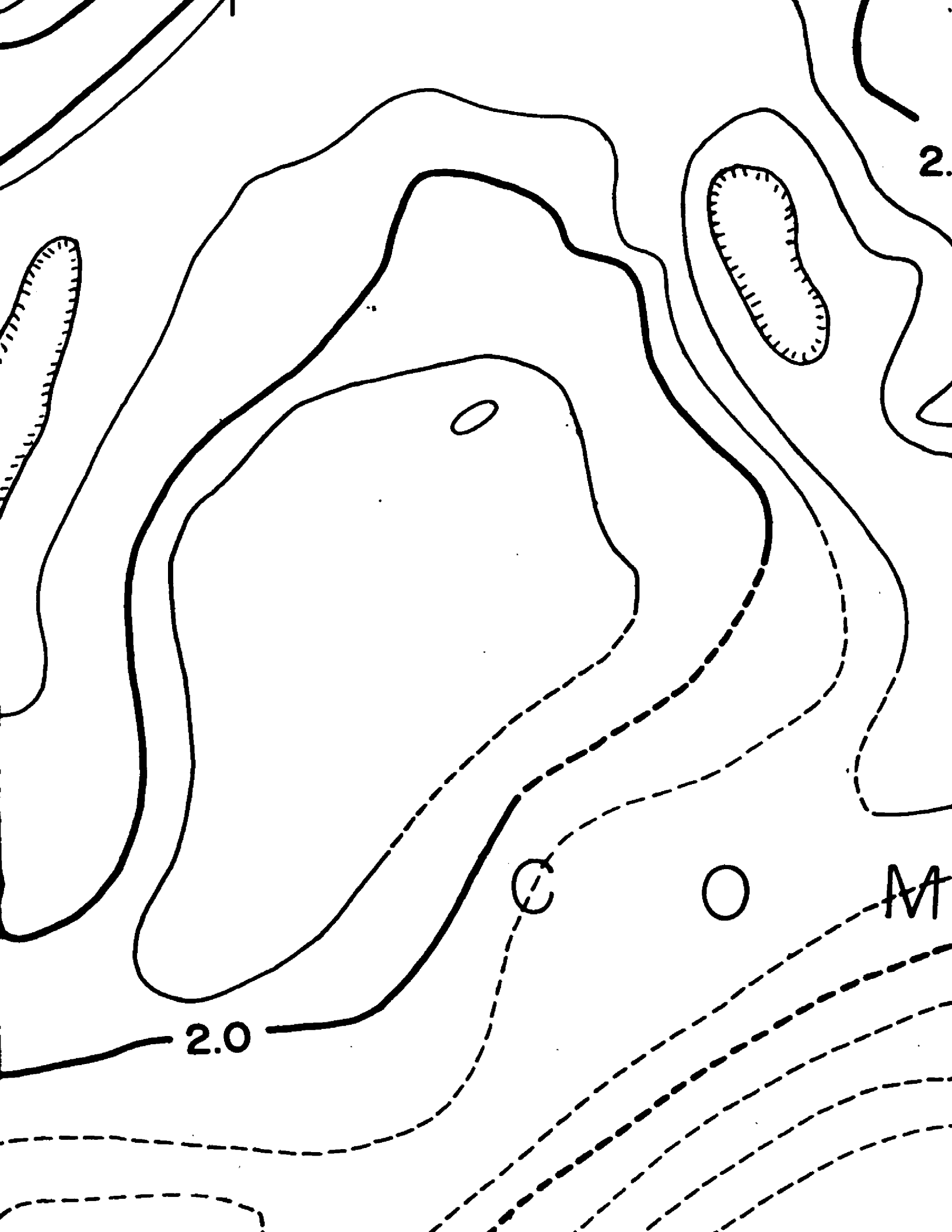


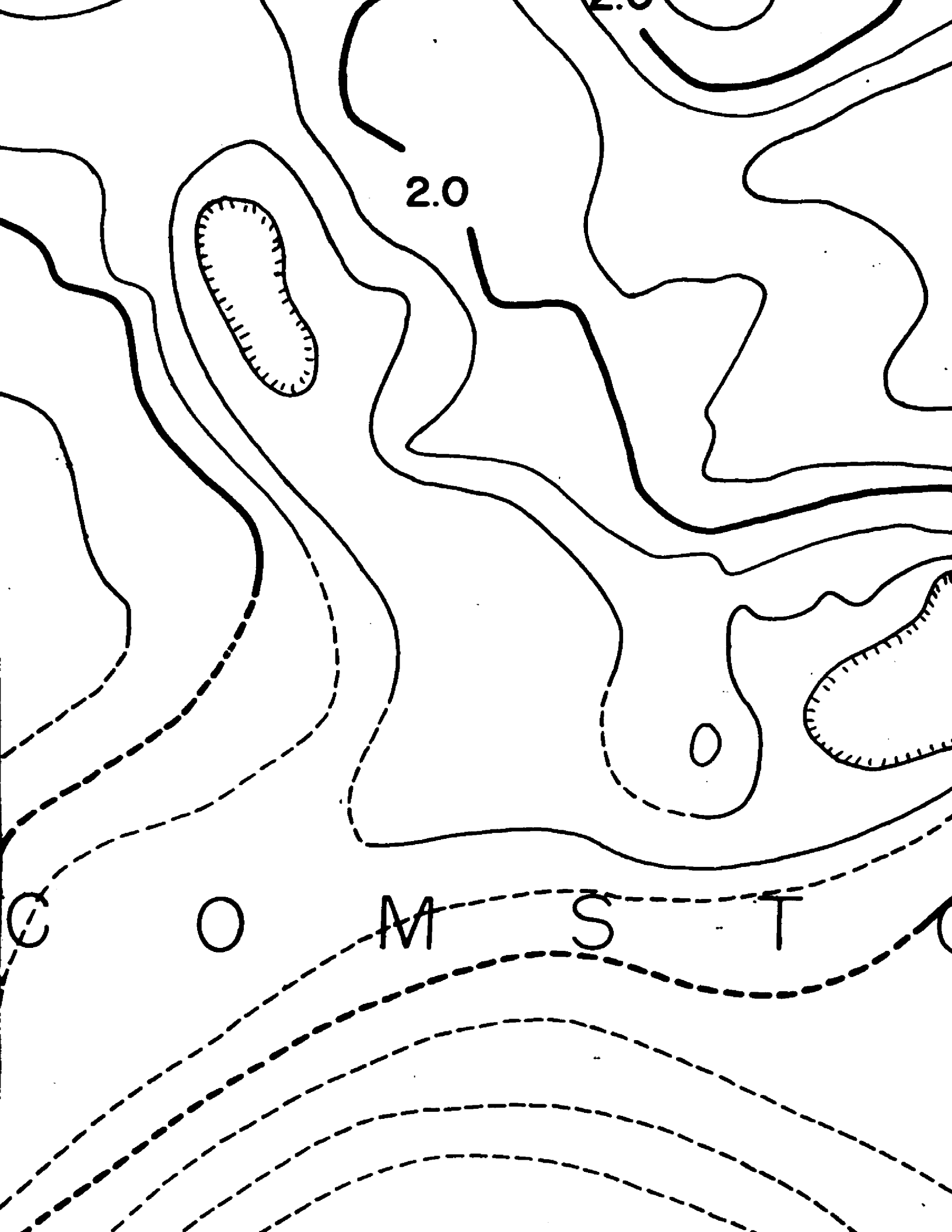


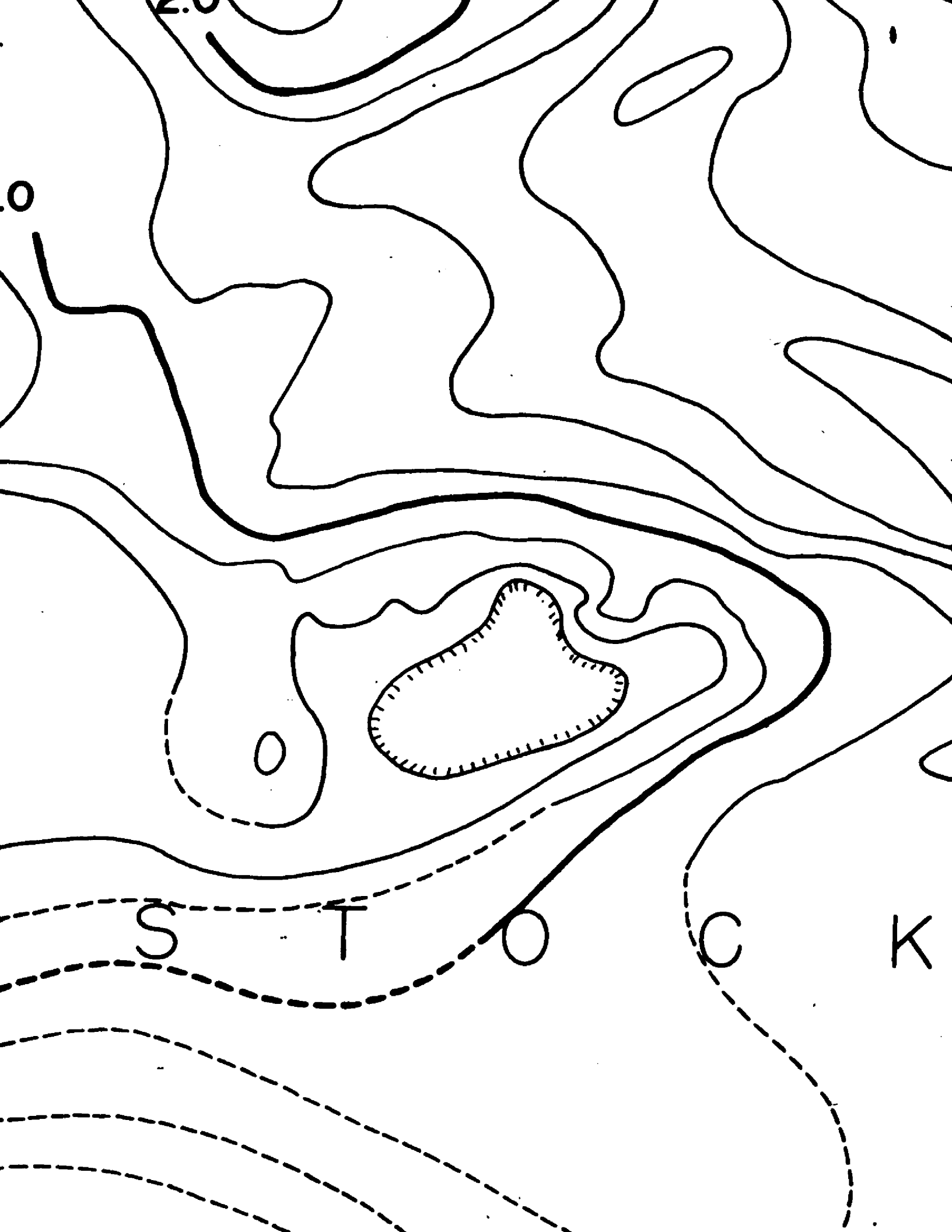


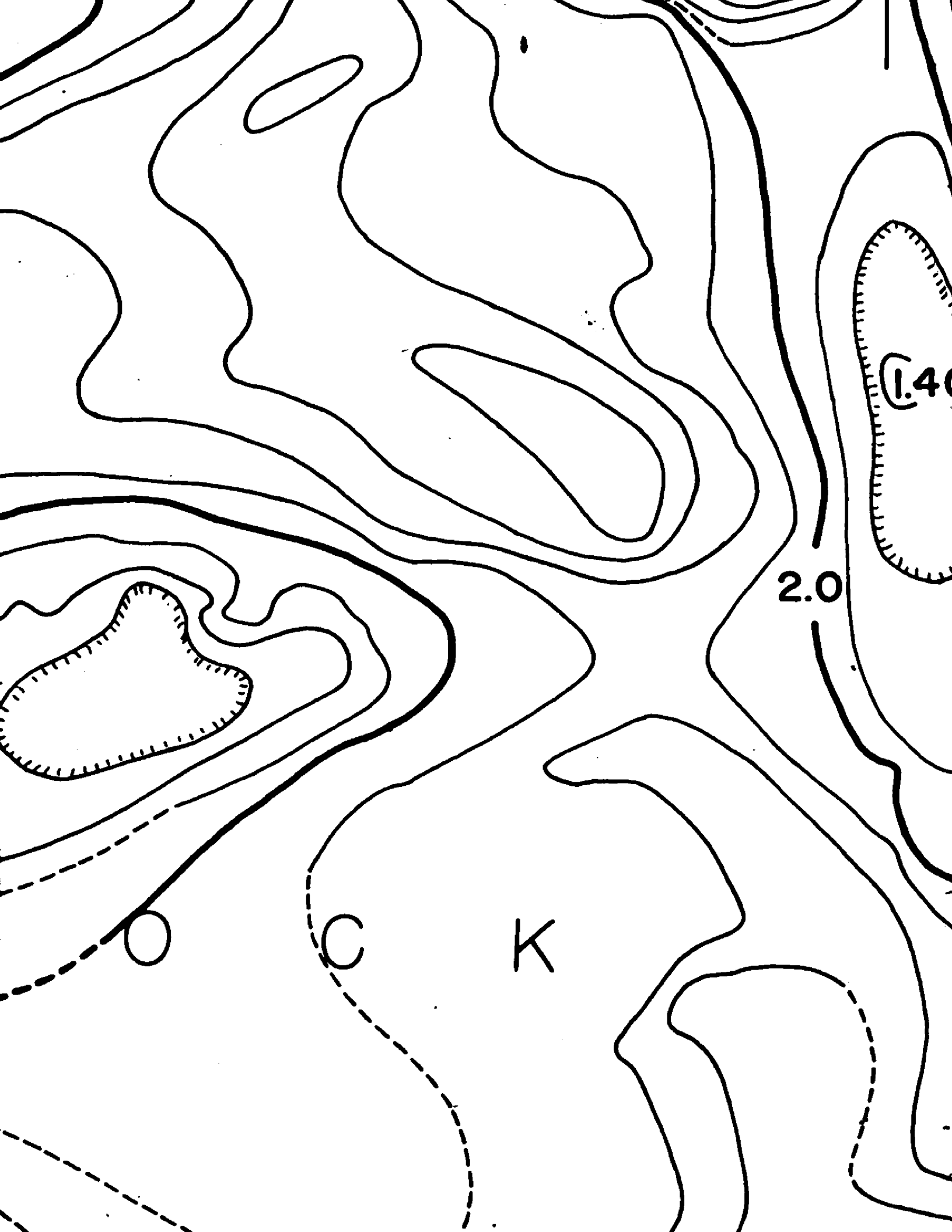




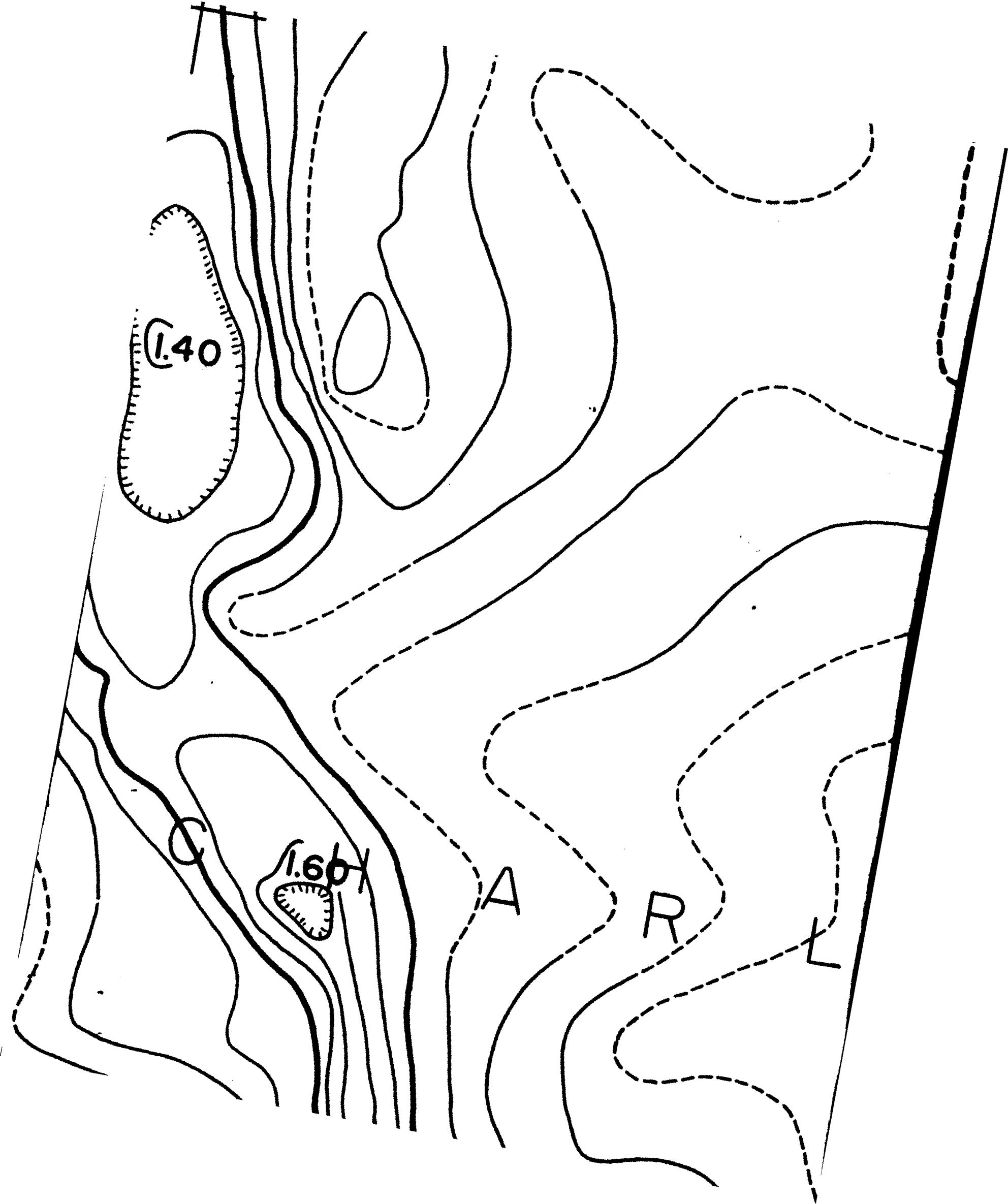


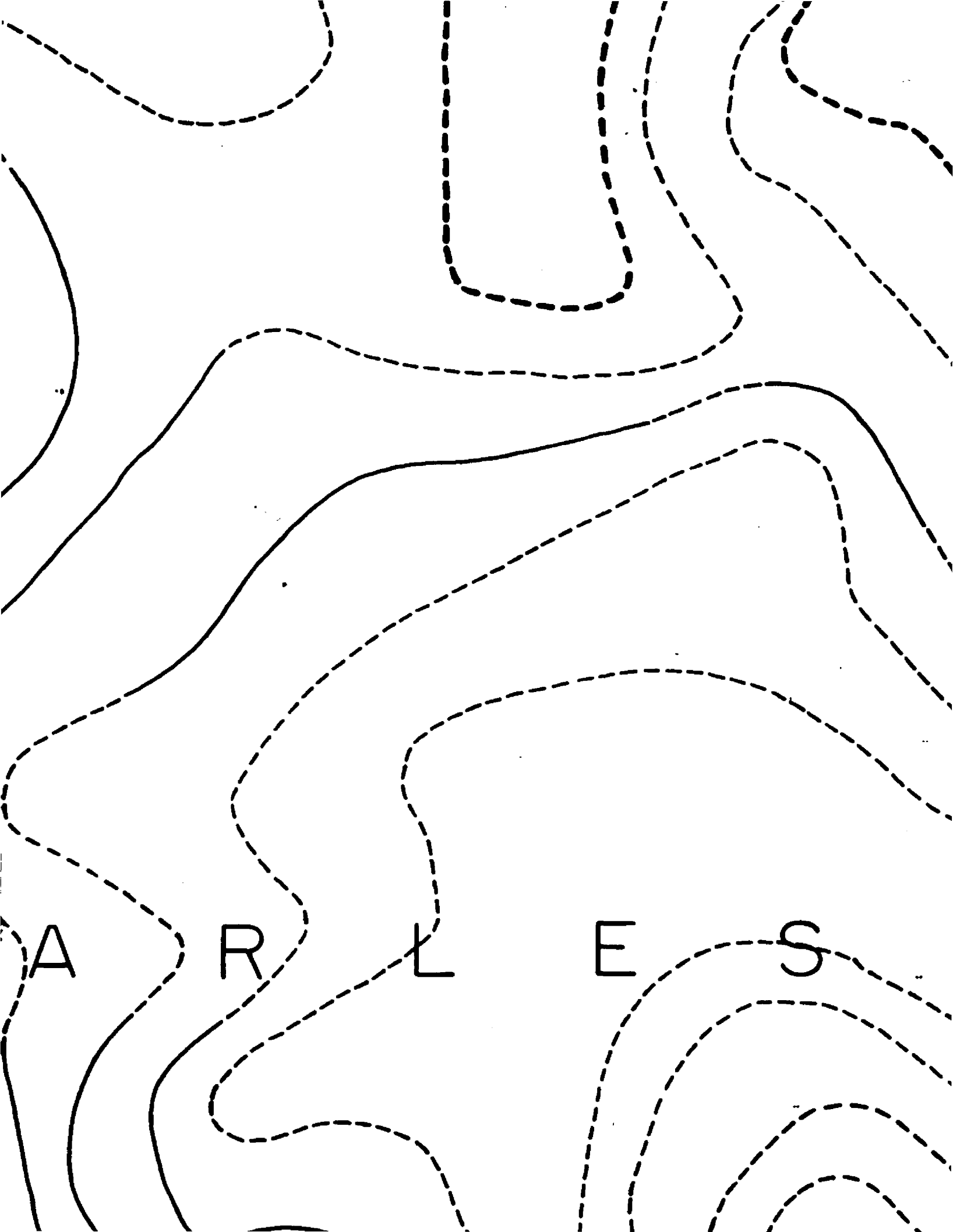












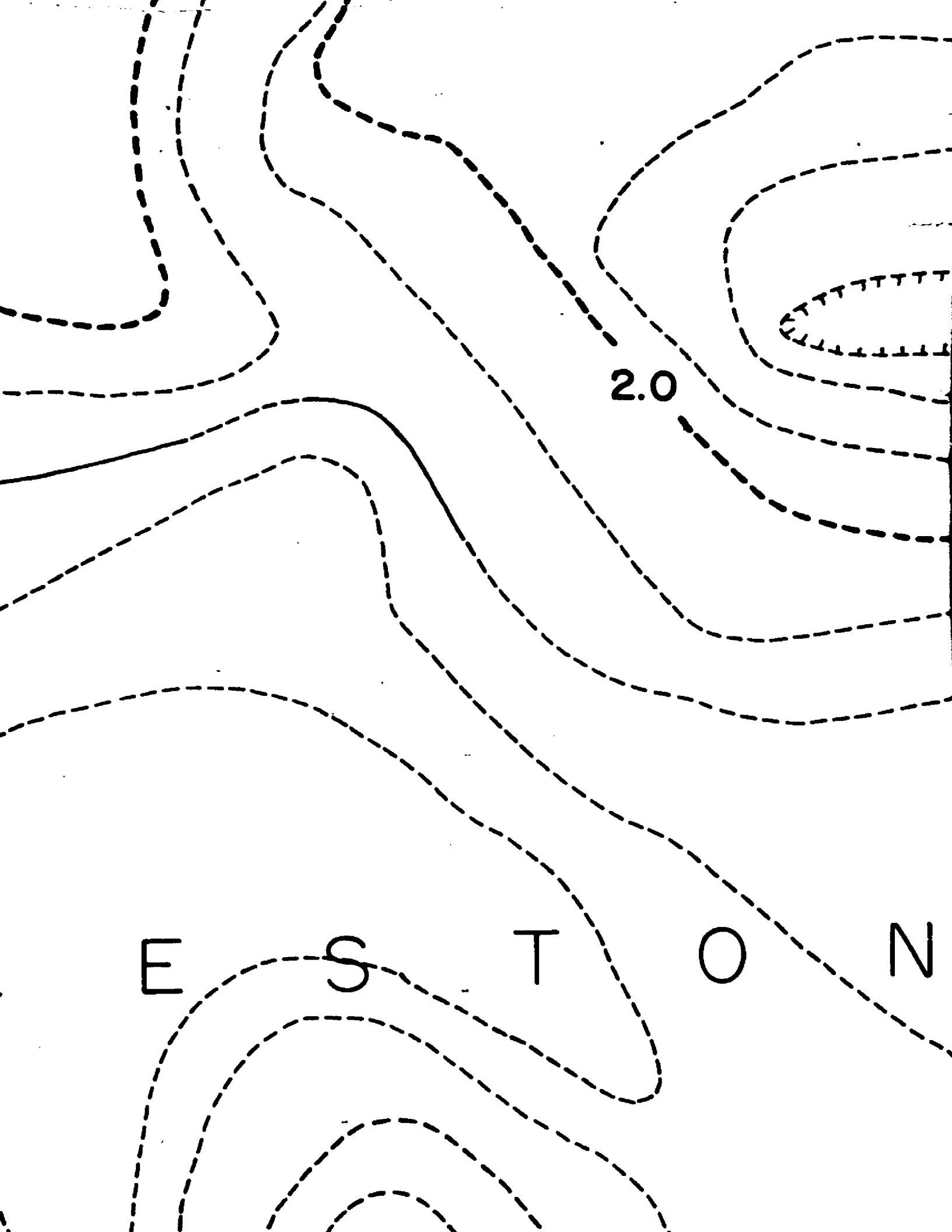
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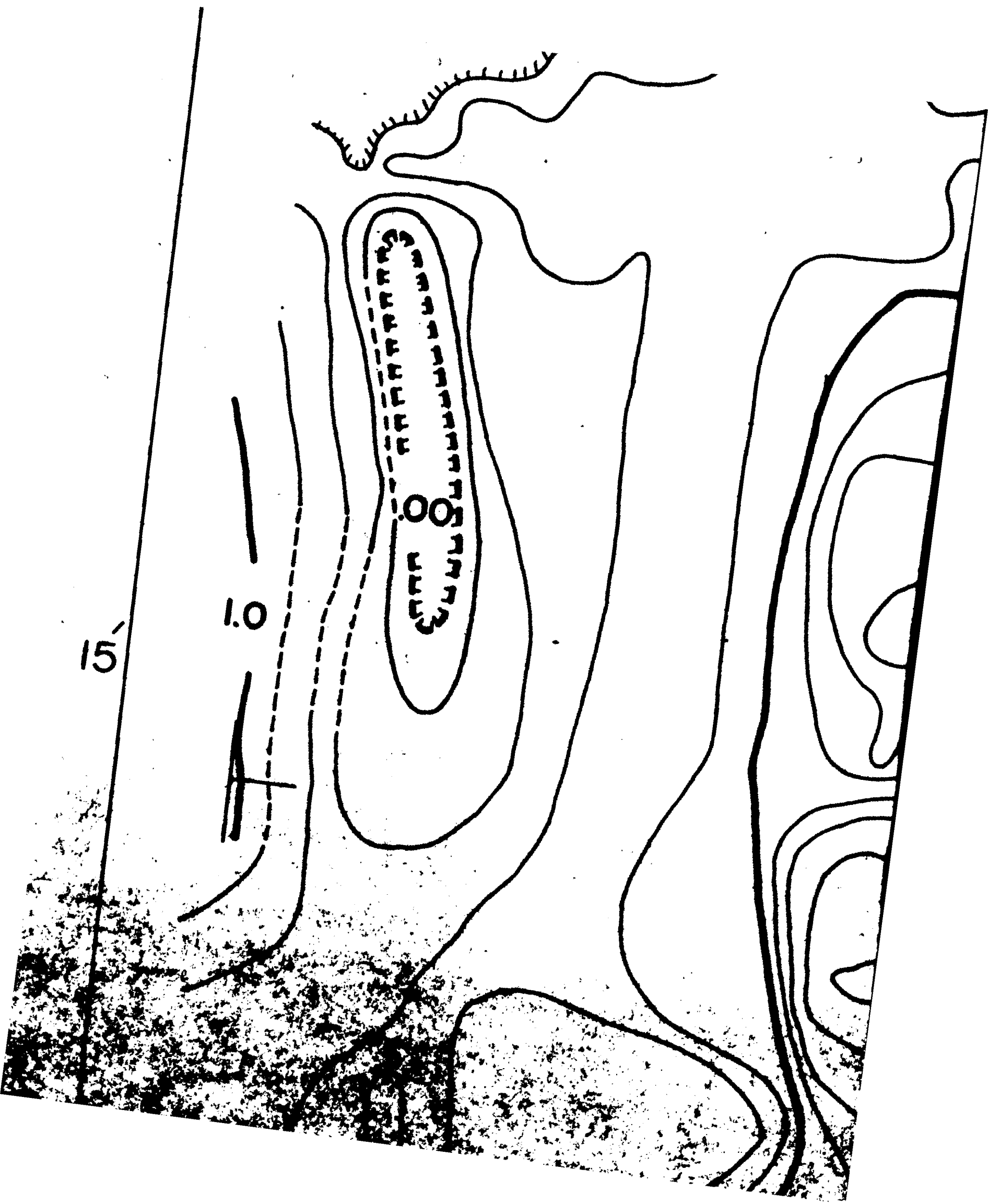
T

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T O N T2S

2.0

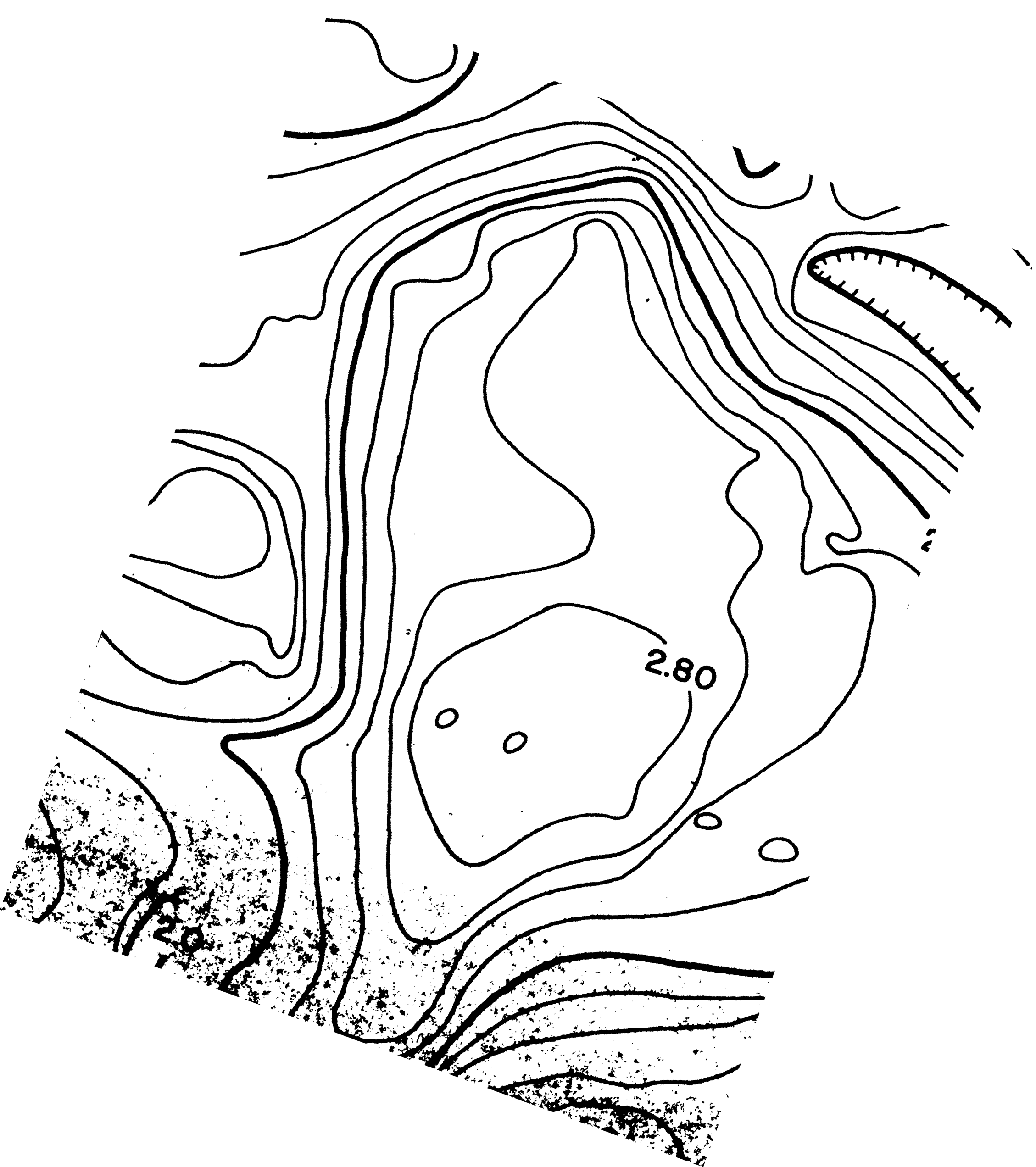




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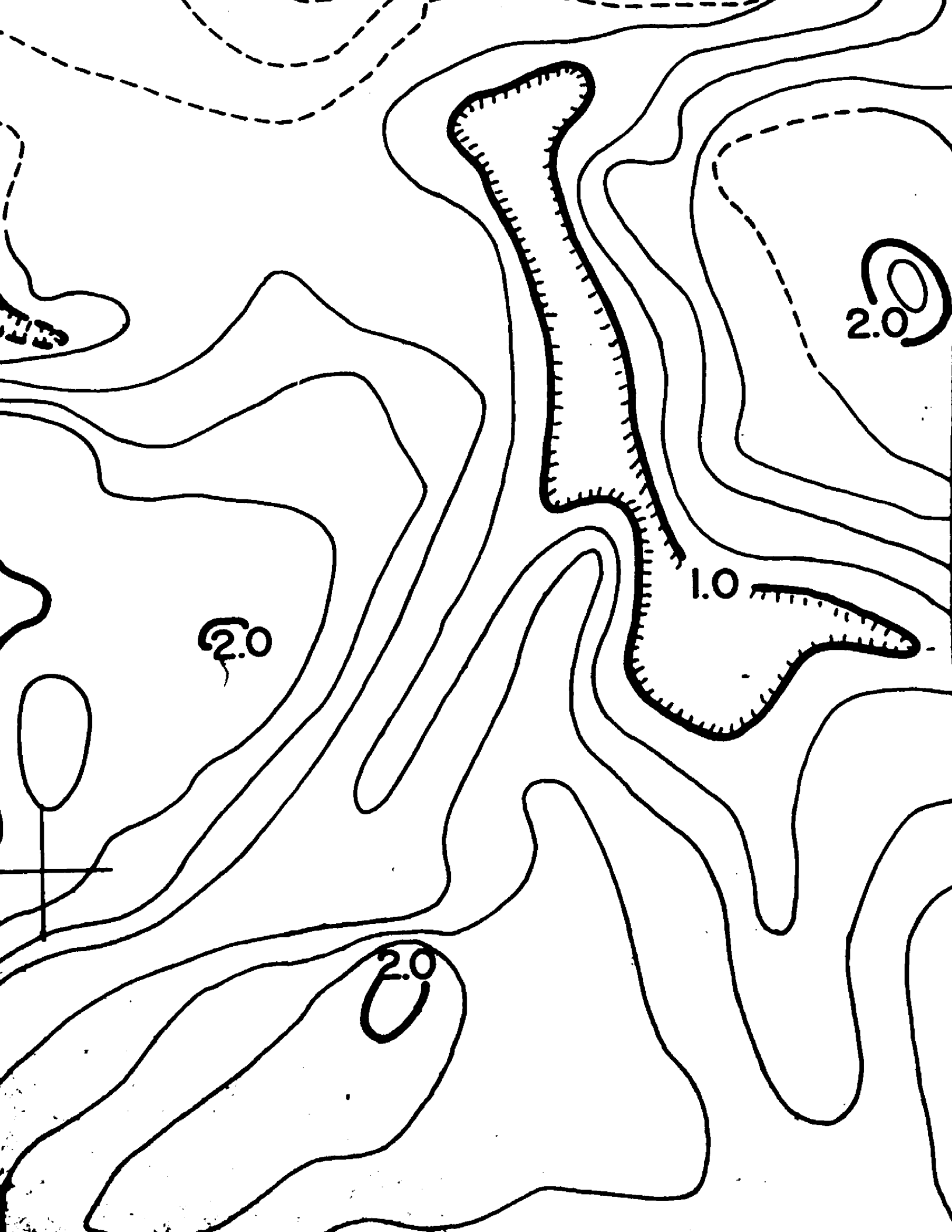
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20

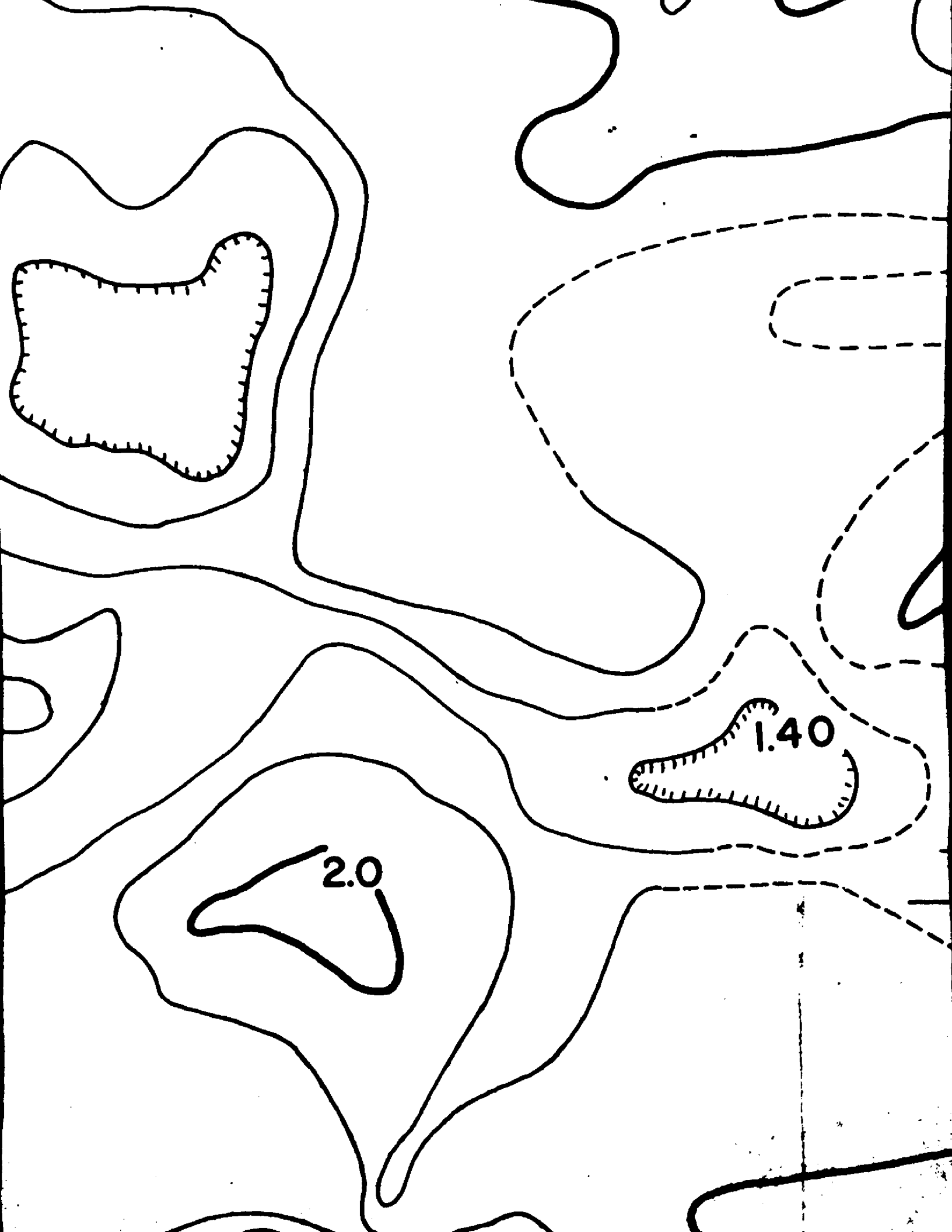








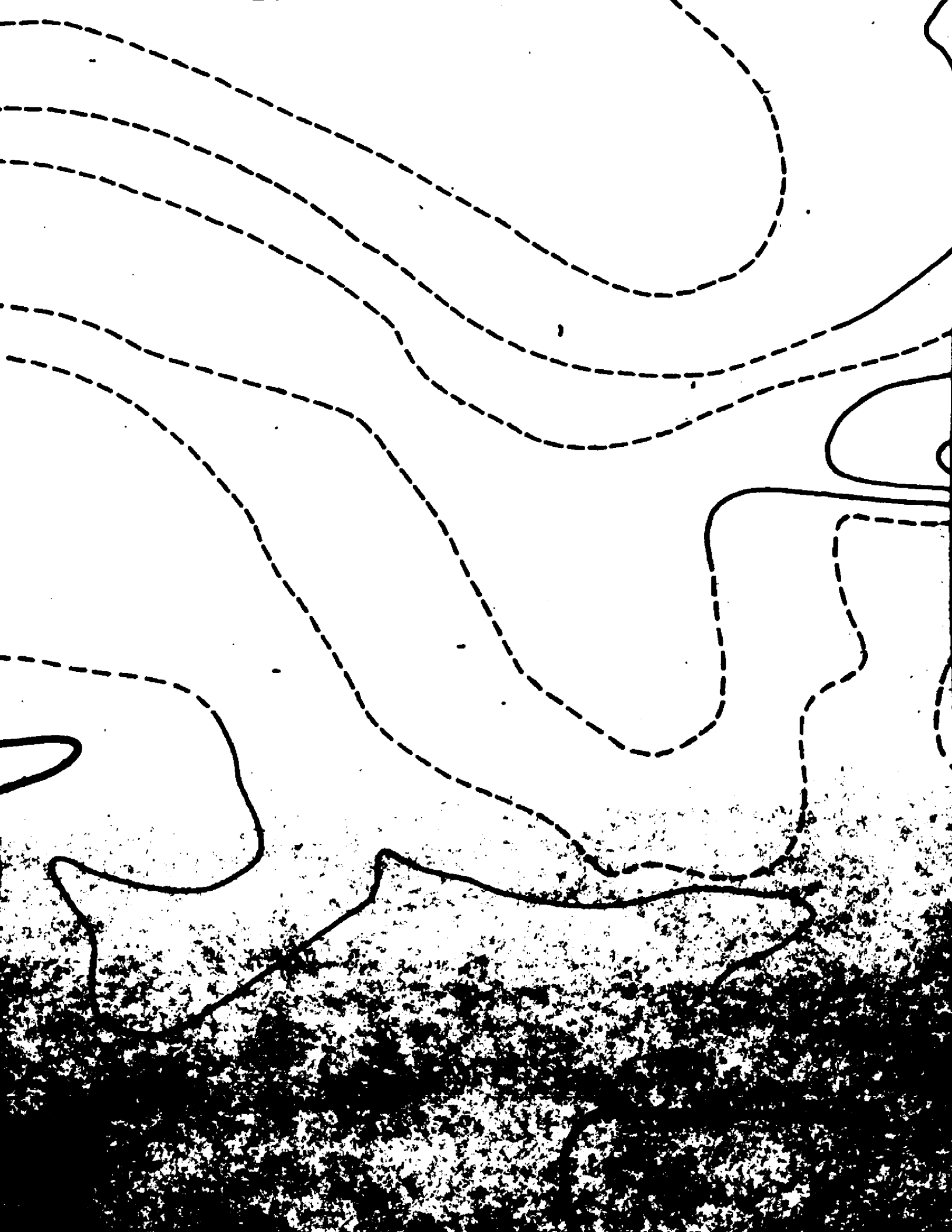






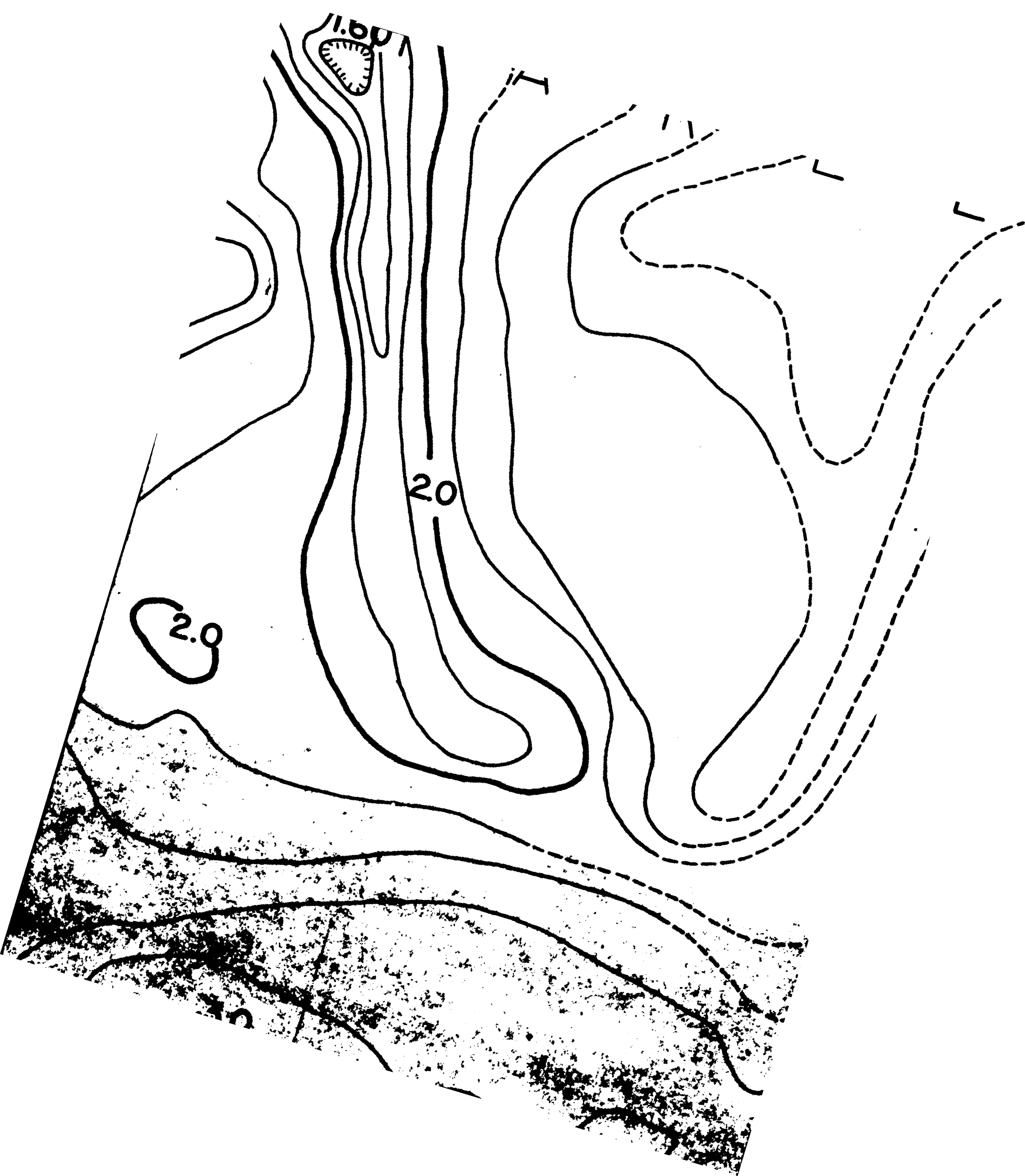


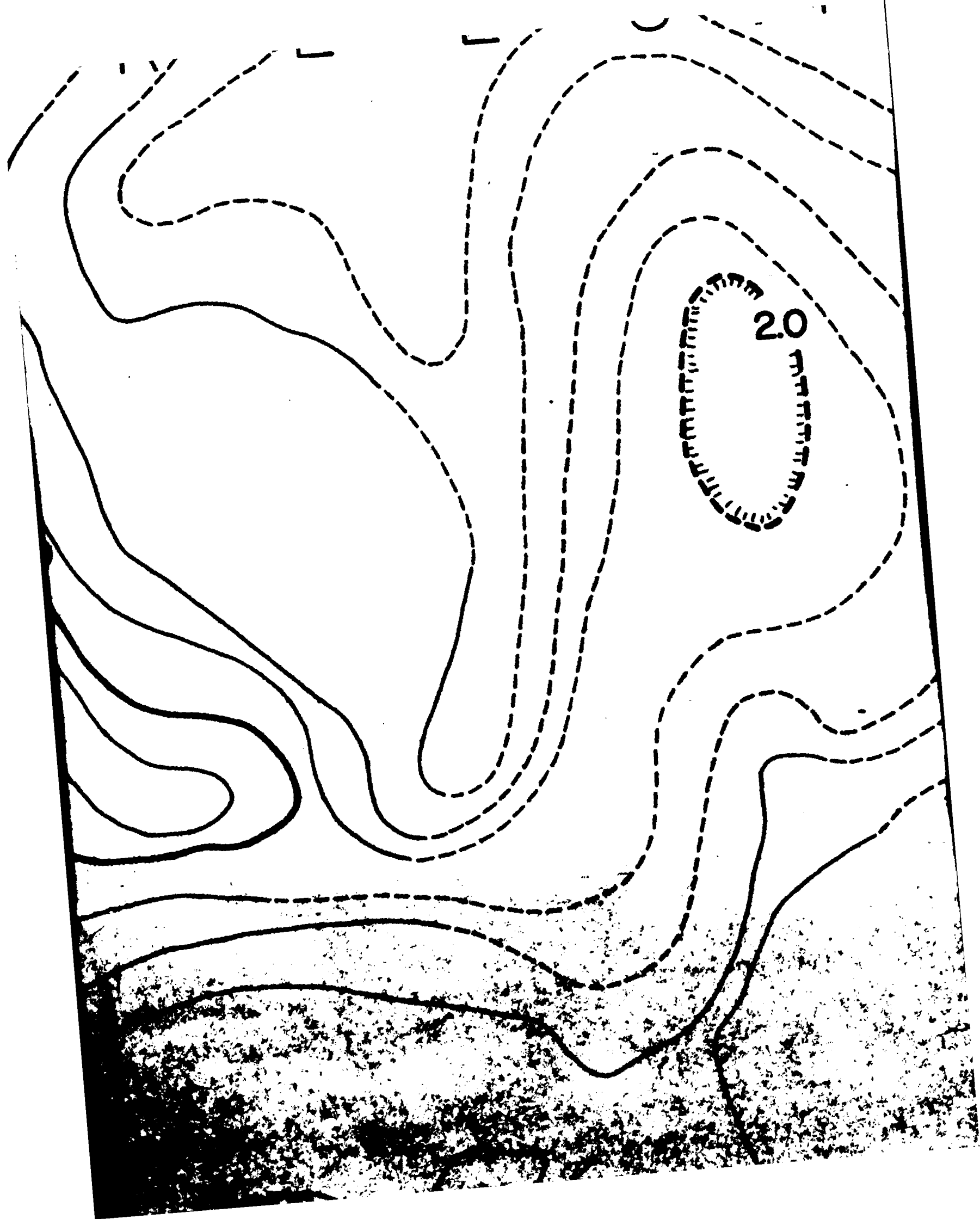


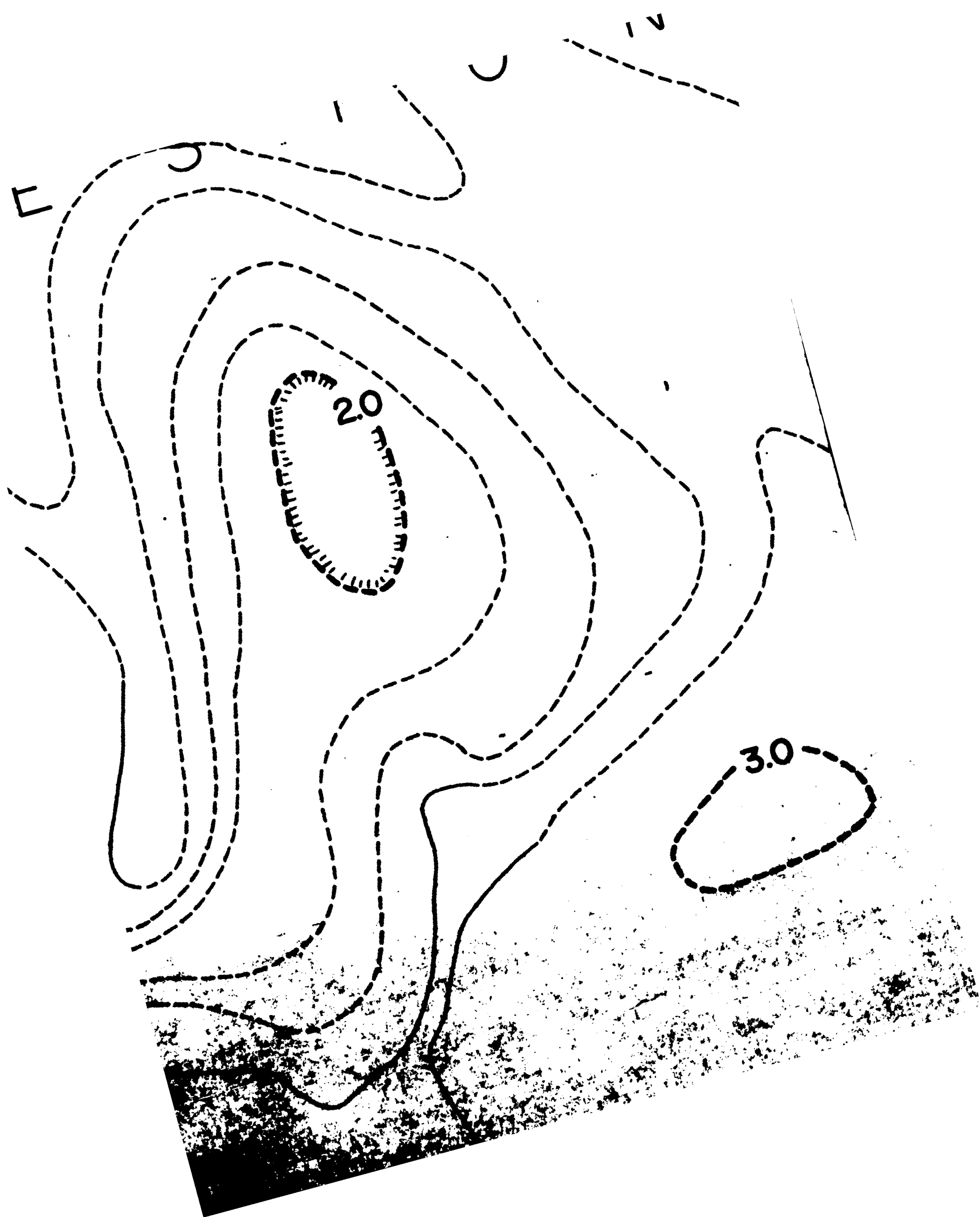


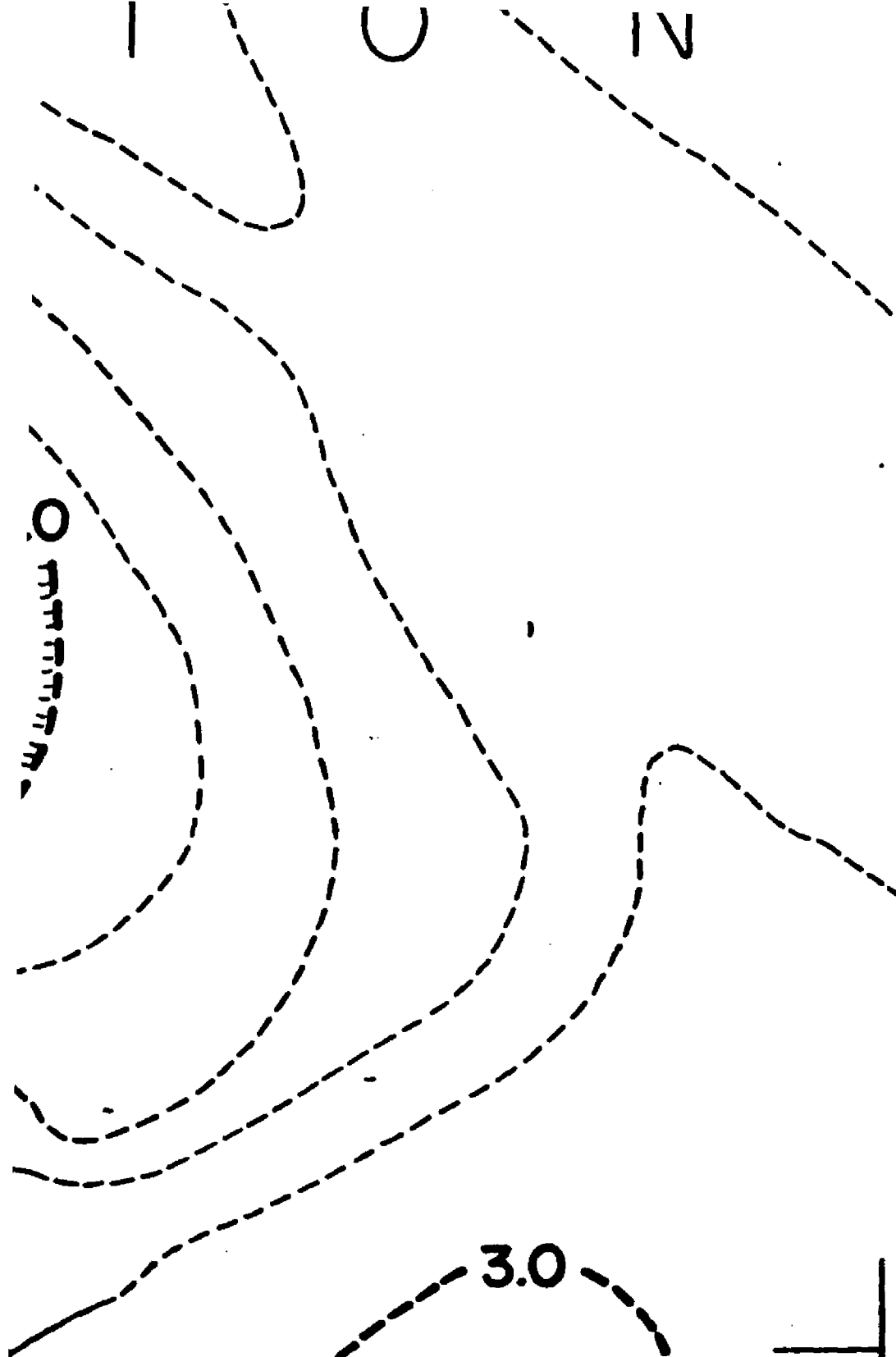












3.0



15'

125

IN

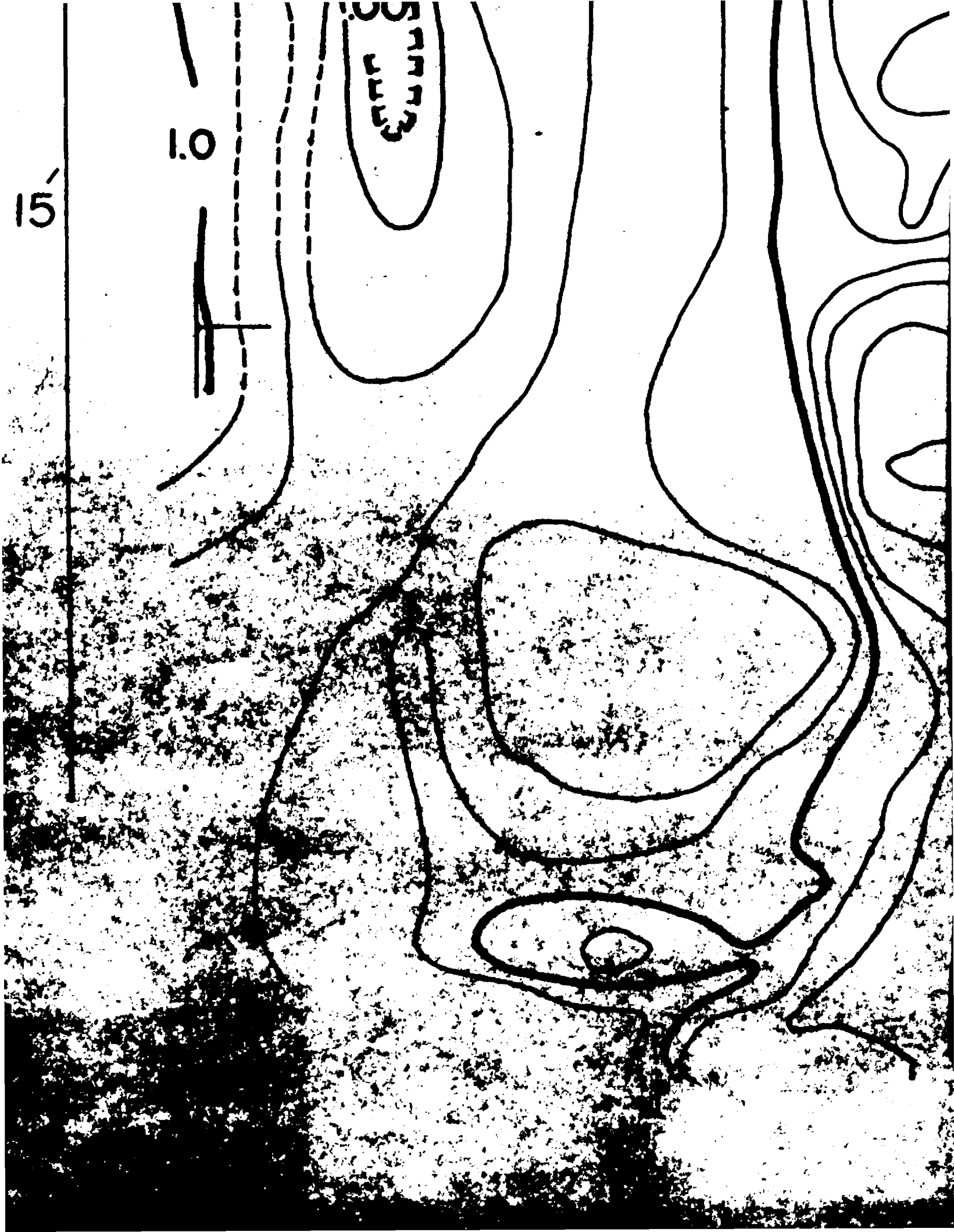
O

I

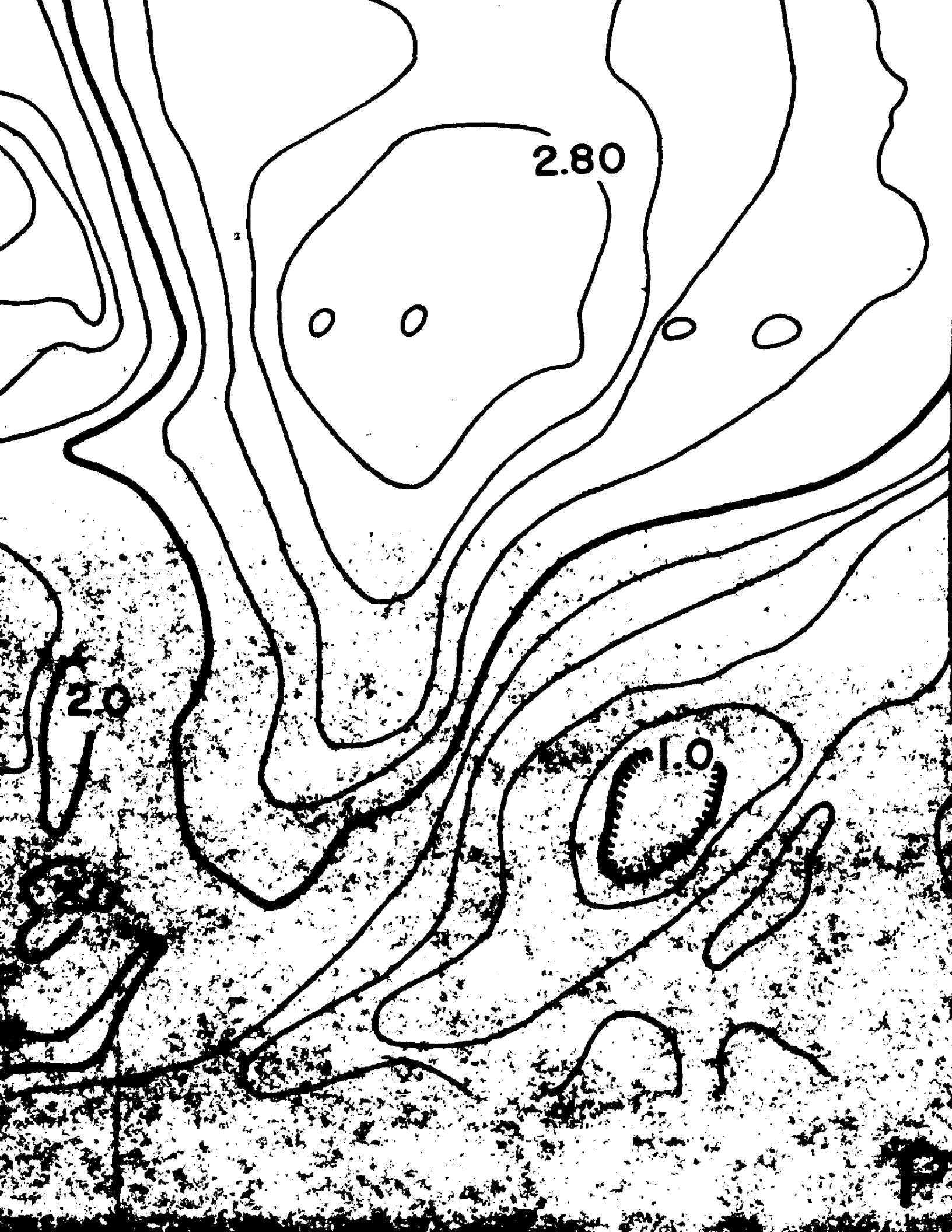
15'

1.0

0.005







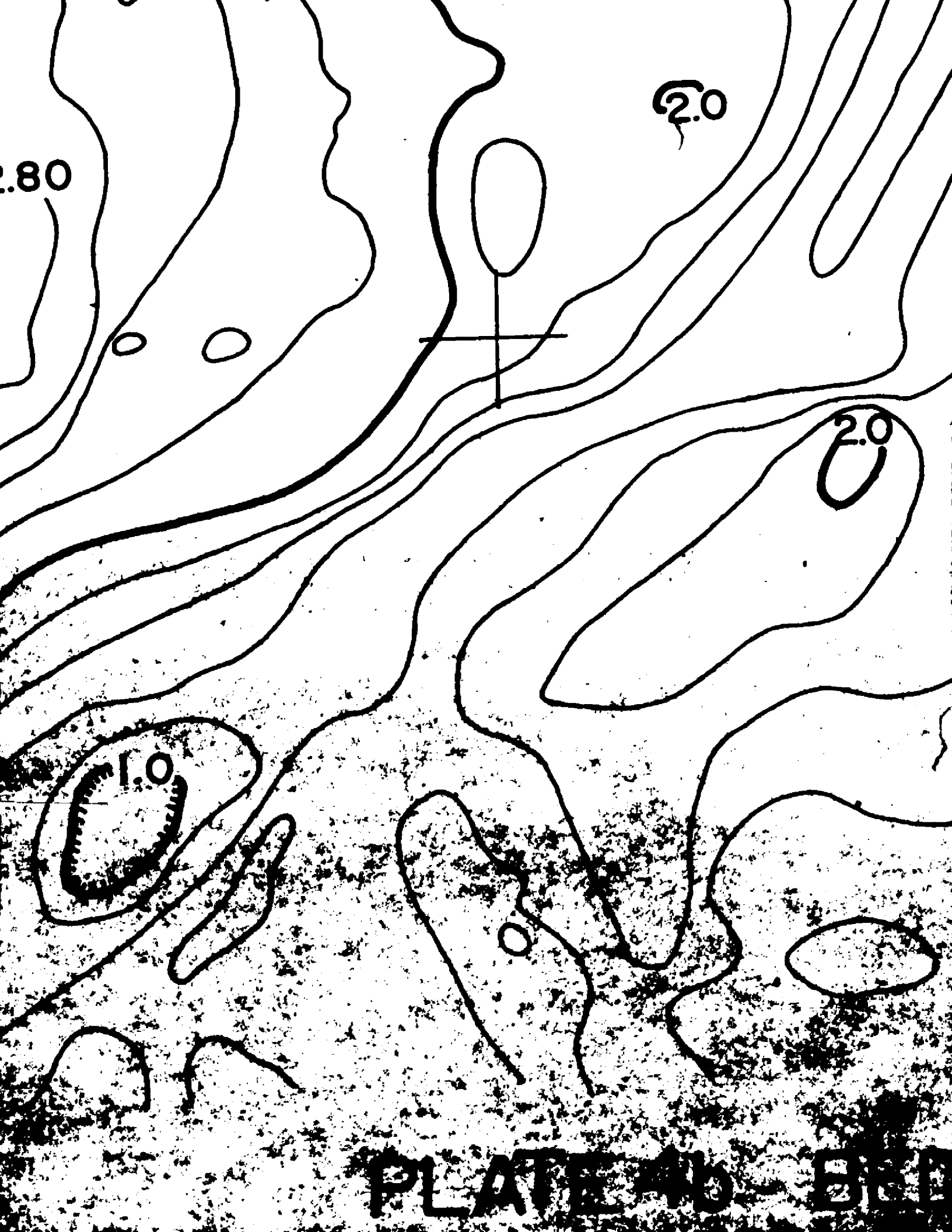


PLATE 46 - BIRD



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TR-46 BEDROCK TOPO



OCK TOPOGRAPHY R

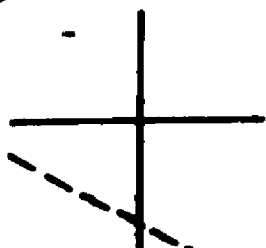
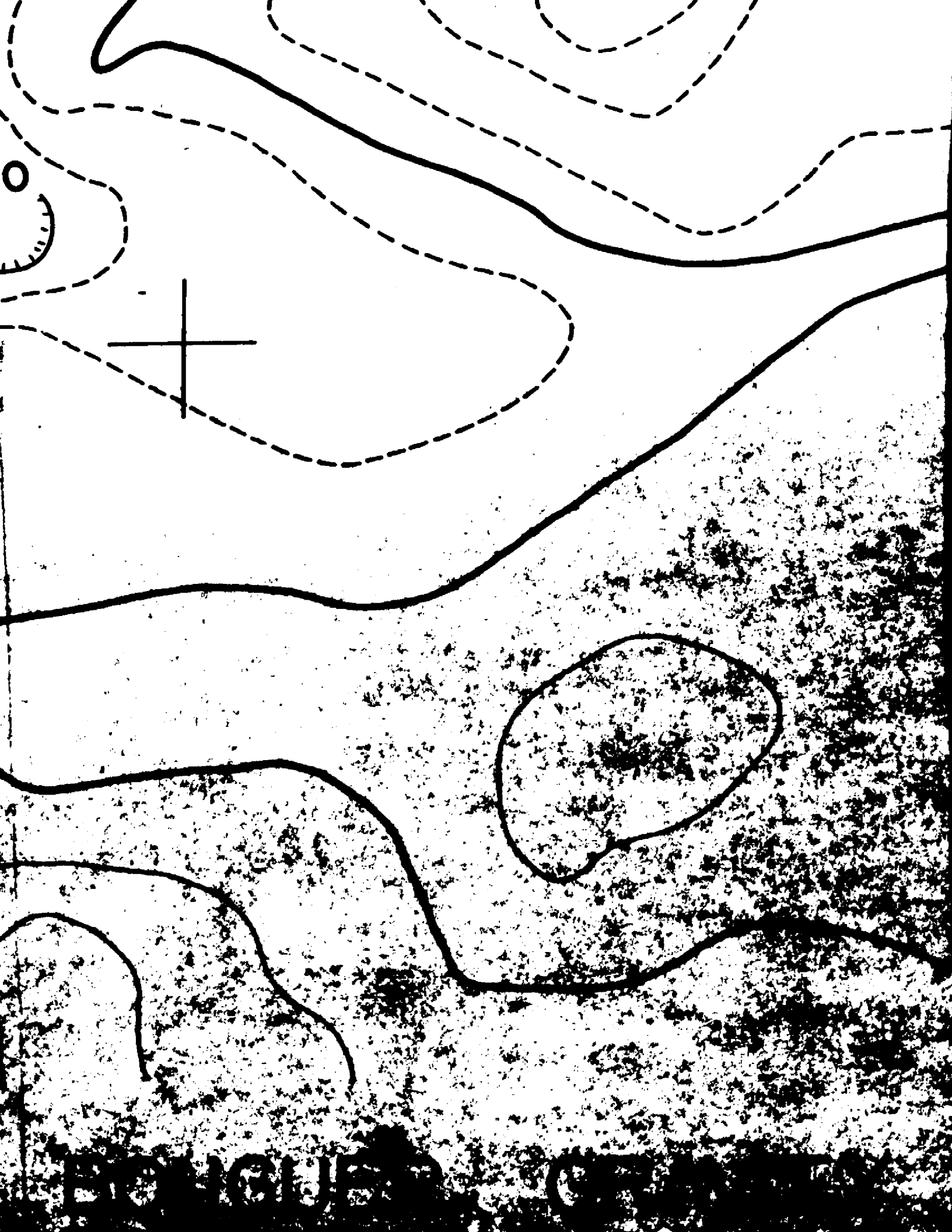


GRAPHY - RESIDUAL



1.40

WIGUER



LEONIGUE & COMPANY



SMALL



MAP



MAP

NORTHERN HALE

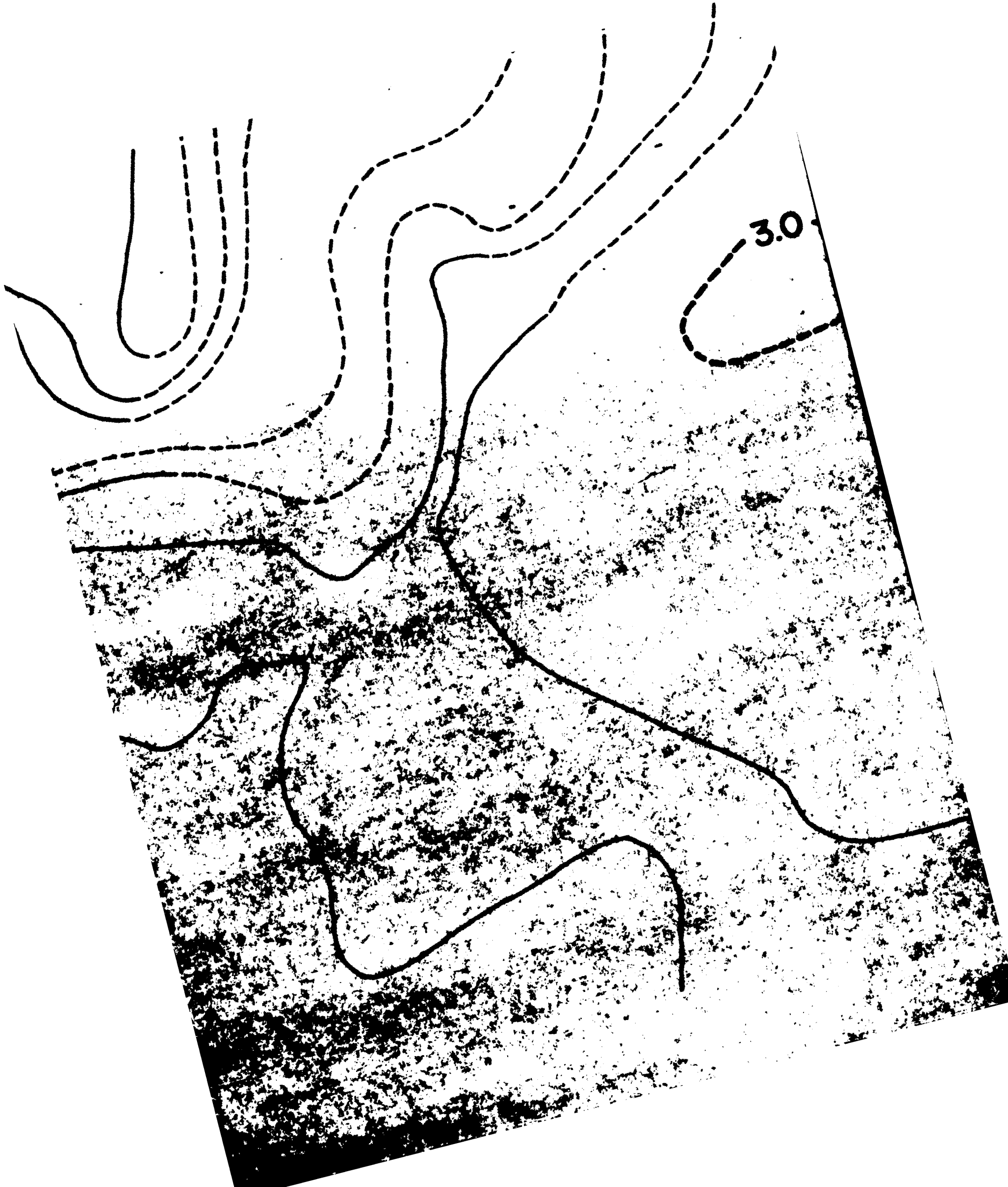


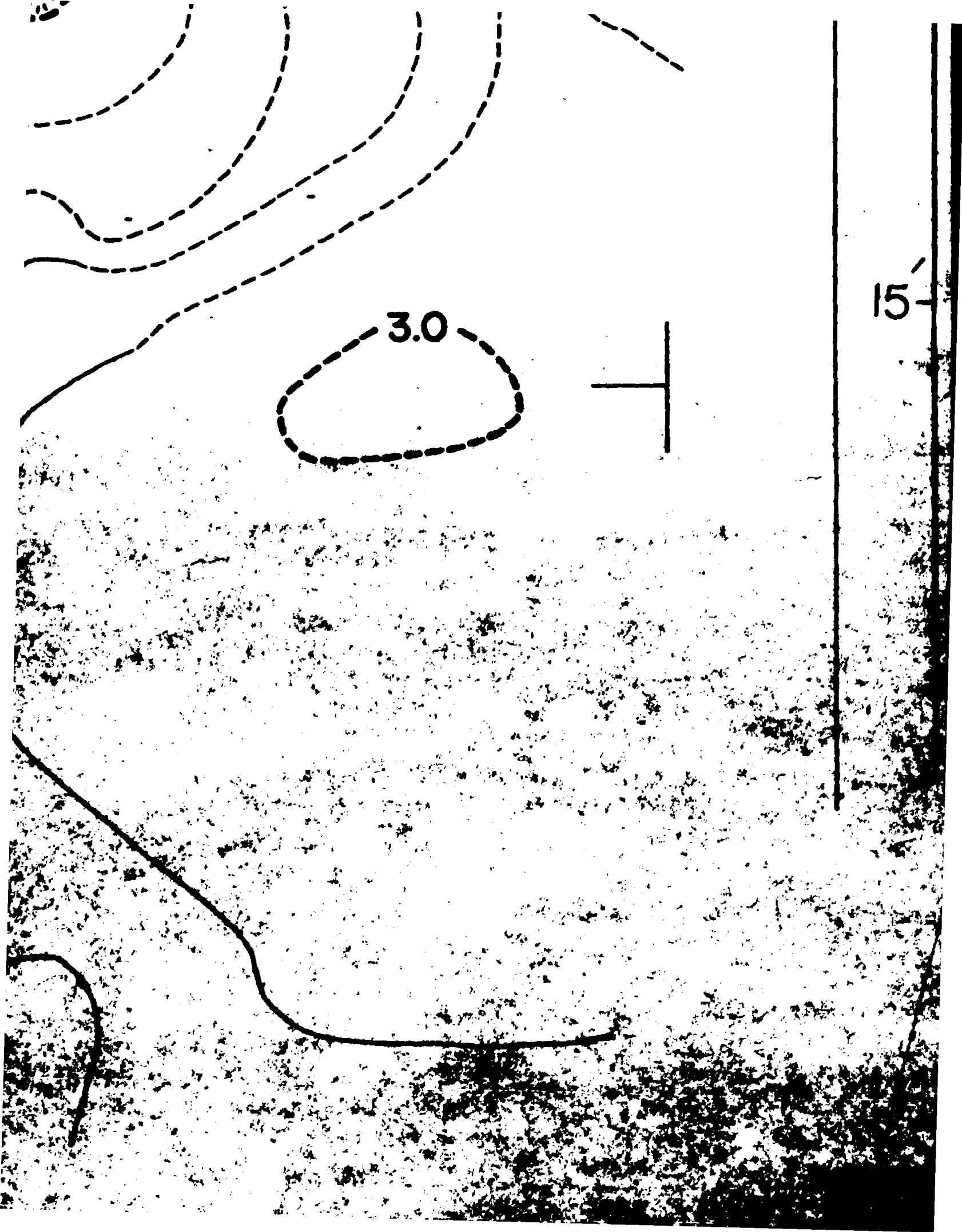
SOUTHERN HALF OF KALAMAZOO



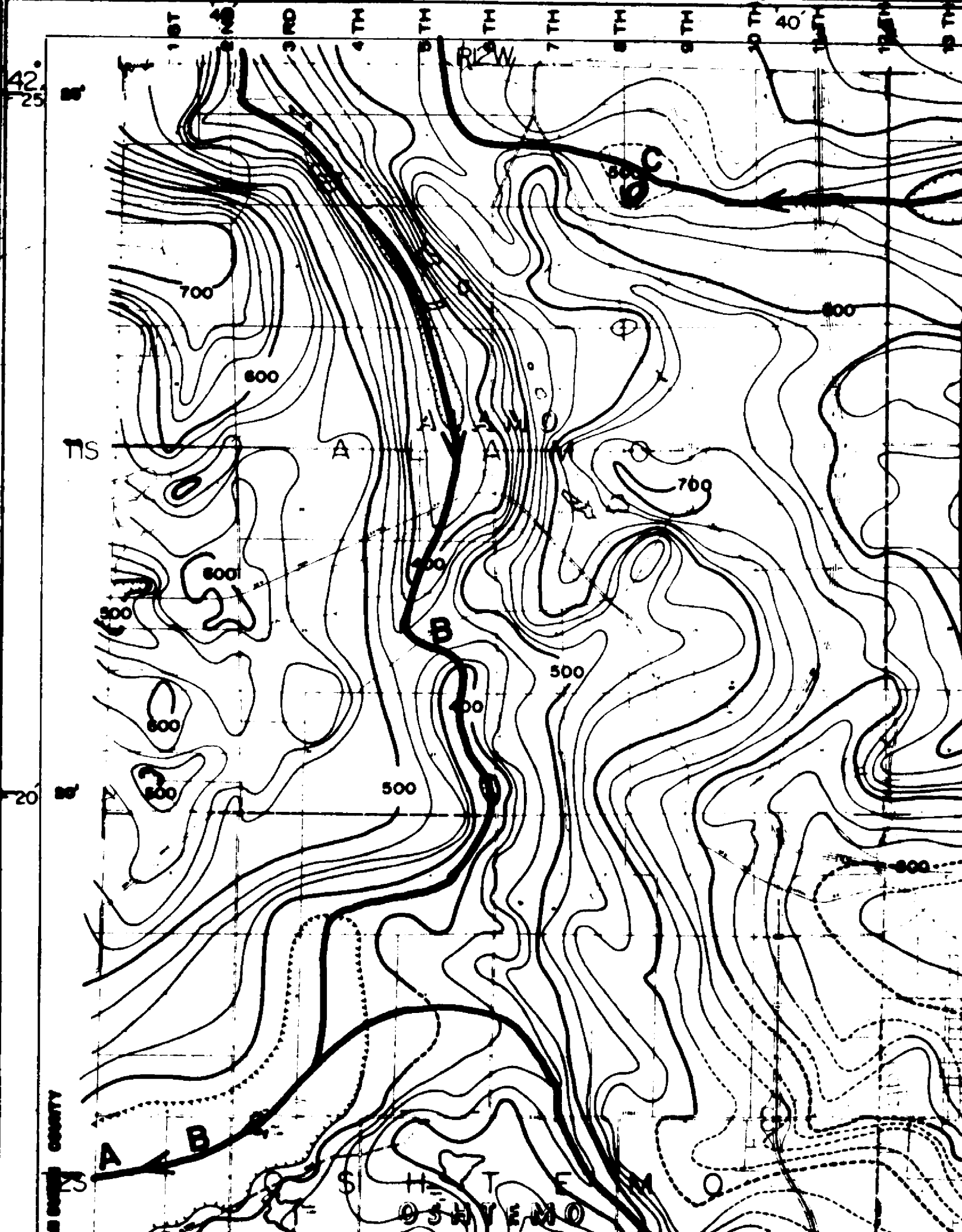
3.0

KALAMAZOO COUNTY

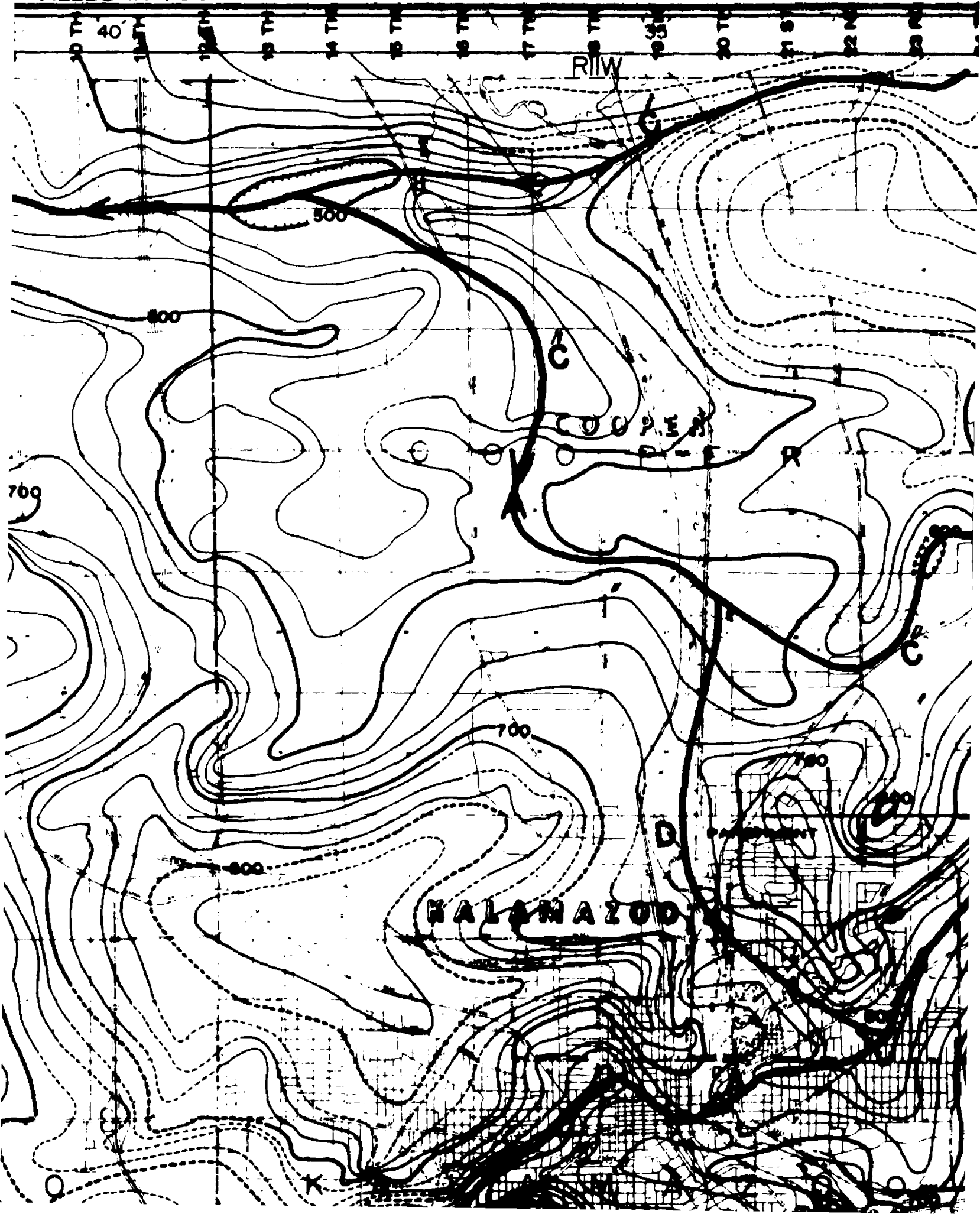


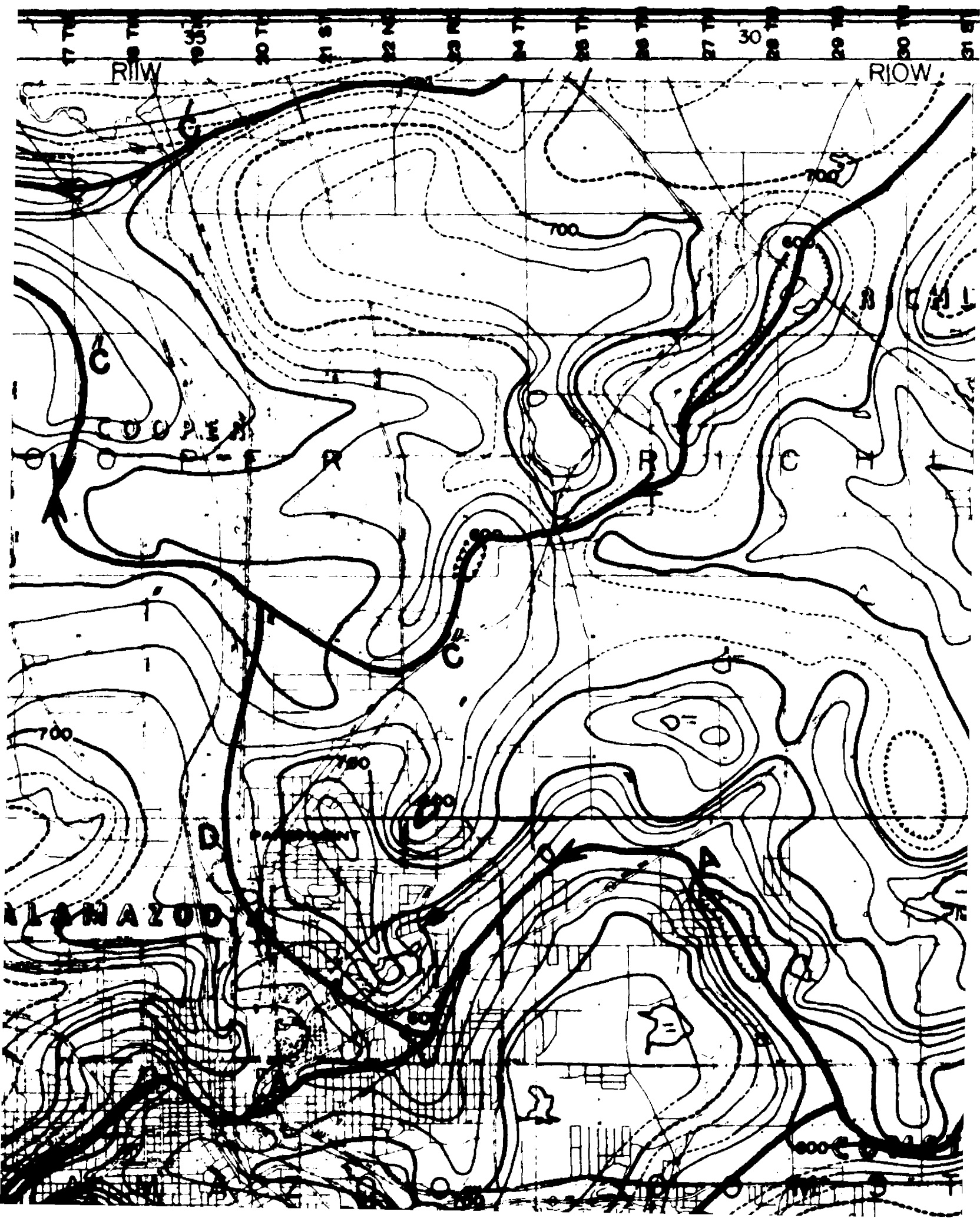


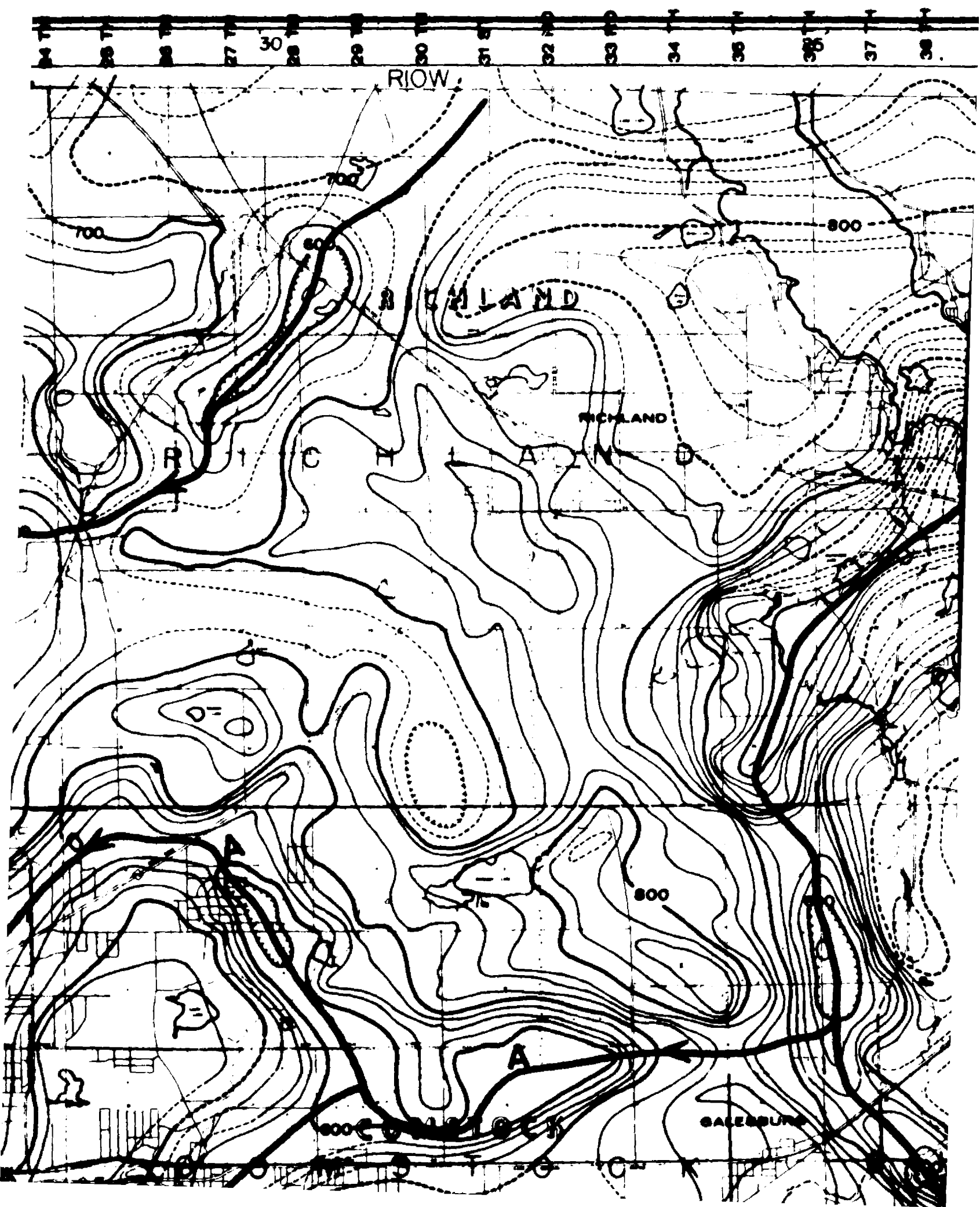
42° 25'



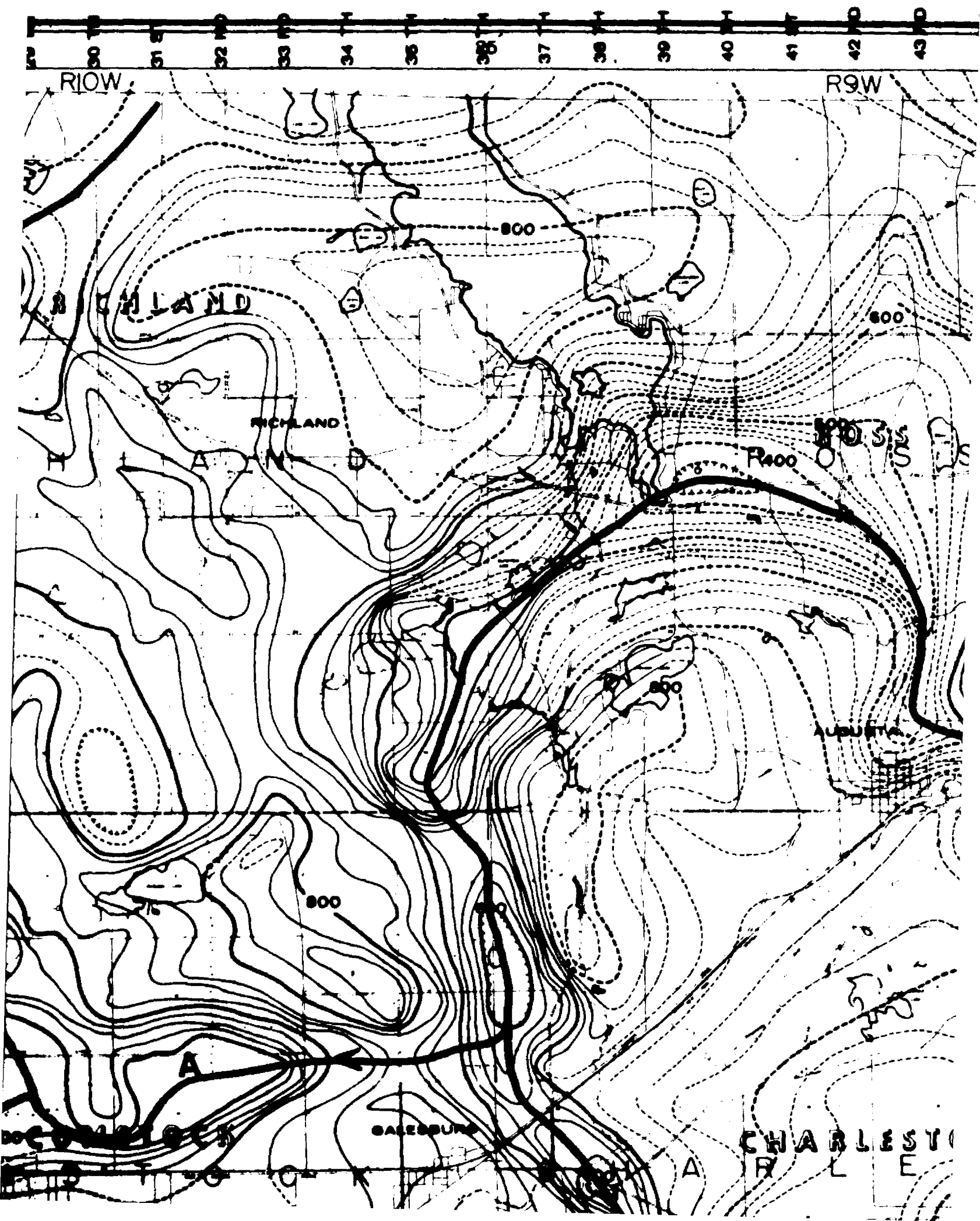
ALLEGAN COUNTY

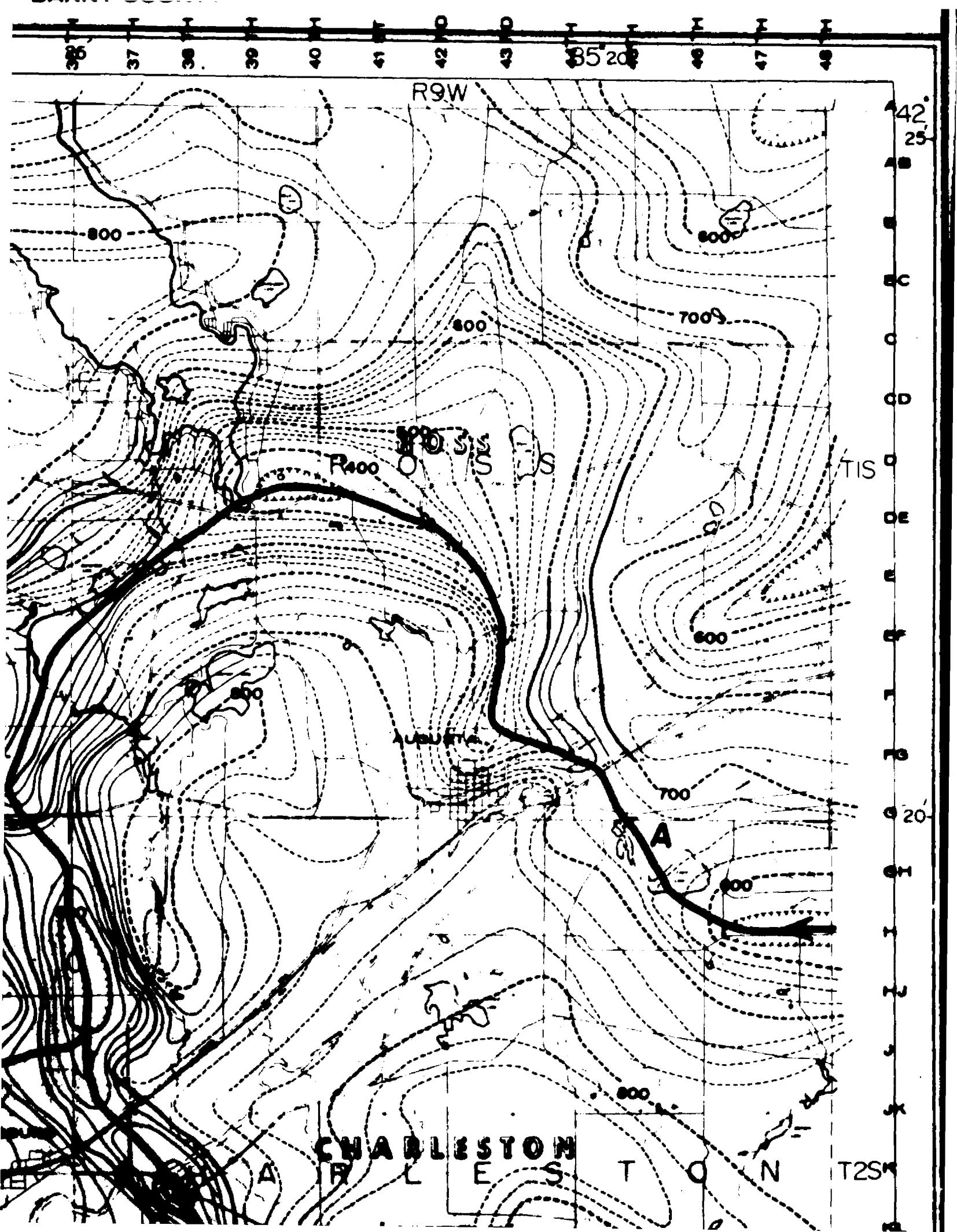


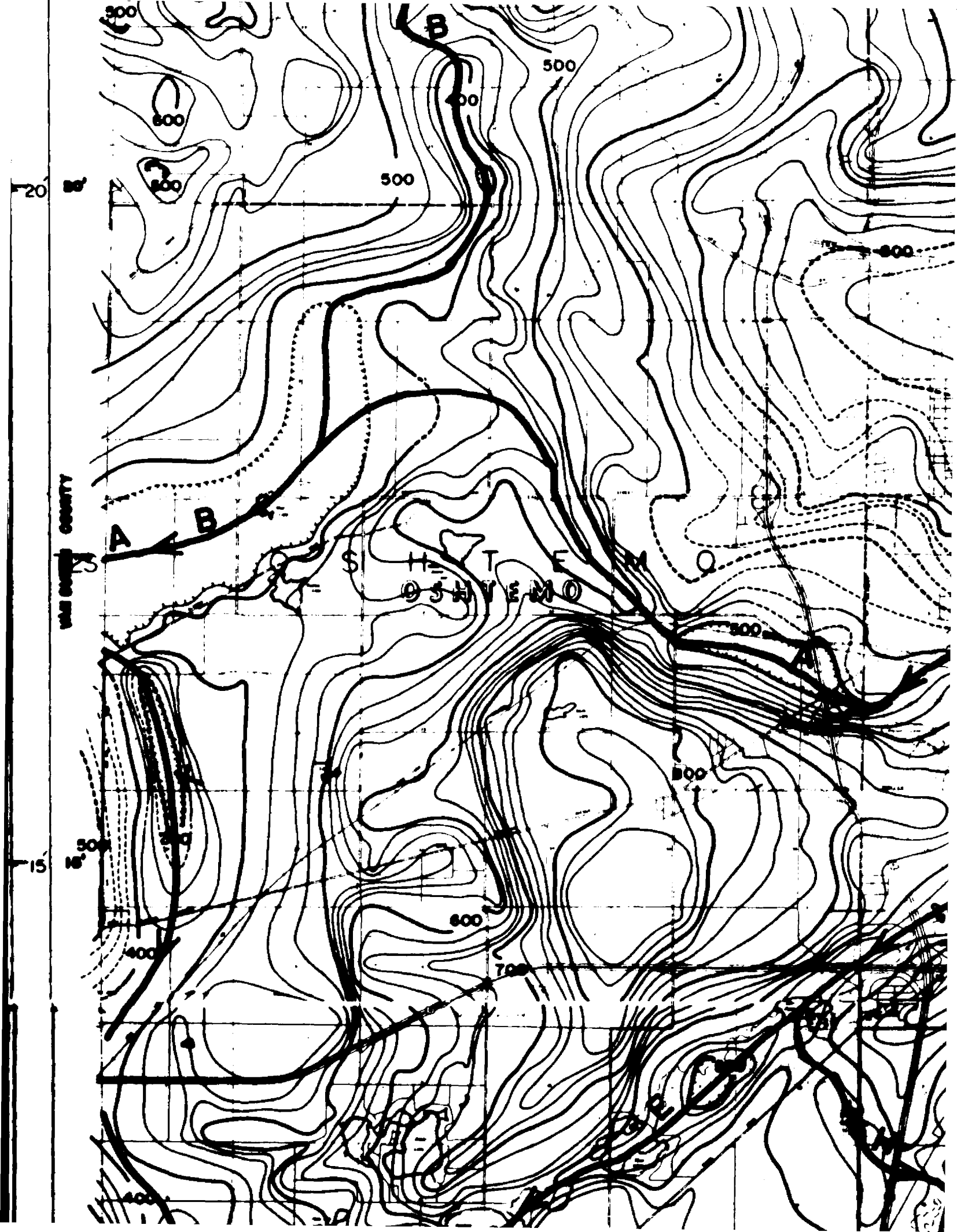


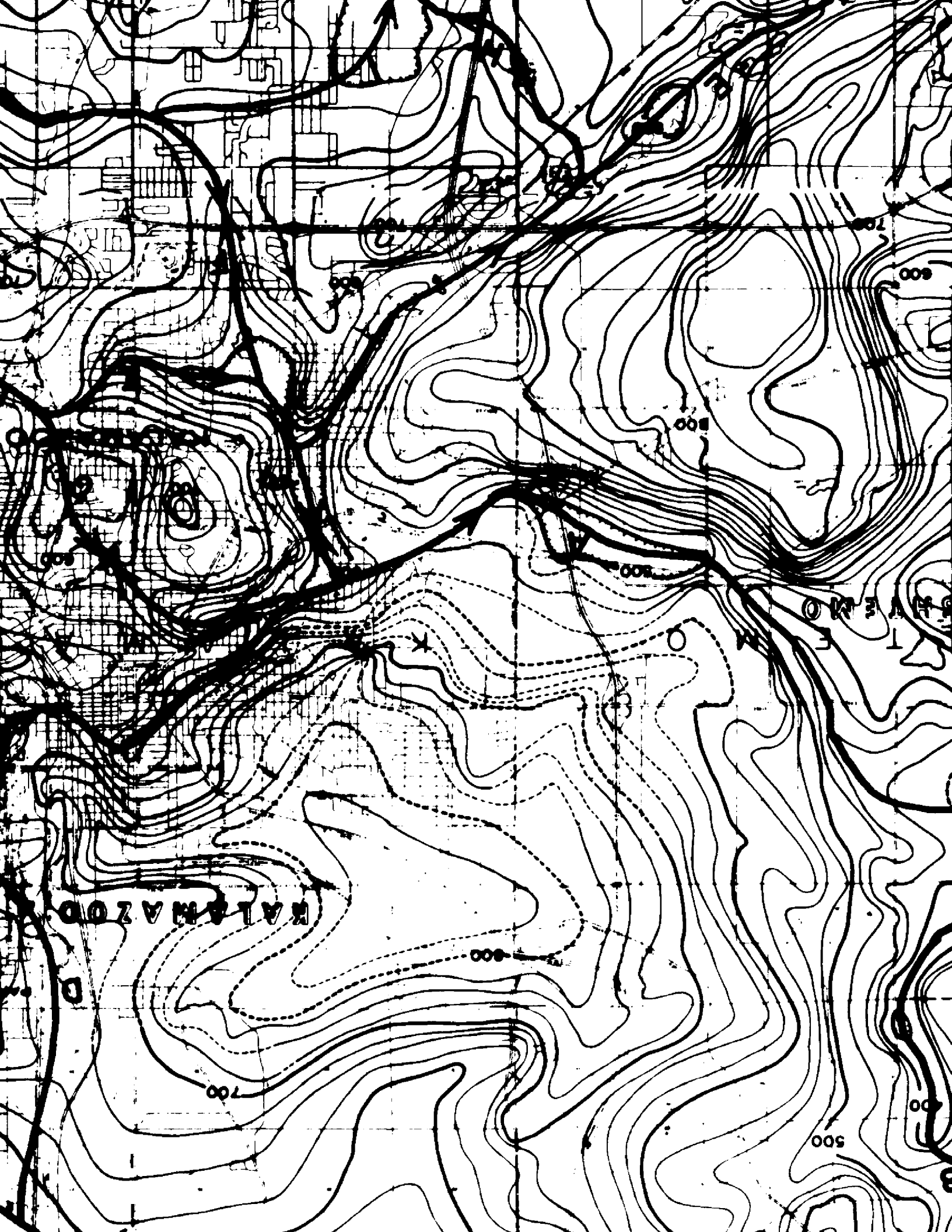


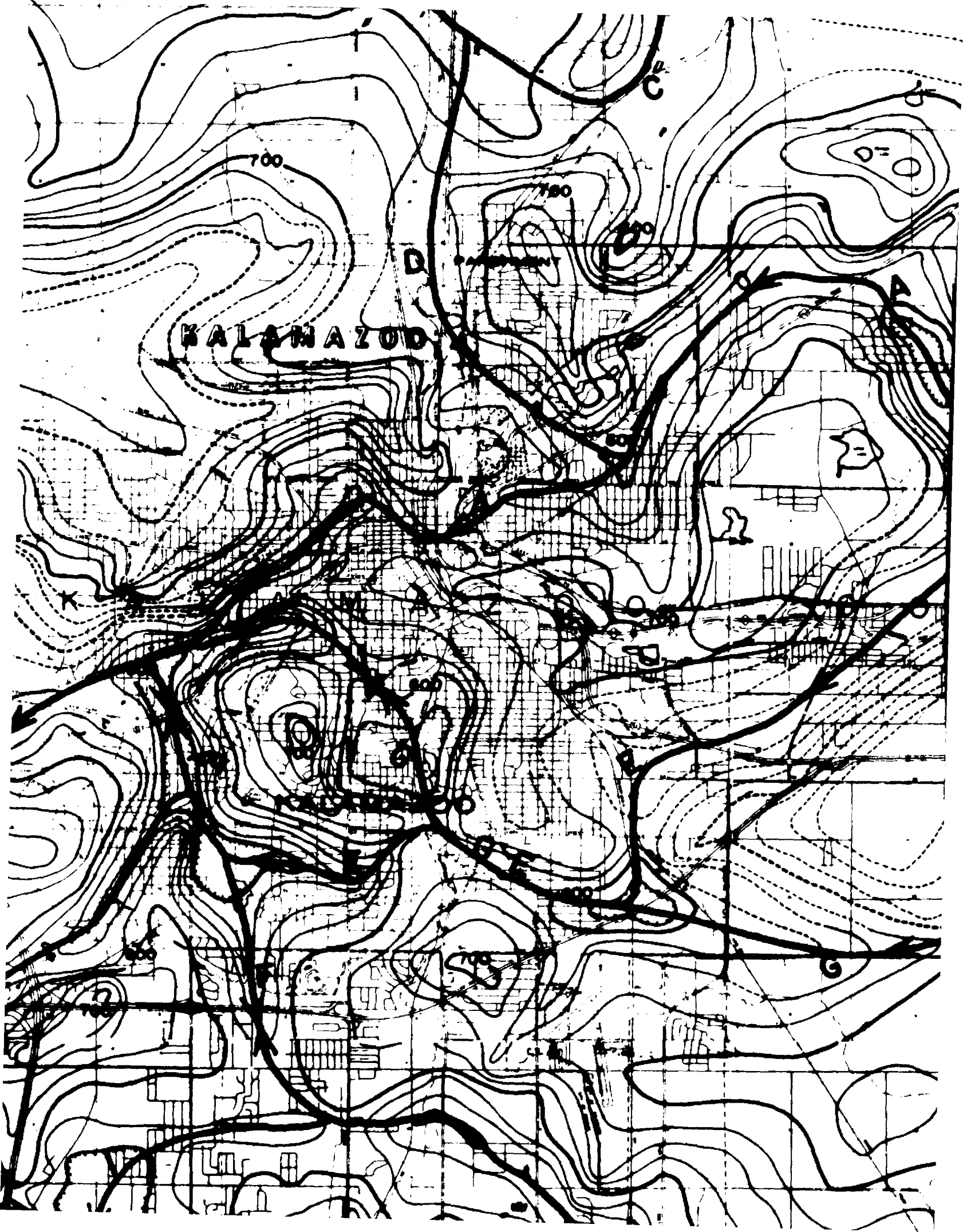
BARRY COUNTY

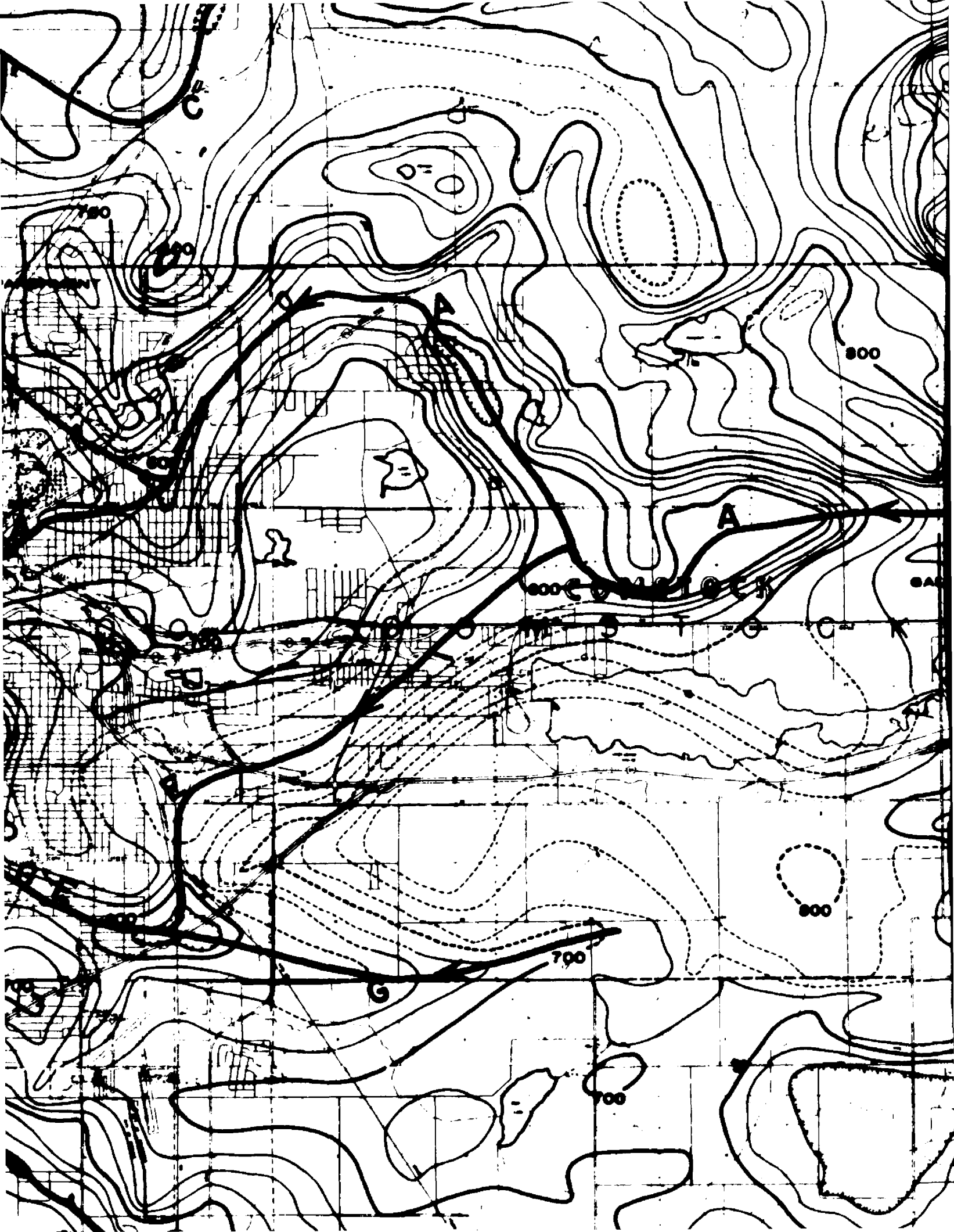


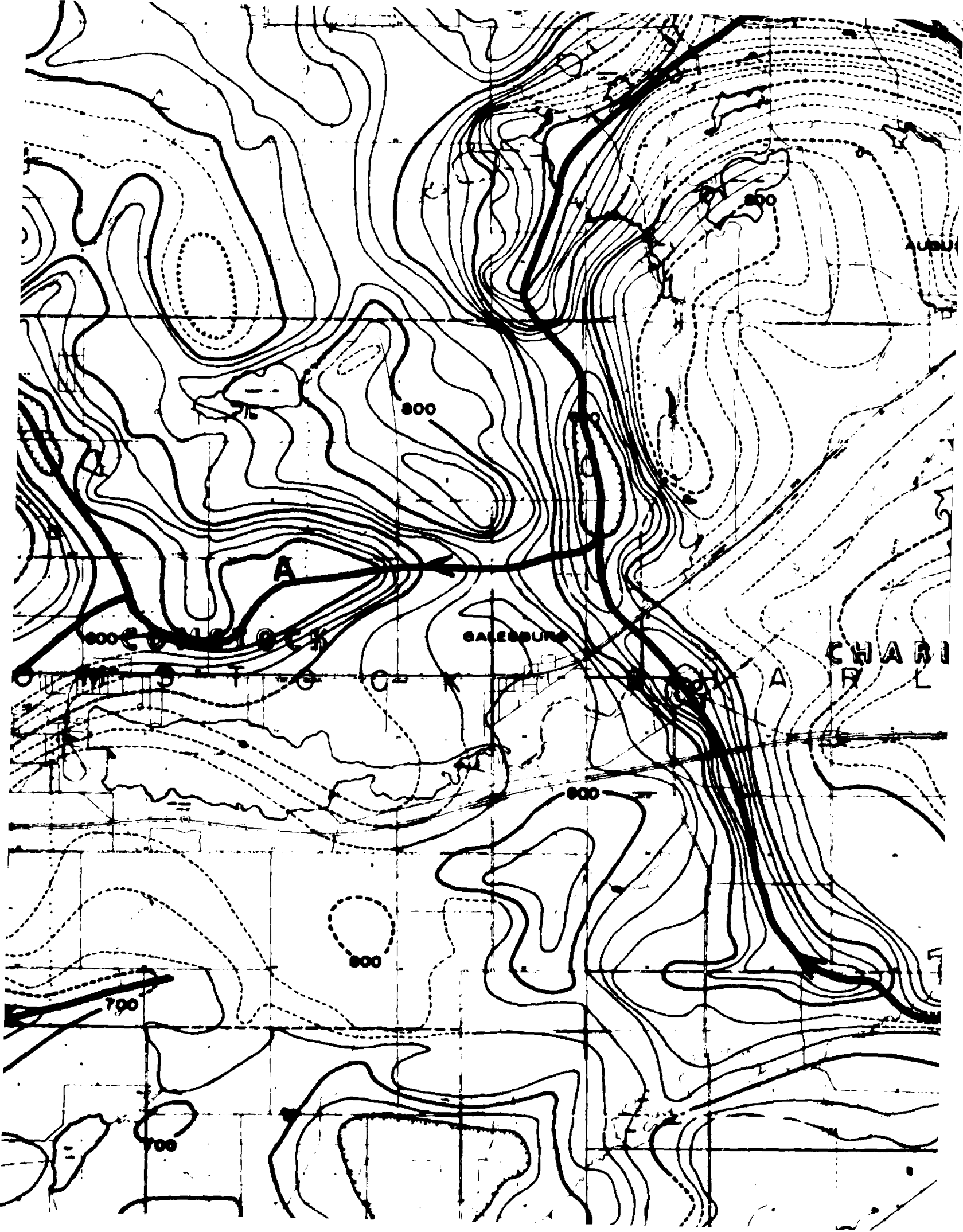


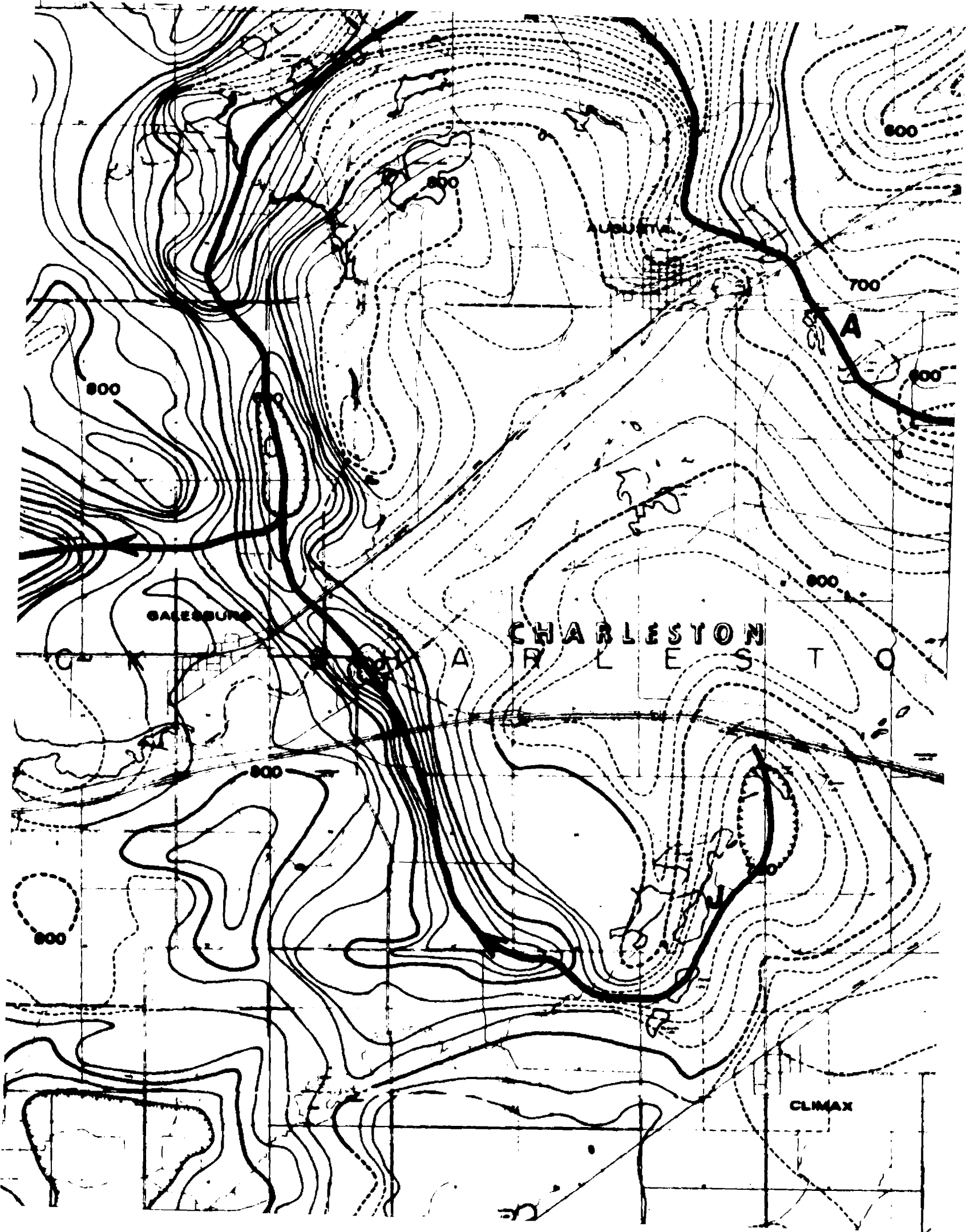


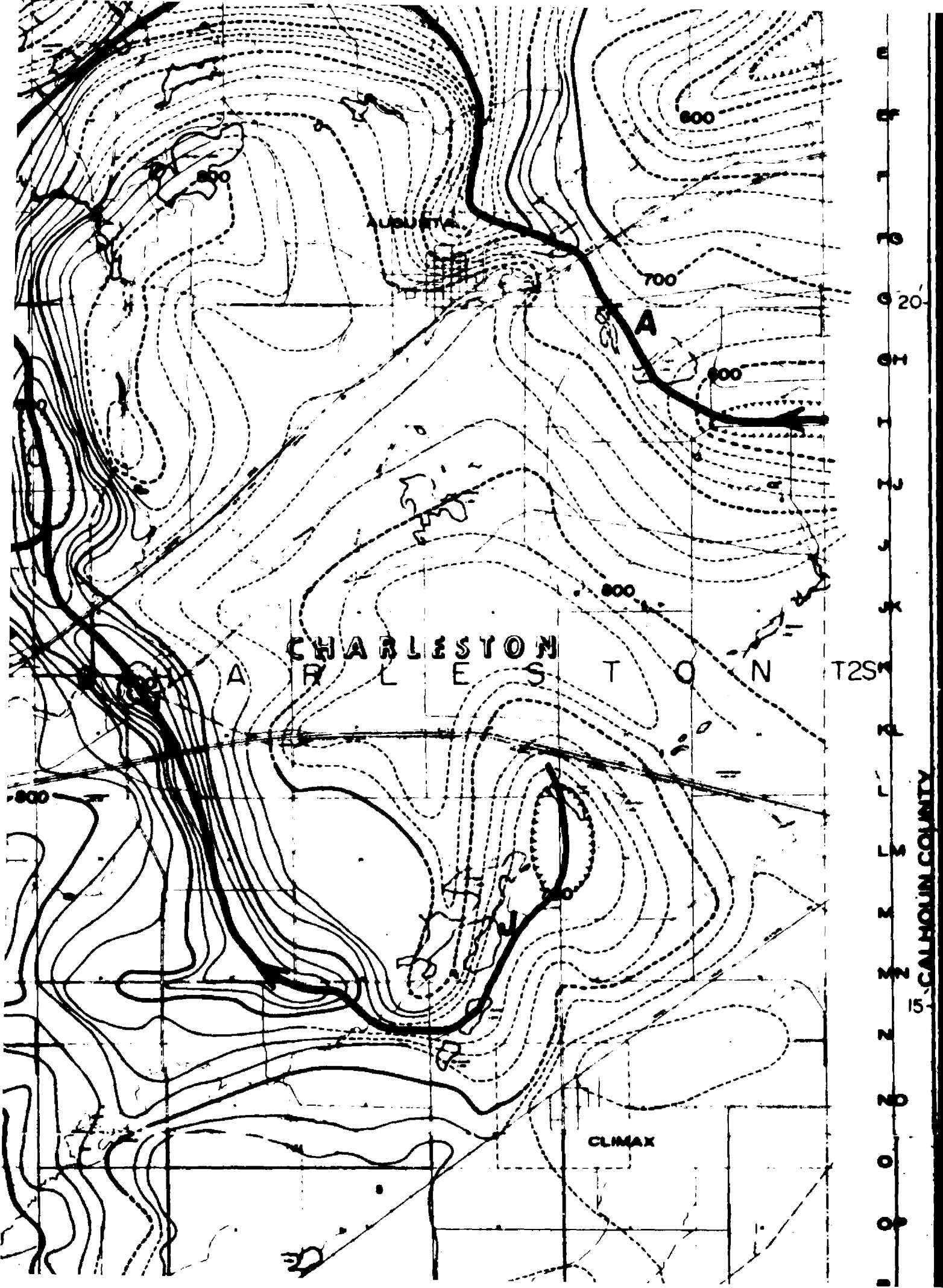


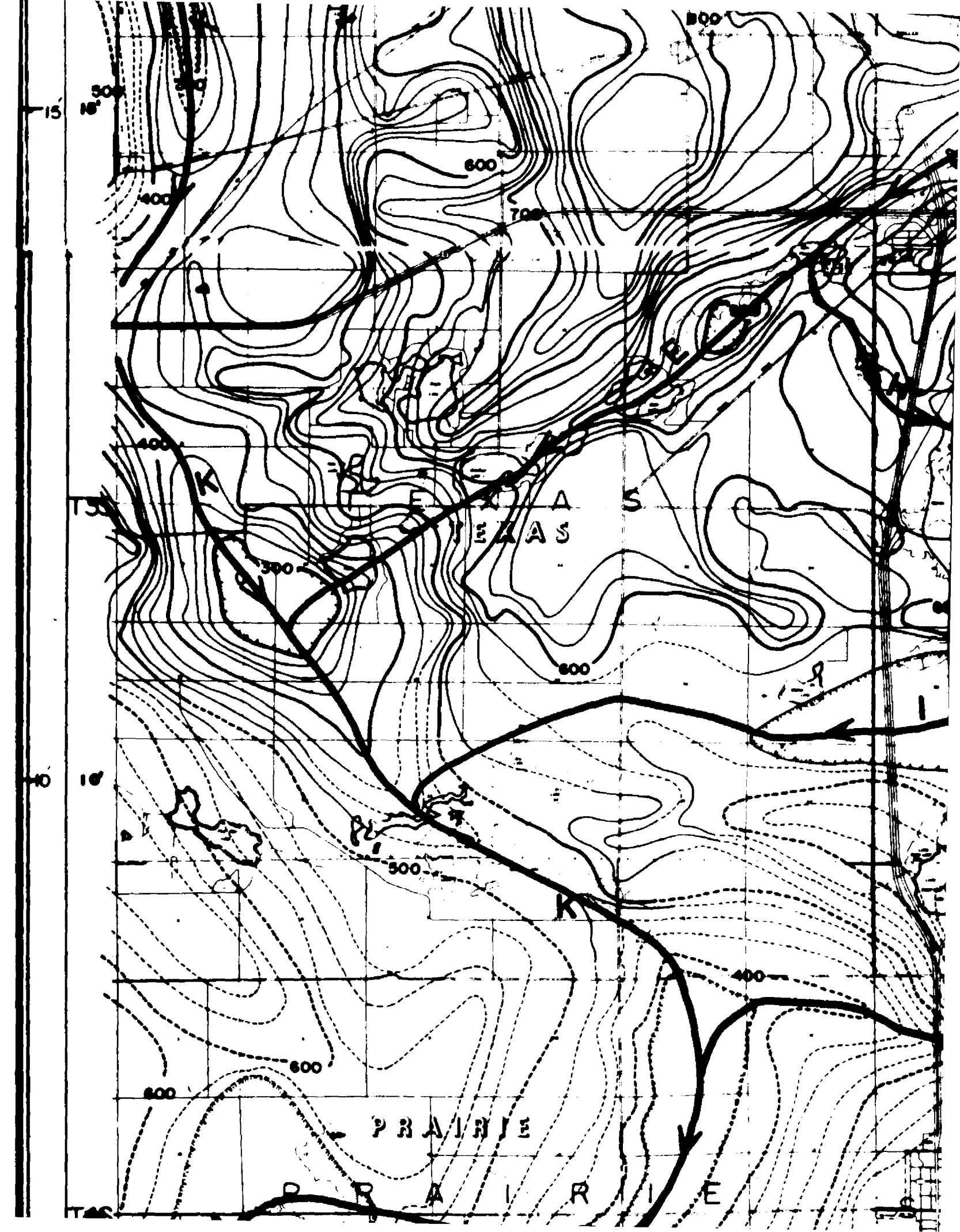


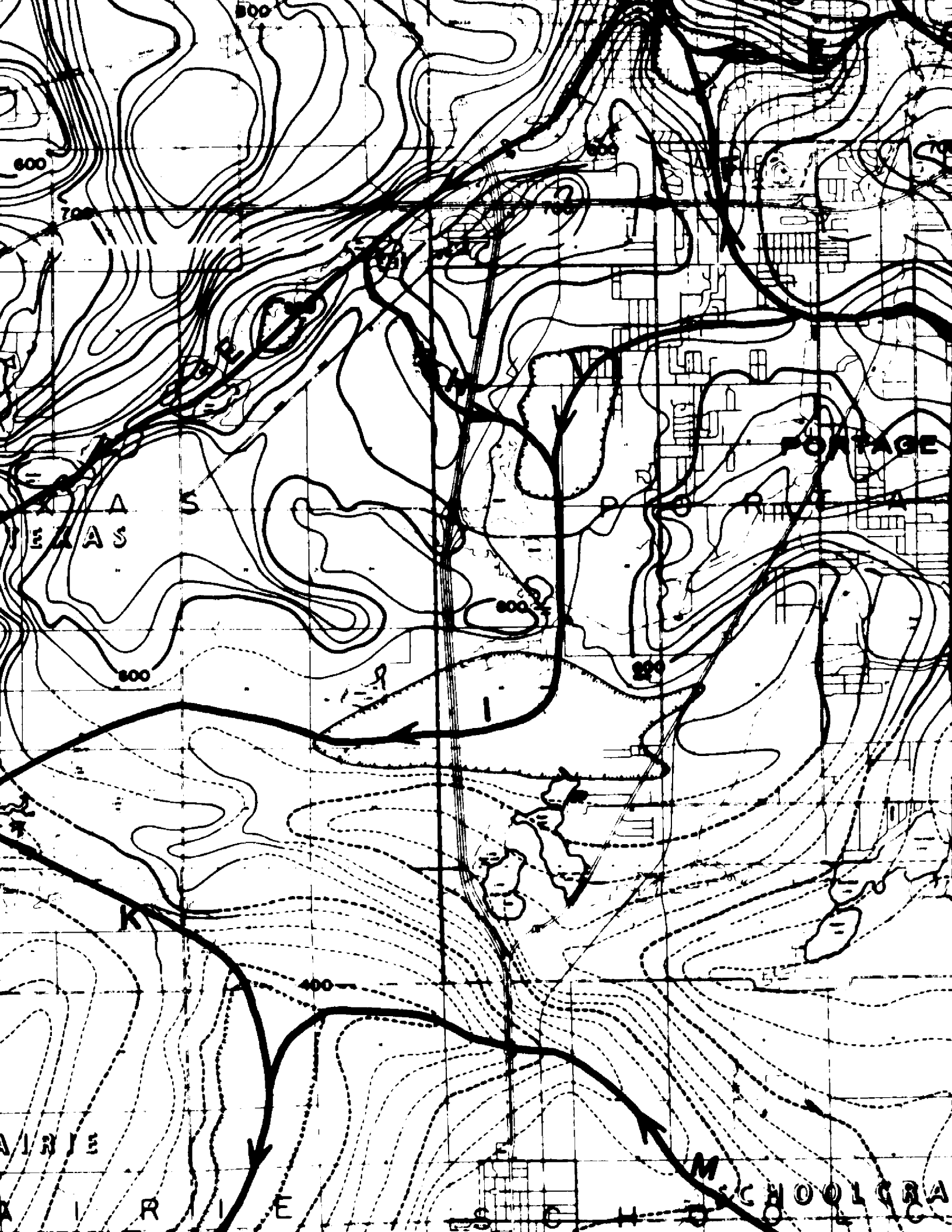


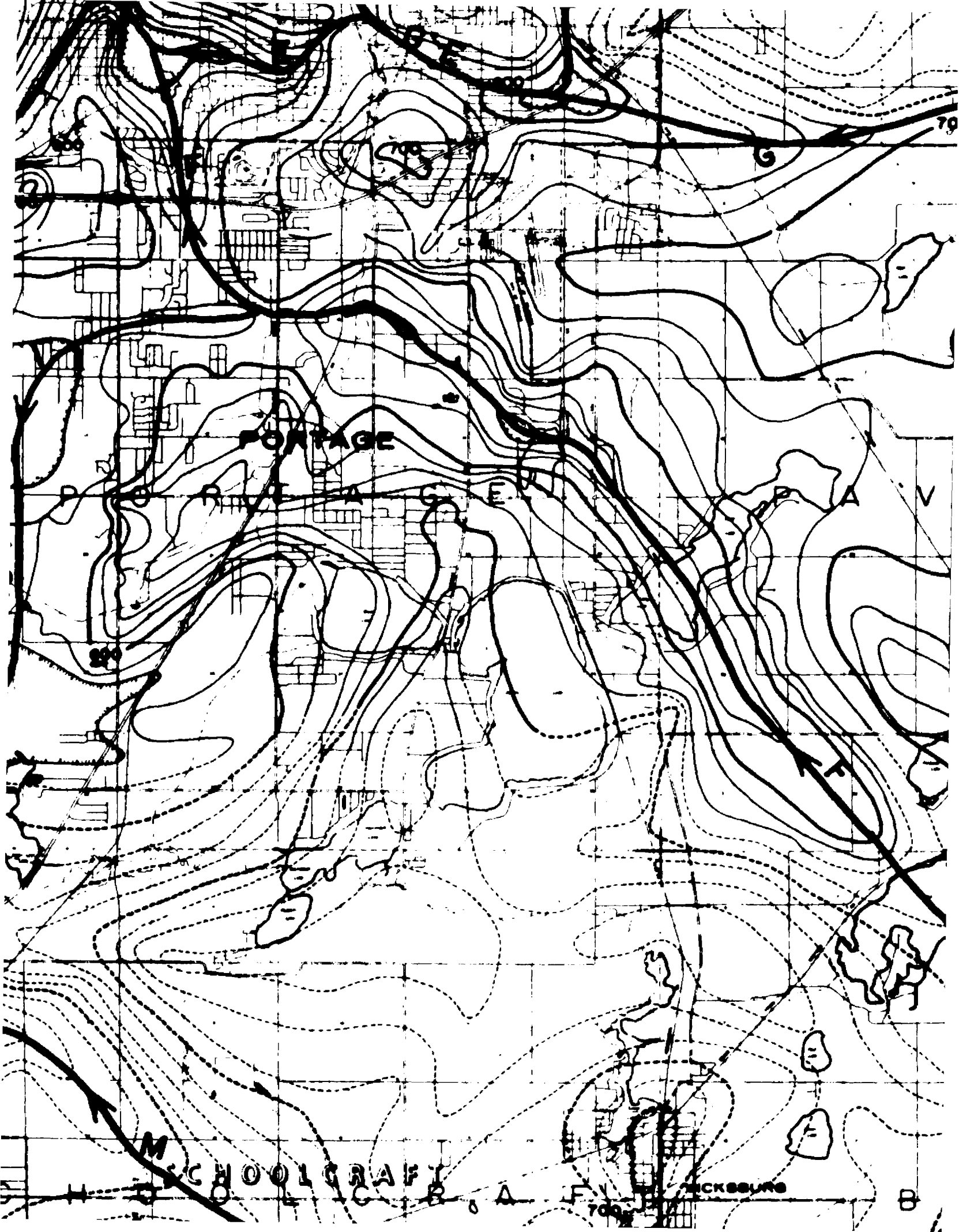


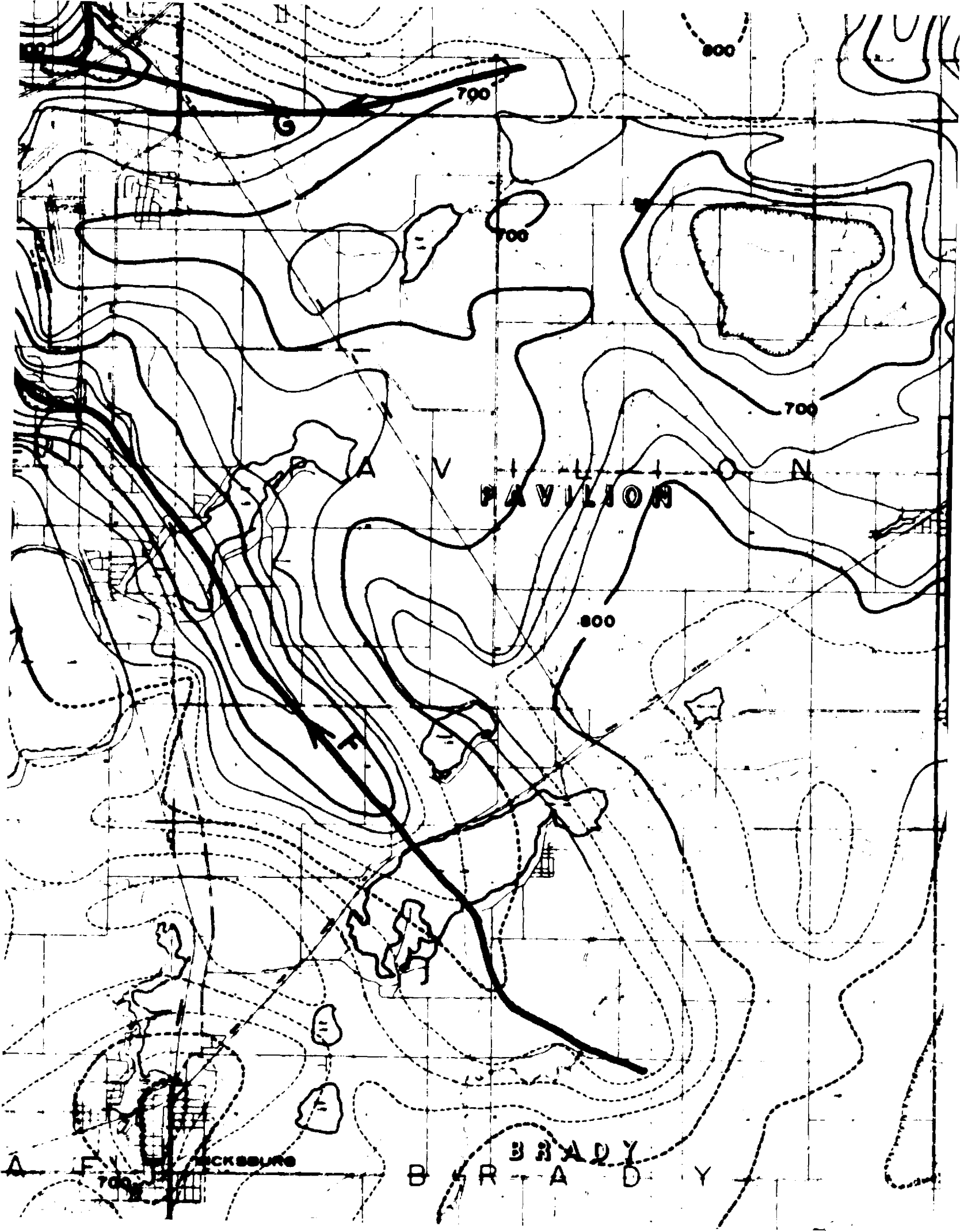


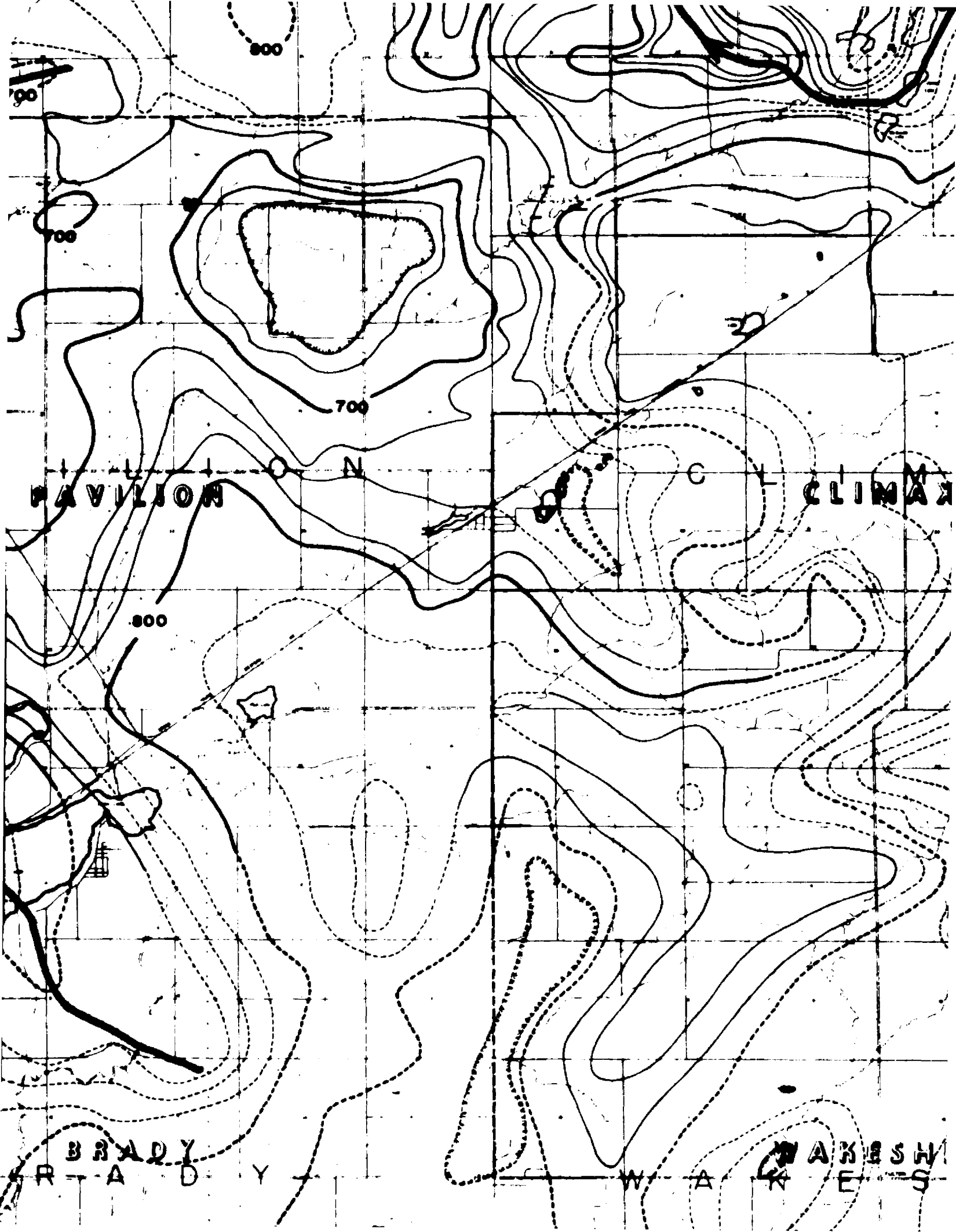


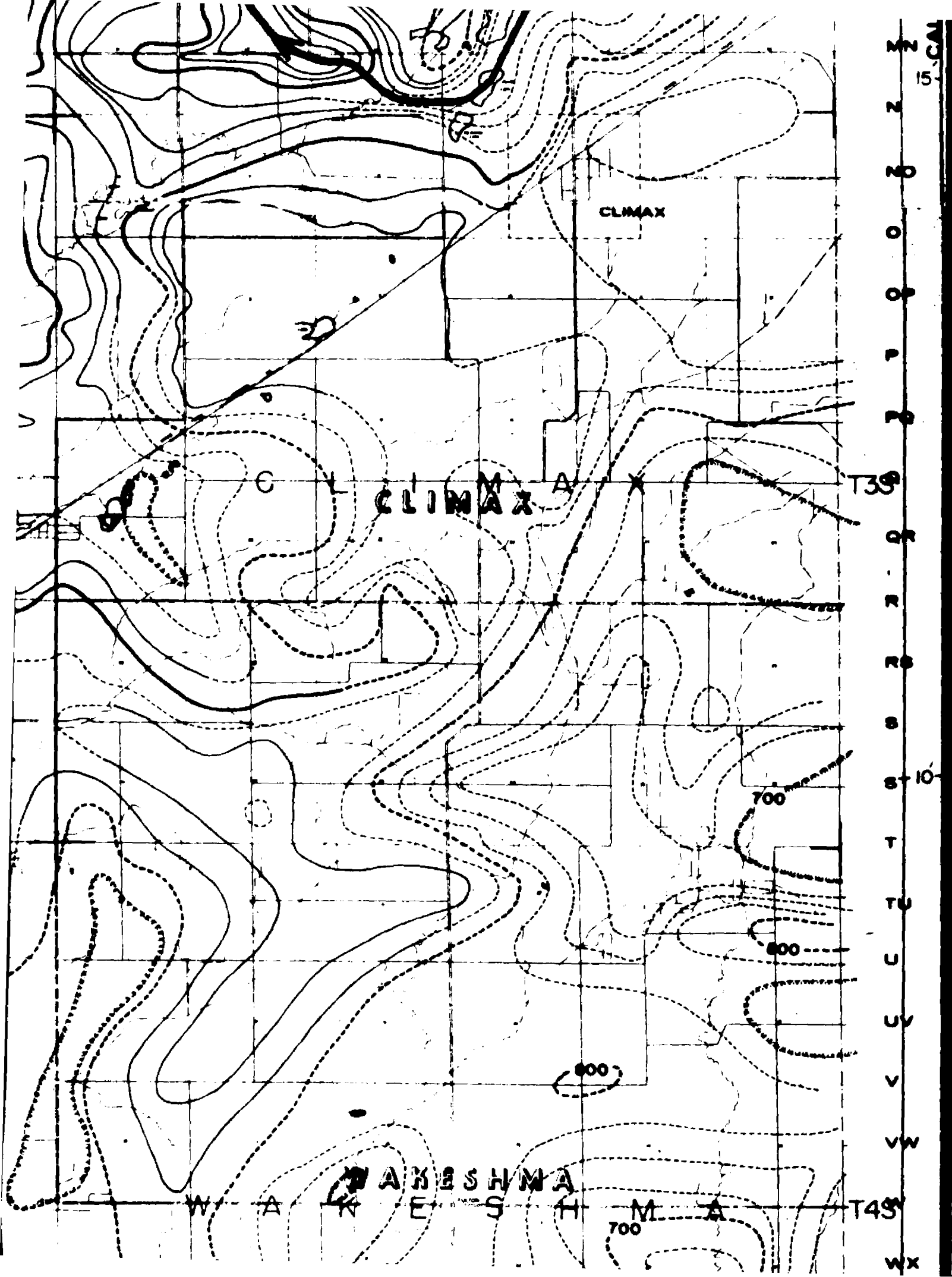


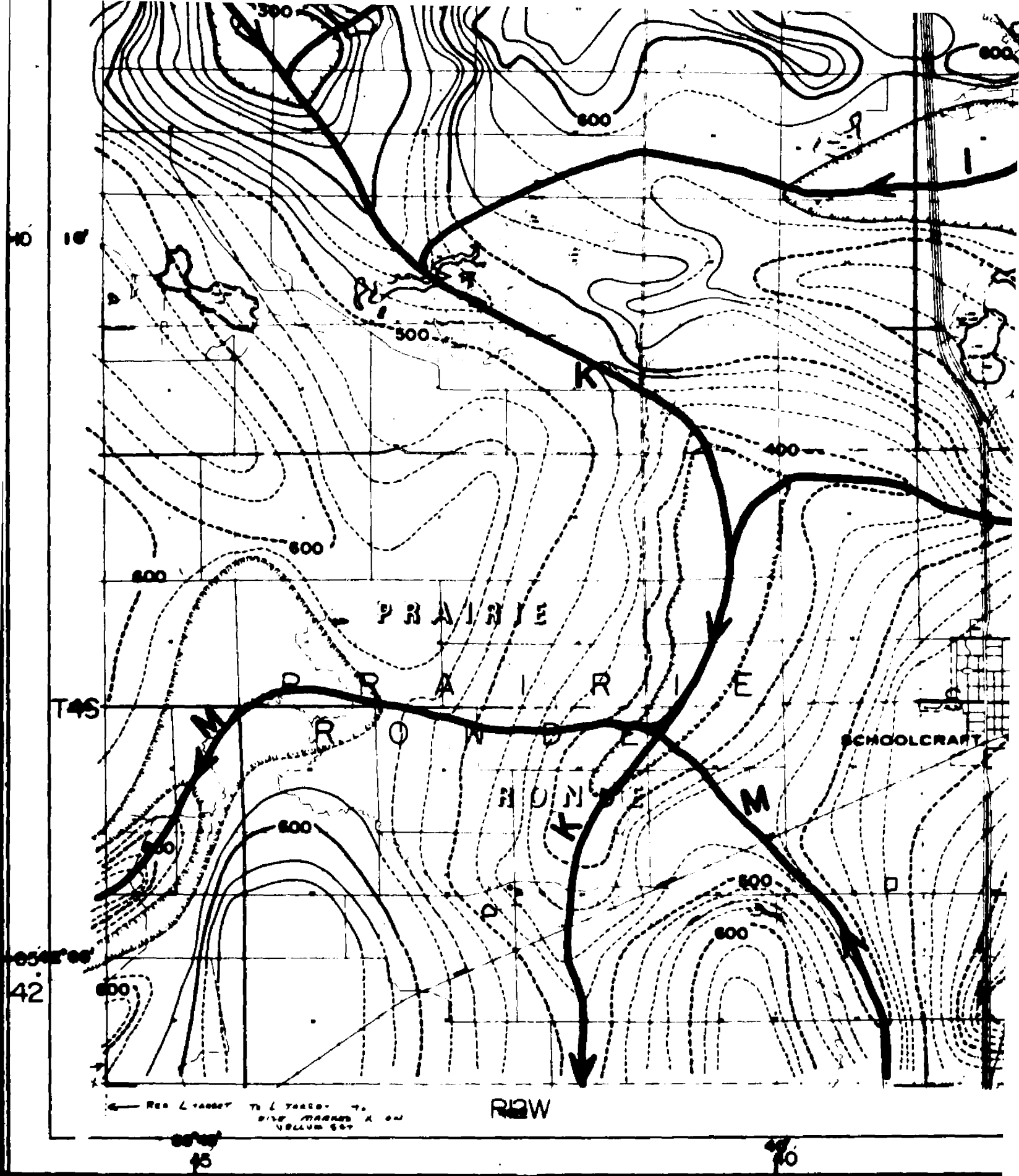


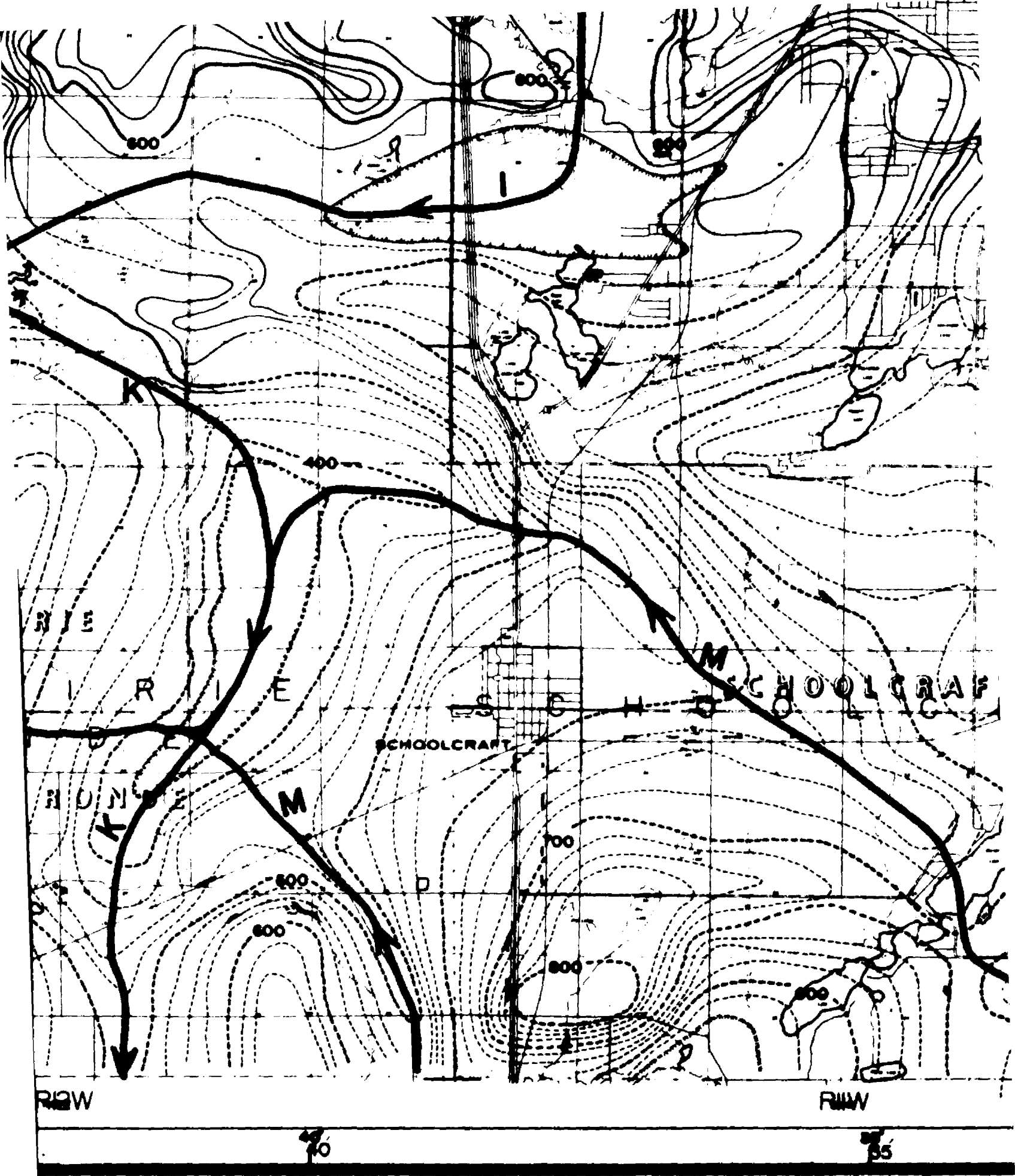


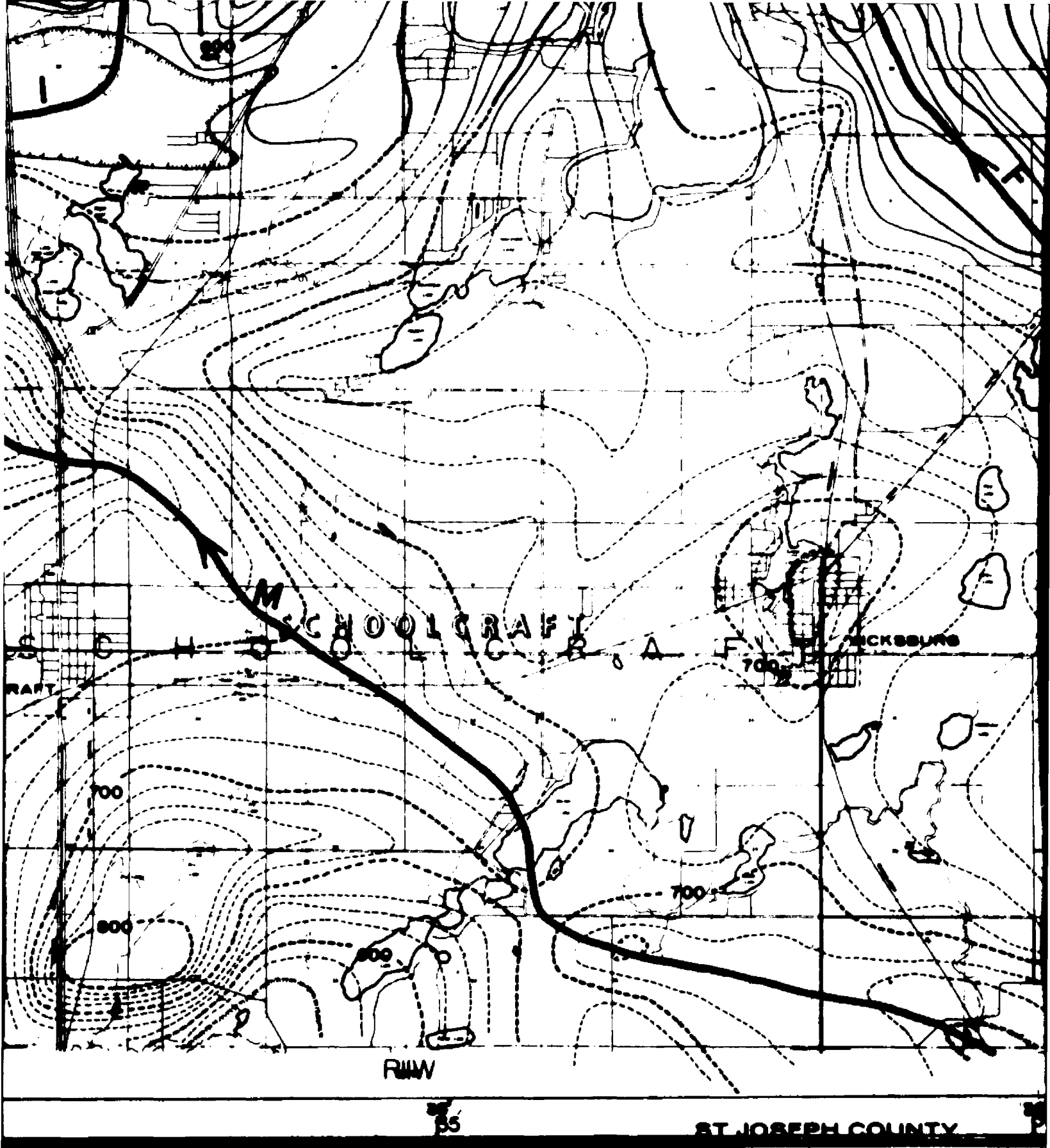




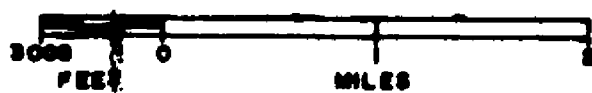


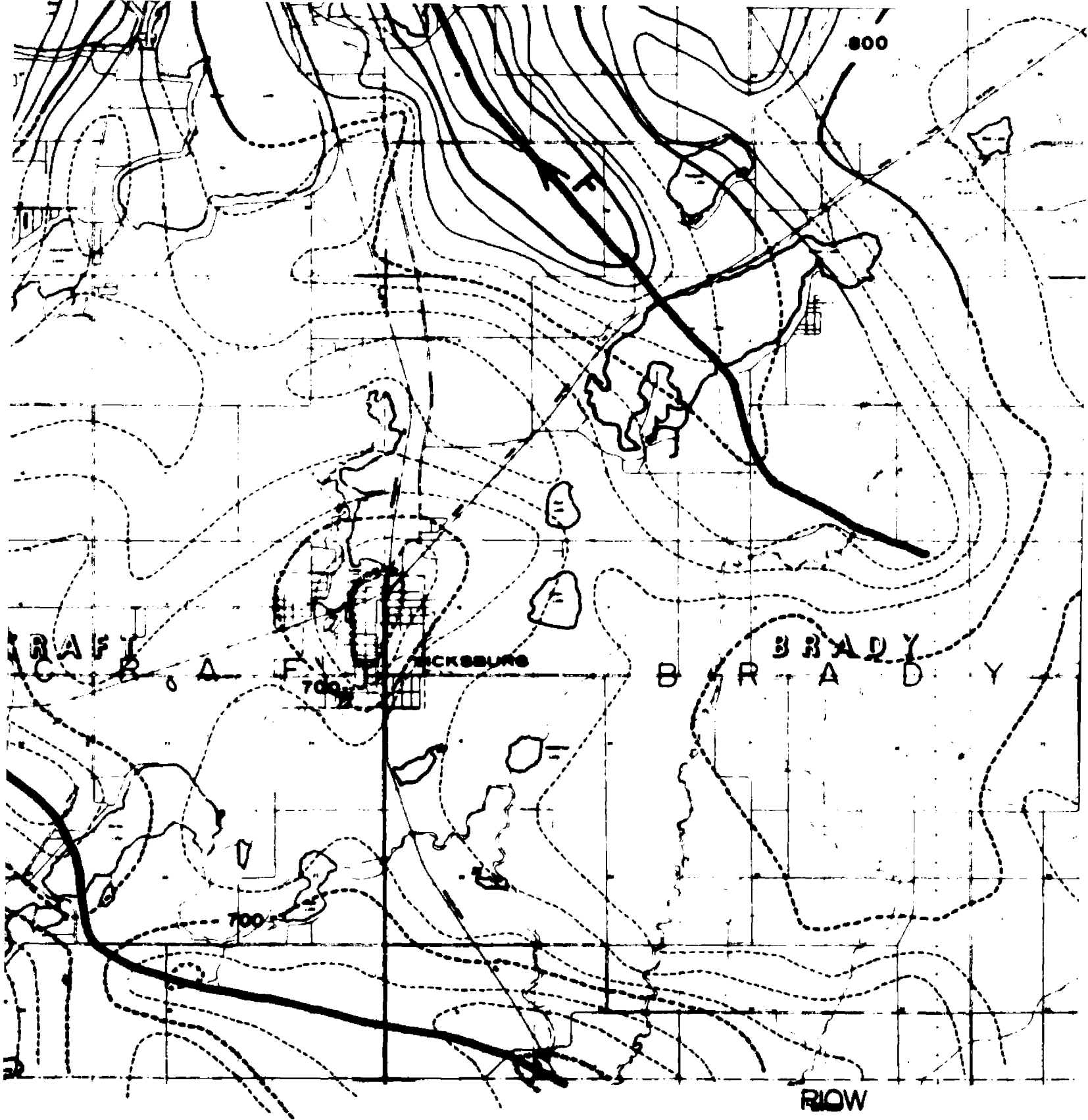






BEDROCK TOPOGRAPHIC MAP OF KALAMAZOO

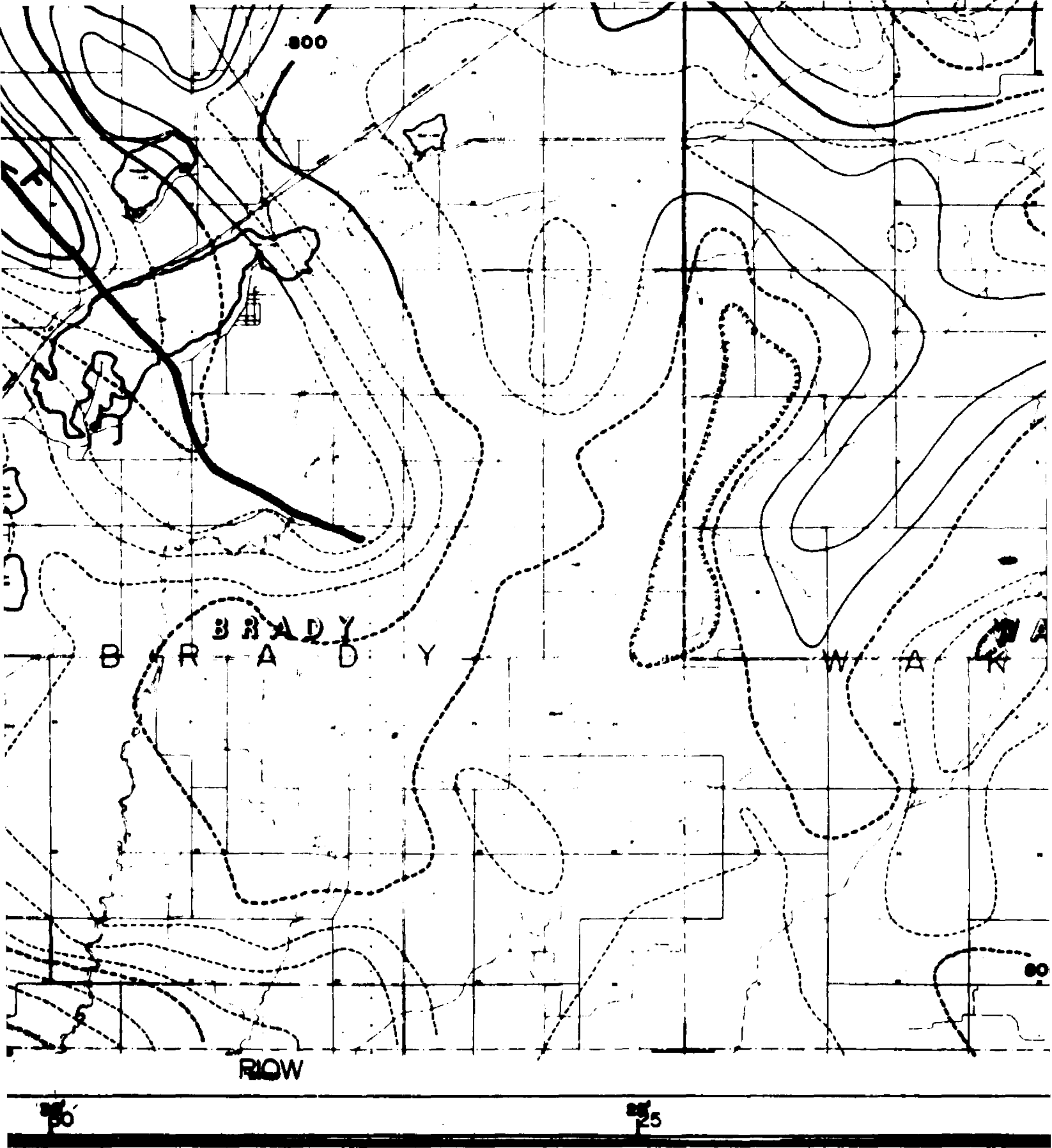




ST. JOSEPH COUNTY

TOPOGRAPHIC MAP OF KALAMAZOO COUNTY, MICHIGAN

CONTOUR INTERVAL 25 FEET
DATUM SEA LEVEL



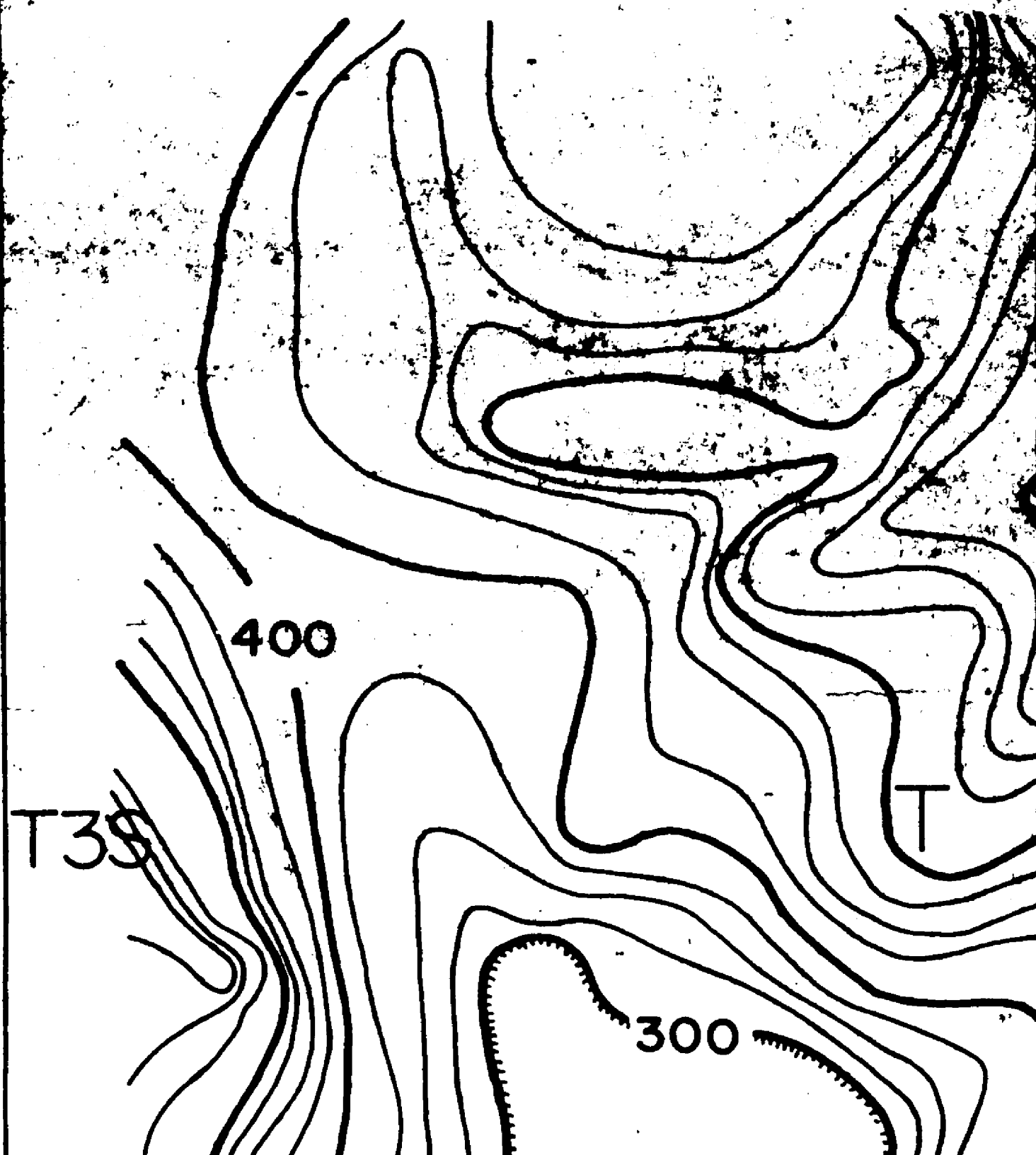
AMAZOO COUNTY, MICHIGAN

CONTOUR INTERVAL 25 FEET

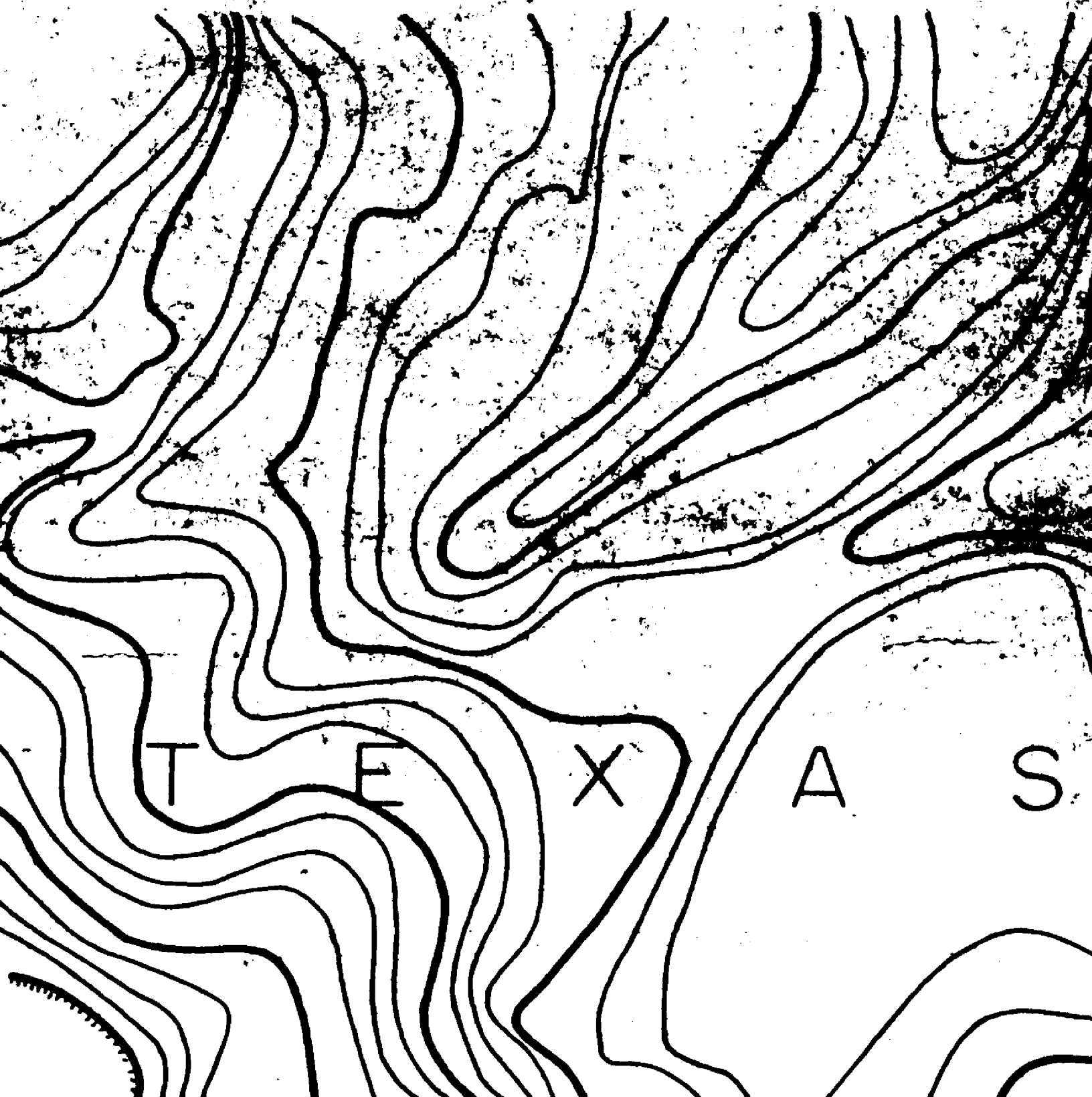
DATUM SEA LEVEL



PLATE E 6



ATE 6a BEDROCK



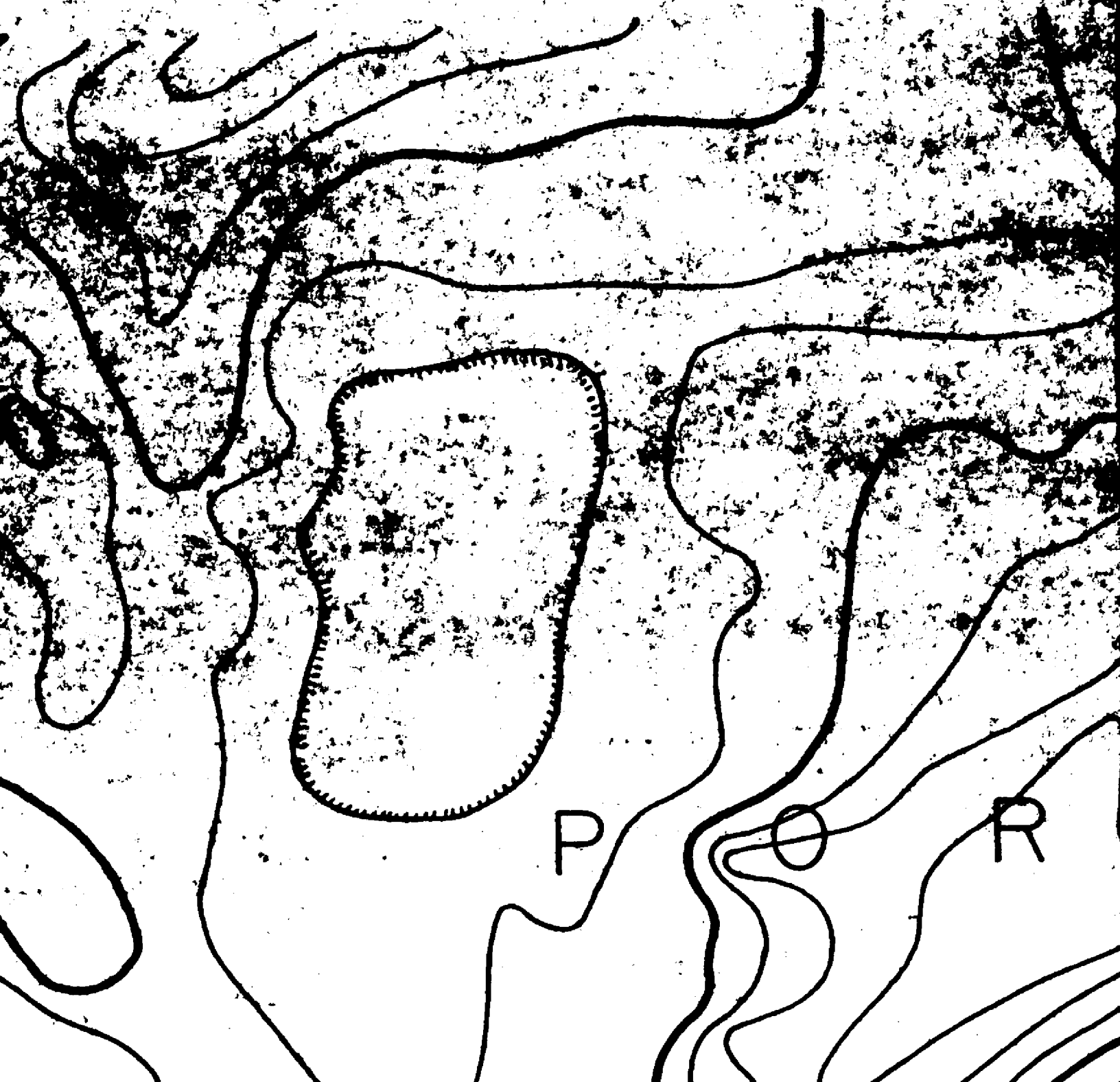


TOPOGRAPHY

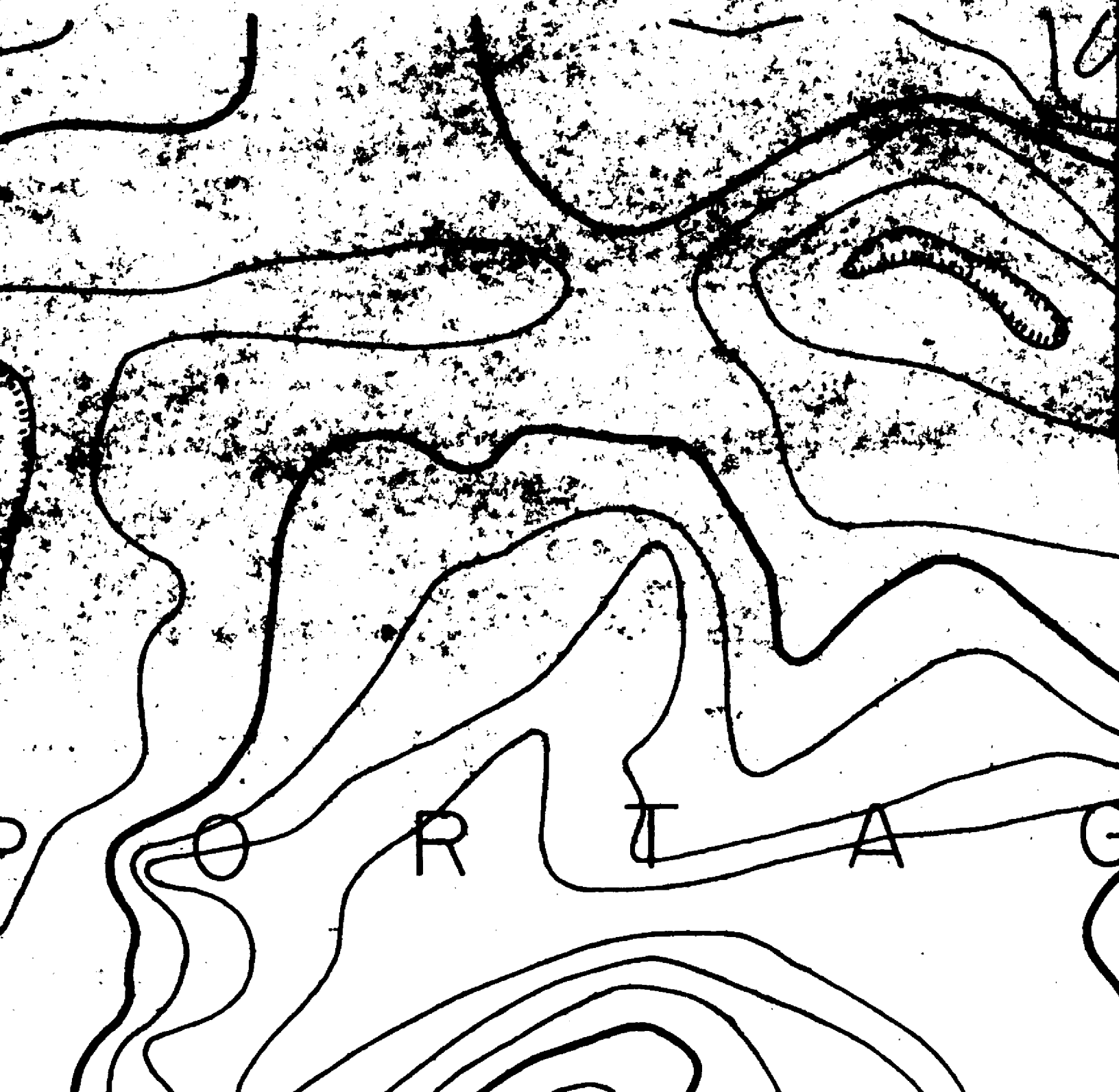
SO



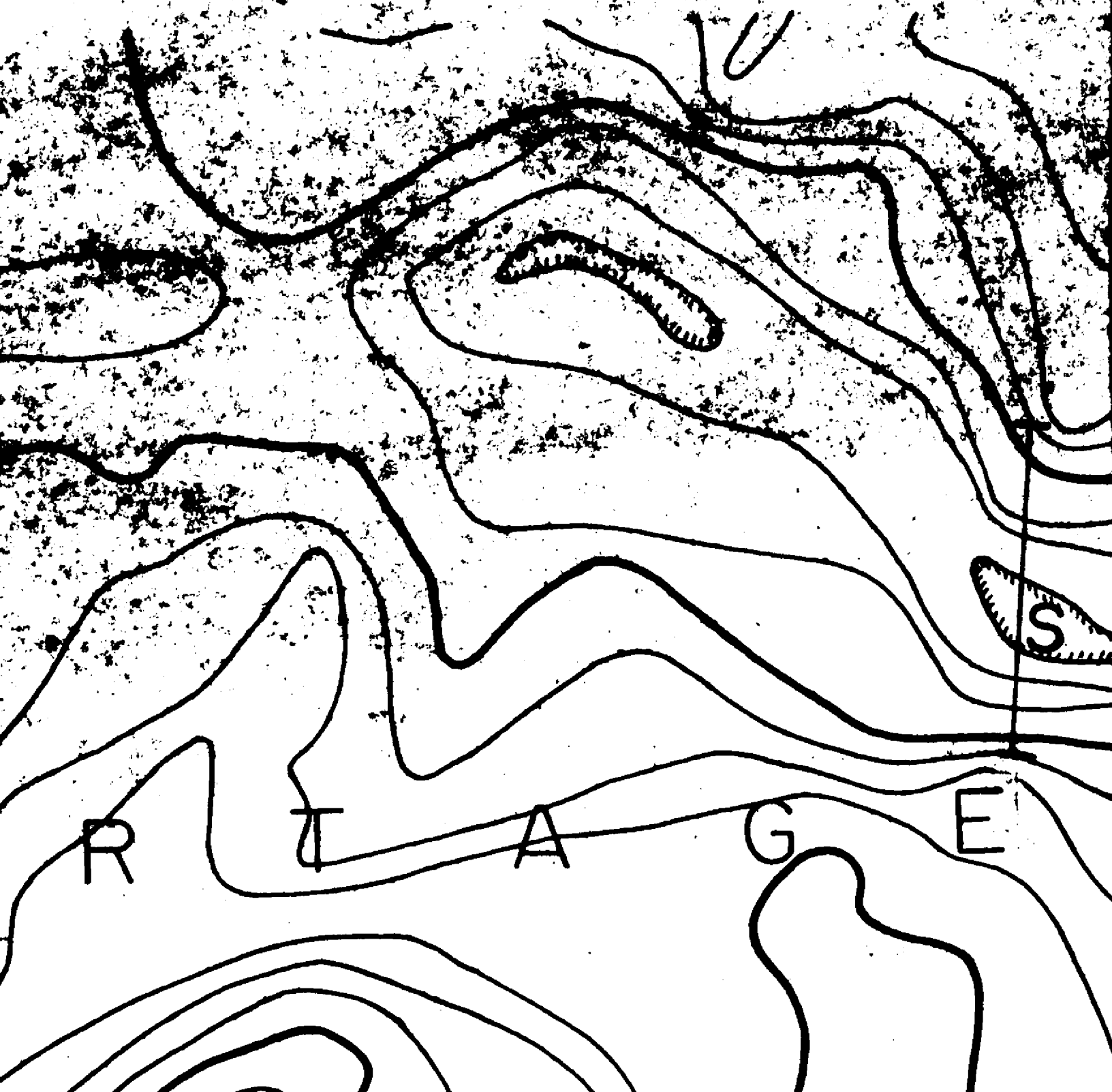
SOUTHERN HALF OF KAL

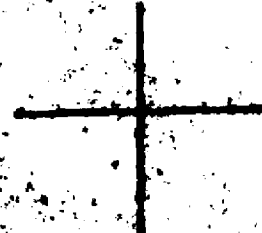


ERN HALF OF KALAMAZOO COUNTY

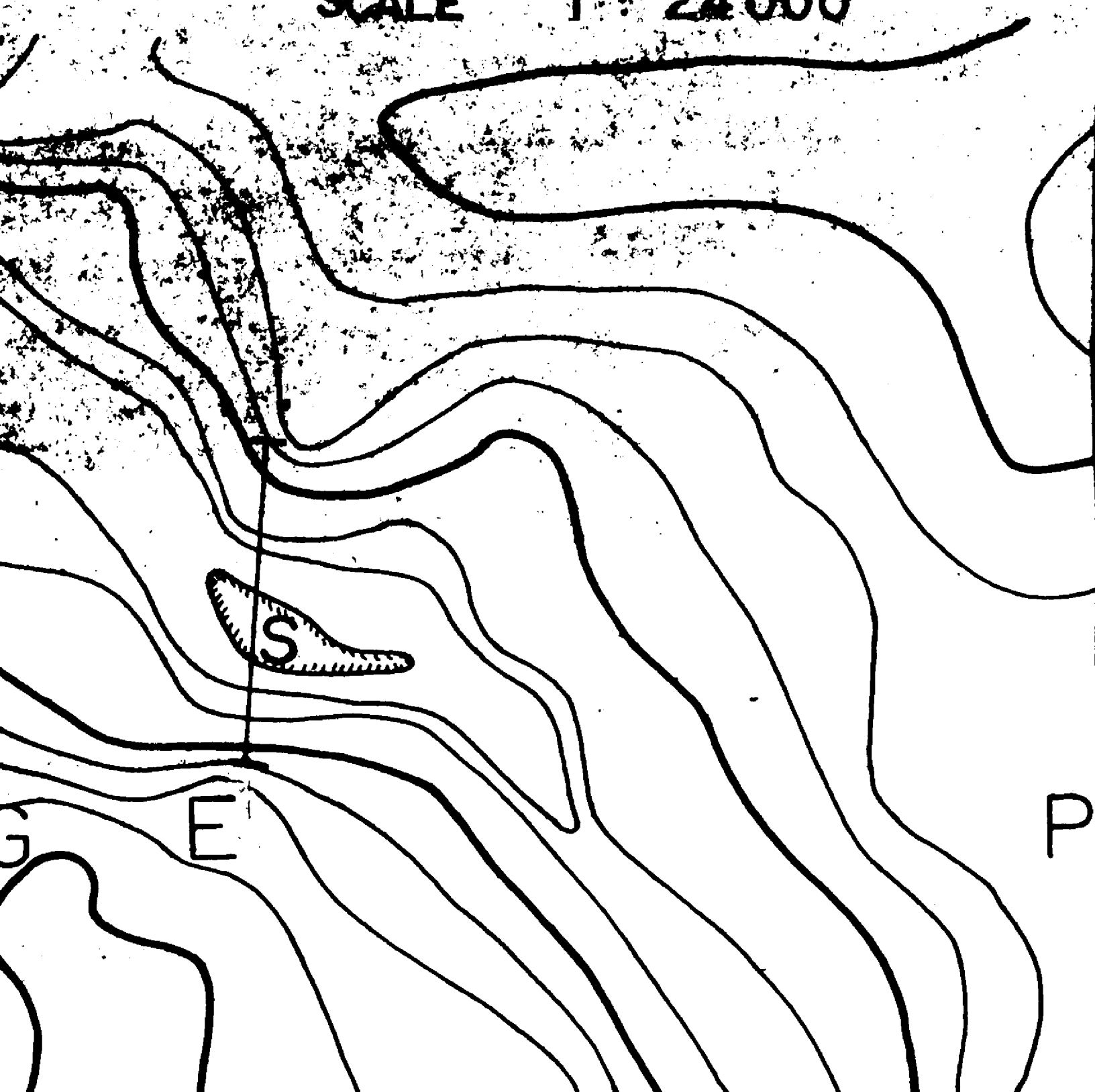


F KALAMAZOO COUNTY

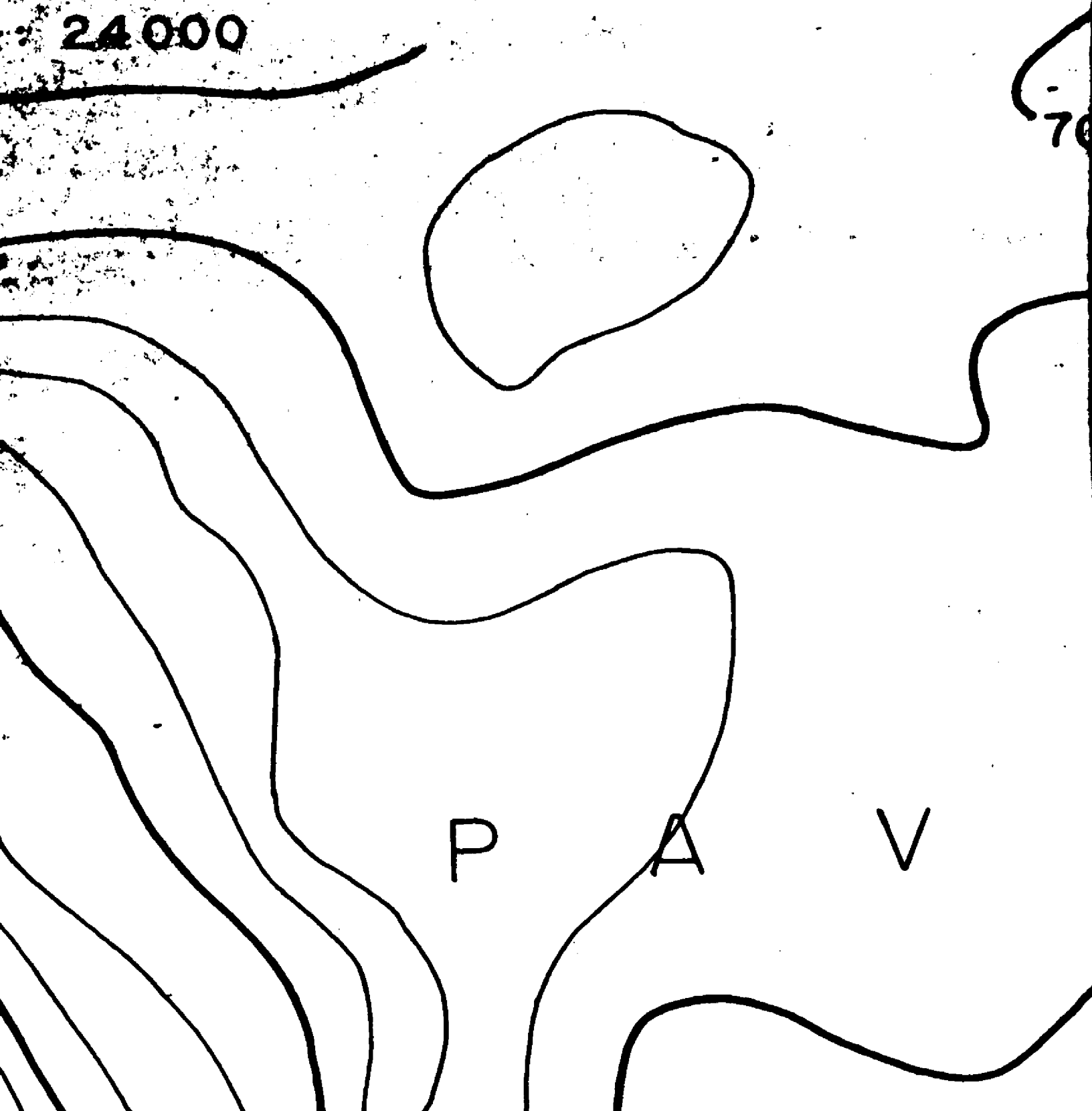




CONTOUR INTERVAL = 25 FEET
SCALE 1 : 24 000

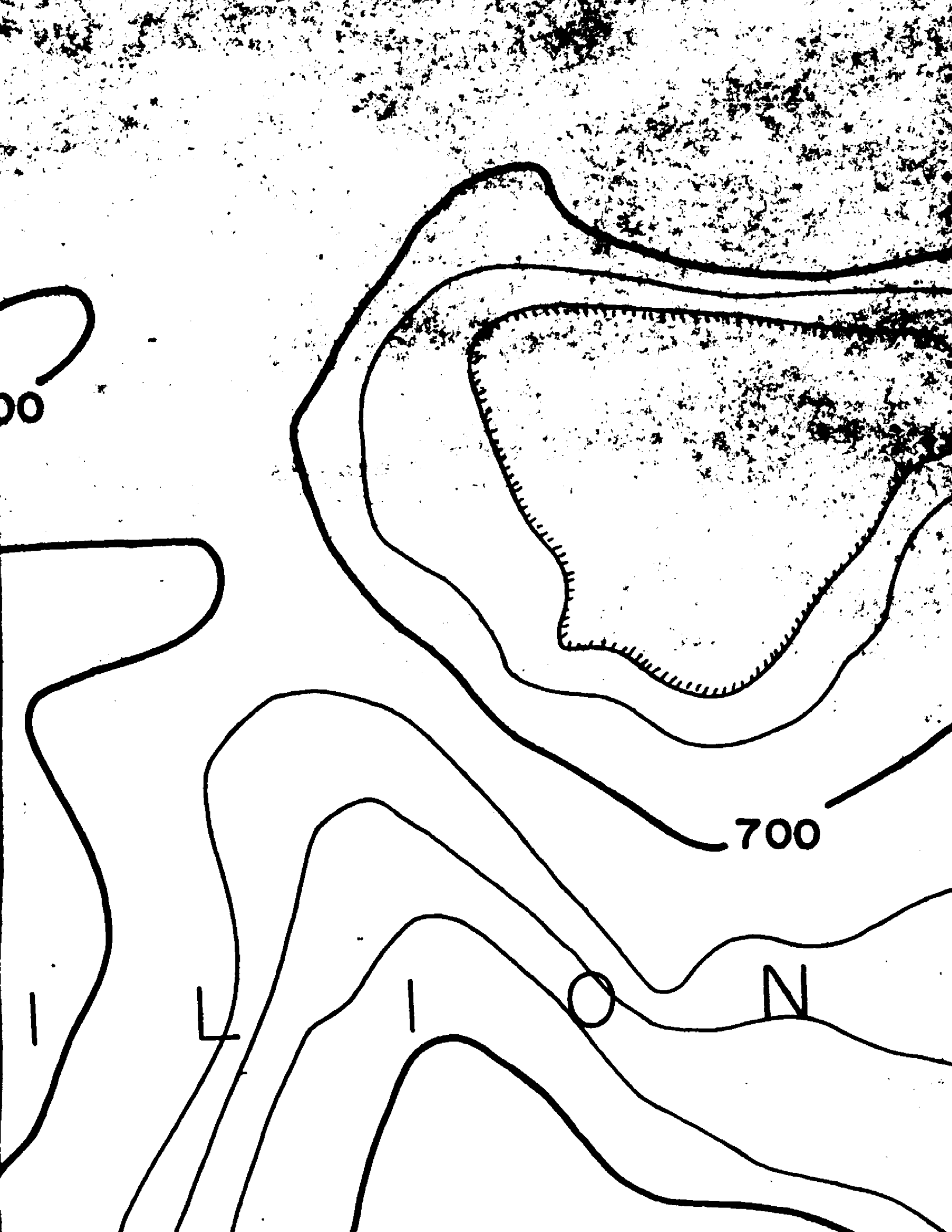


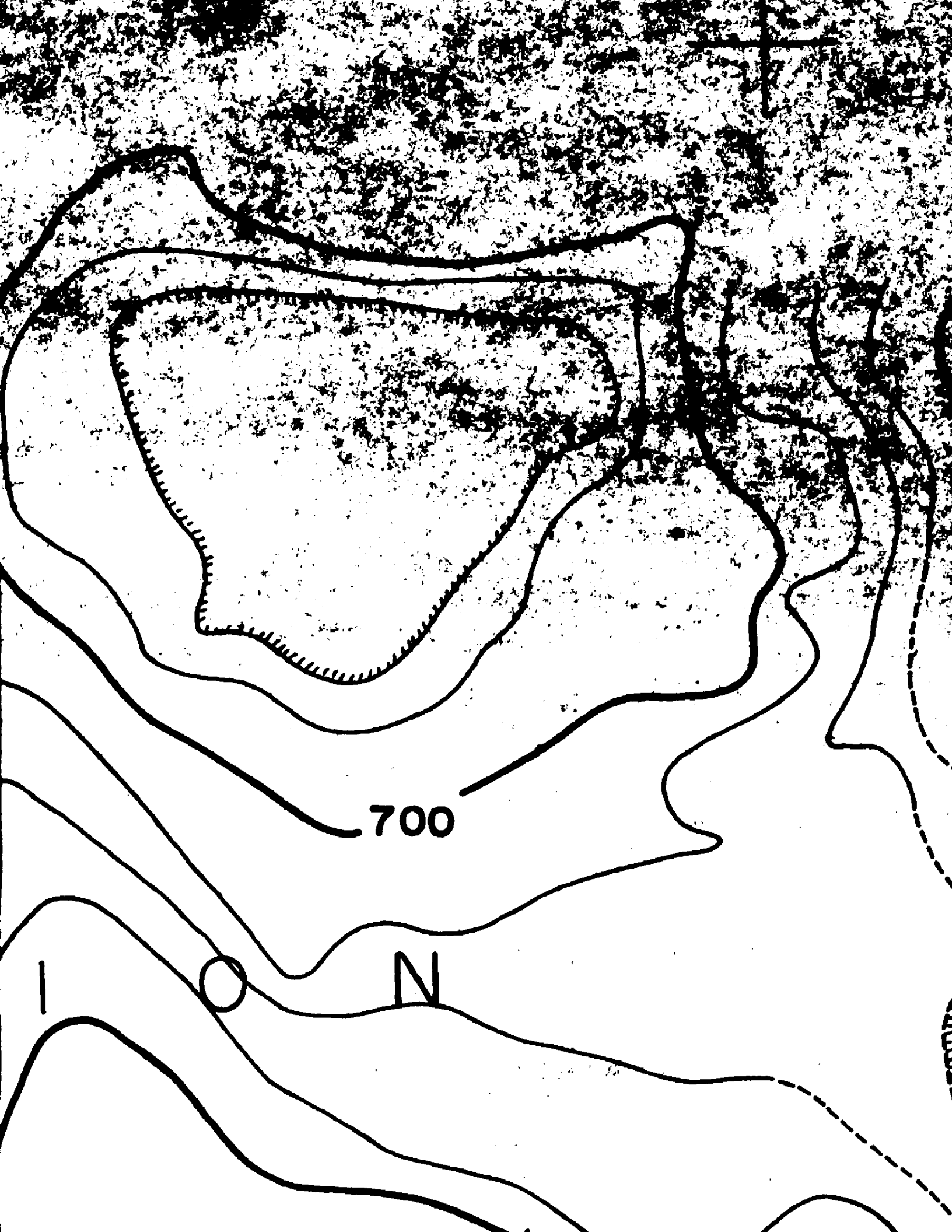
INTERVAL = 25 FEET
24000

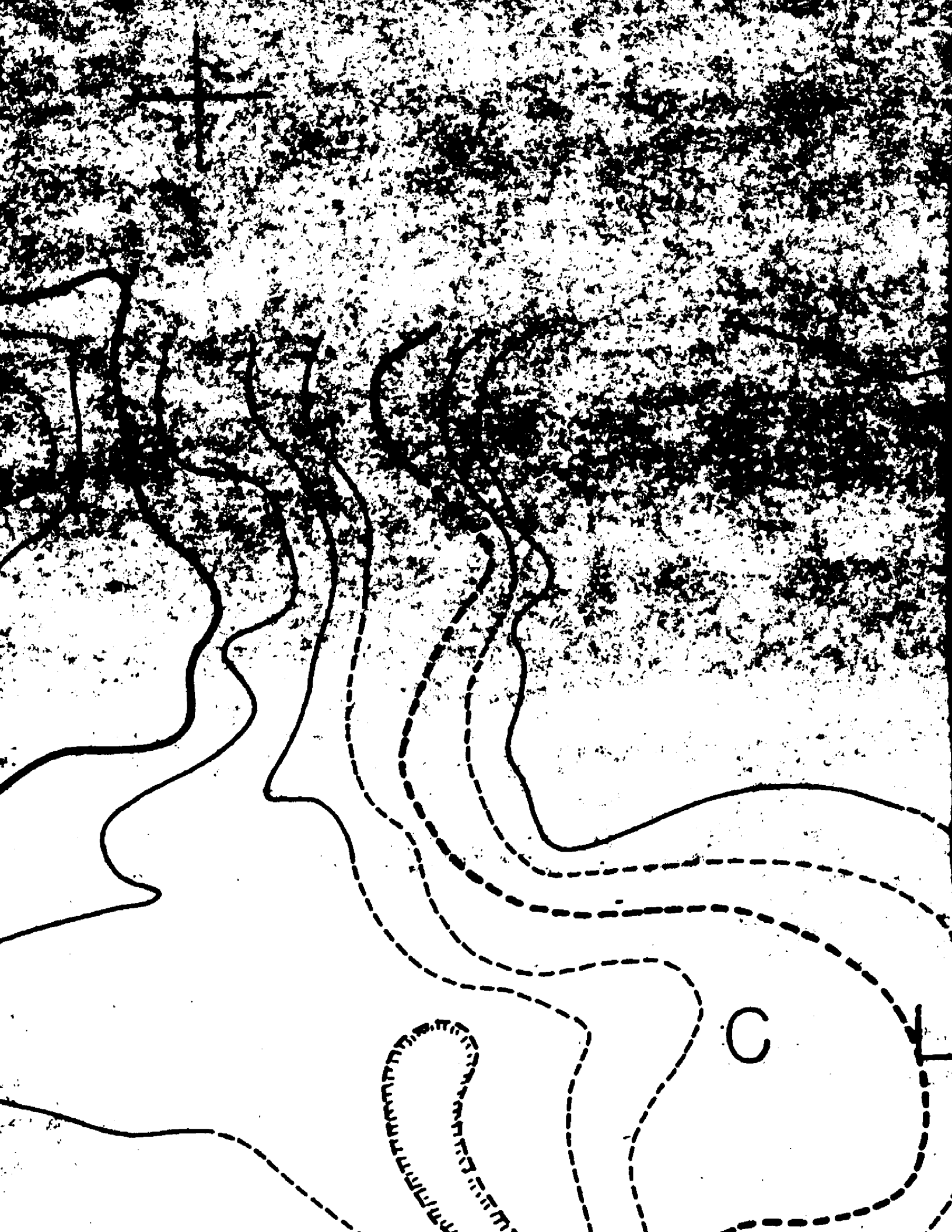


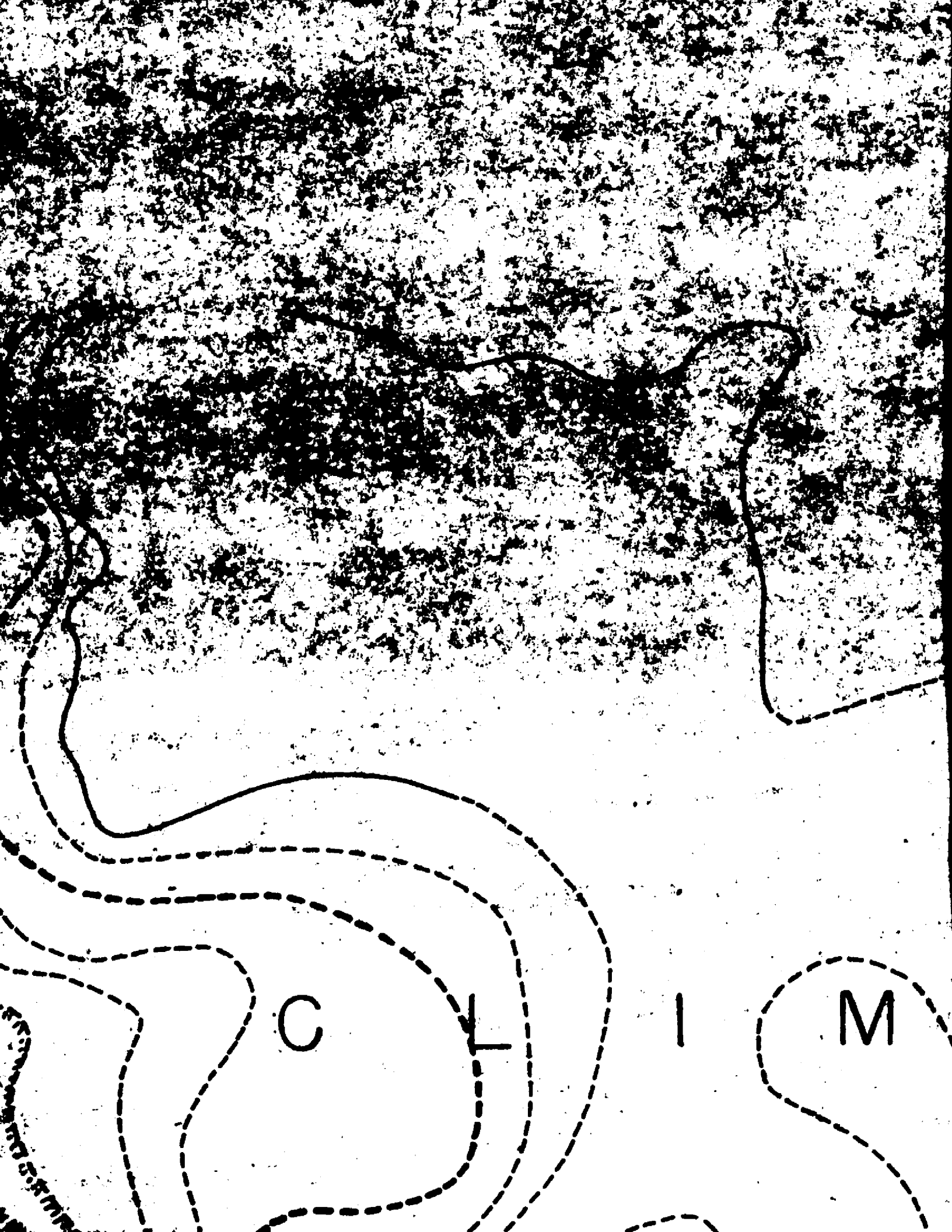
700













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M

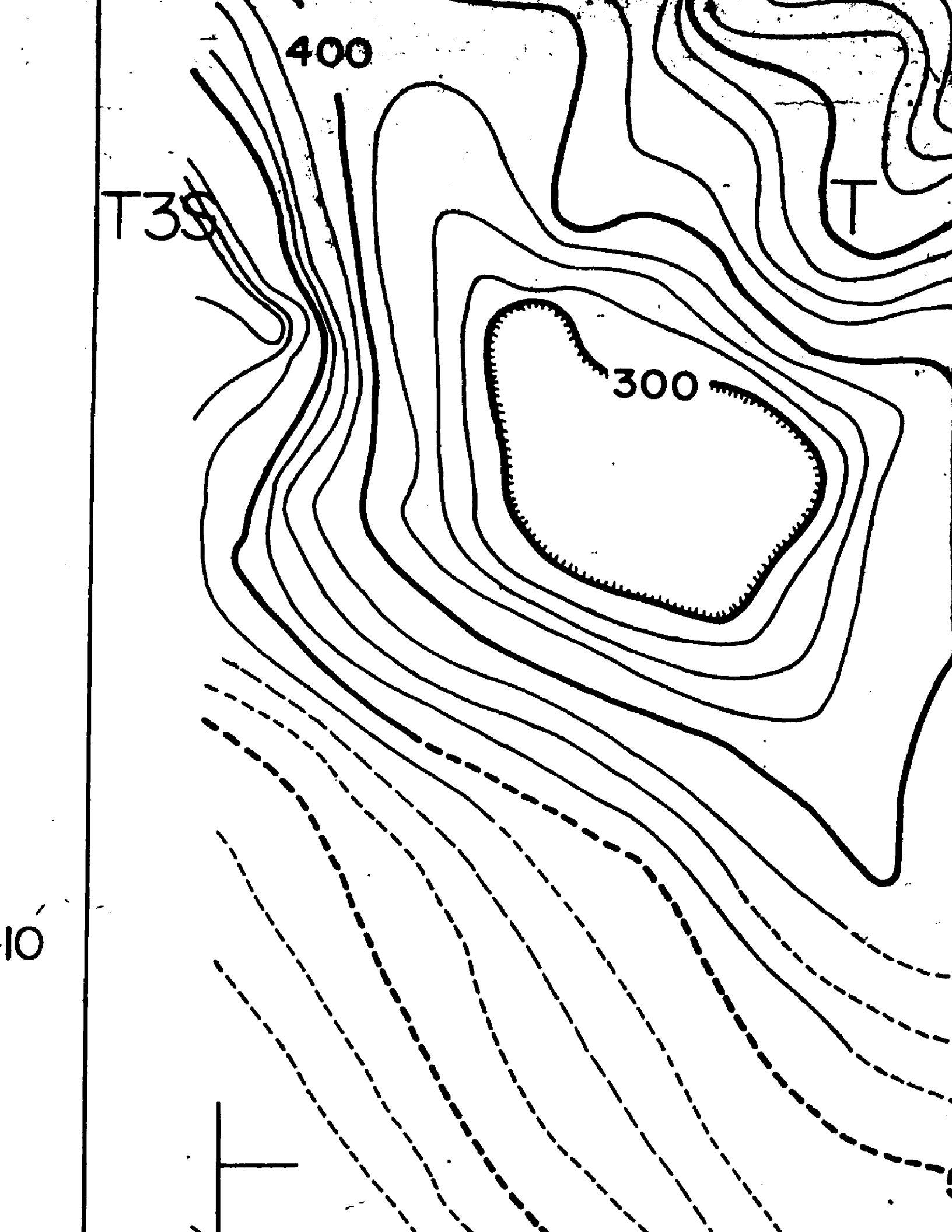
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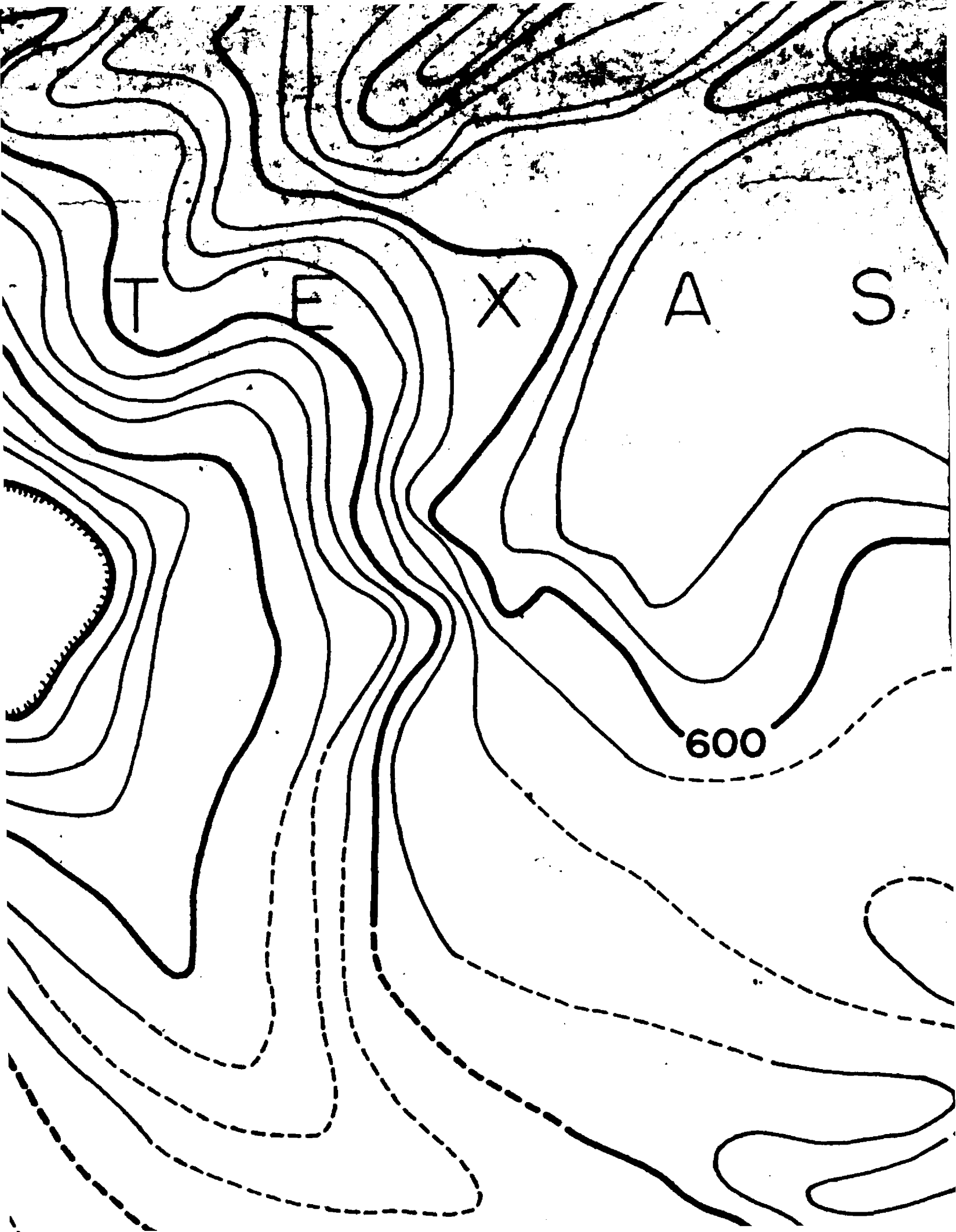
X

מחלקת המידע וההדפסה



T3S





T

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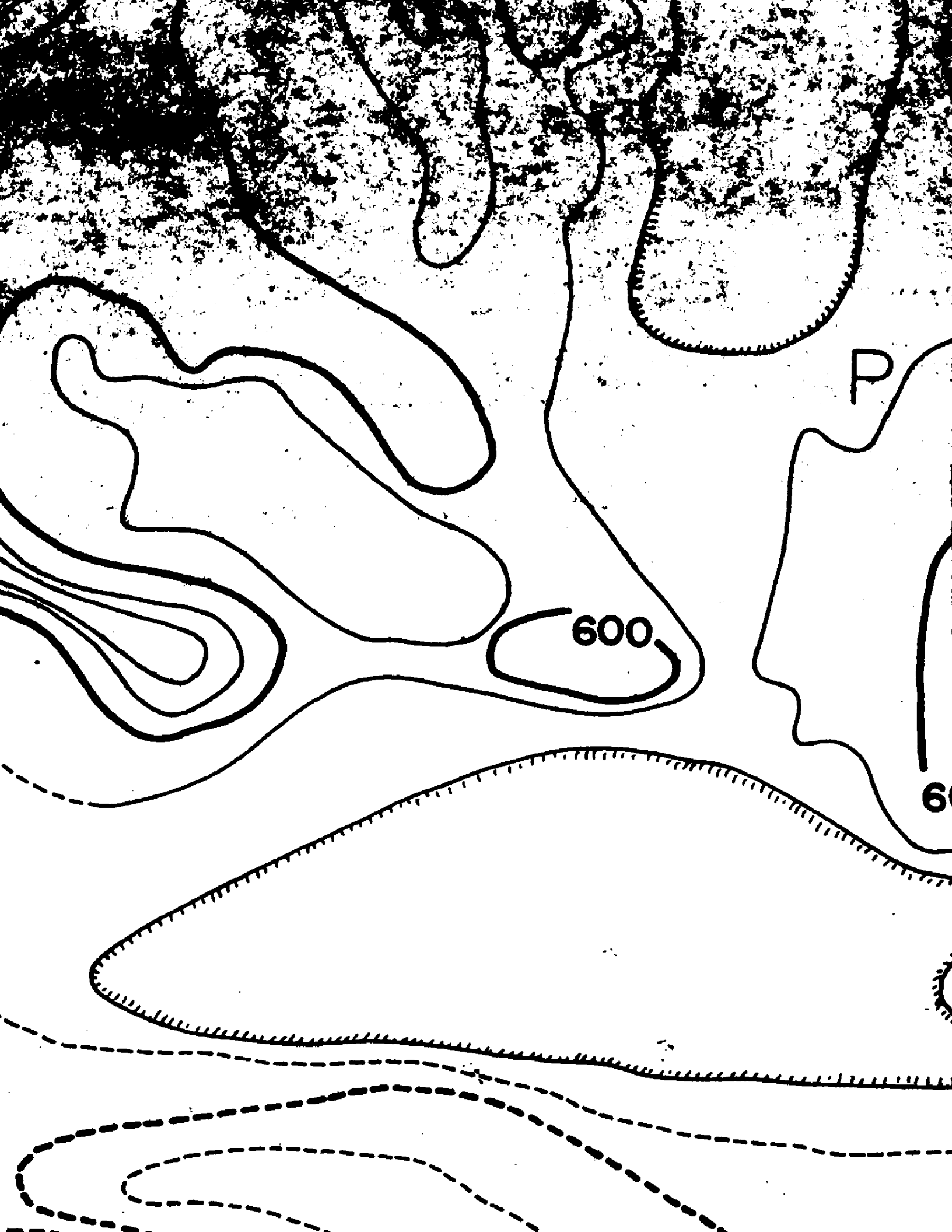
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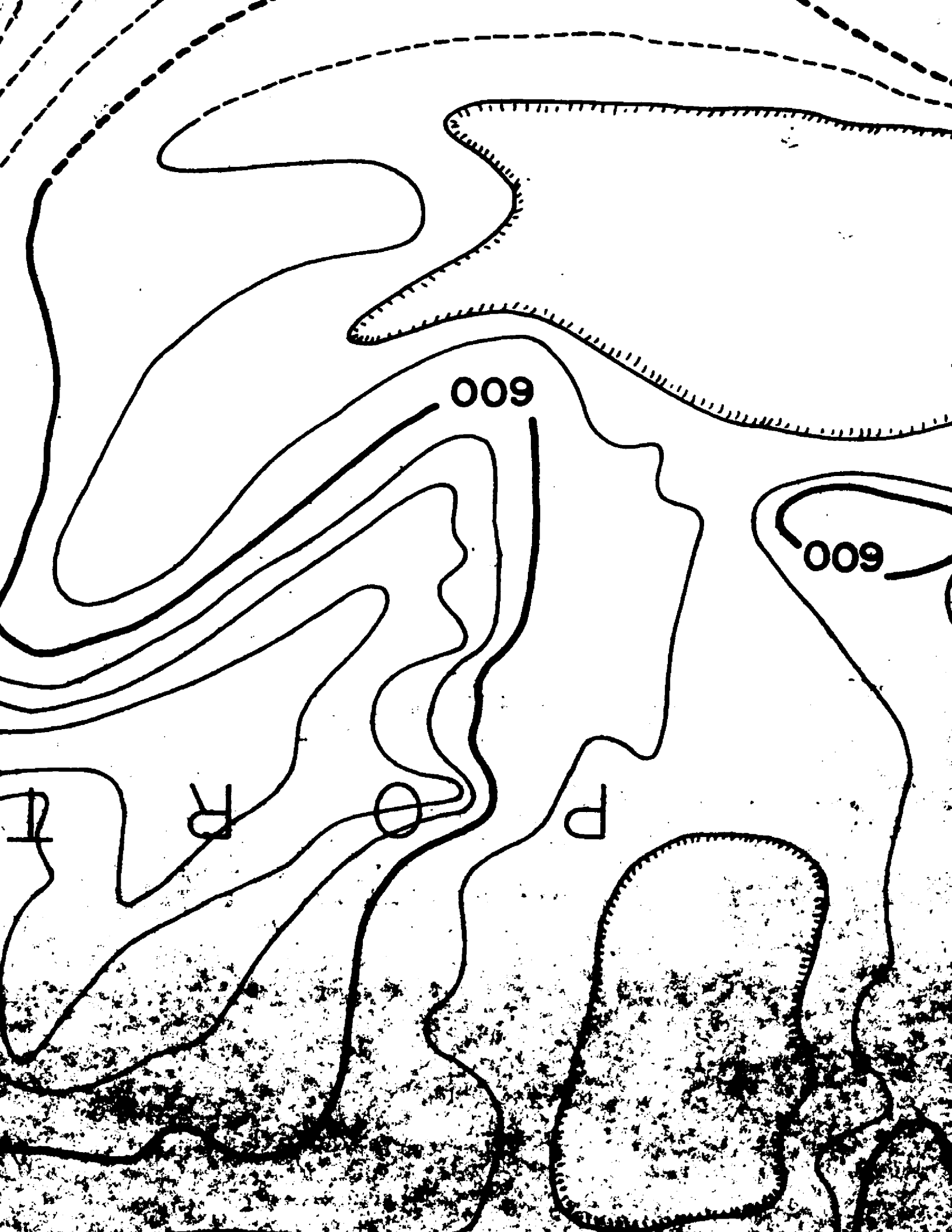
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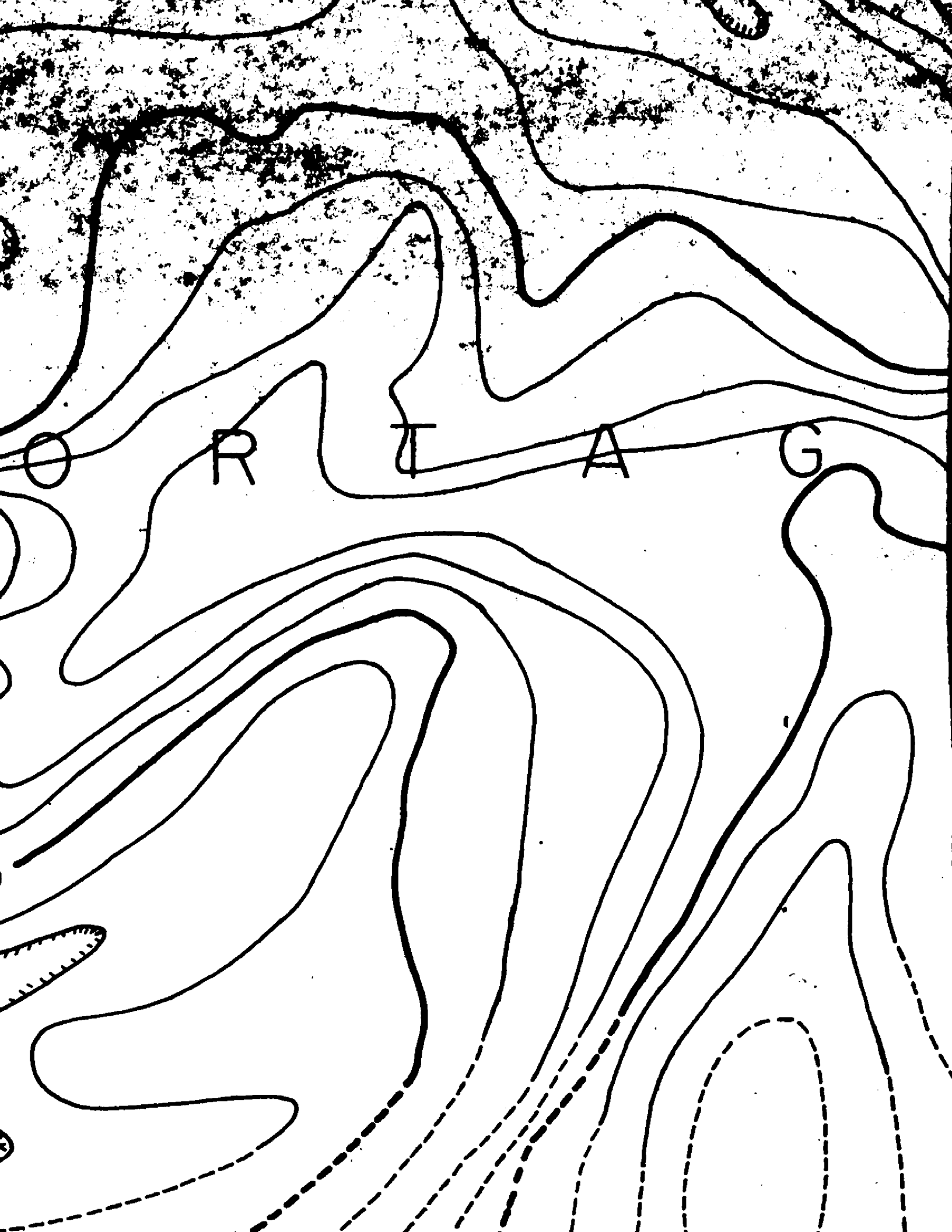
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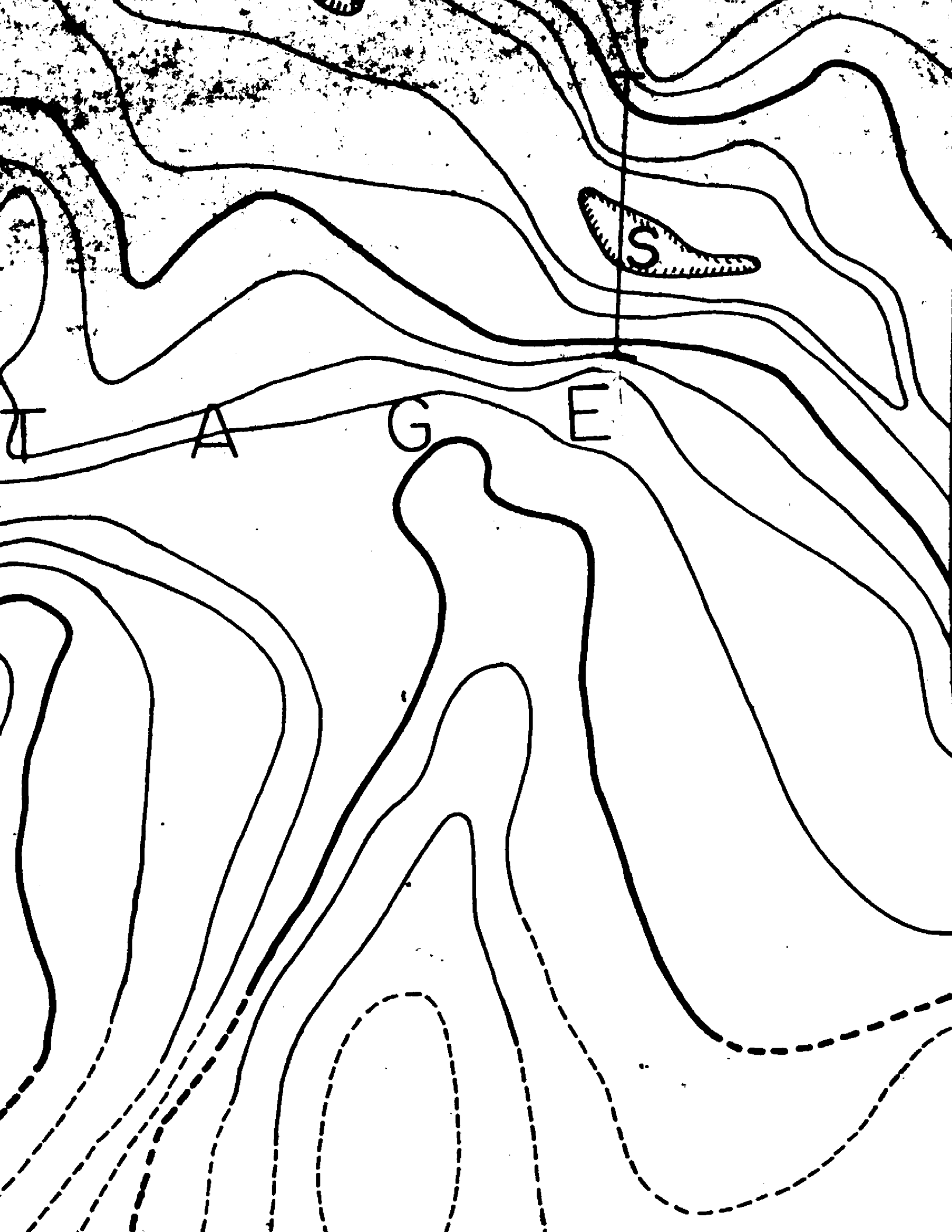
600

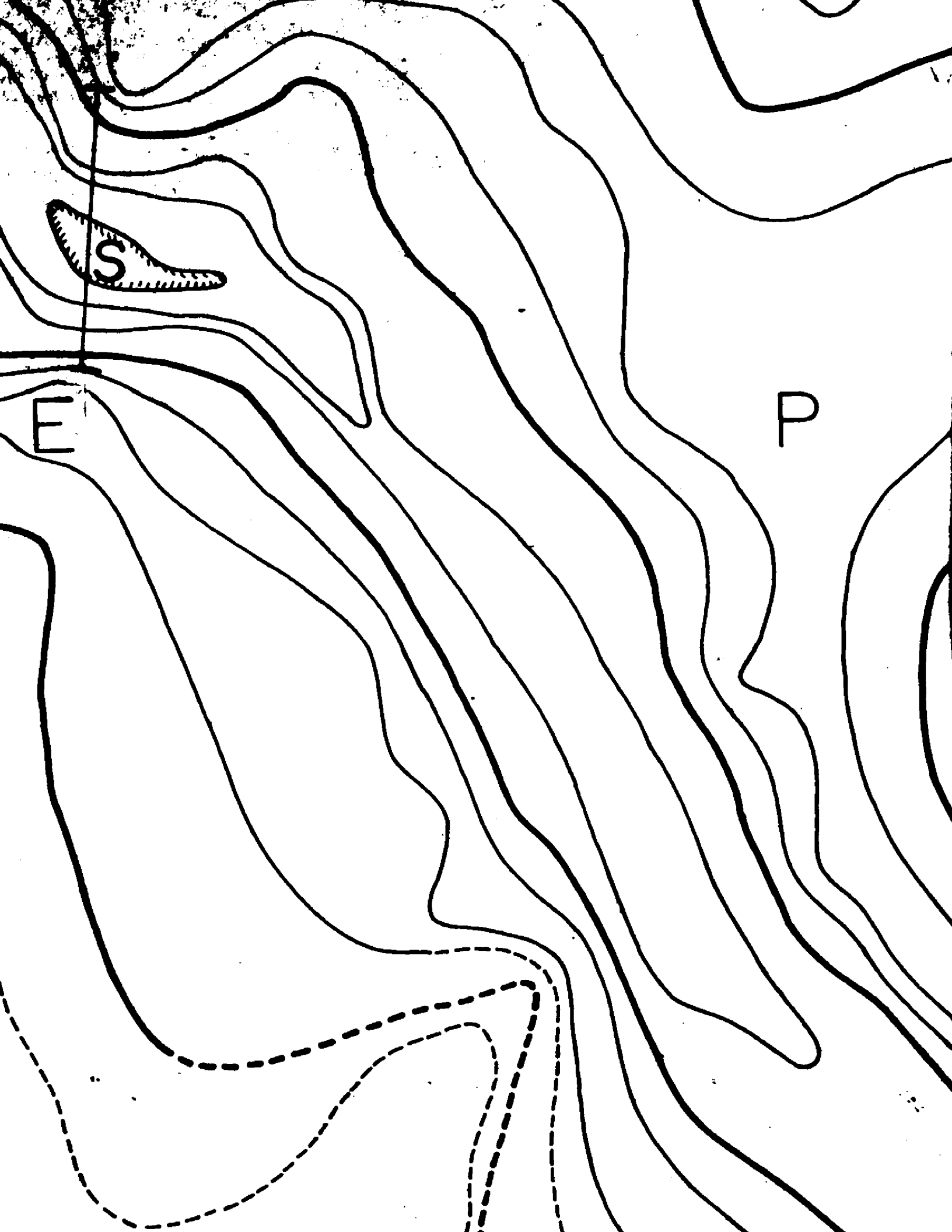


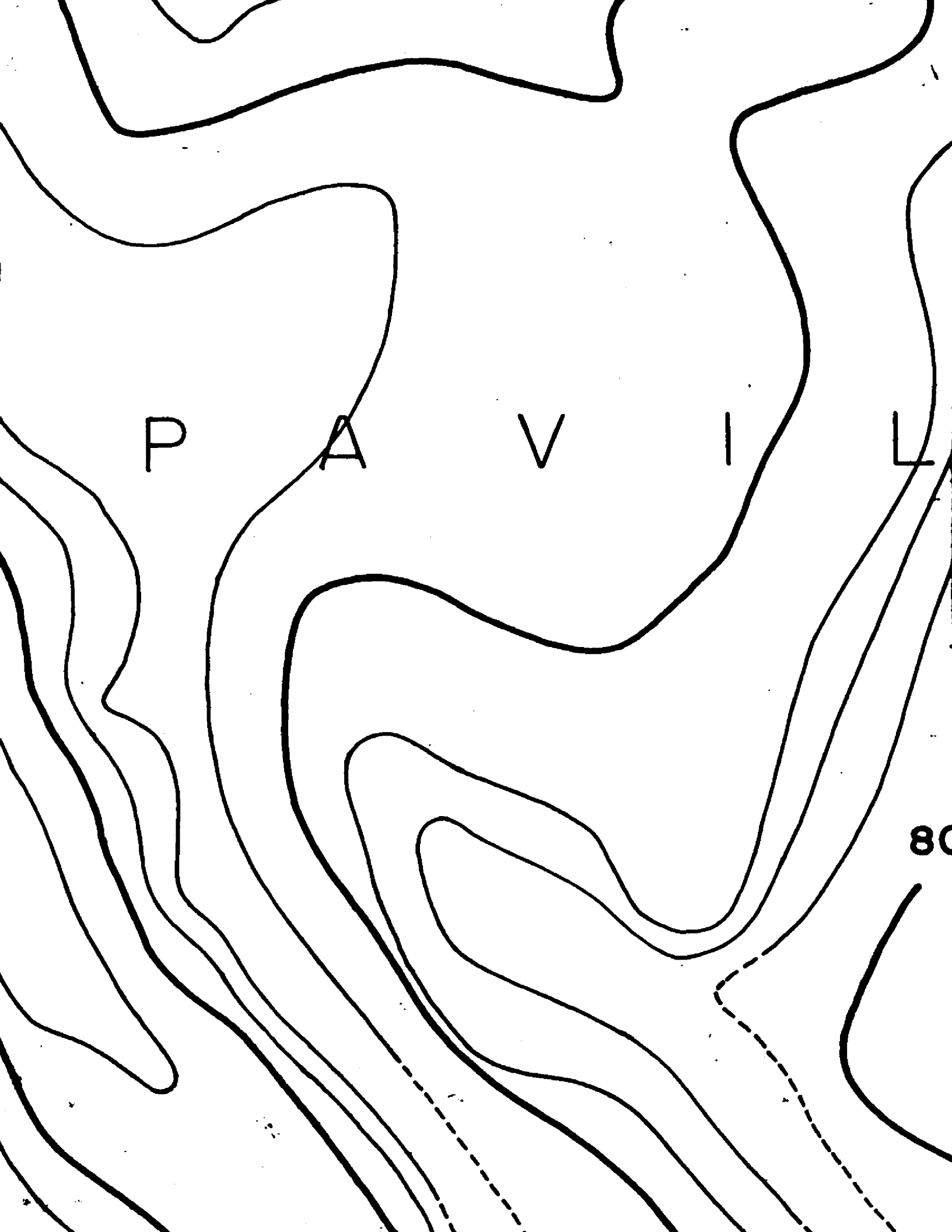










A topographic map featuring several contour lines of varying thicknesses. The lines are irregular and wavy, representing elevation changes. In the center of the map, the word 'PAVIL' is written in a simple, sans-serif font, with each letter spaced out. The letters are positioned as follows: 'P' on the left, 'A' to its right, 'V' further right, 'I' to the right of 'V', and 'L' on the far right. The map also includes a dashed line in the lower right quadrant and a solid line in the upper right quadrant. The overall style is minimalist and technical.

P

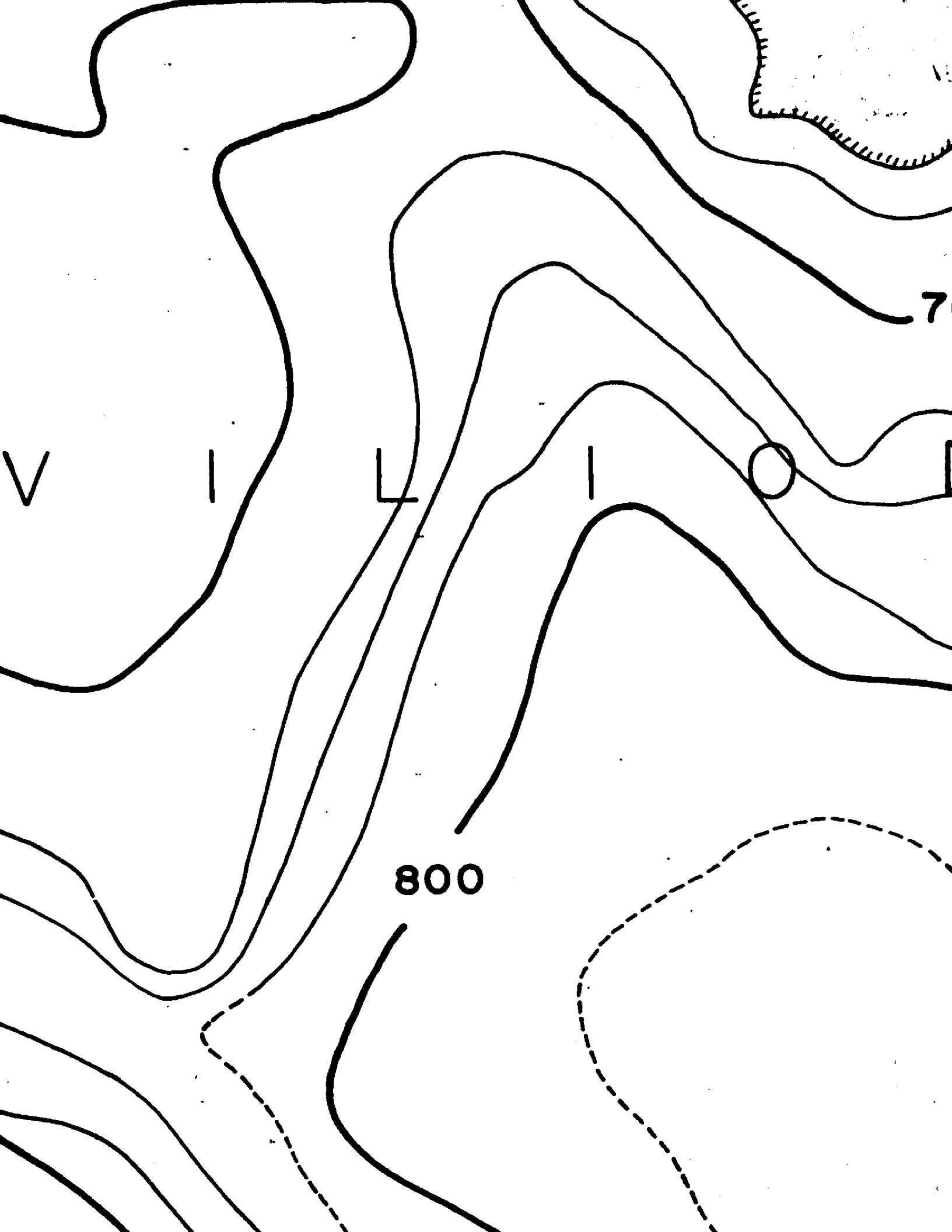
A

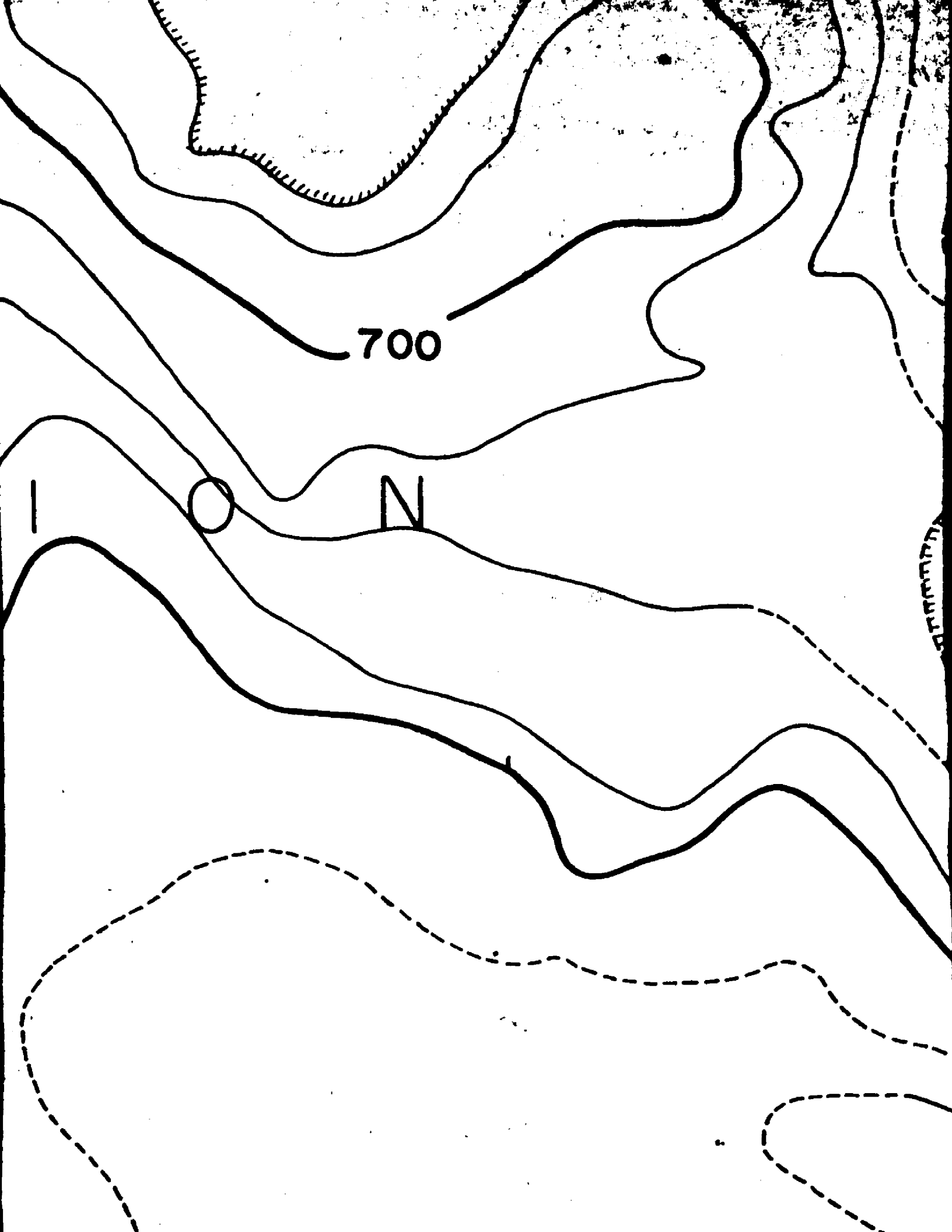
V

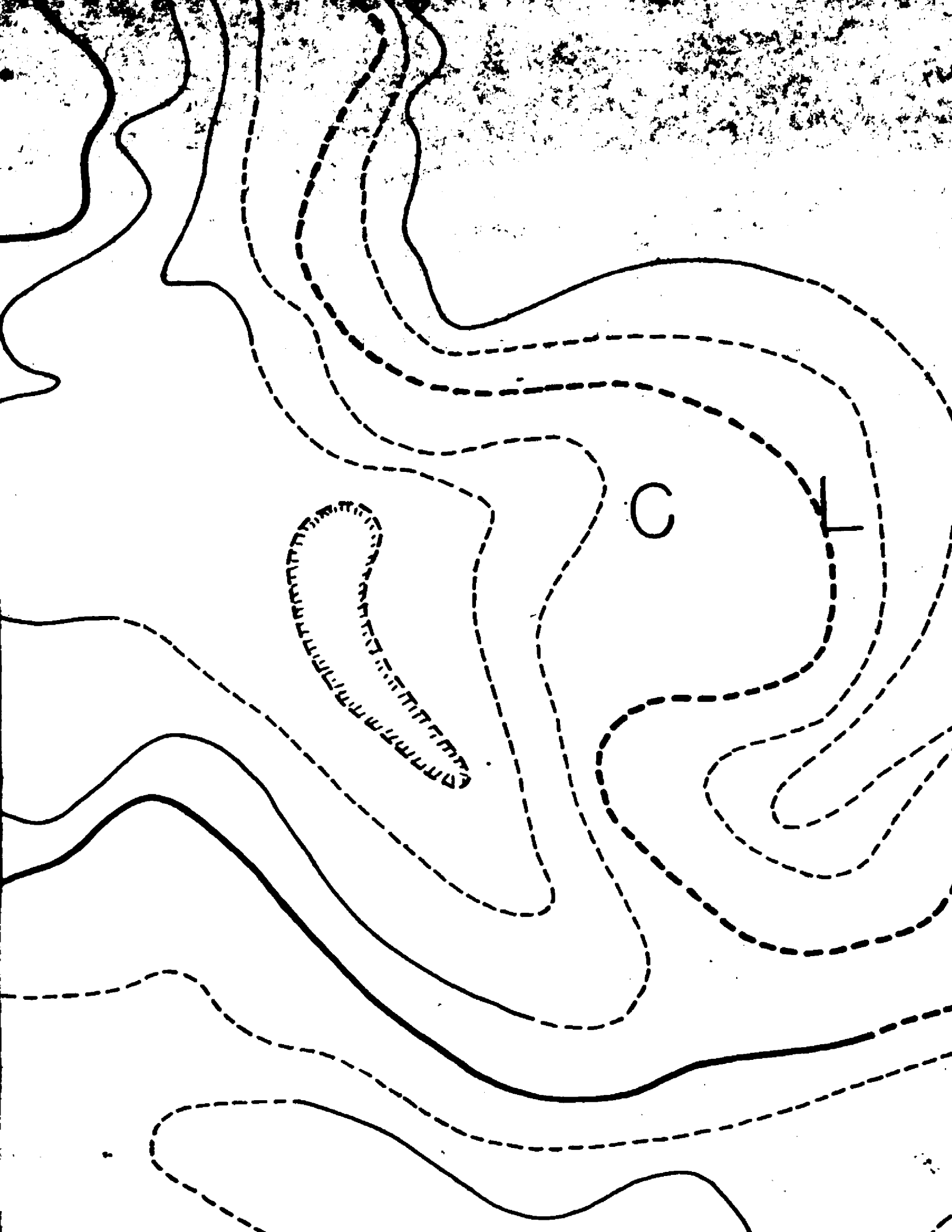
I

L

80

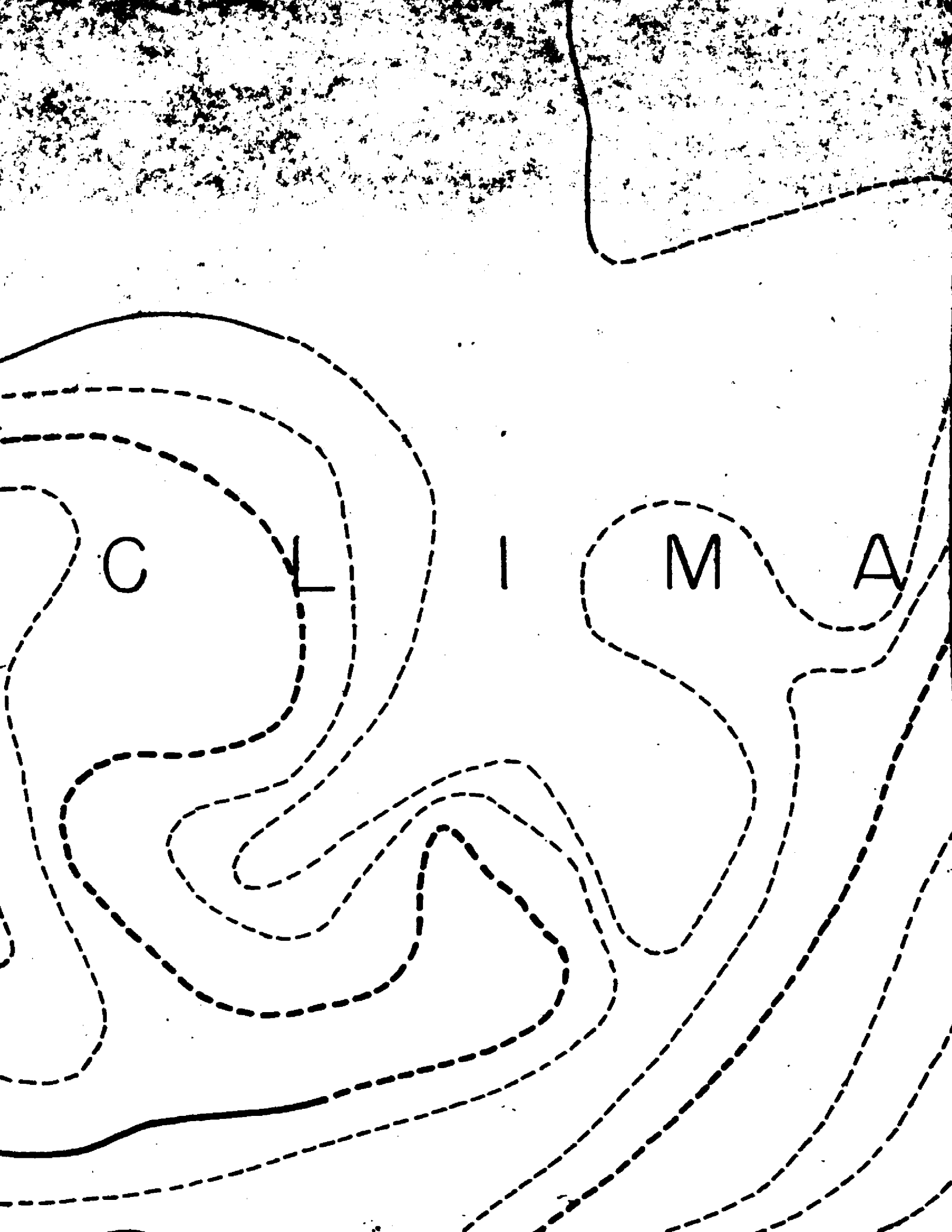


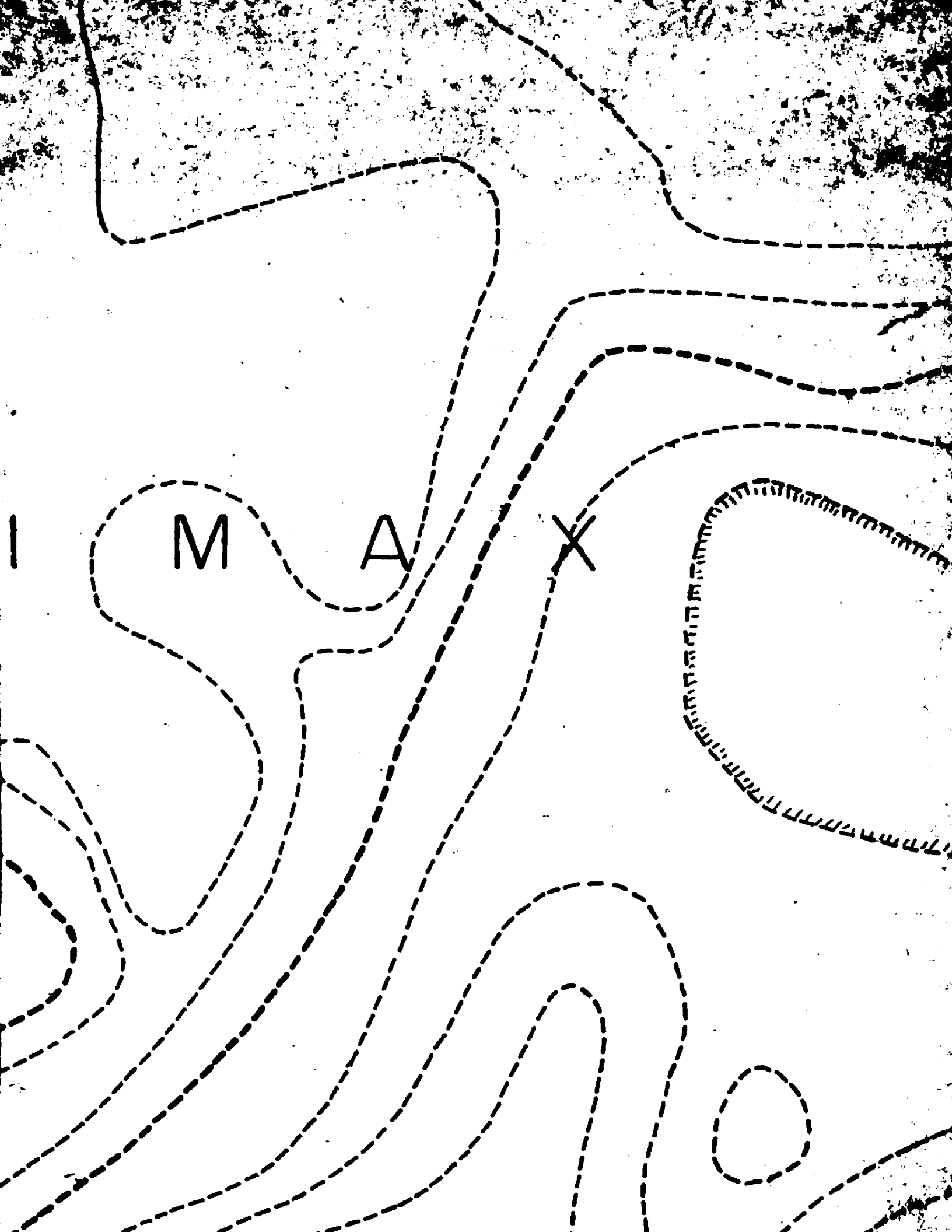


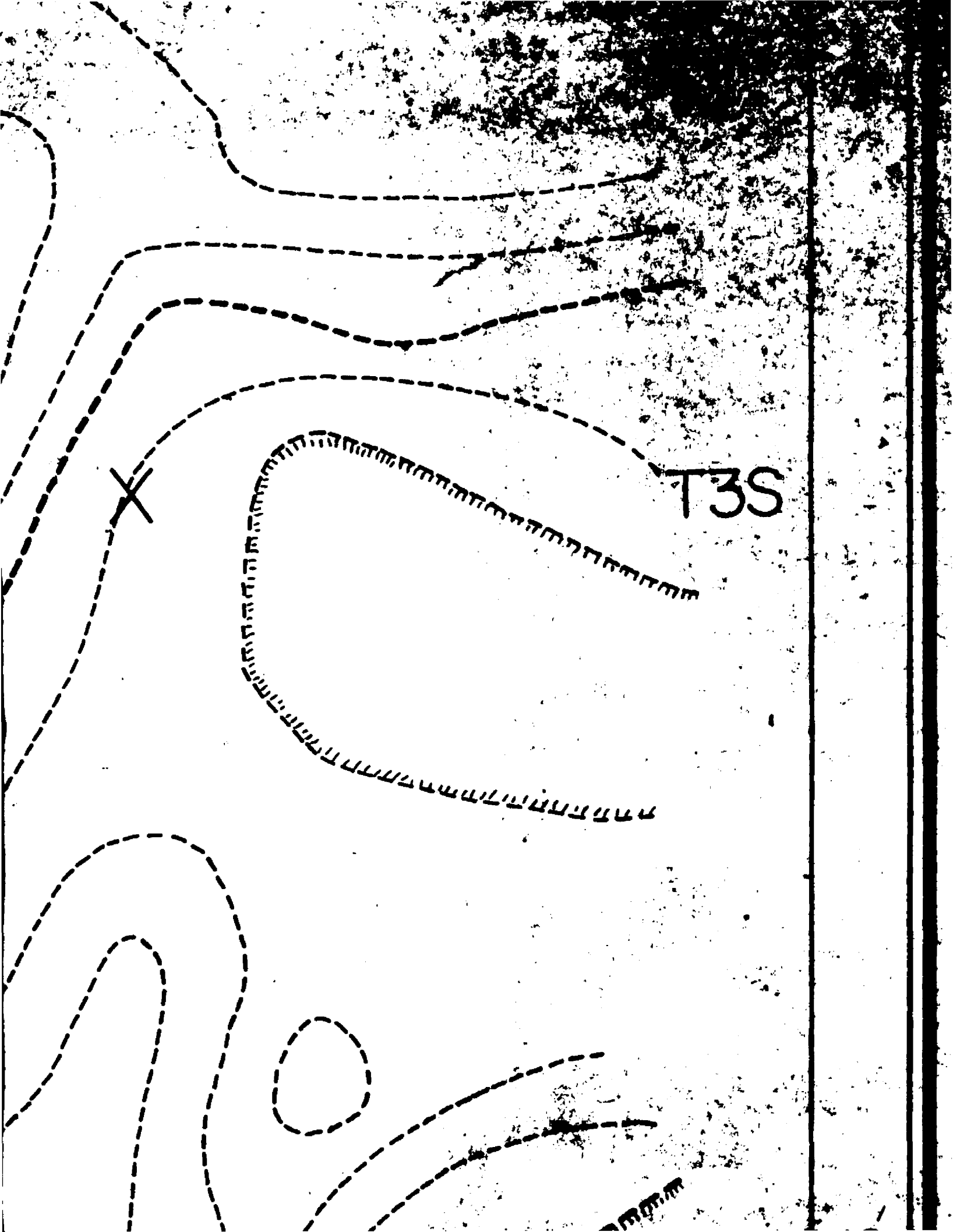


C

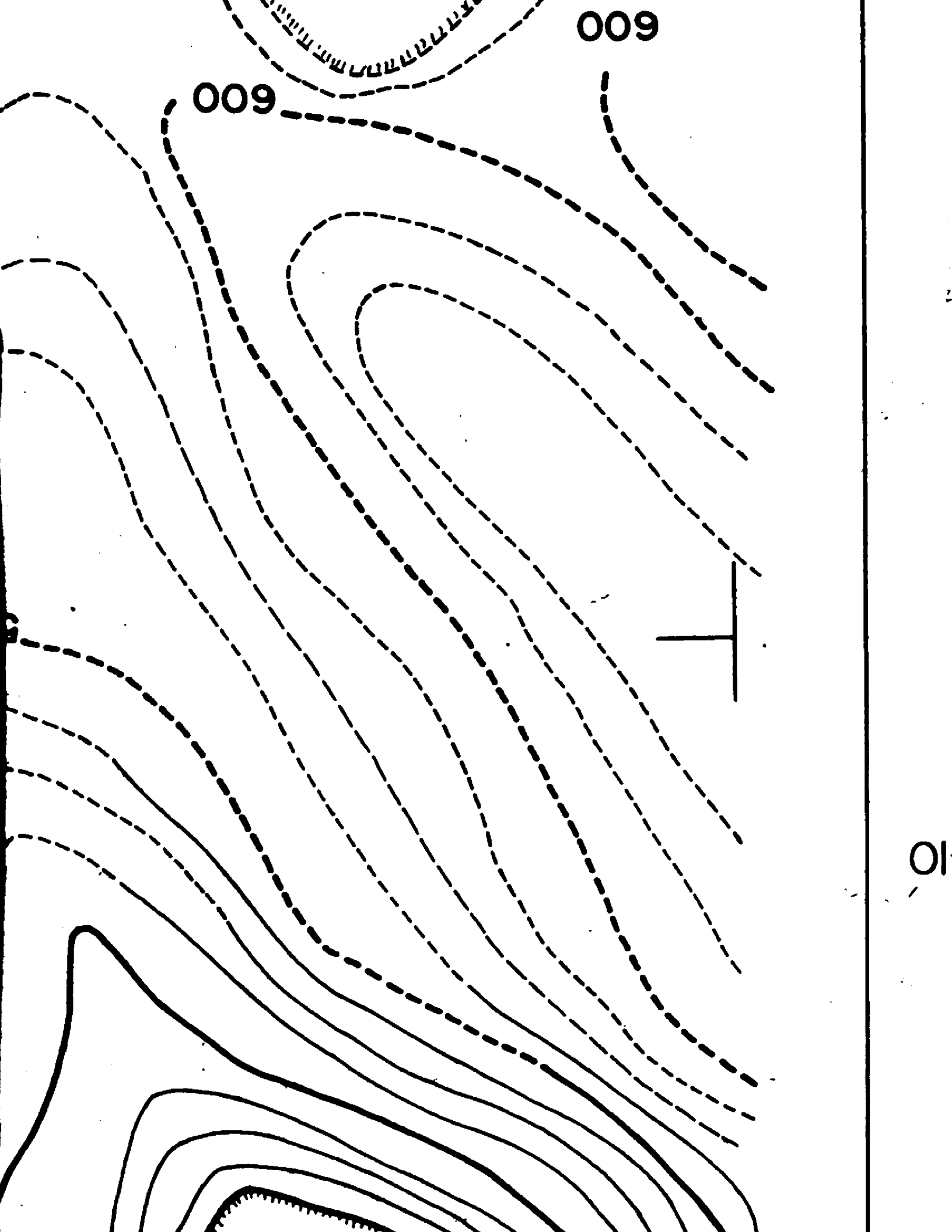
צמחיה ודגים
במחוזות השונים

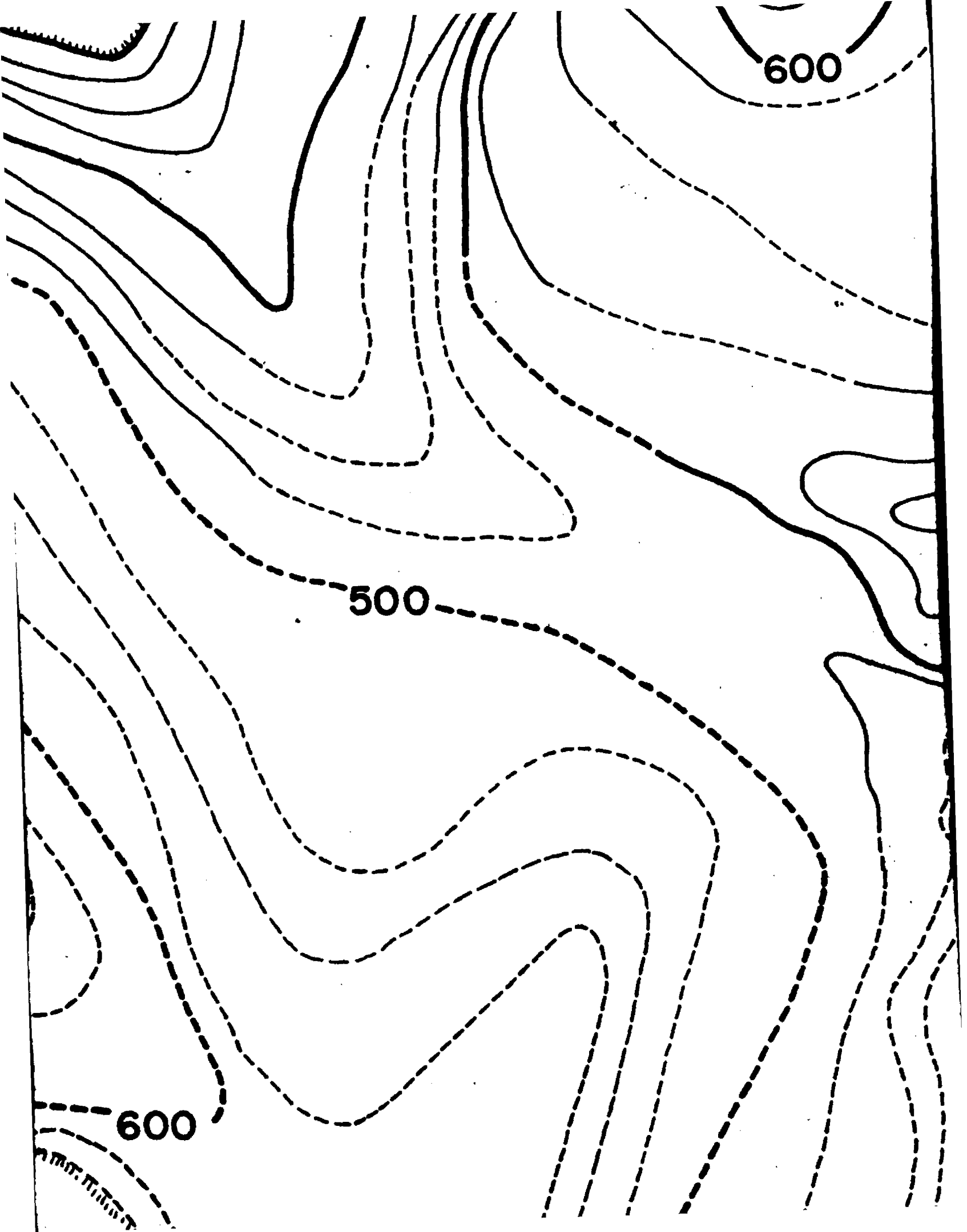


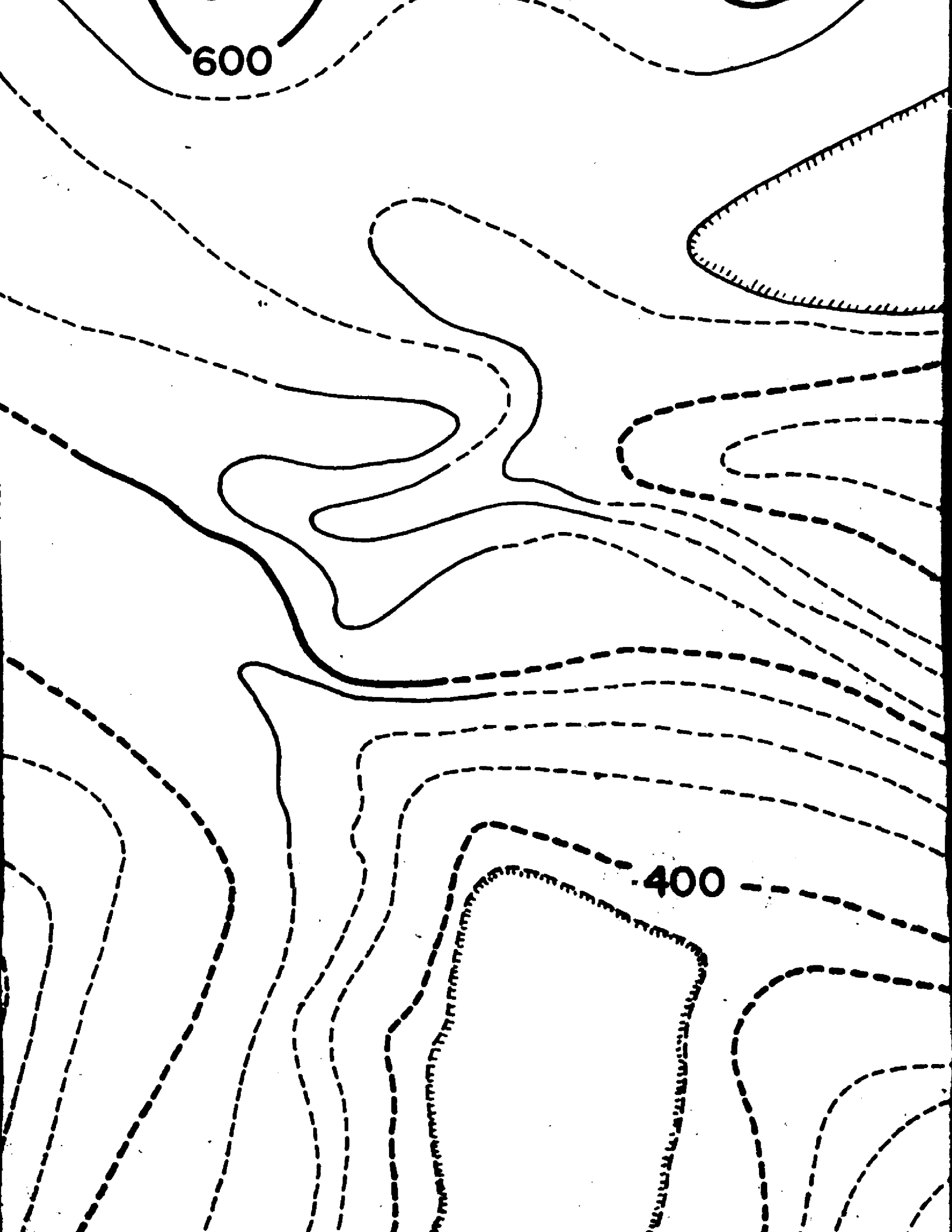


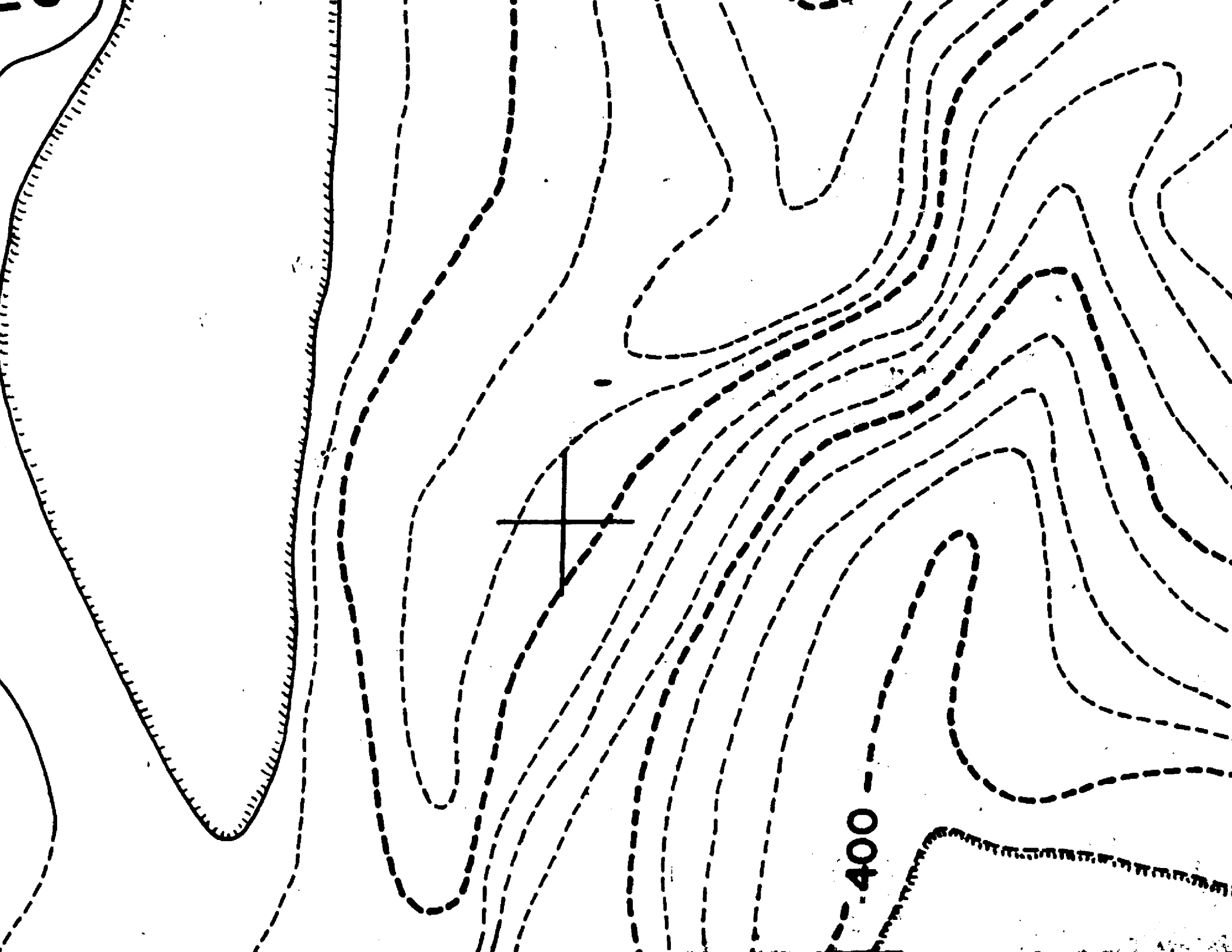


T3S







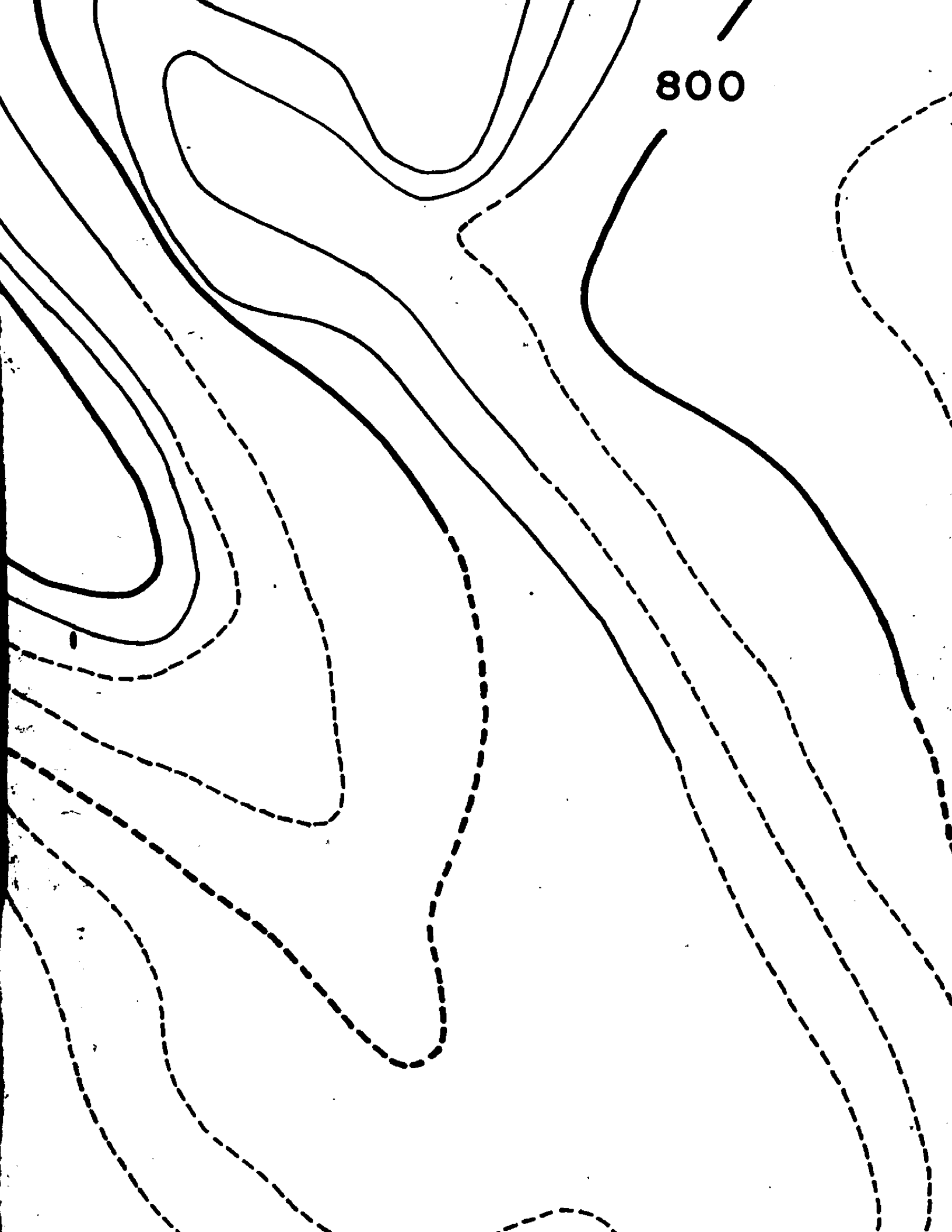




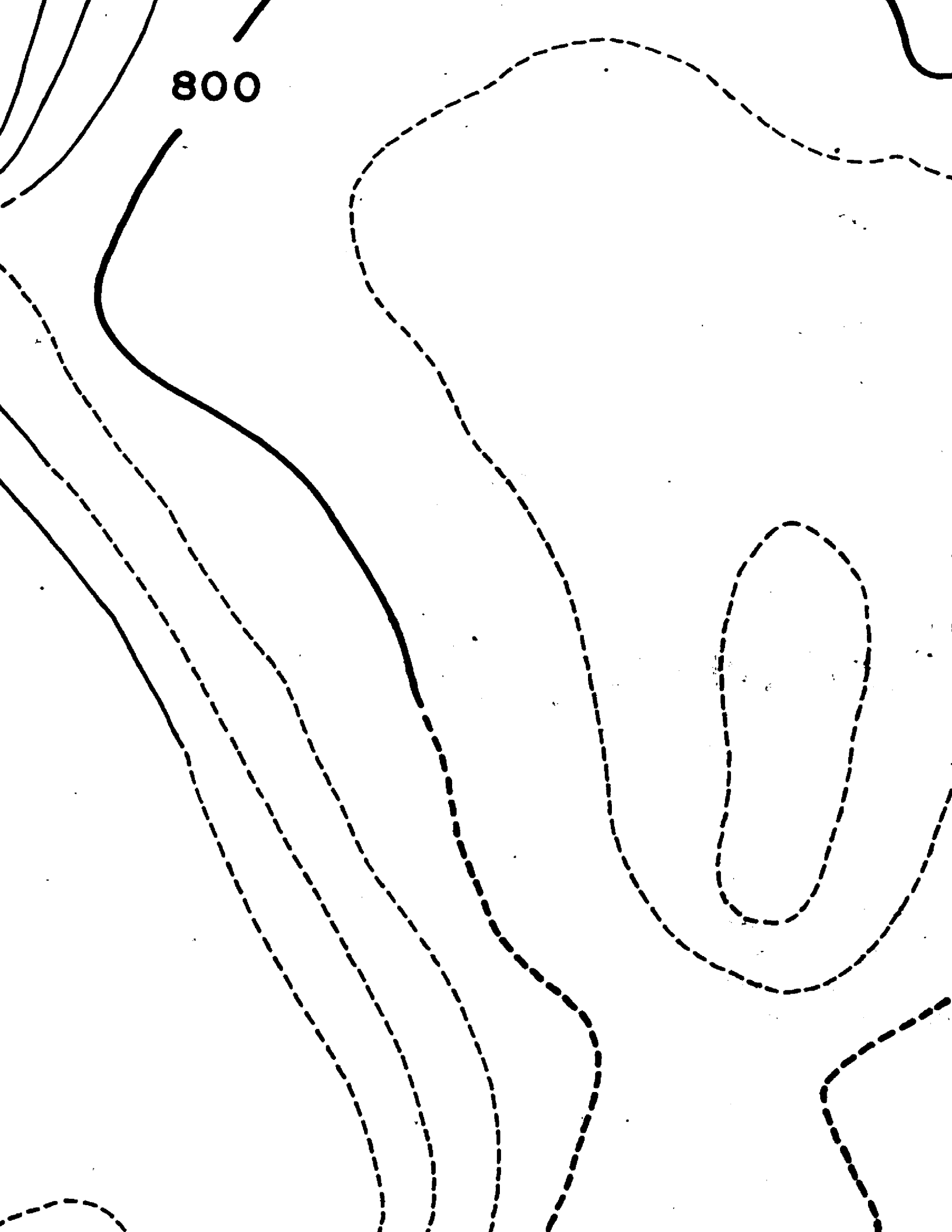


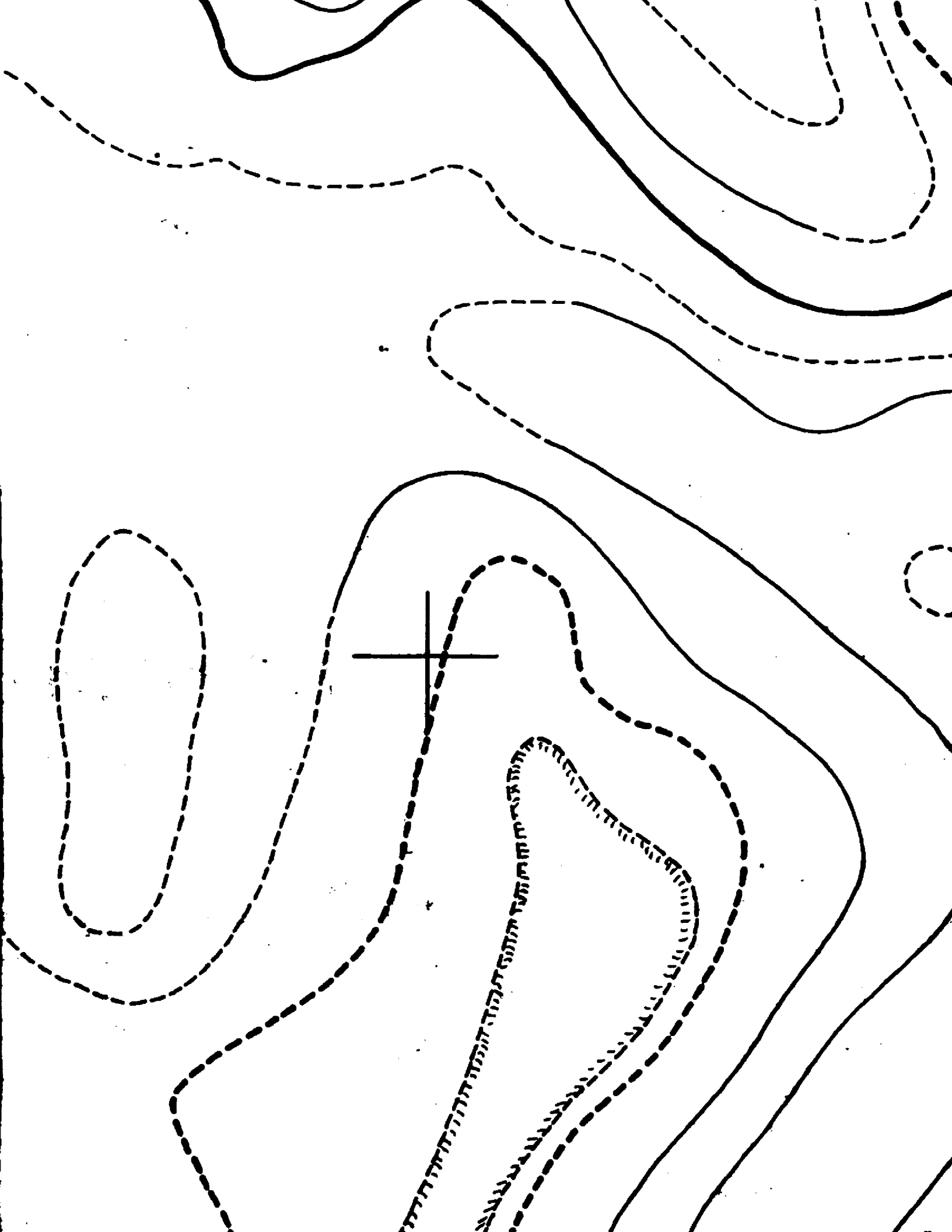


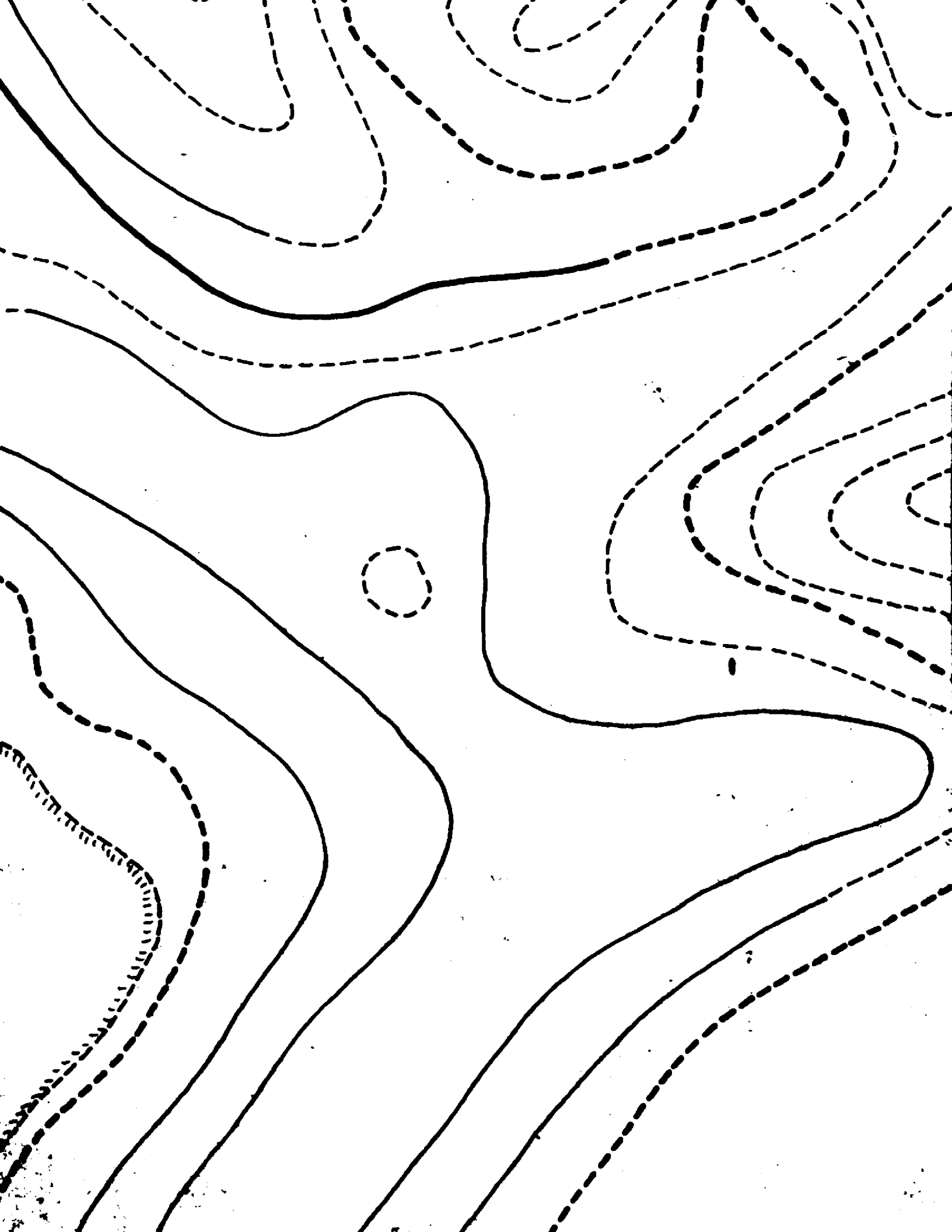
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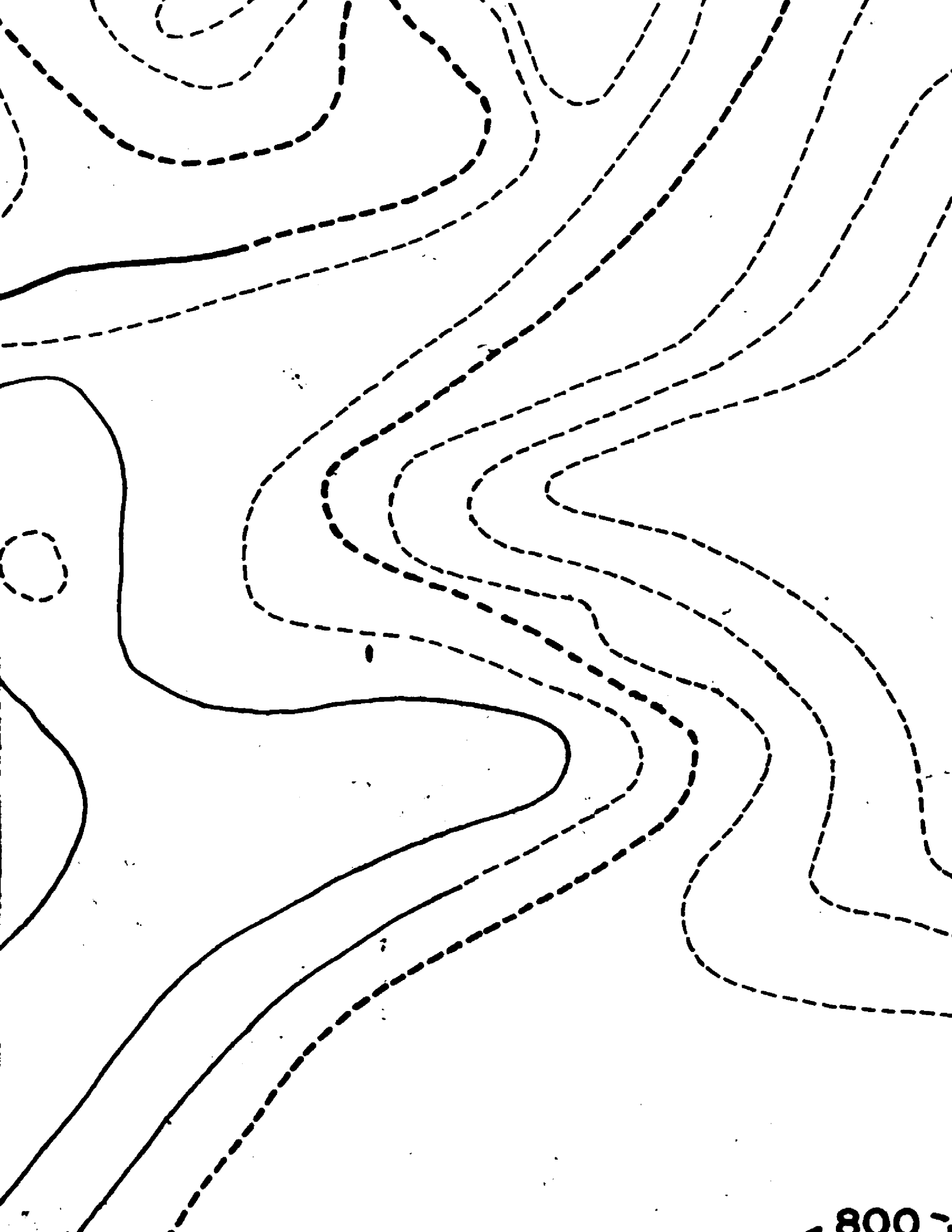


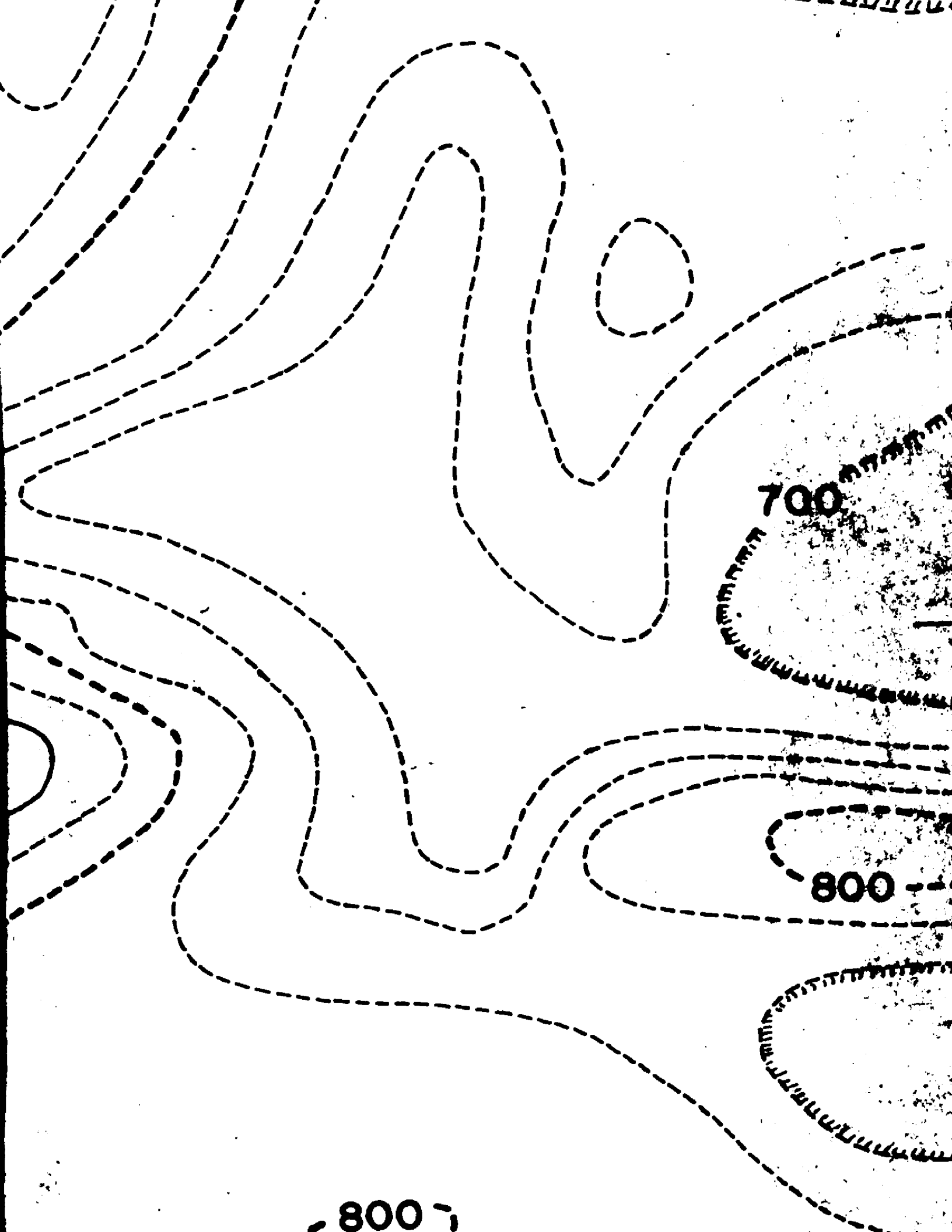
800











05

009

009

T4S

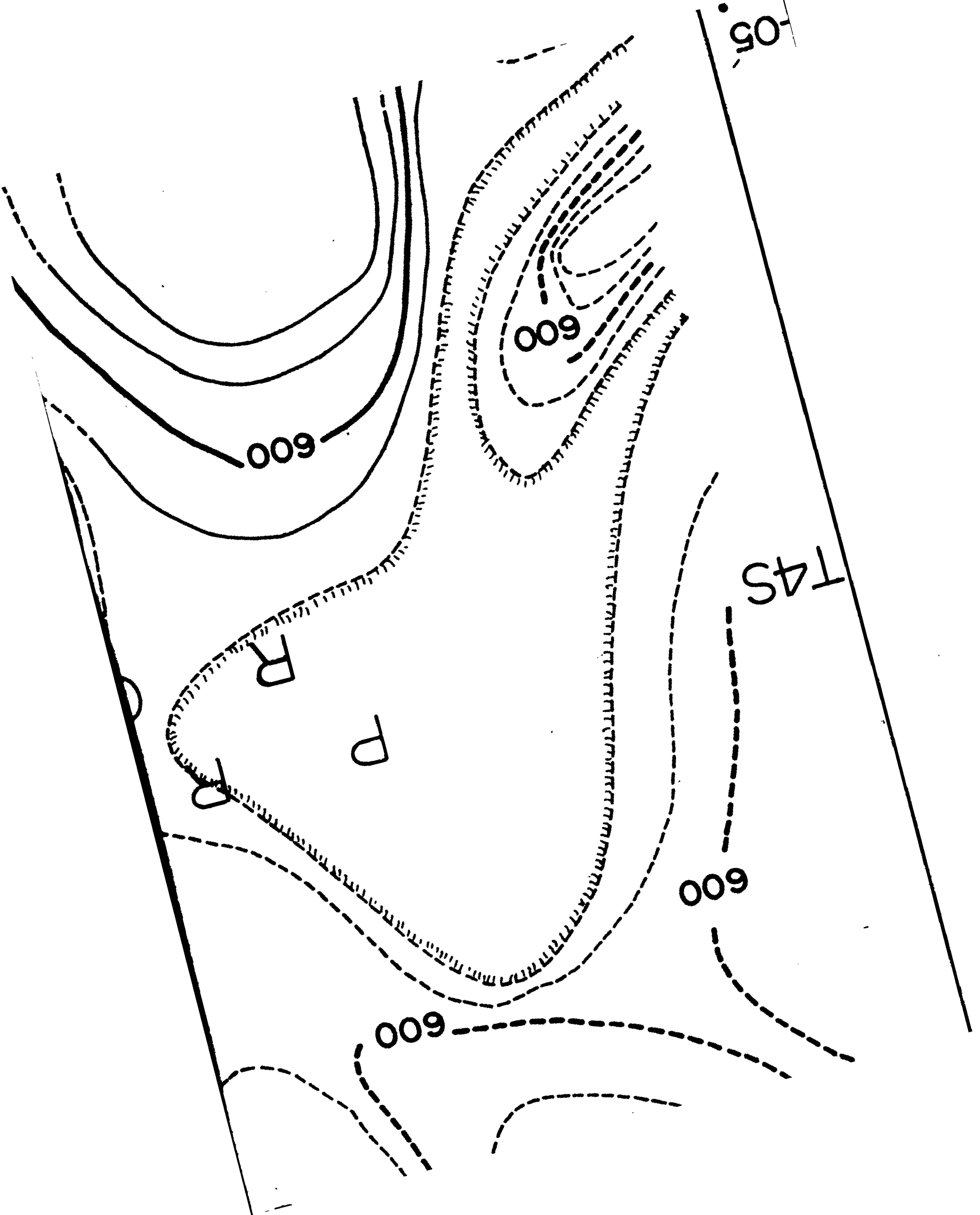
600

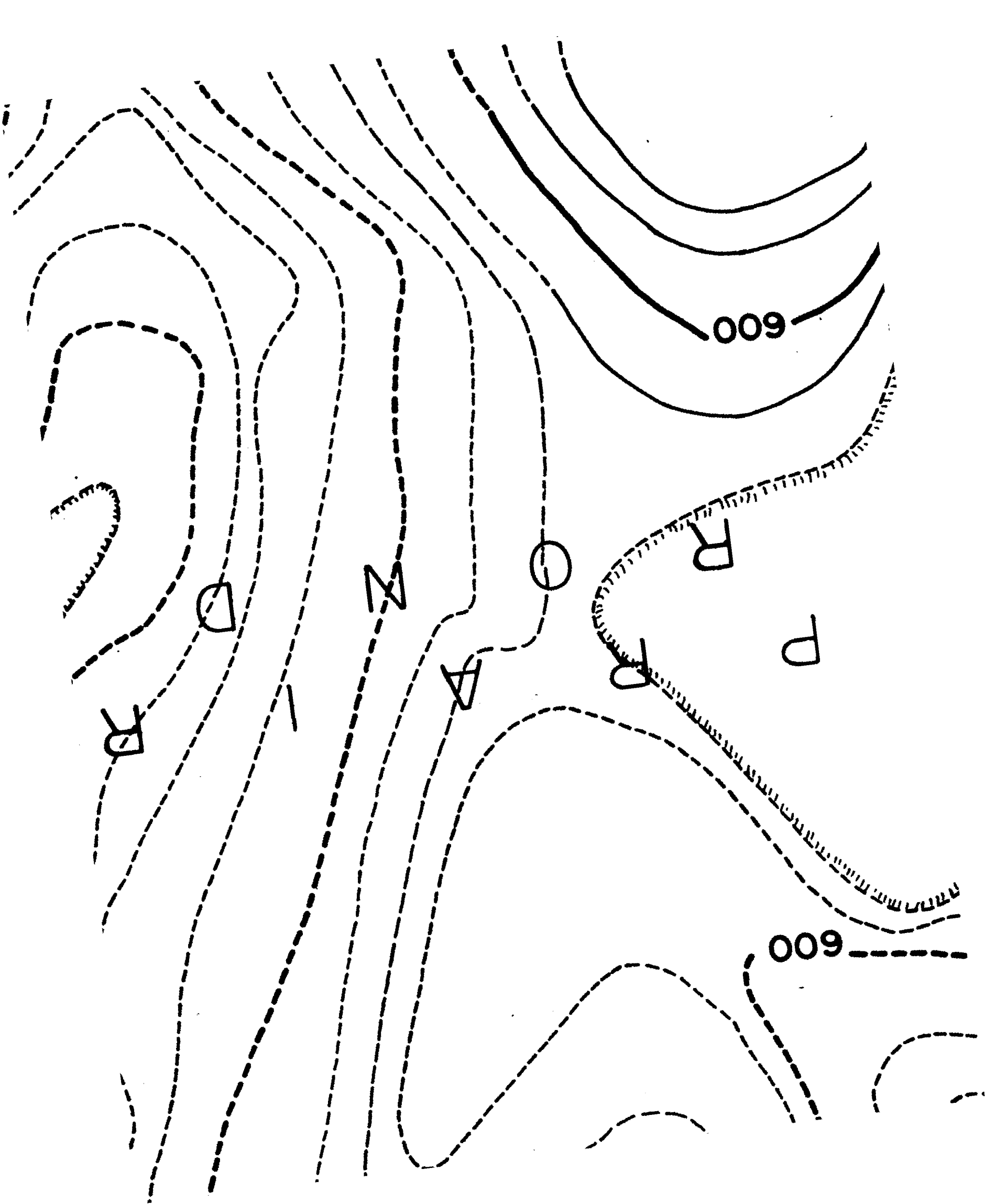
009

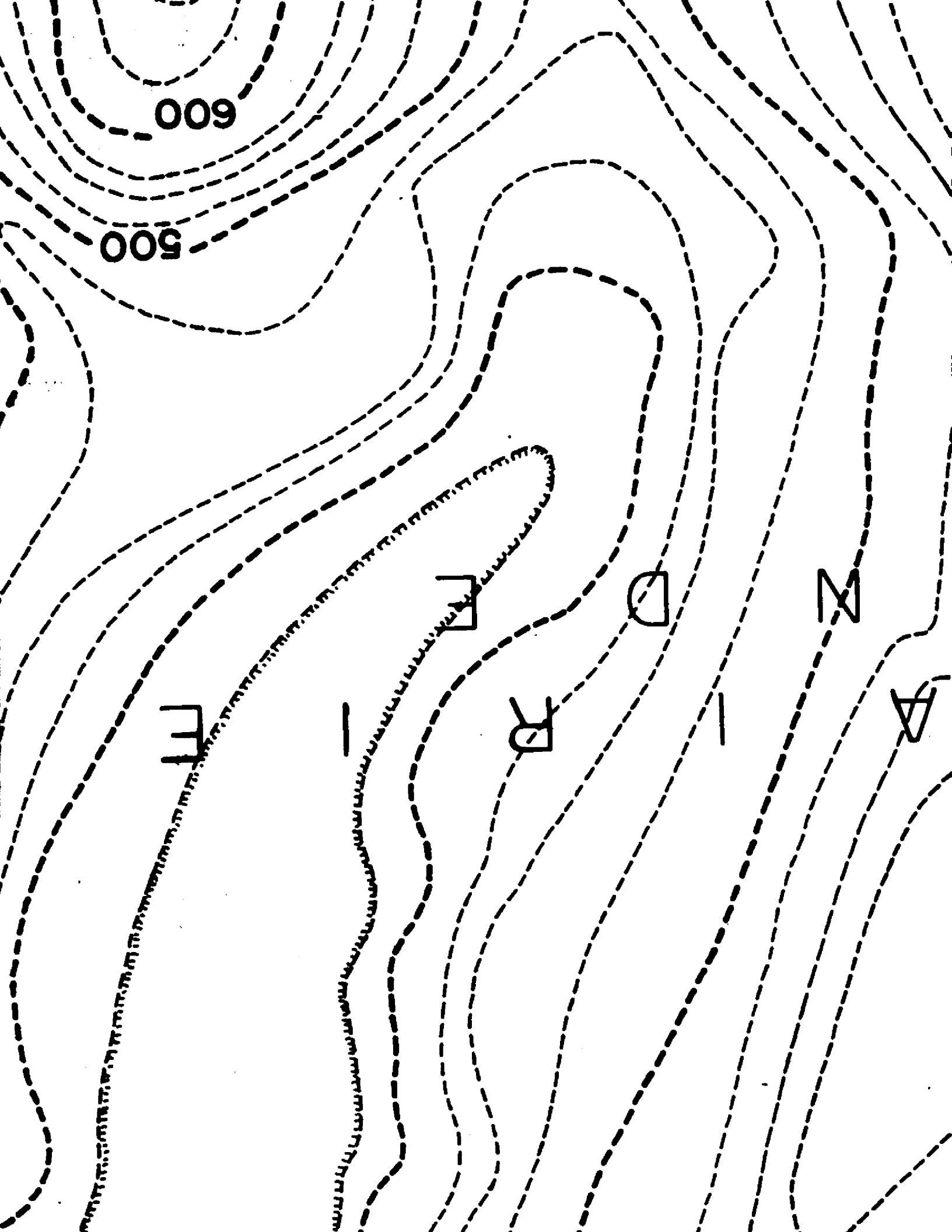
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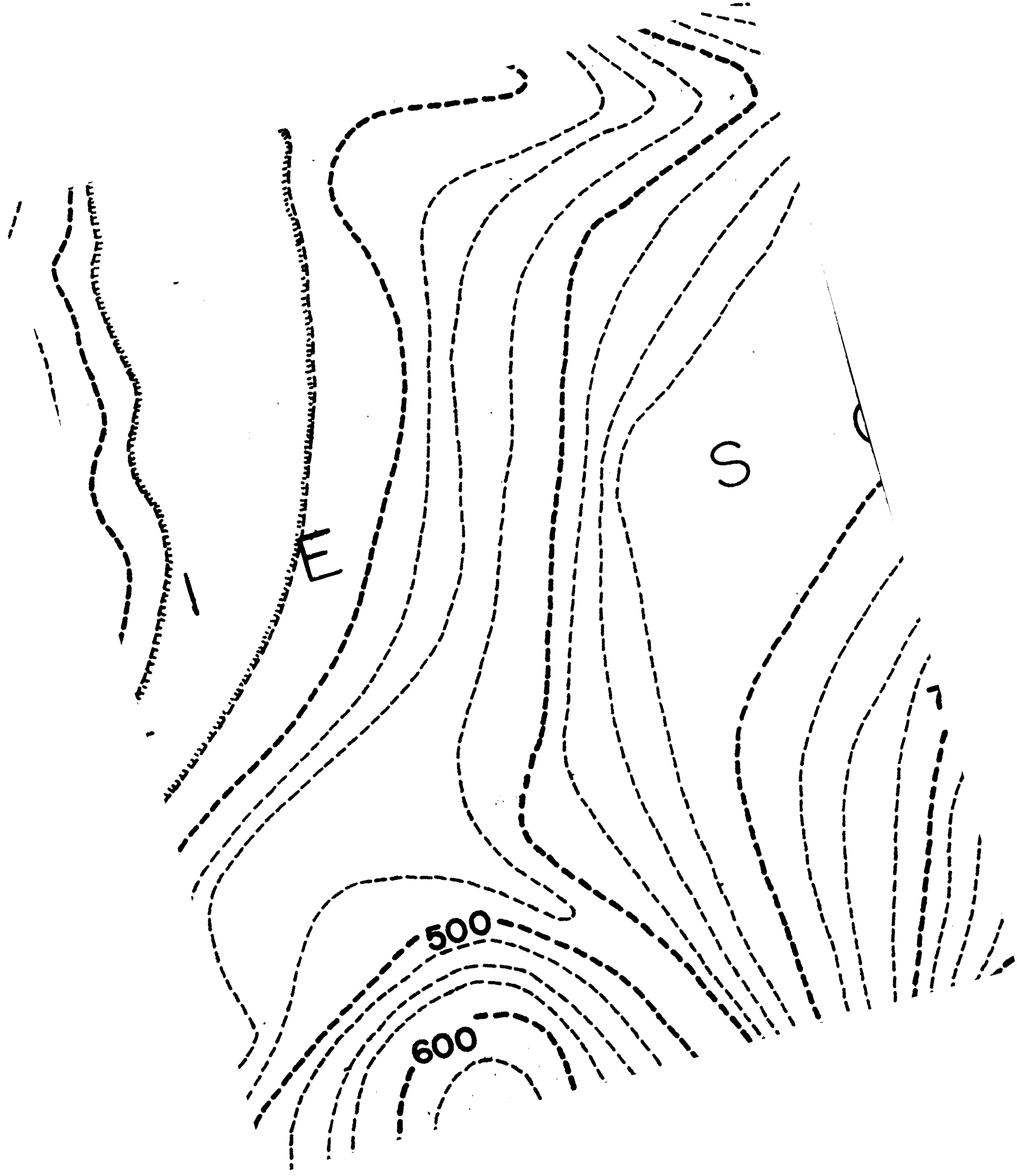
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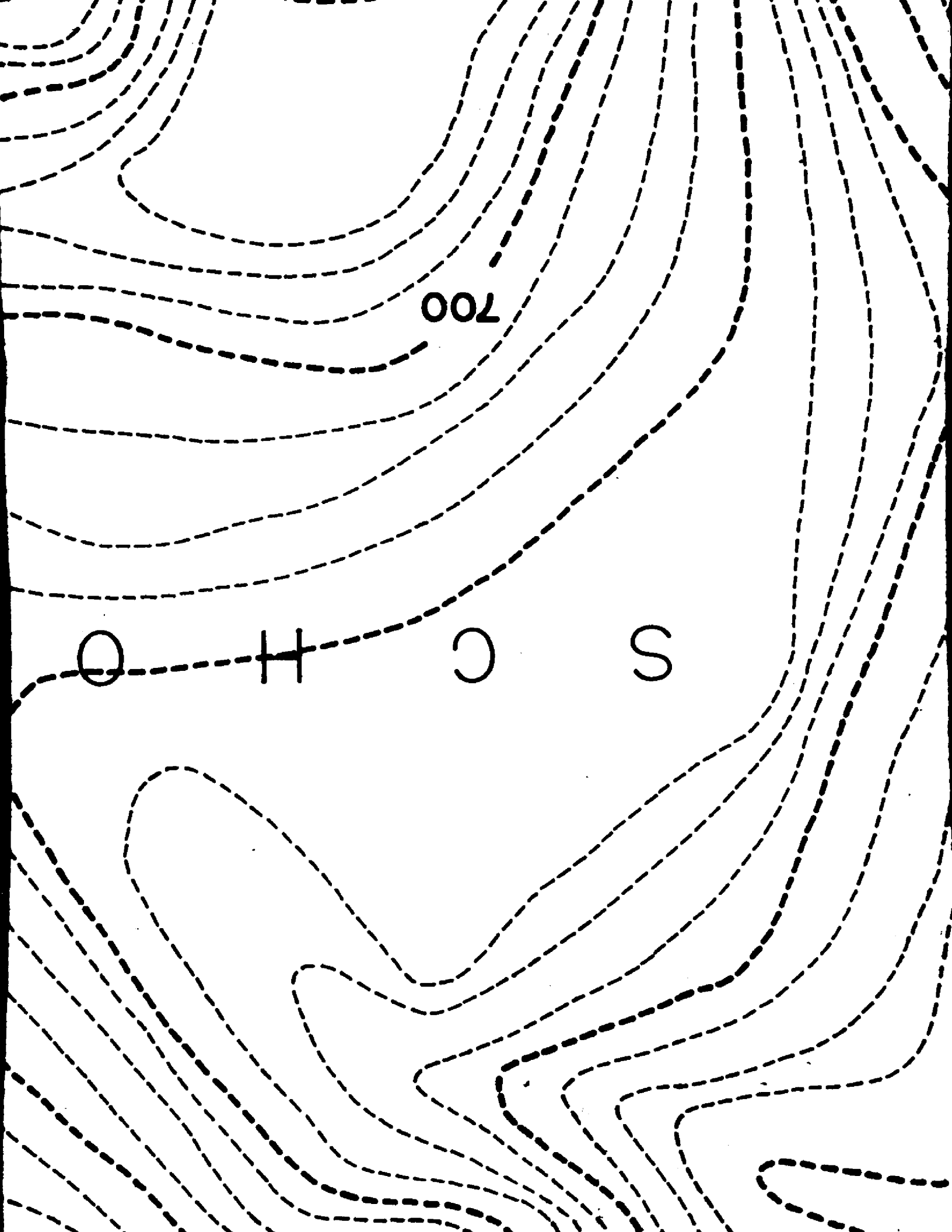
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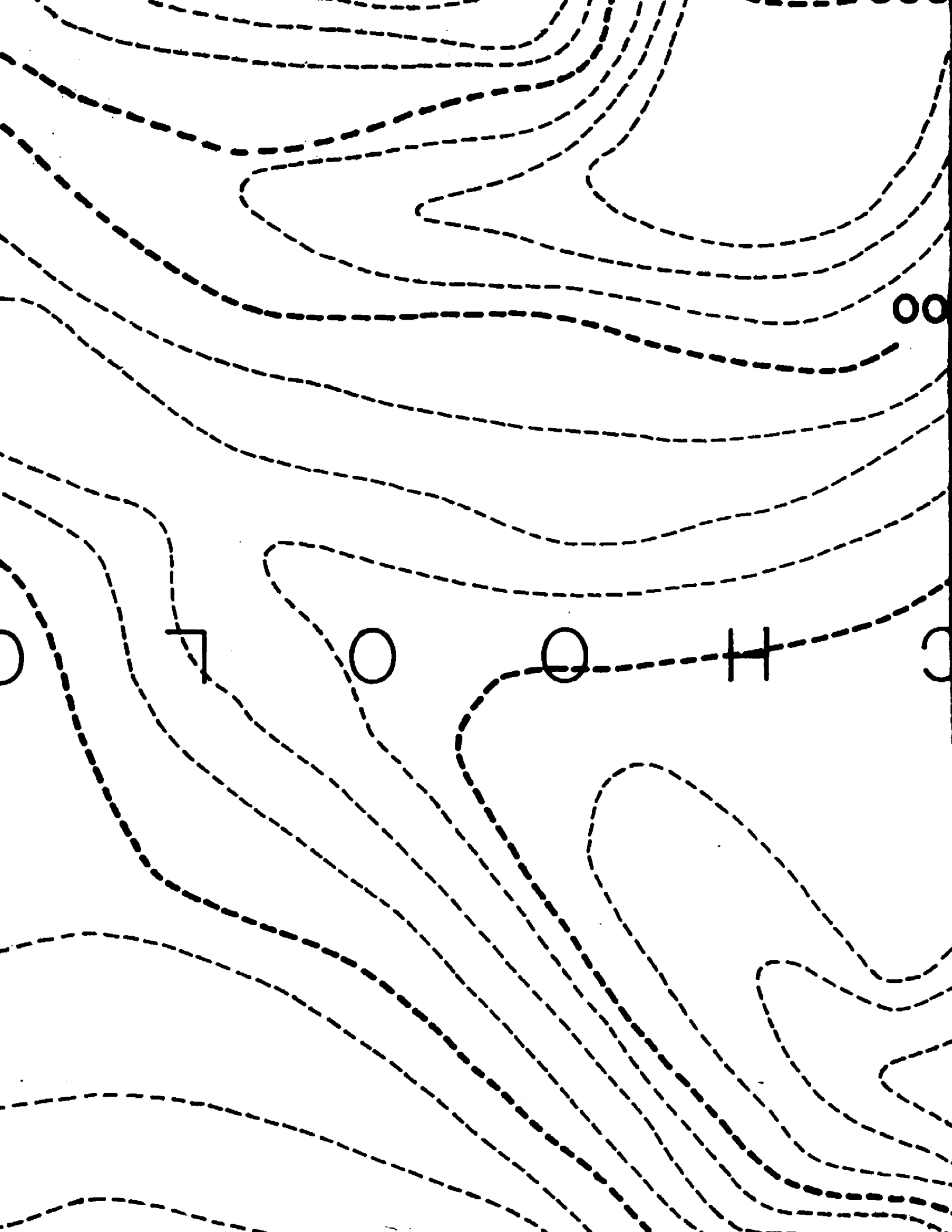


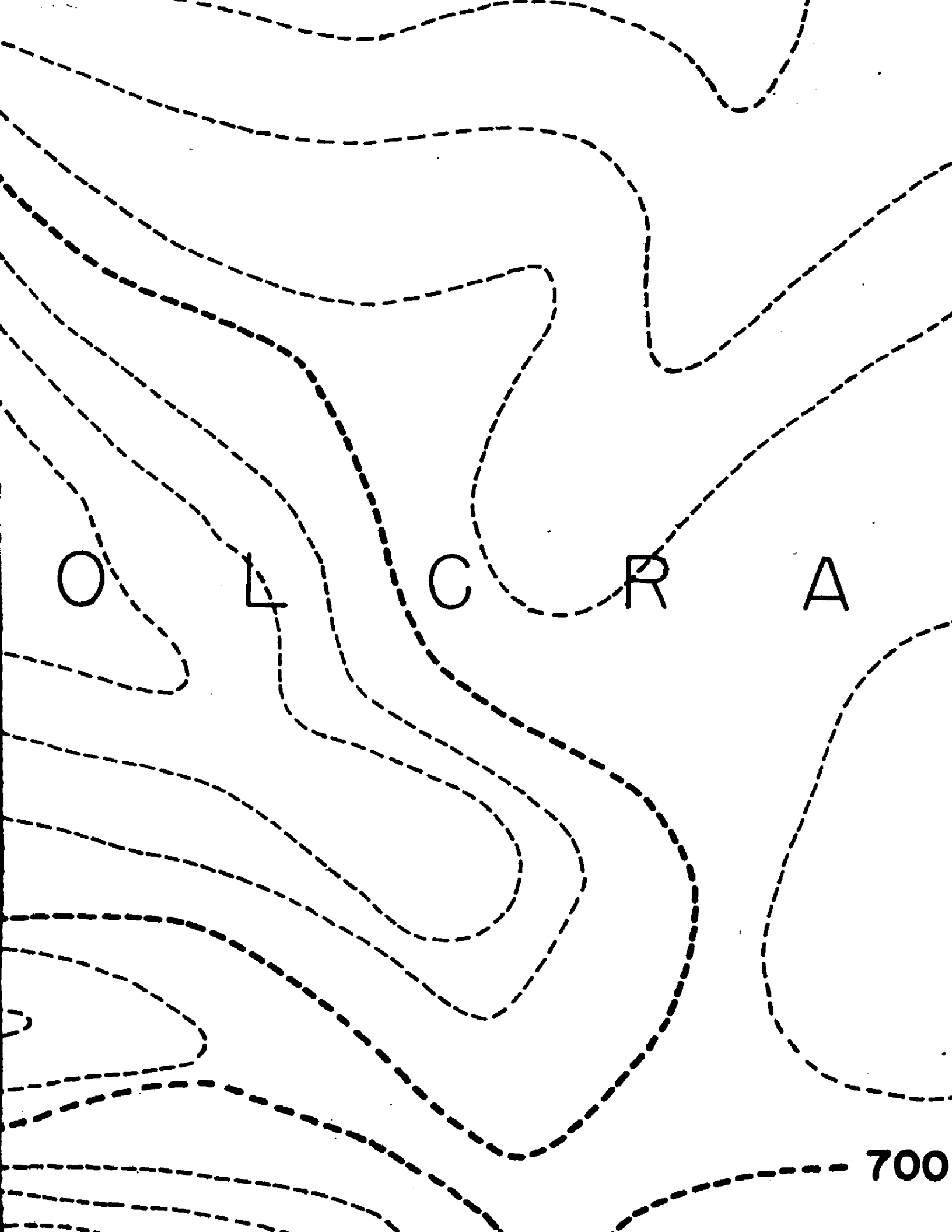












O

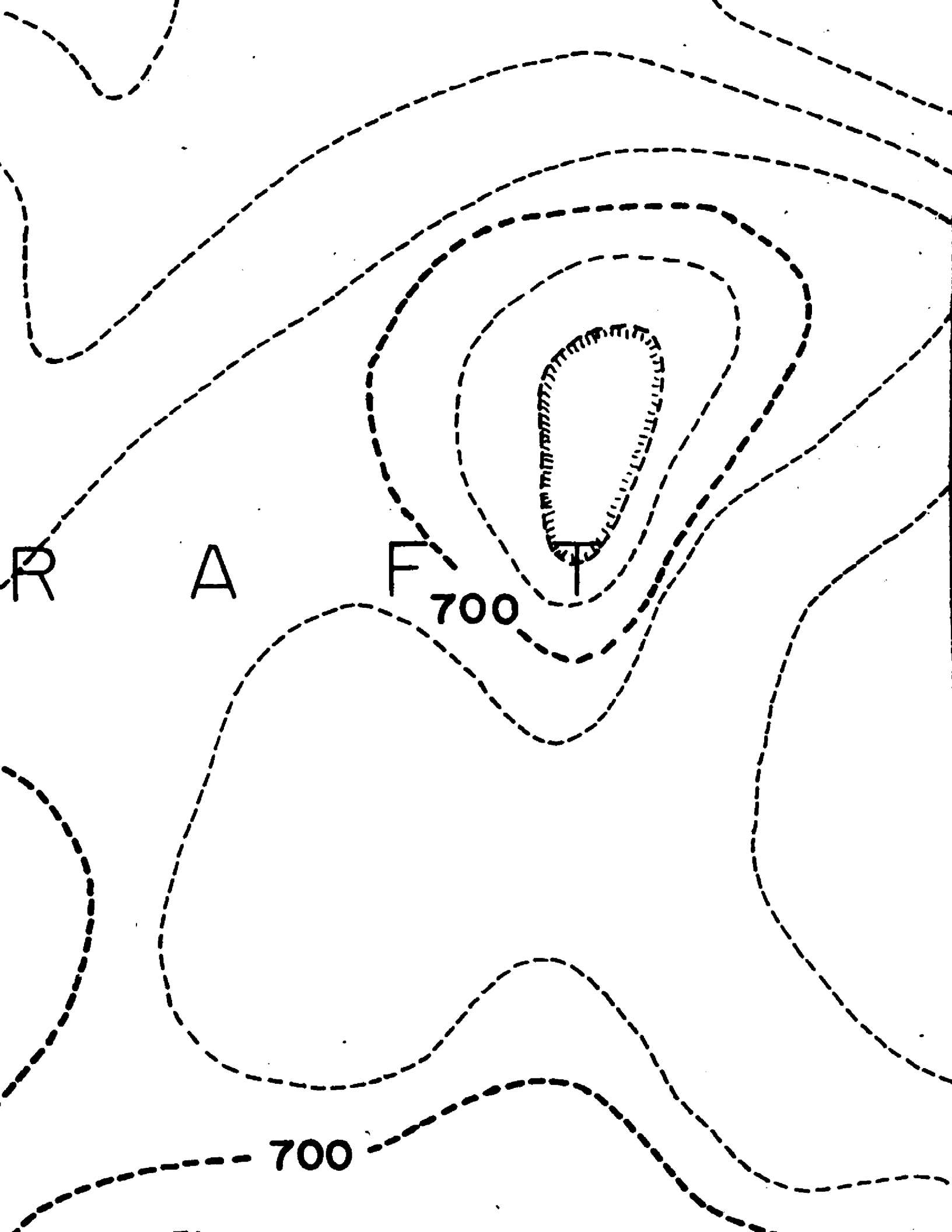
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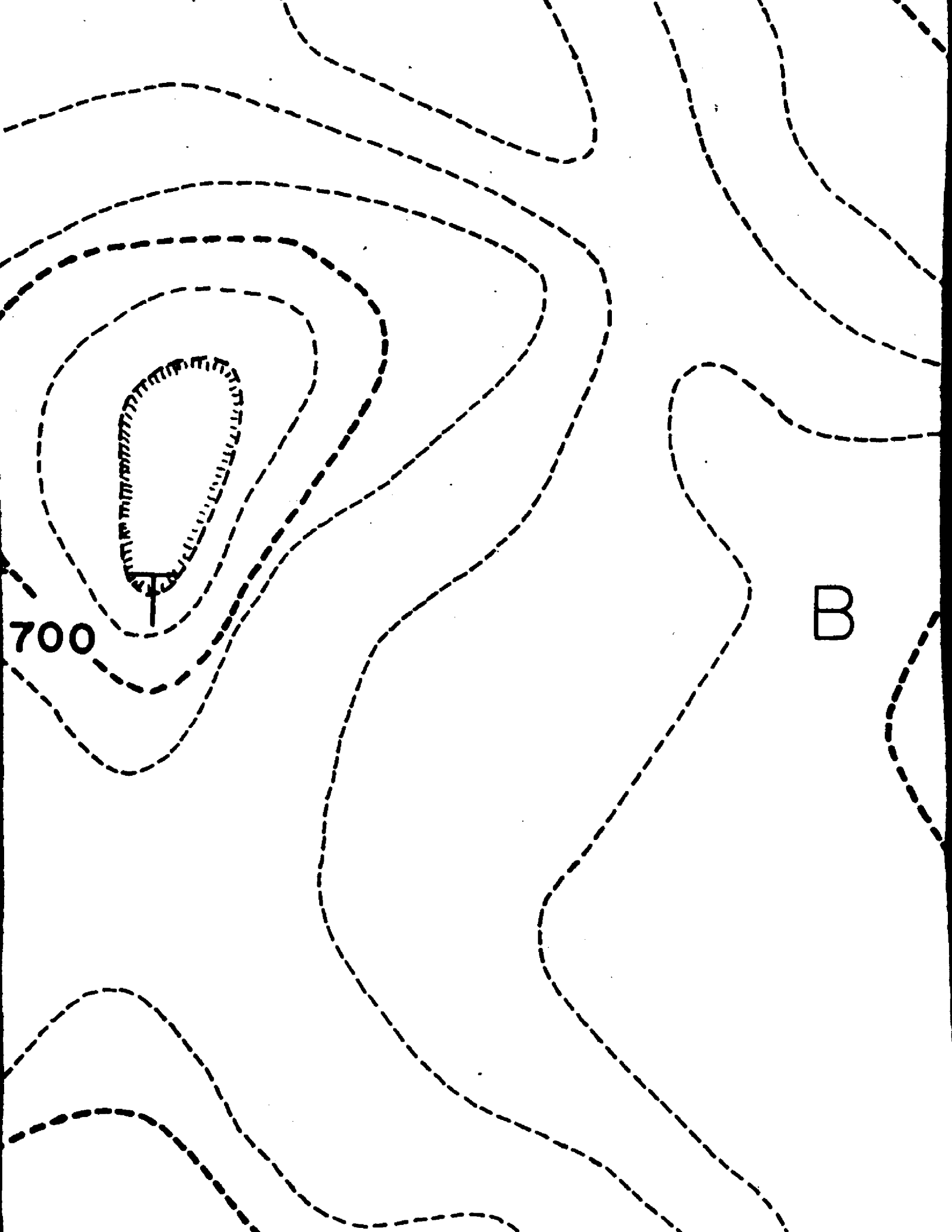
C

R

A

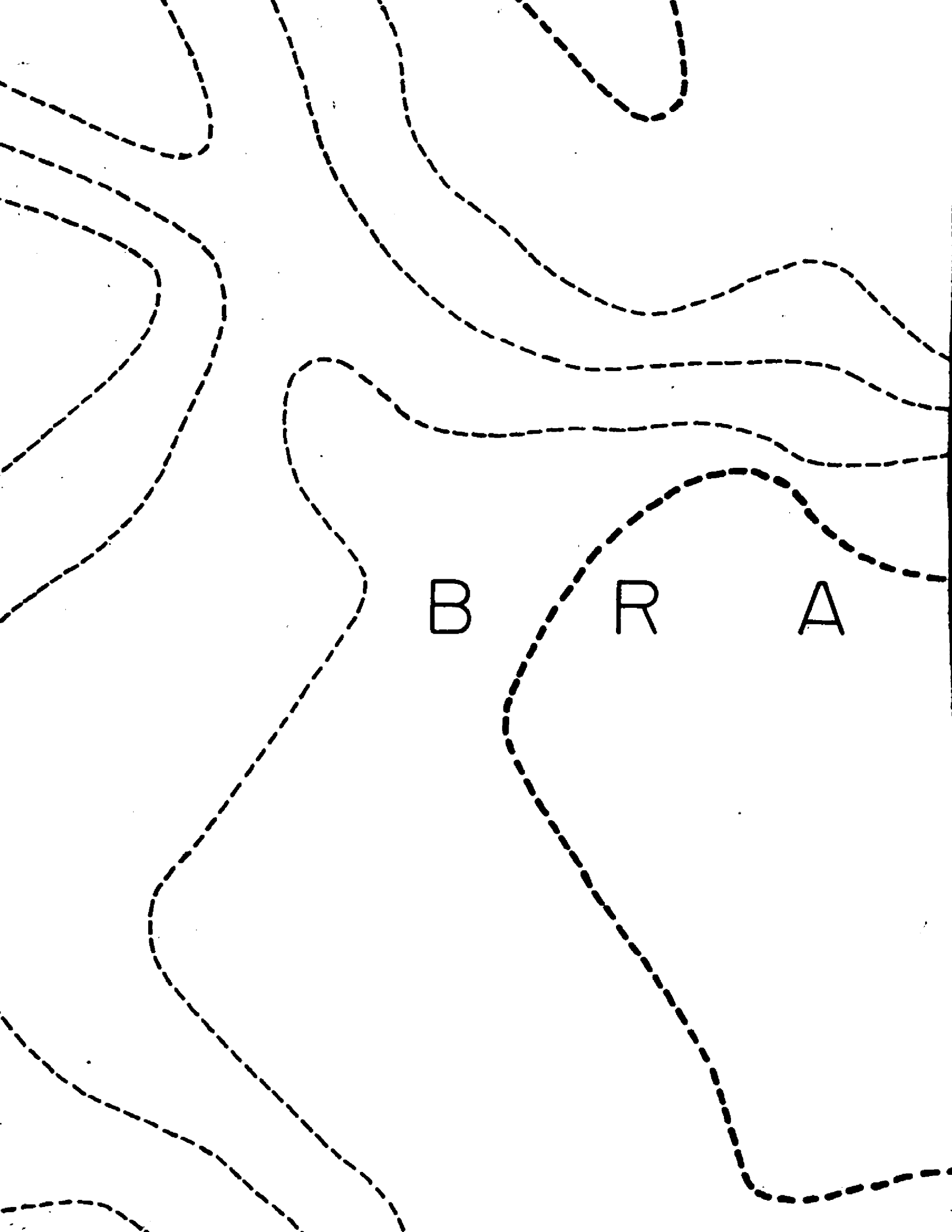
700

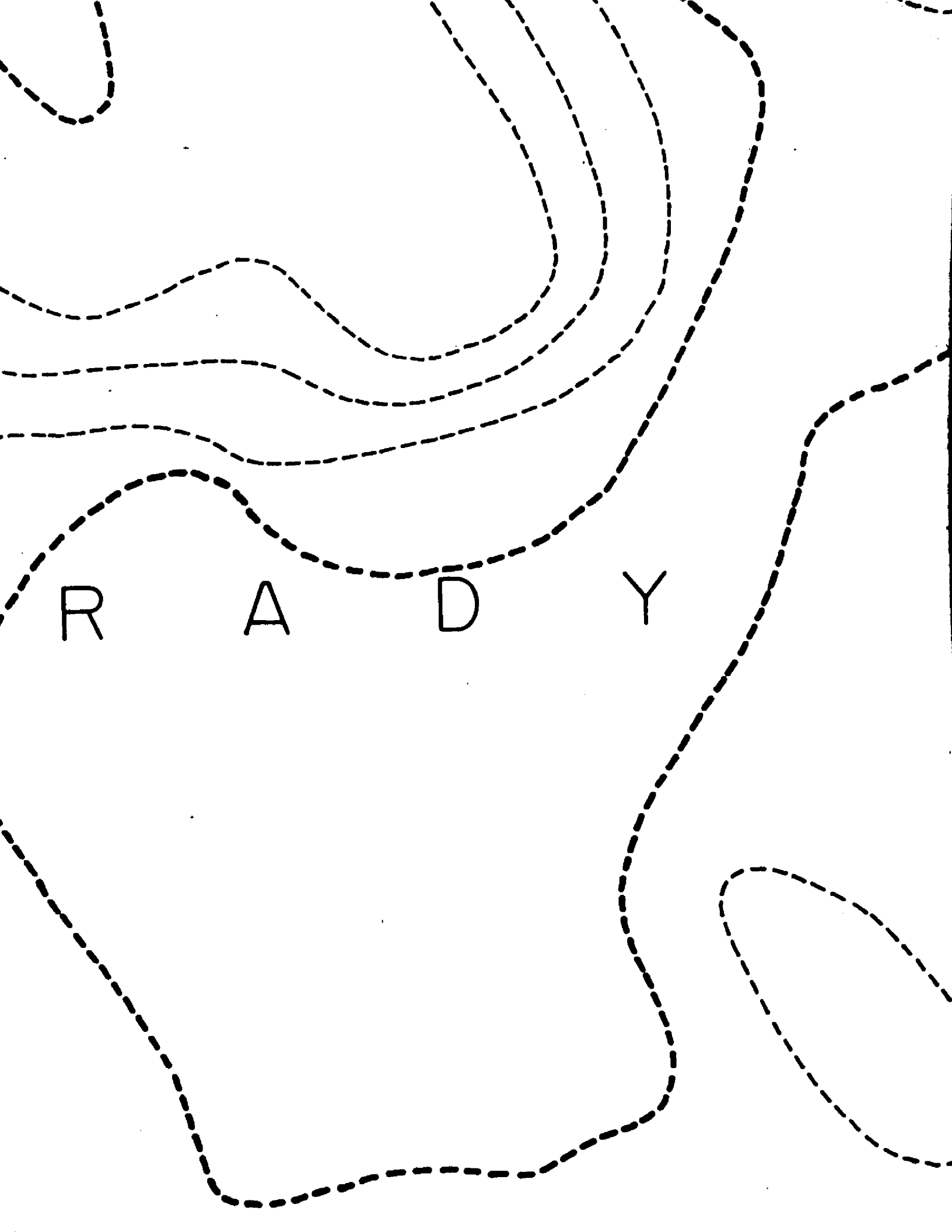




700

B



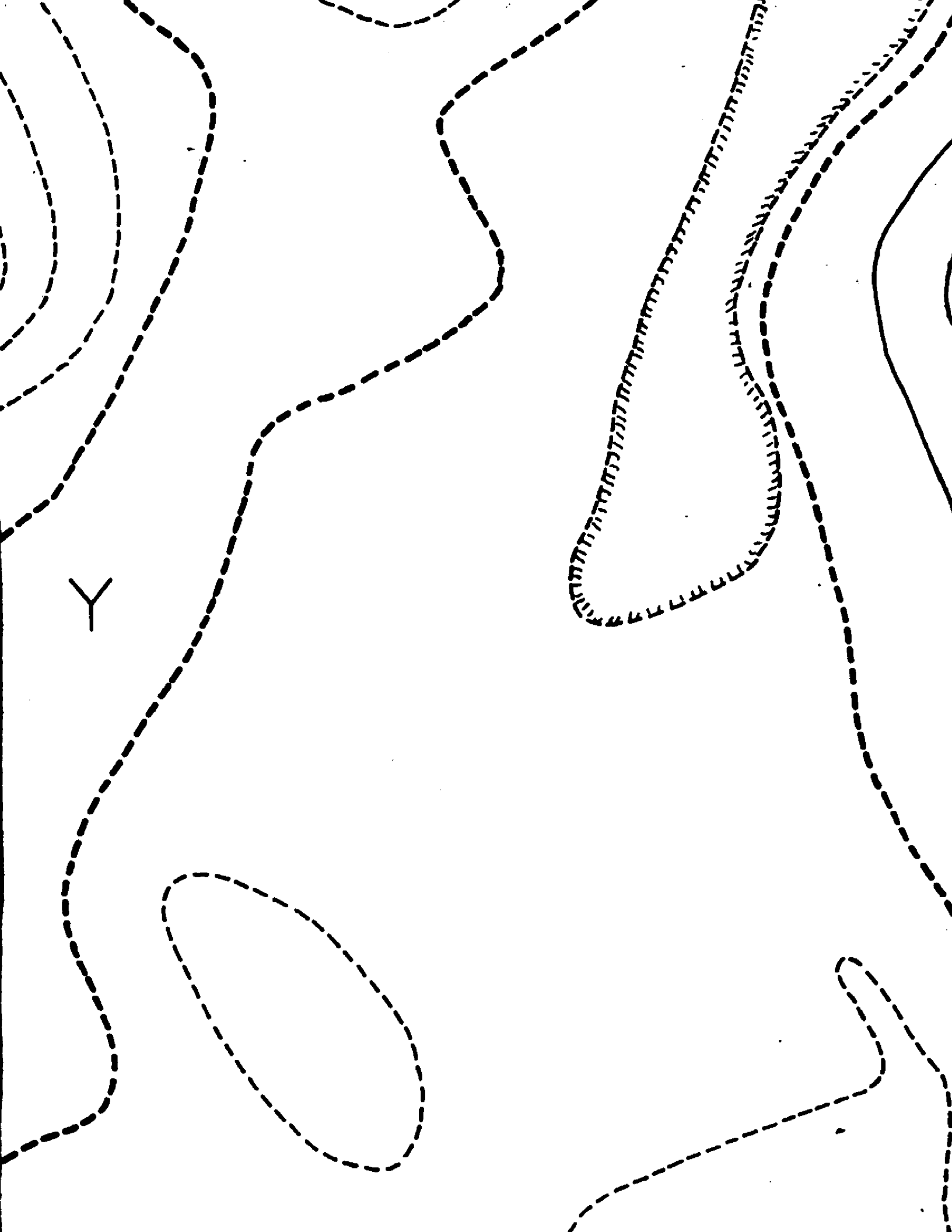


R

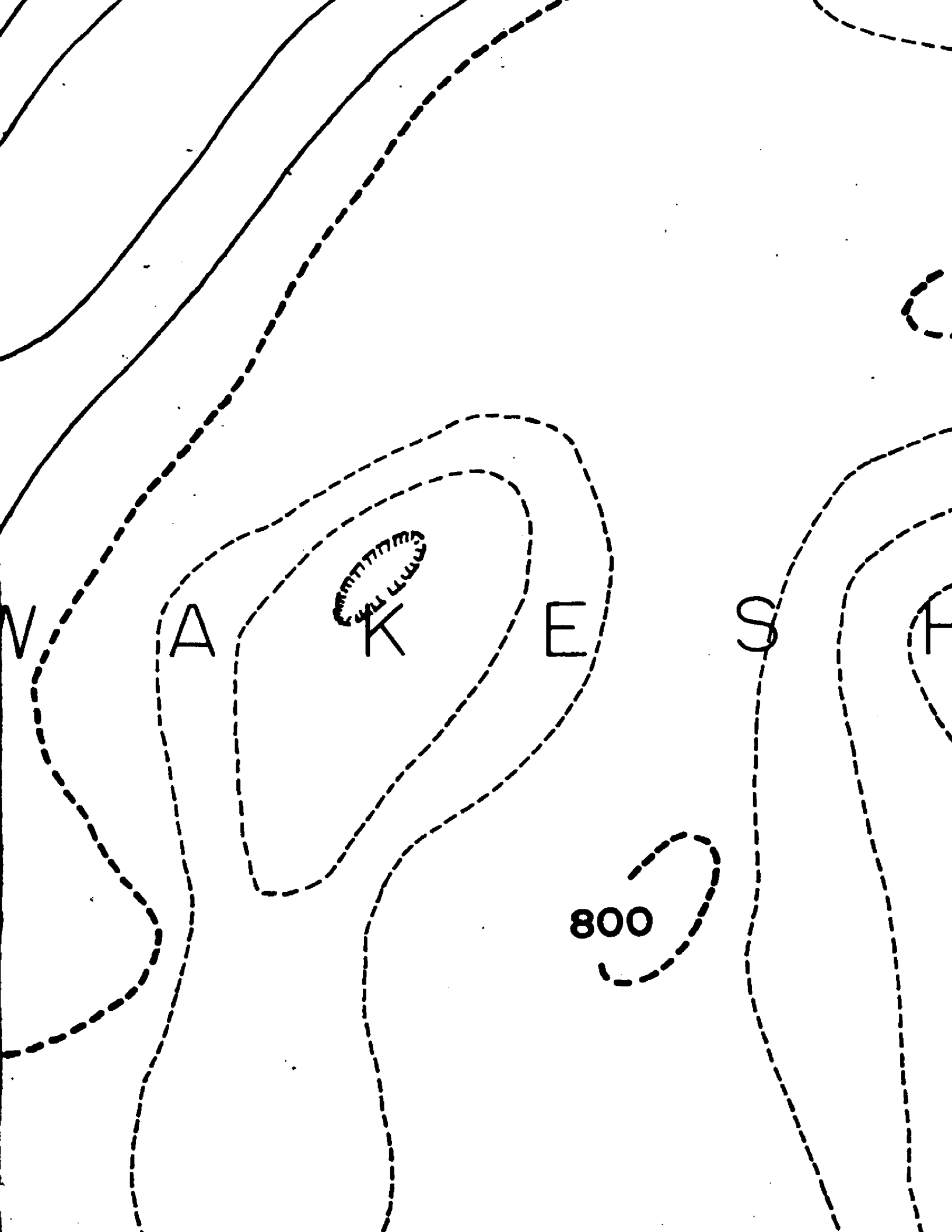
A

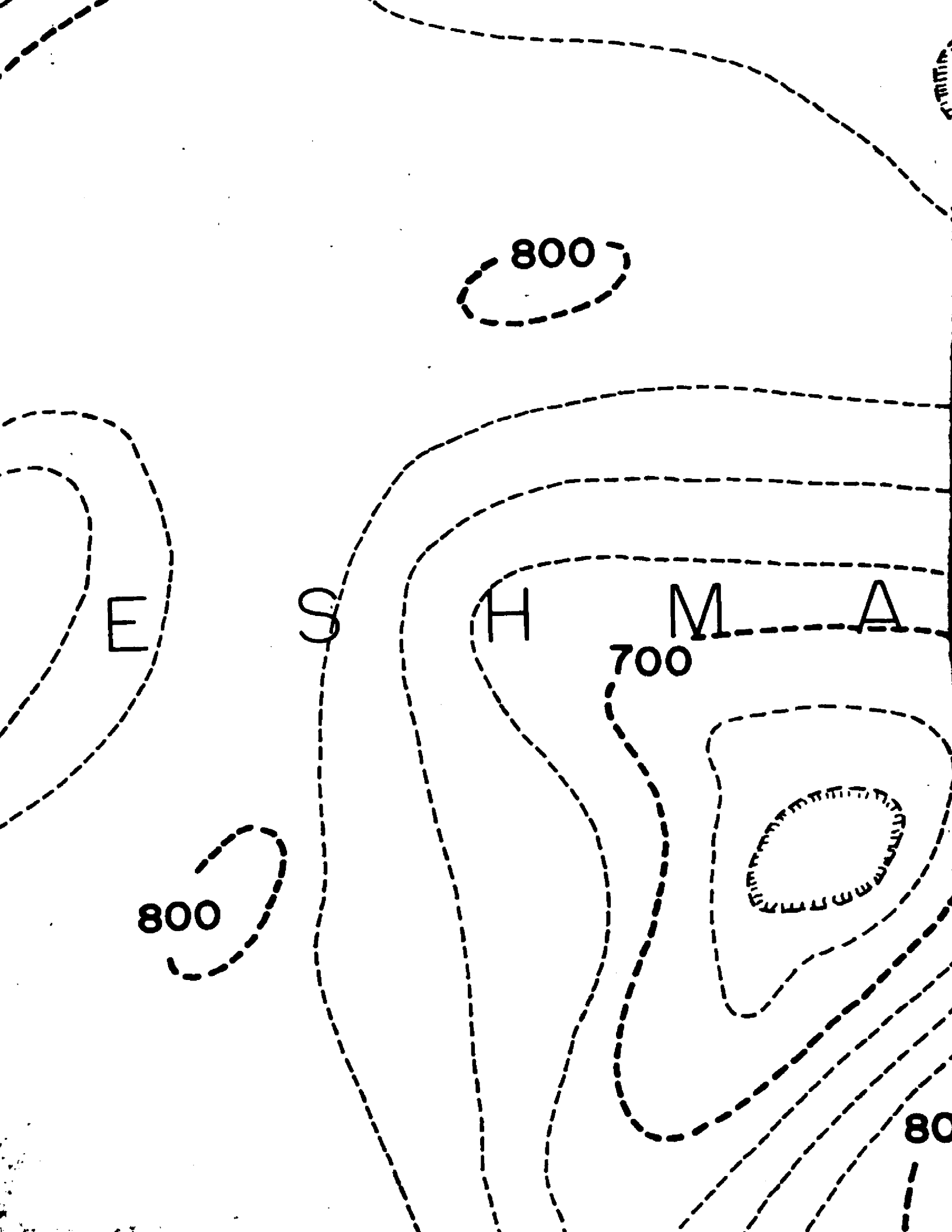
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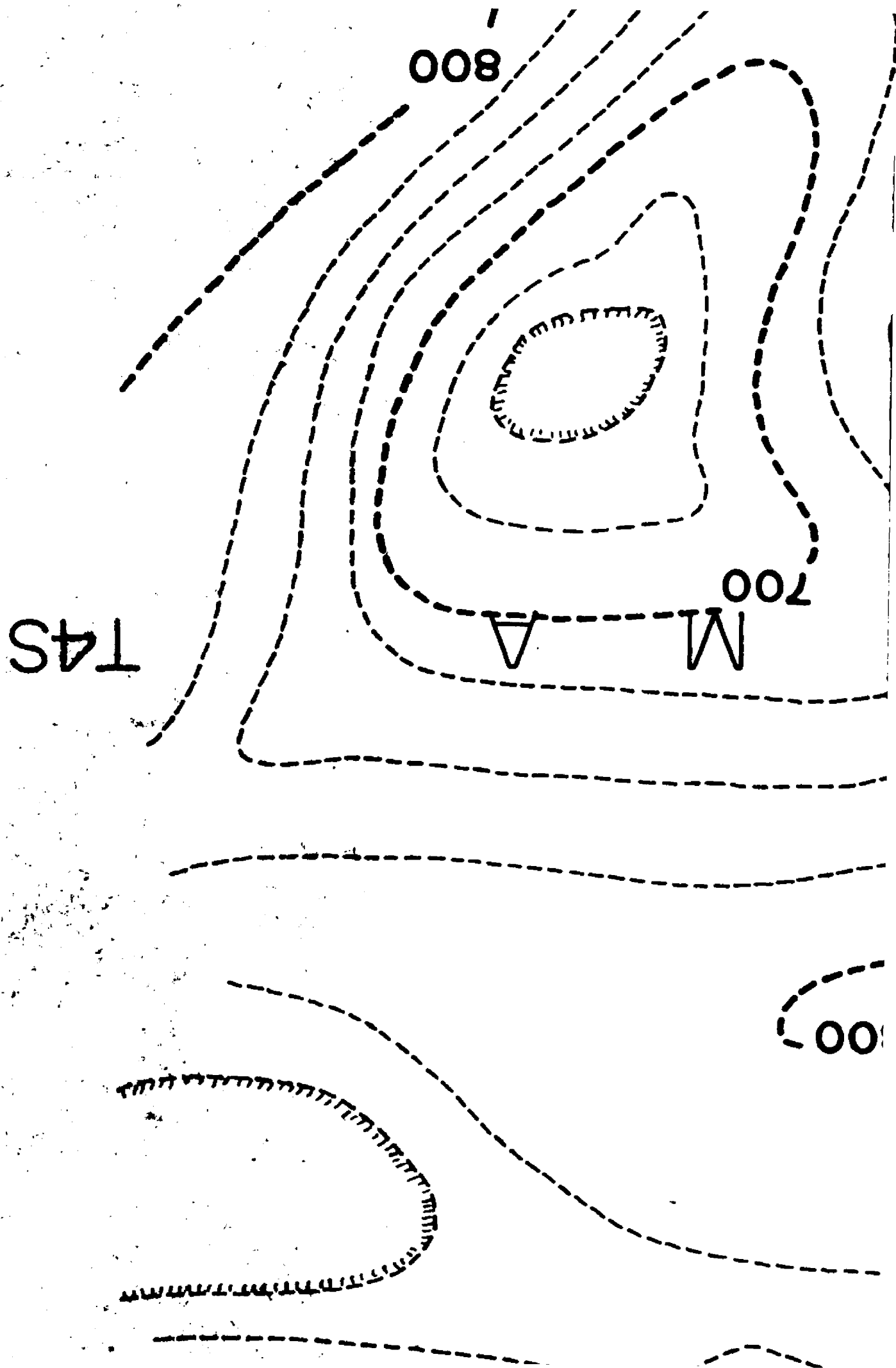
Y











R

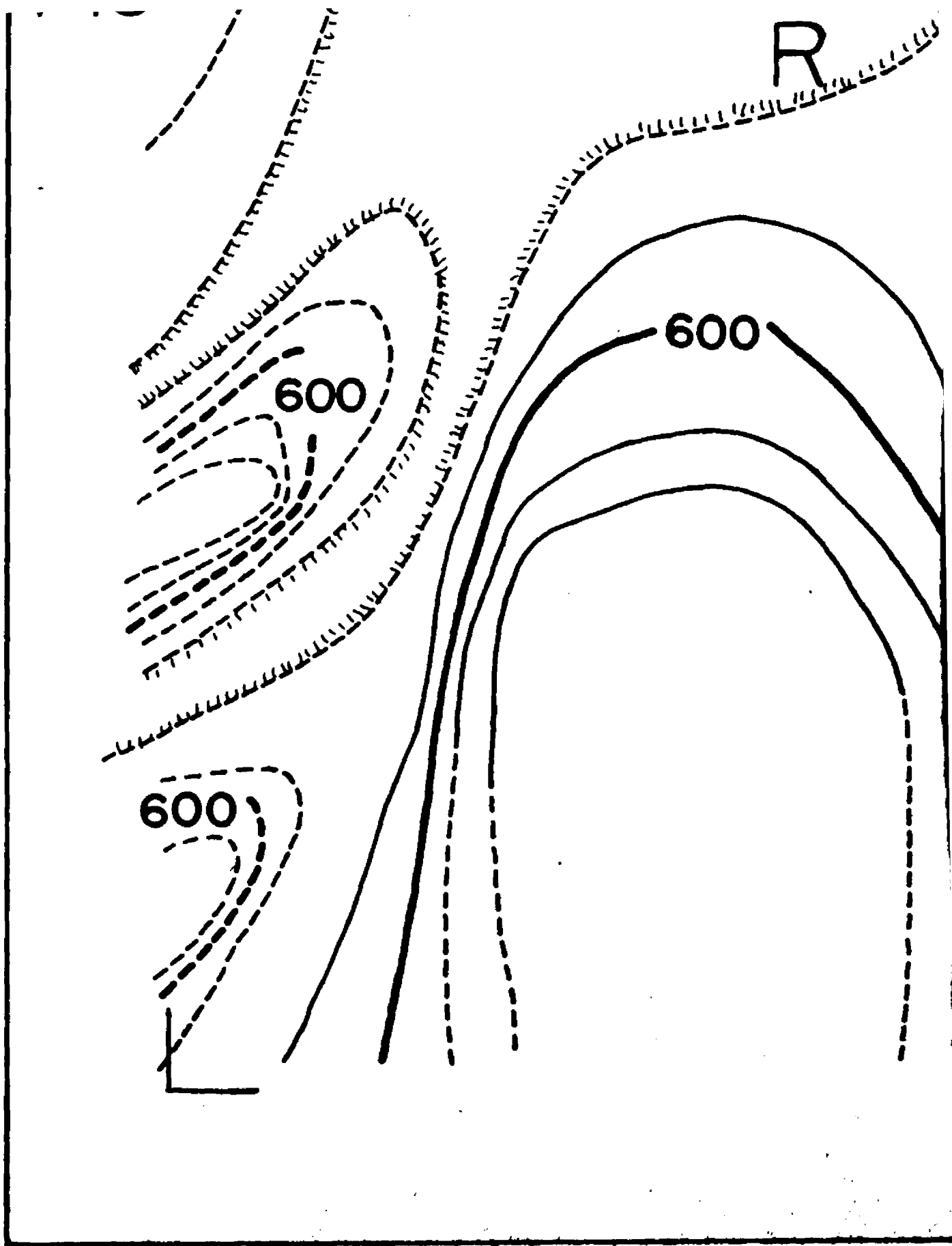
600

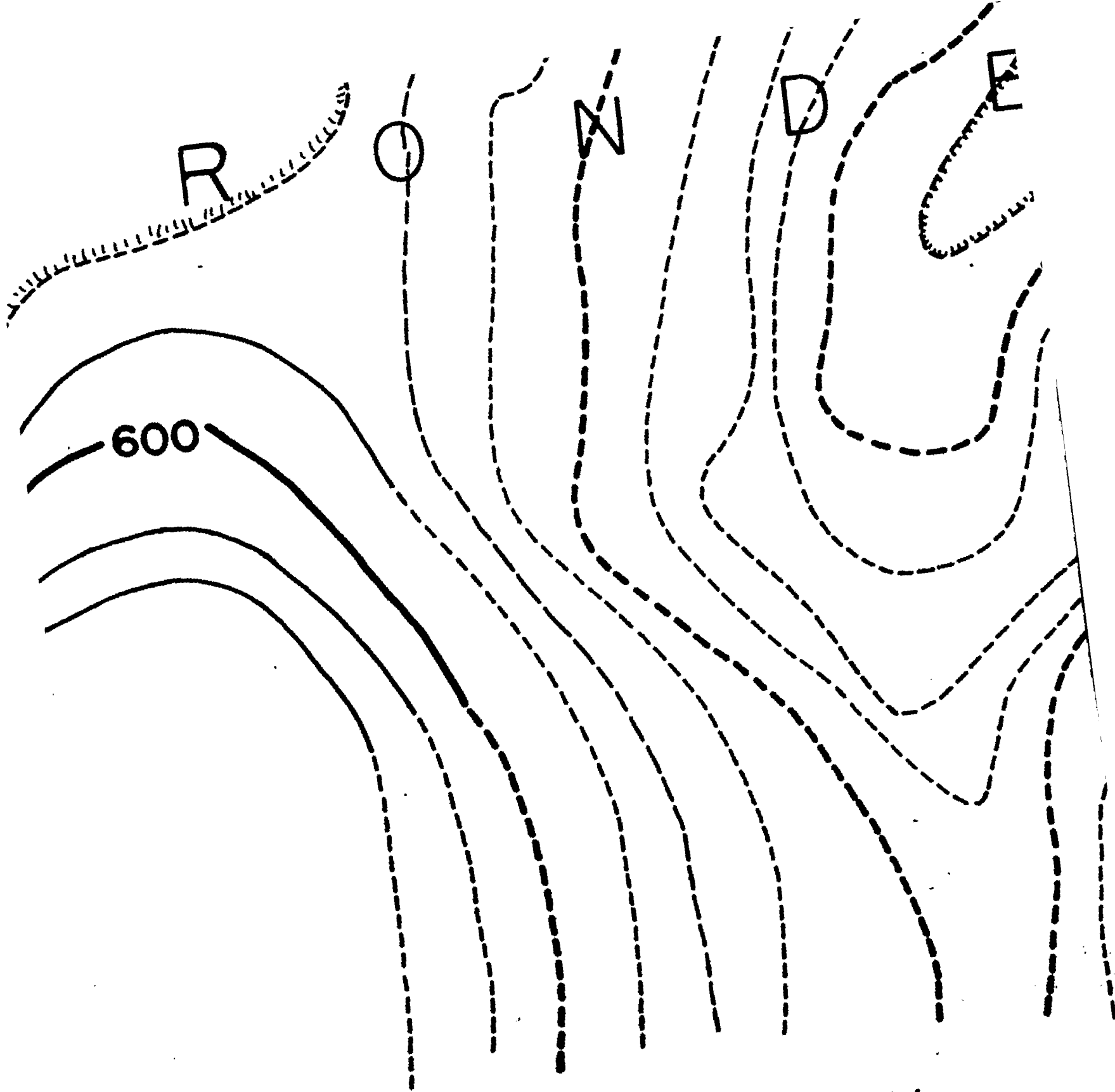
600

600

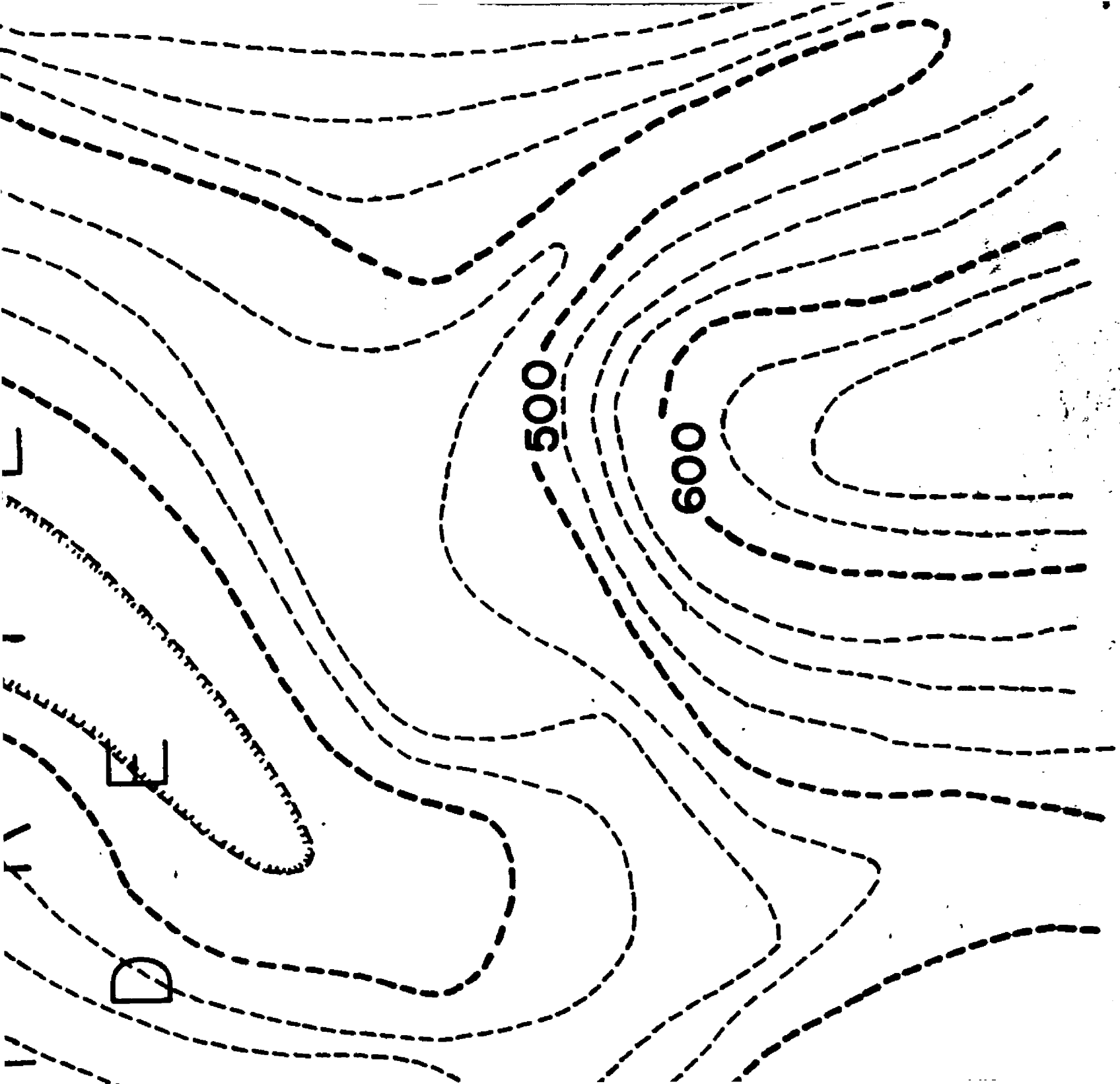
05.
42

45



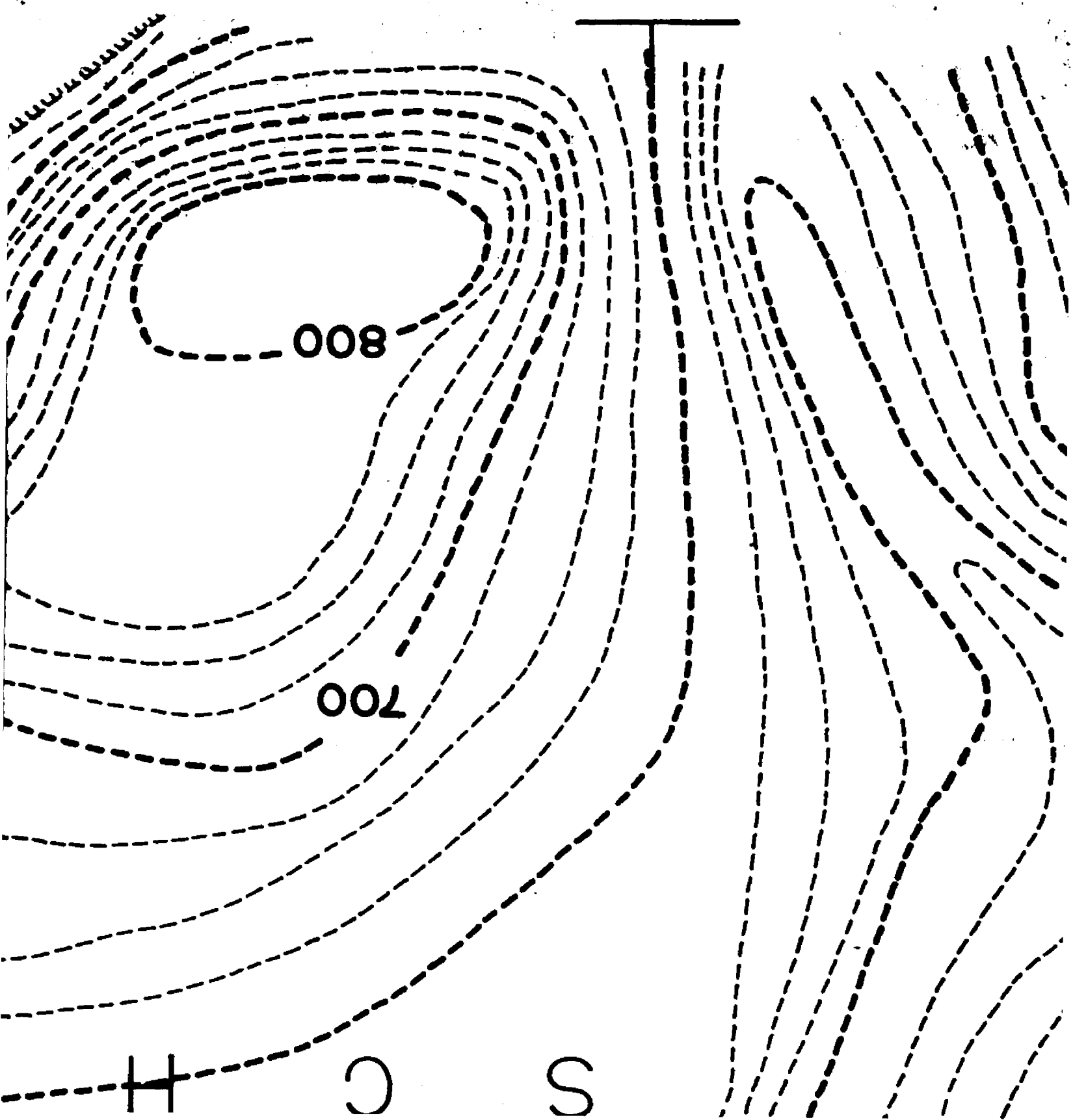


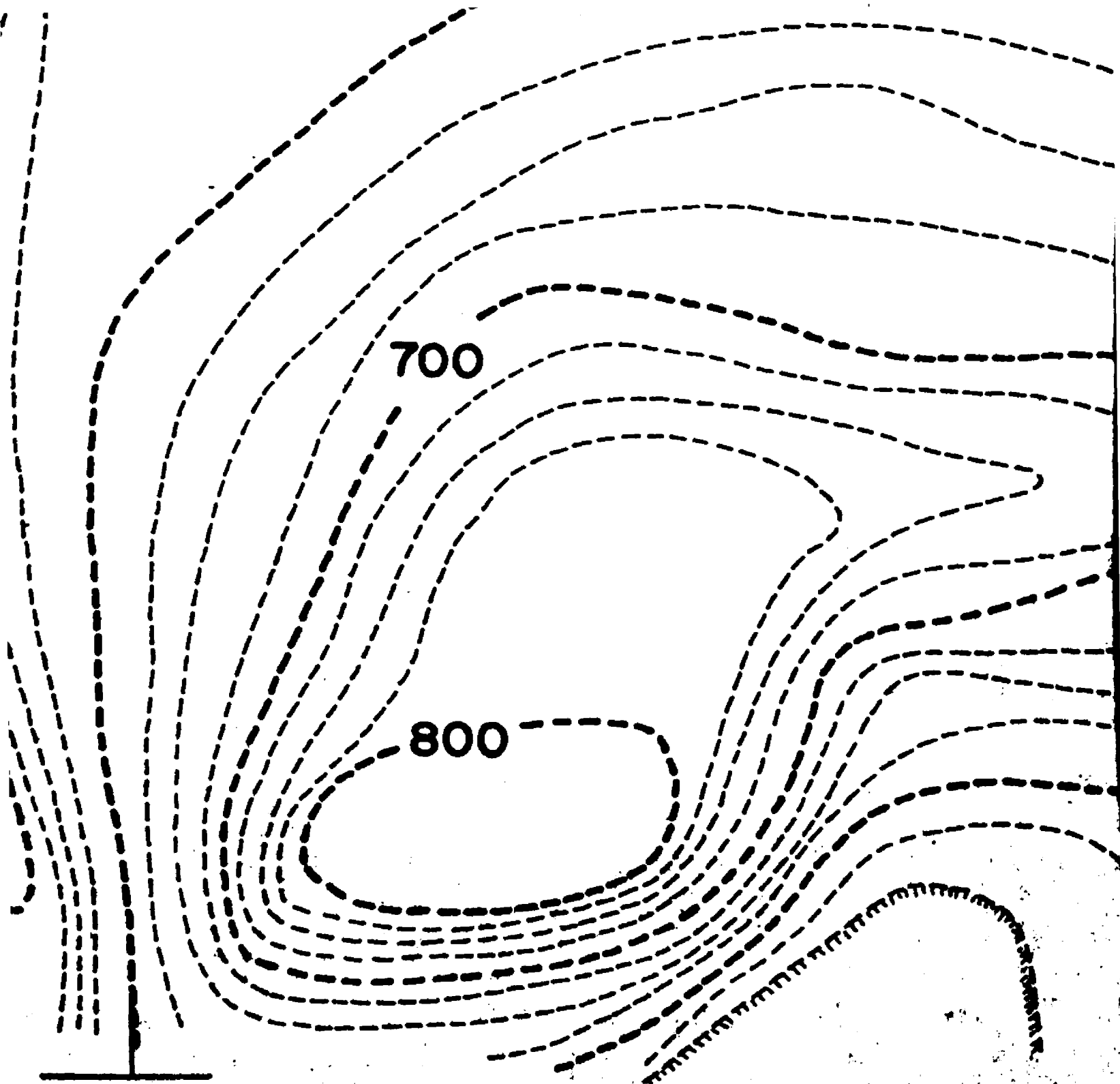
R12W

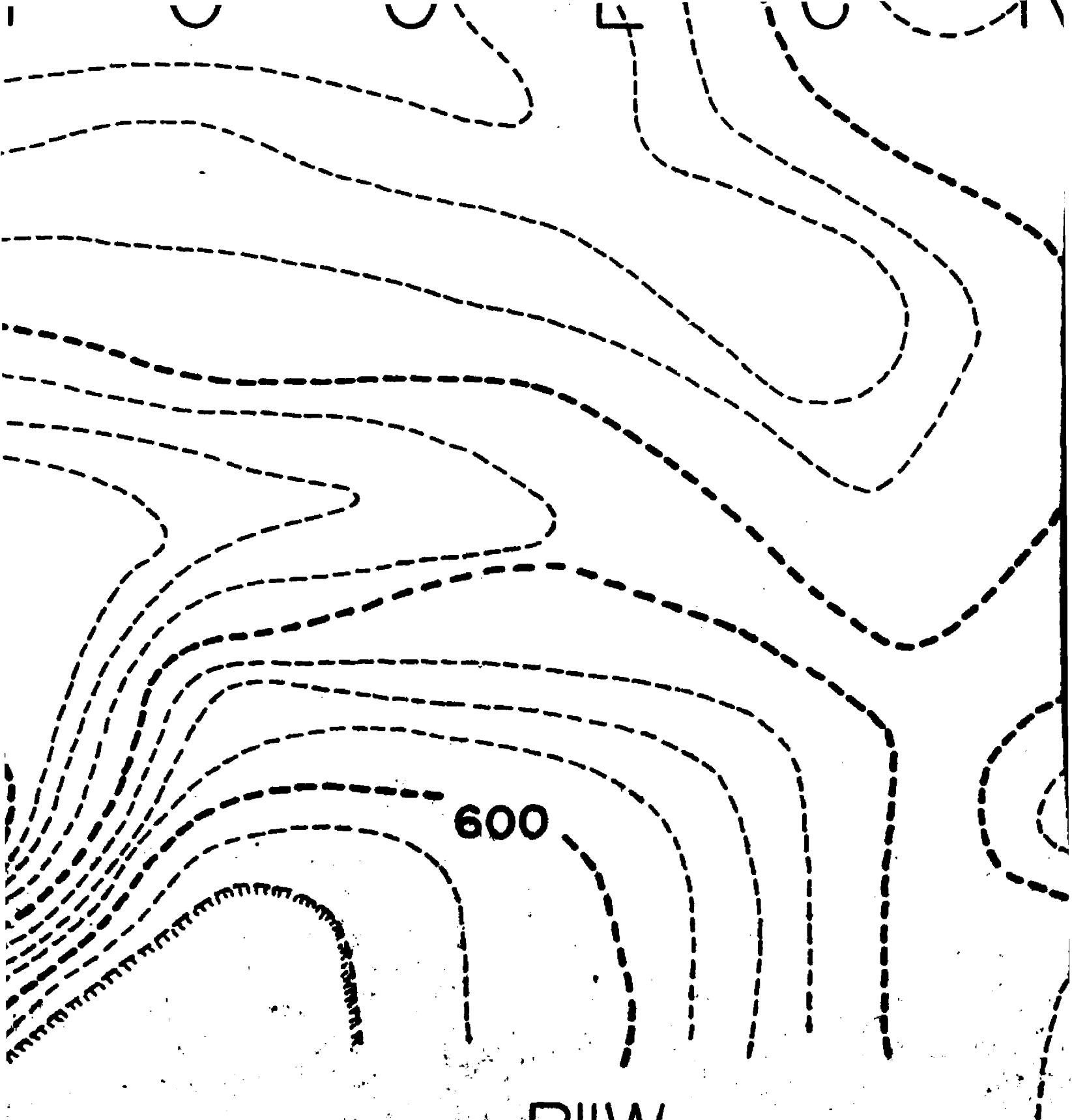


12W

40

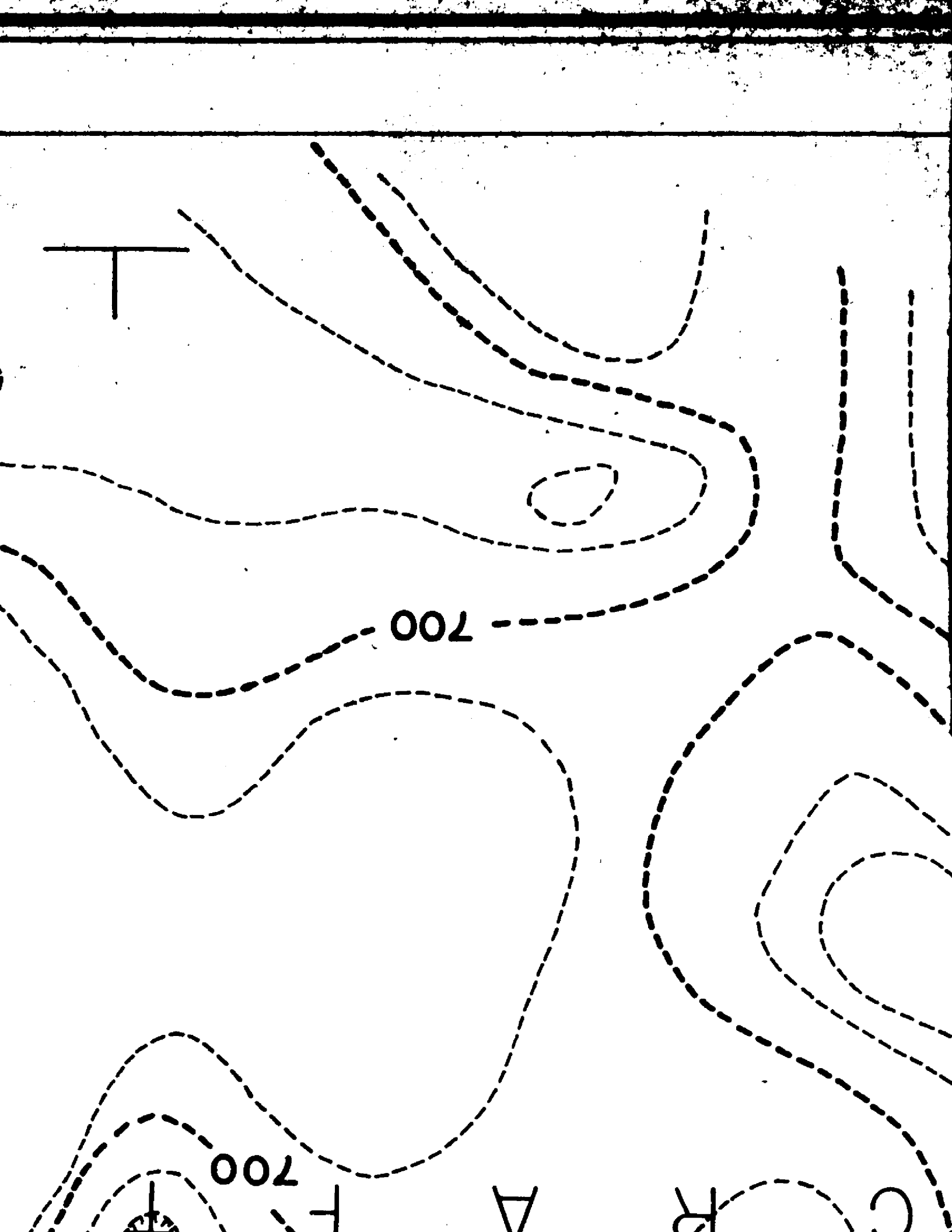






600

RIIW

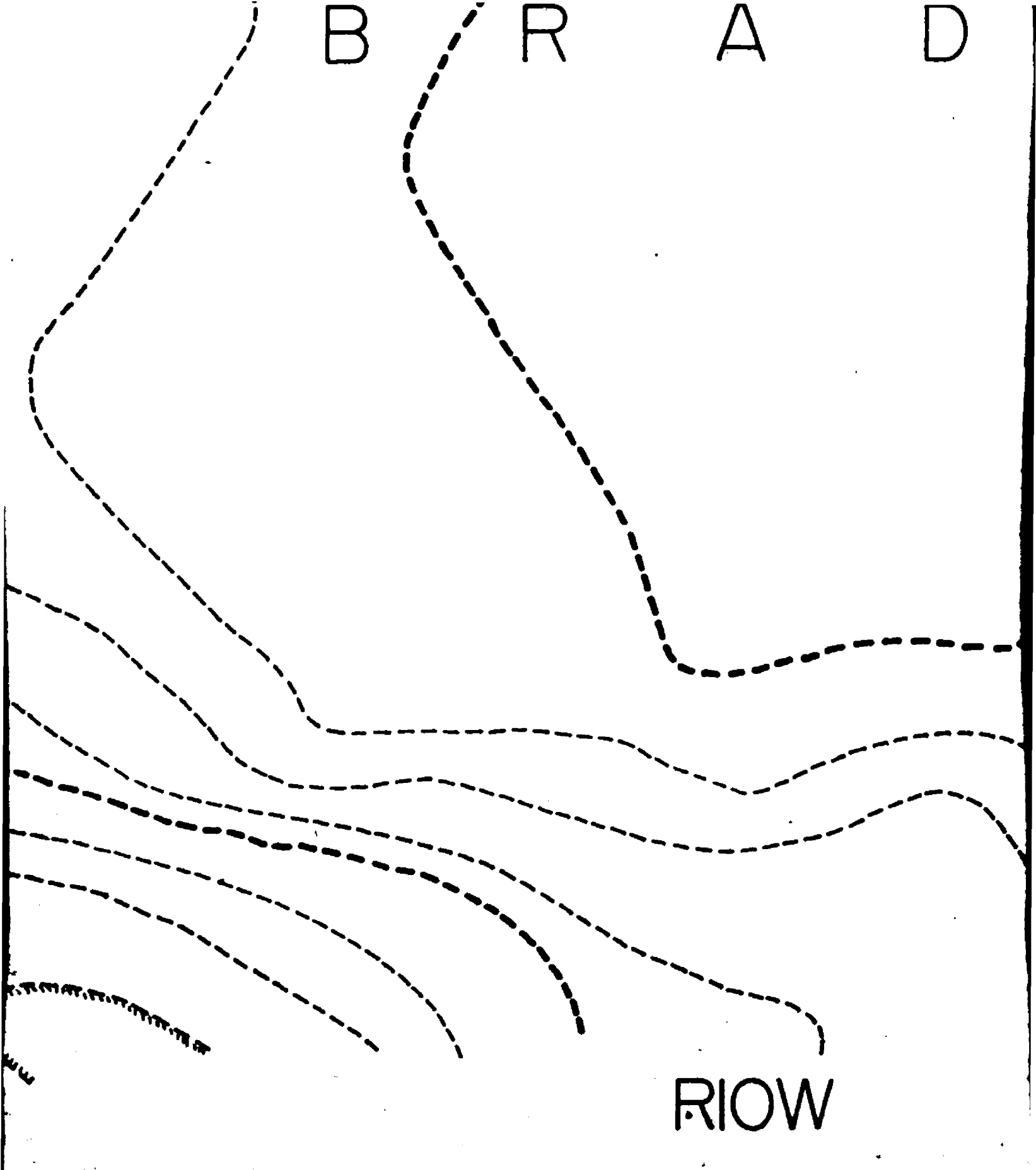


B

R

A

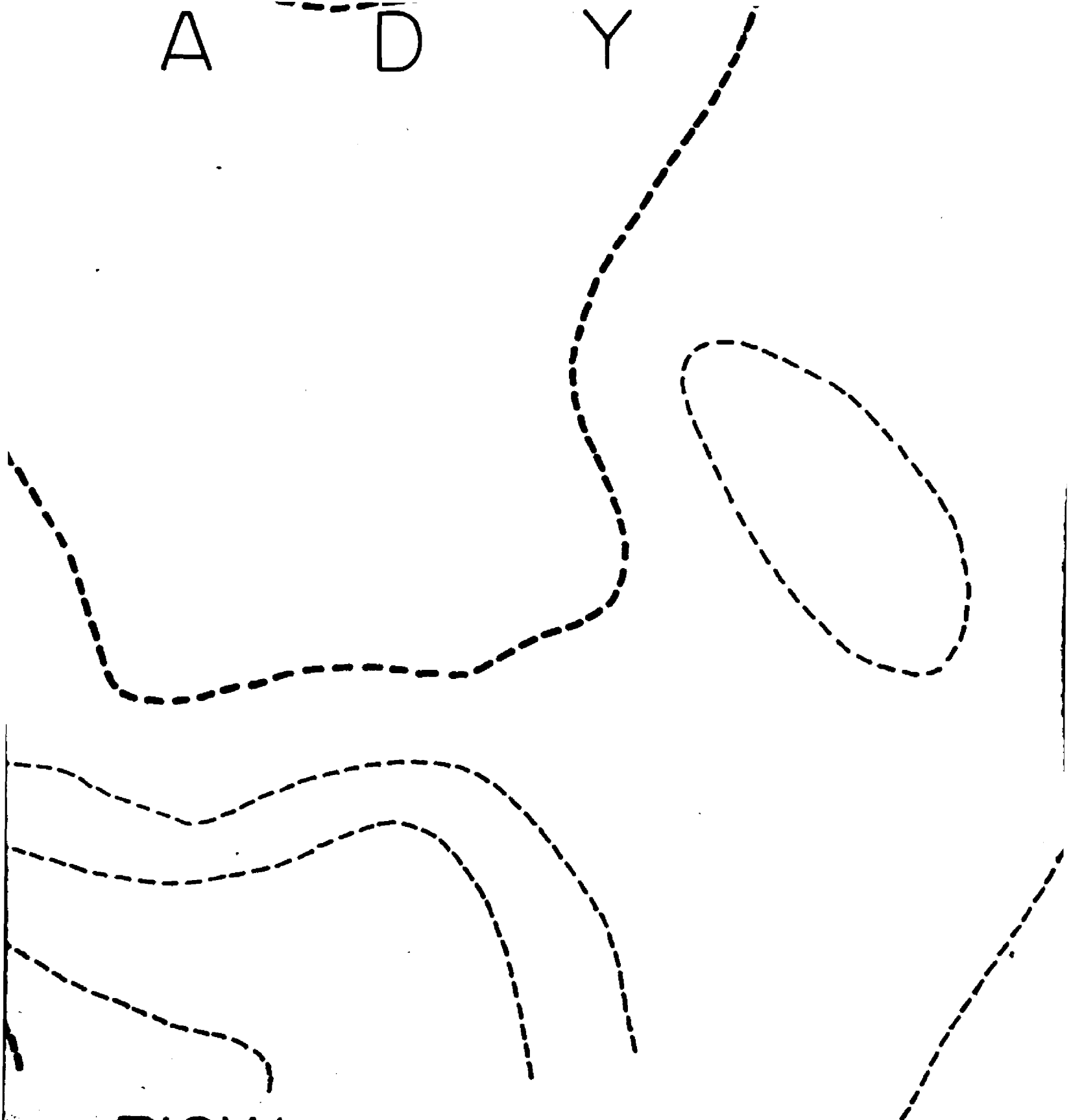
D



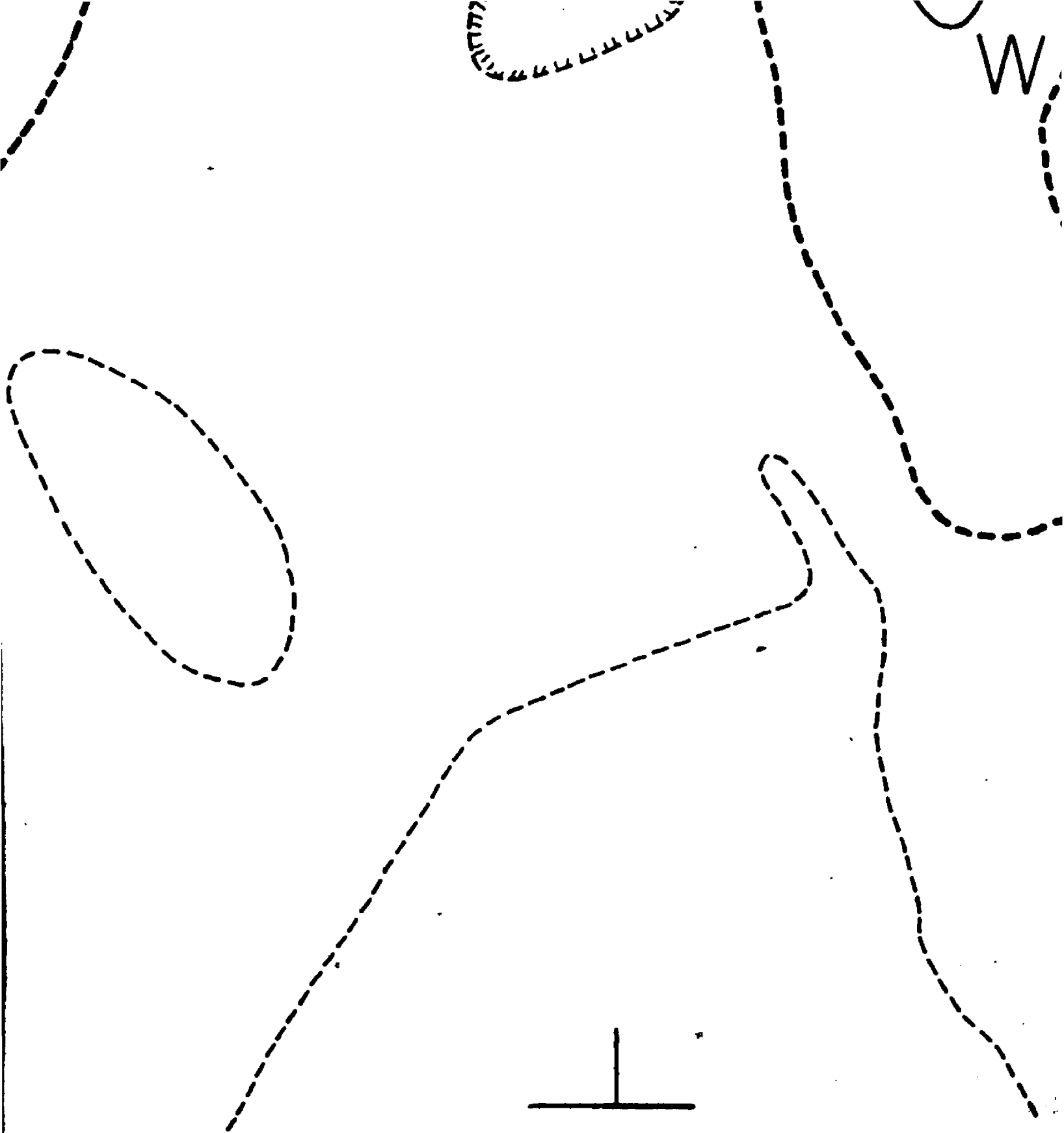
RIOW

30'

A D Y



RIOW



008

8

E

K

A

W

W

85.20

R9W

800

800

700

M

H

S

E

T

M.A.

140

700

800

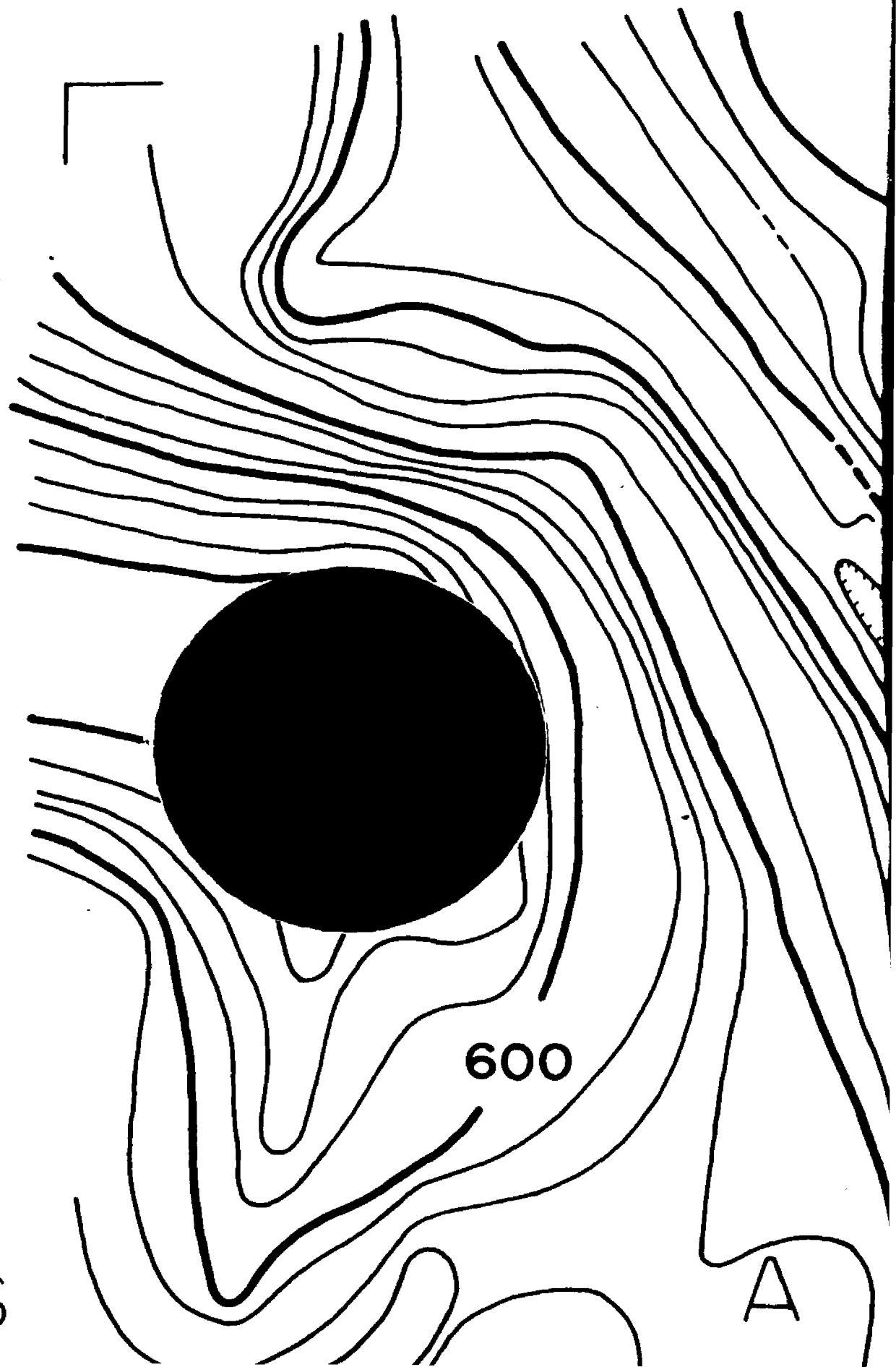
05.42



20

45'

42°
25'



600

TIS

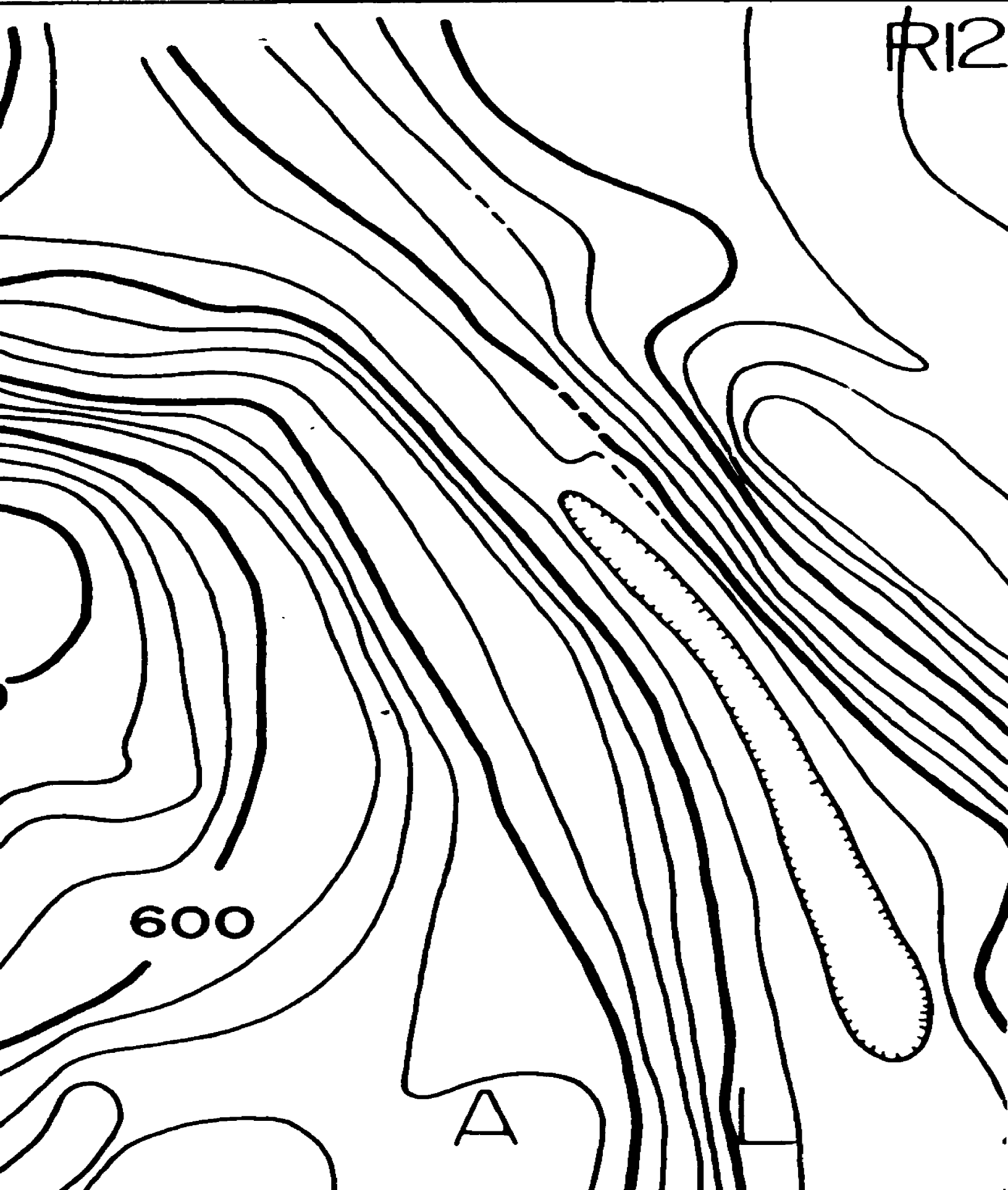
A

45'

R12

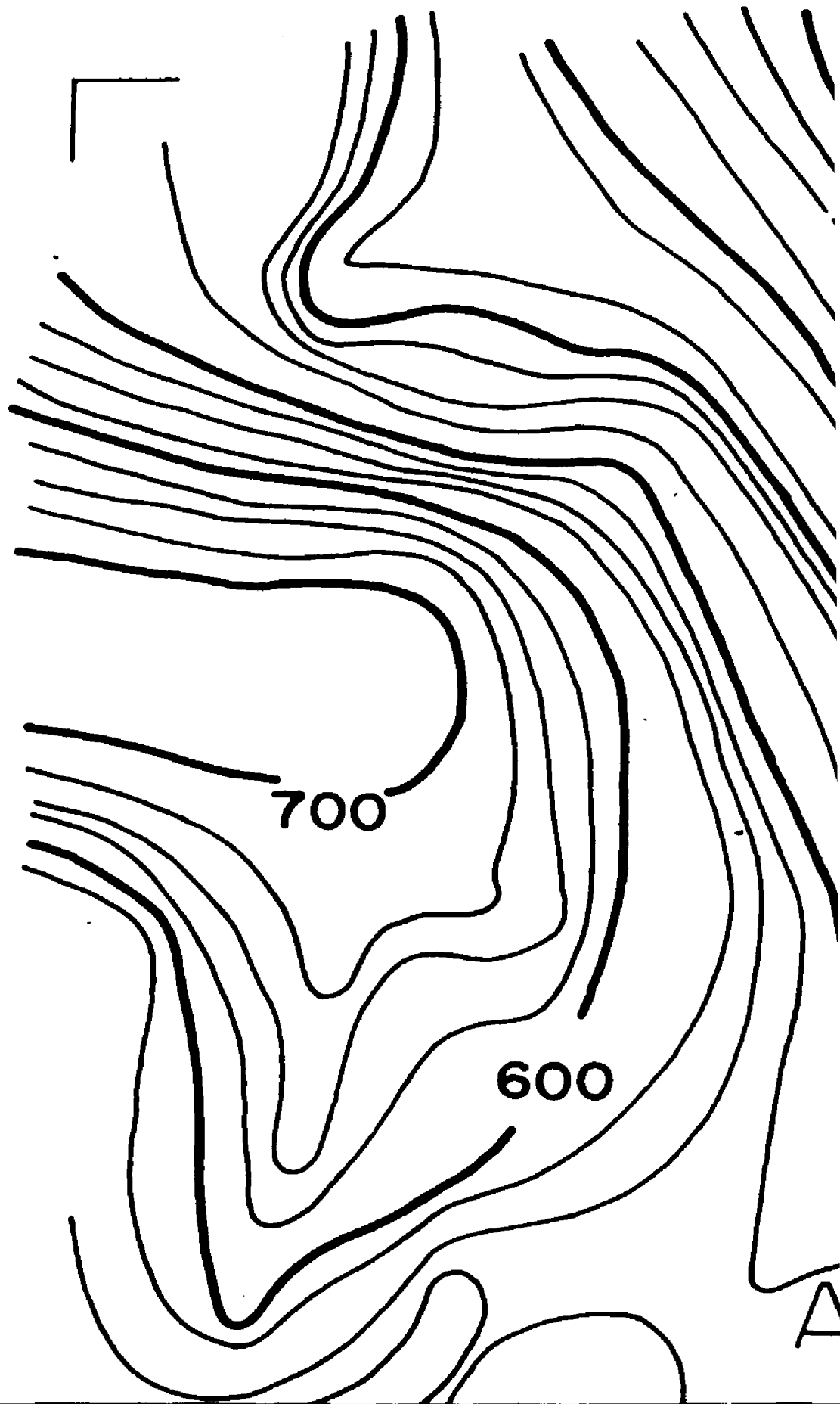
600

A



45'

42°
25'



TIS

A

45'

R12W

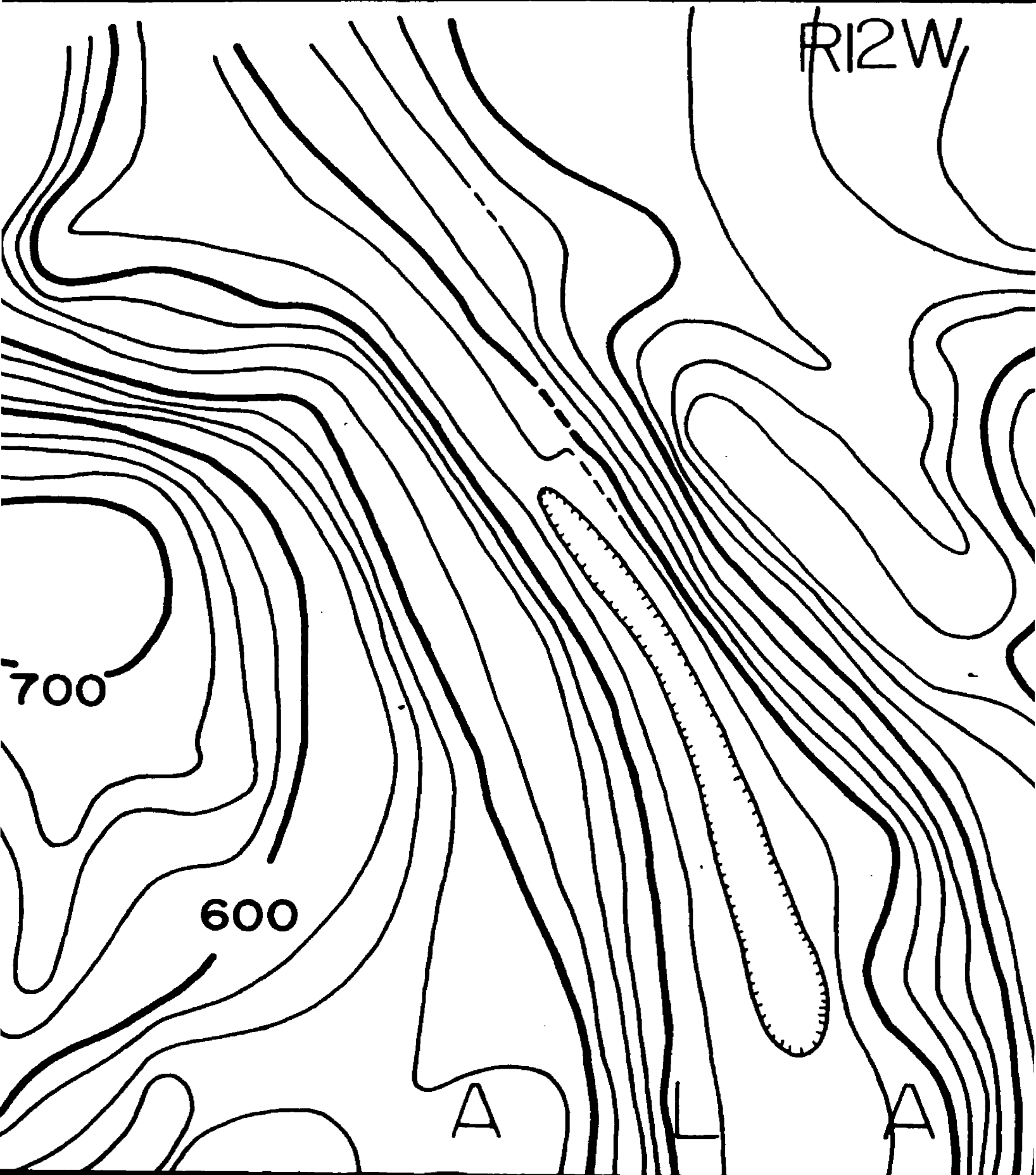
700

600

A

L

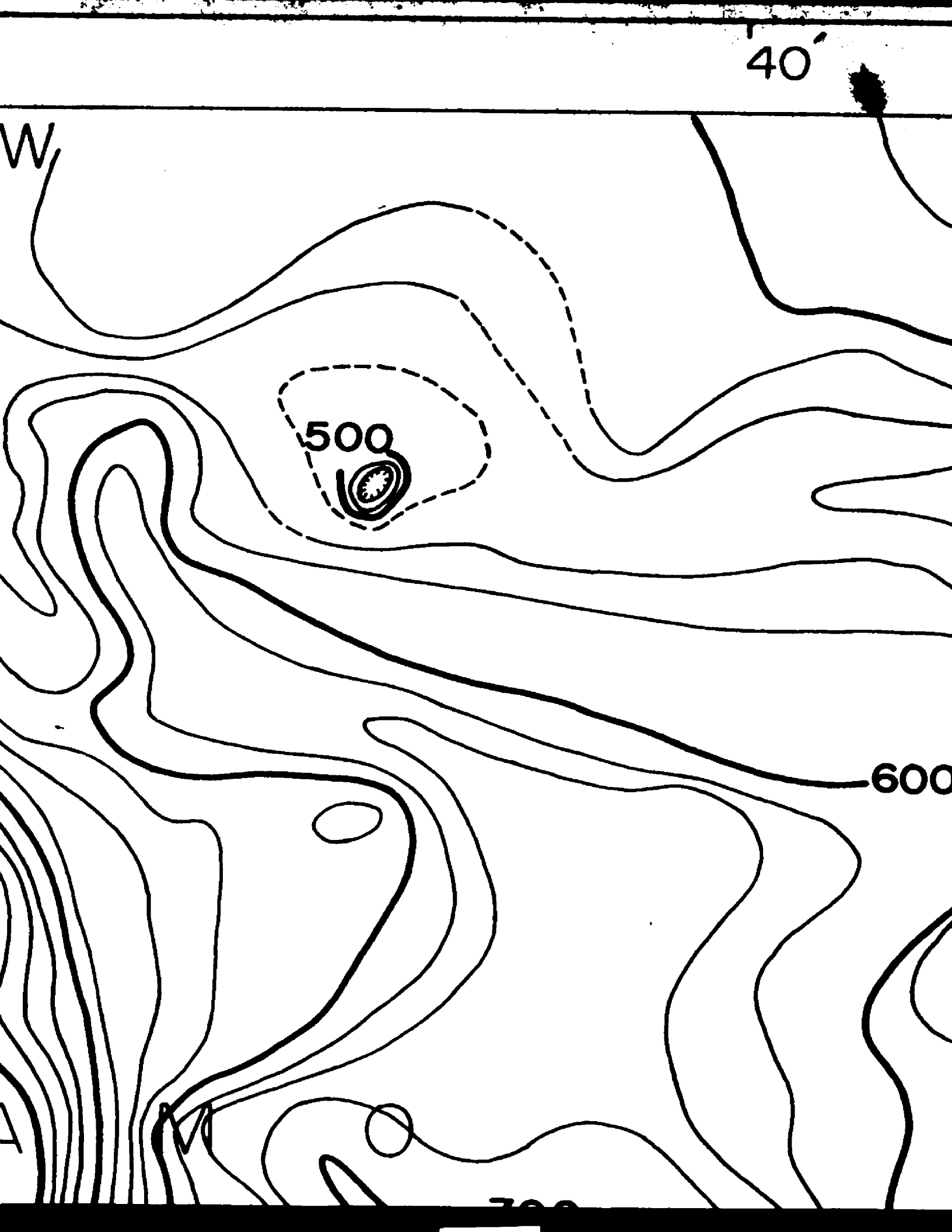
A





40'

W



600

V

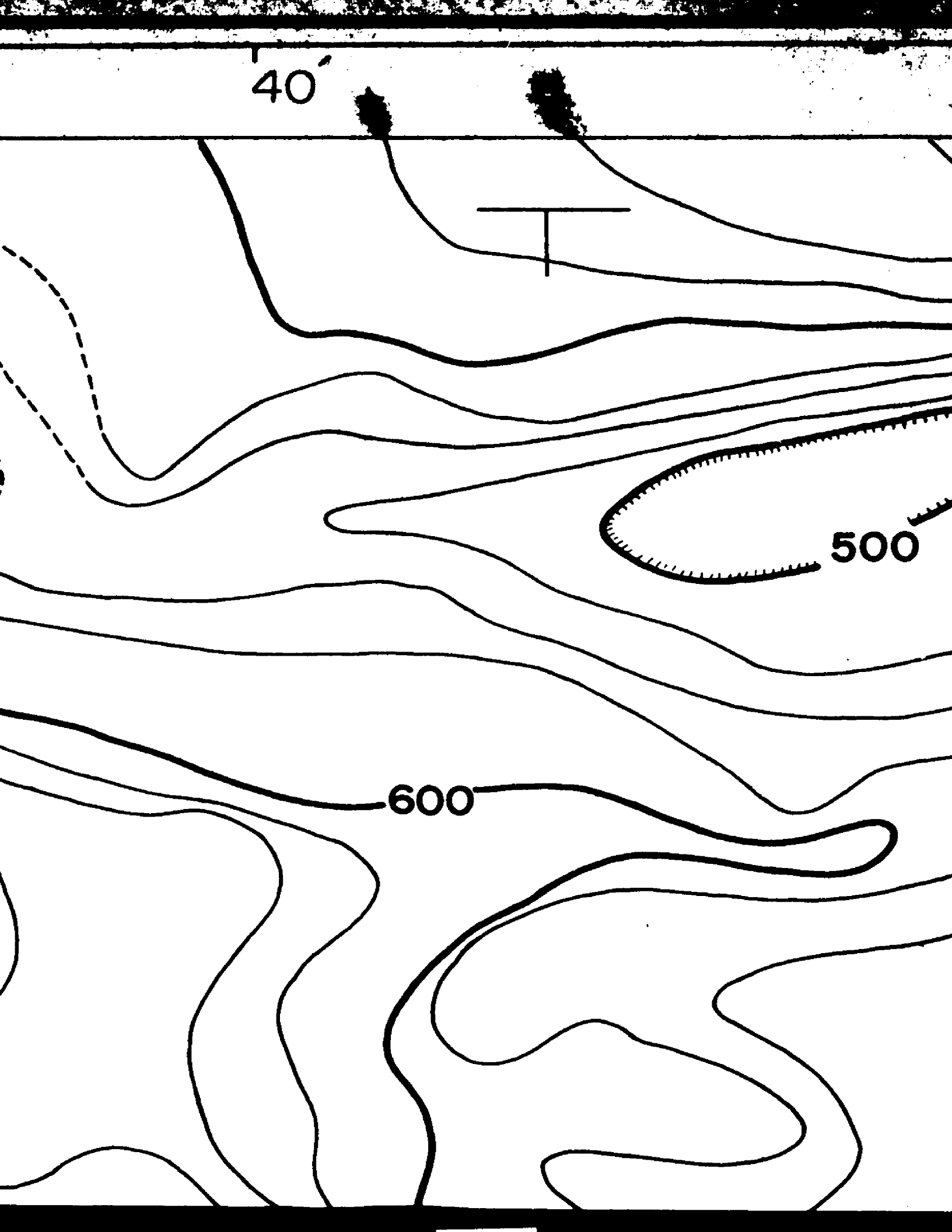
300

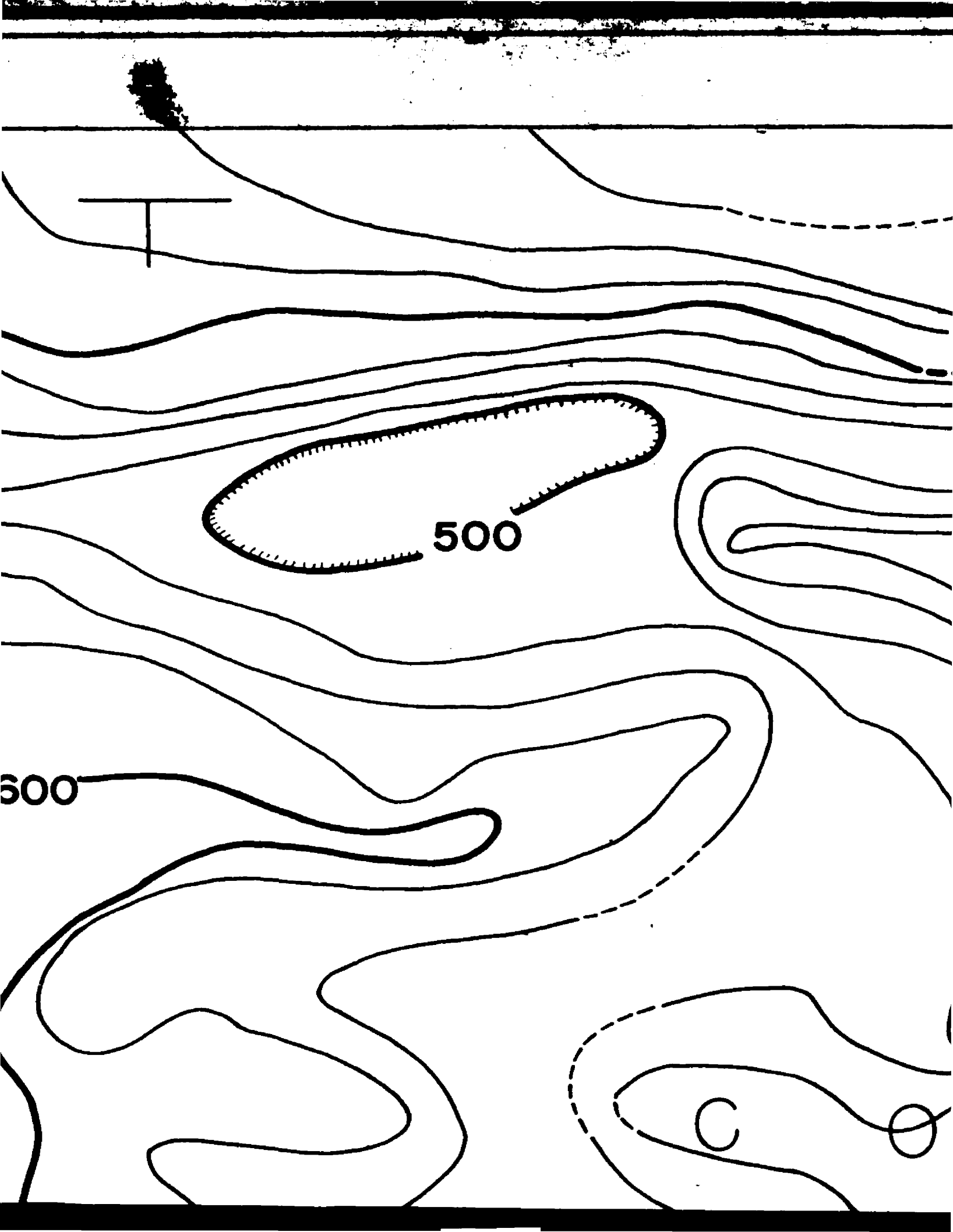
40'



500

600







RIIV

35'

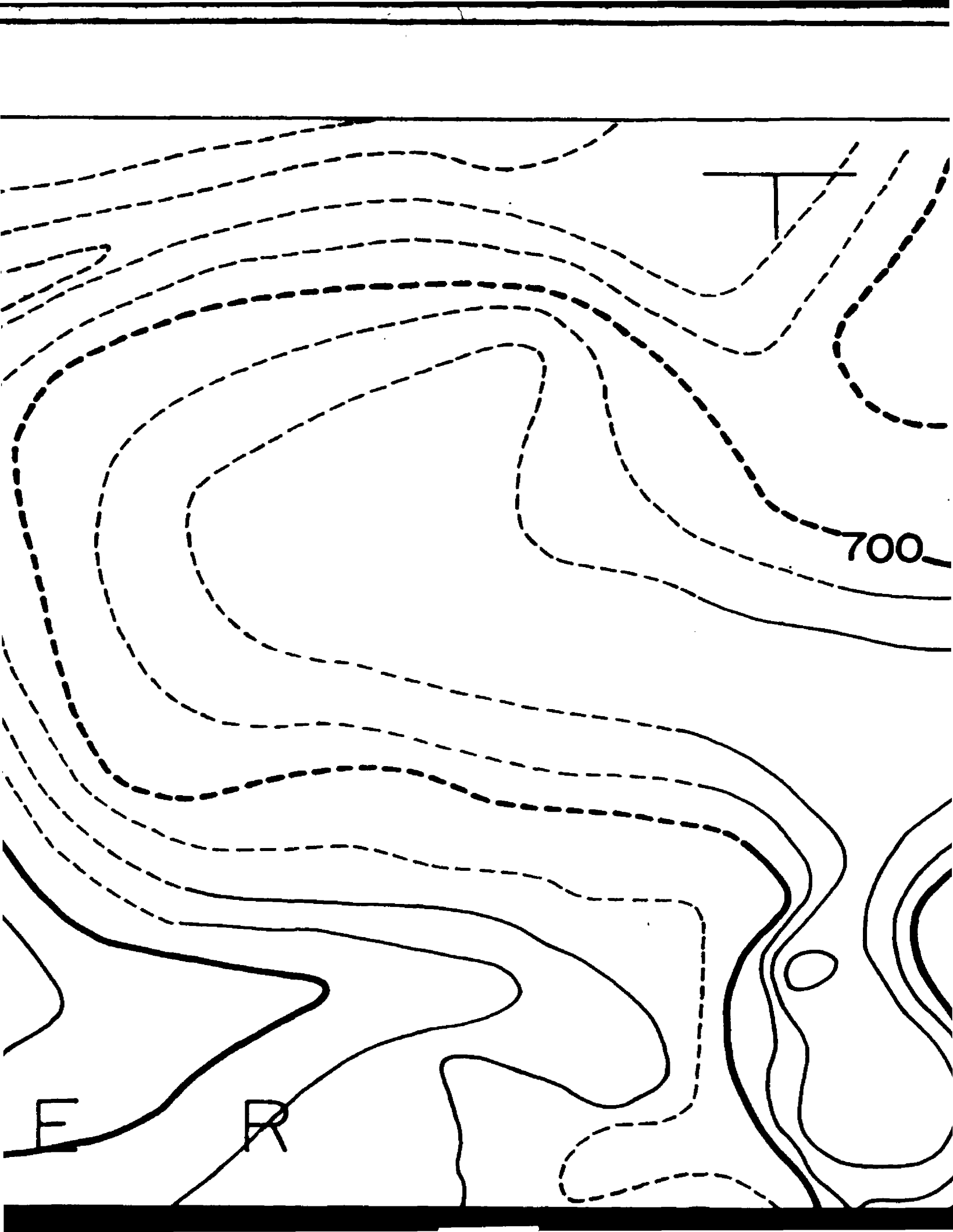
RIIW

O

P

E

R



30



30

RIOW

700

600

R

I

C

H

30

RIOW

700

600

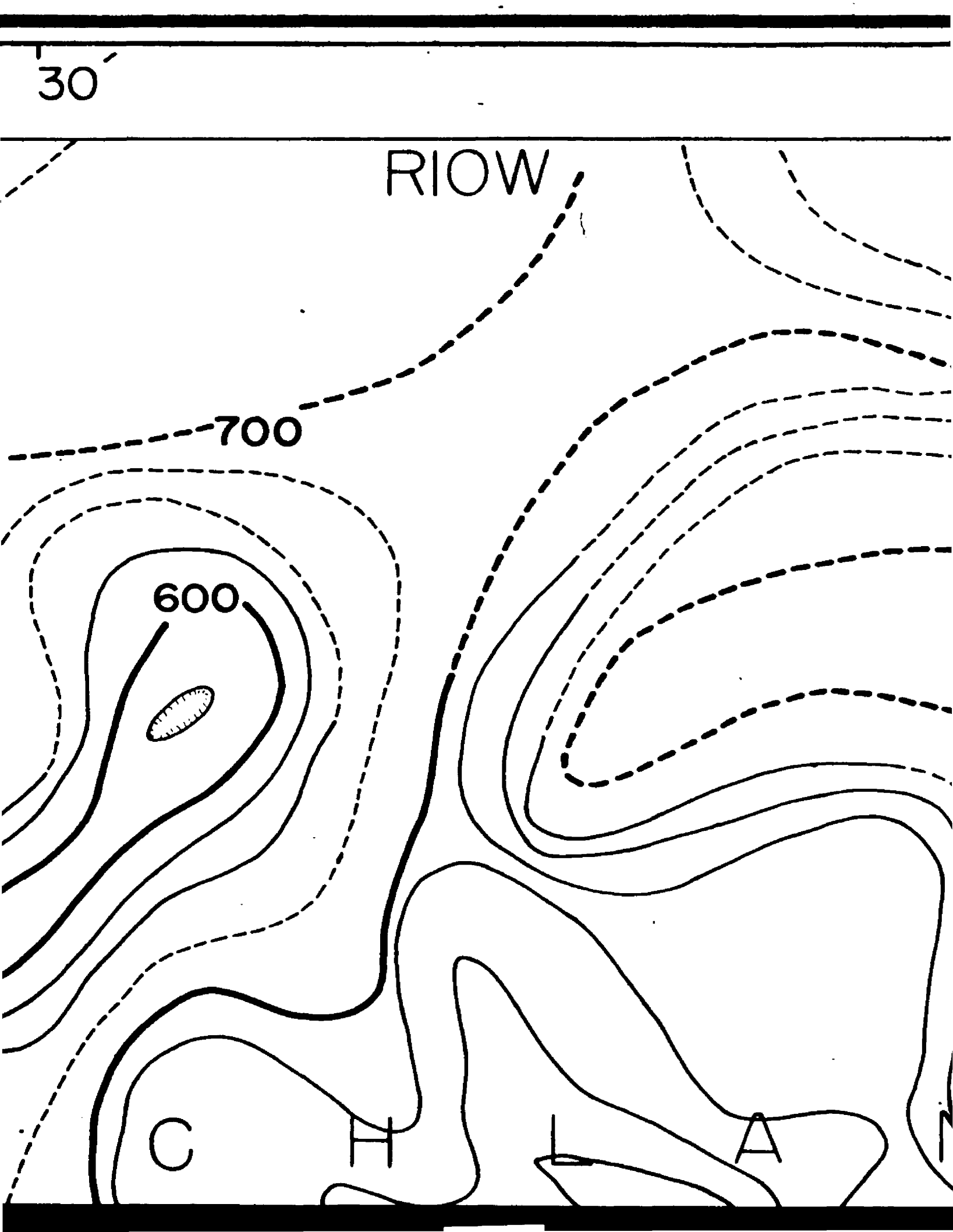
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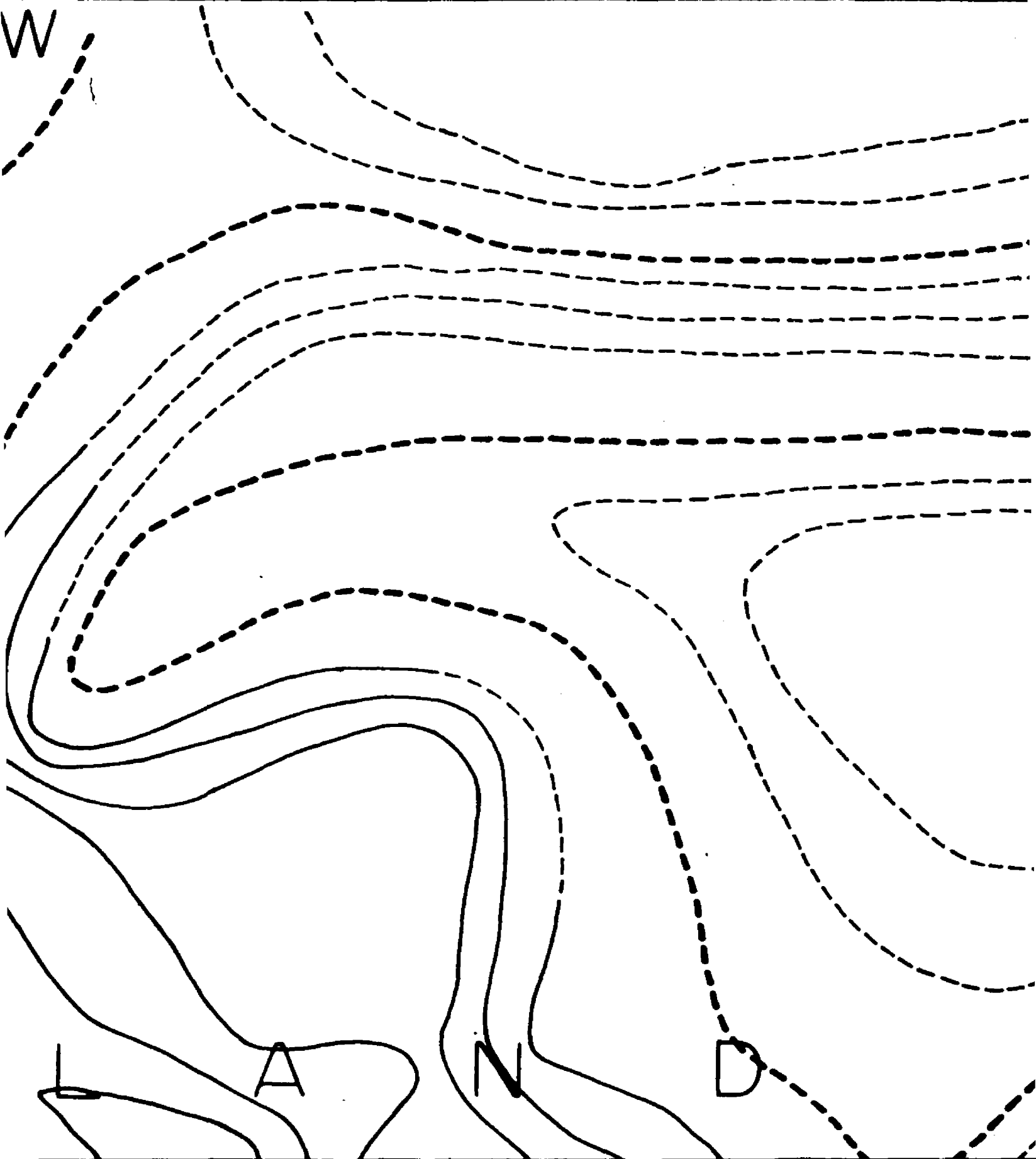
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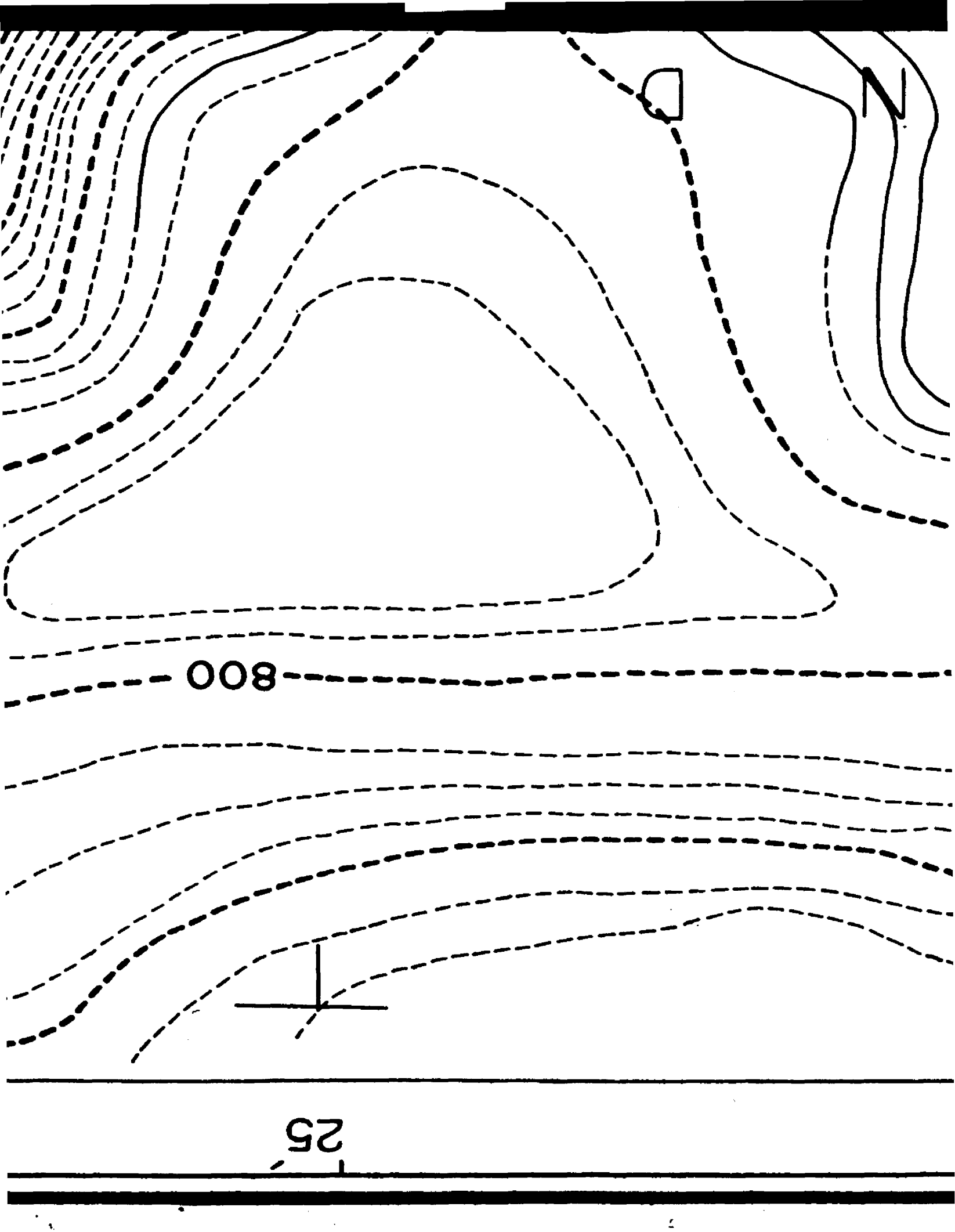
L

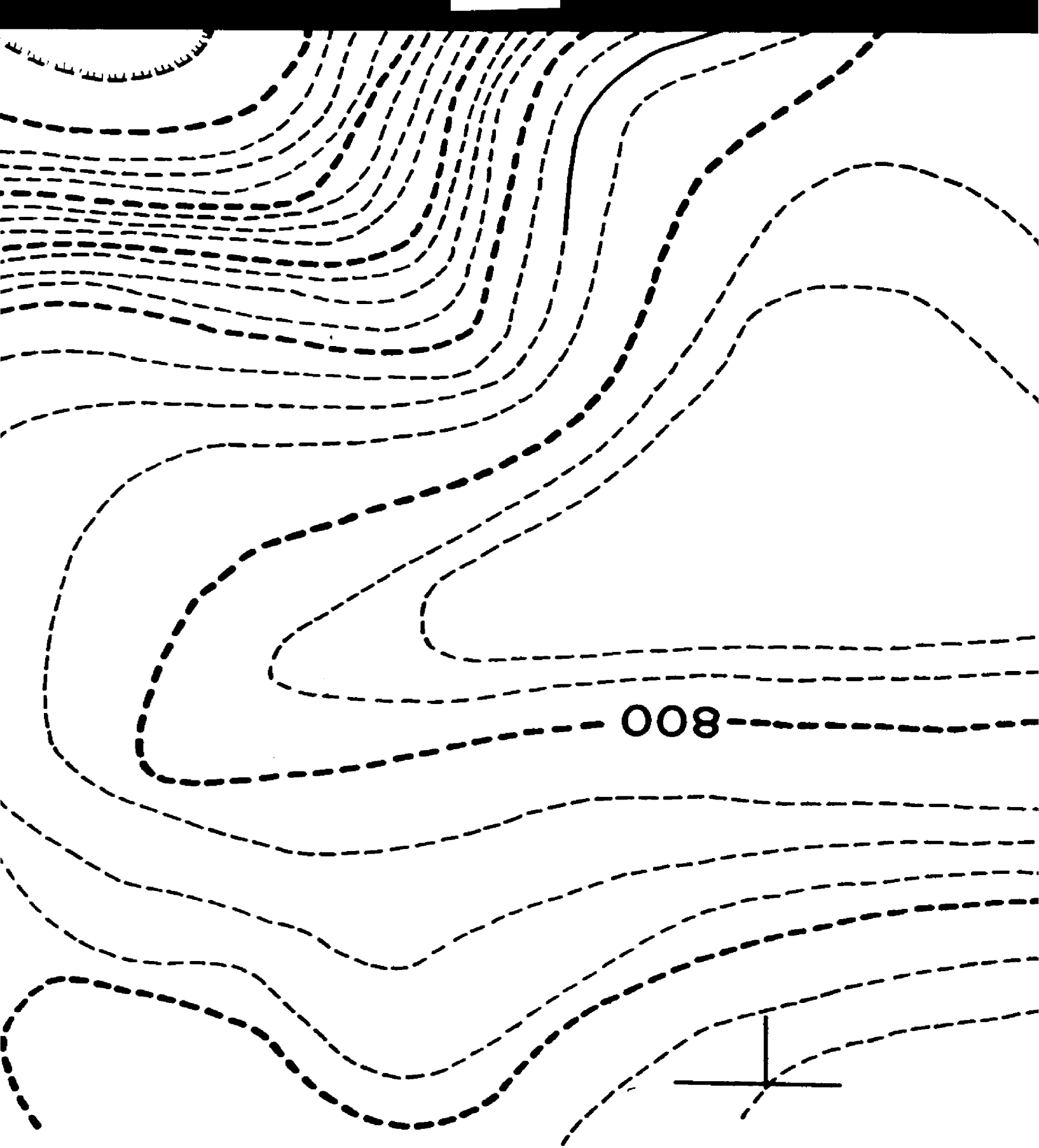
A

N









25

R9W

600

500

R400



85° 20'

R9W

600

500

R400

0

S

S

85° 20'

R9W

600

700

600

500

S

S

20'

42°
25'

600

700

TIS

TIS

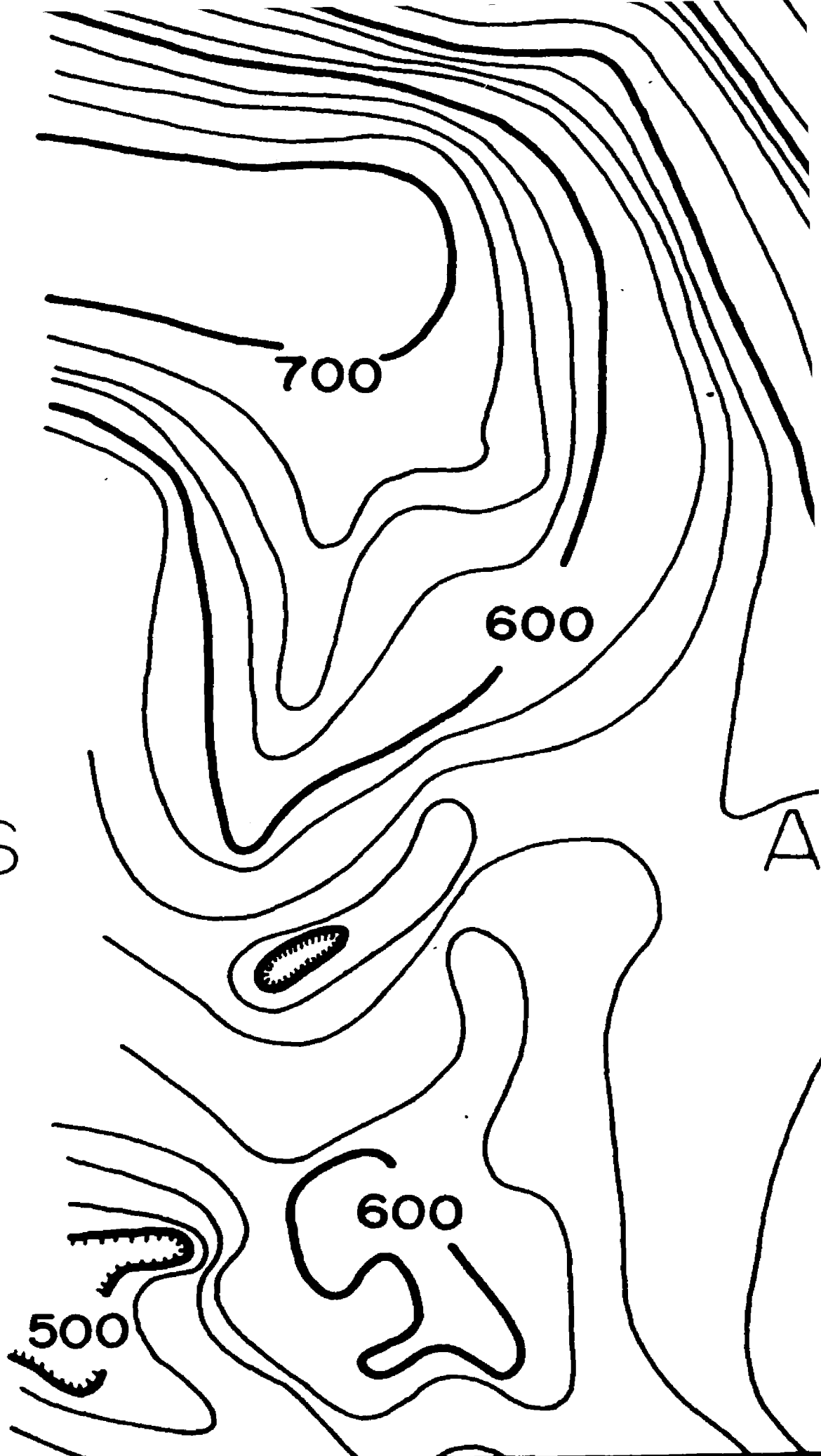
700

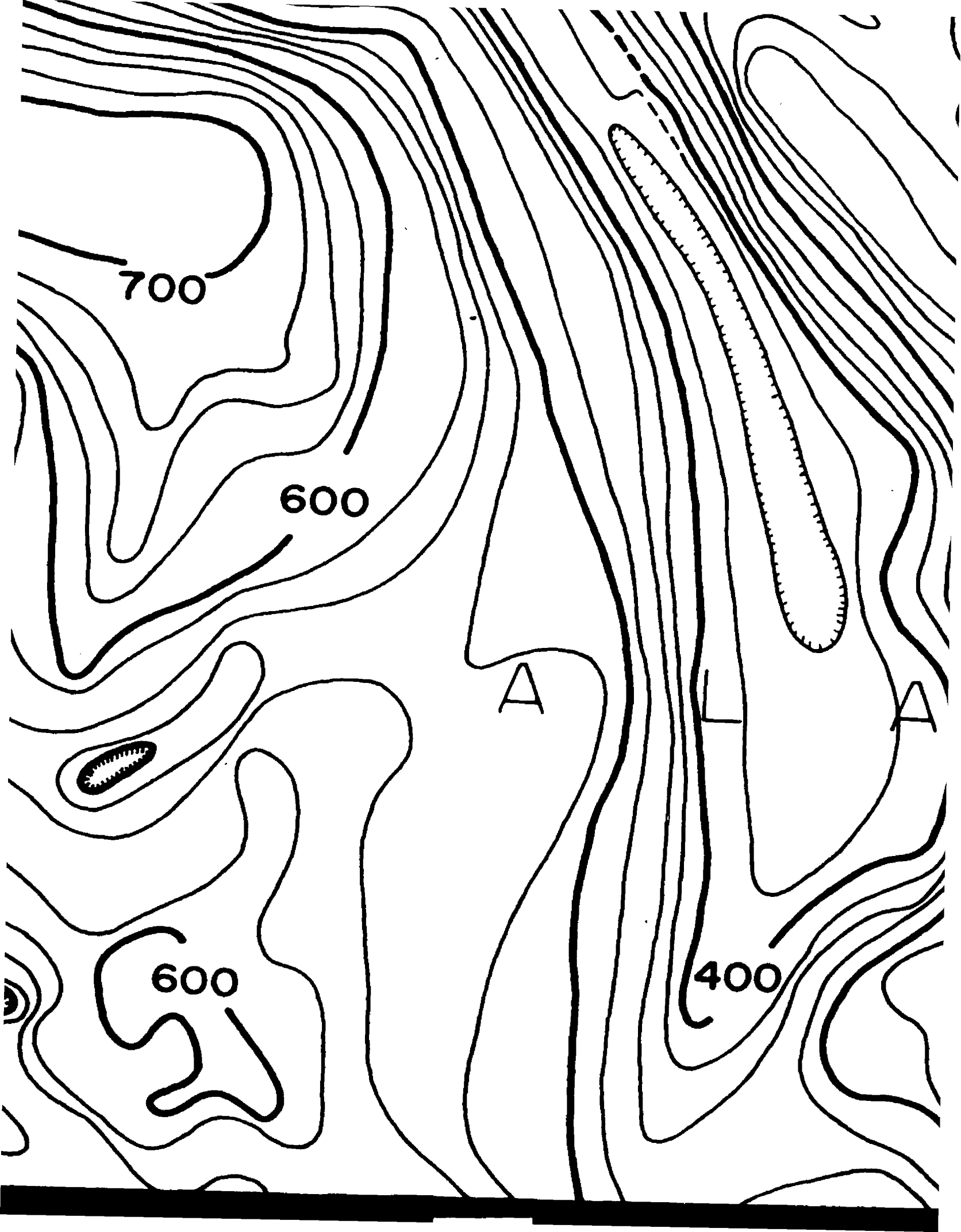
600

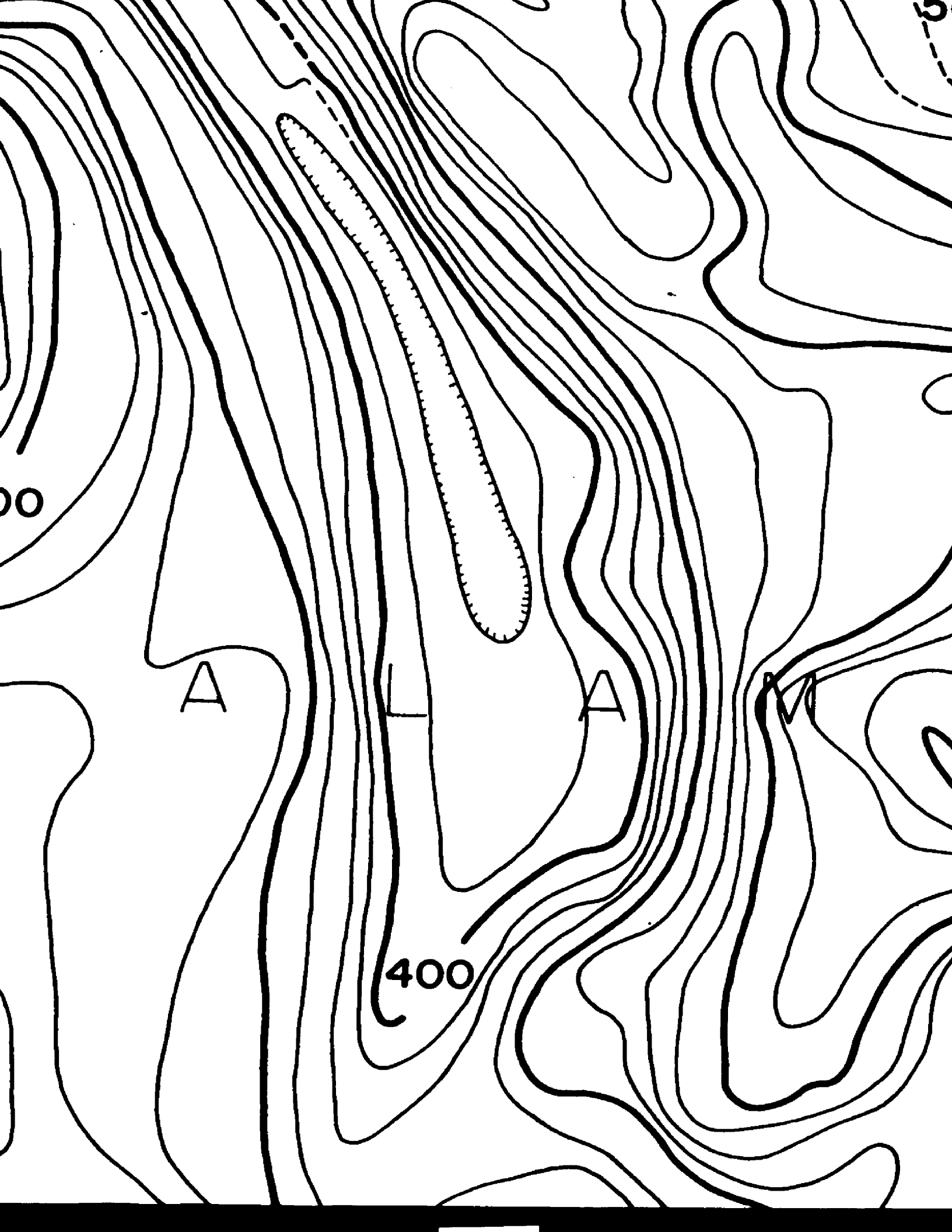
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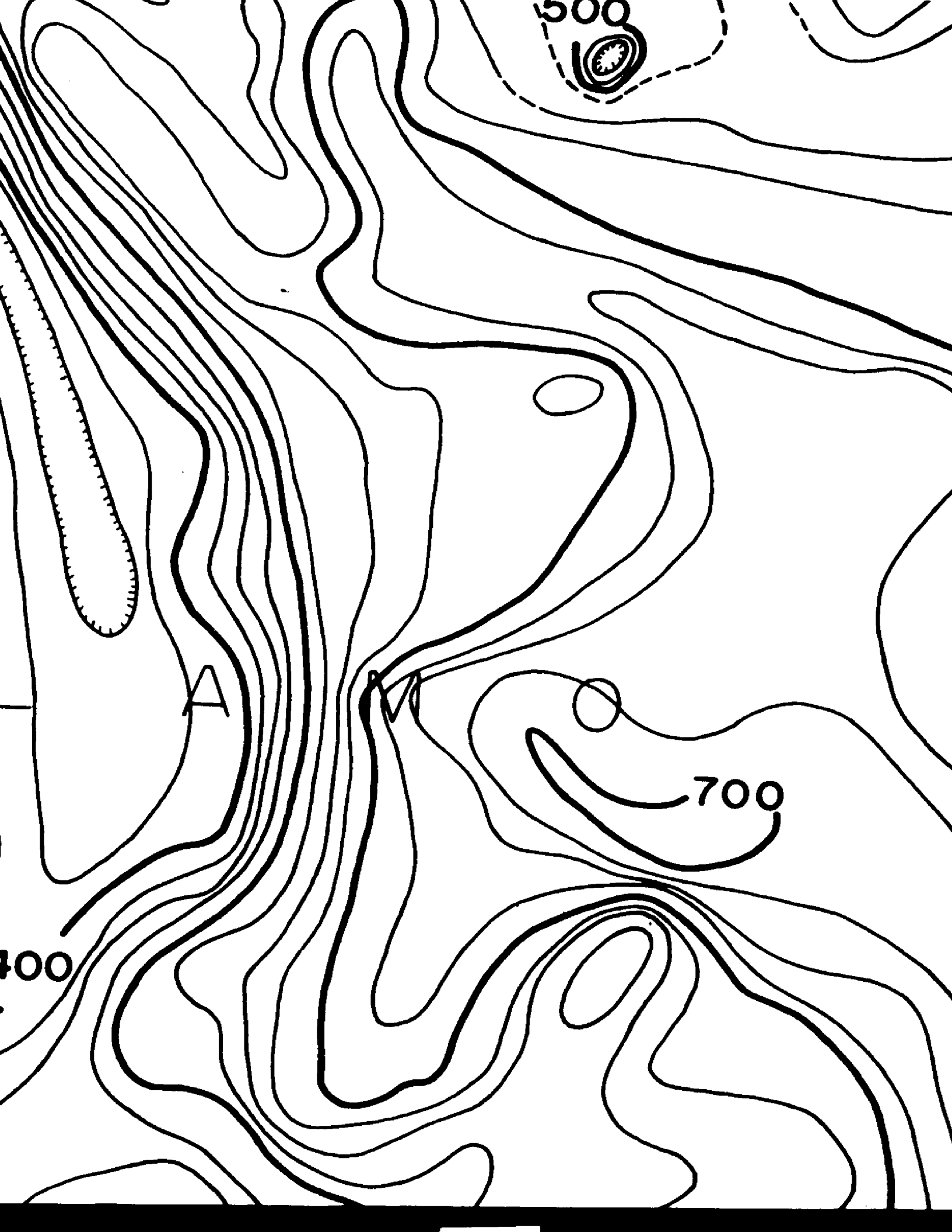
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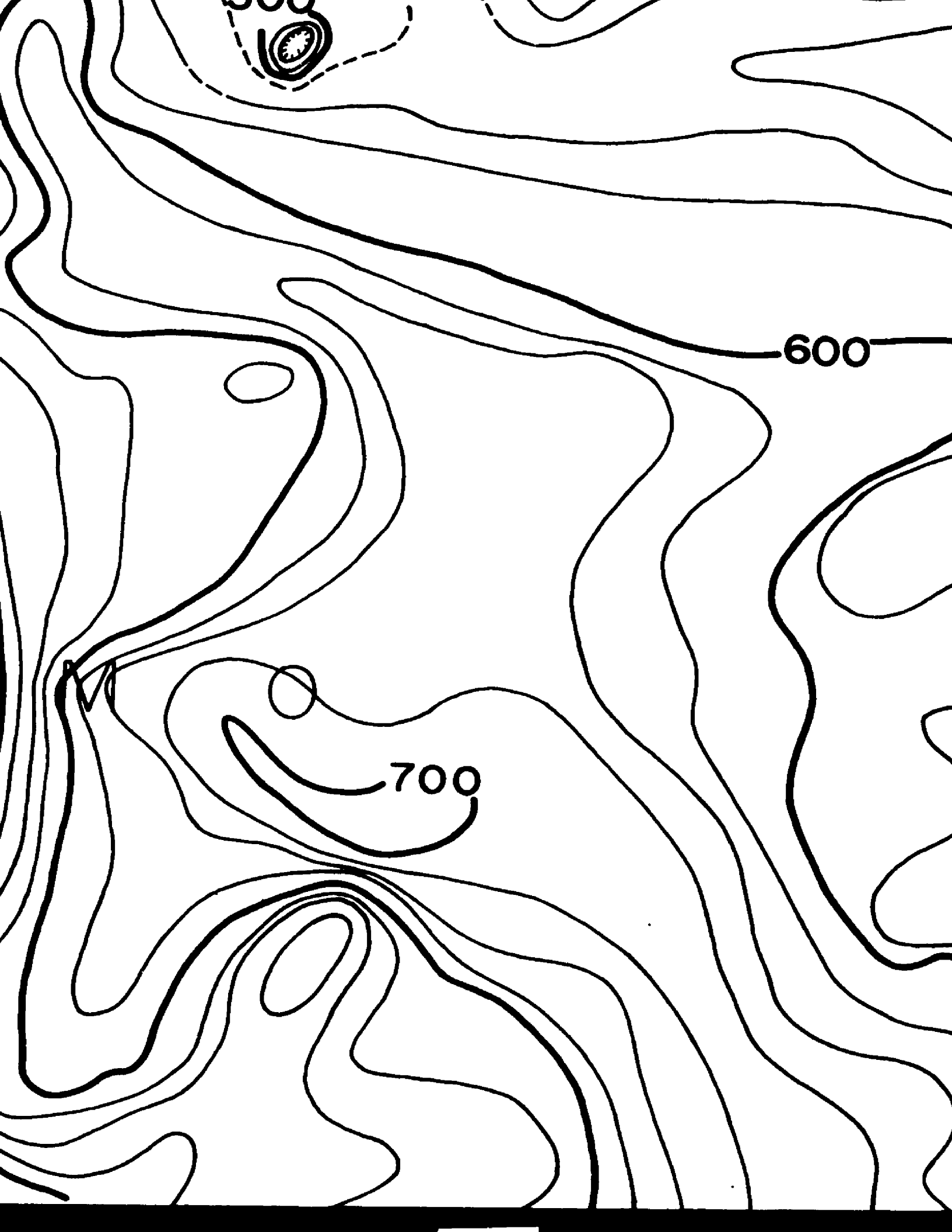
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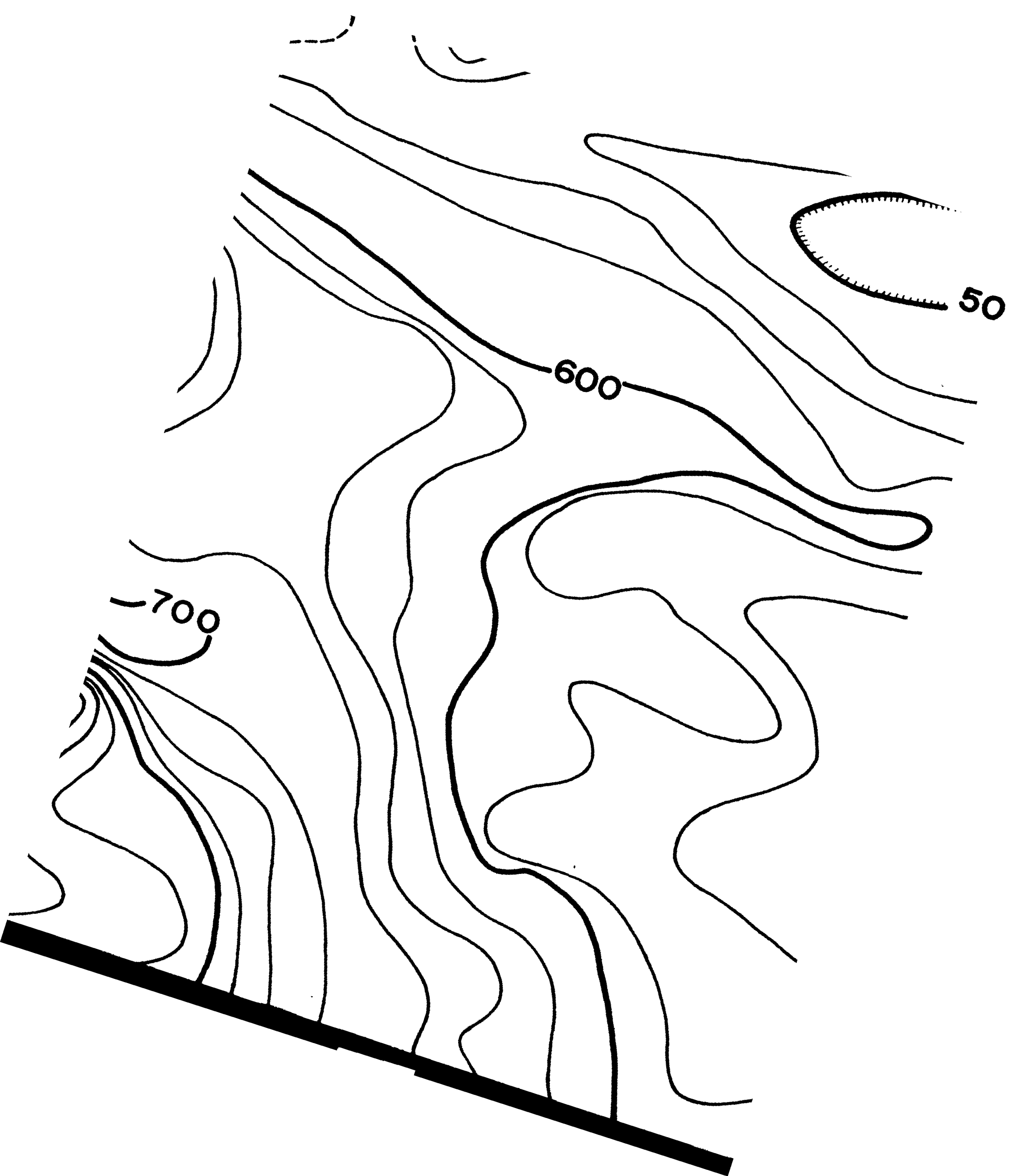


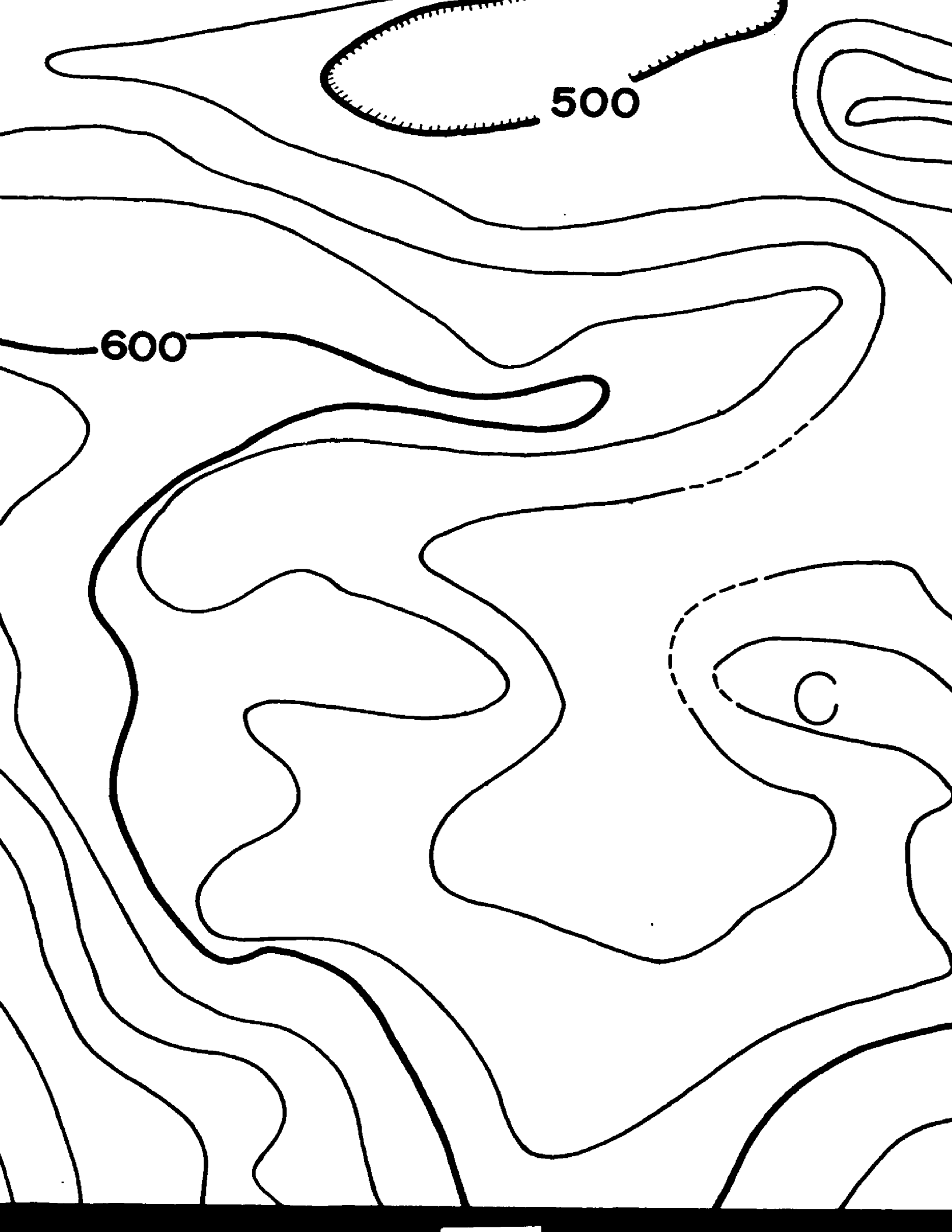


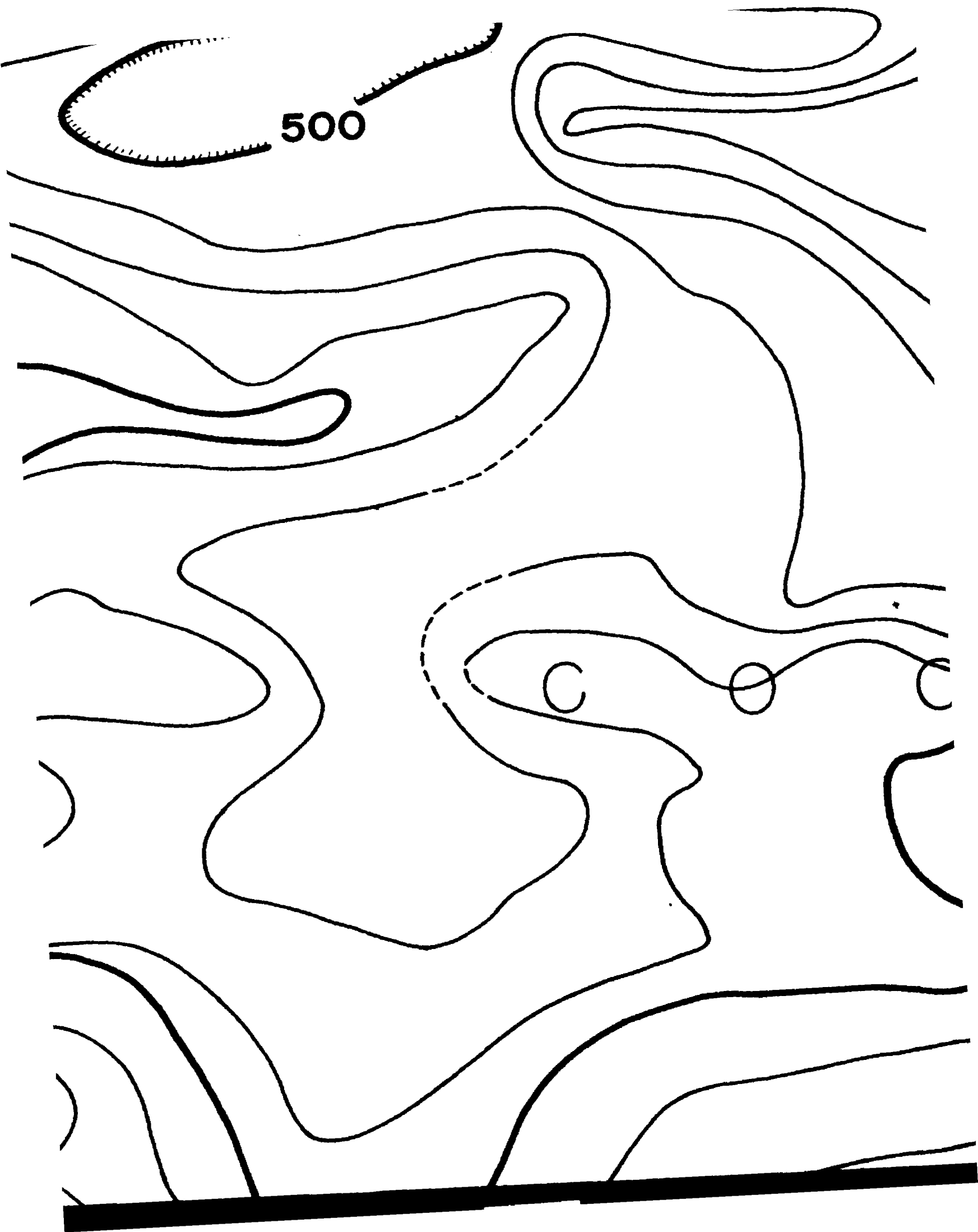














500

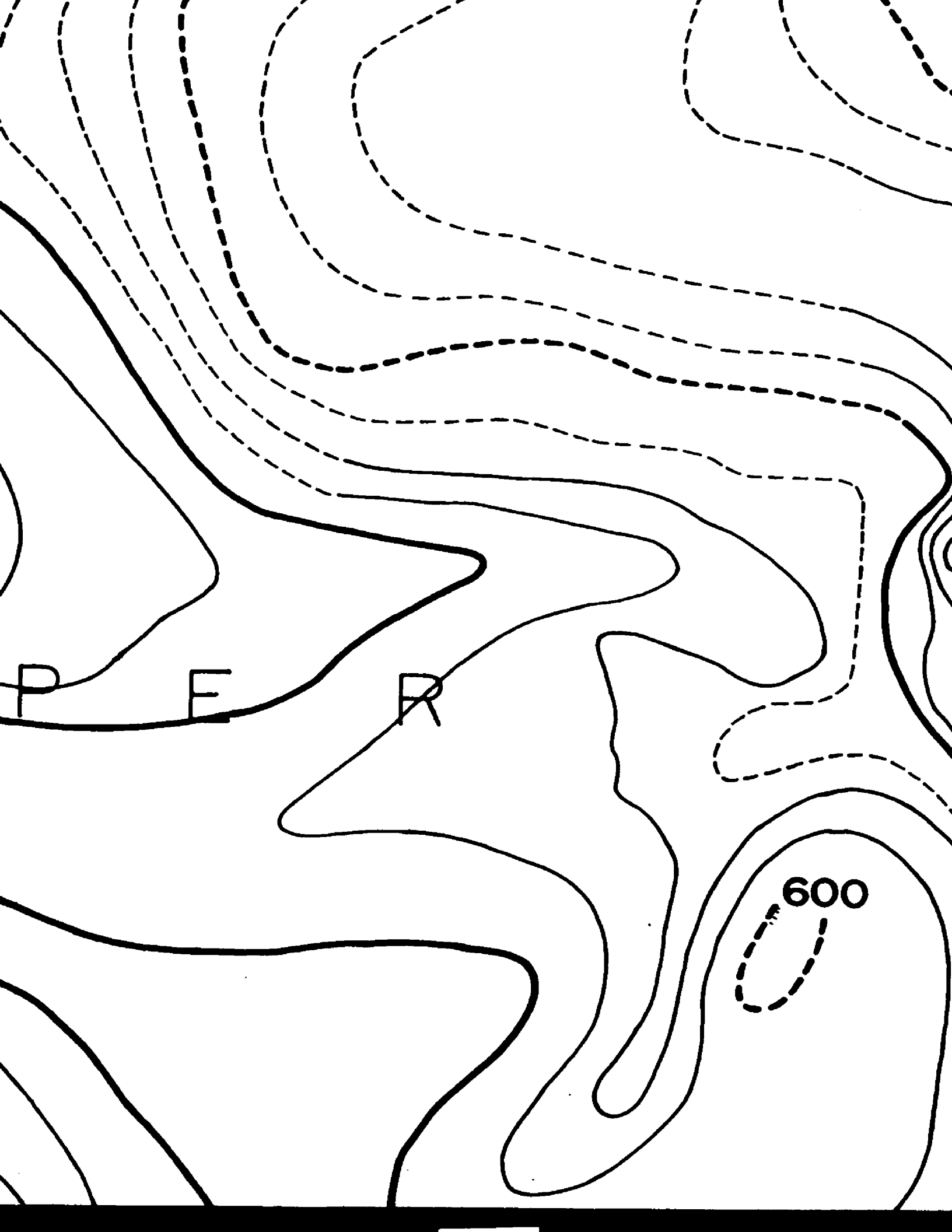
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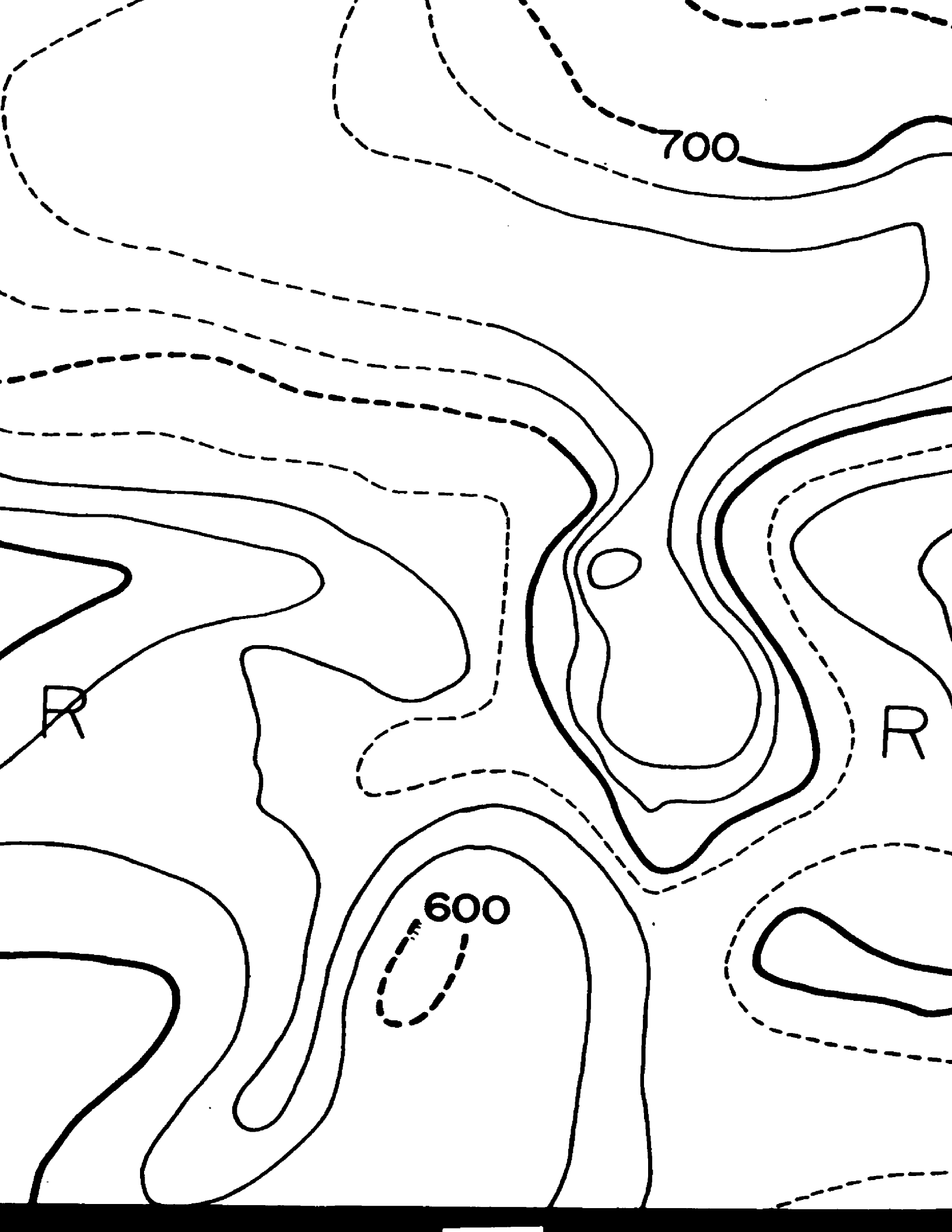
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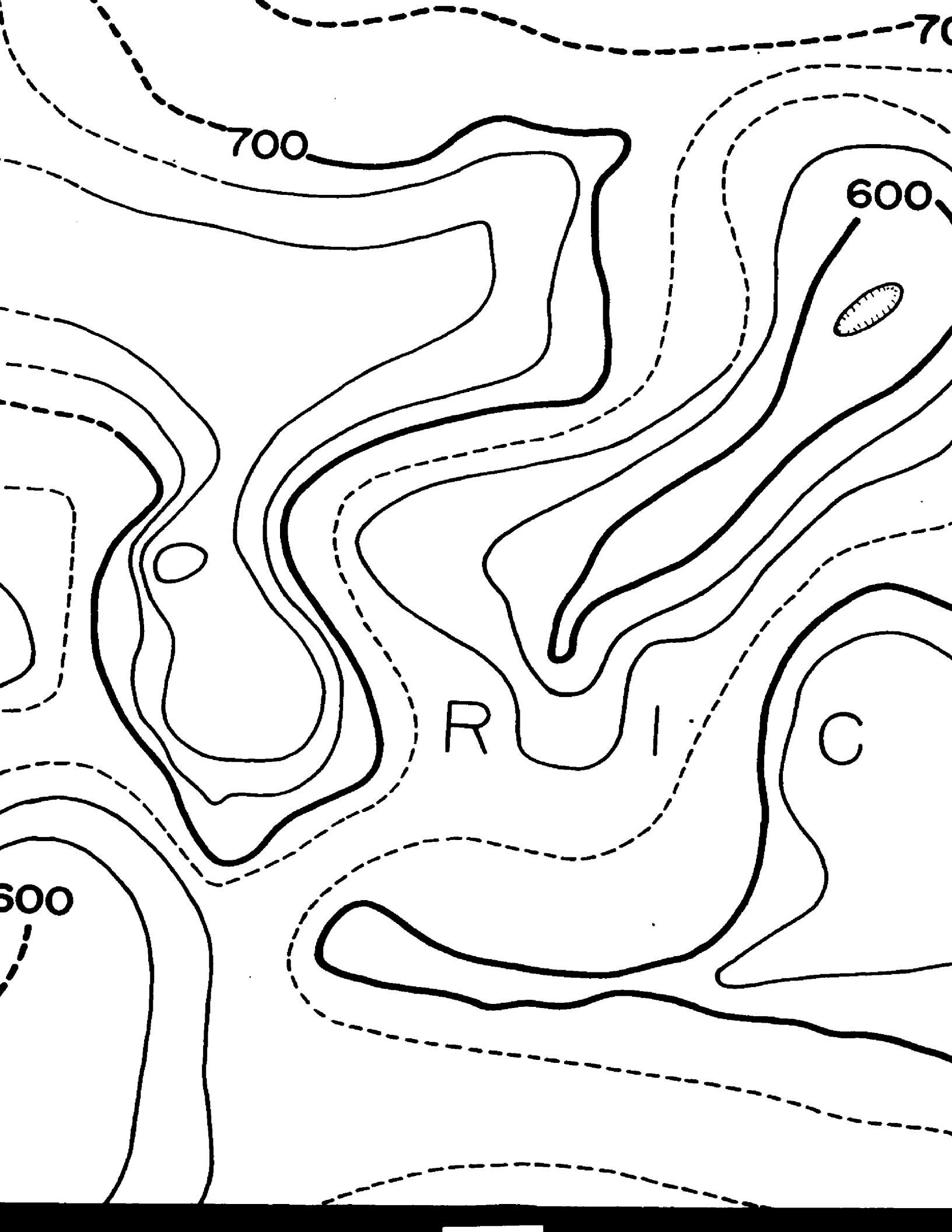
O

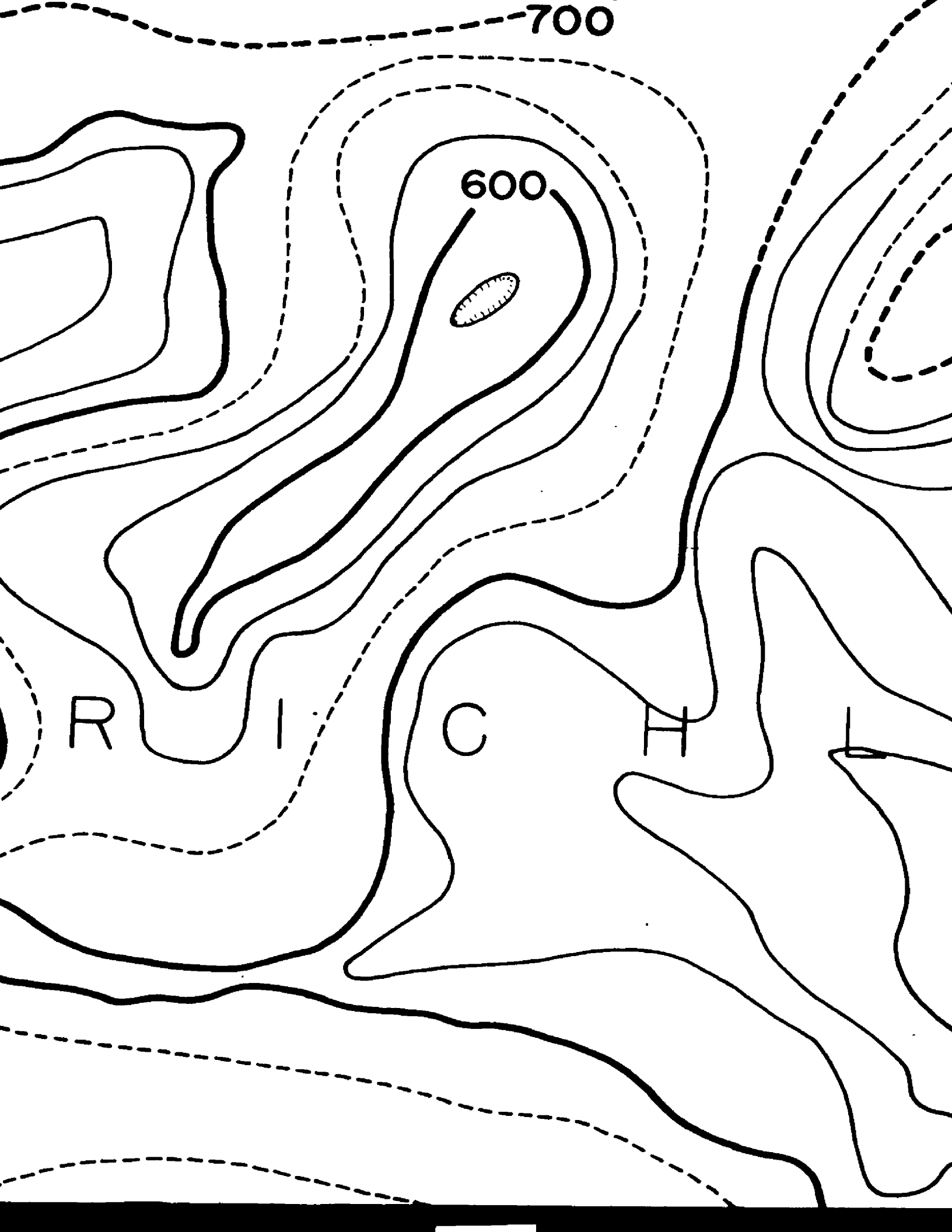
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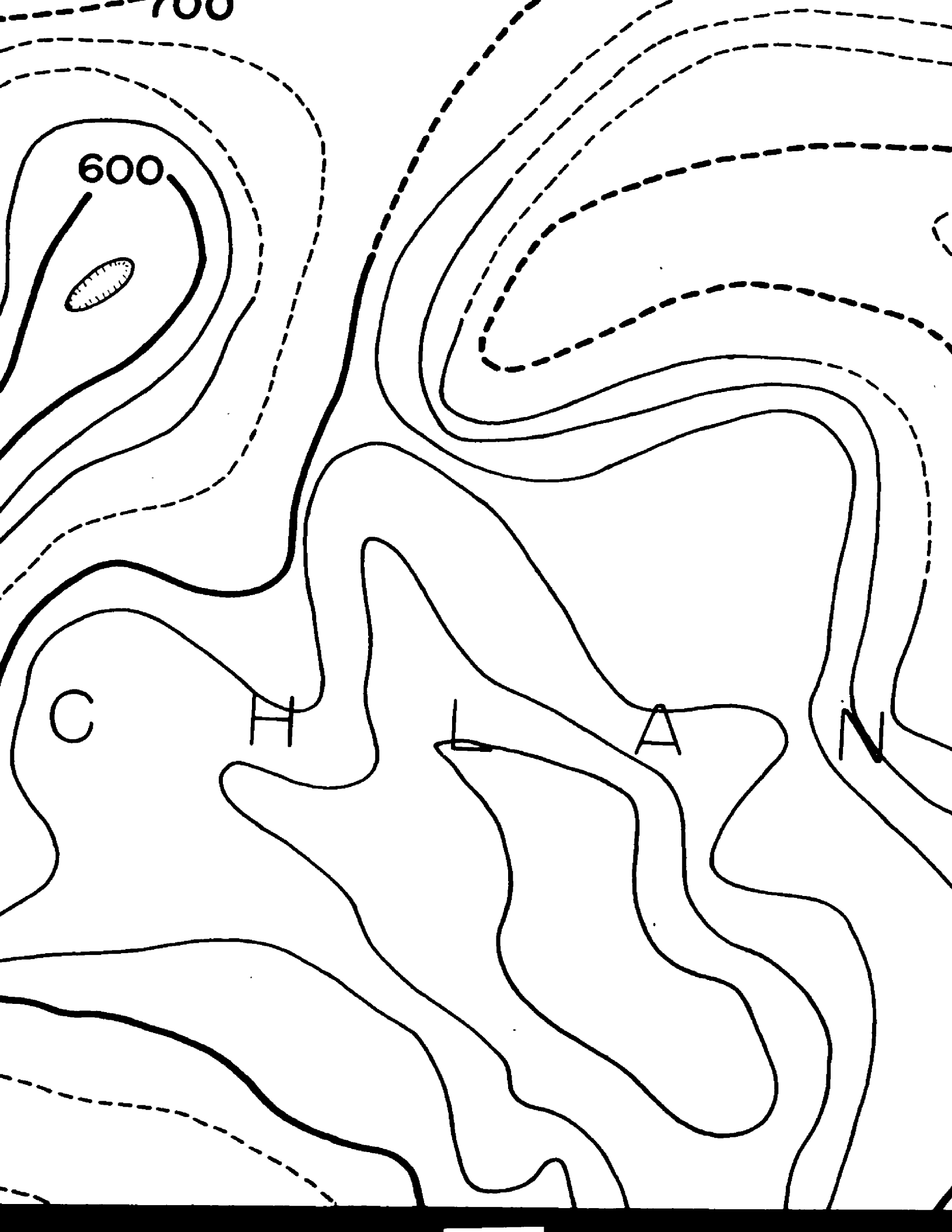




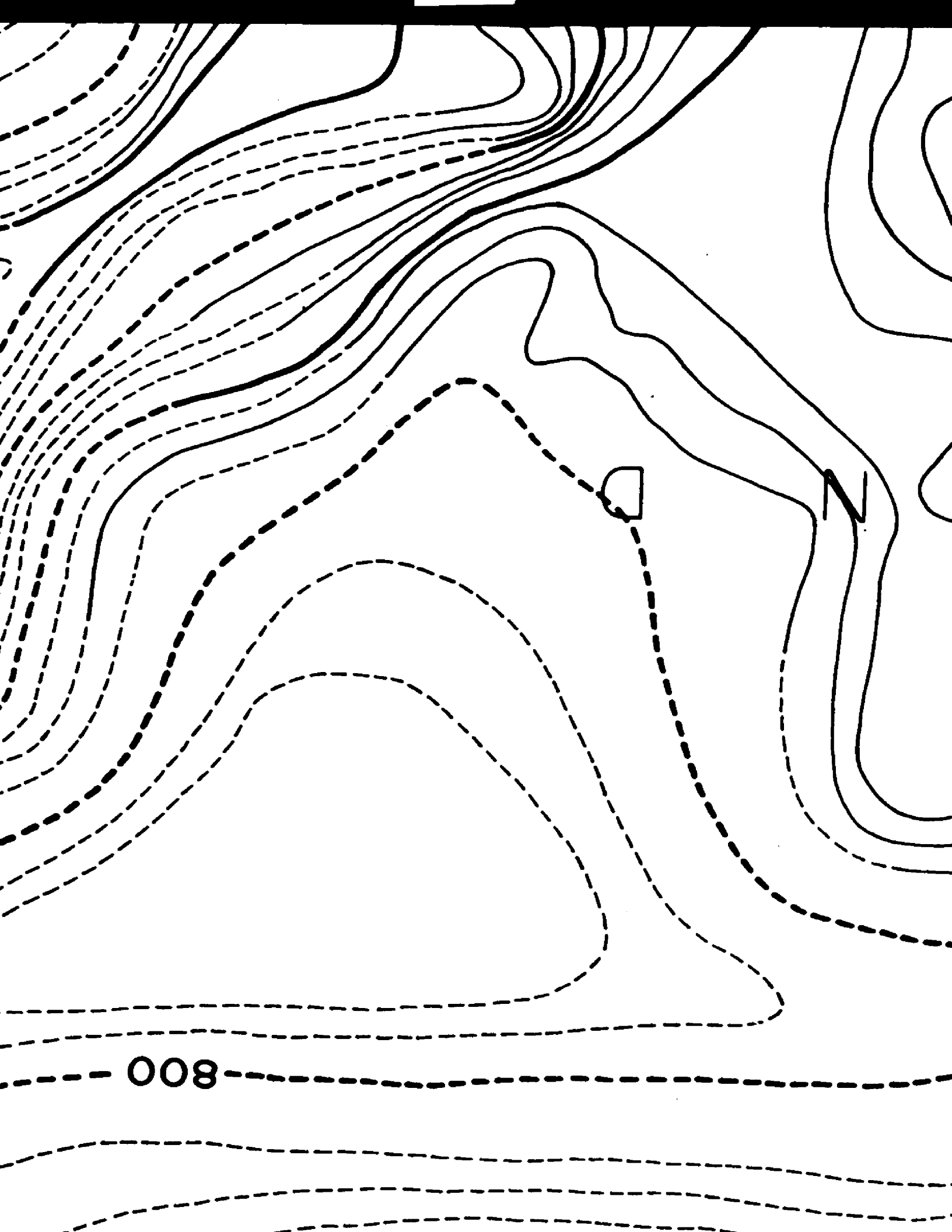


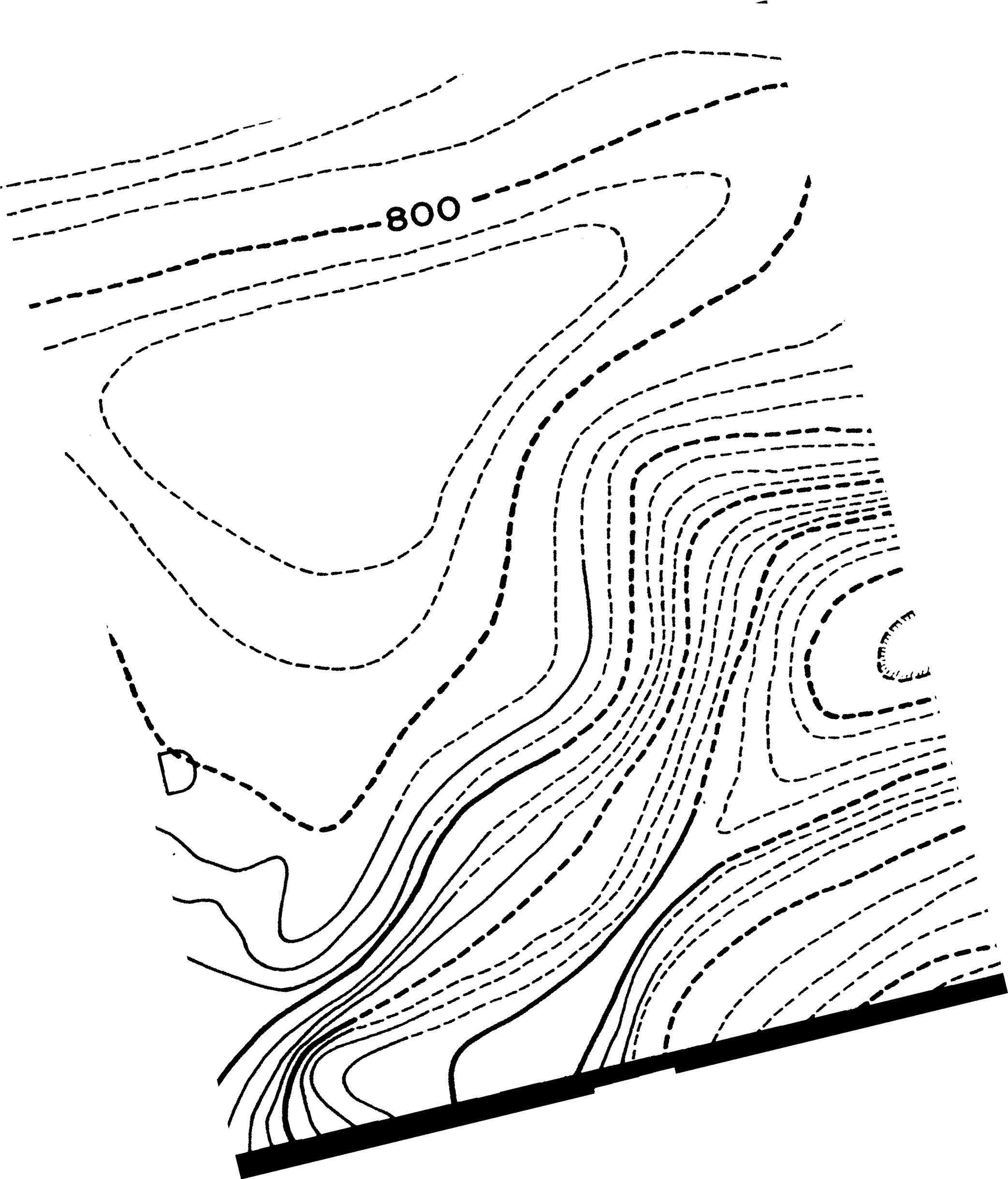


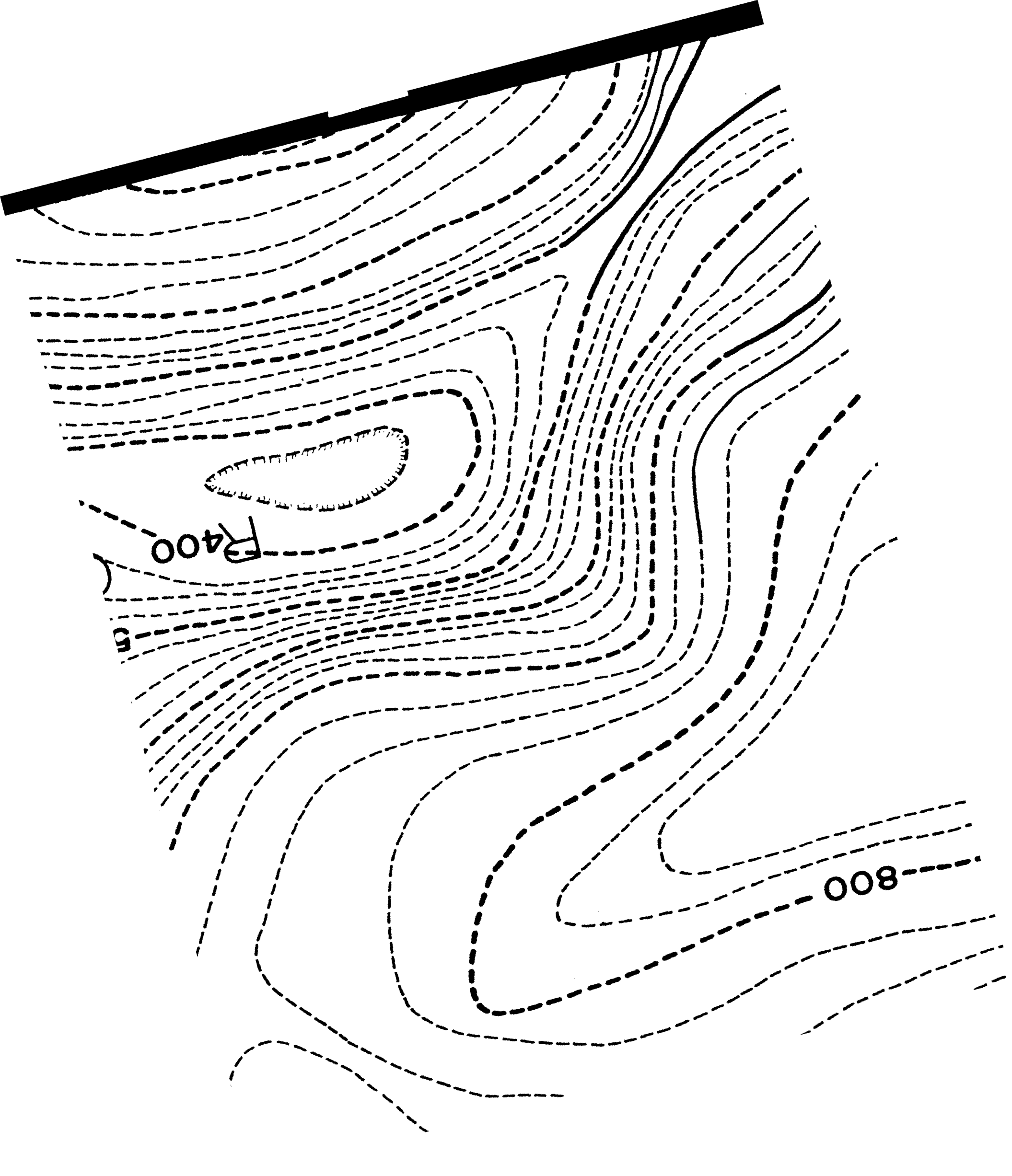


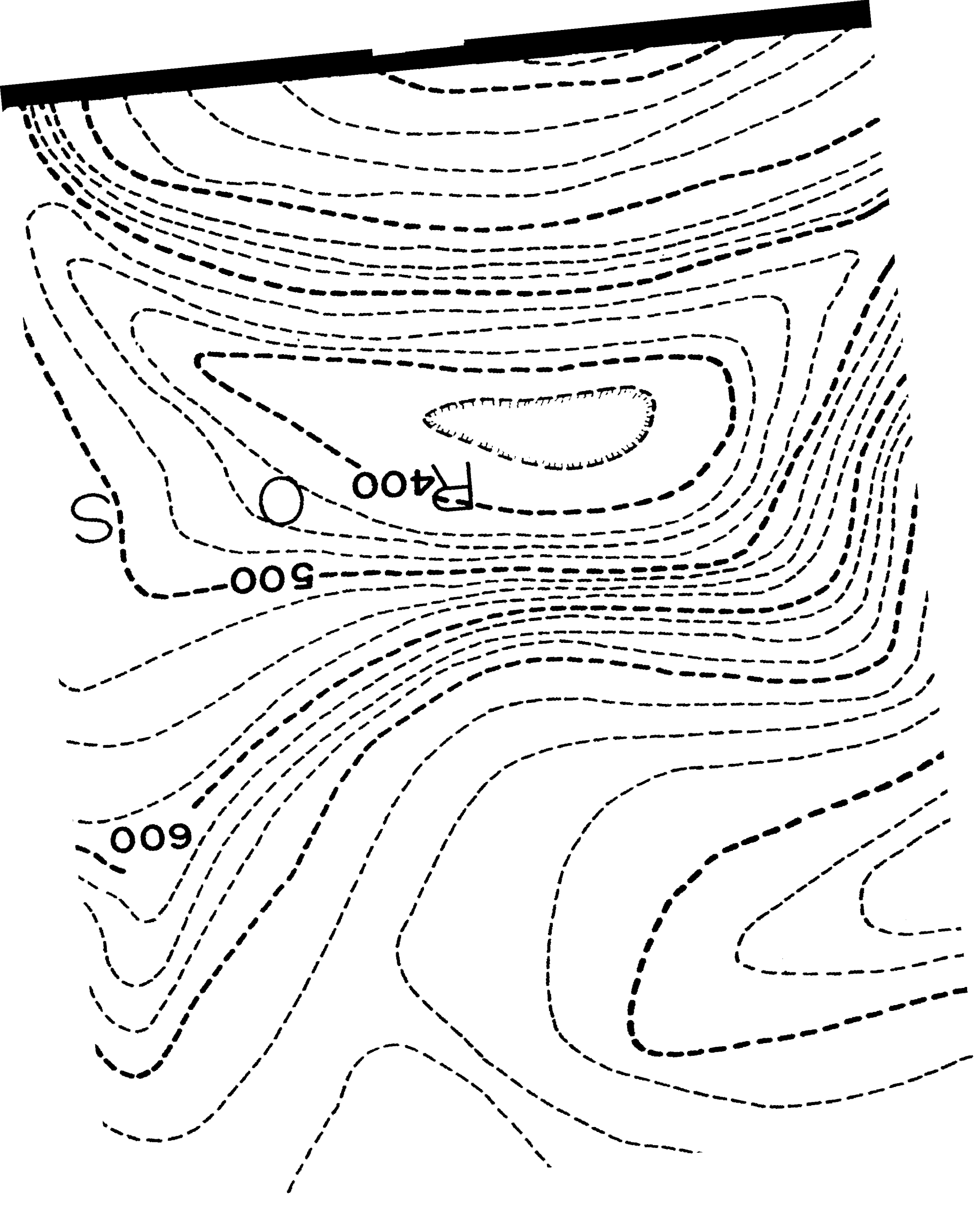


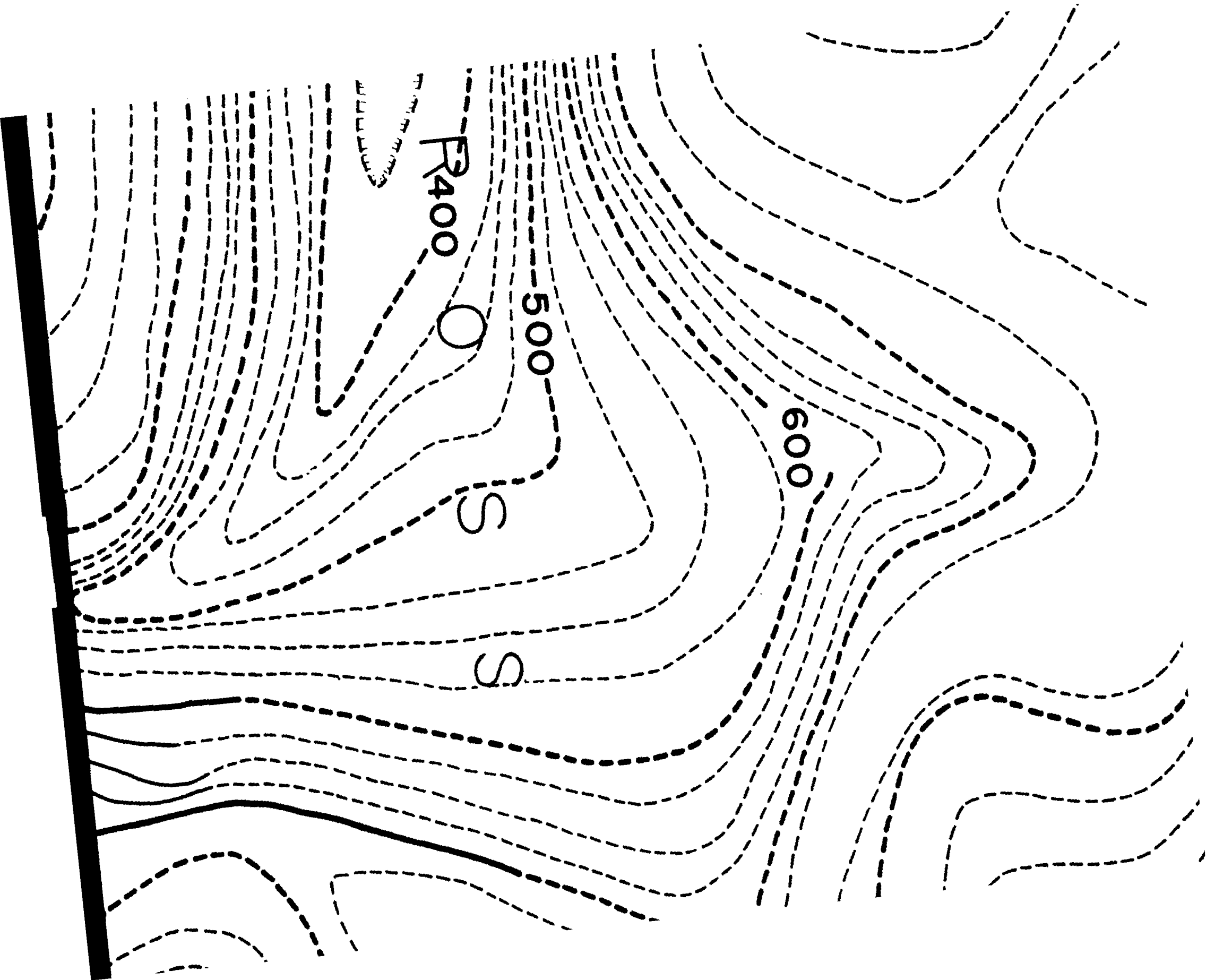


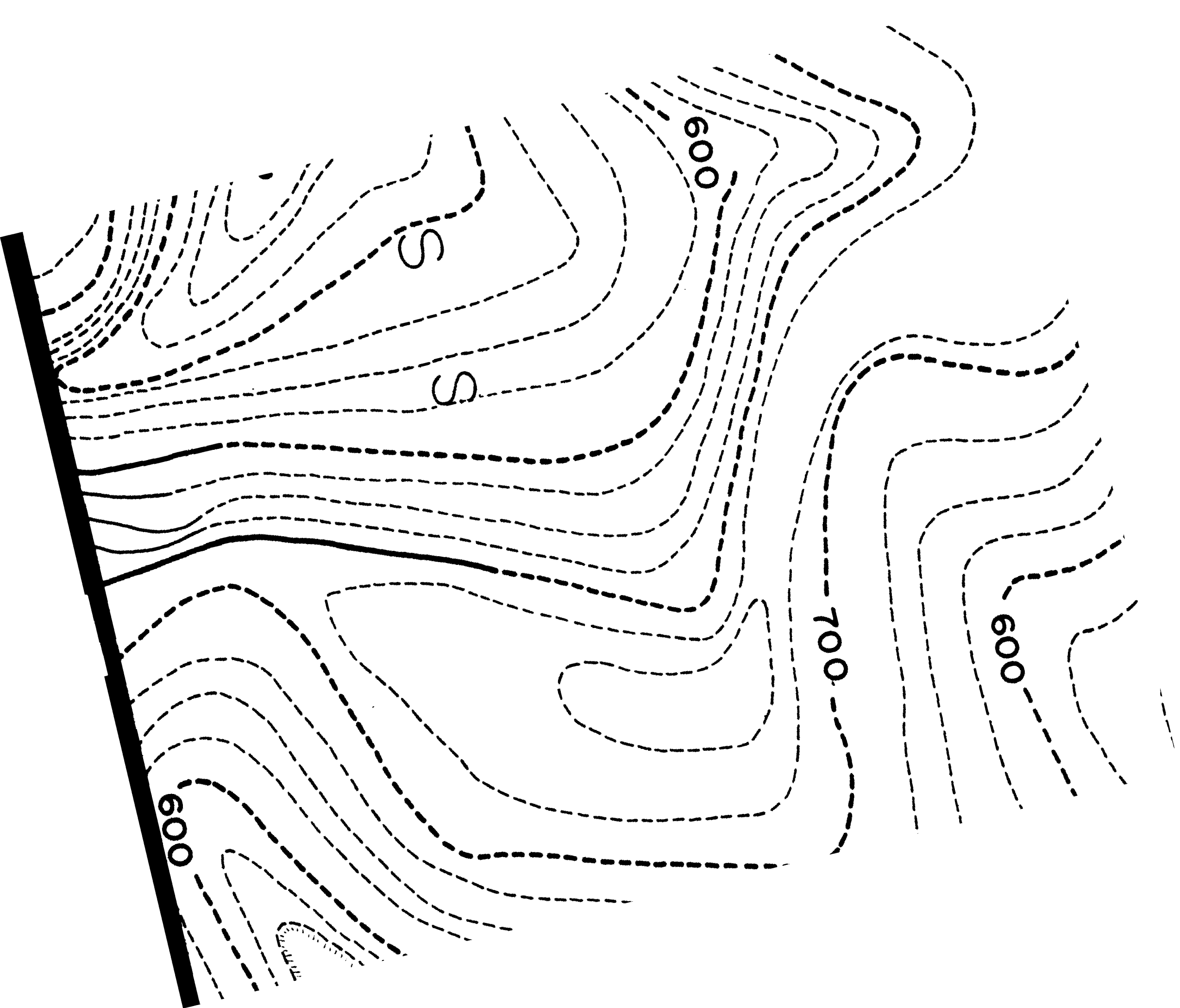


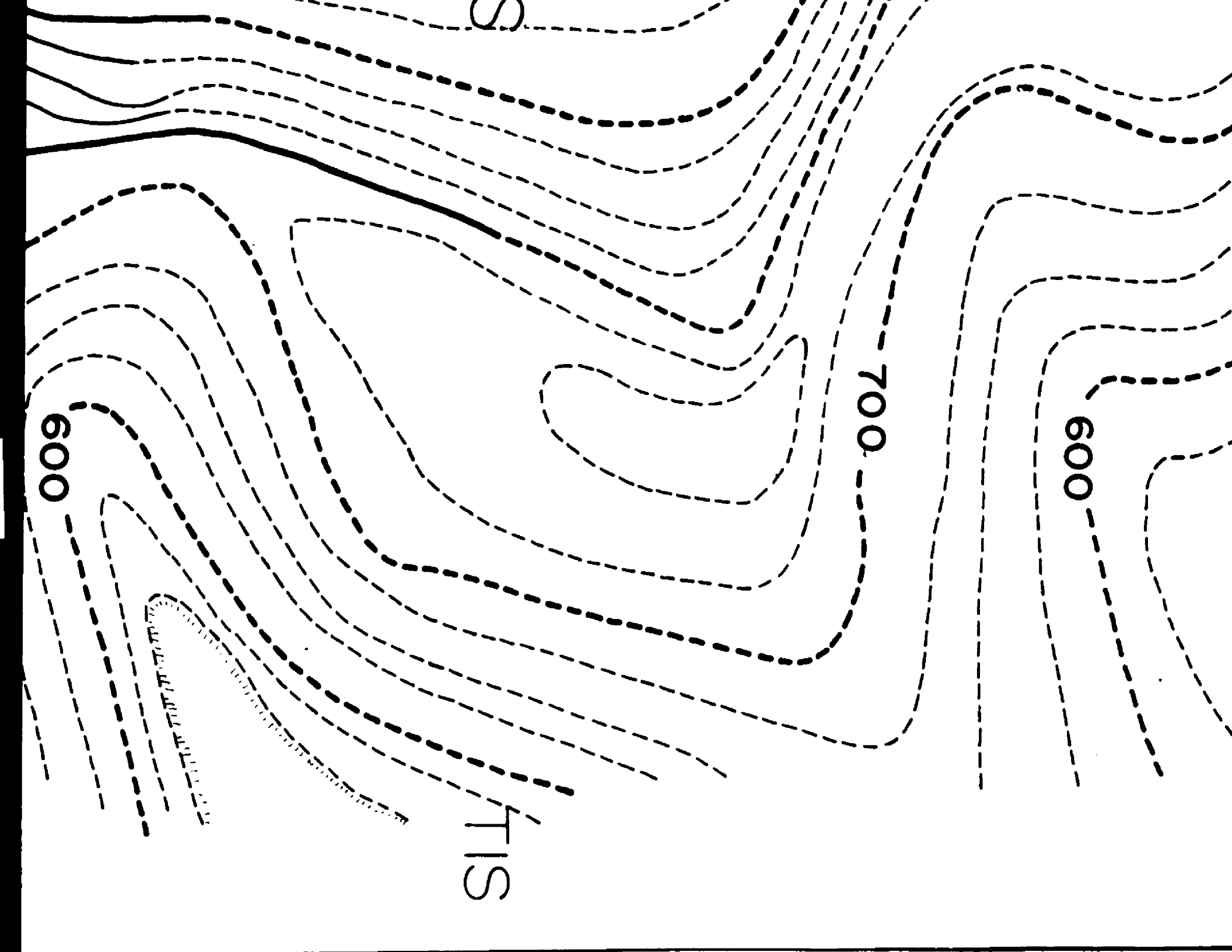


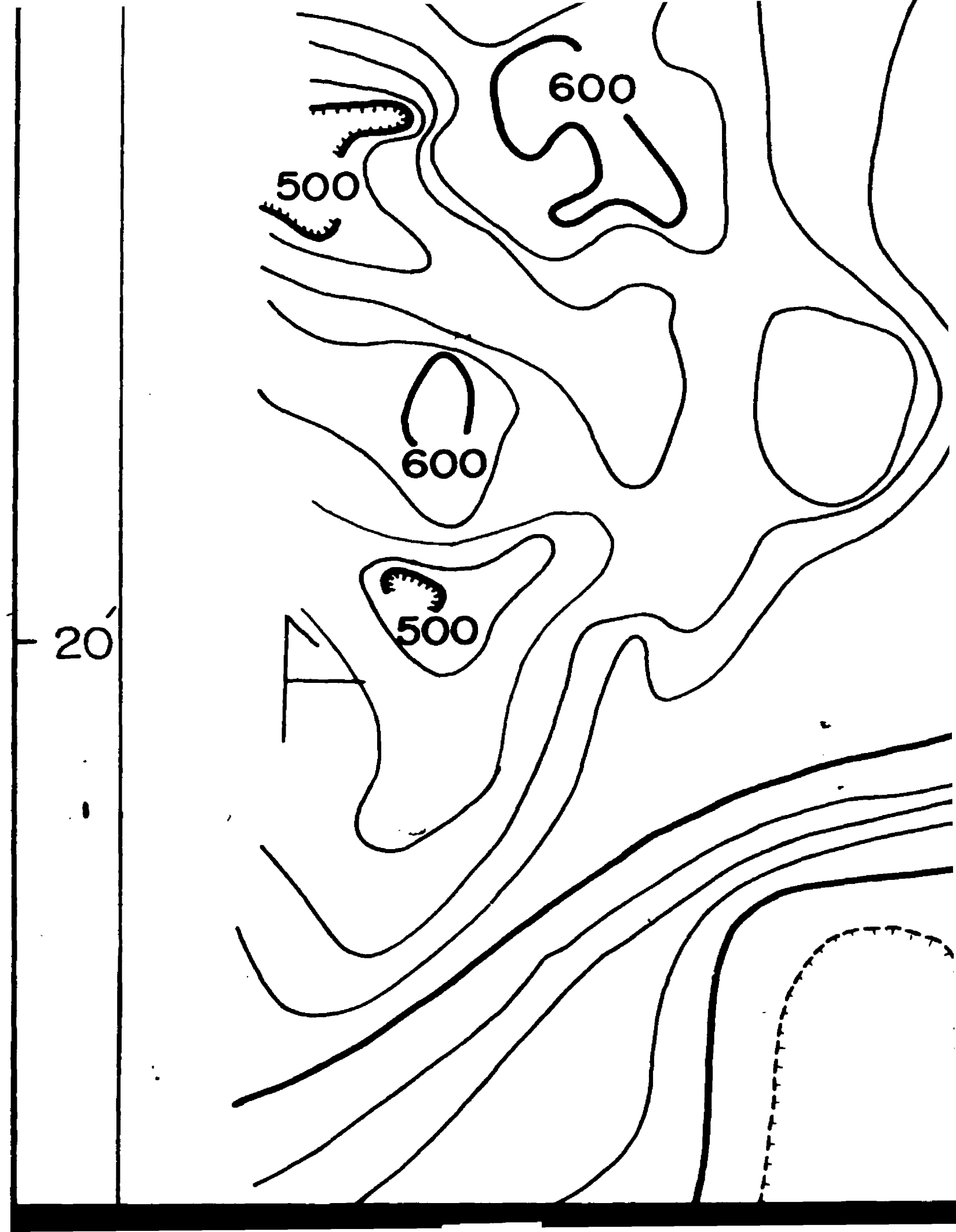


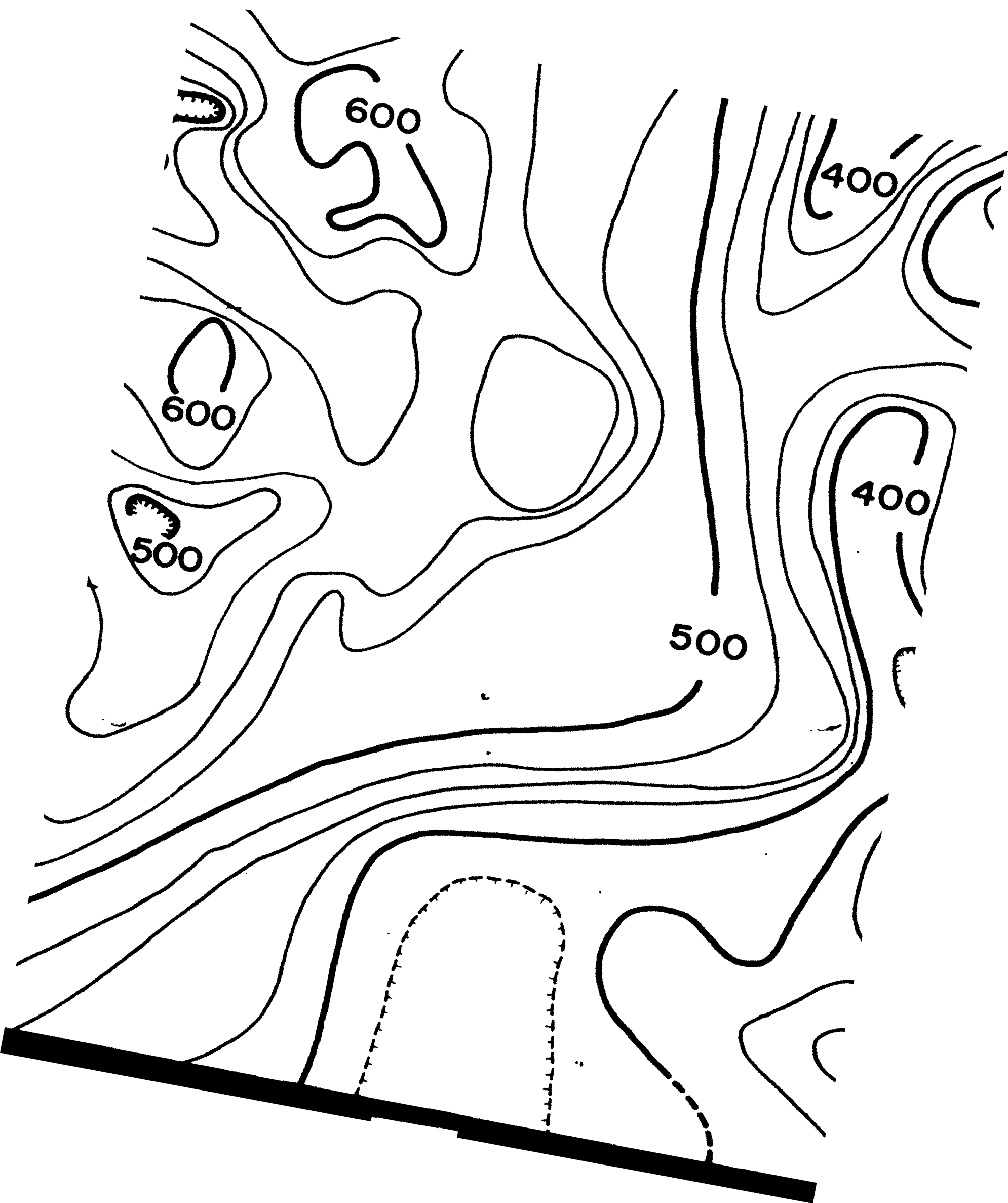


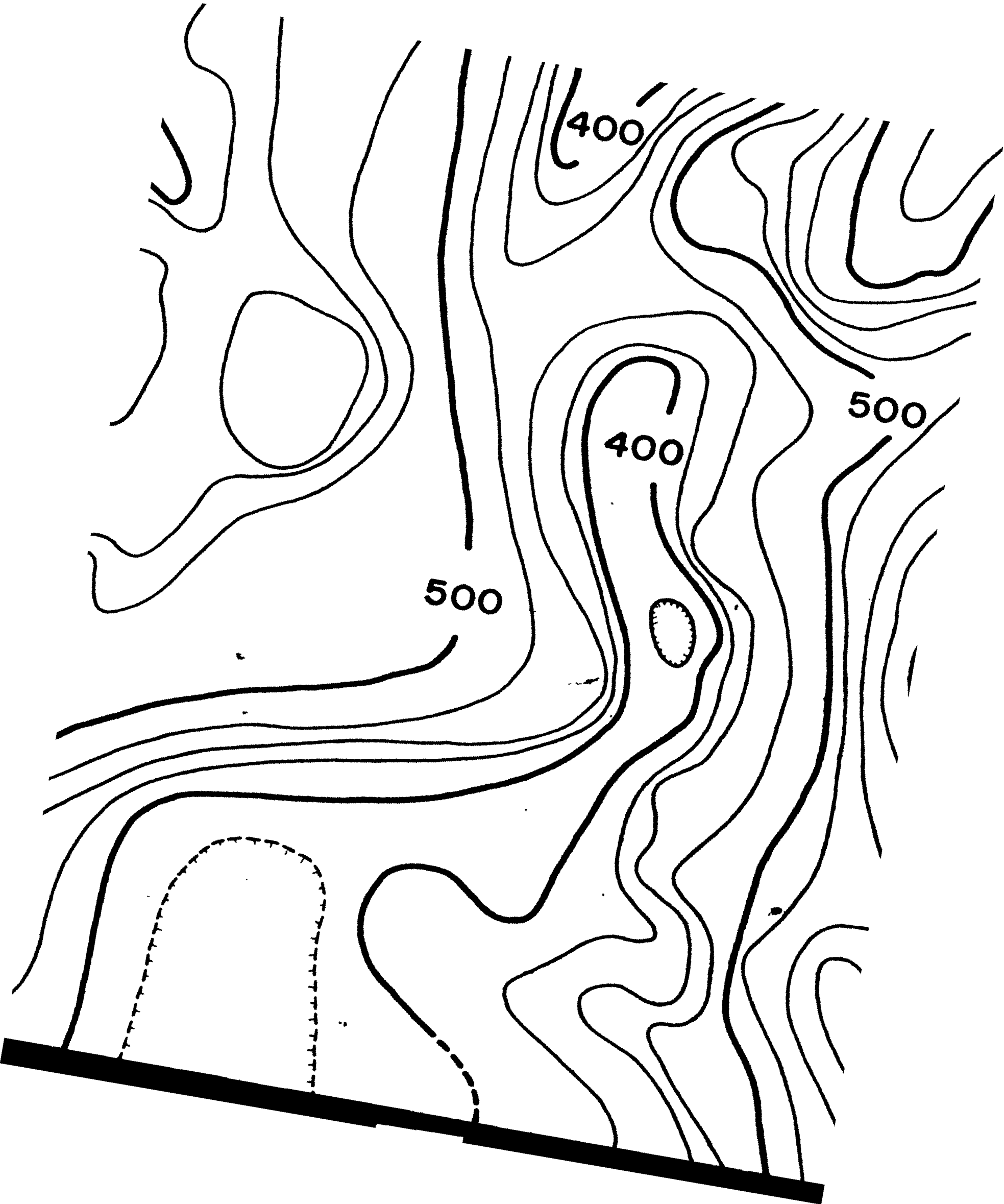


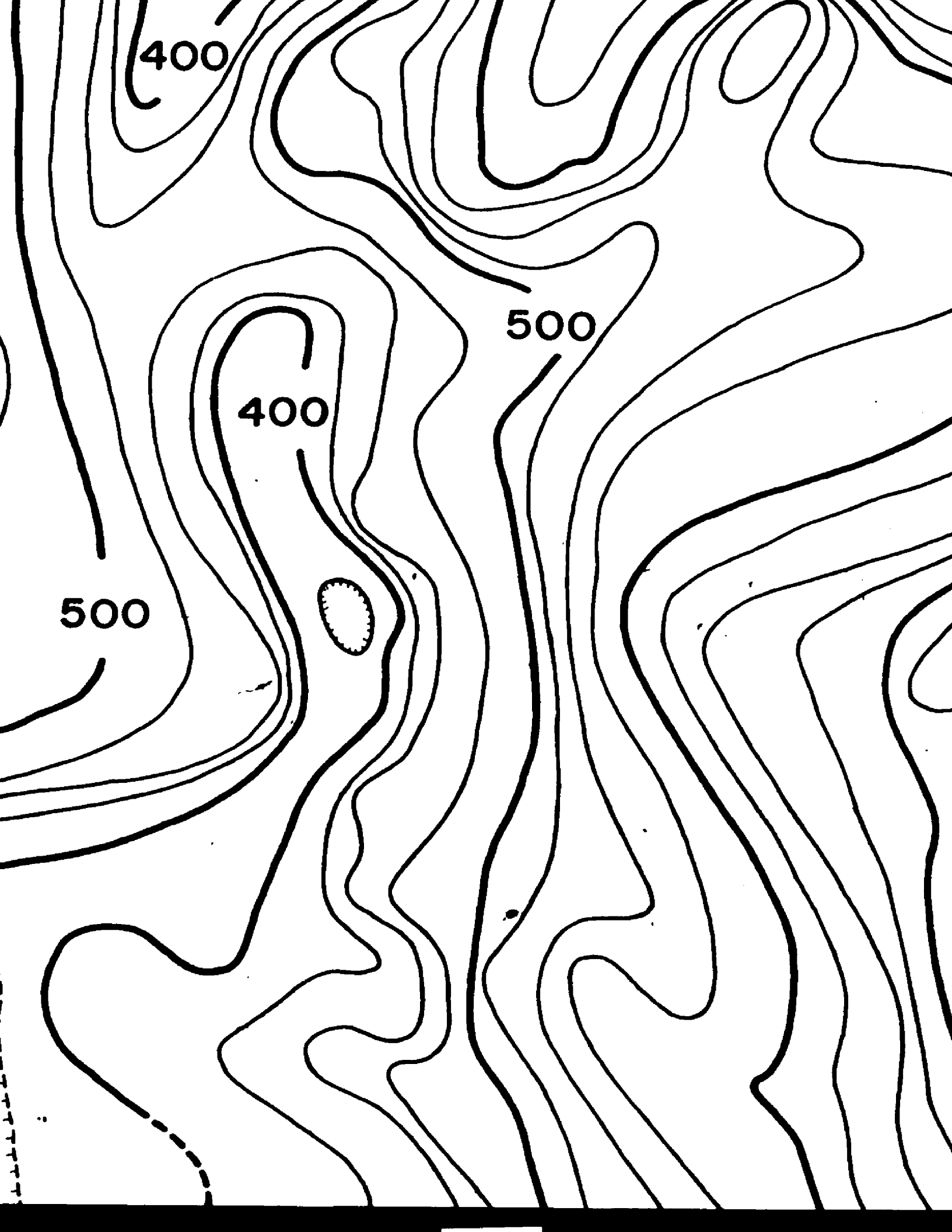


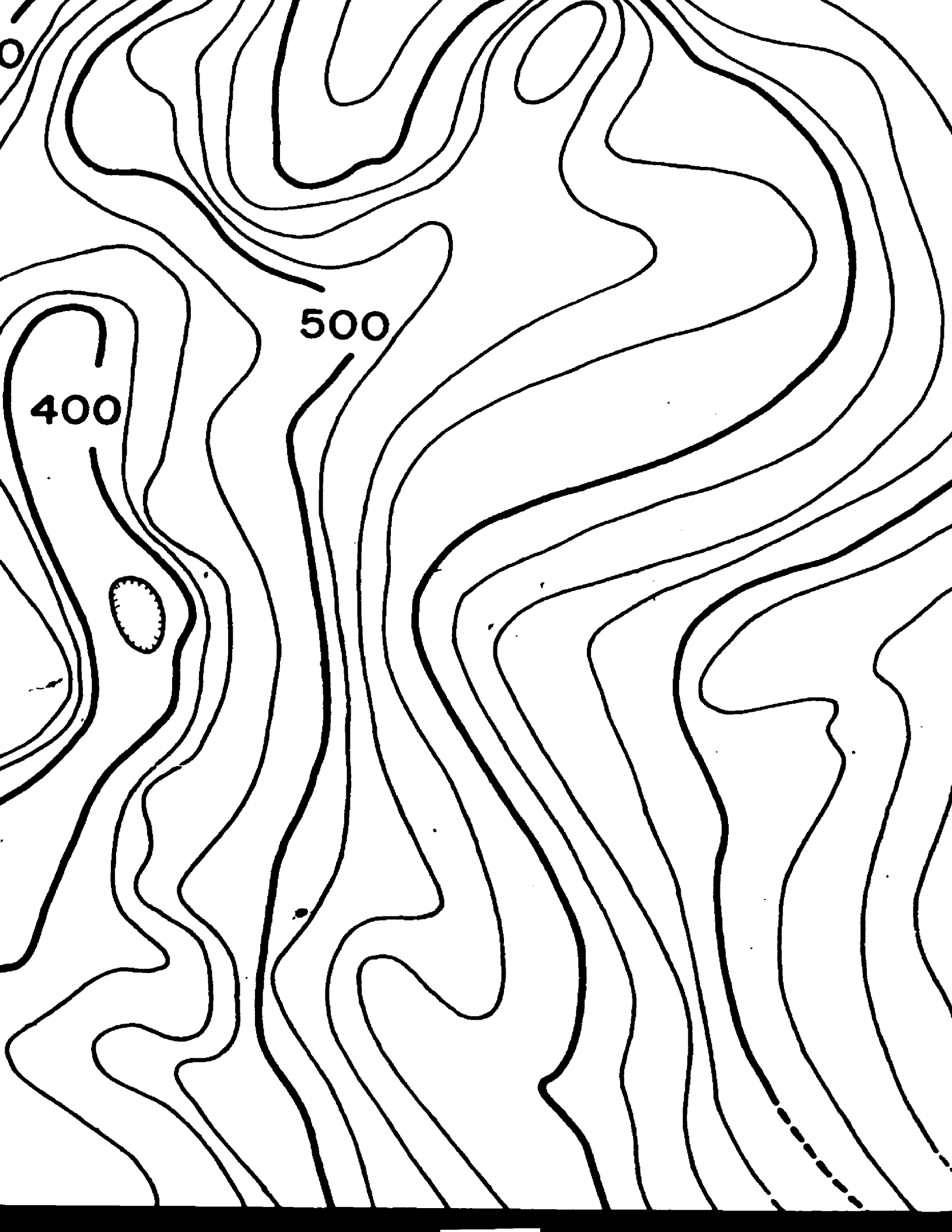


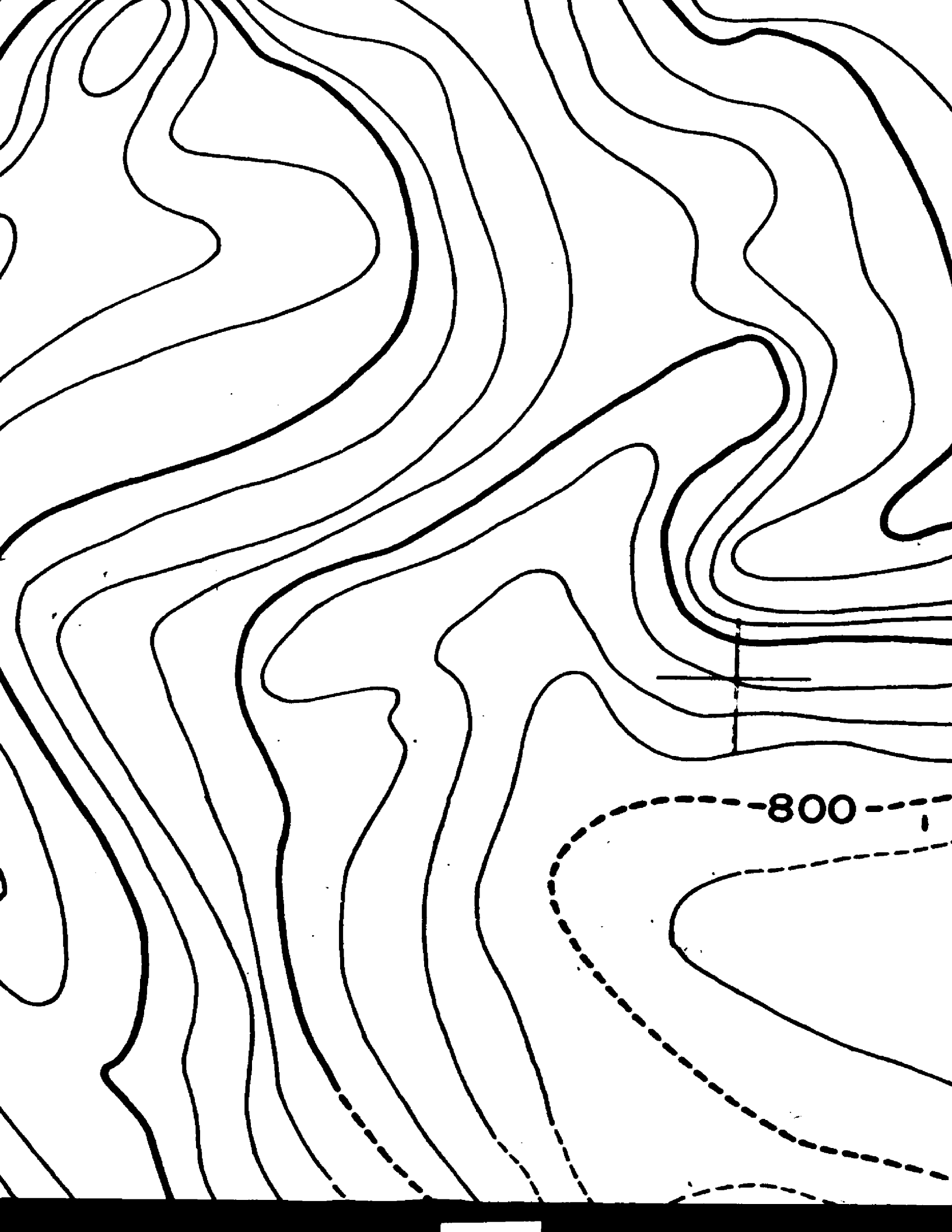


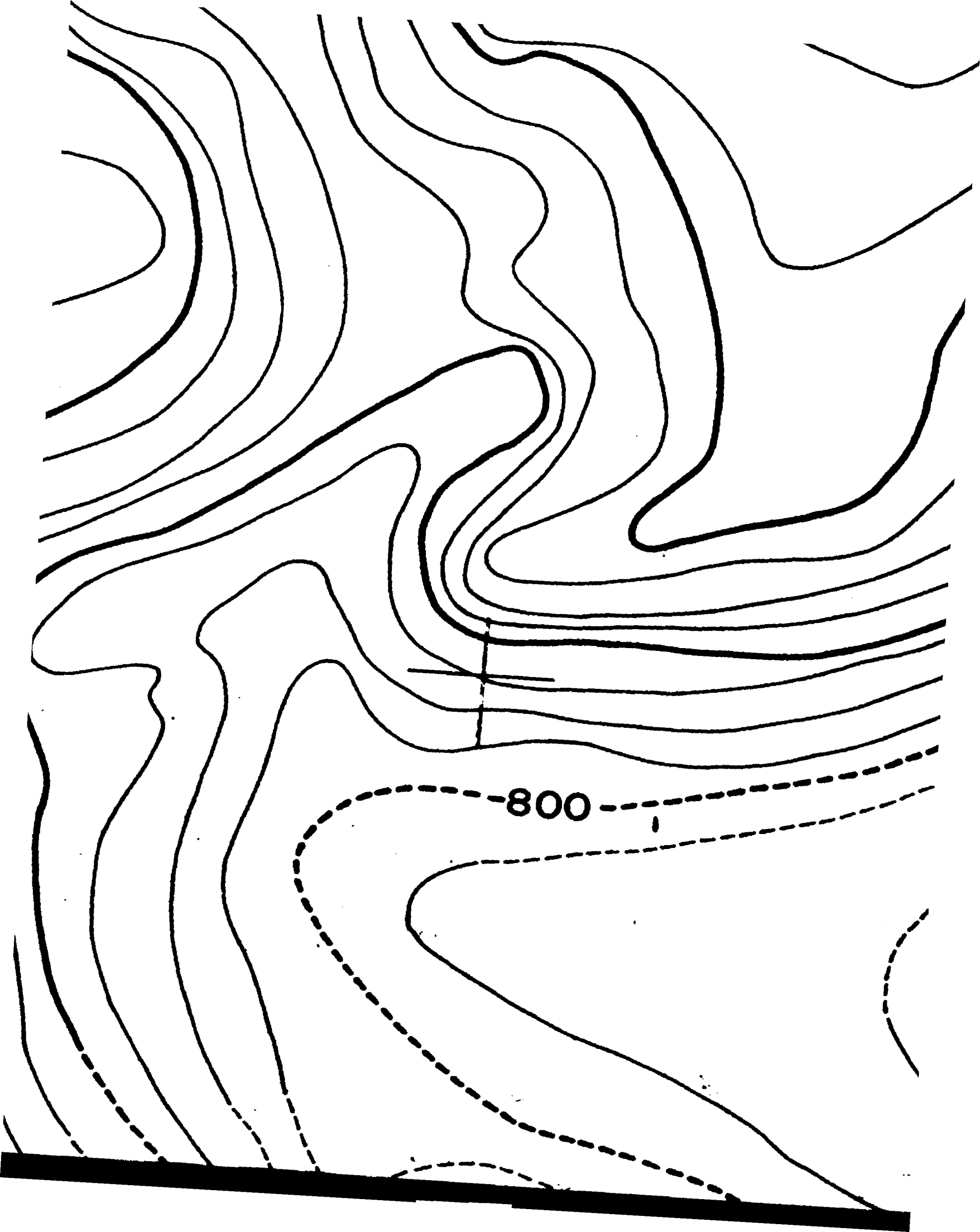




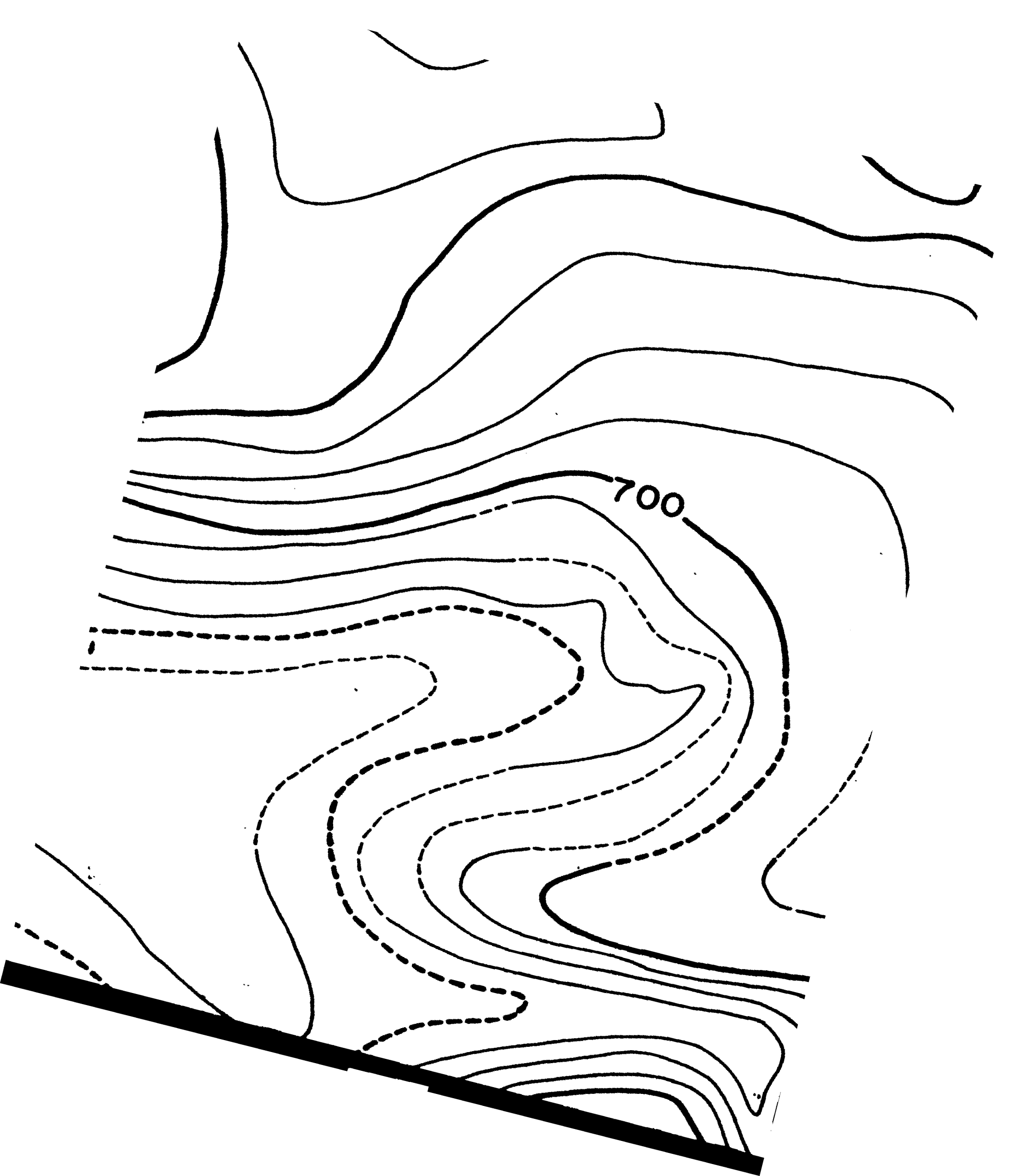






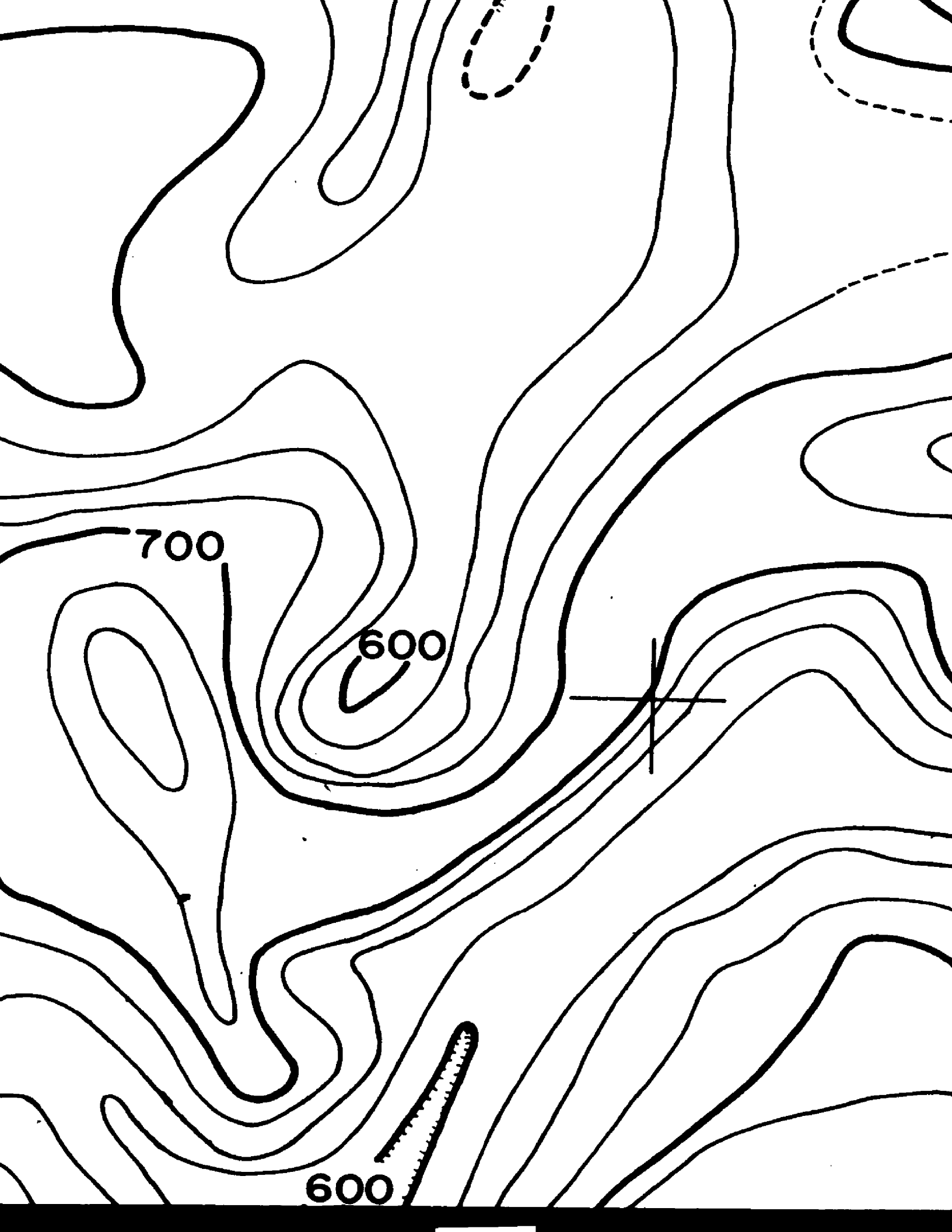


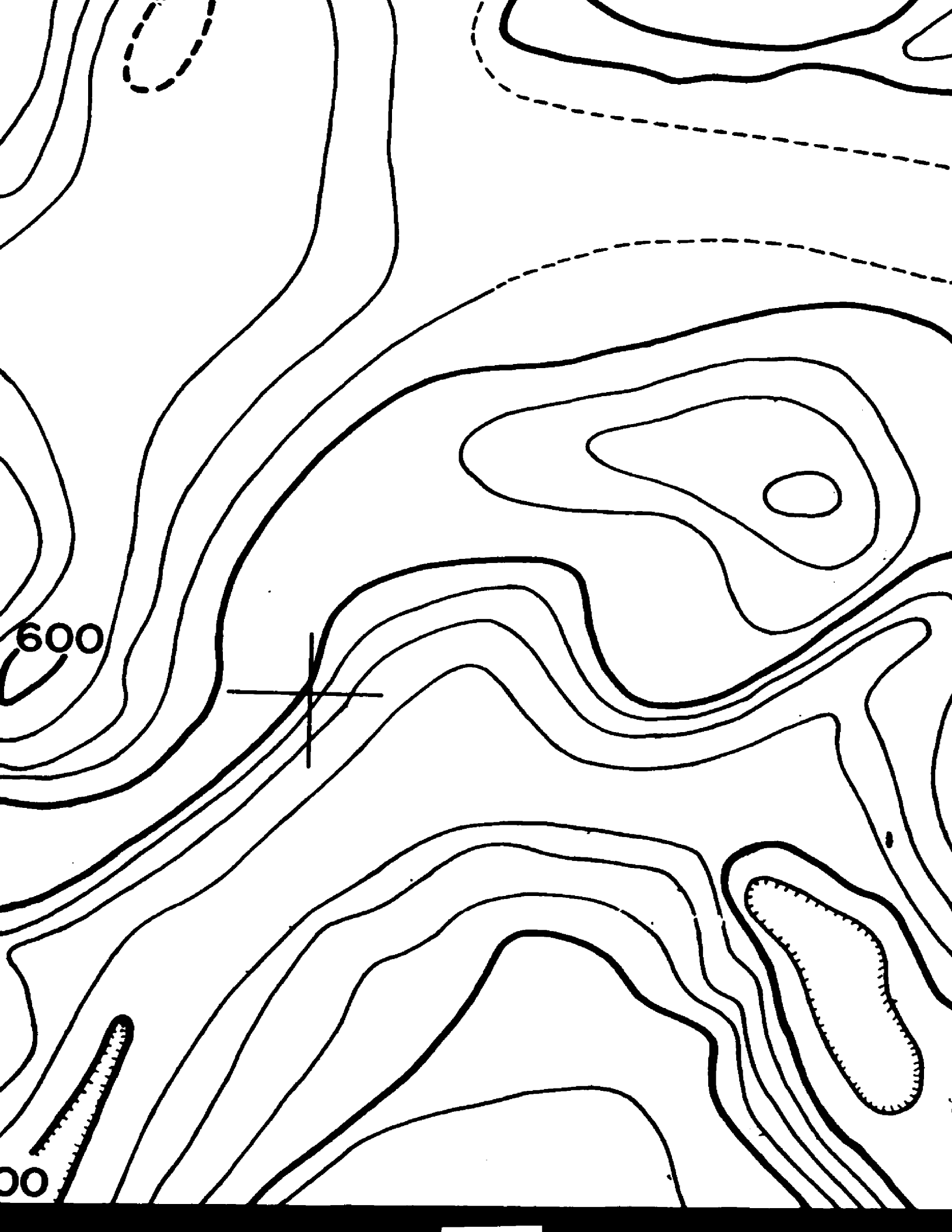






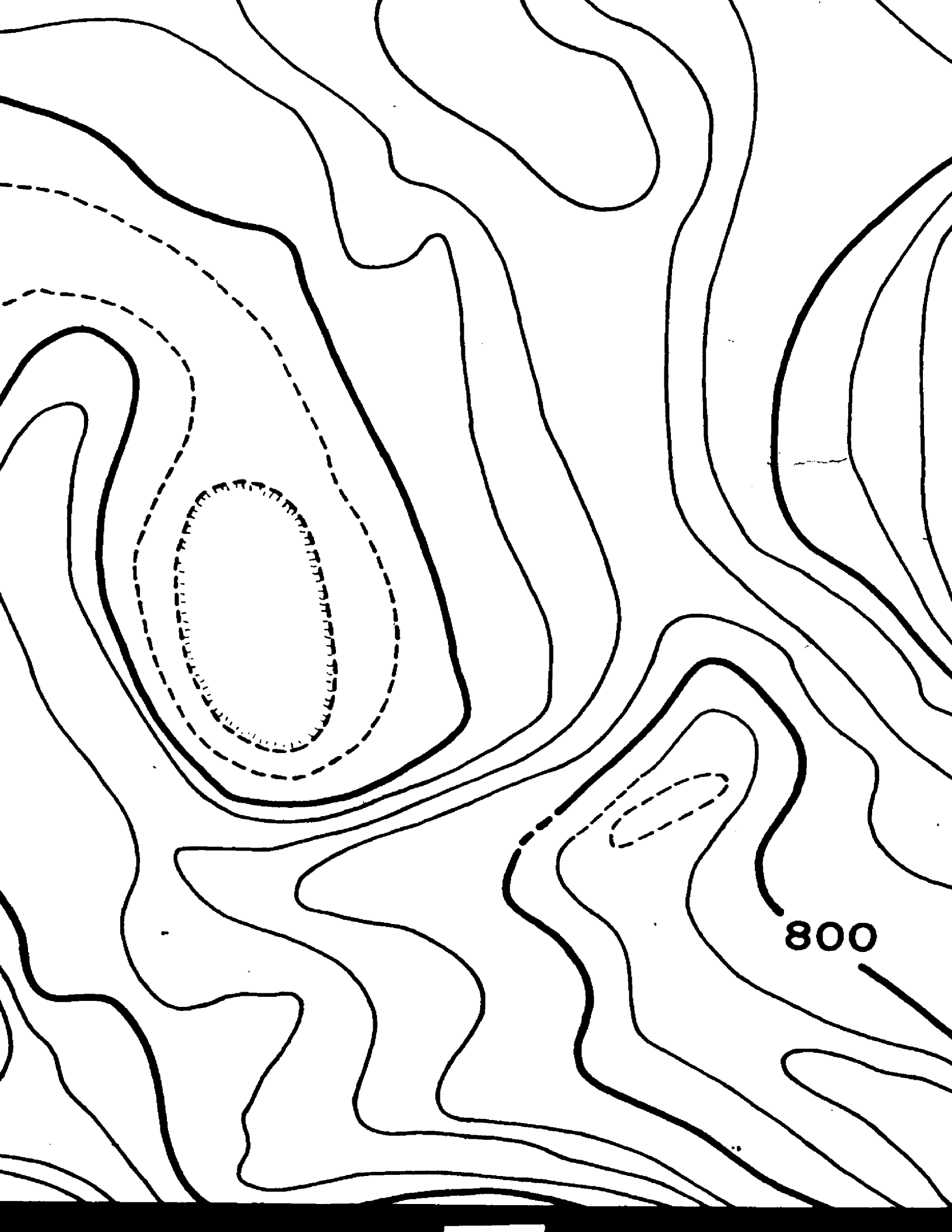


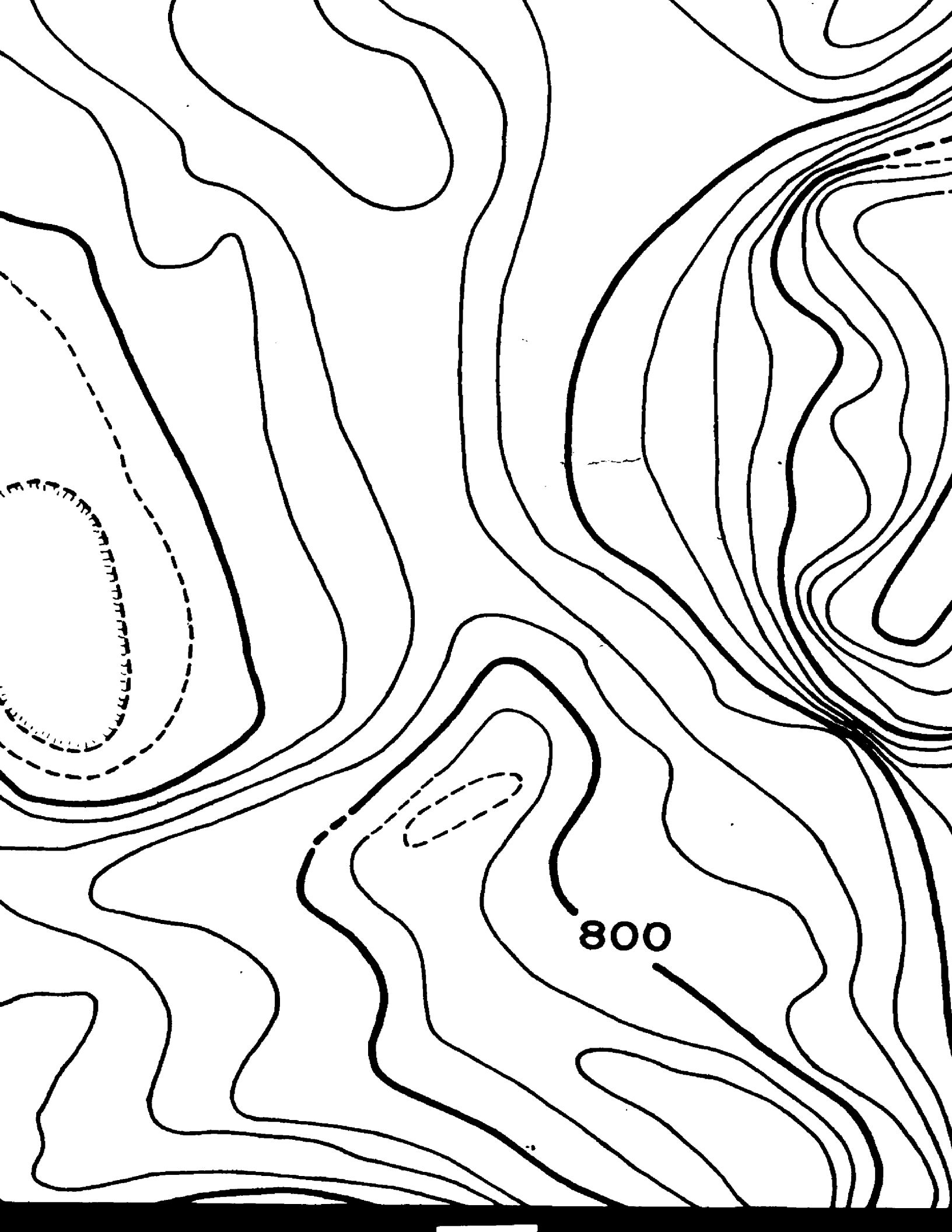




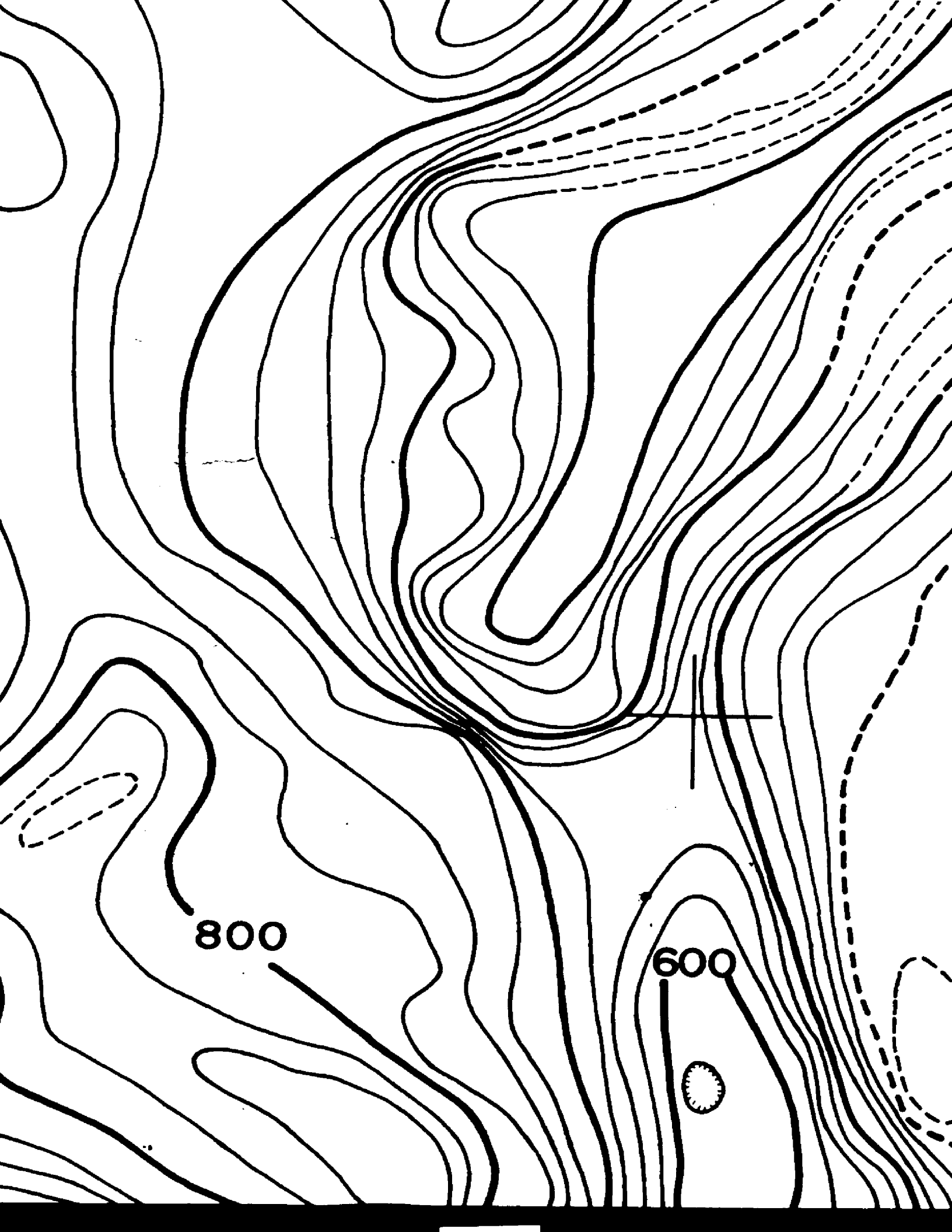


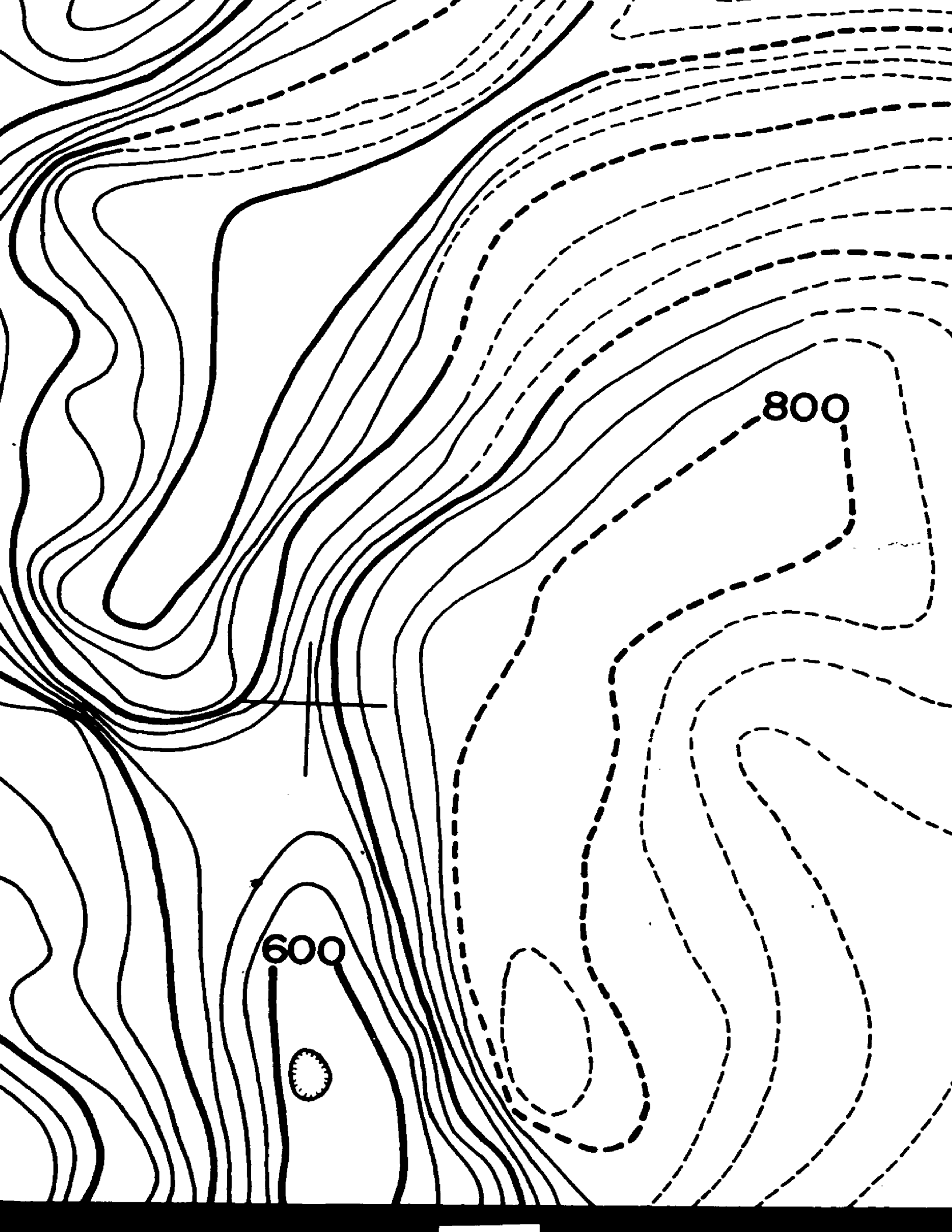


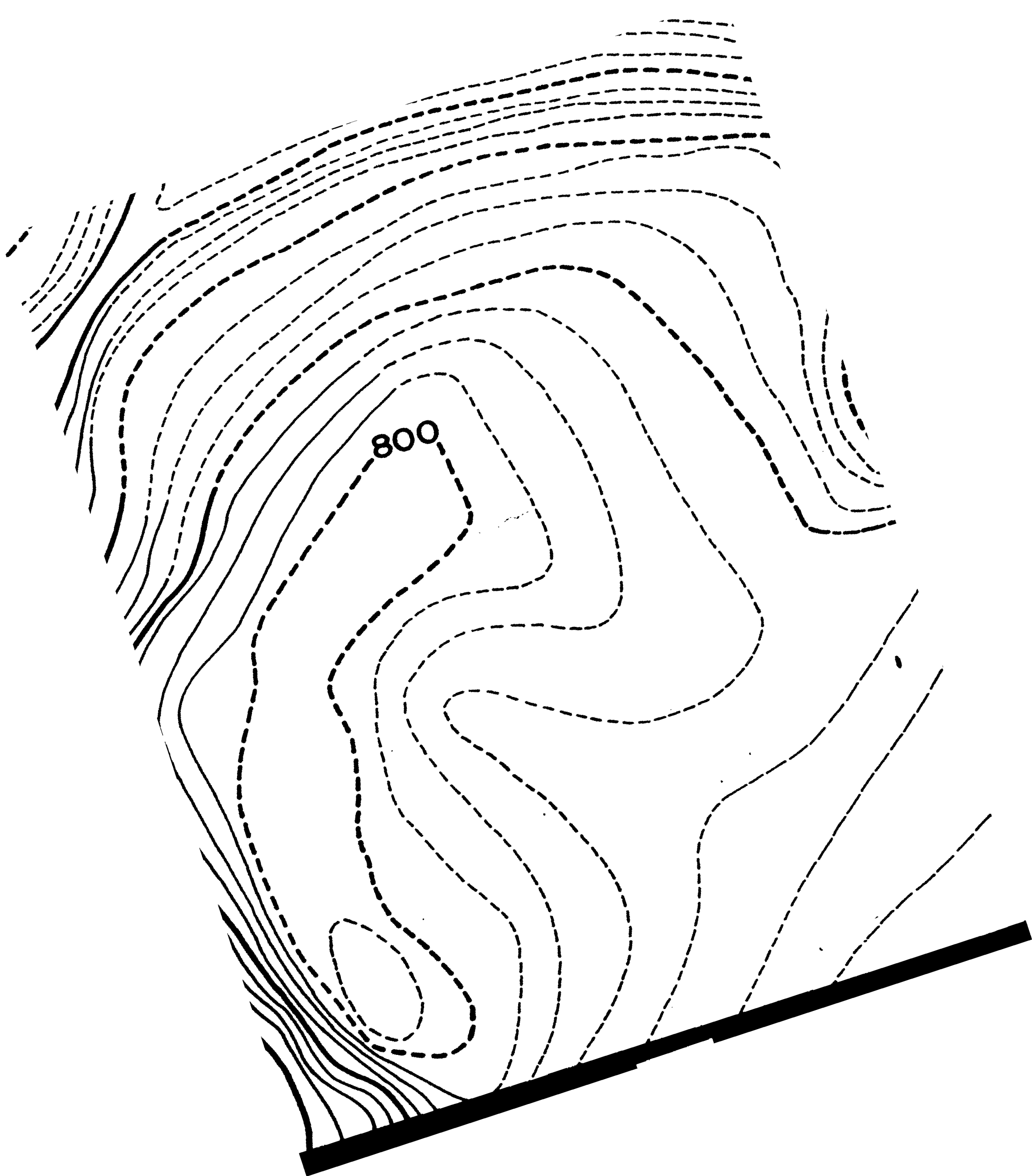


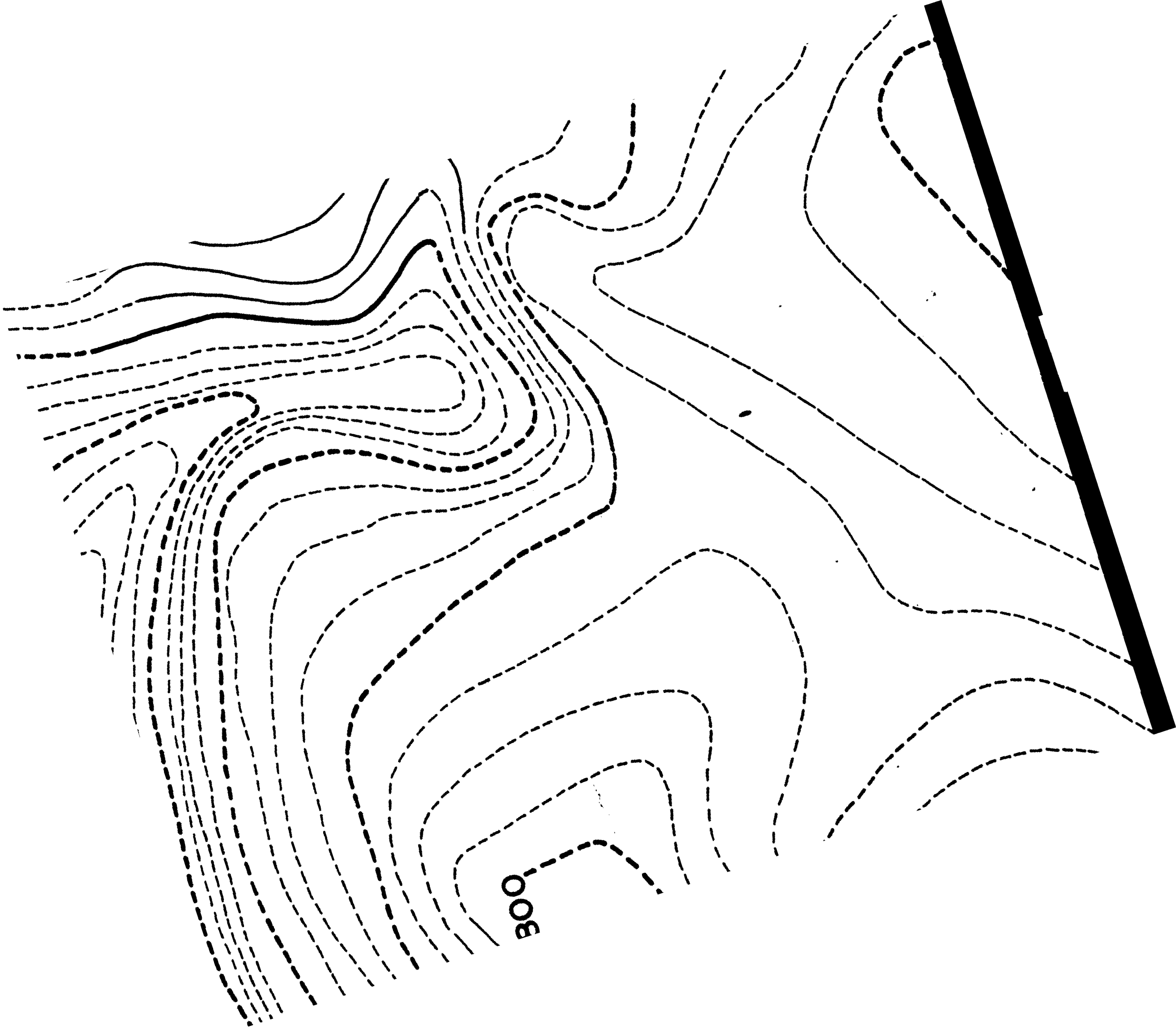


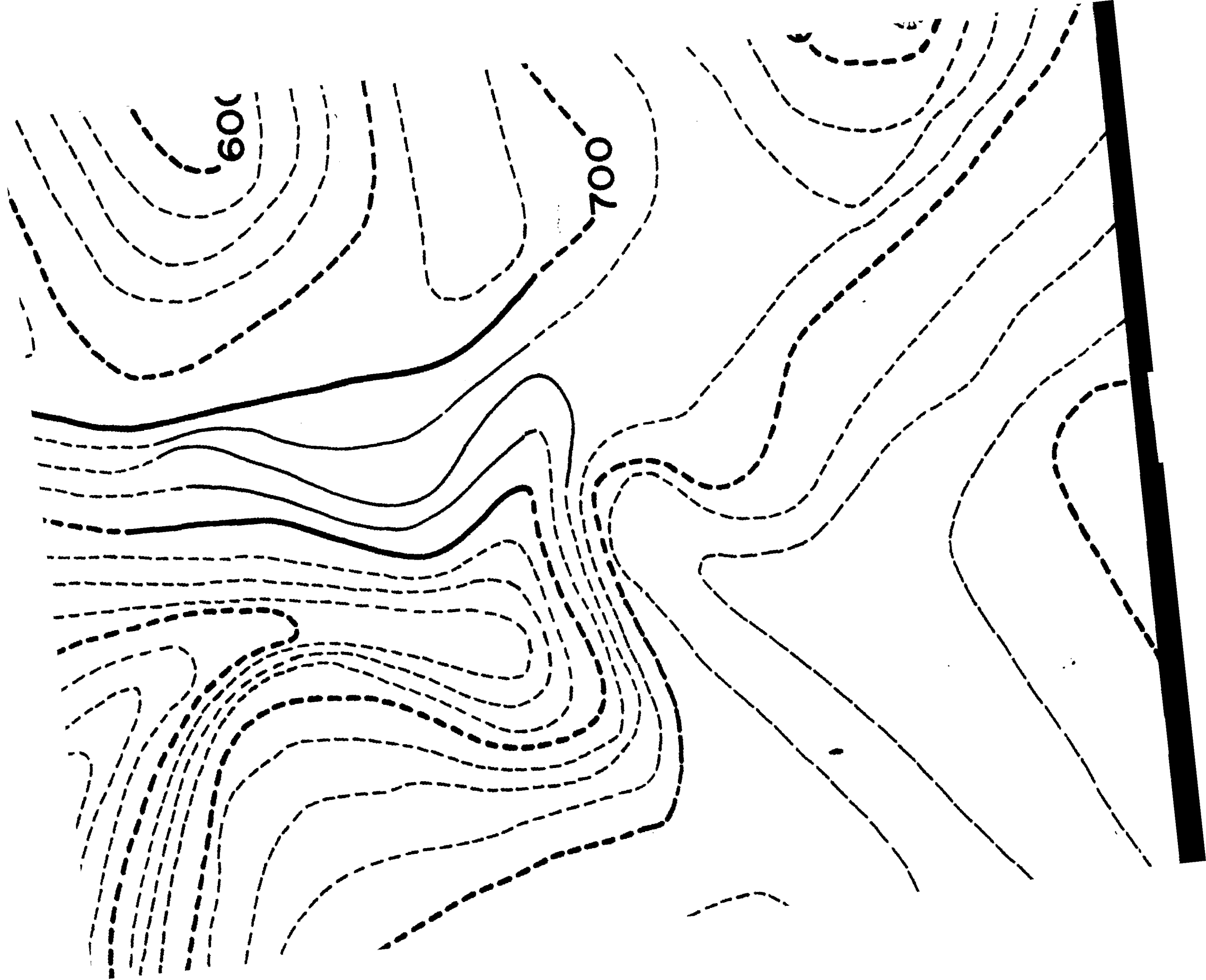
800

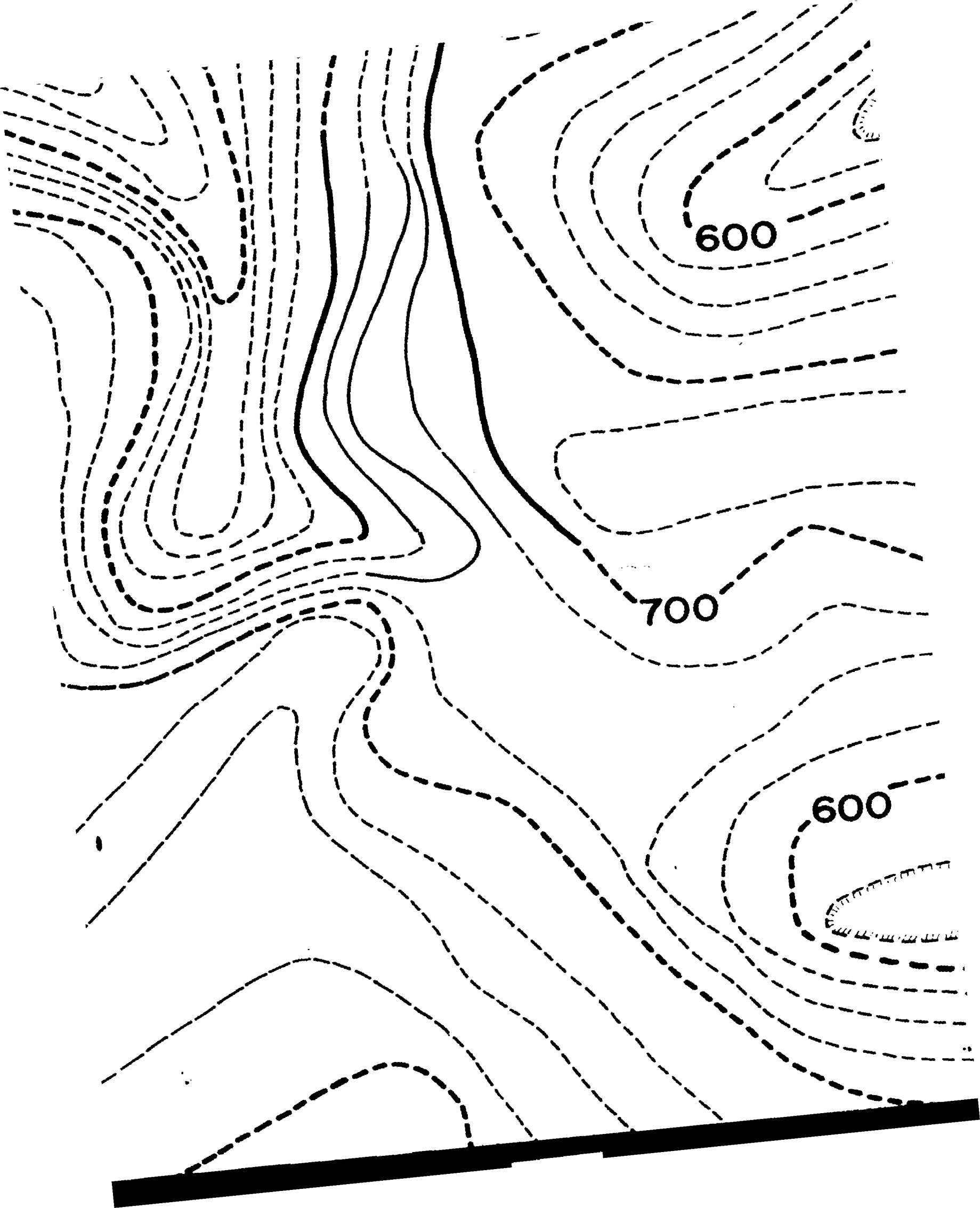


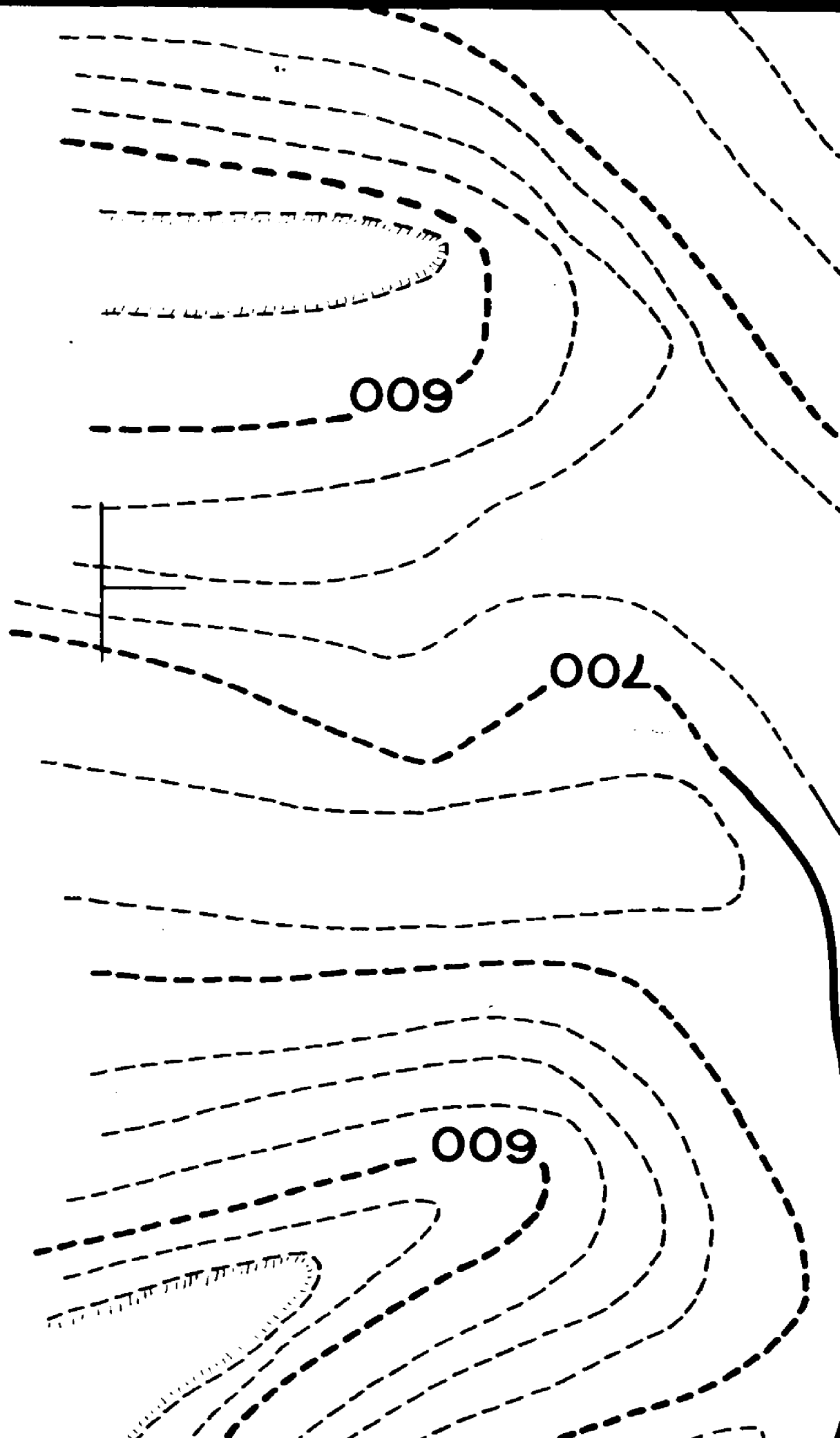












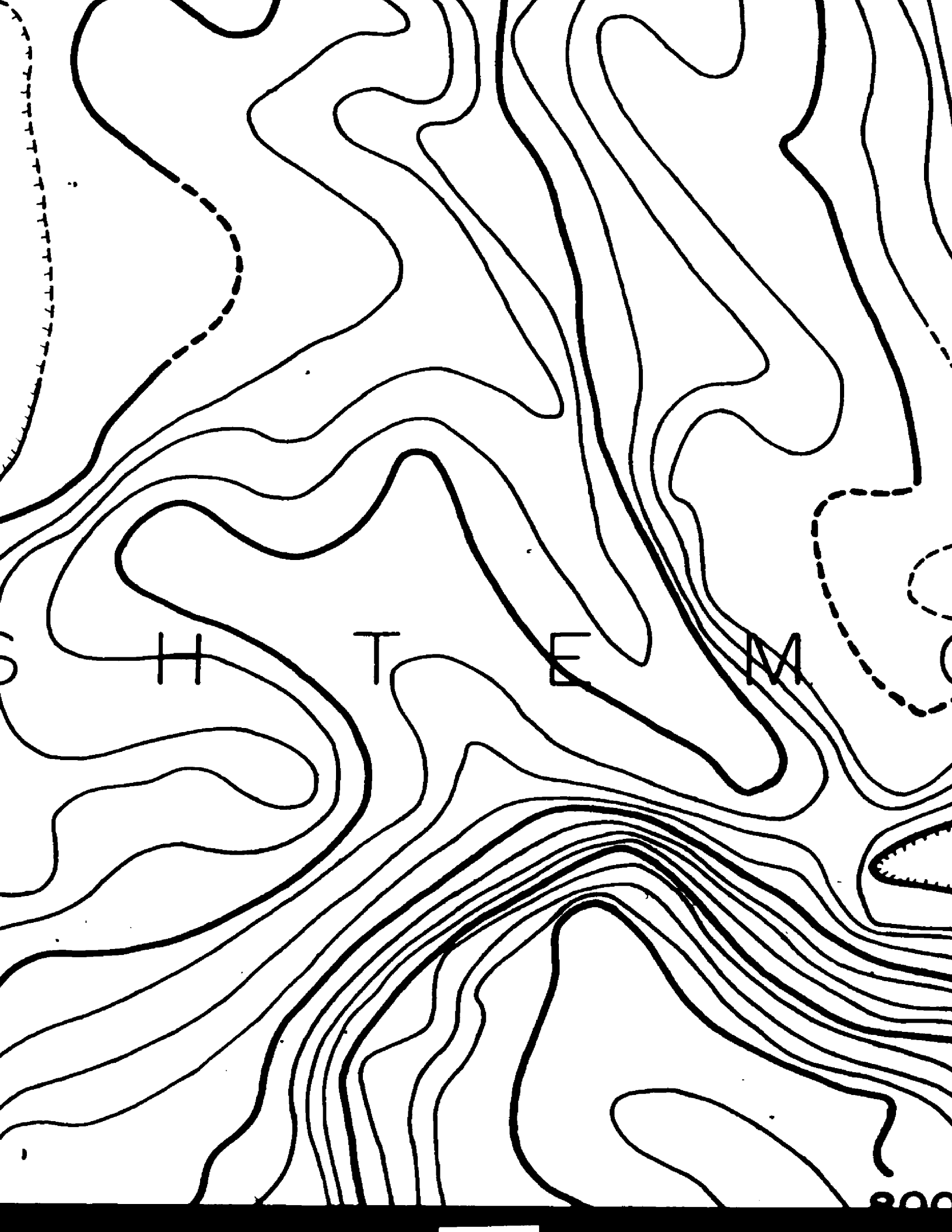
20'

T2S









S

H

T

E

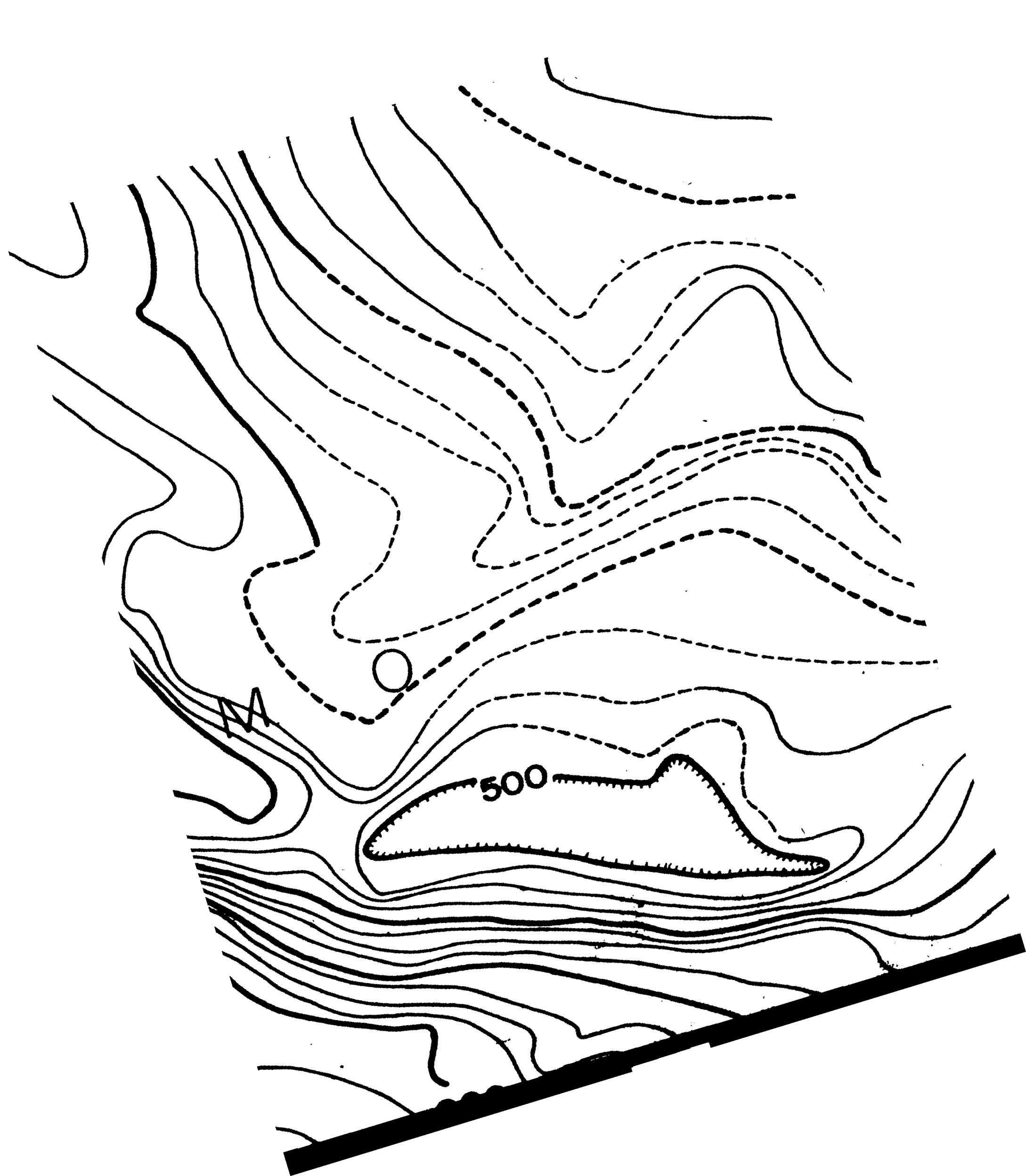
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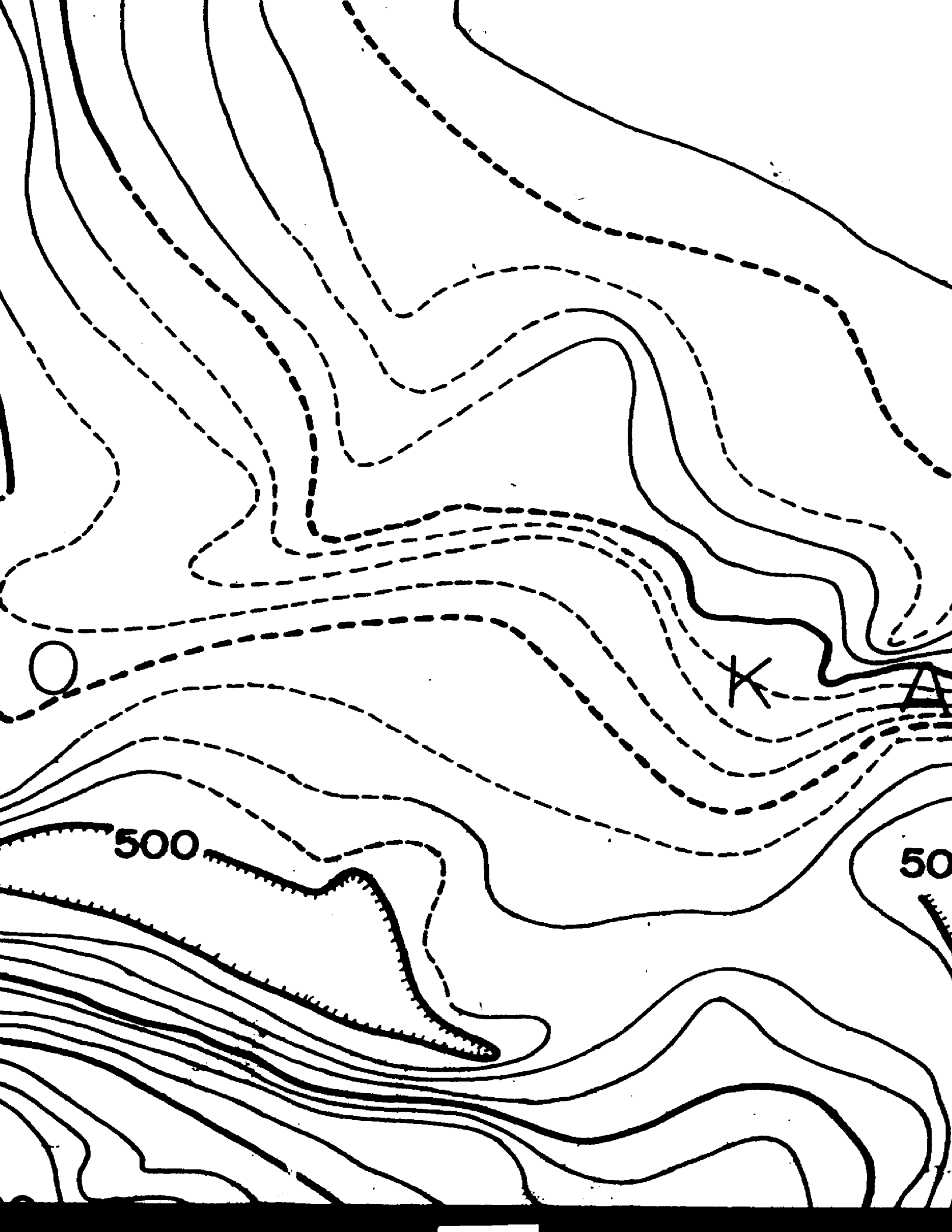
800

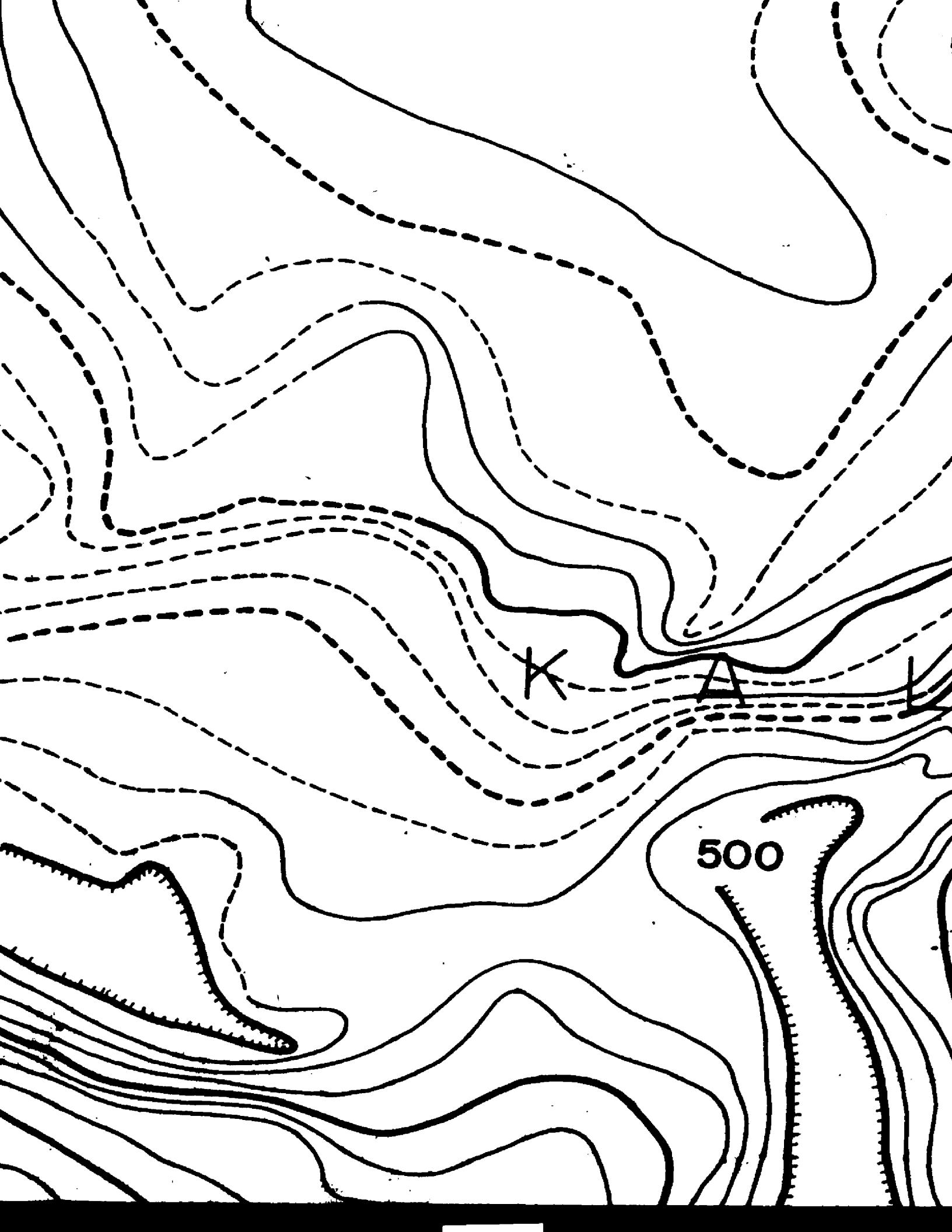


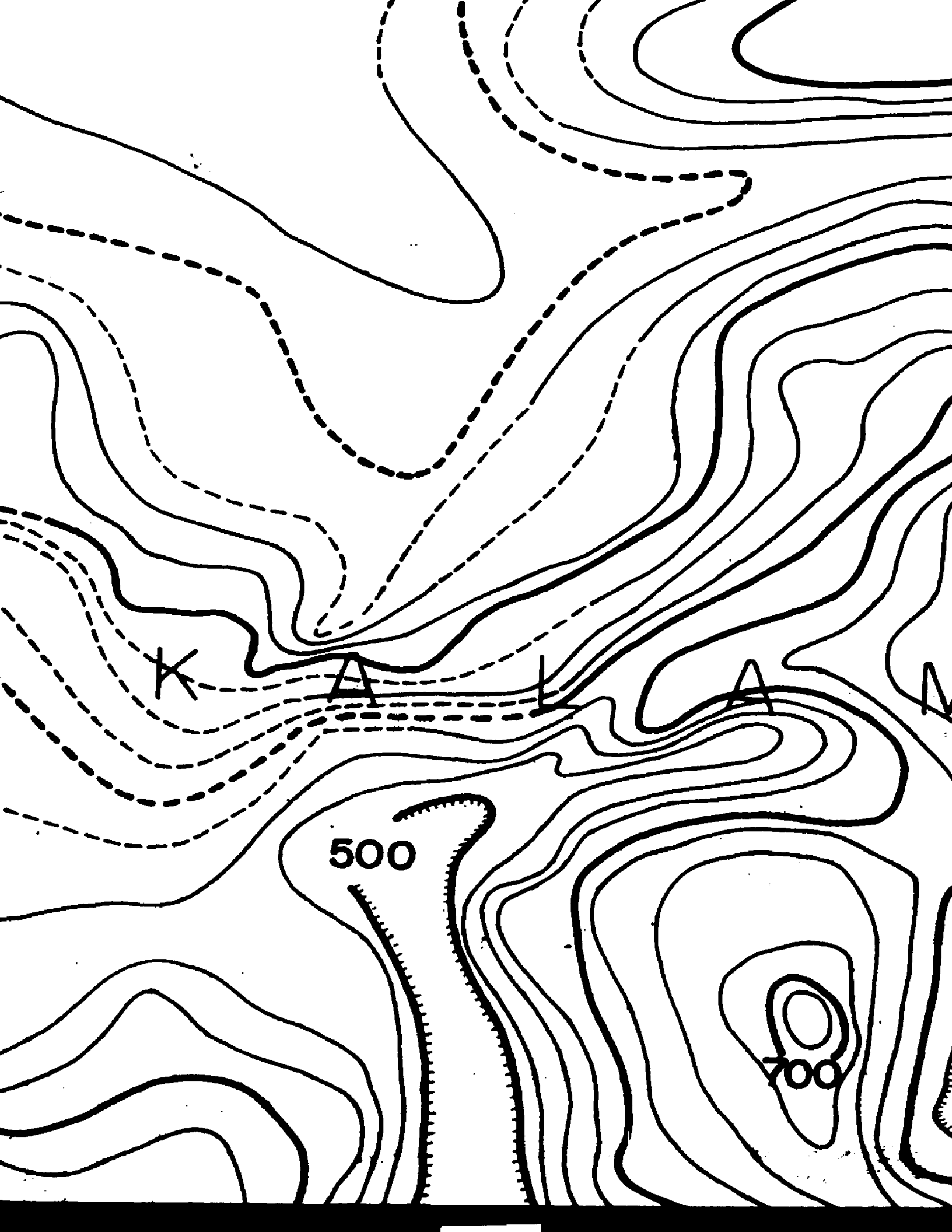
T E M O

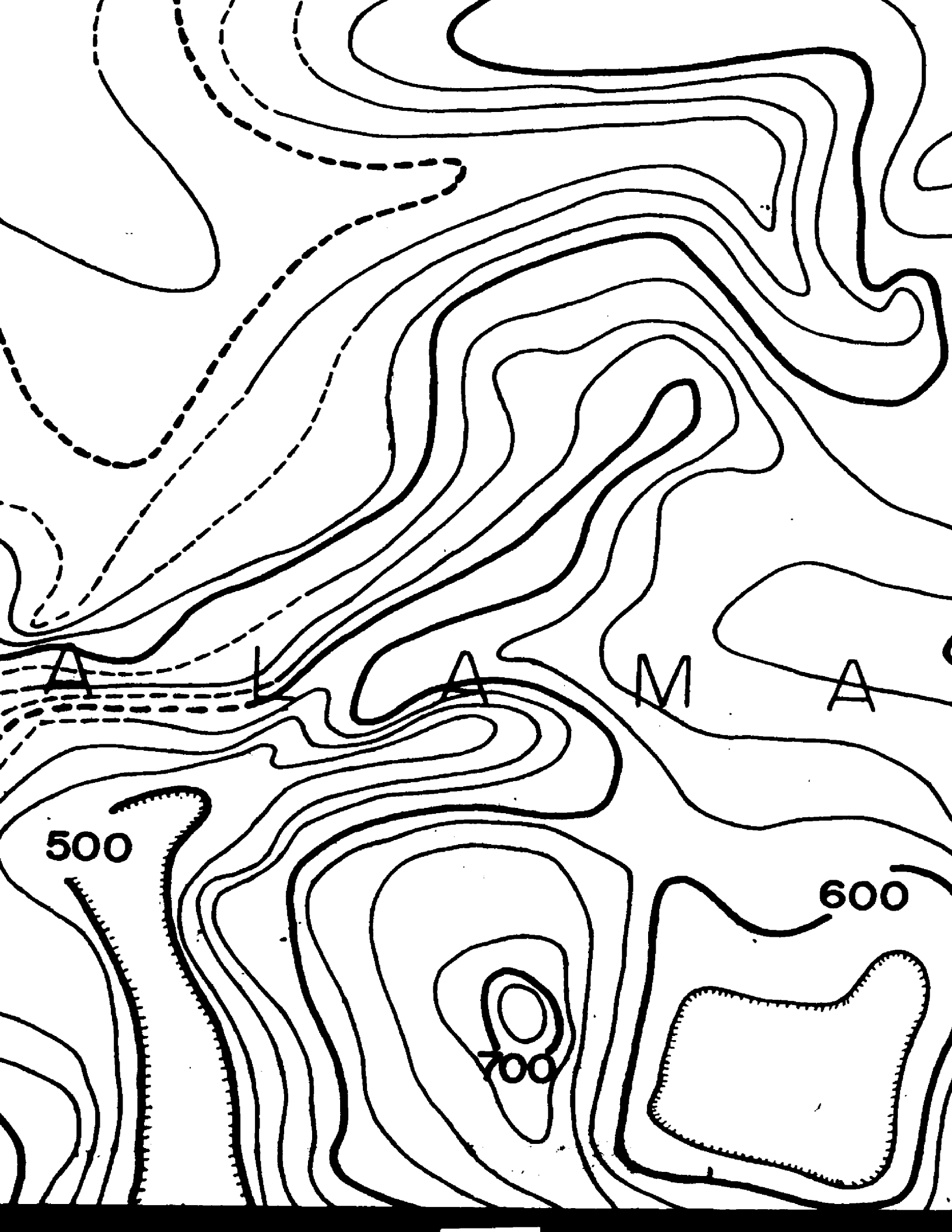
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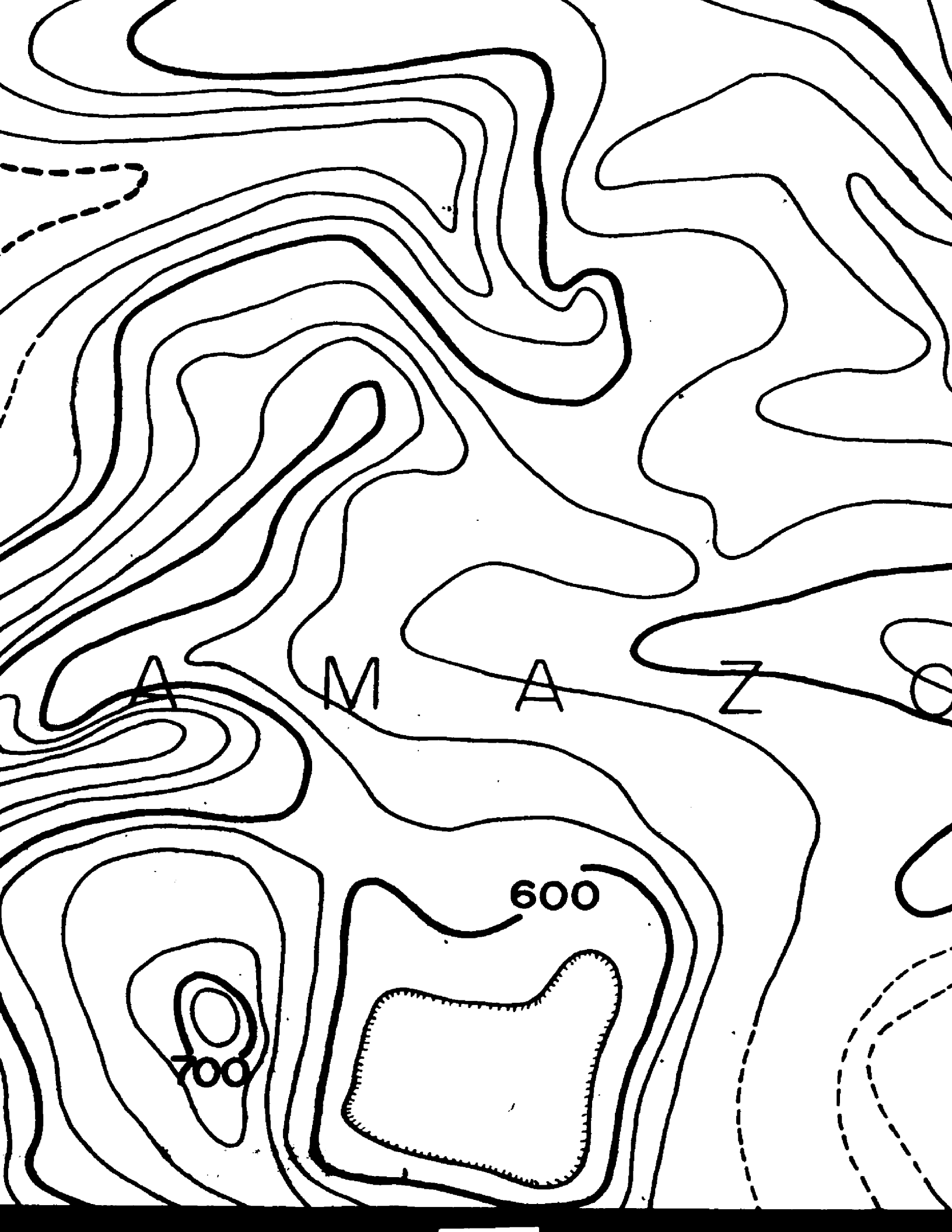


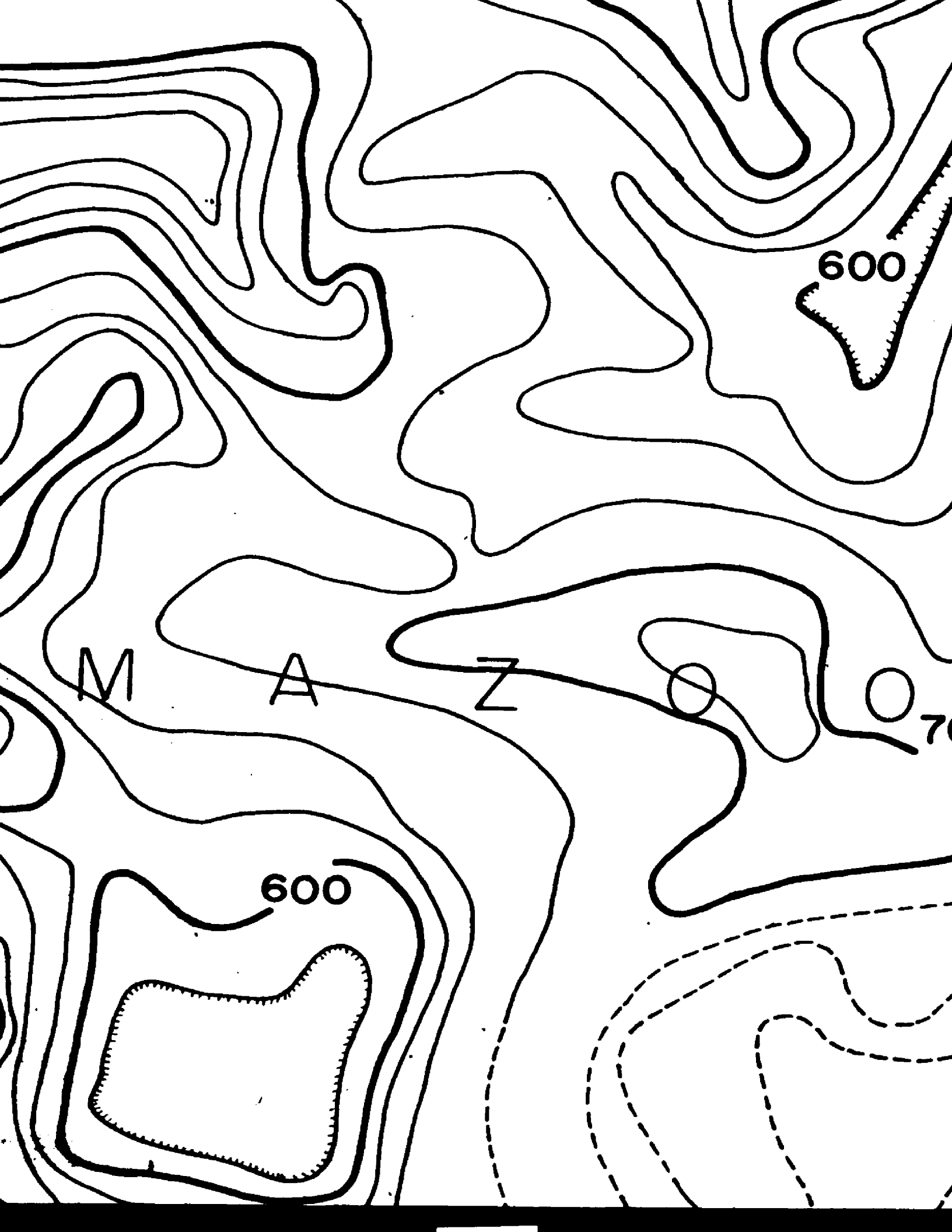






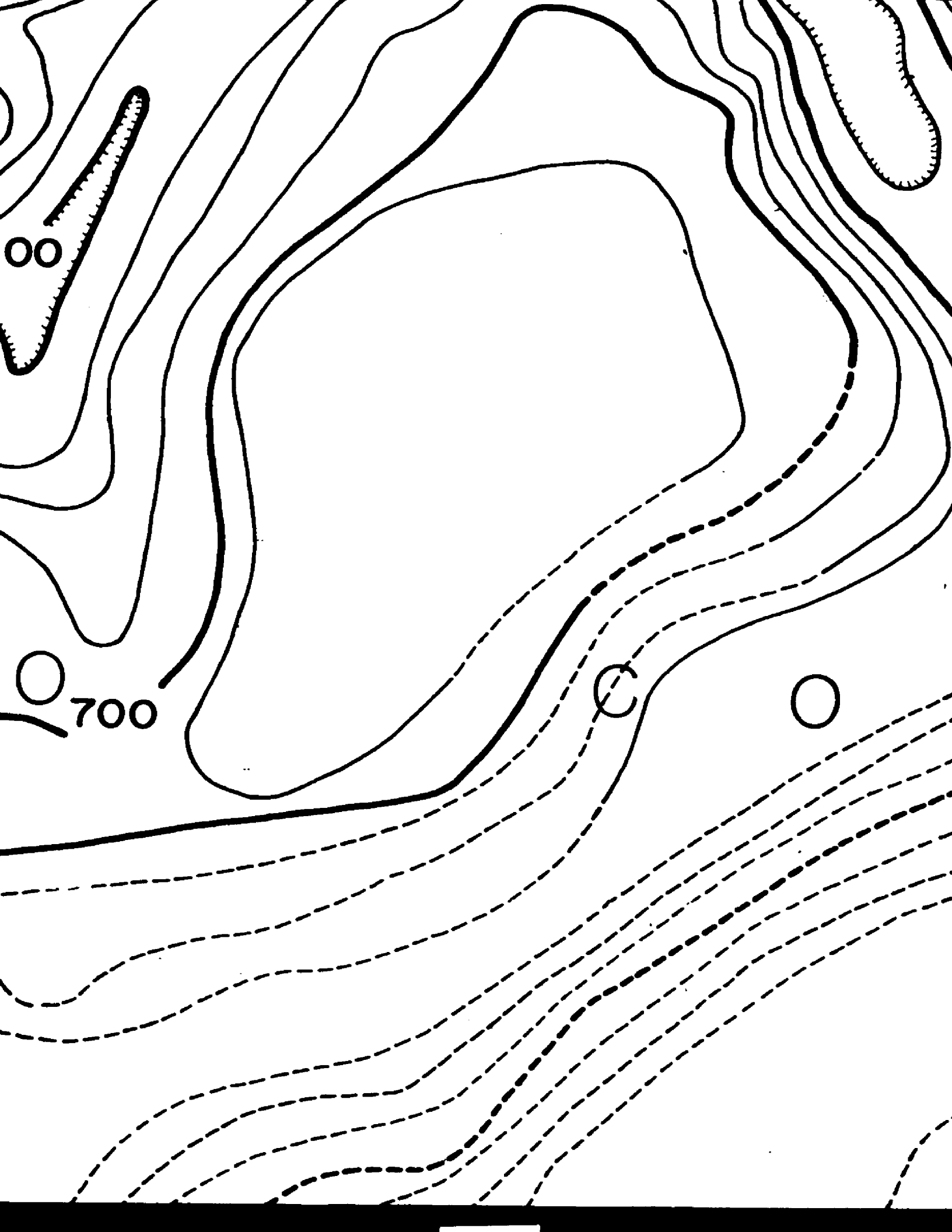


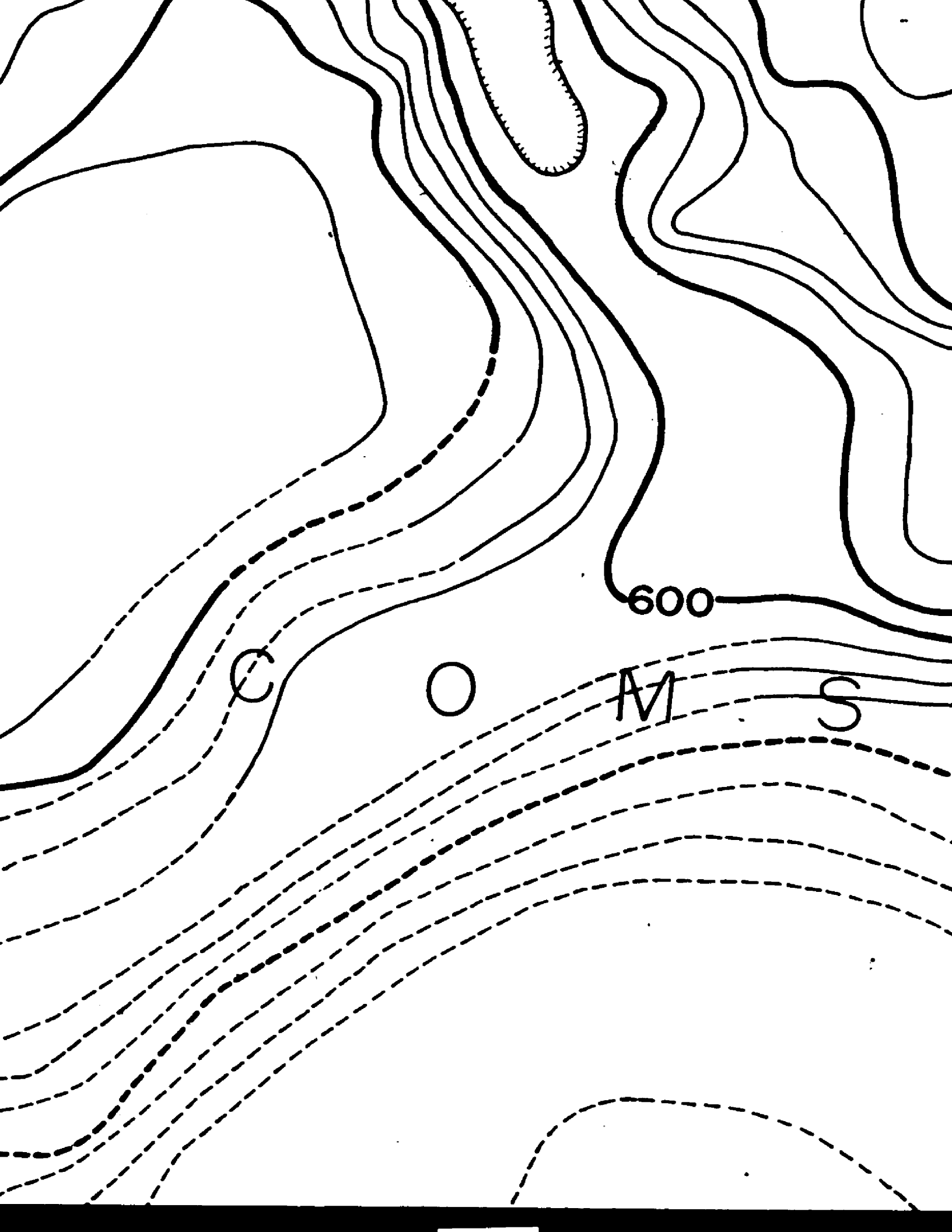


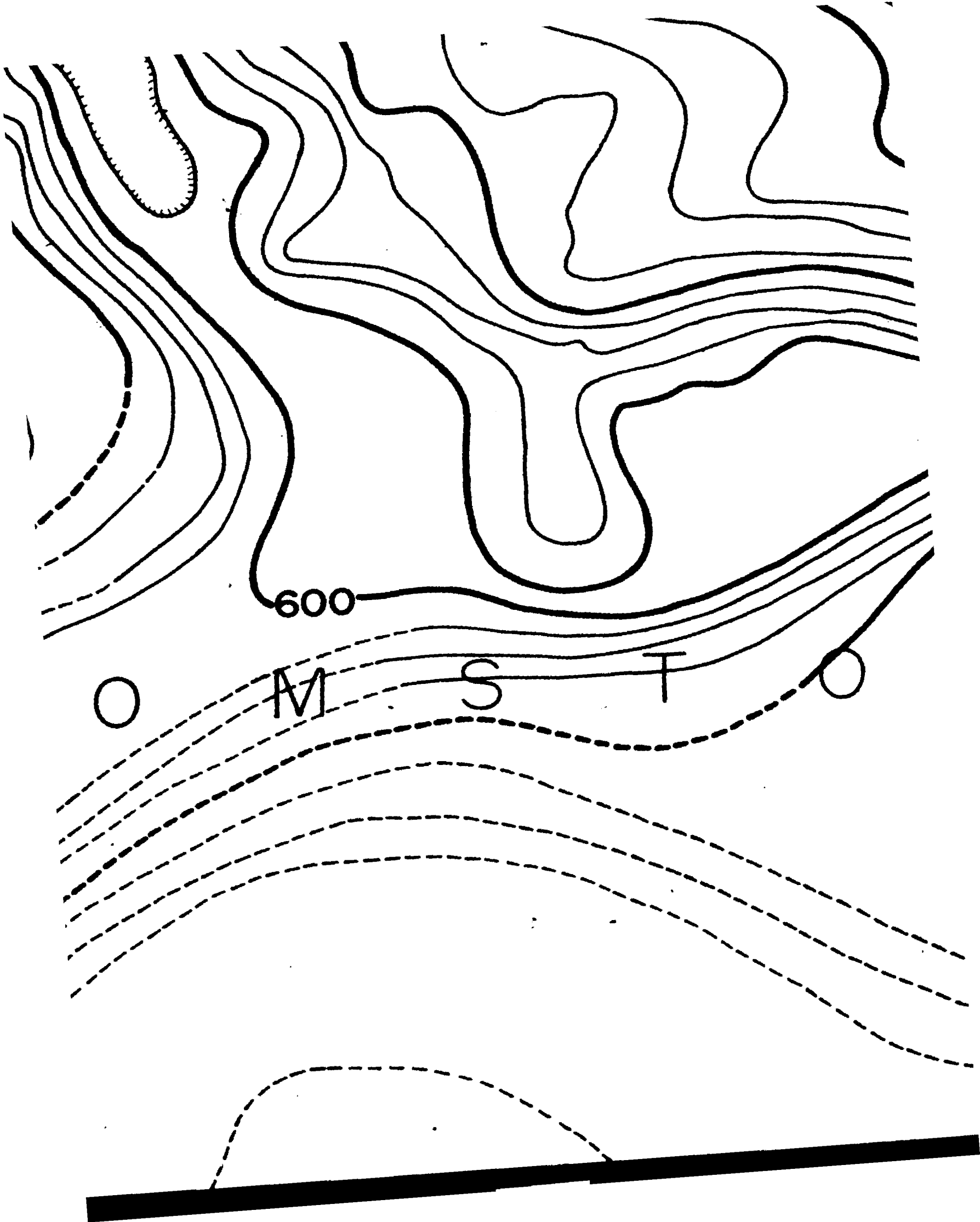


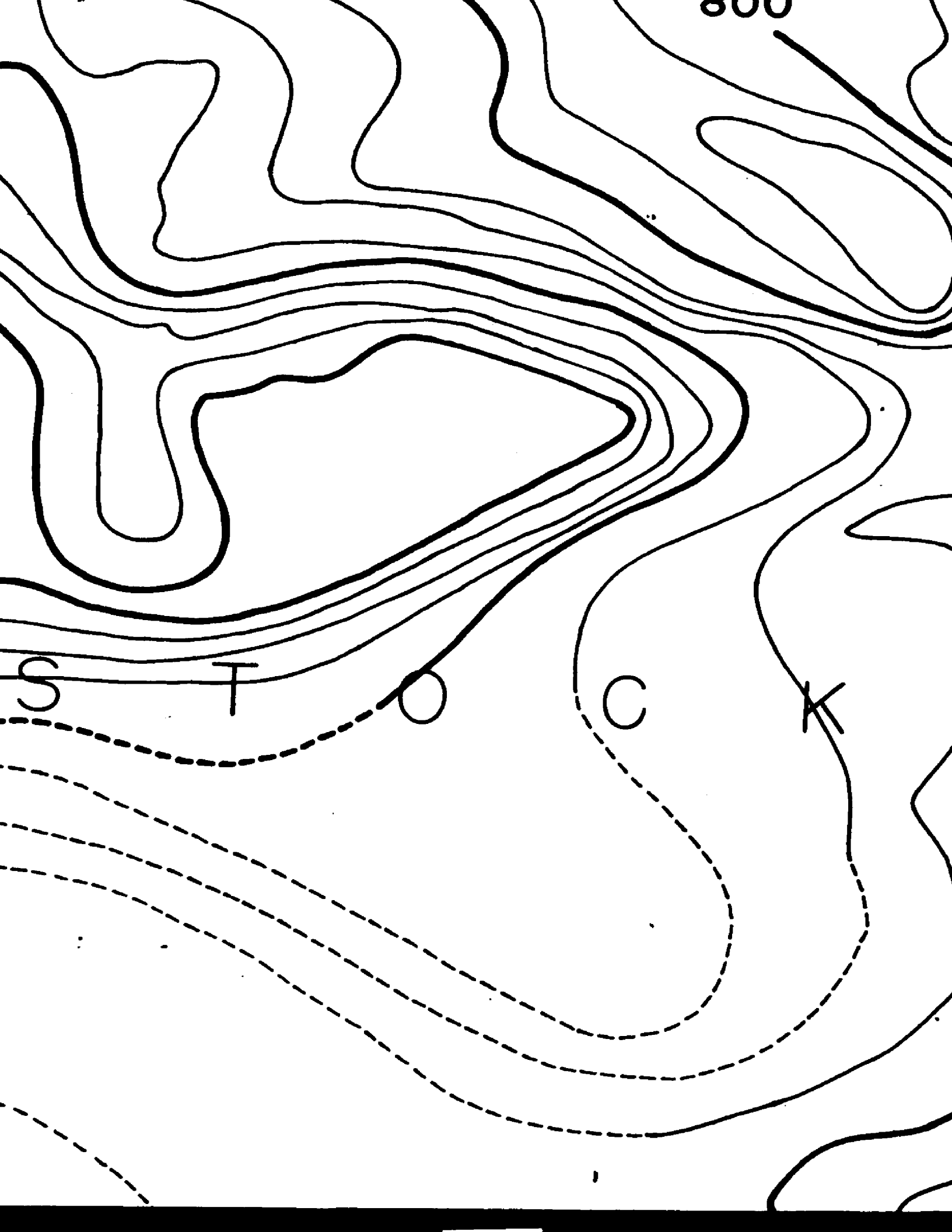


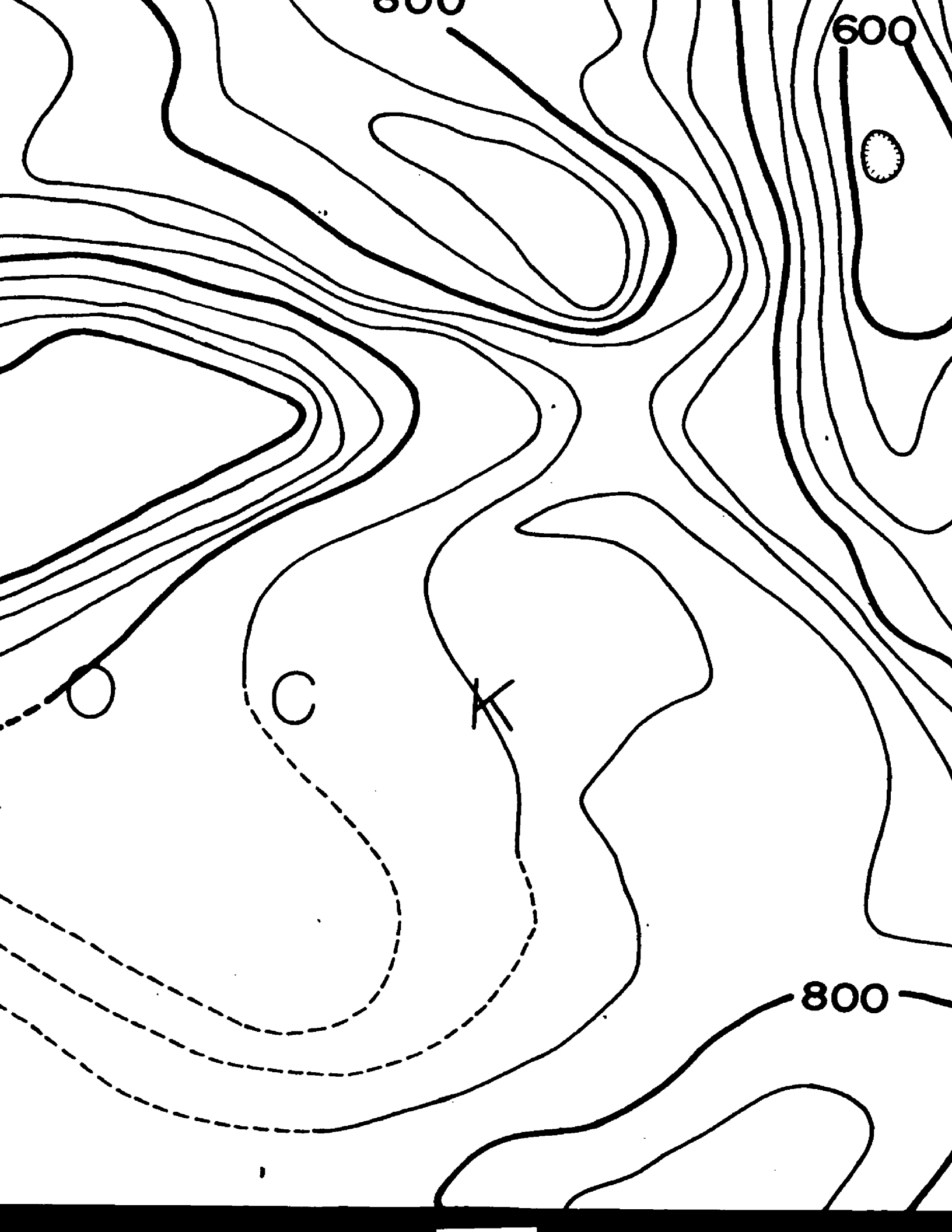


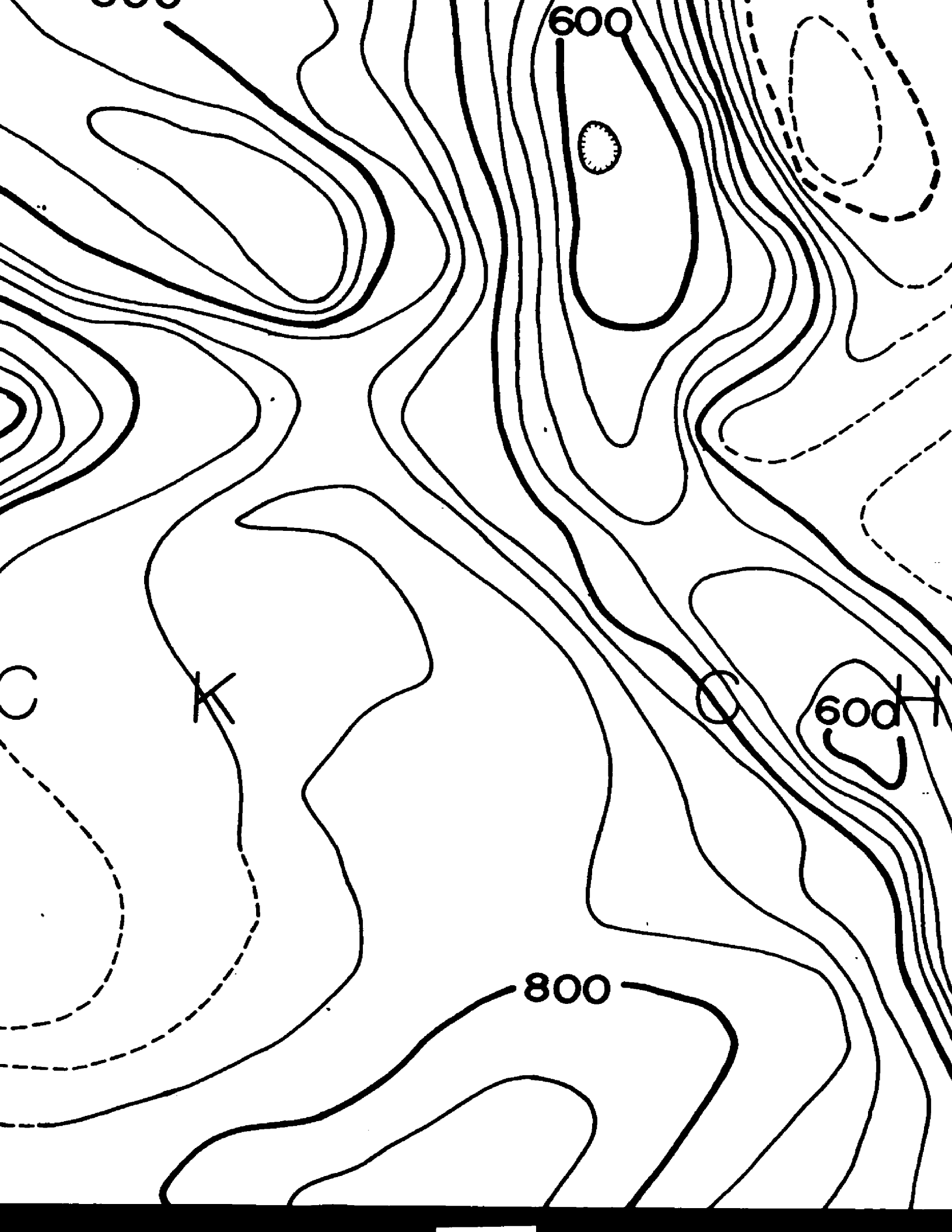


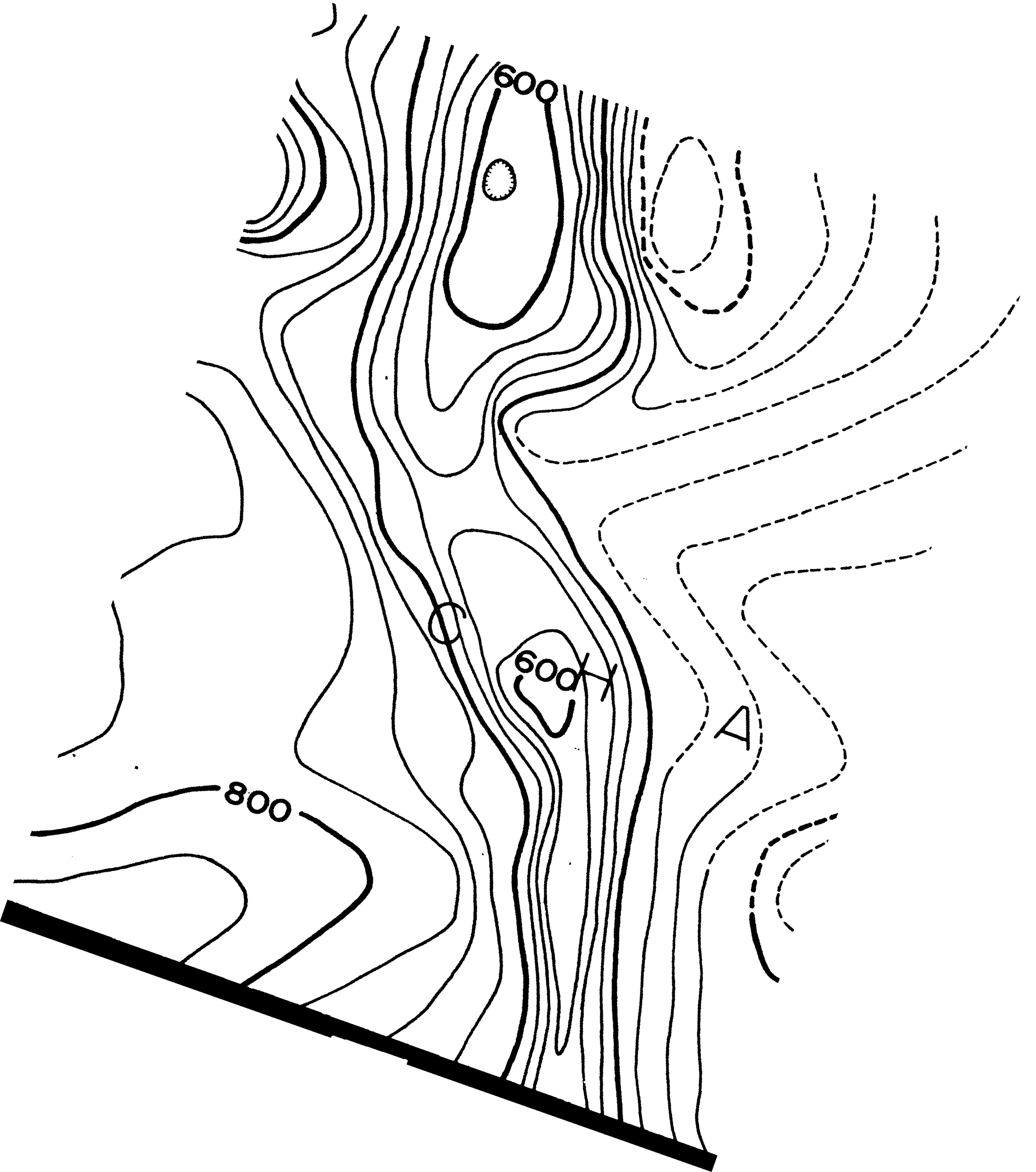




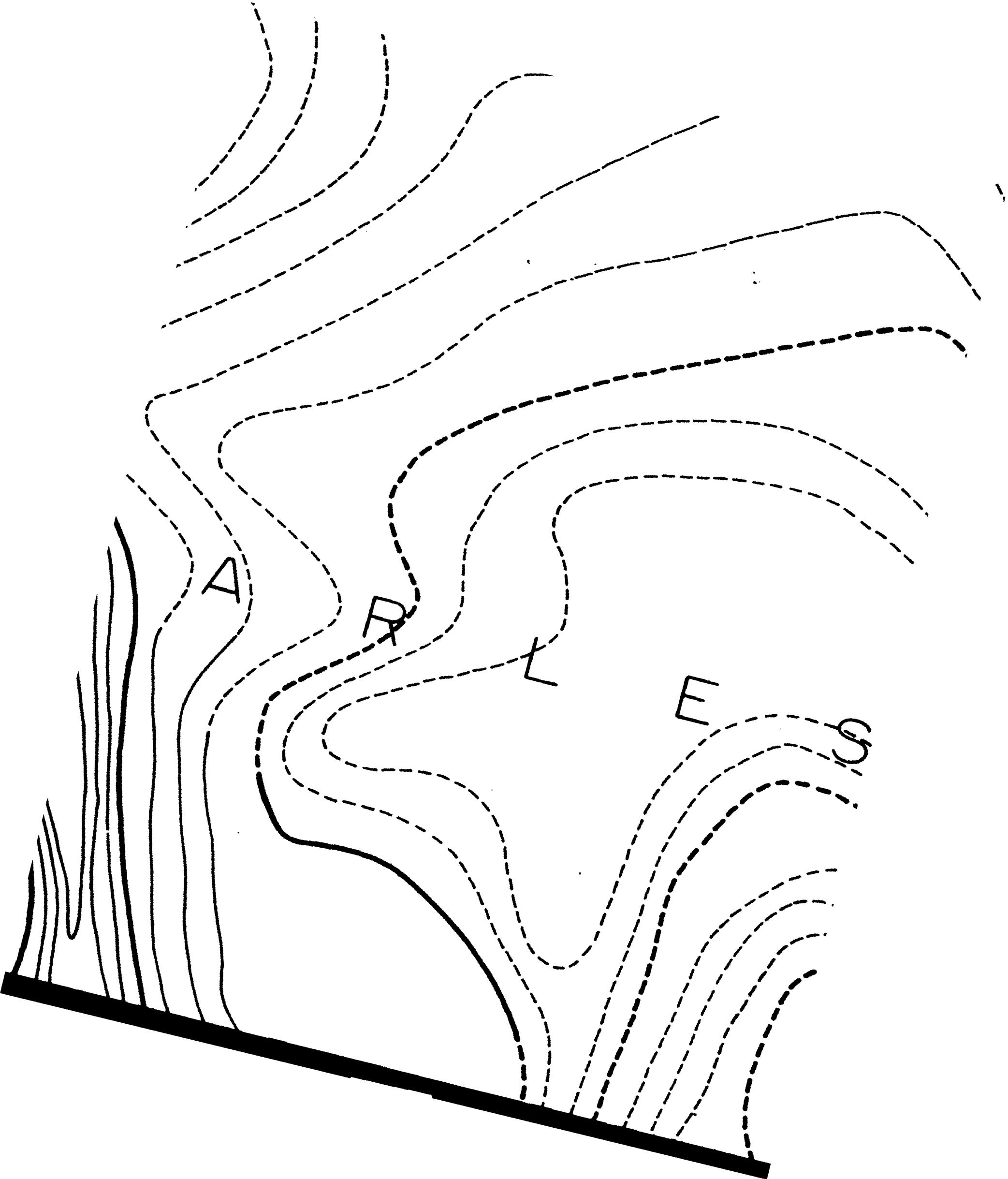


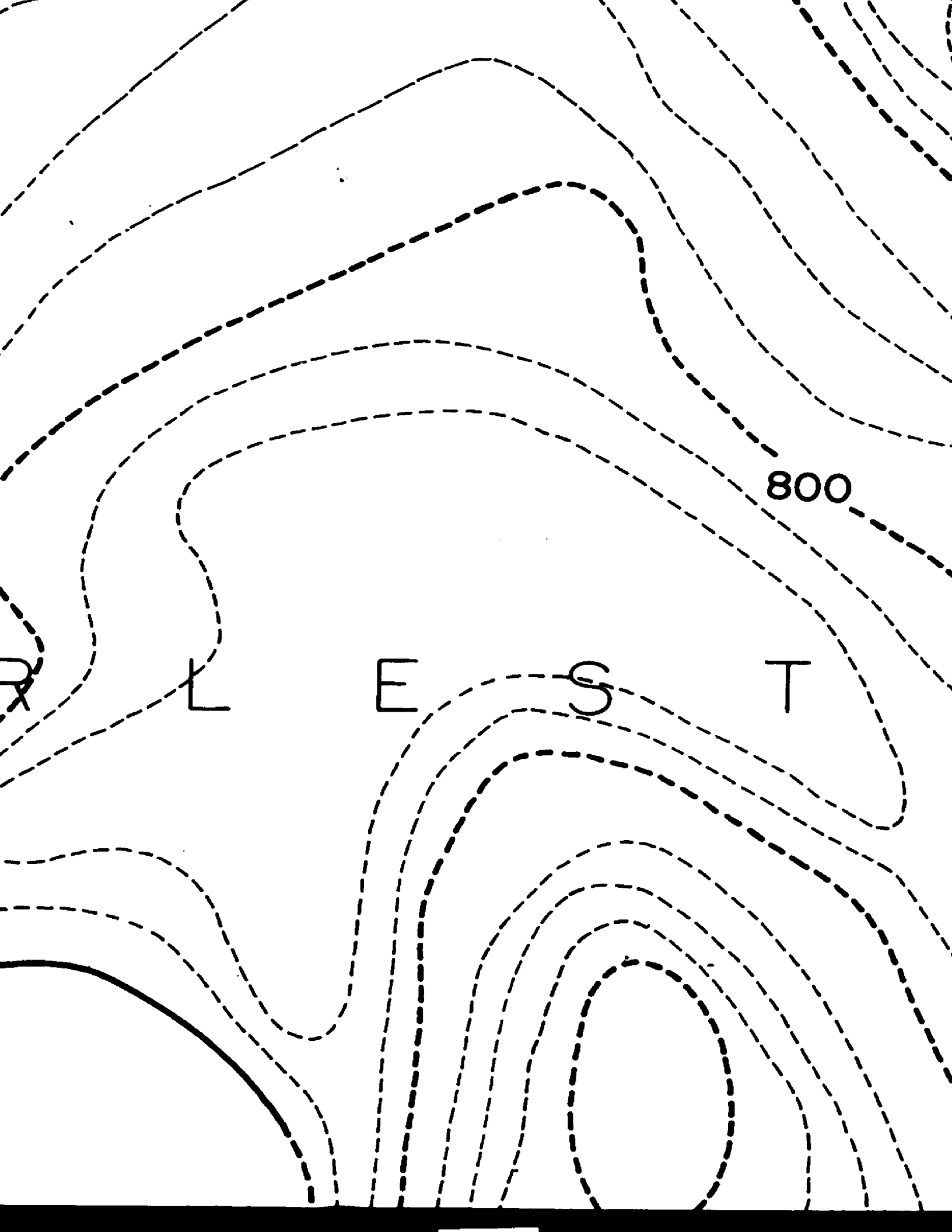


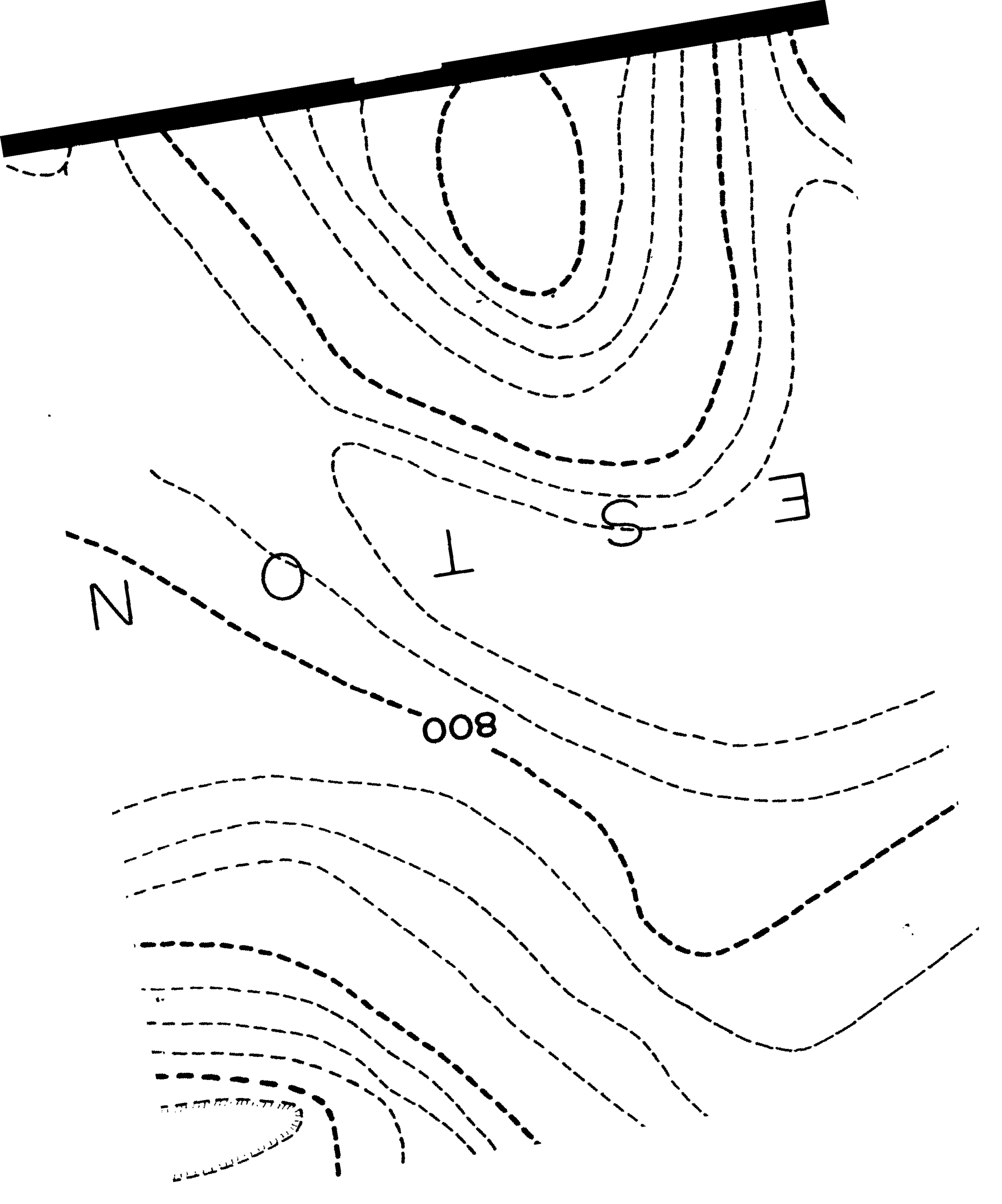


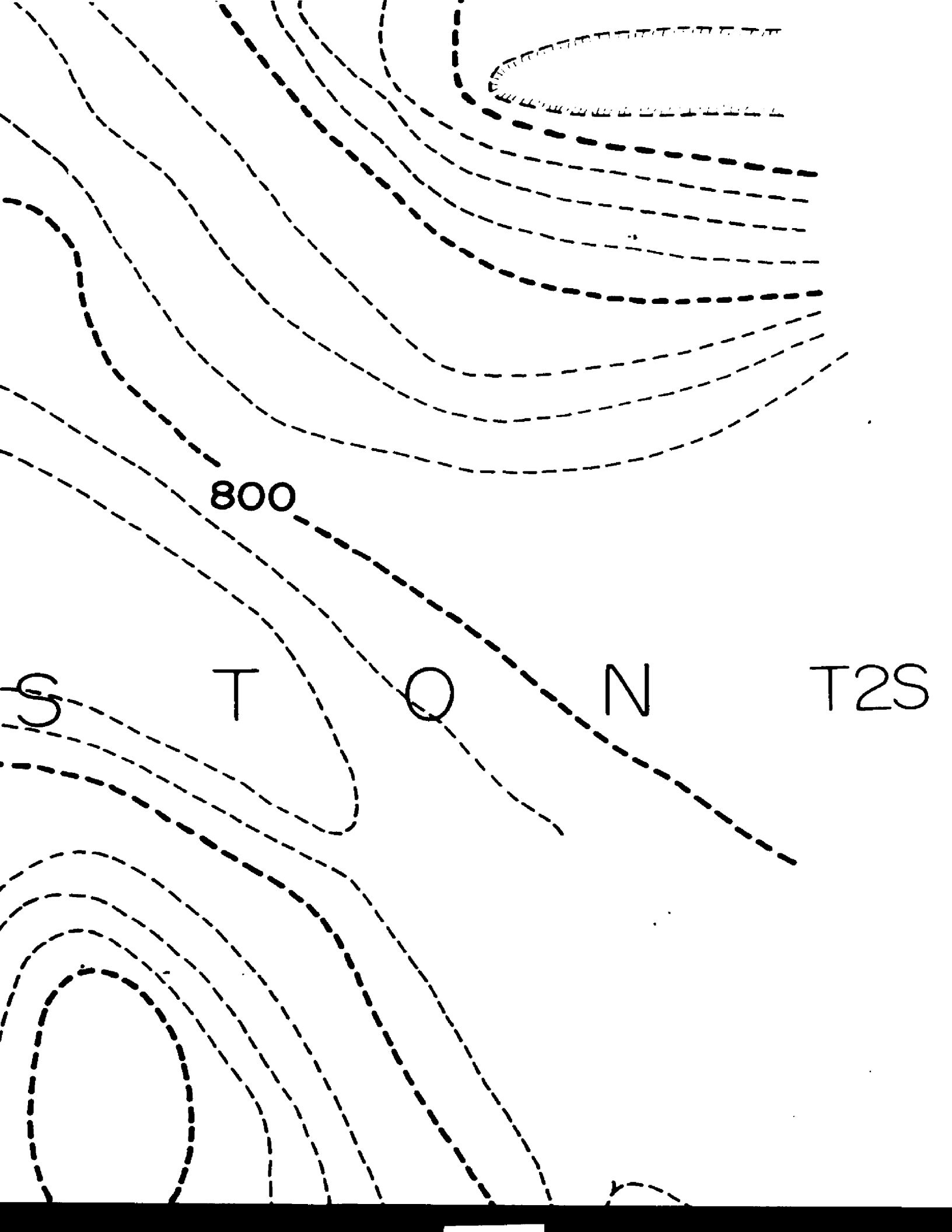












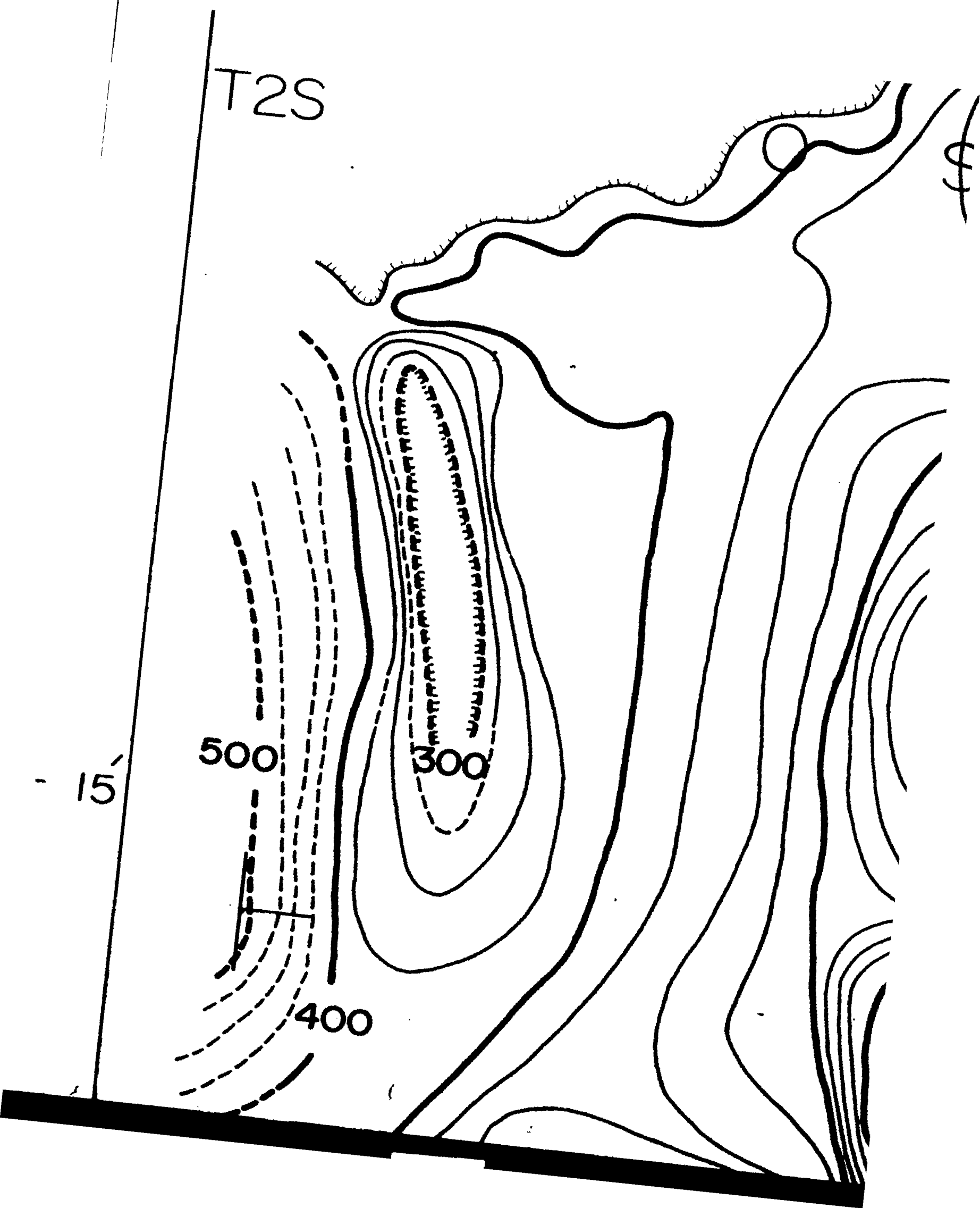
T2S

15'

500

500

400



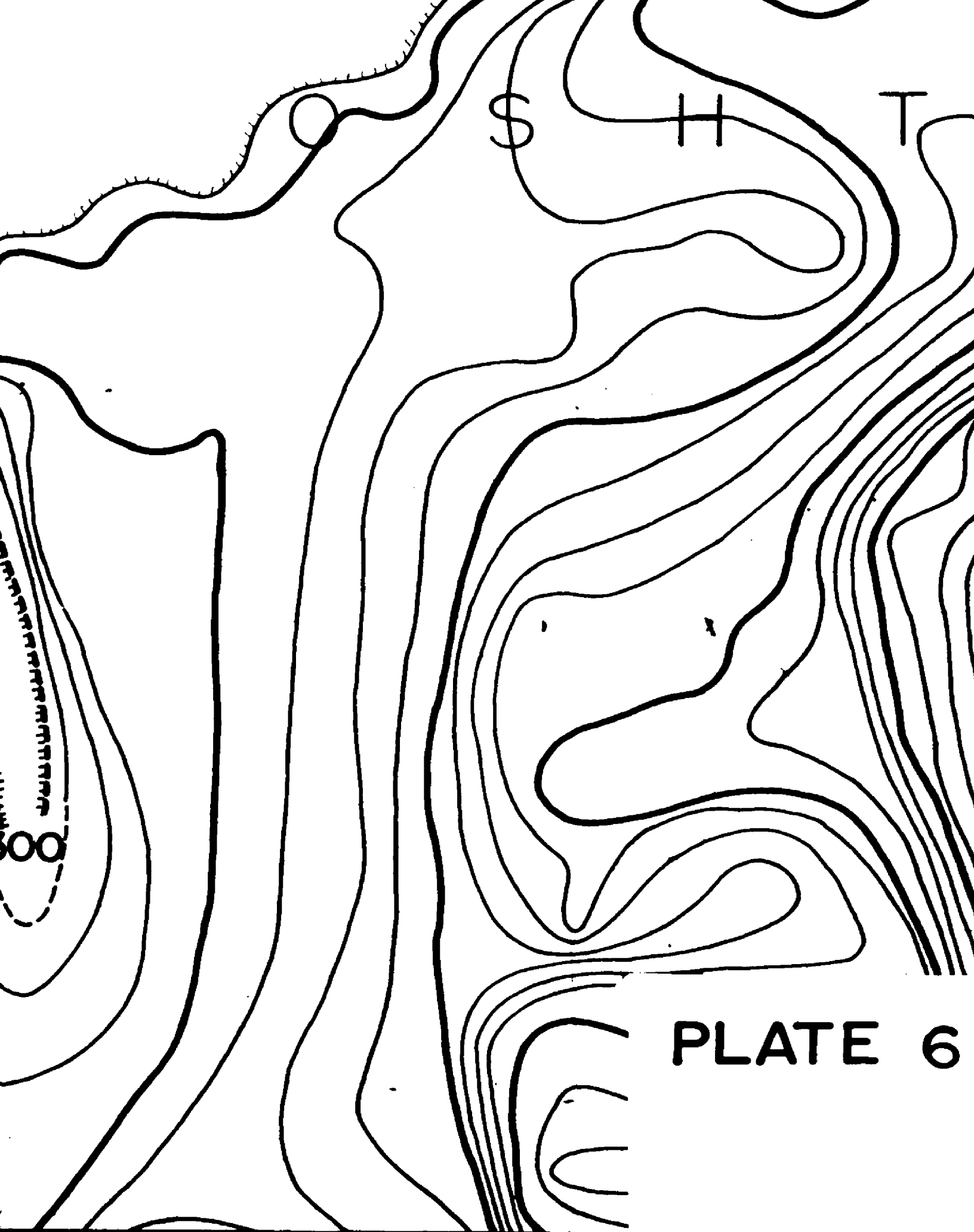


PLATE 6

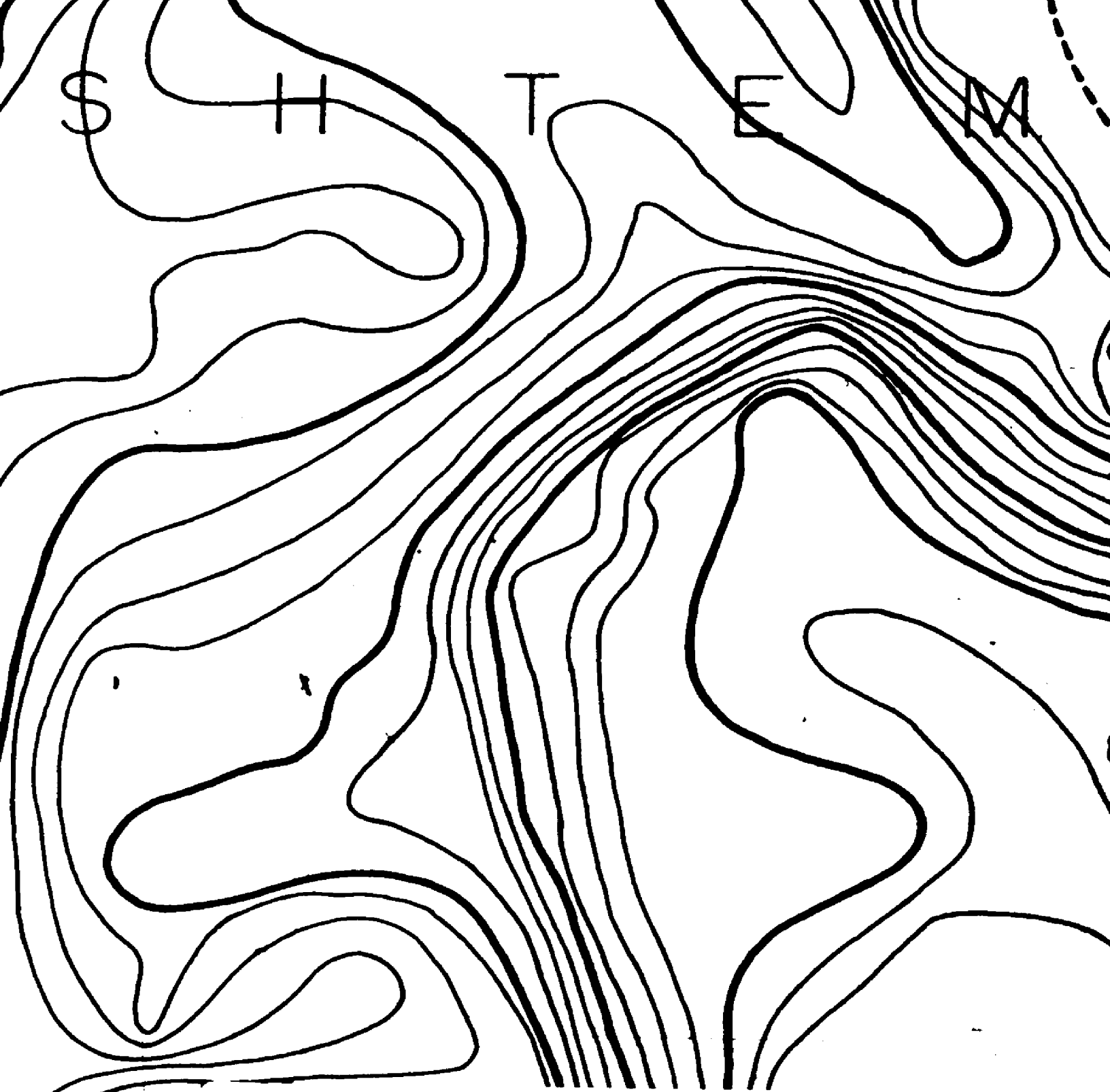
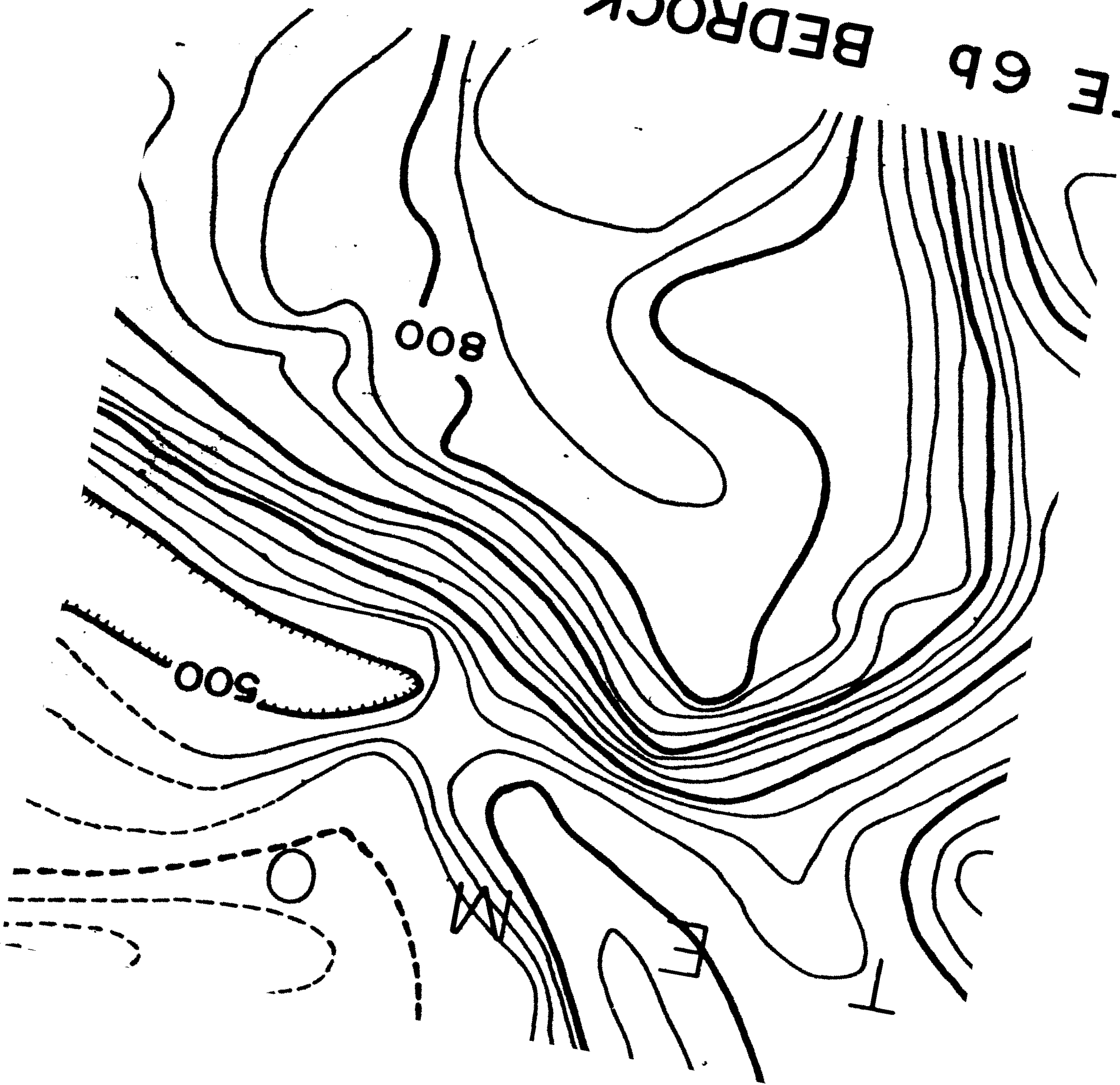
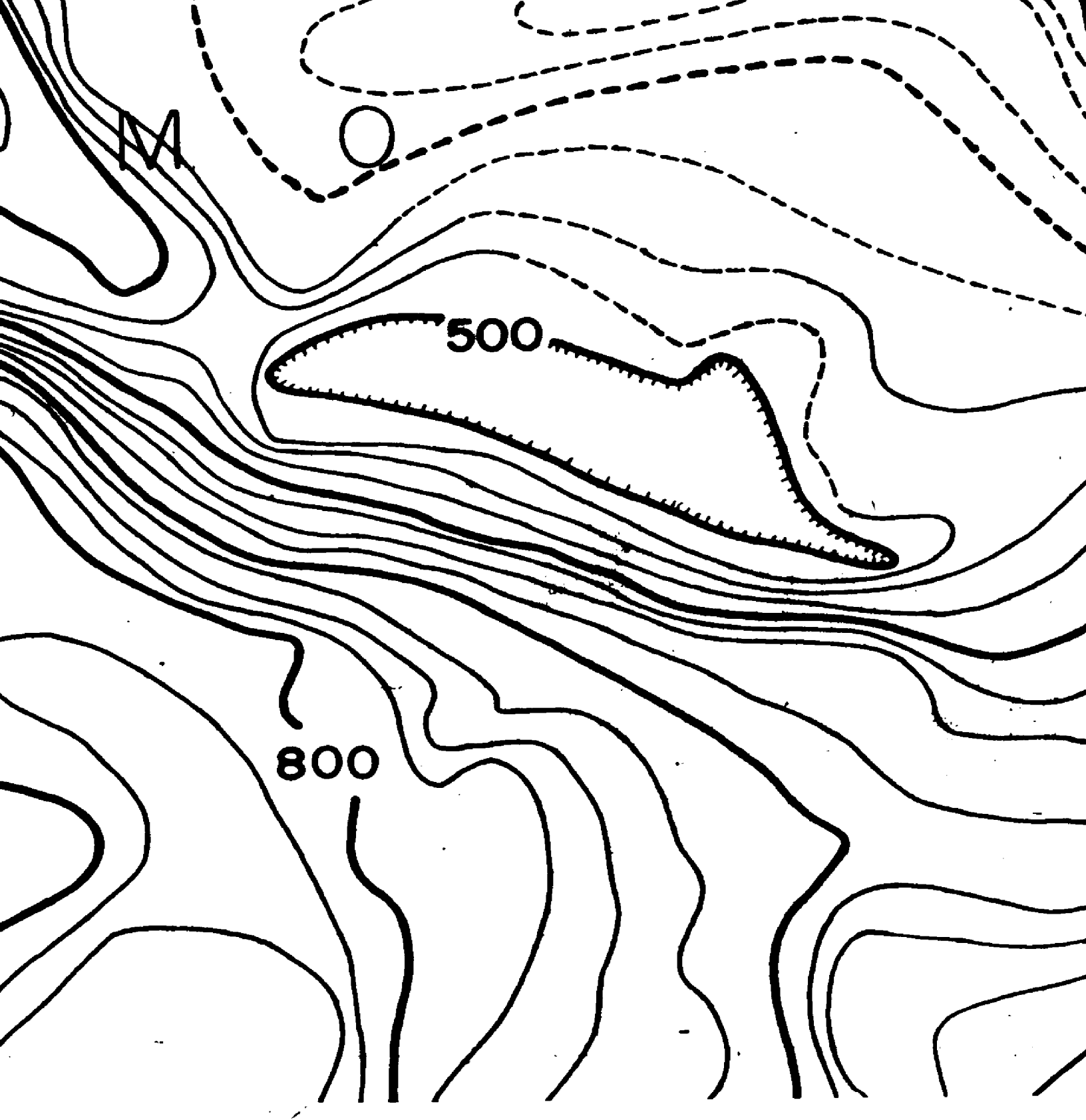


PLATE 6b BEDROCK

NORTHERN HAL

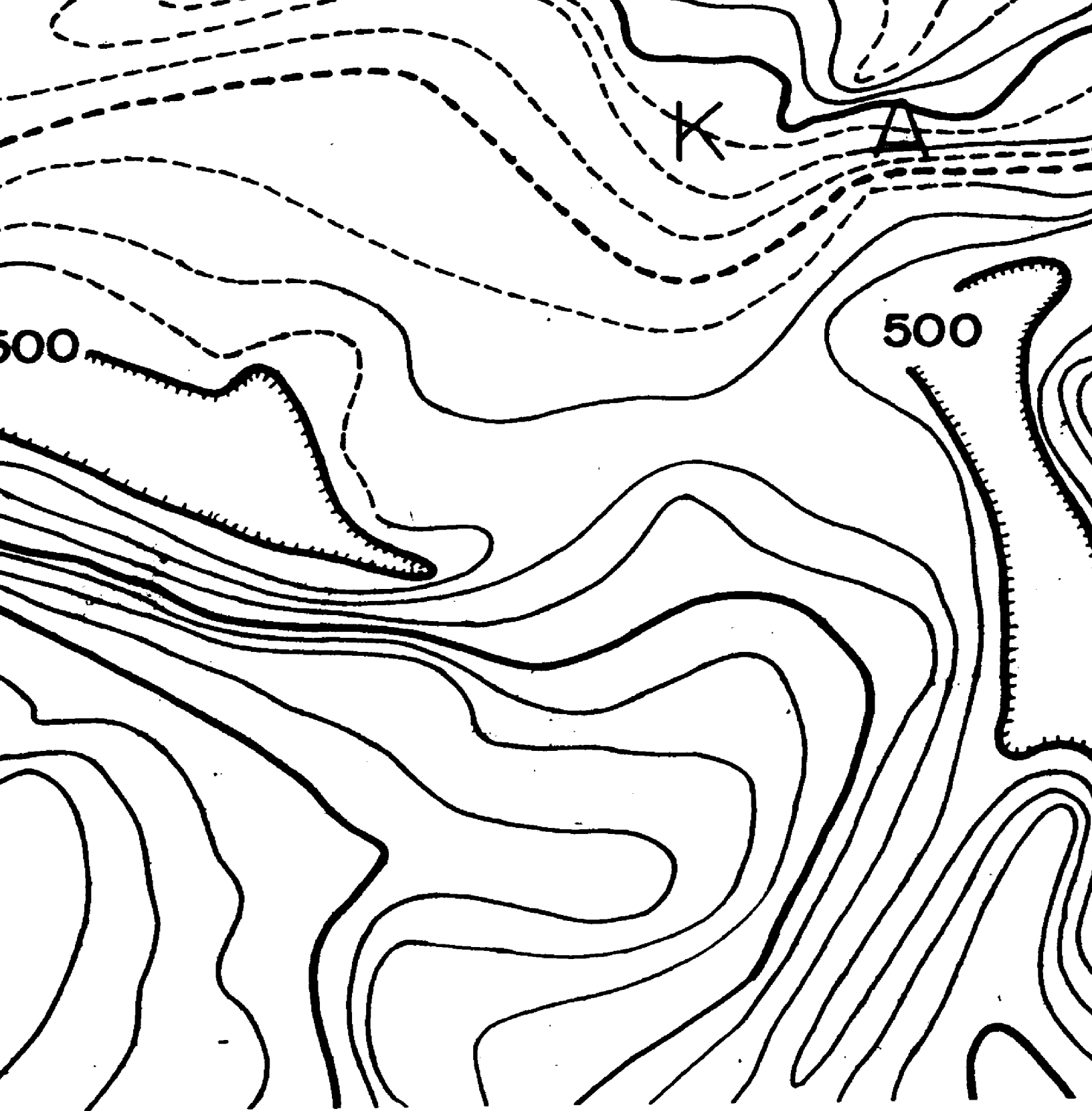
E 6b
BEDROCK
NORTHERN HALF
TOPOGRAPH





EDROCK TOPOGRAPHY

THERN HALF

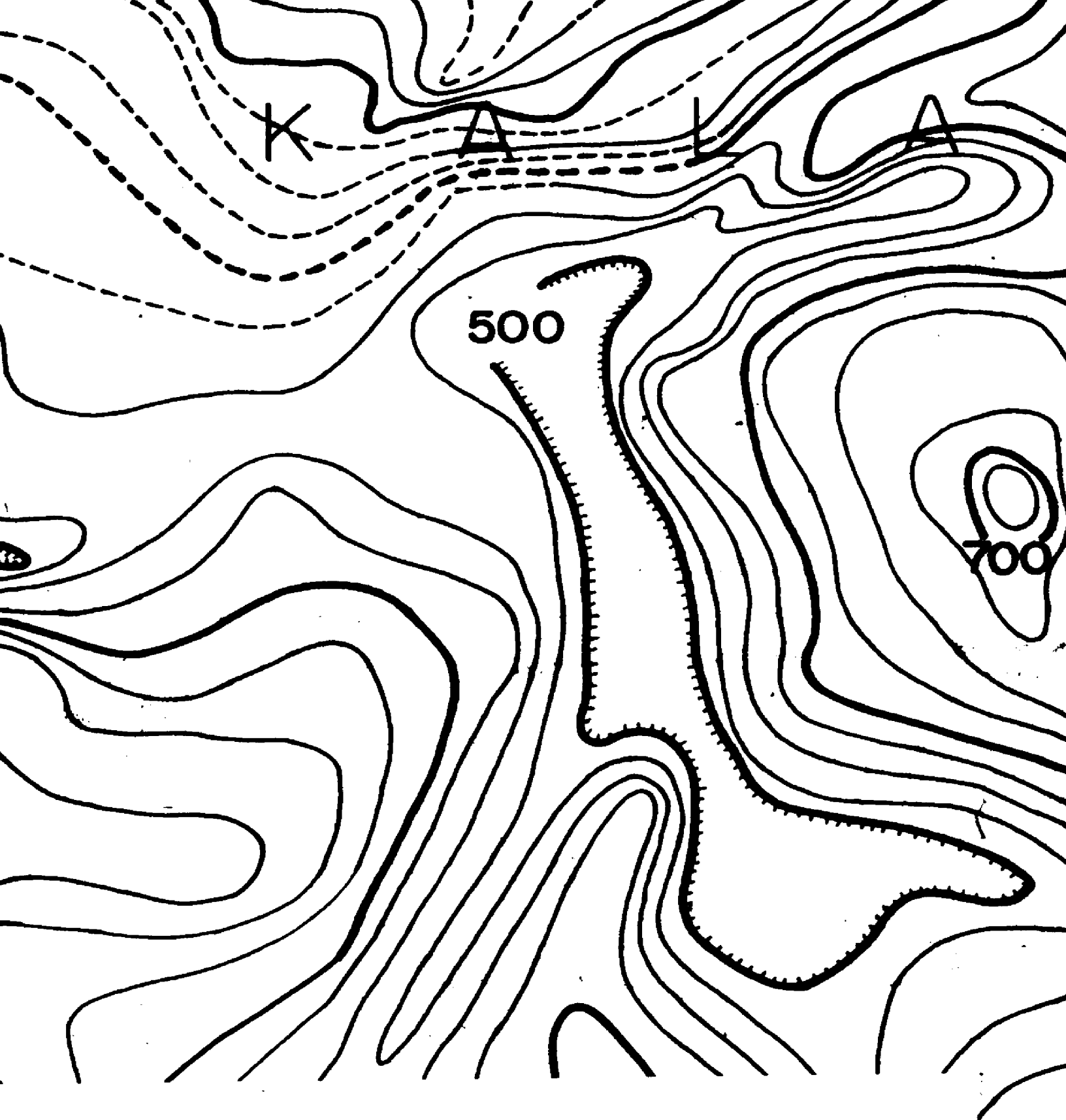


TOPOGRAPHY

CONTOUR INTERVAL

DATUM SEA LEVEL

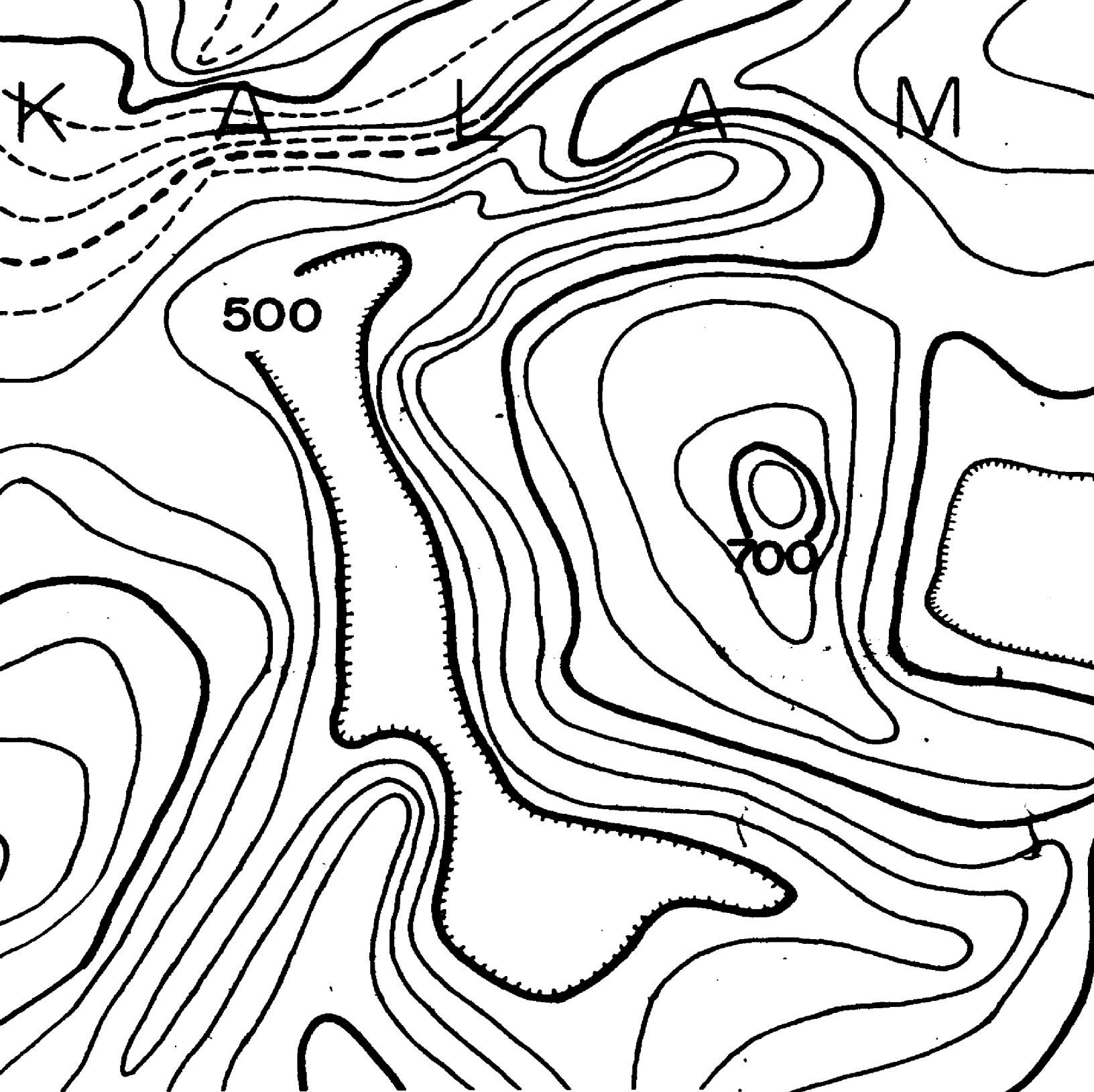
SCALE 1 : 240



CONTOUR INTERVAL 25 FEET

DATUM SEA LEVEL

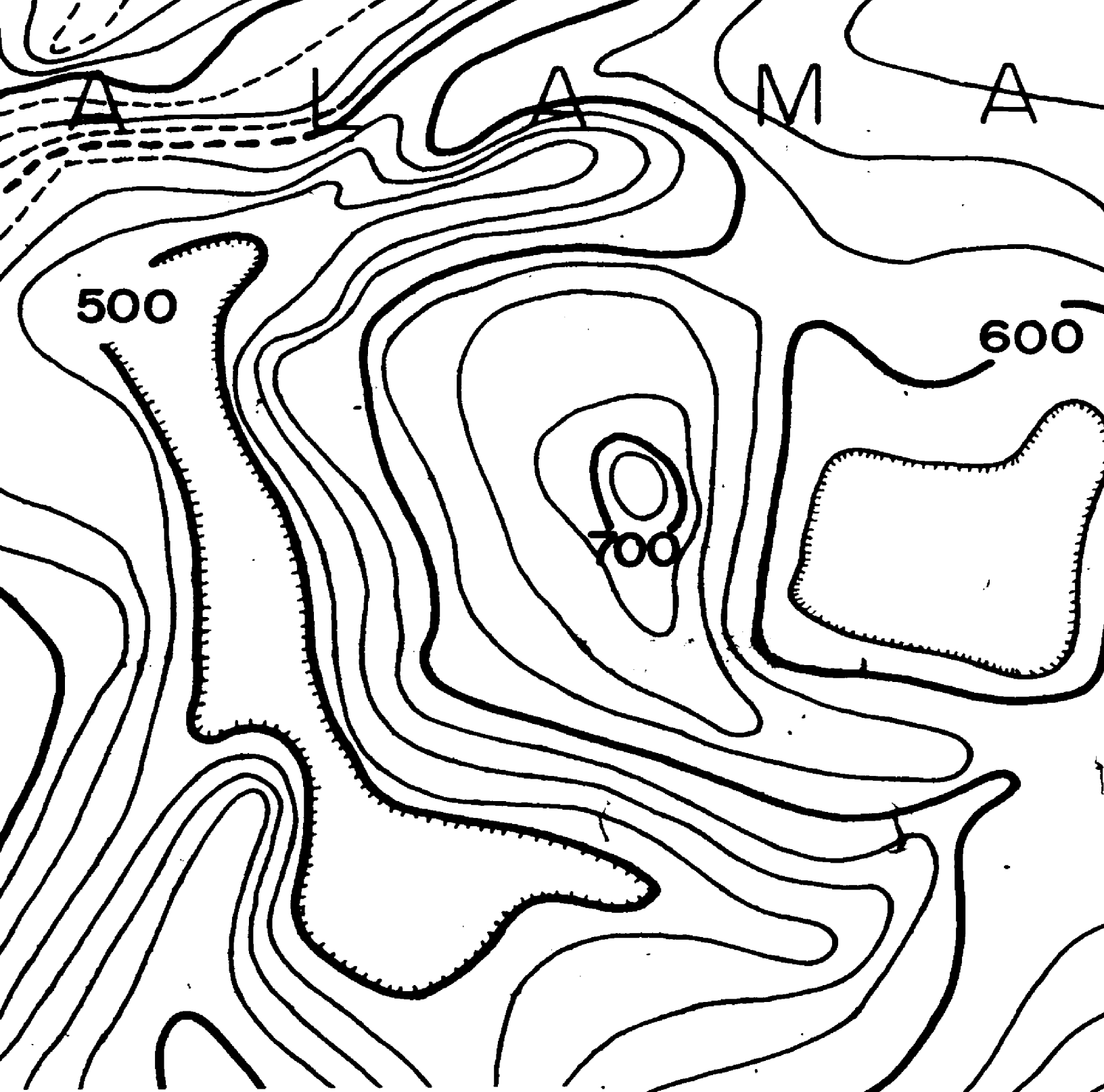
SCALE 1 : 24000



CONTOUR INTERVAL 25 FEET

DATUM SEA LEVEL

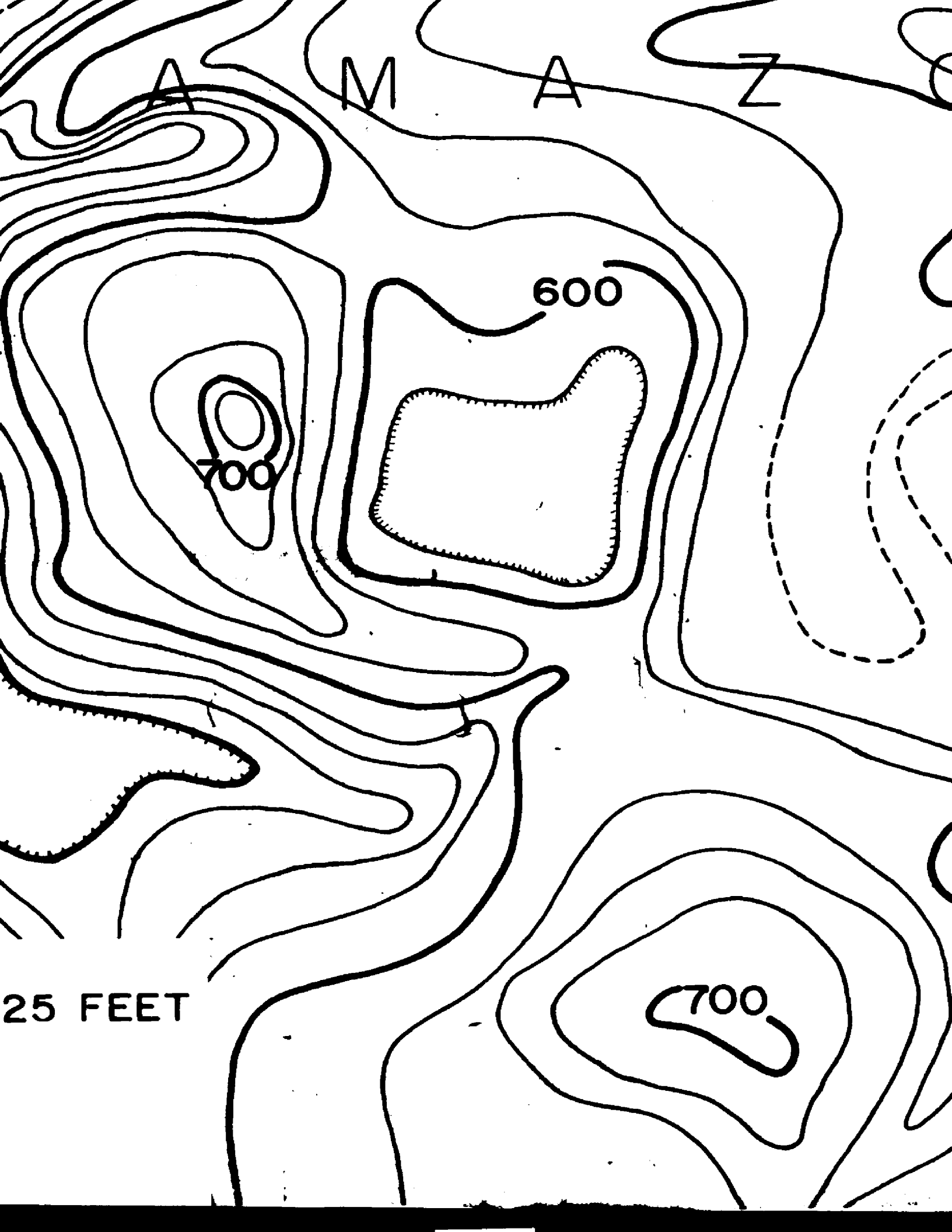
SCALE 1 : 24000



R INTERVAL 25 FEET

UM SEA LEVEL

1 : 24000



A

M

A

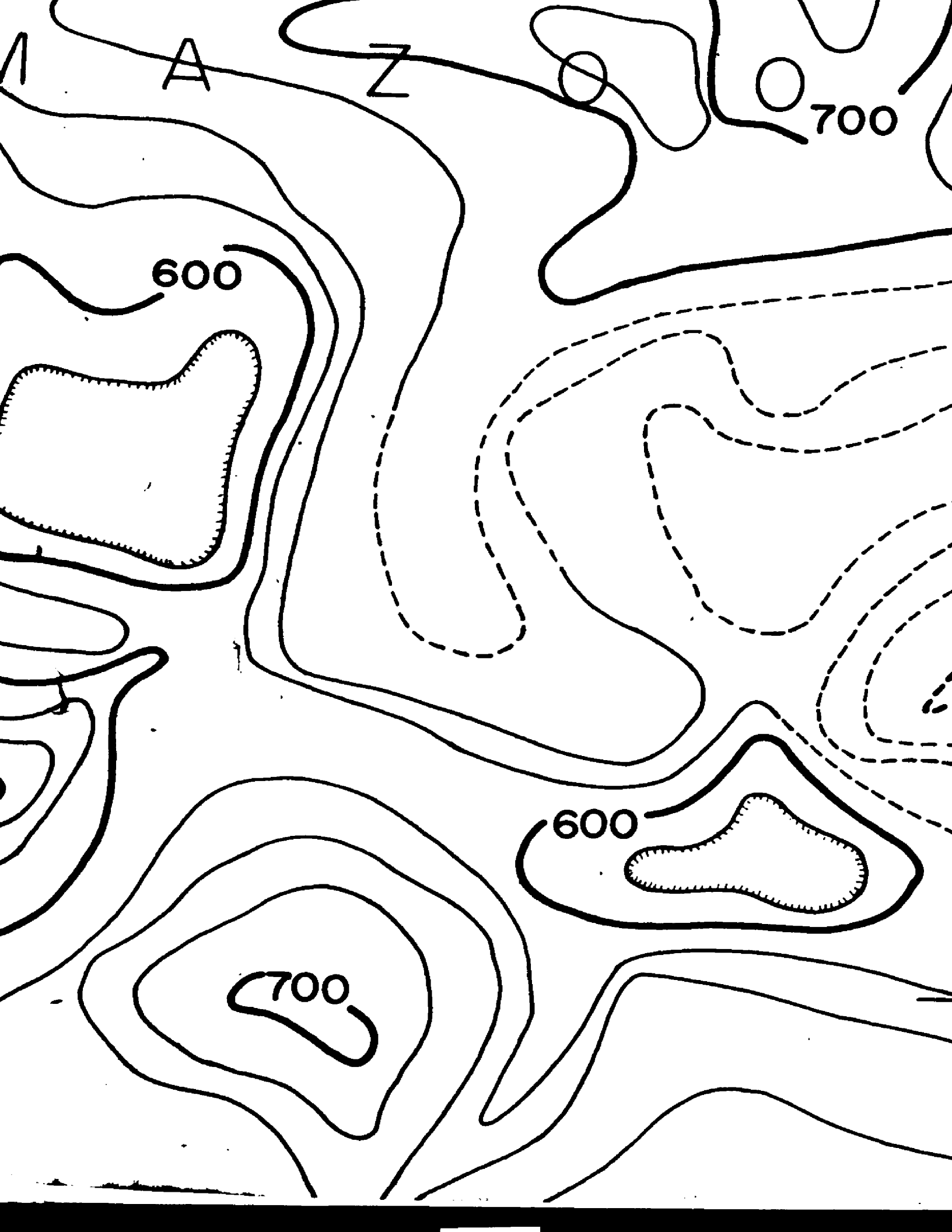
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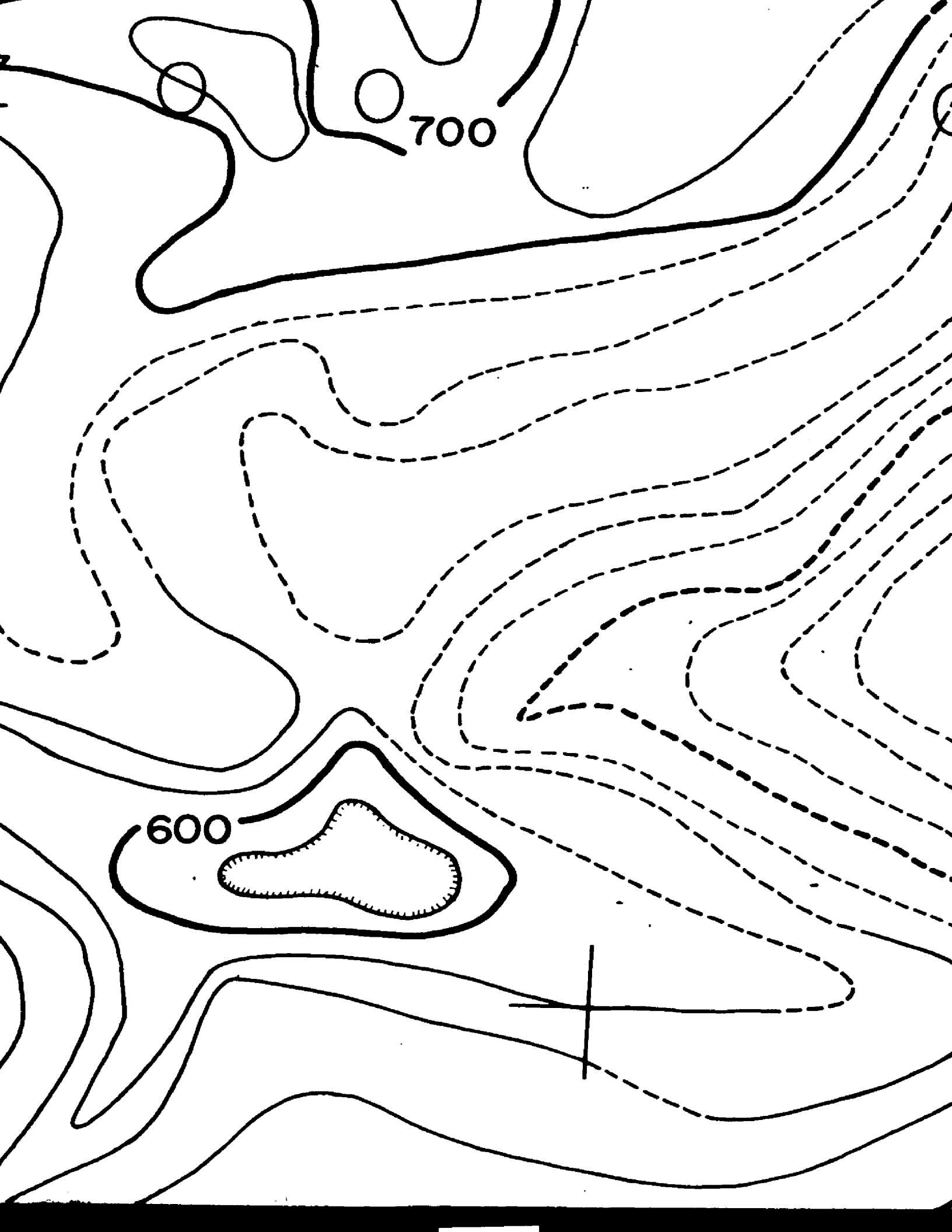
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700

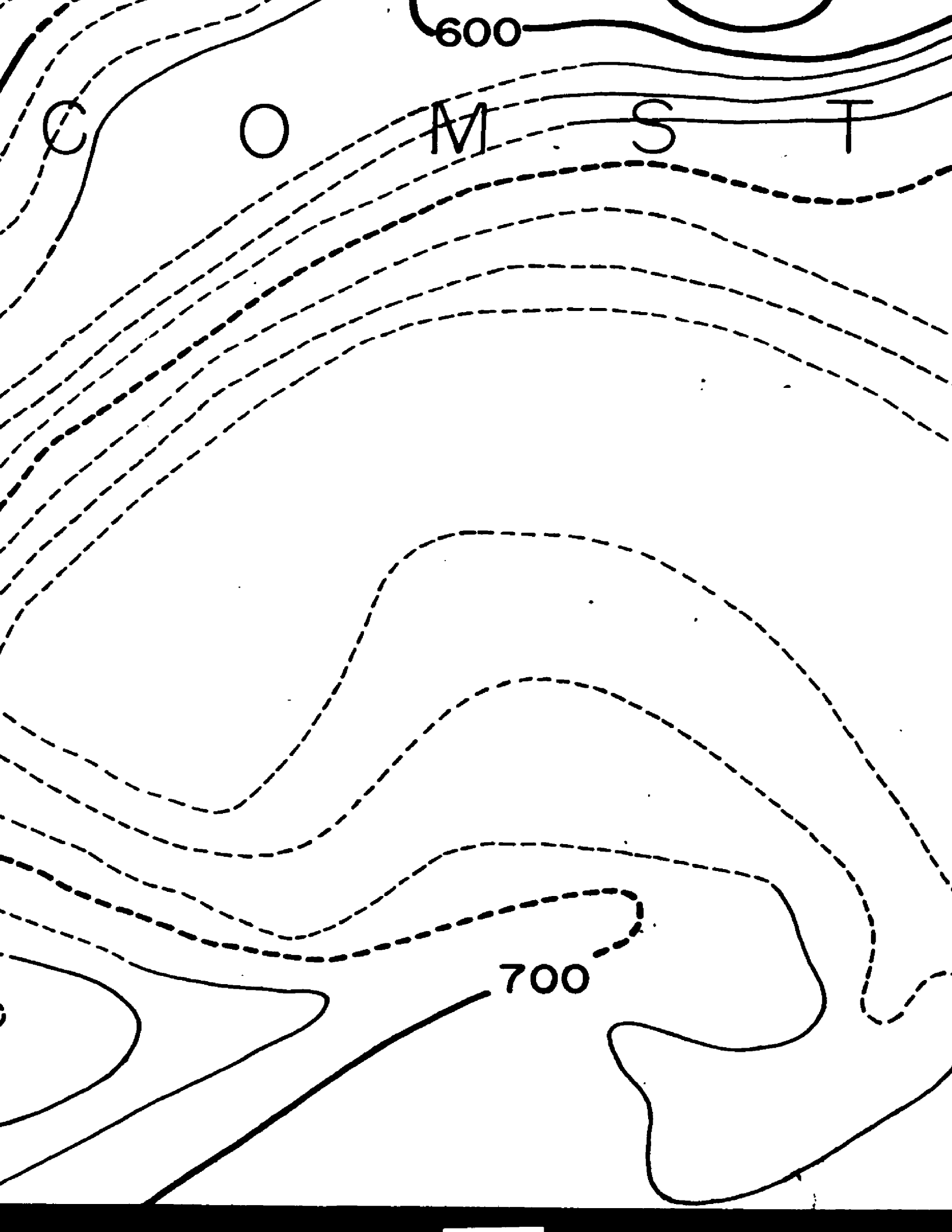
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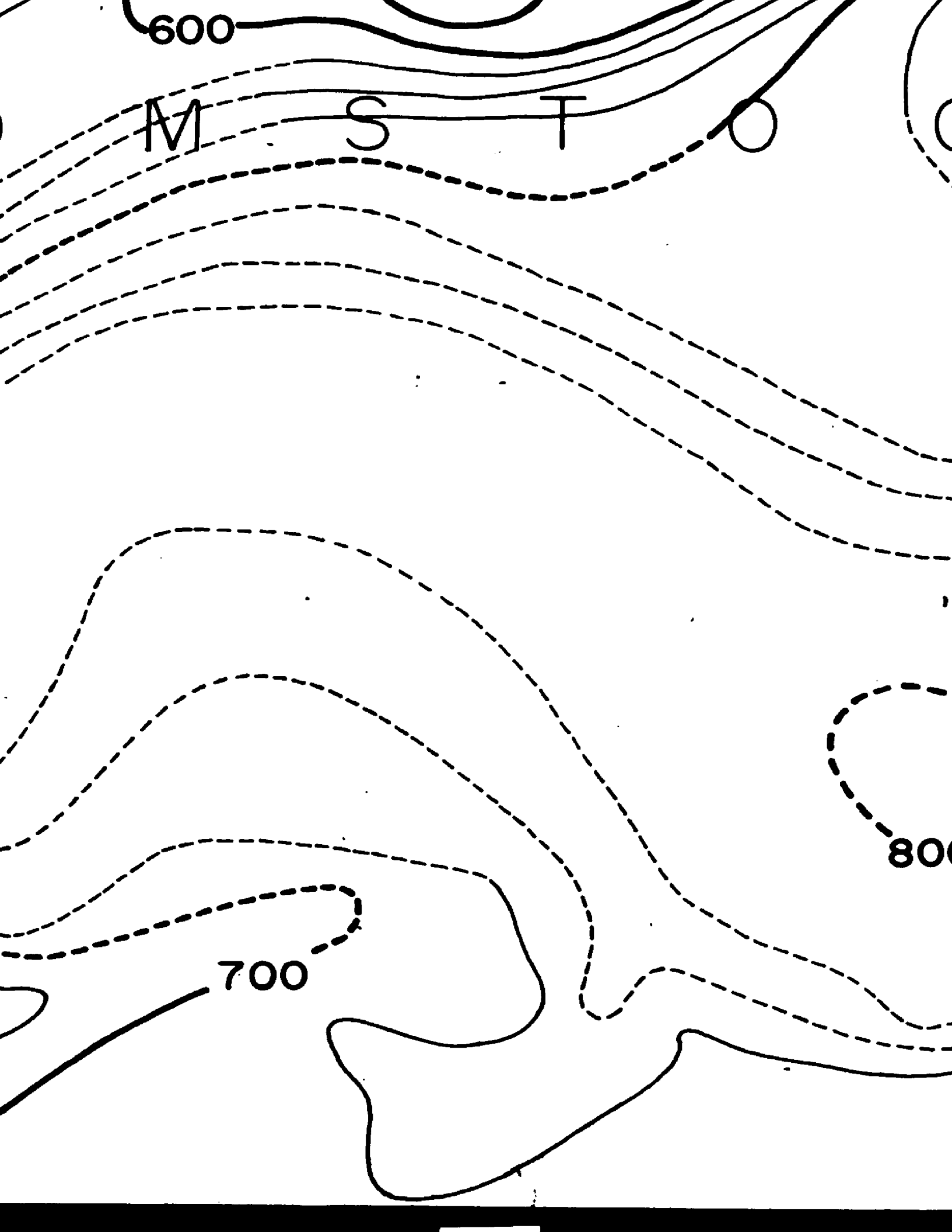
25 FEET











600

M

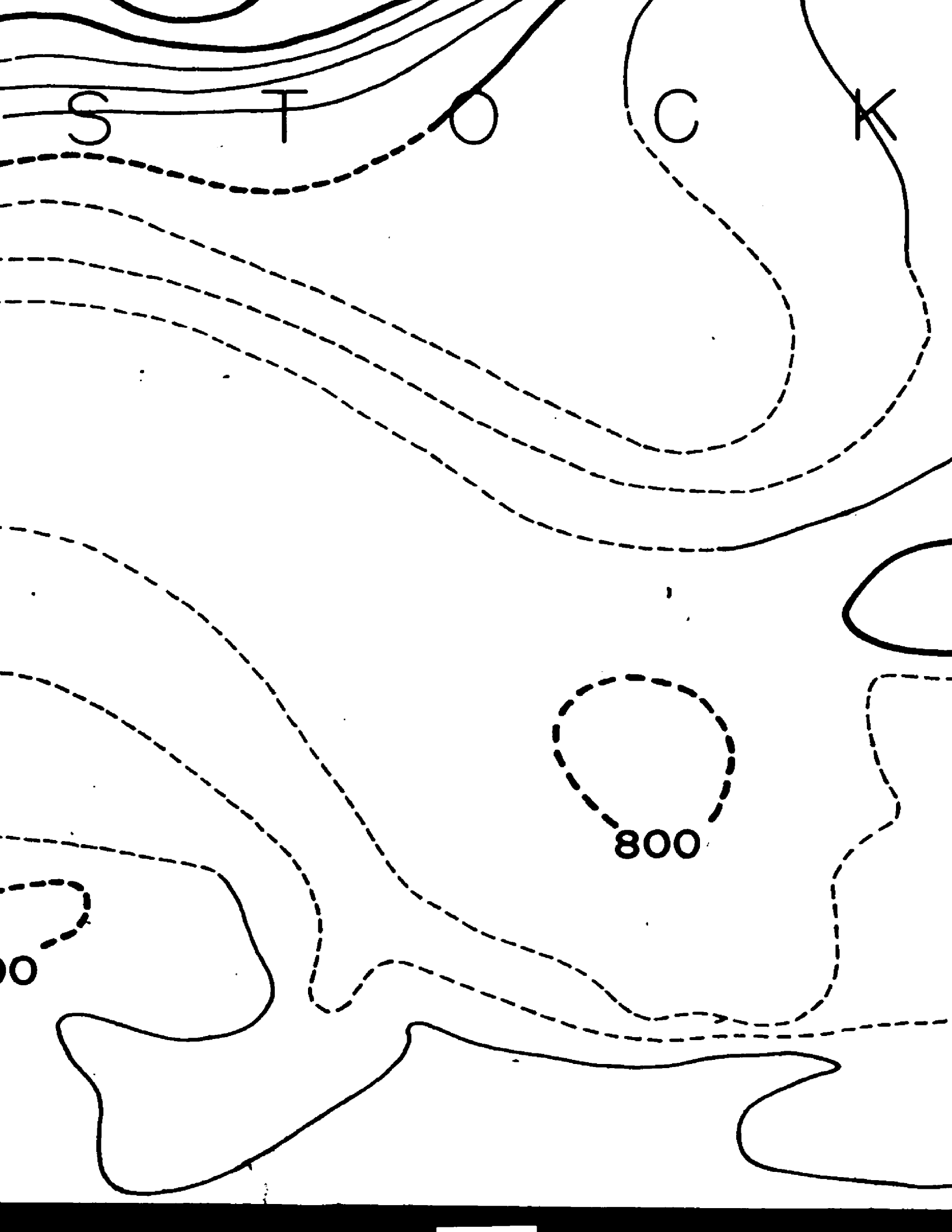
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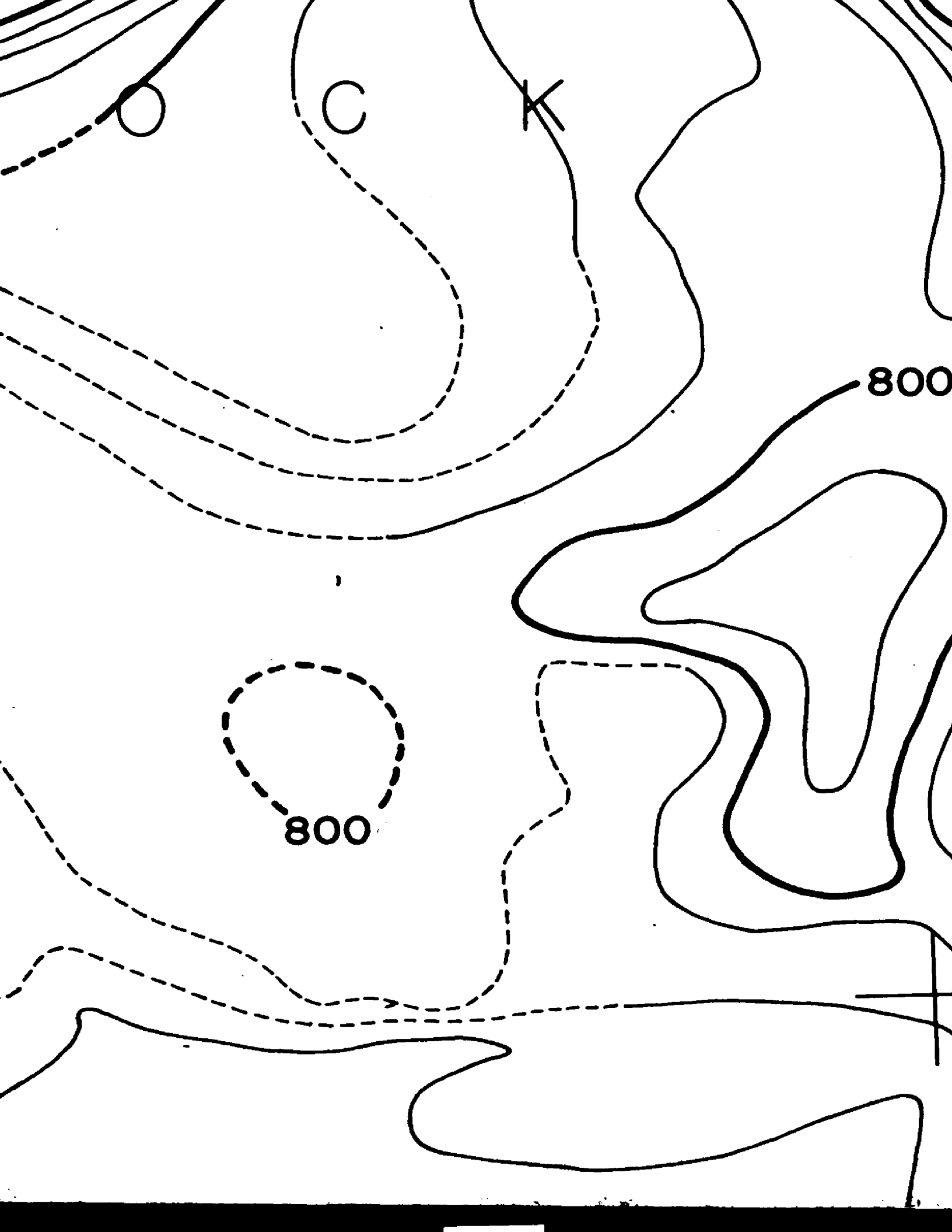
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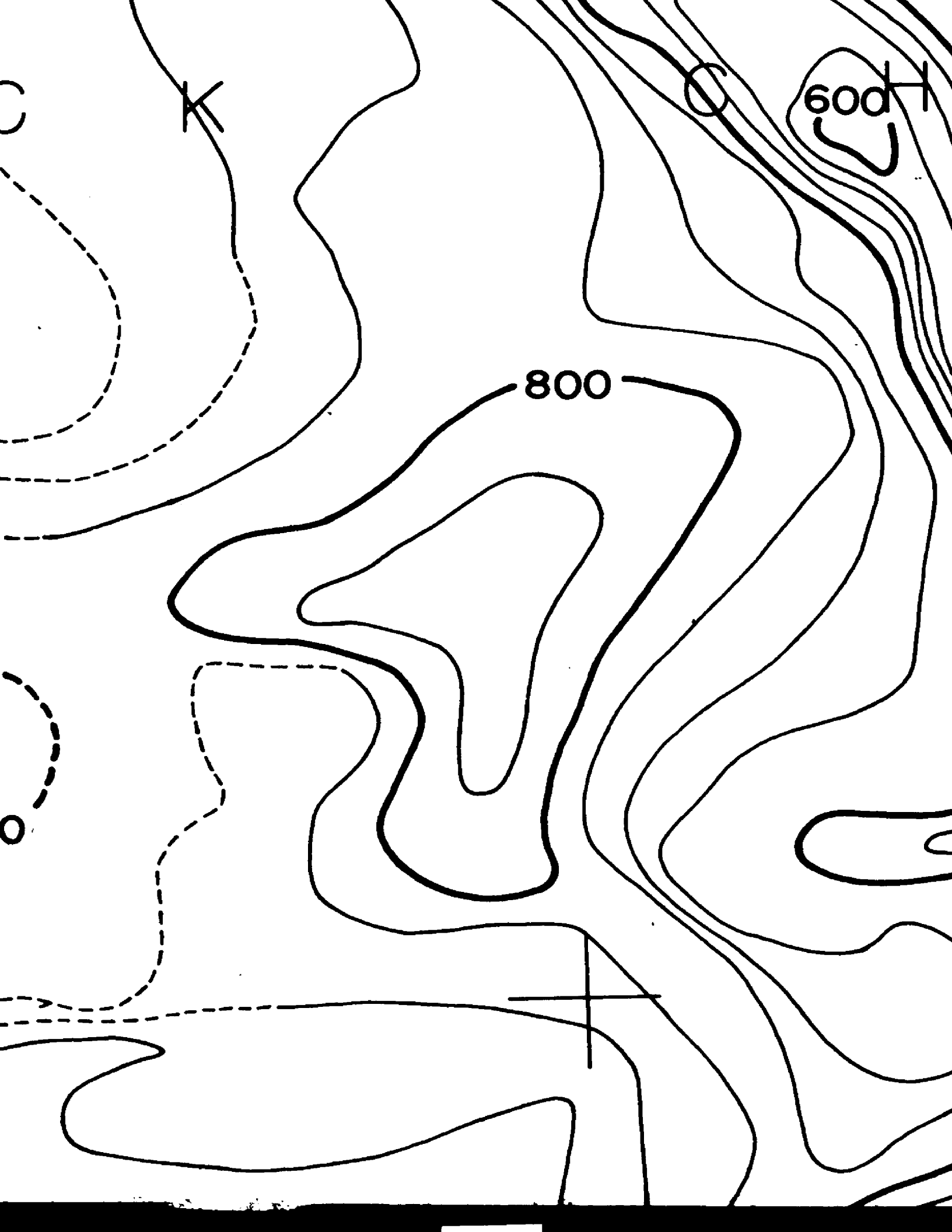
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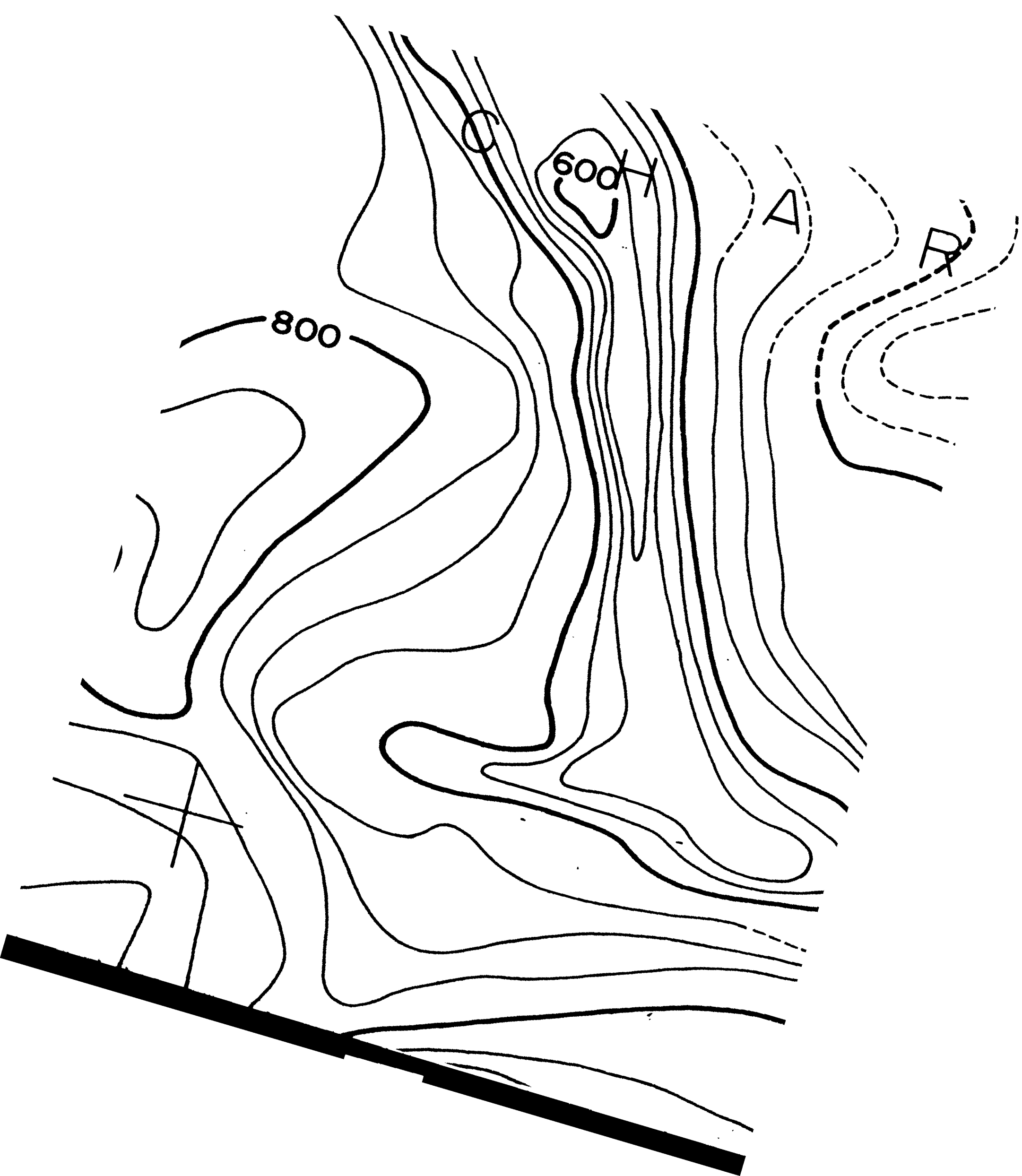
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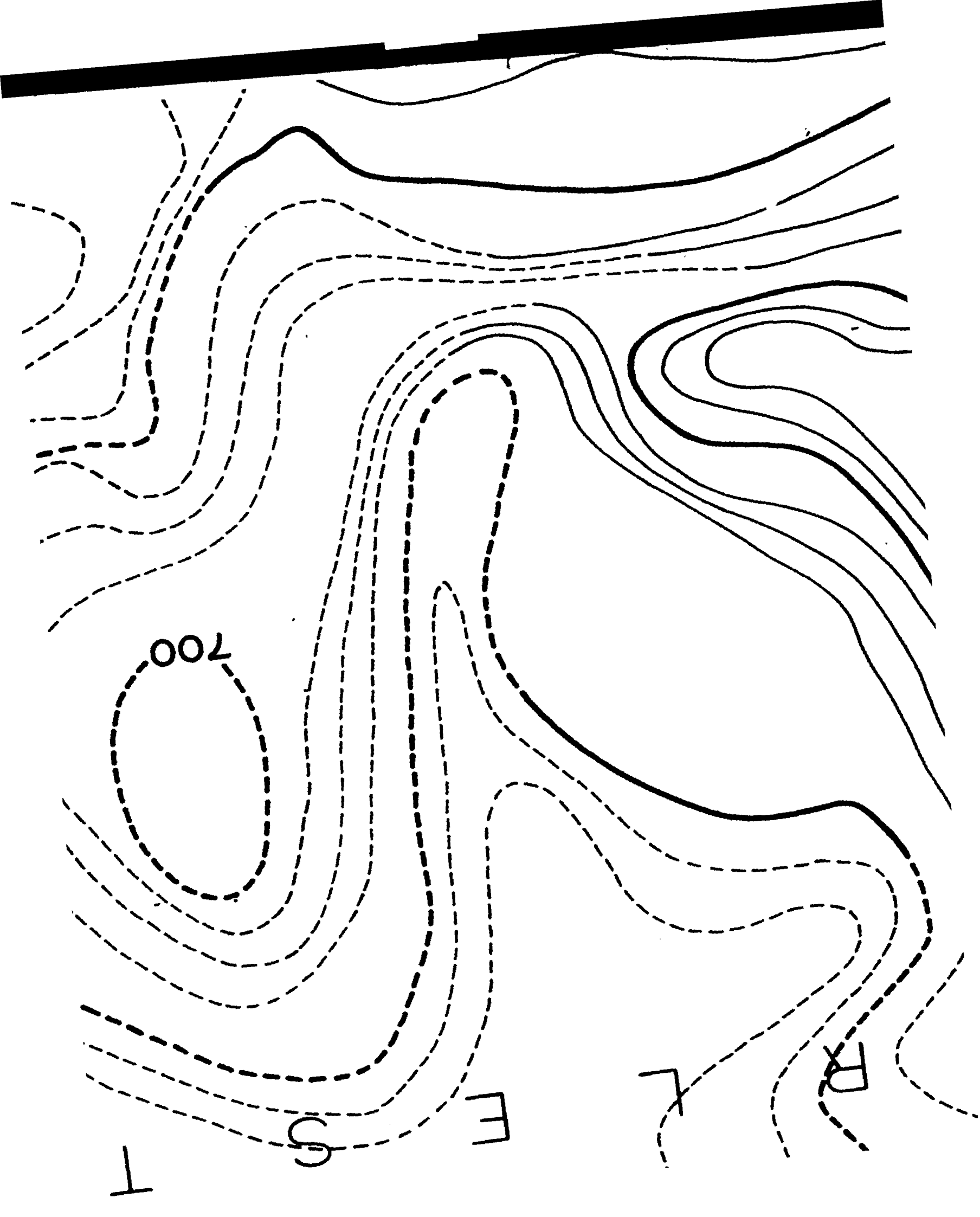


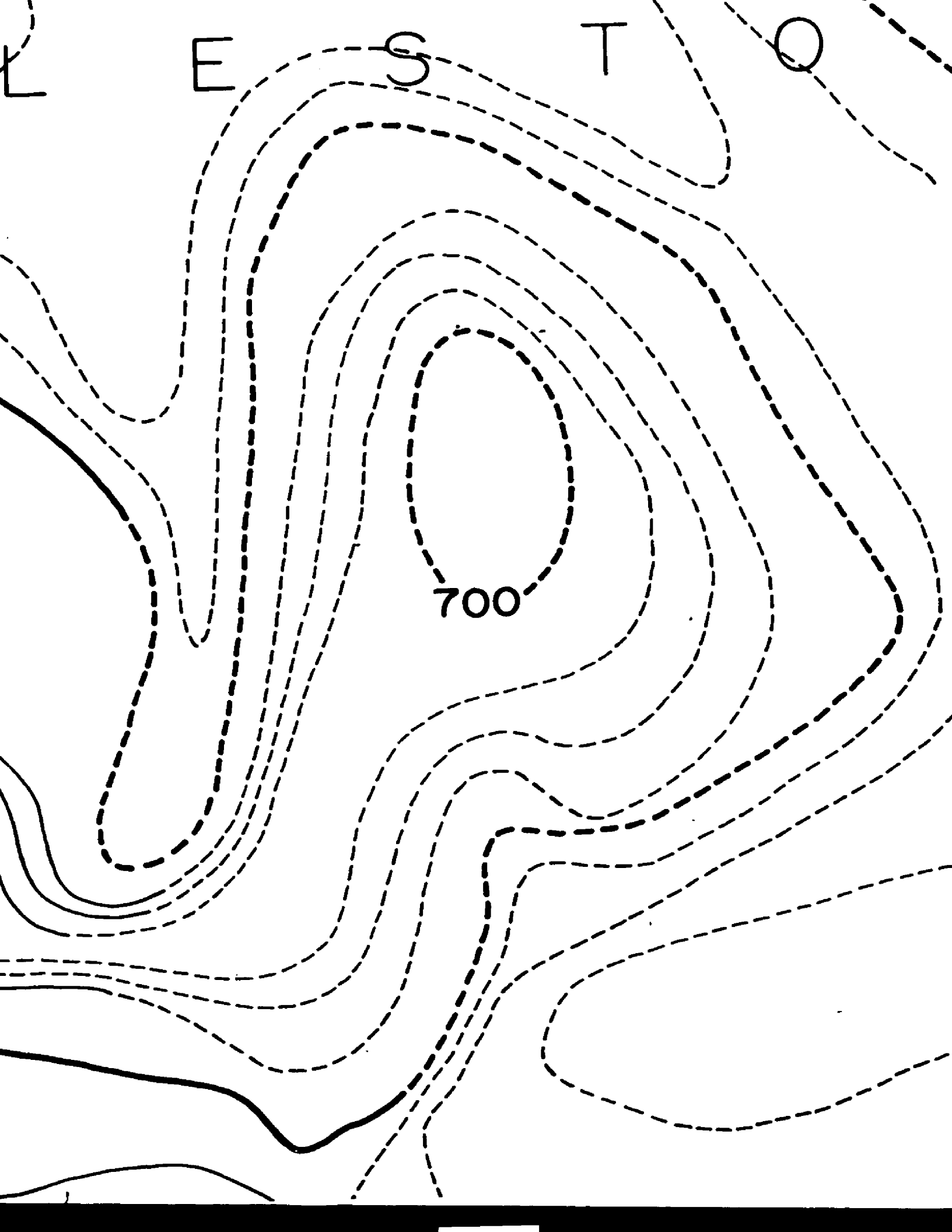


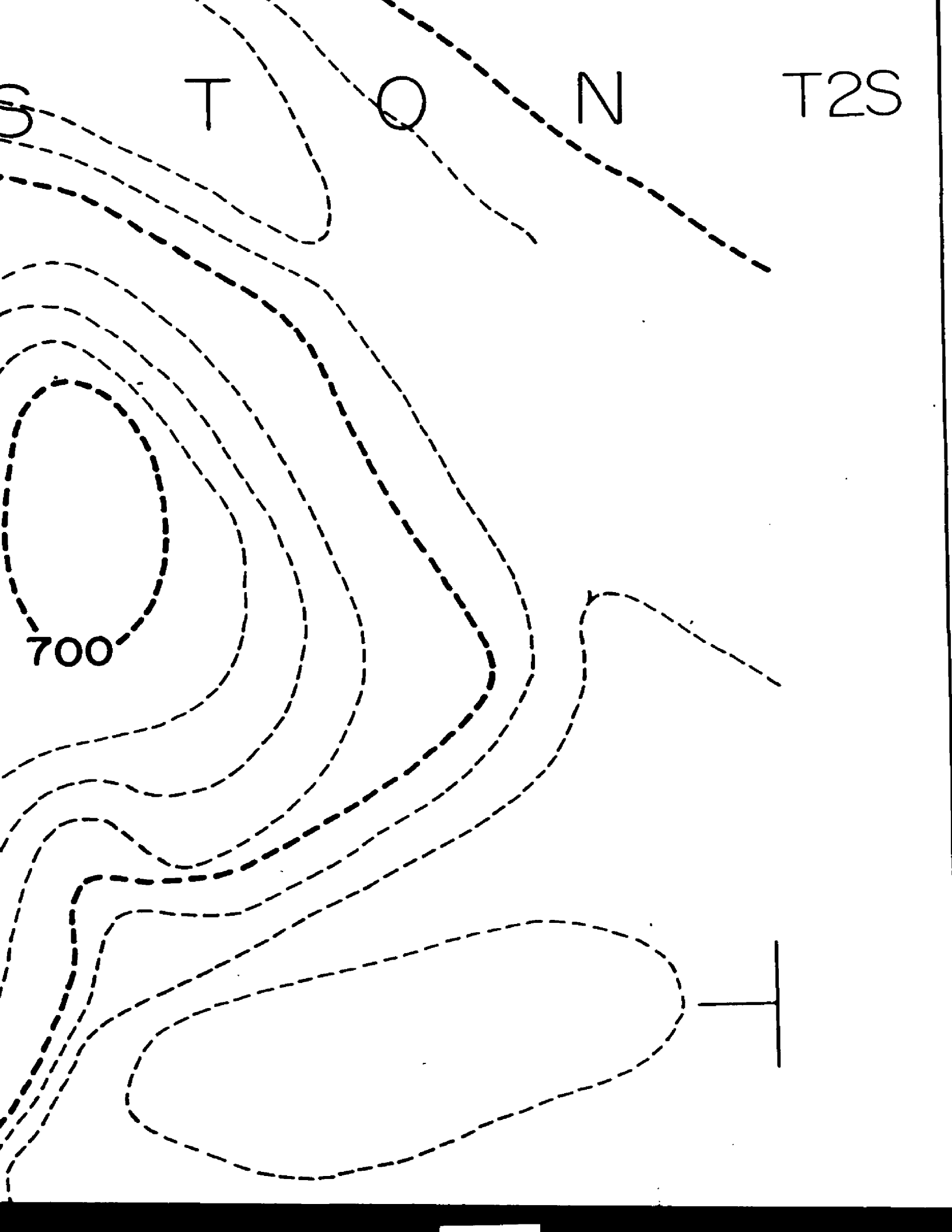












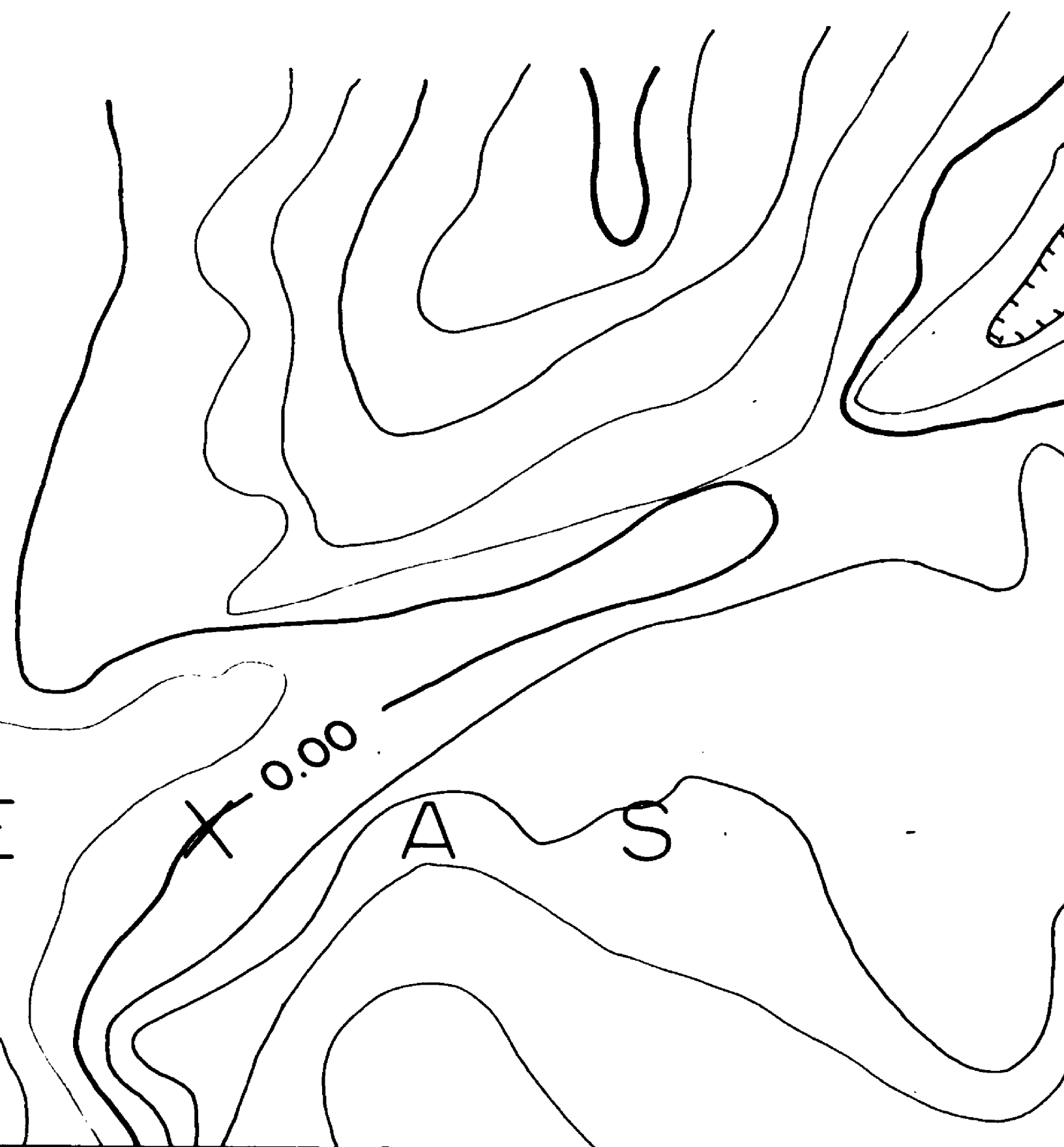
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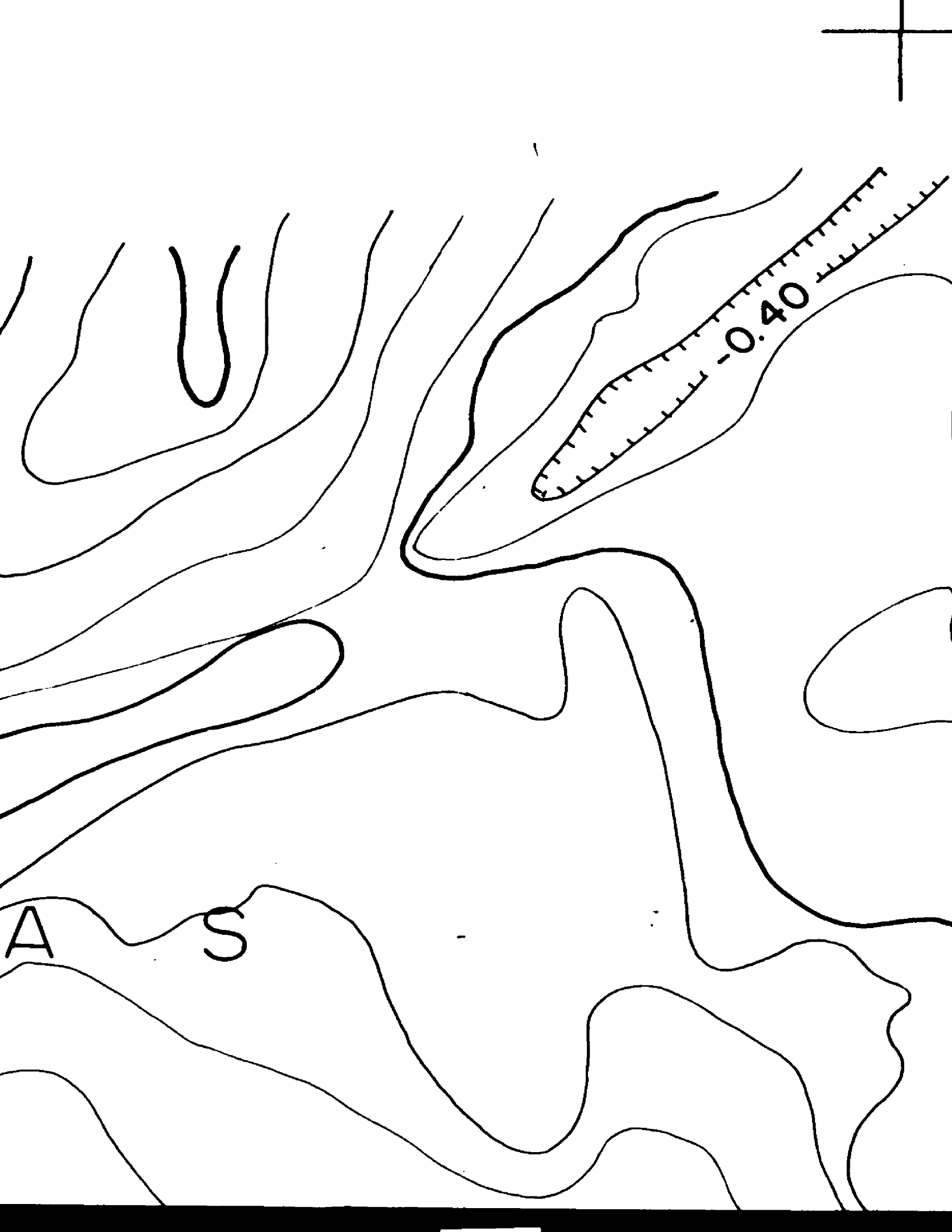
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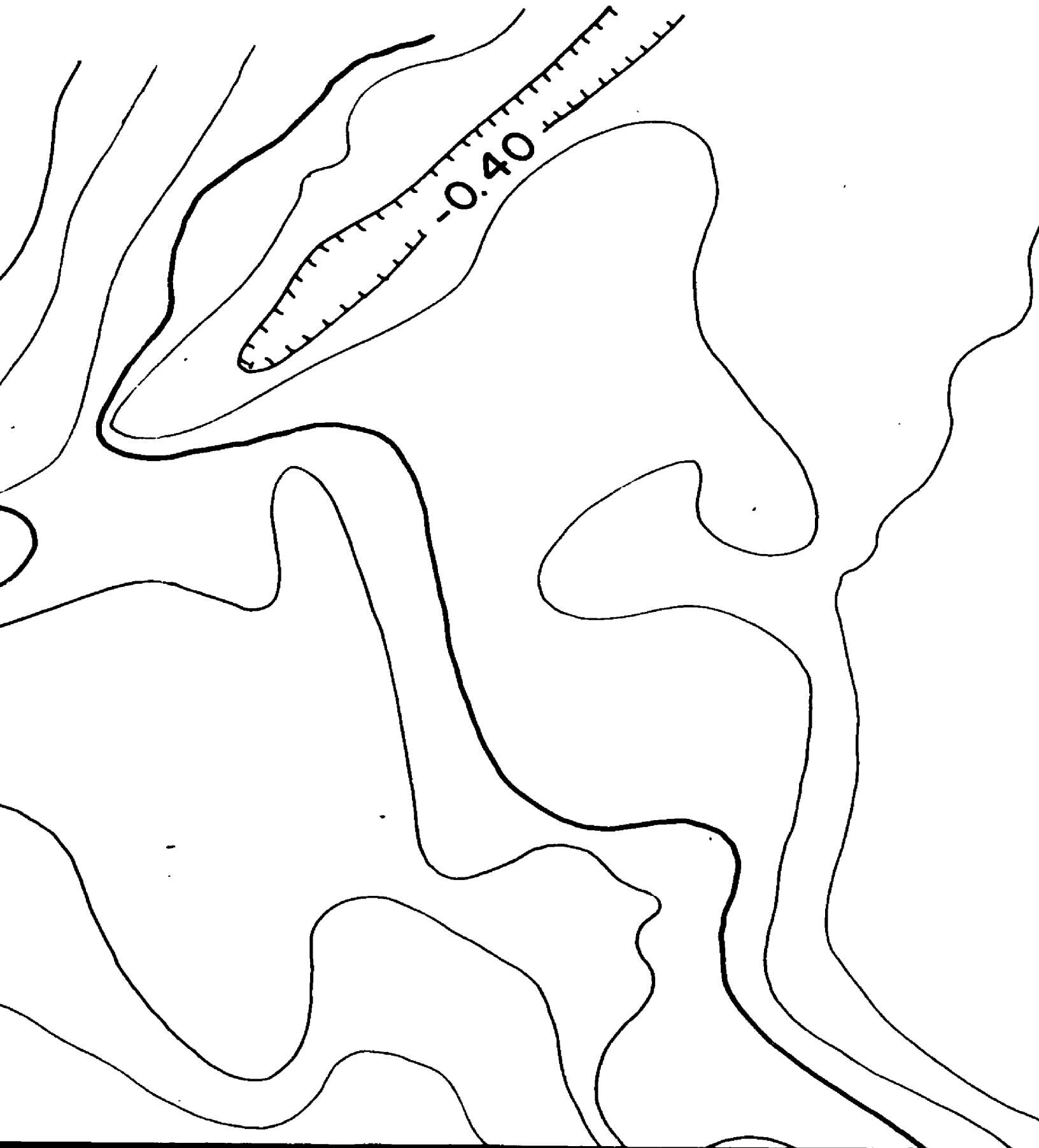
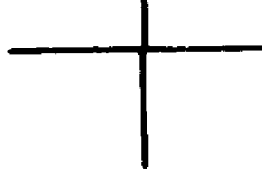
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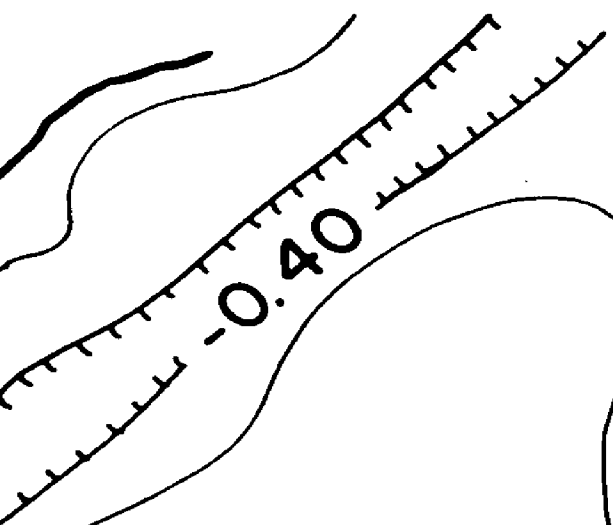








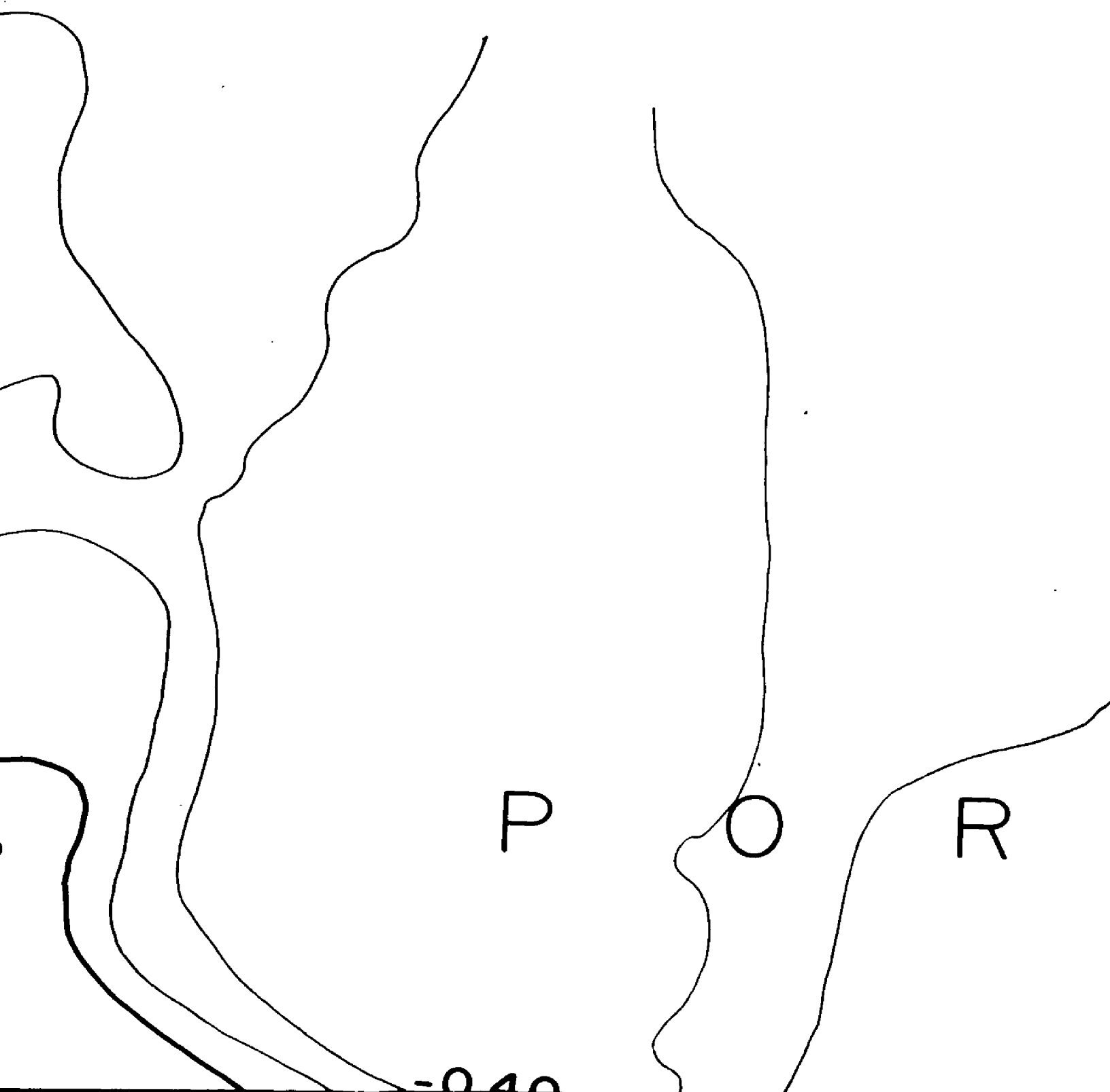
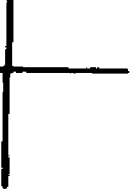


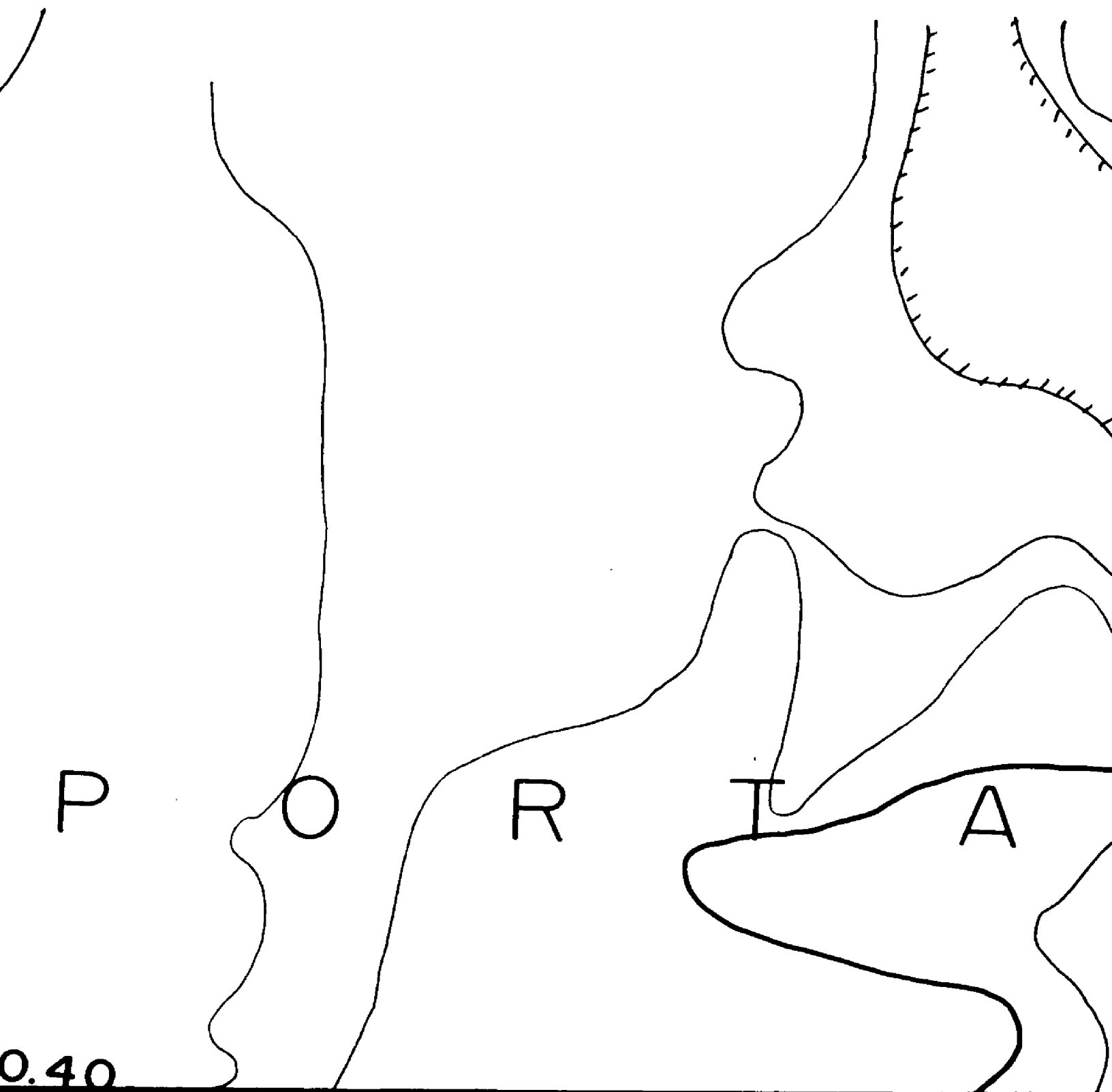


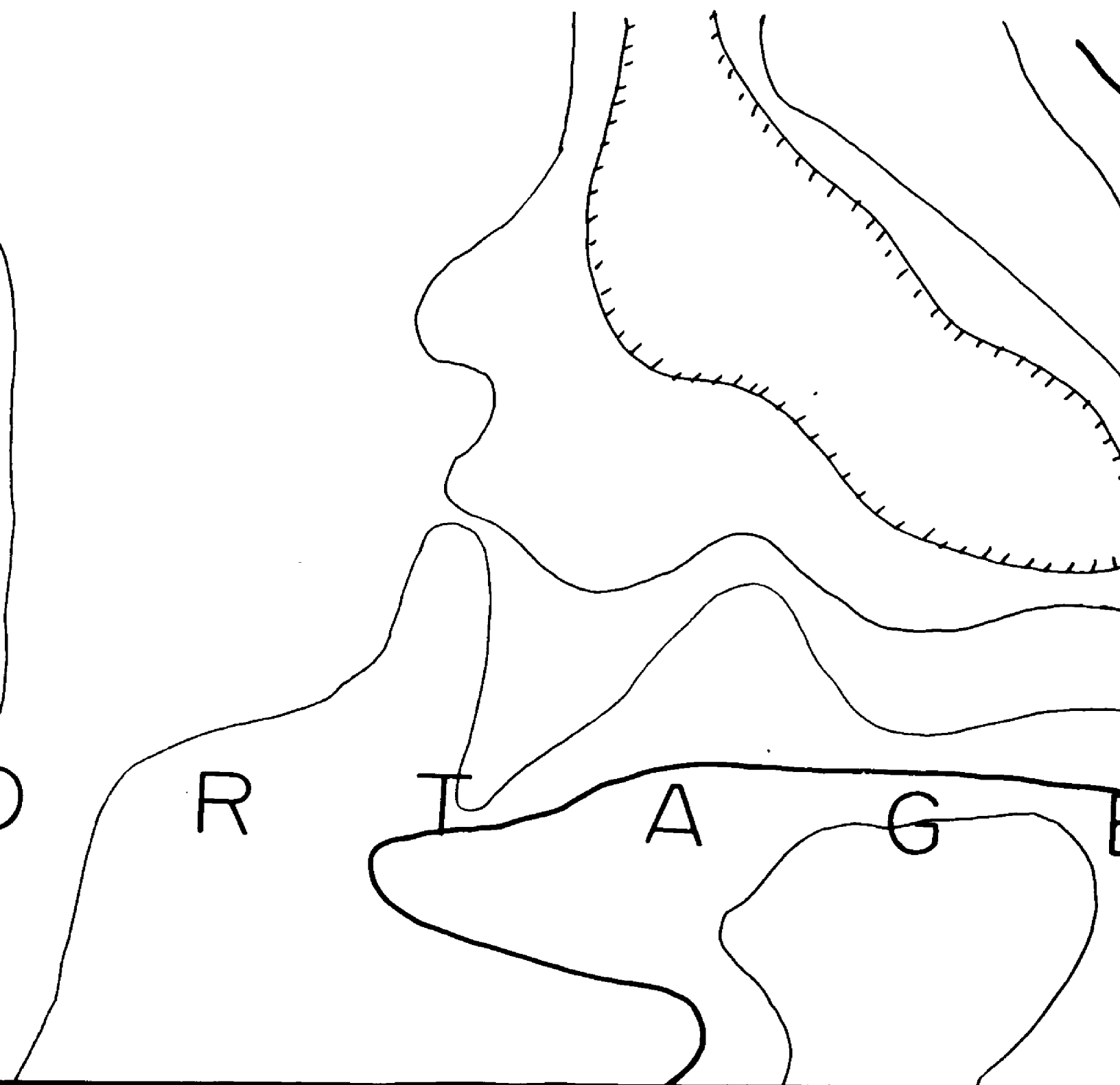
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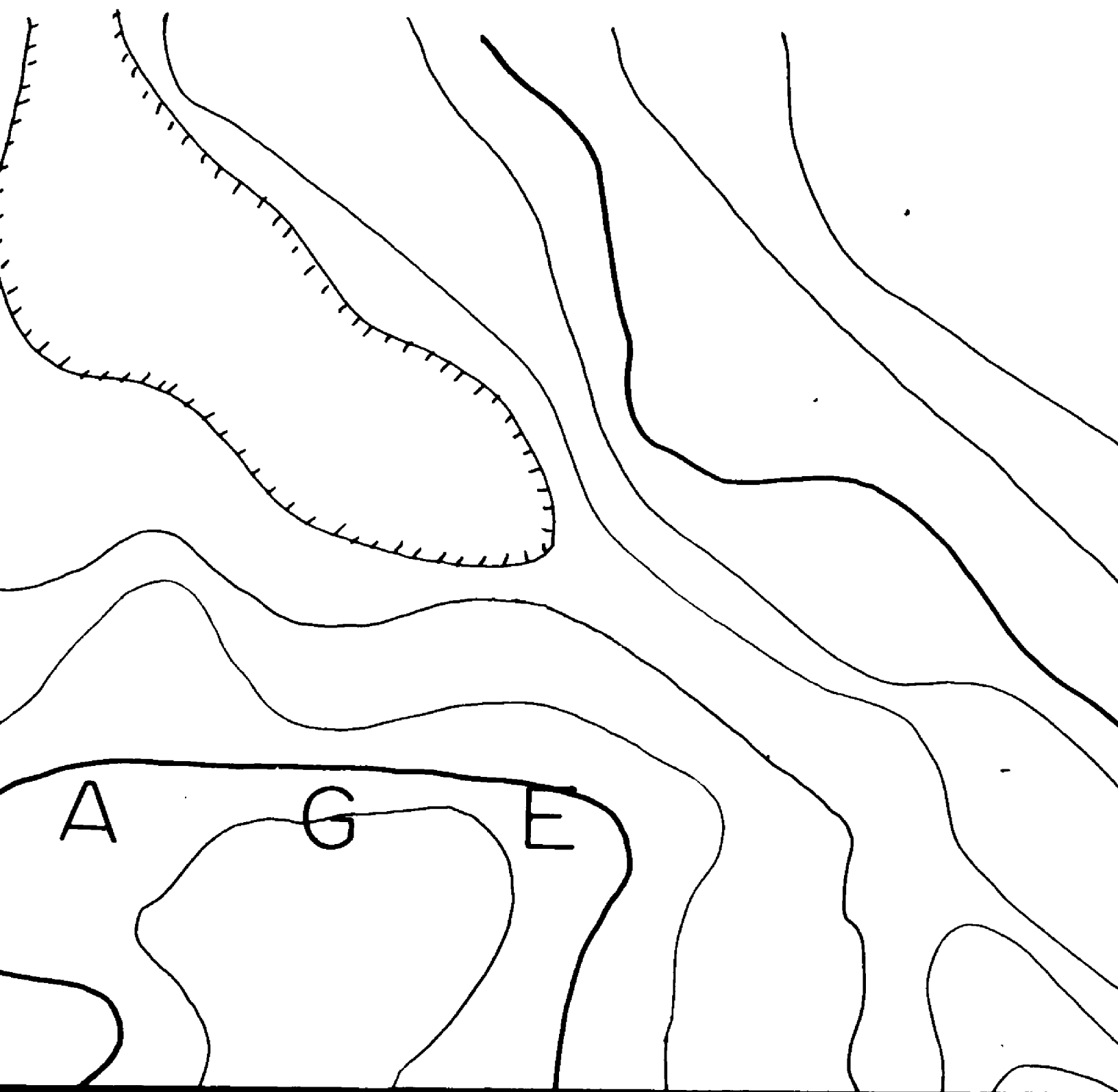
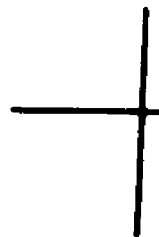
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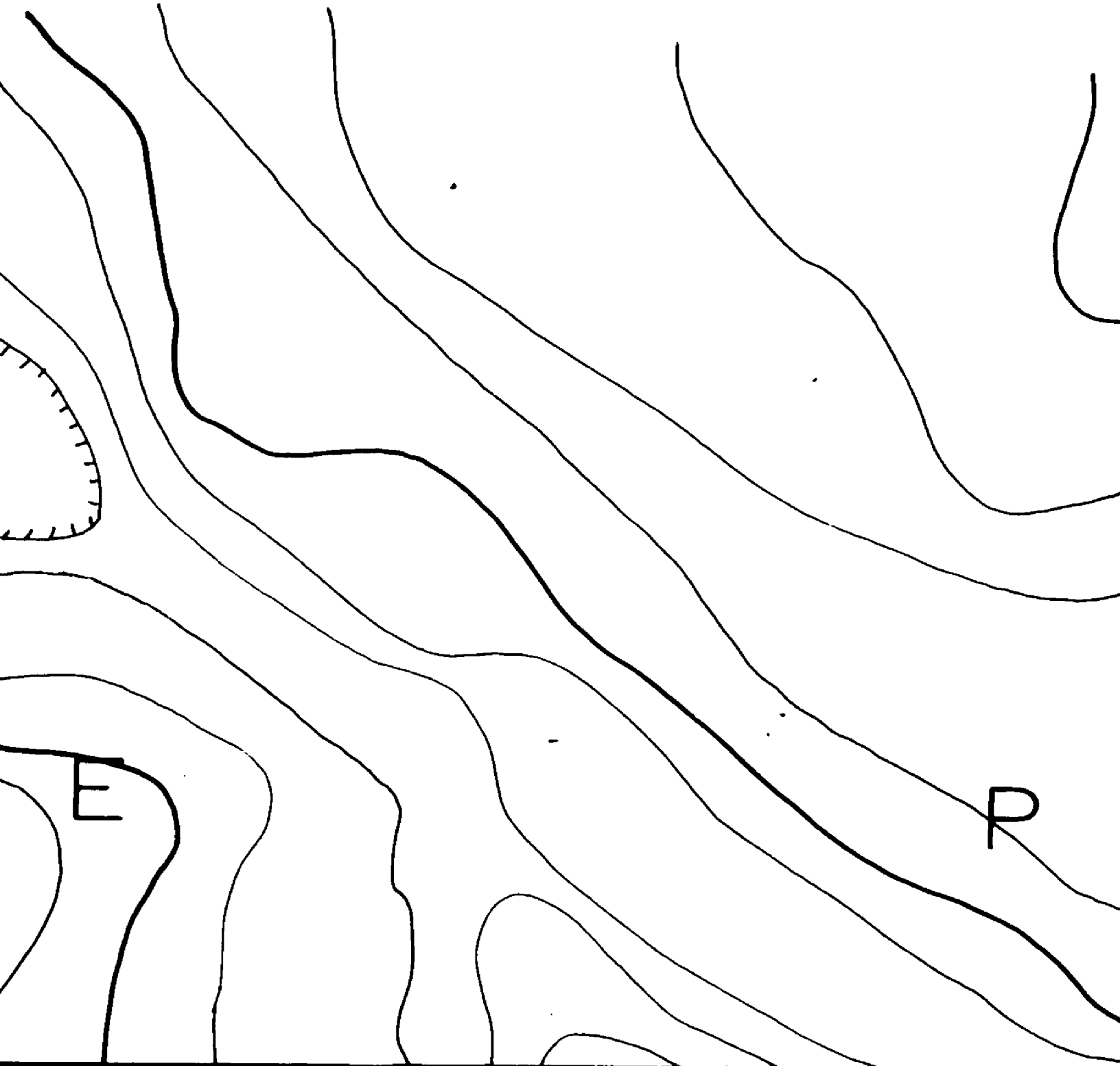
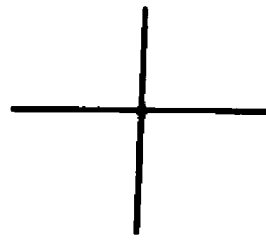
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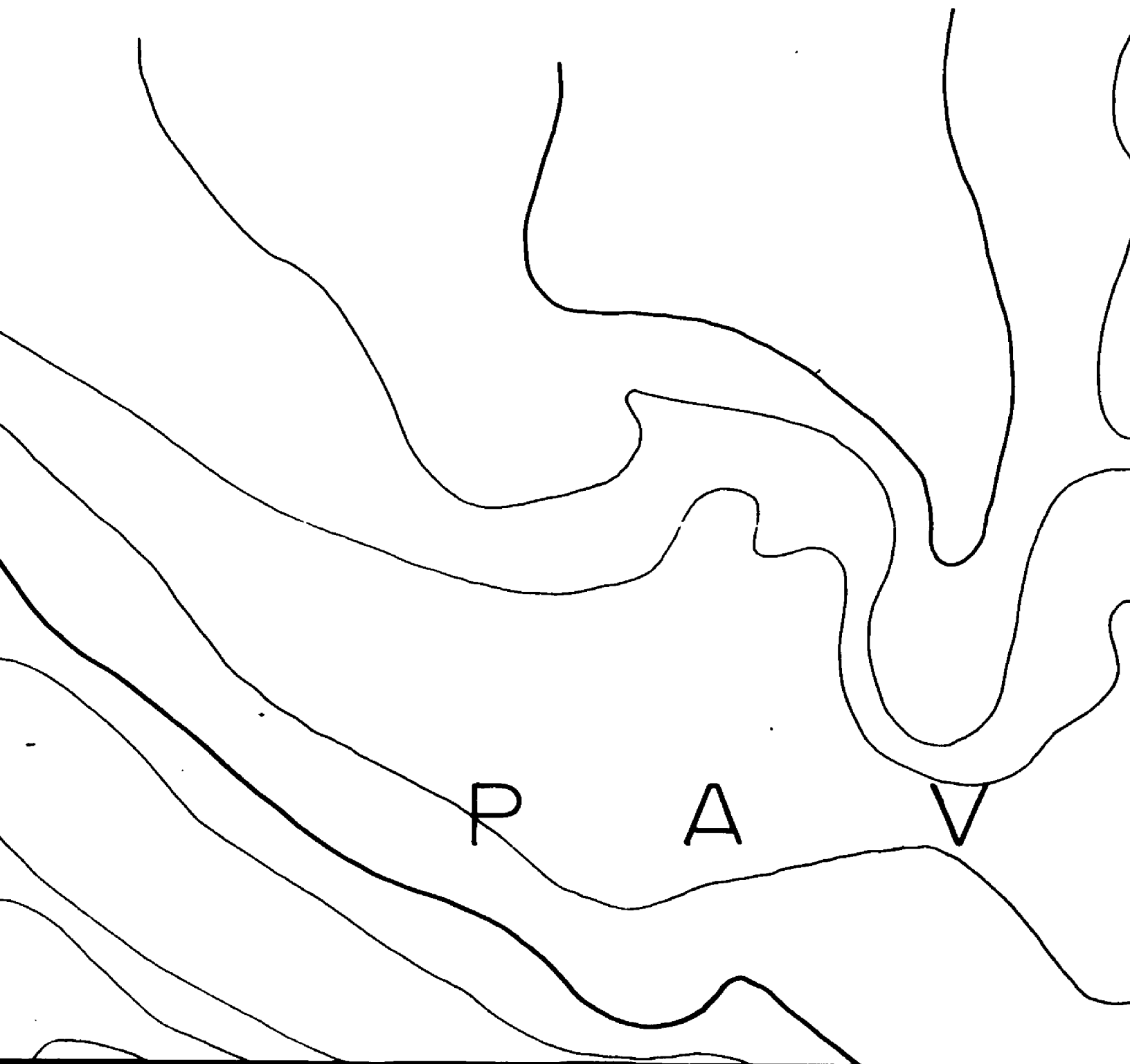
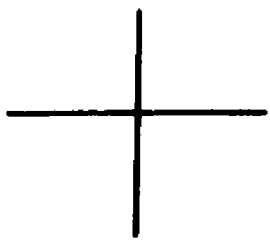










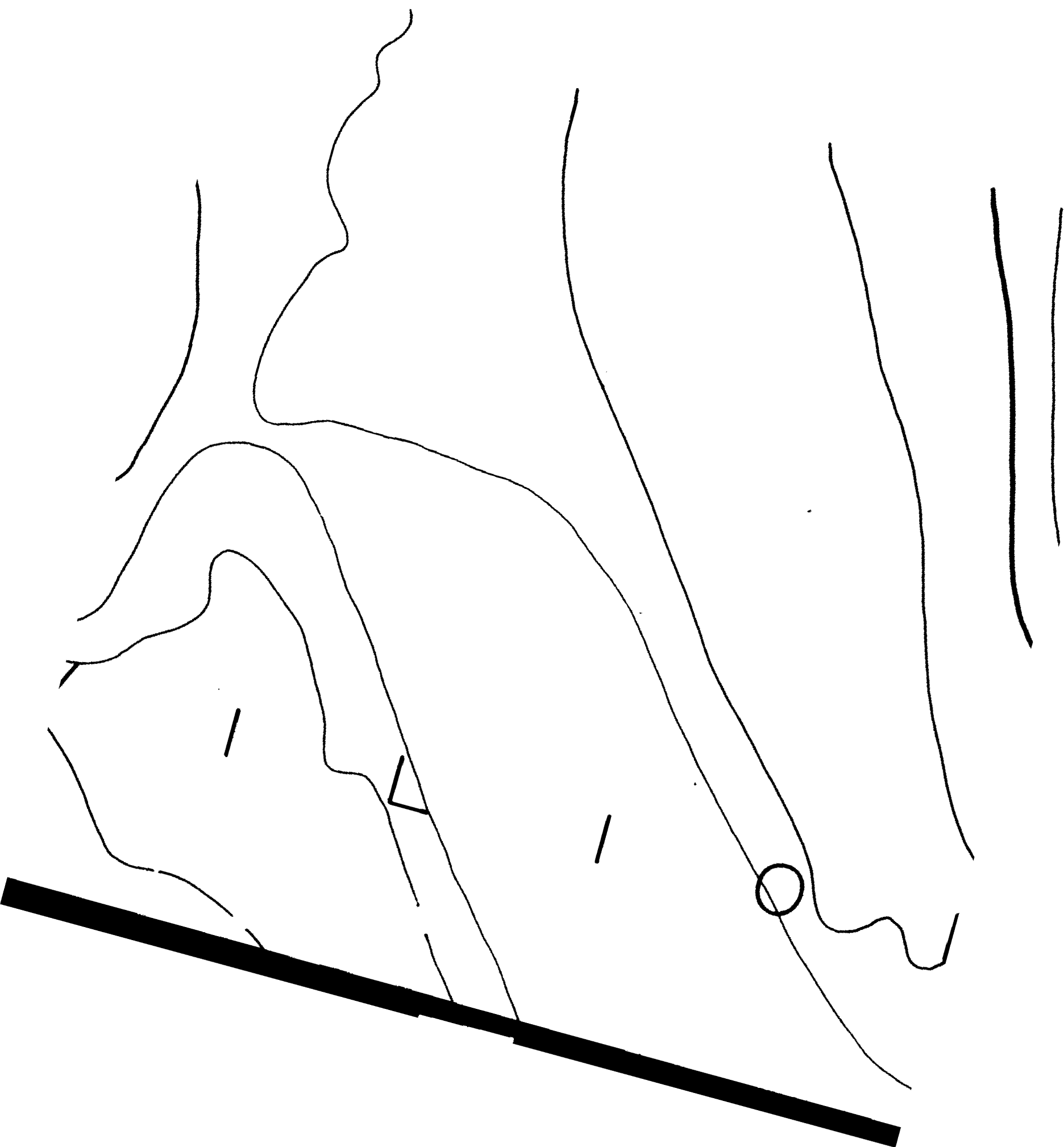


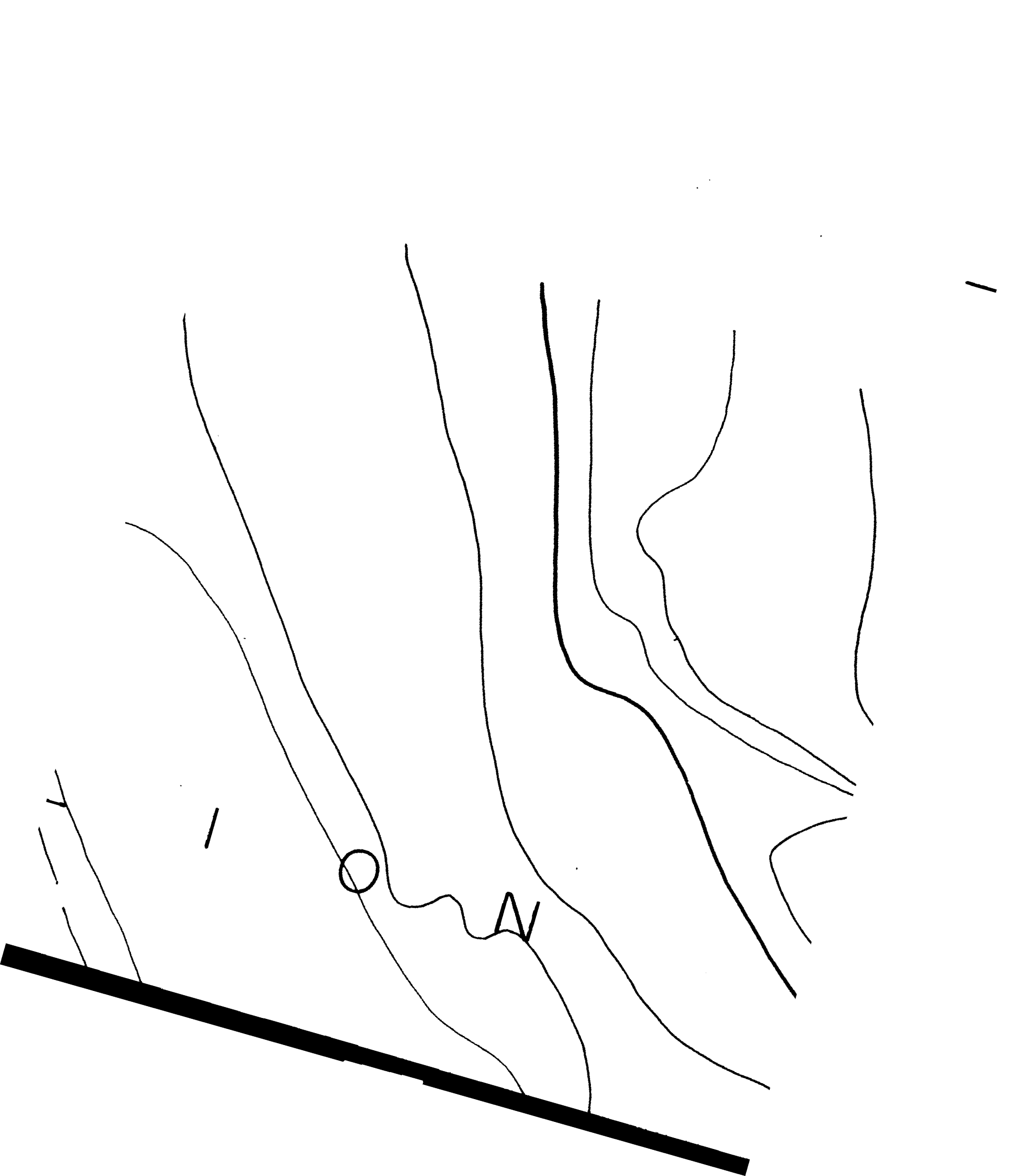
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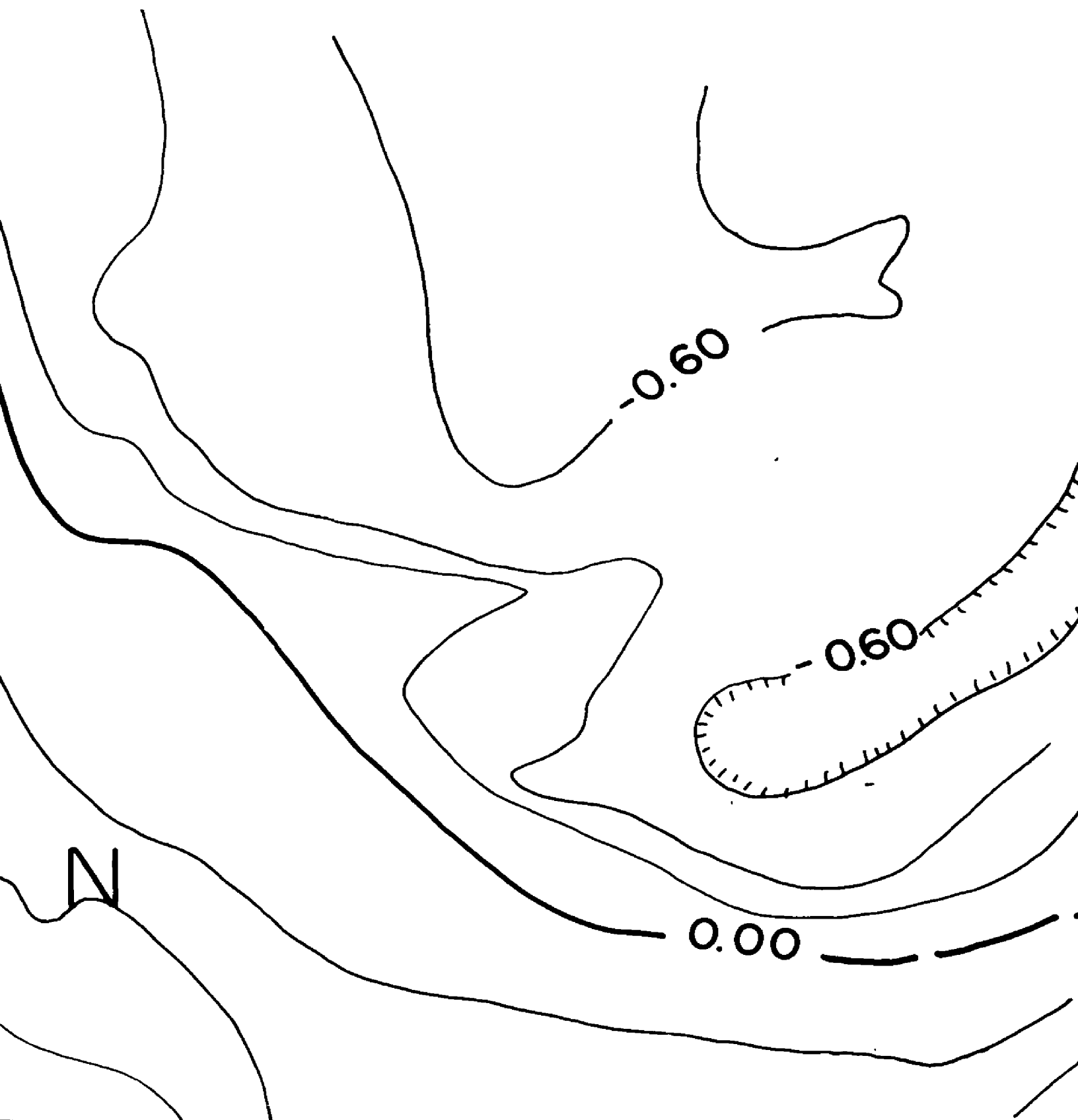
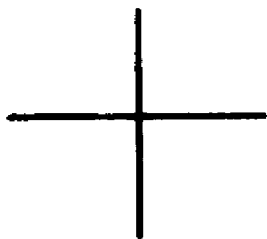
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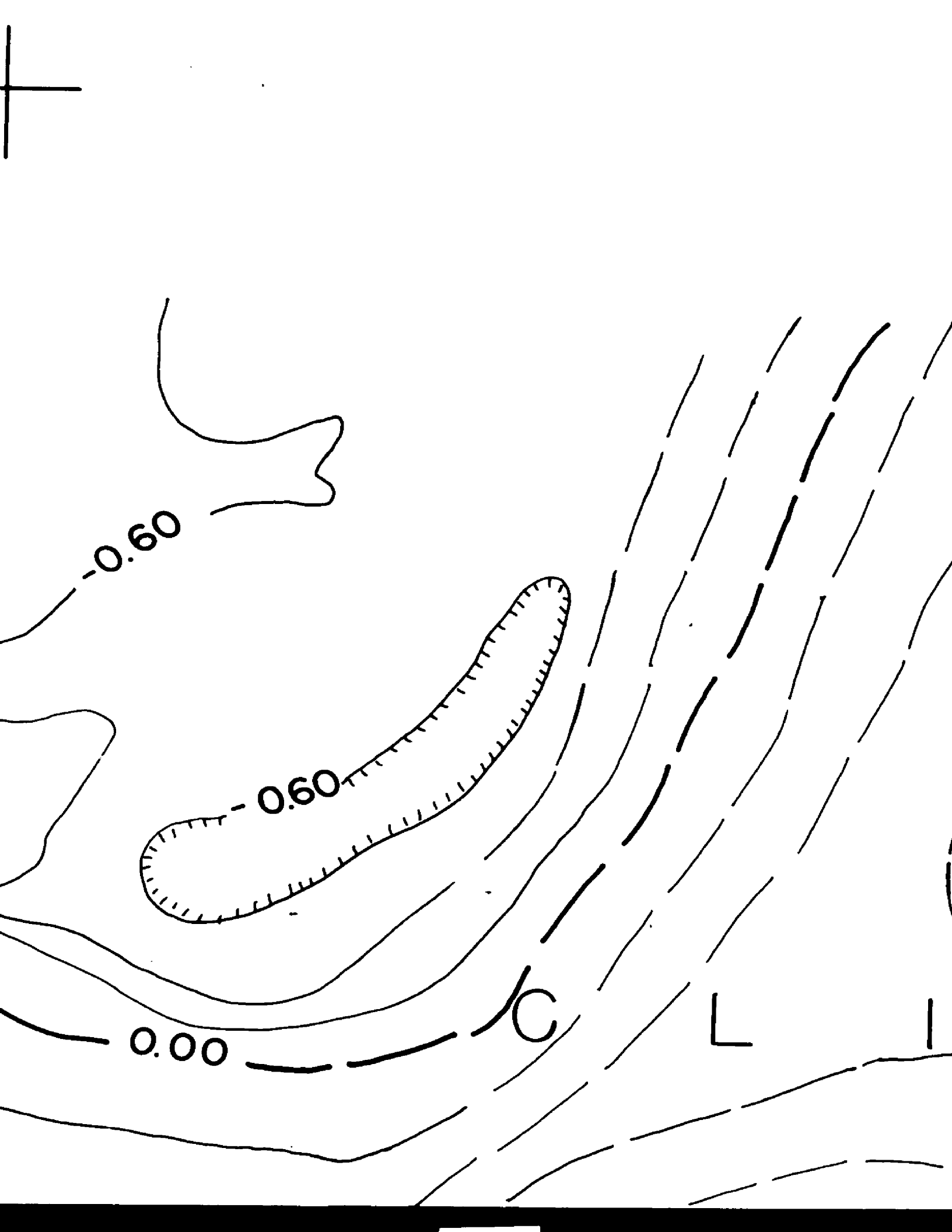
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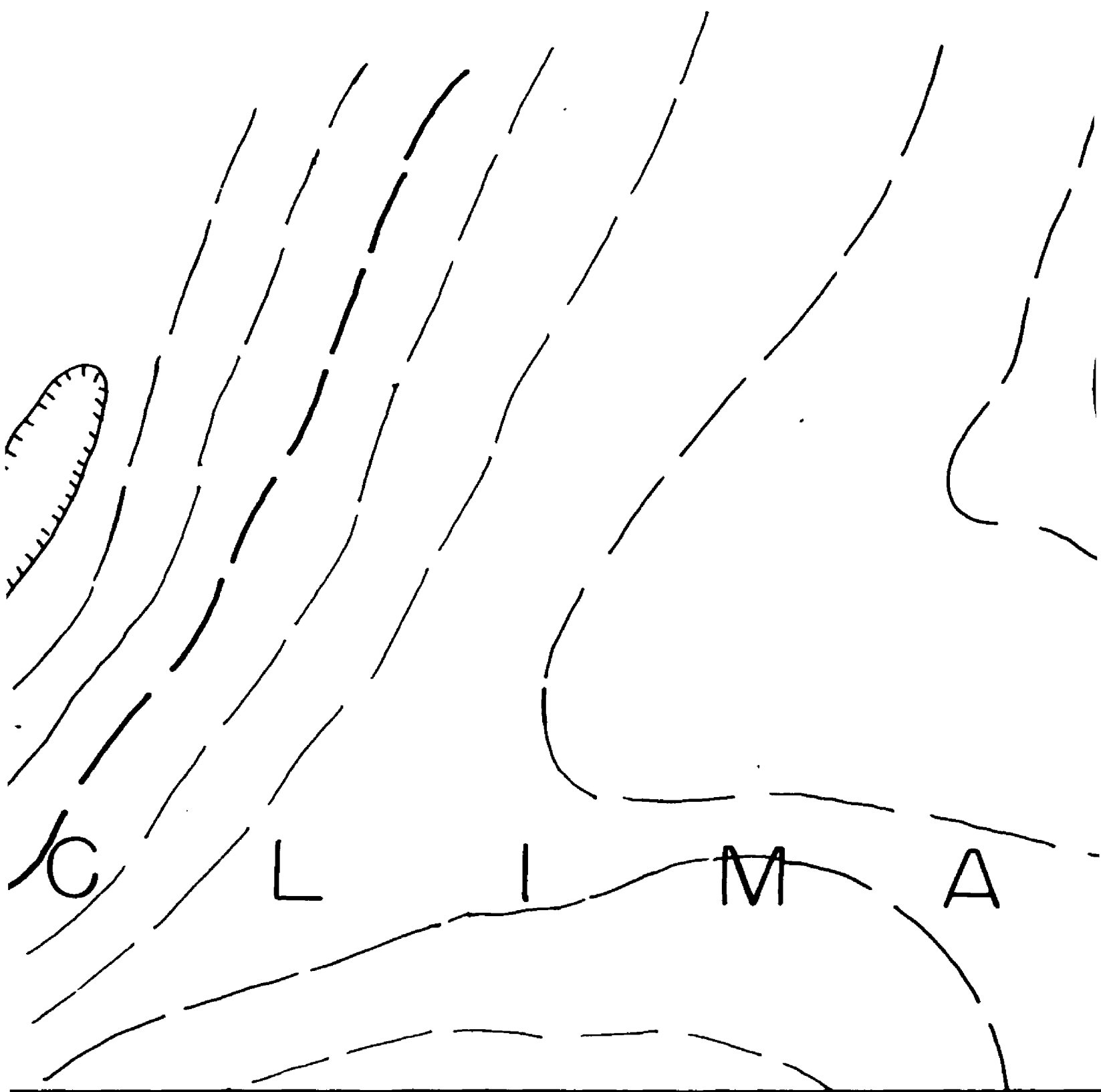


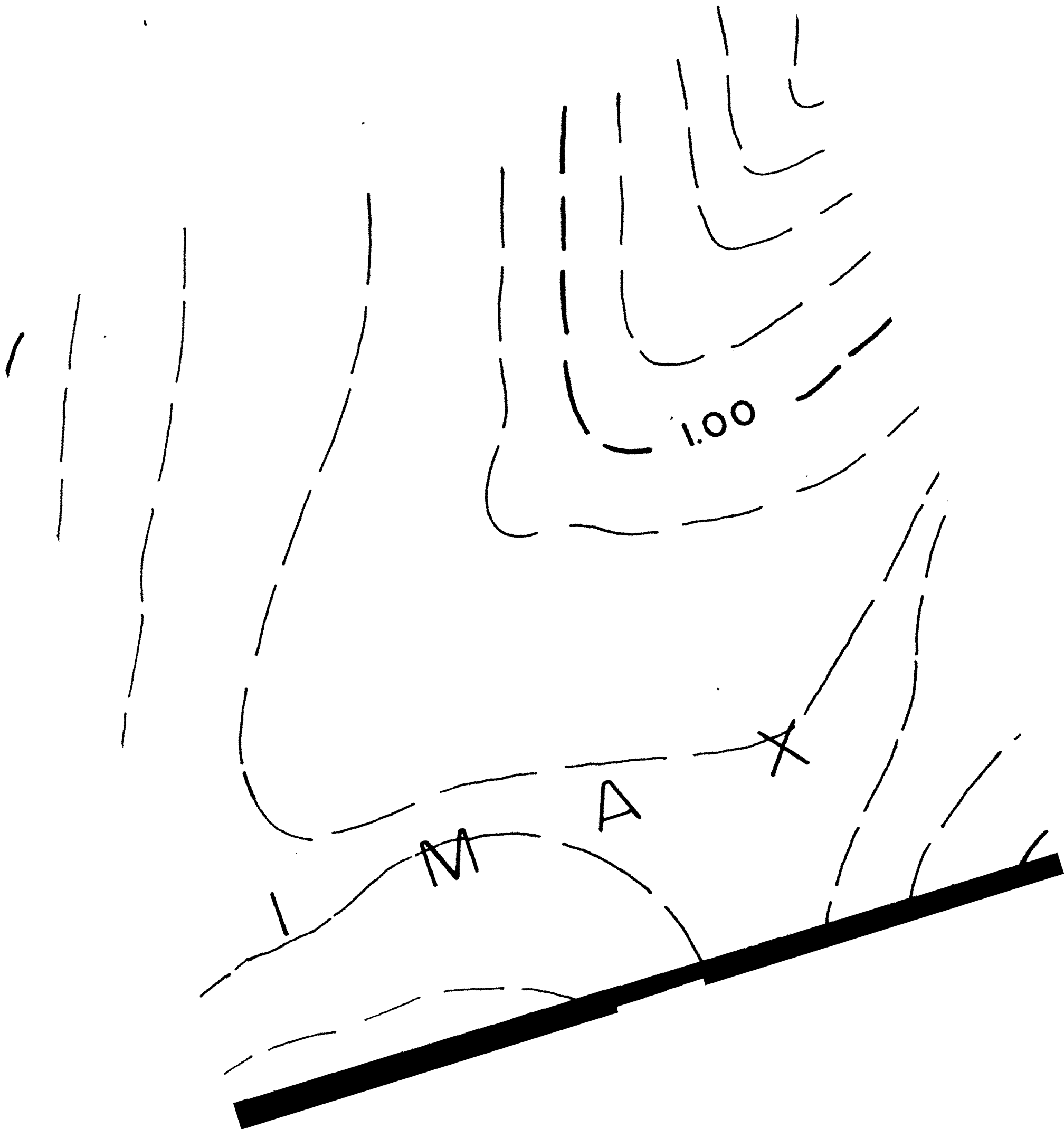


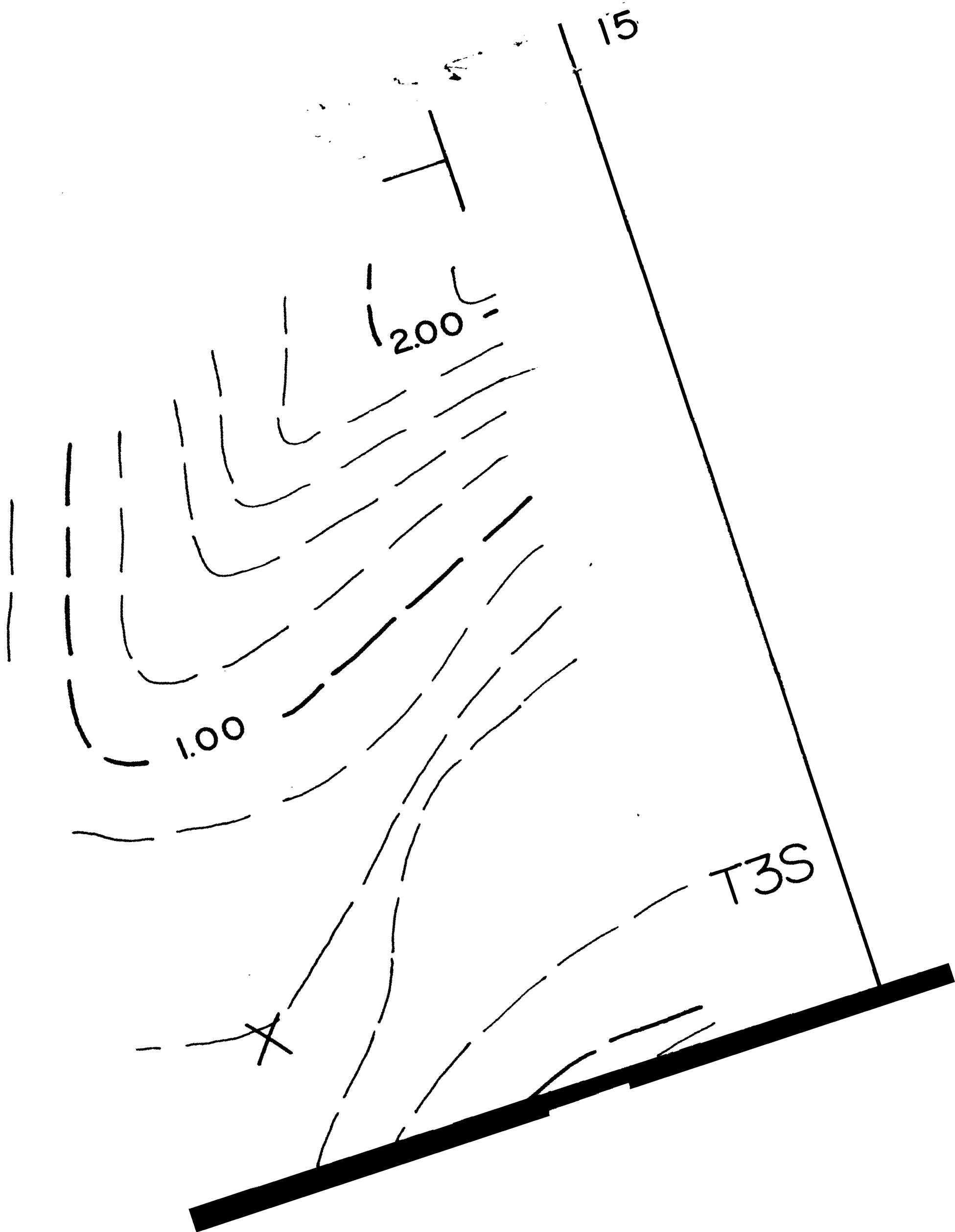










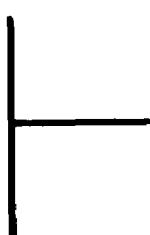


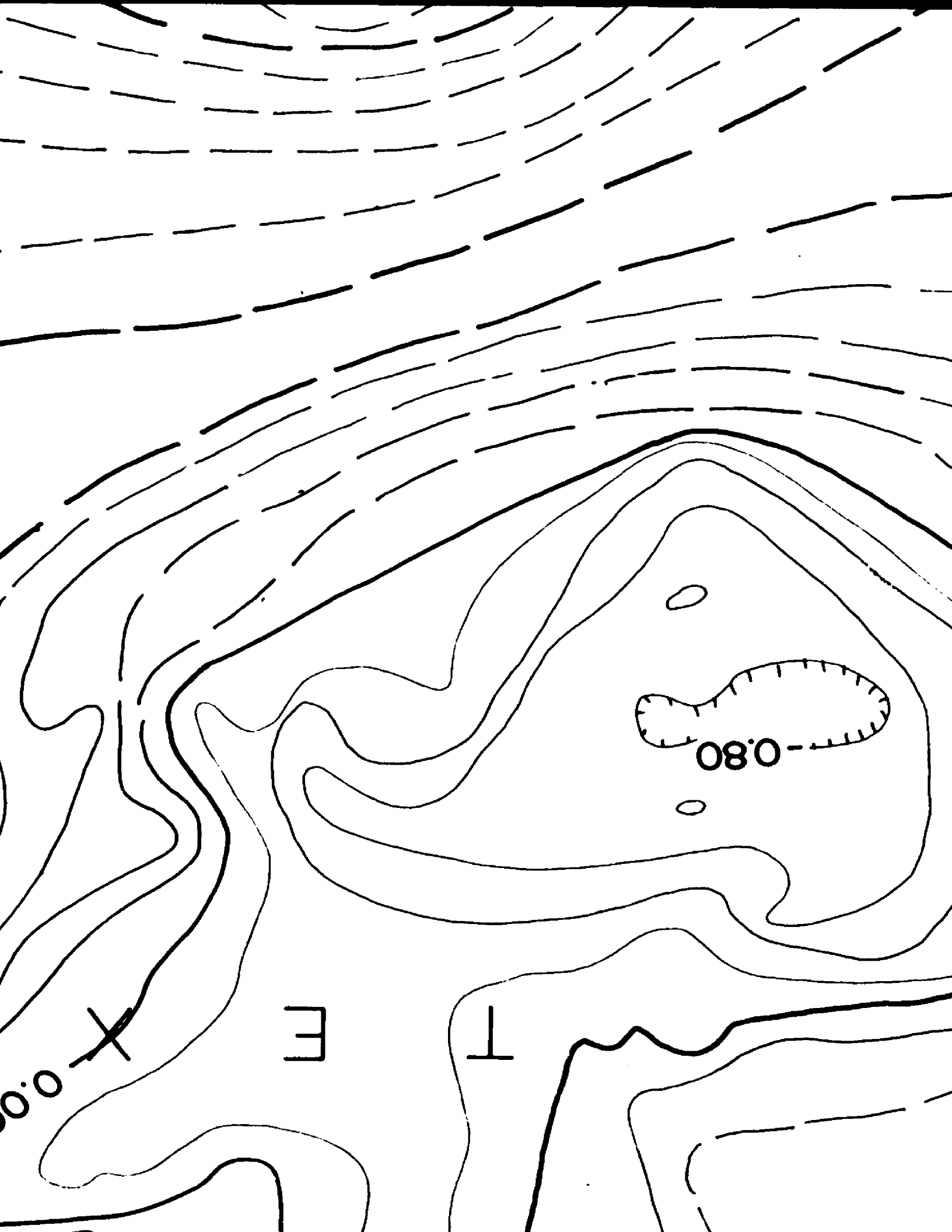
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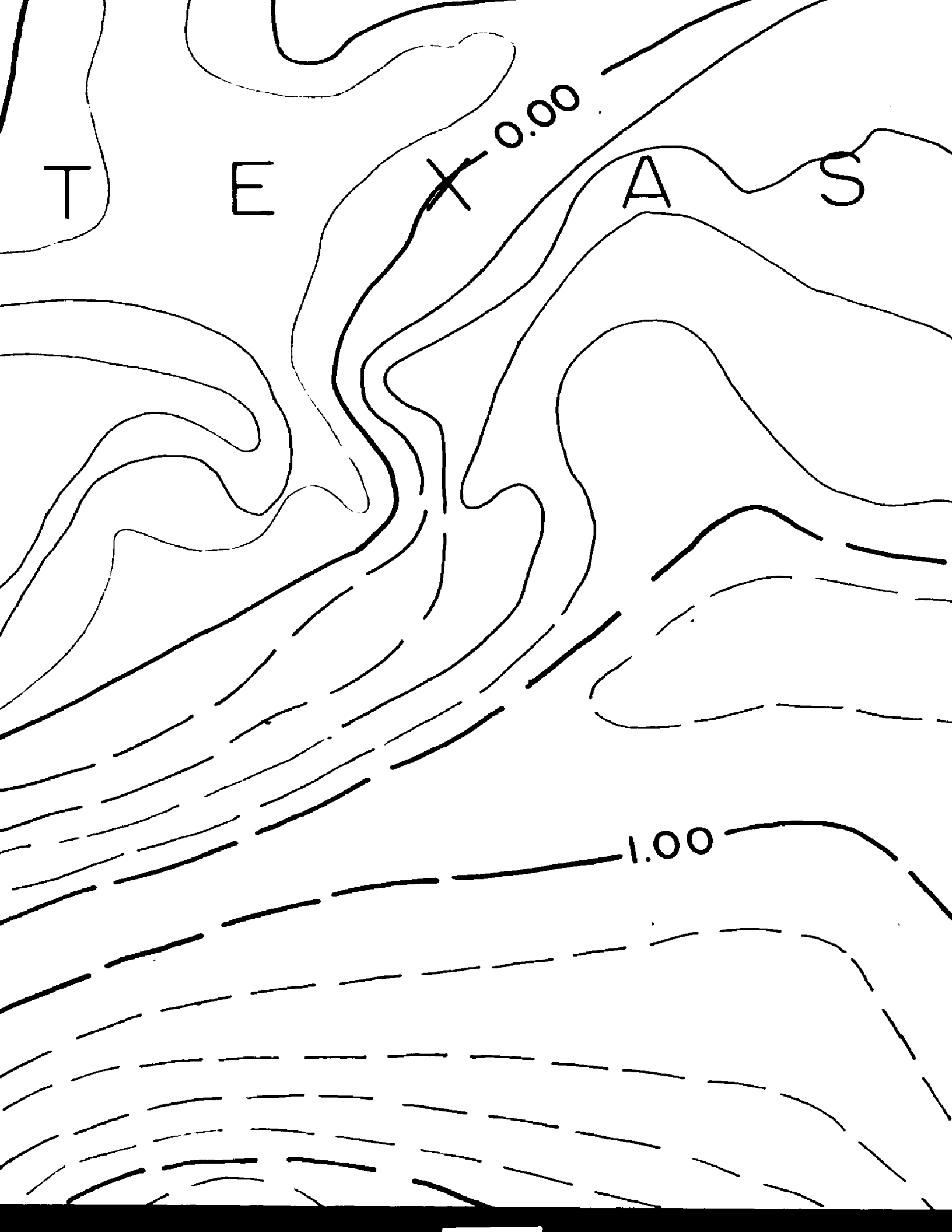
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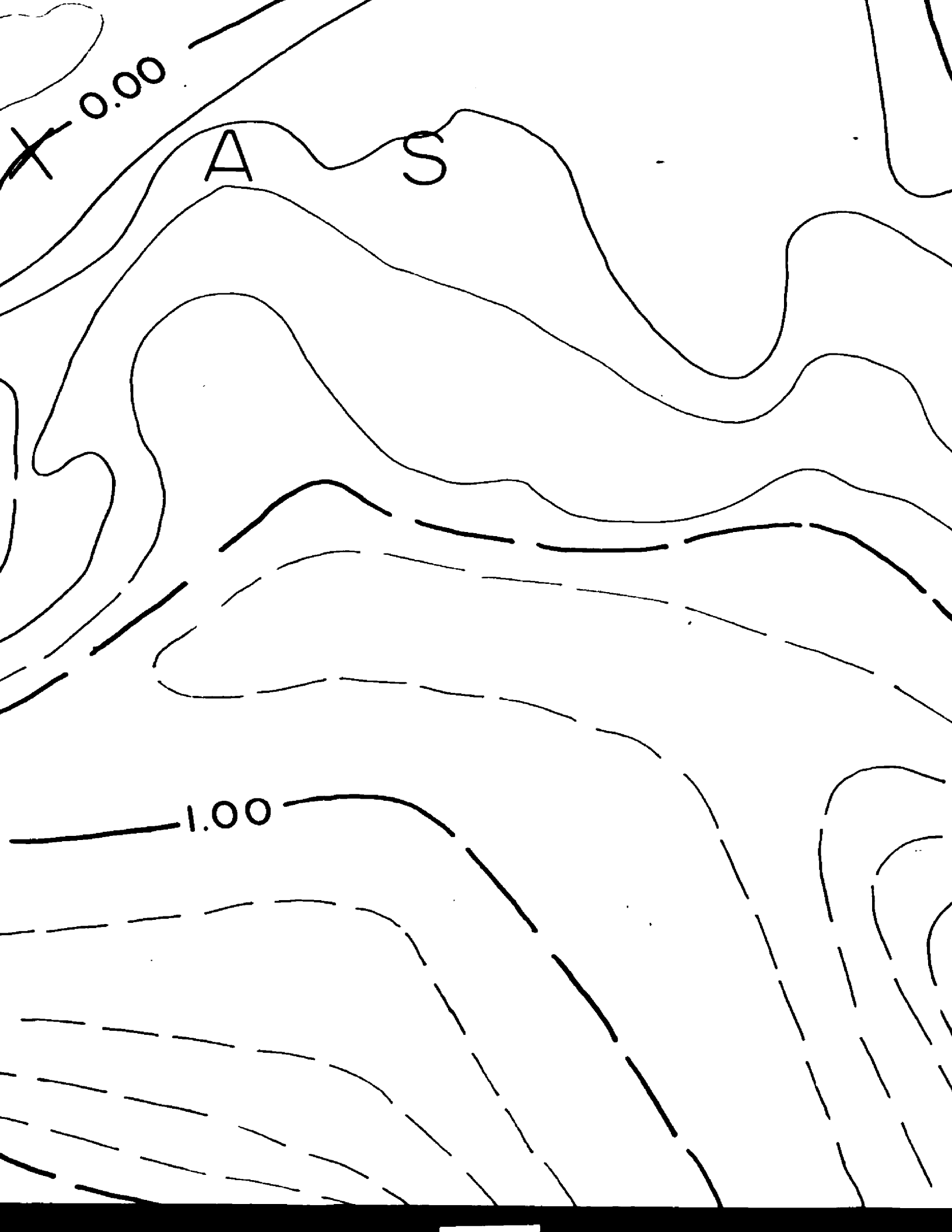
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-10'

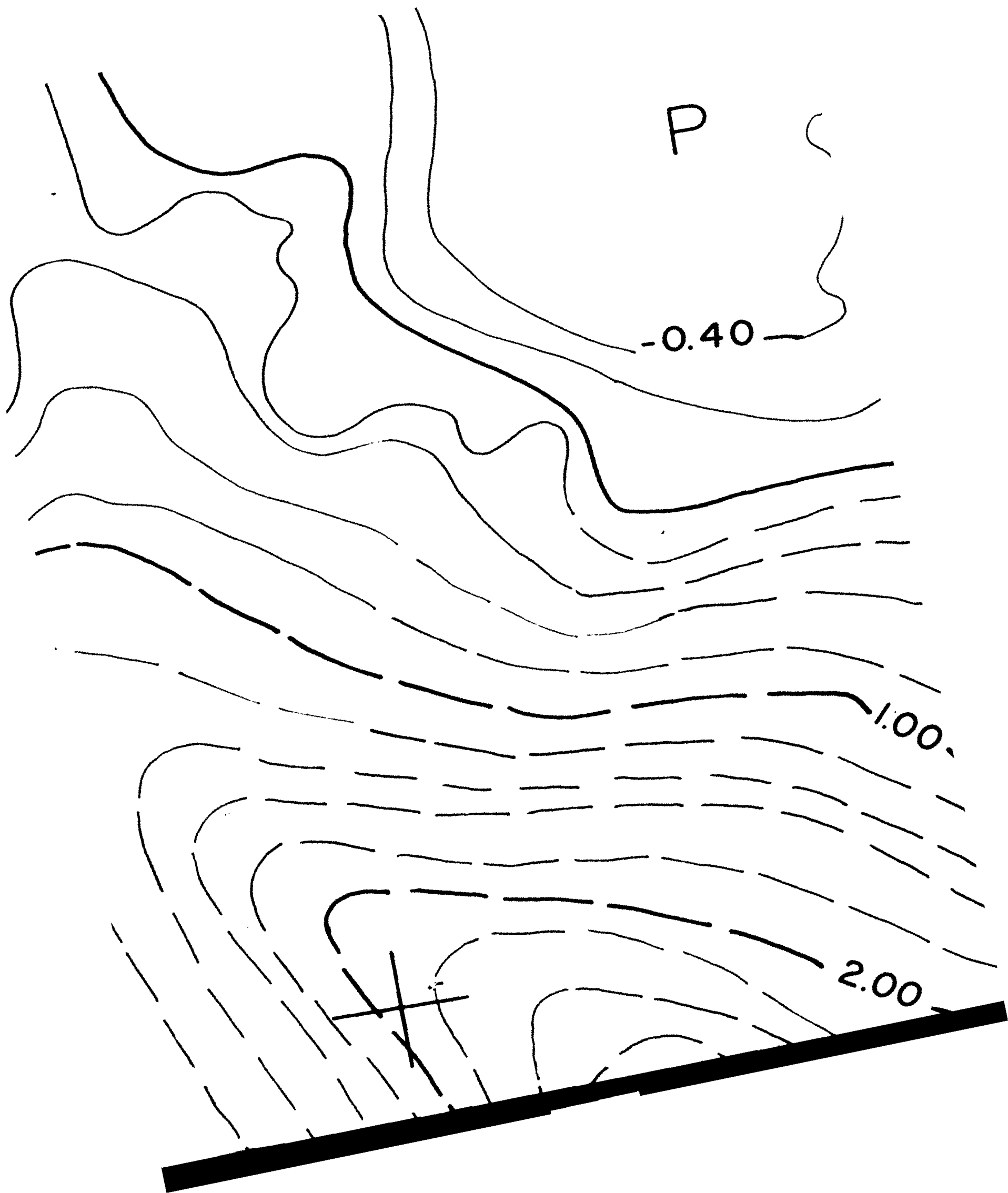


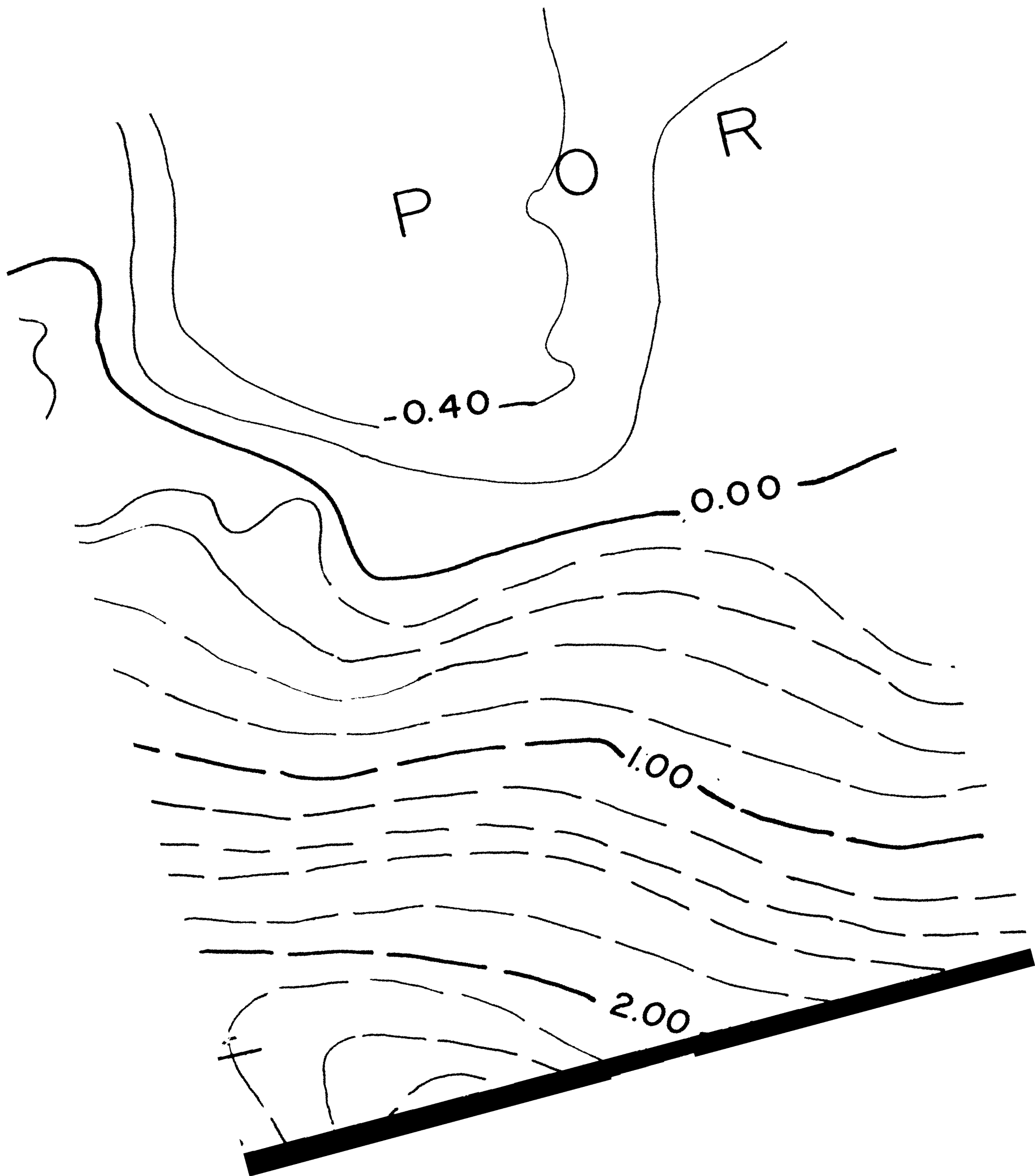


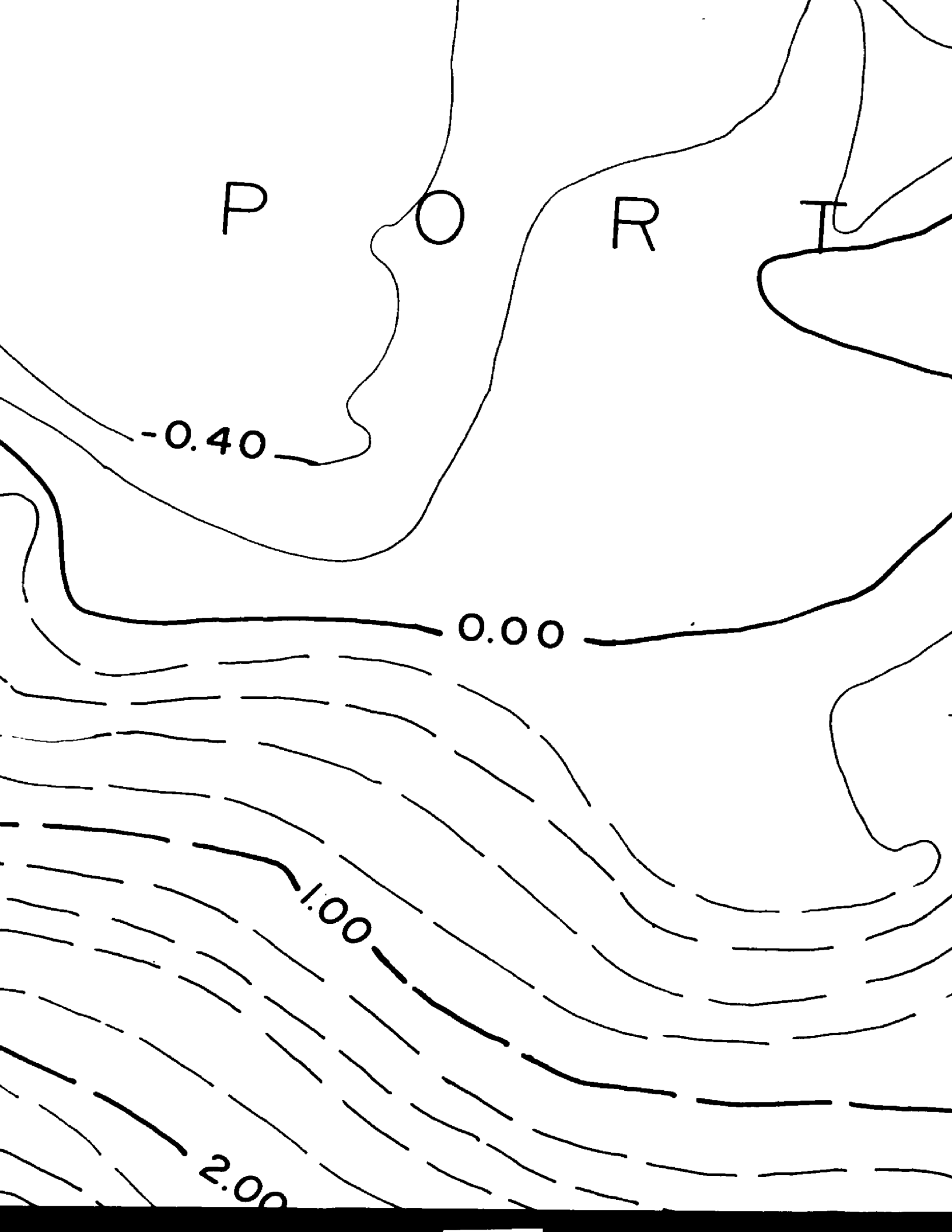


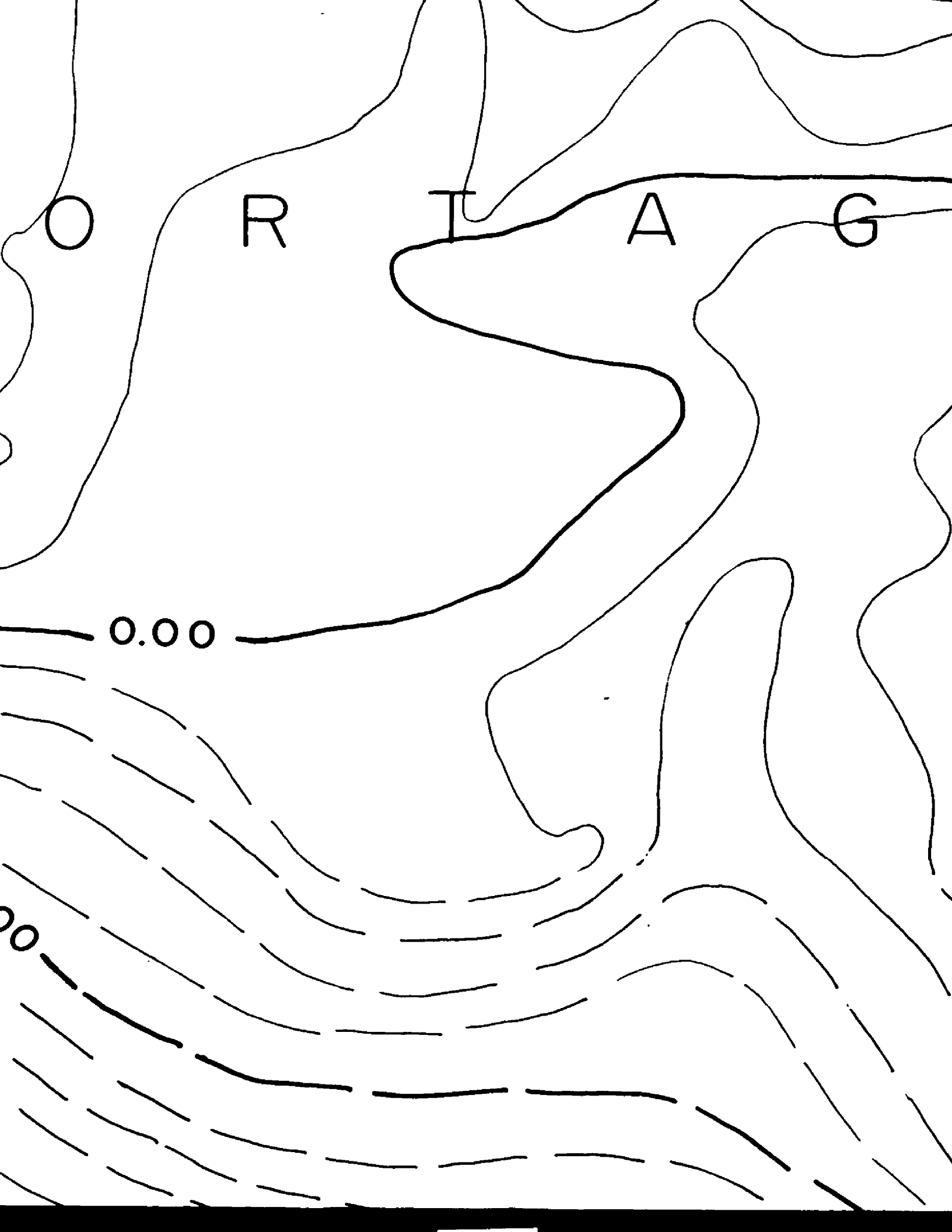


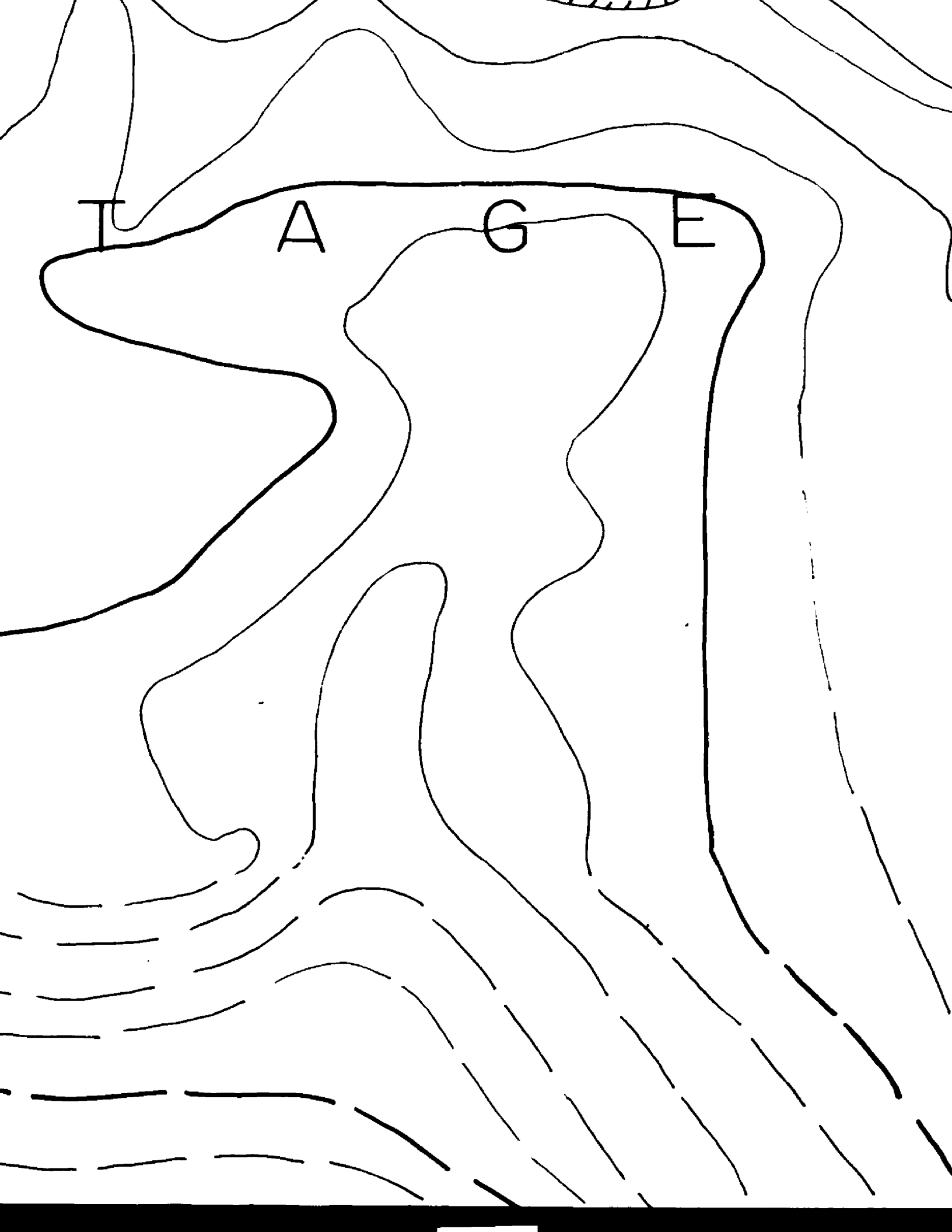






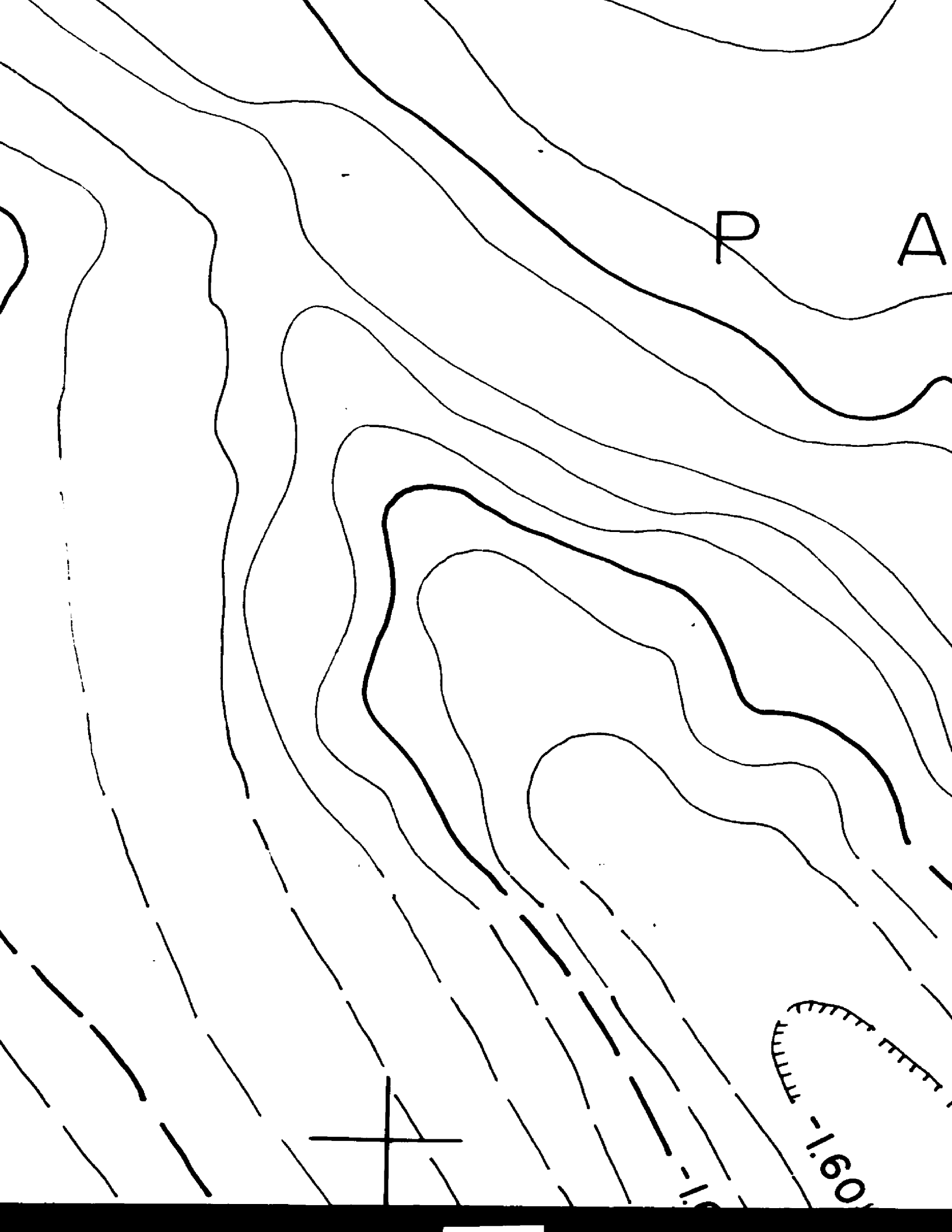






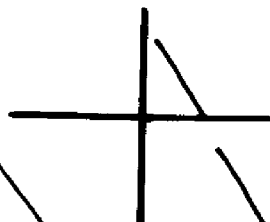




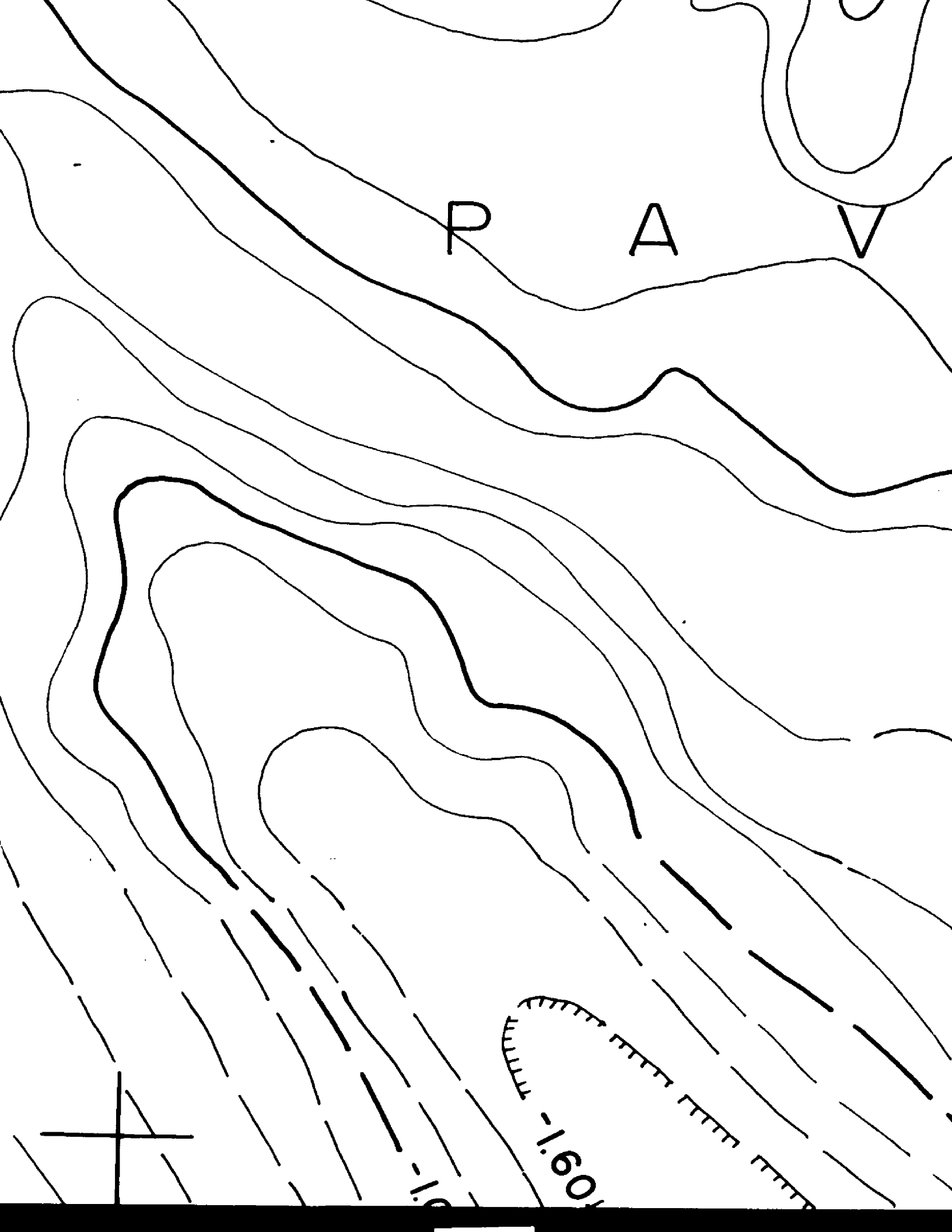


P

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-1.60



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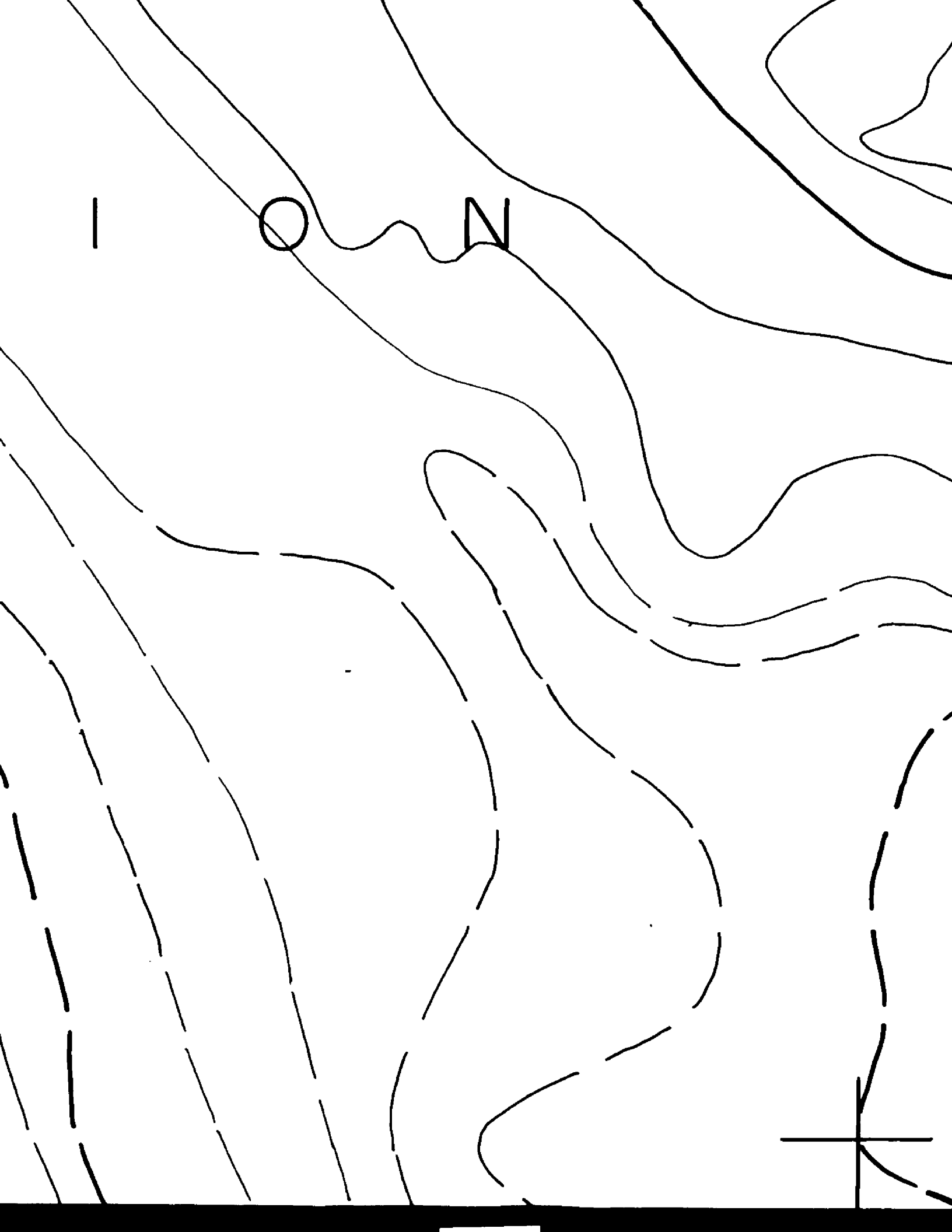


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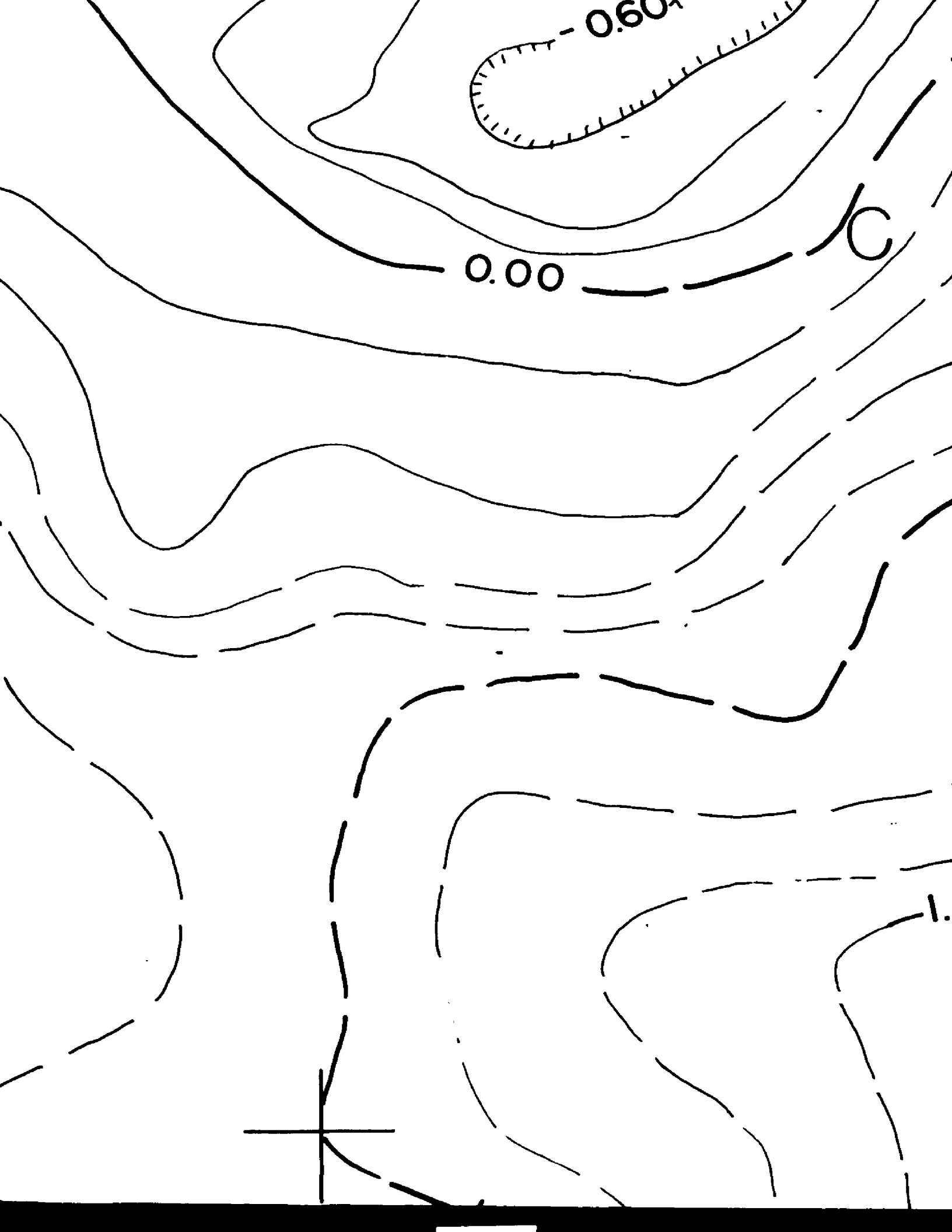
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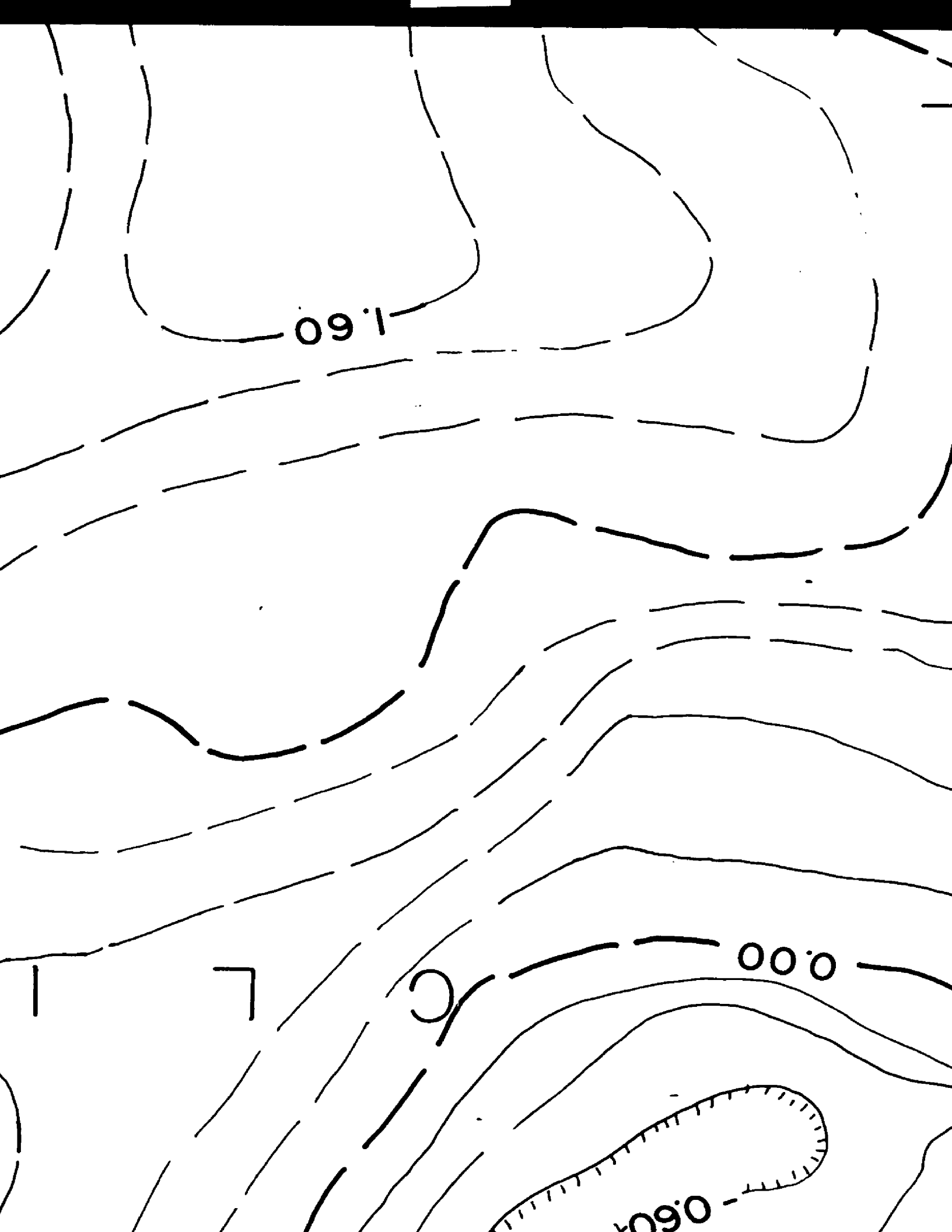
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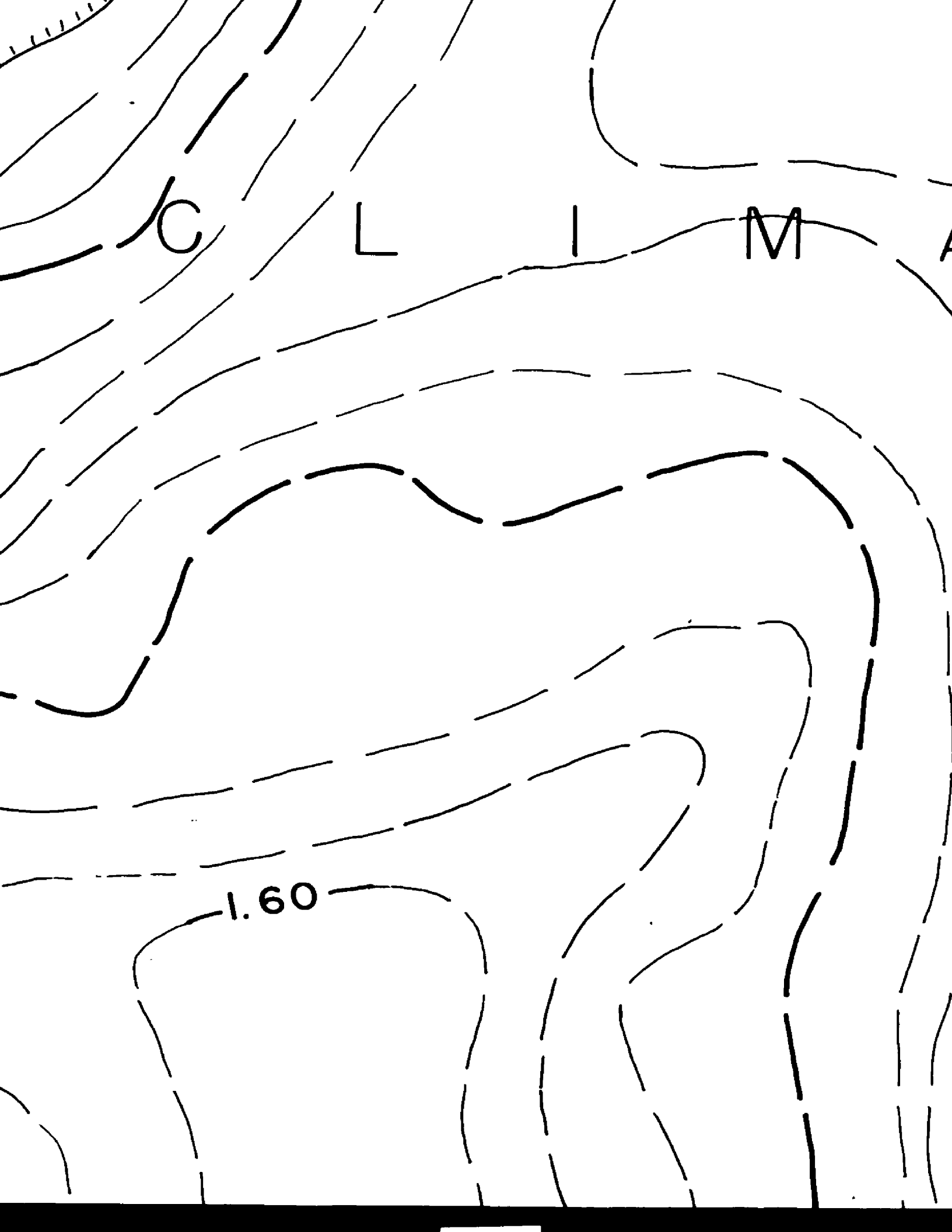
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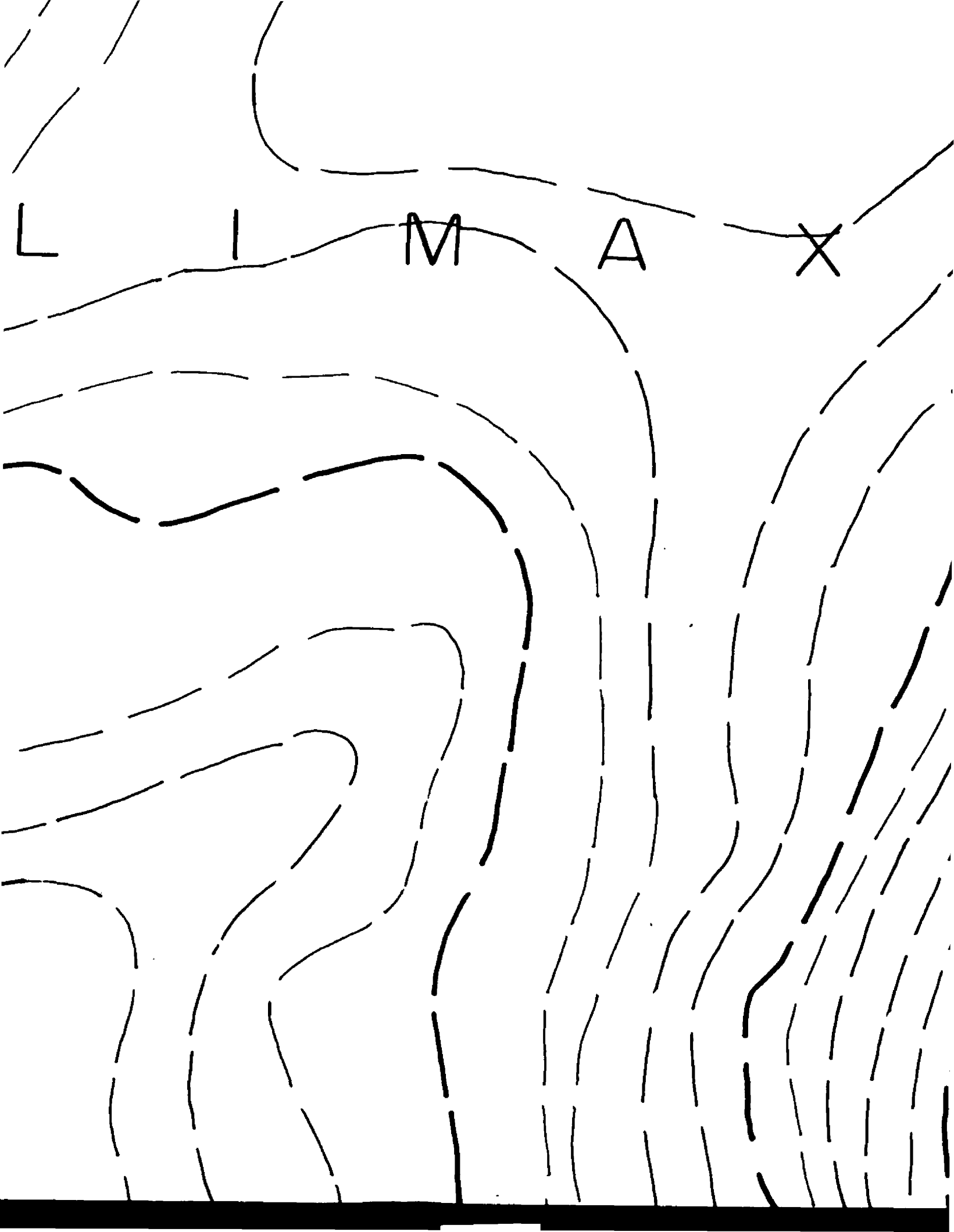












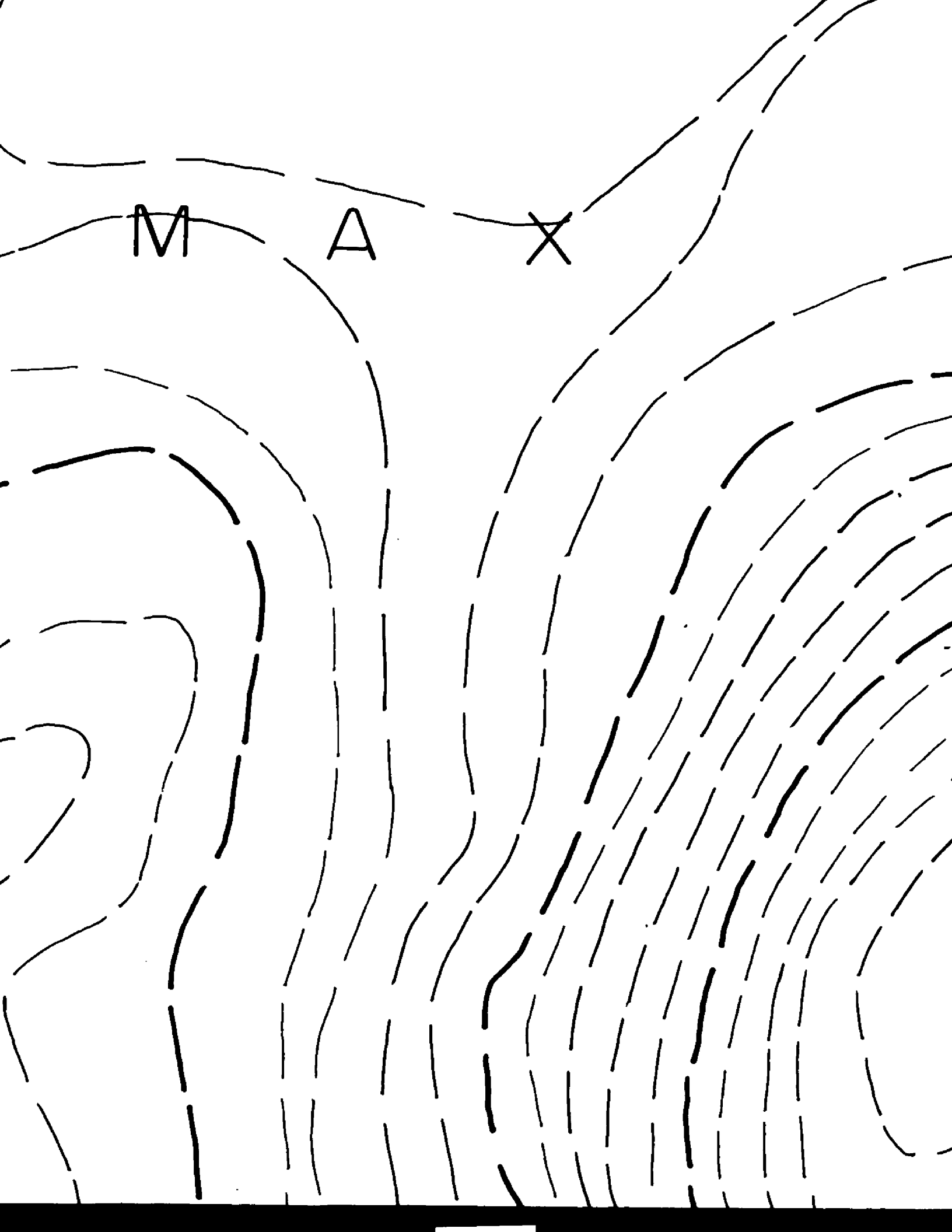
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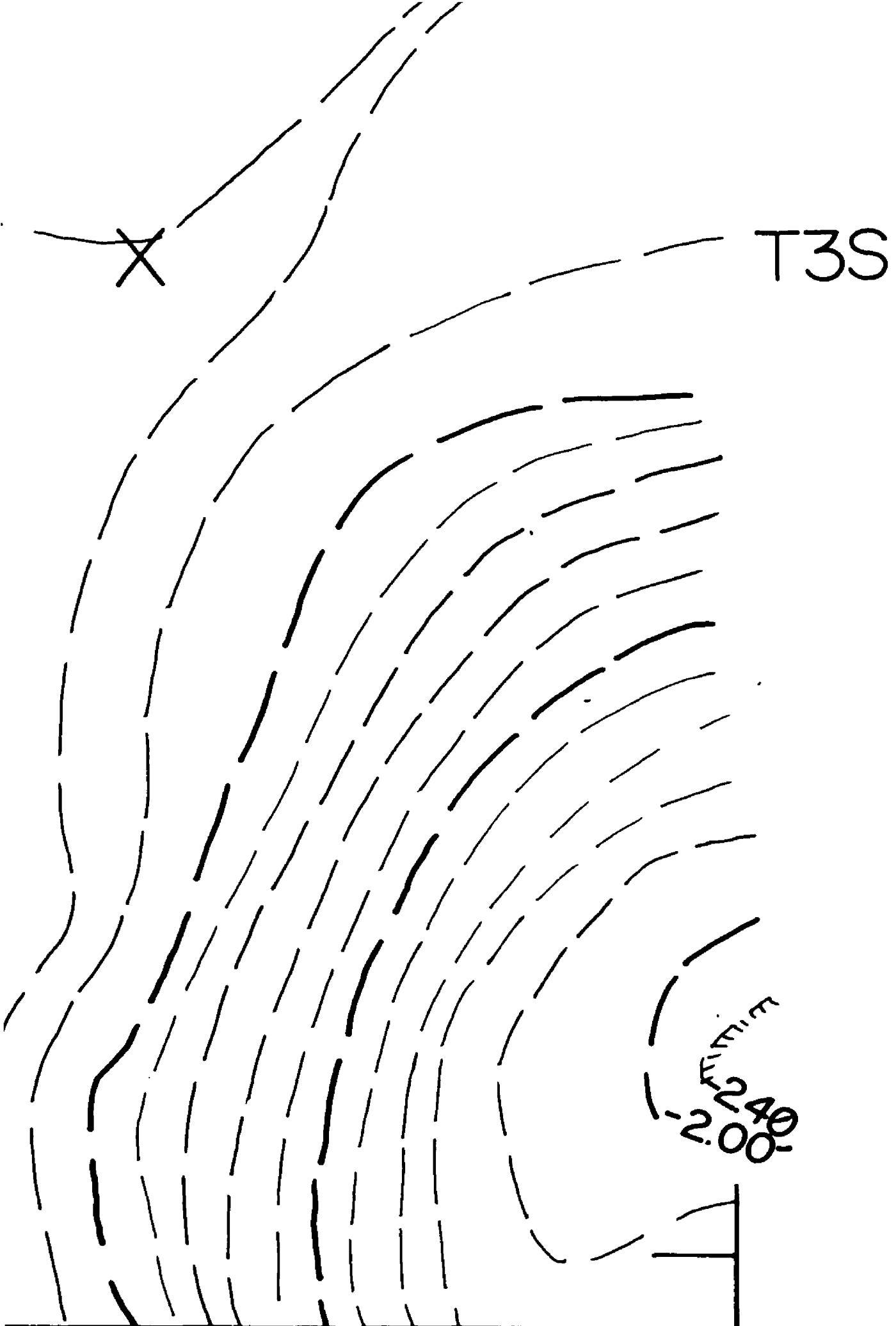
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M

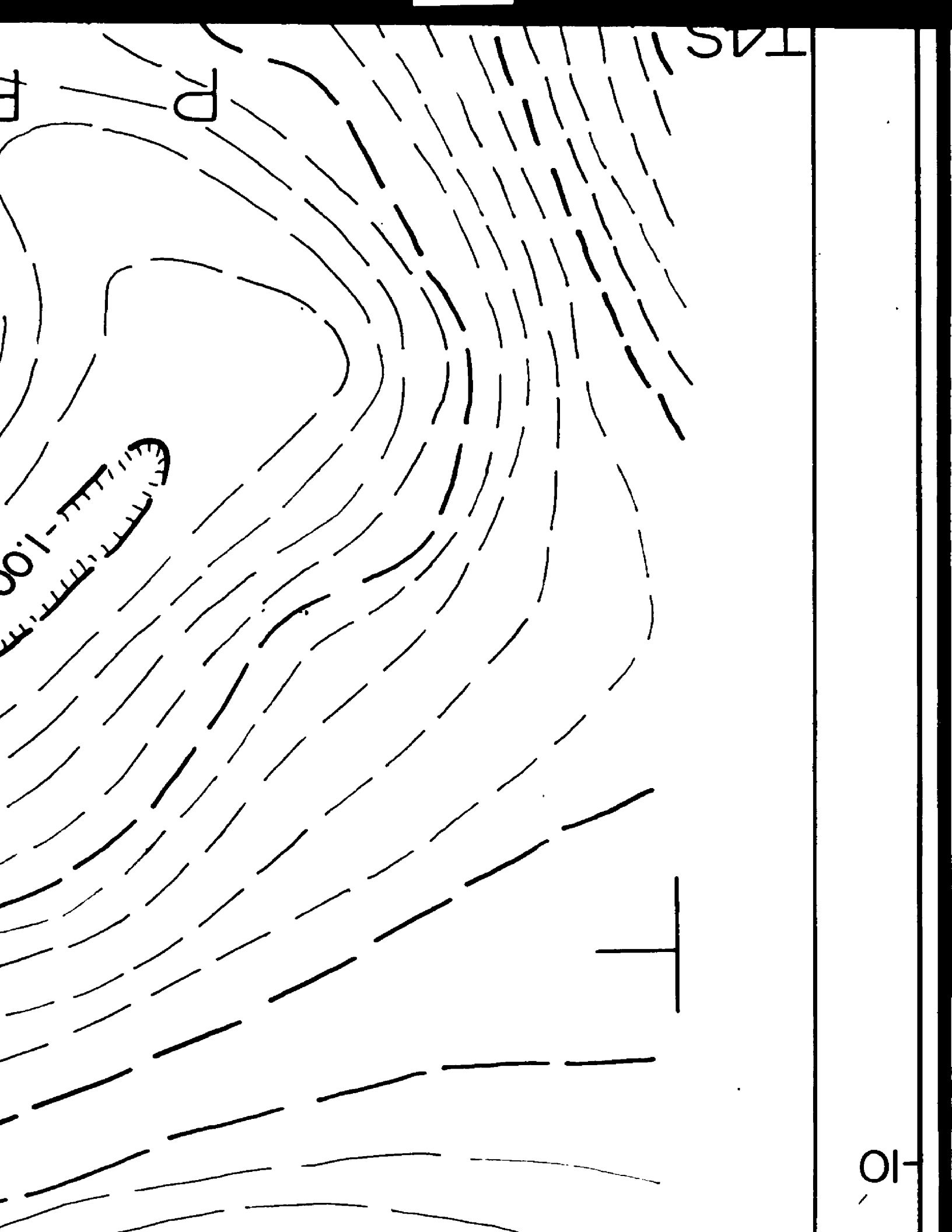
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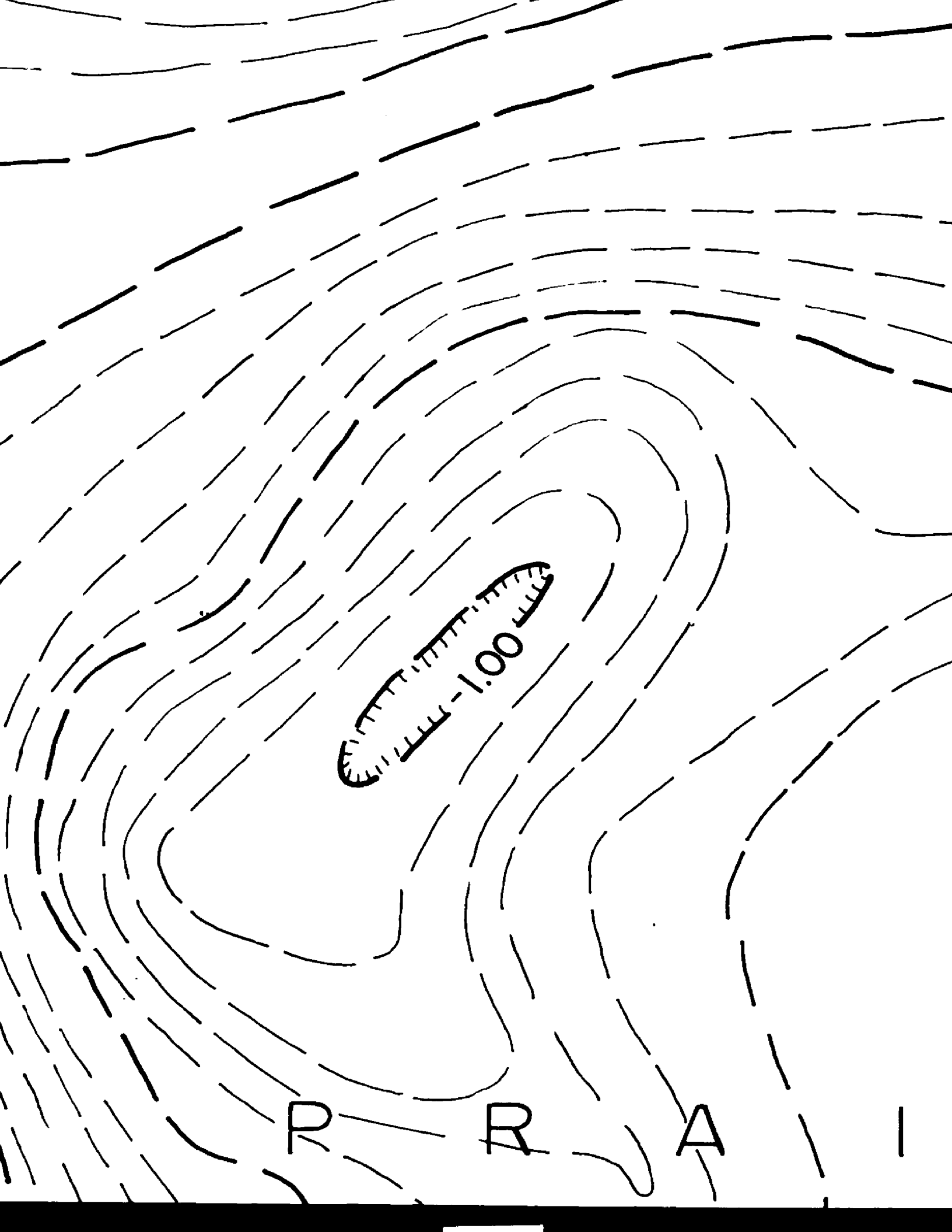
X





10'



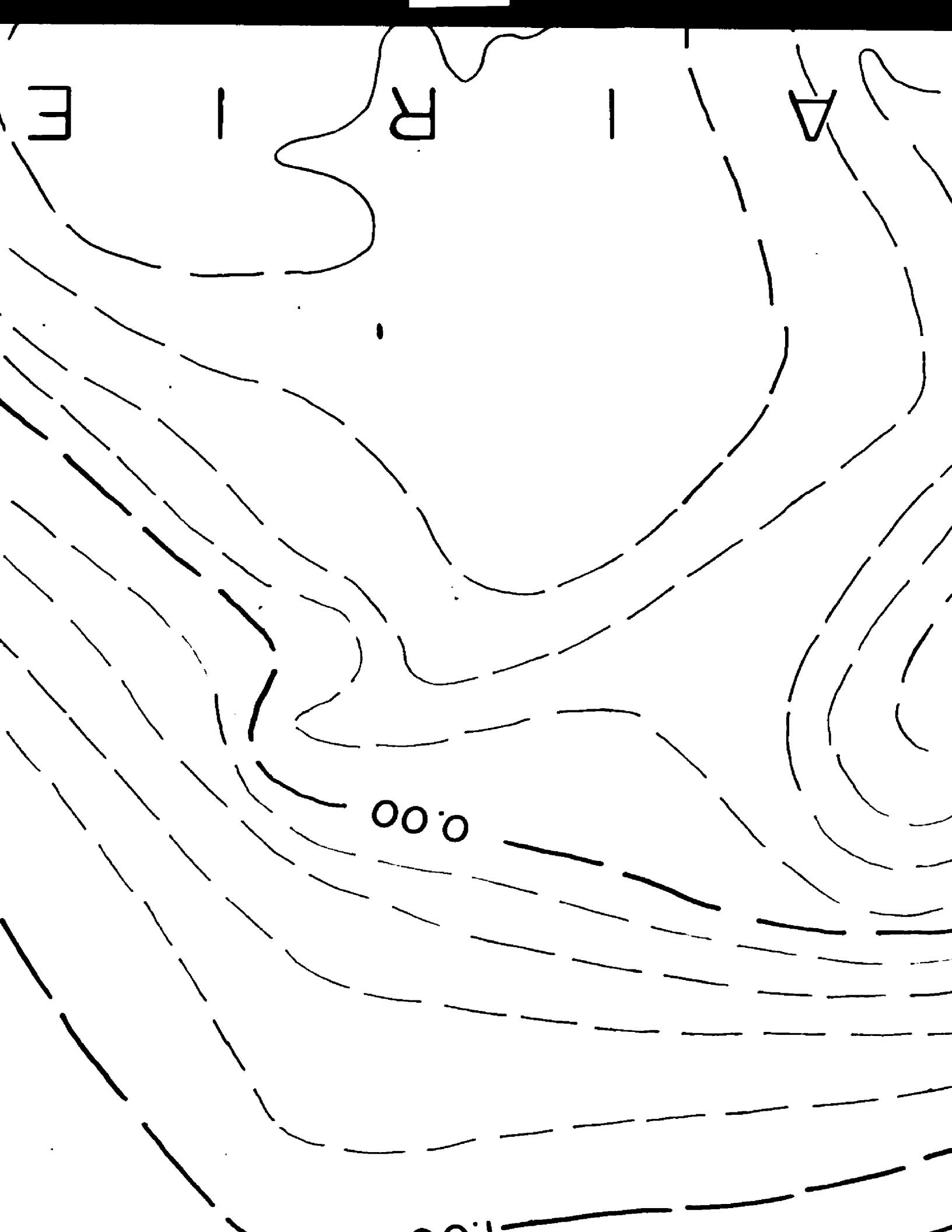


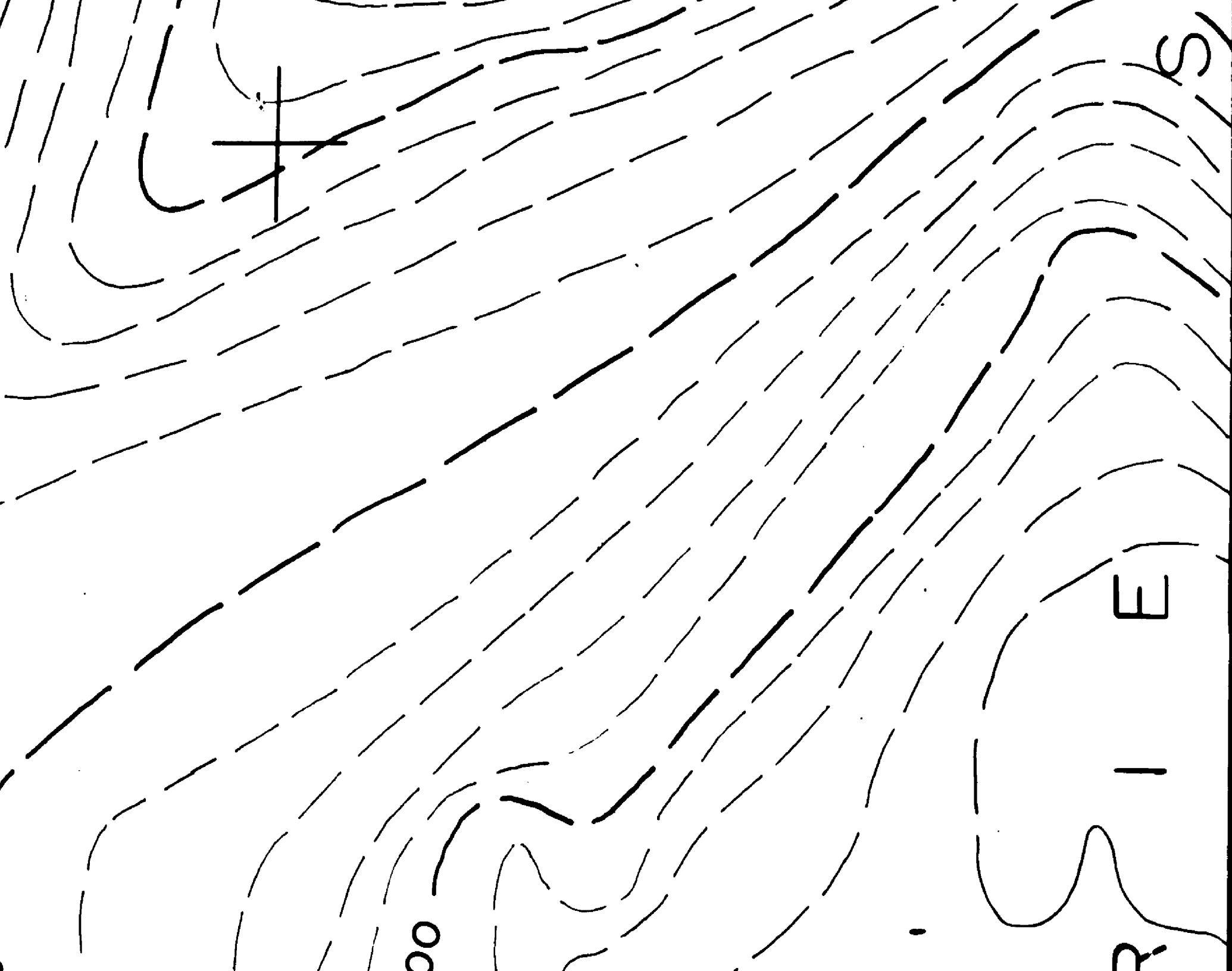
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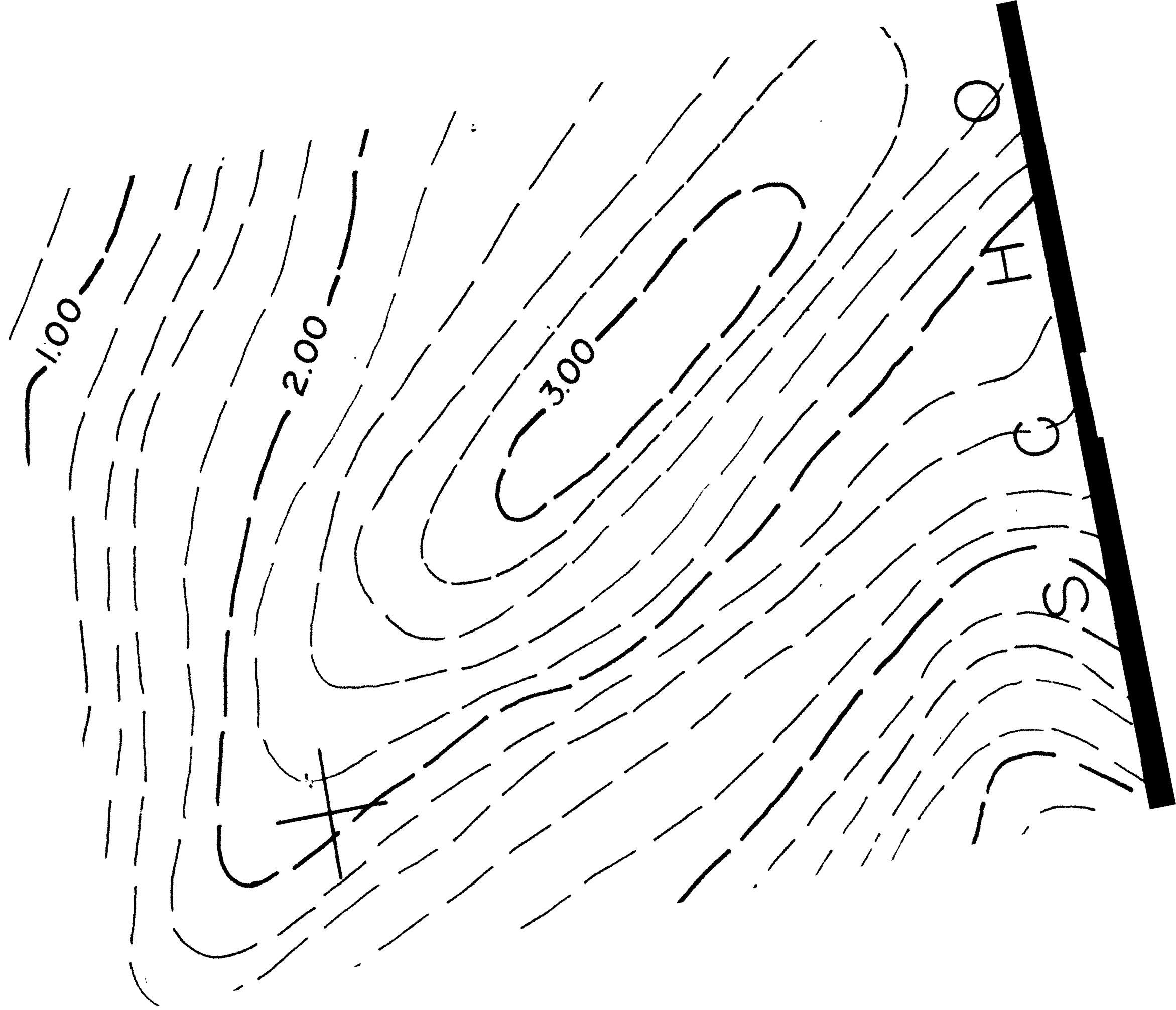
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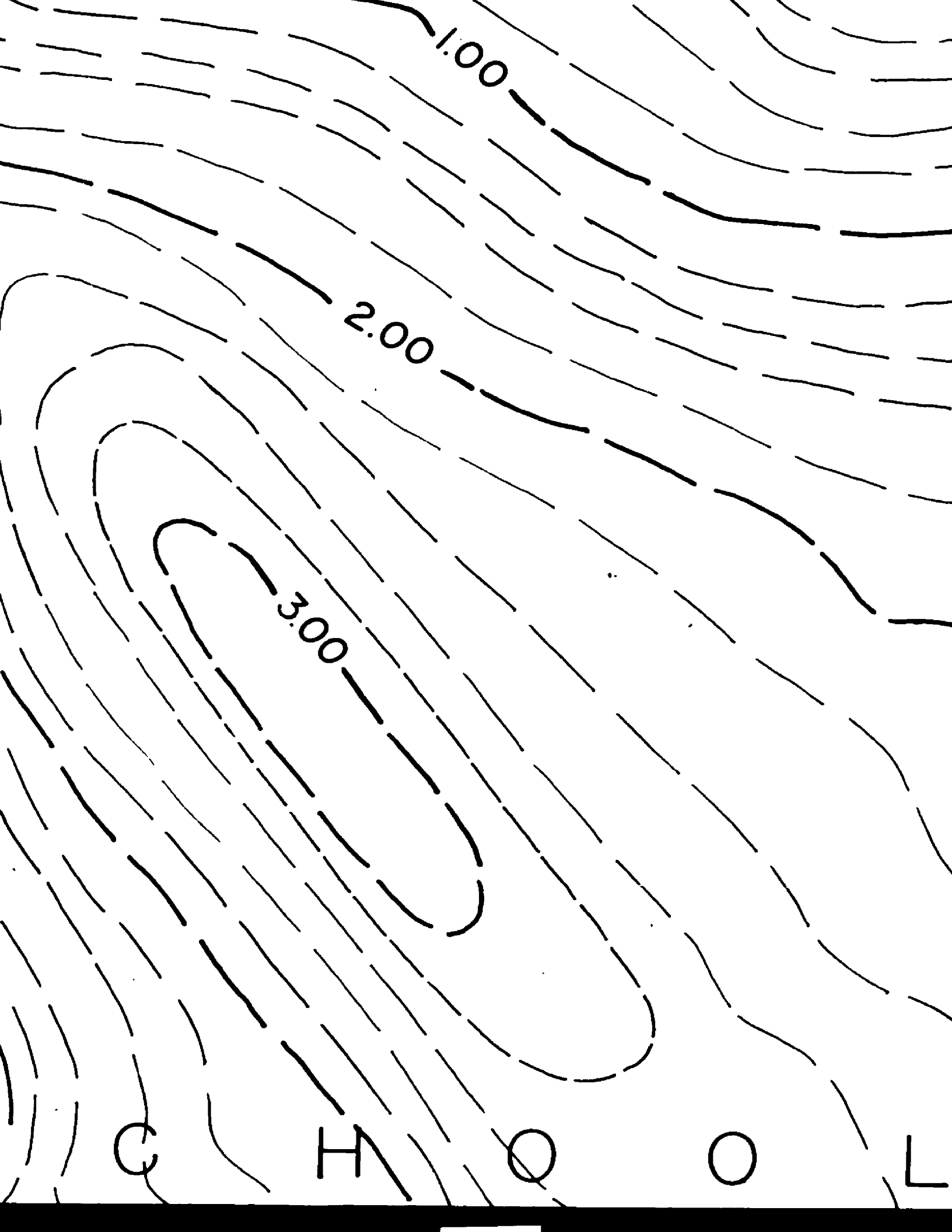
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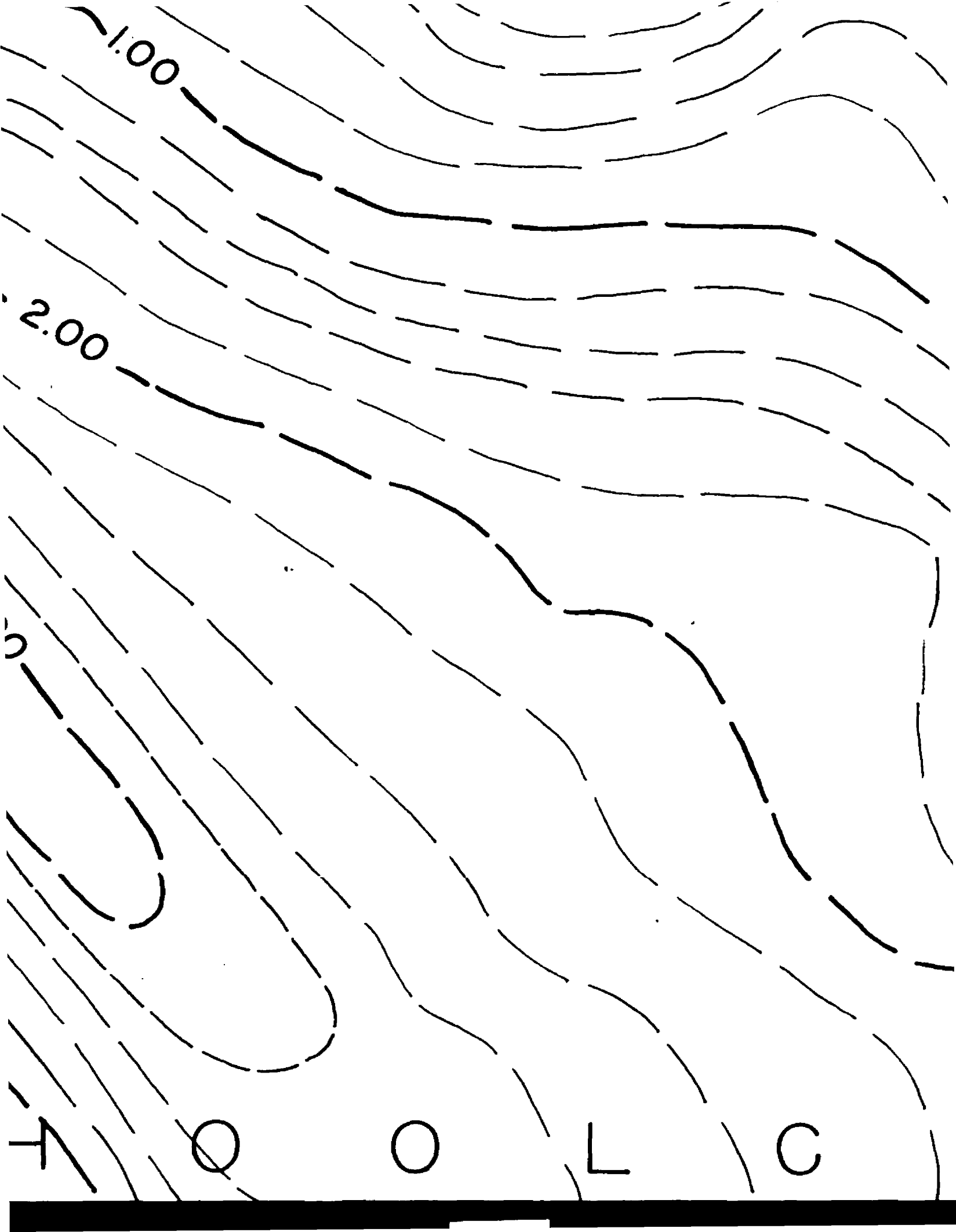
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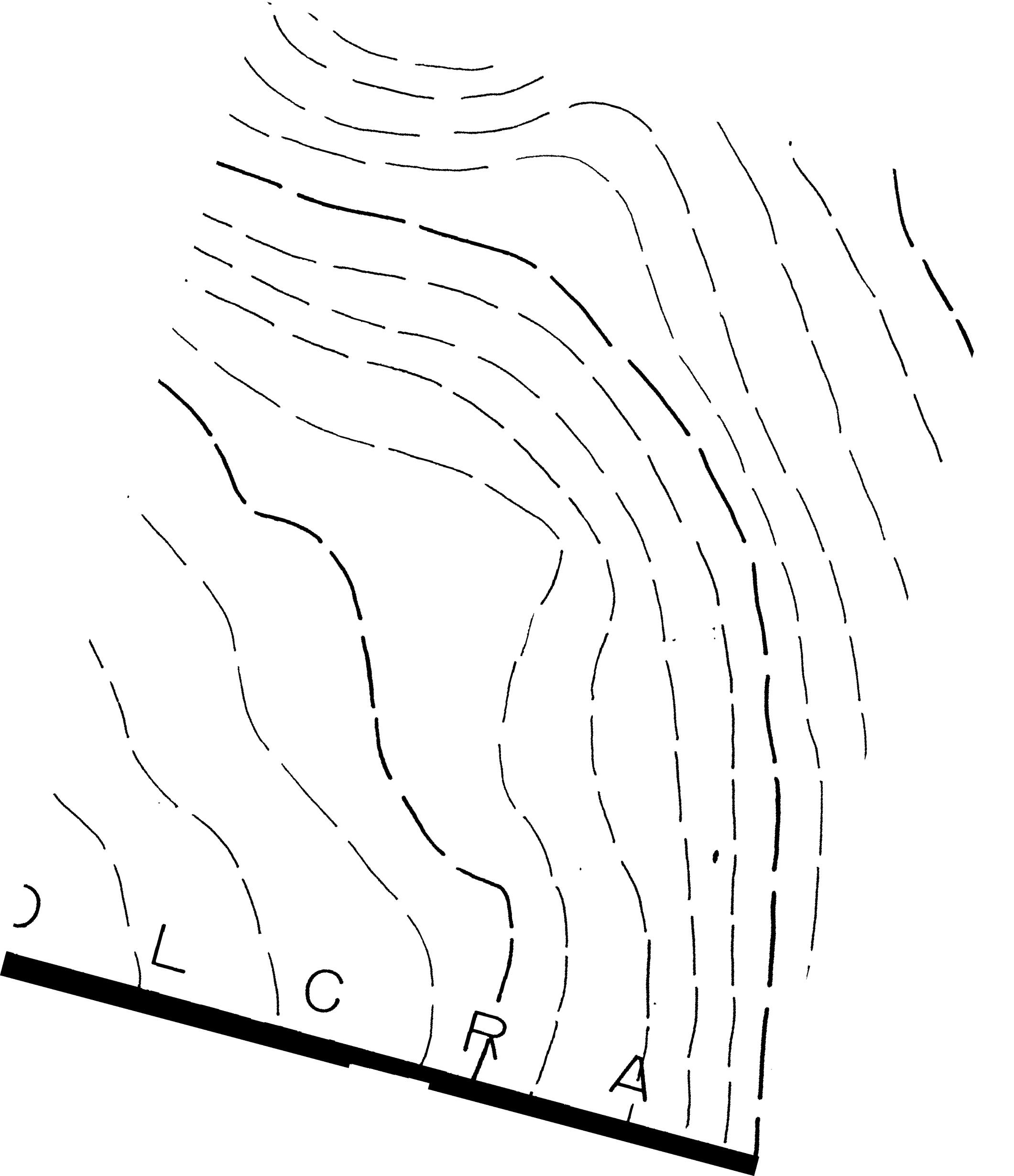


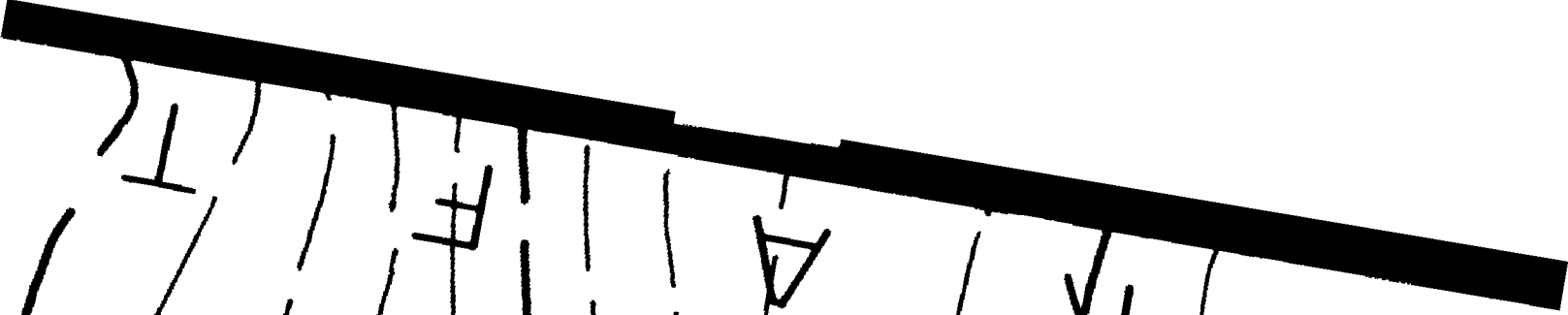












C

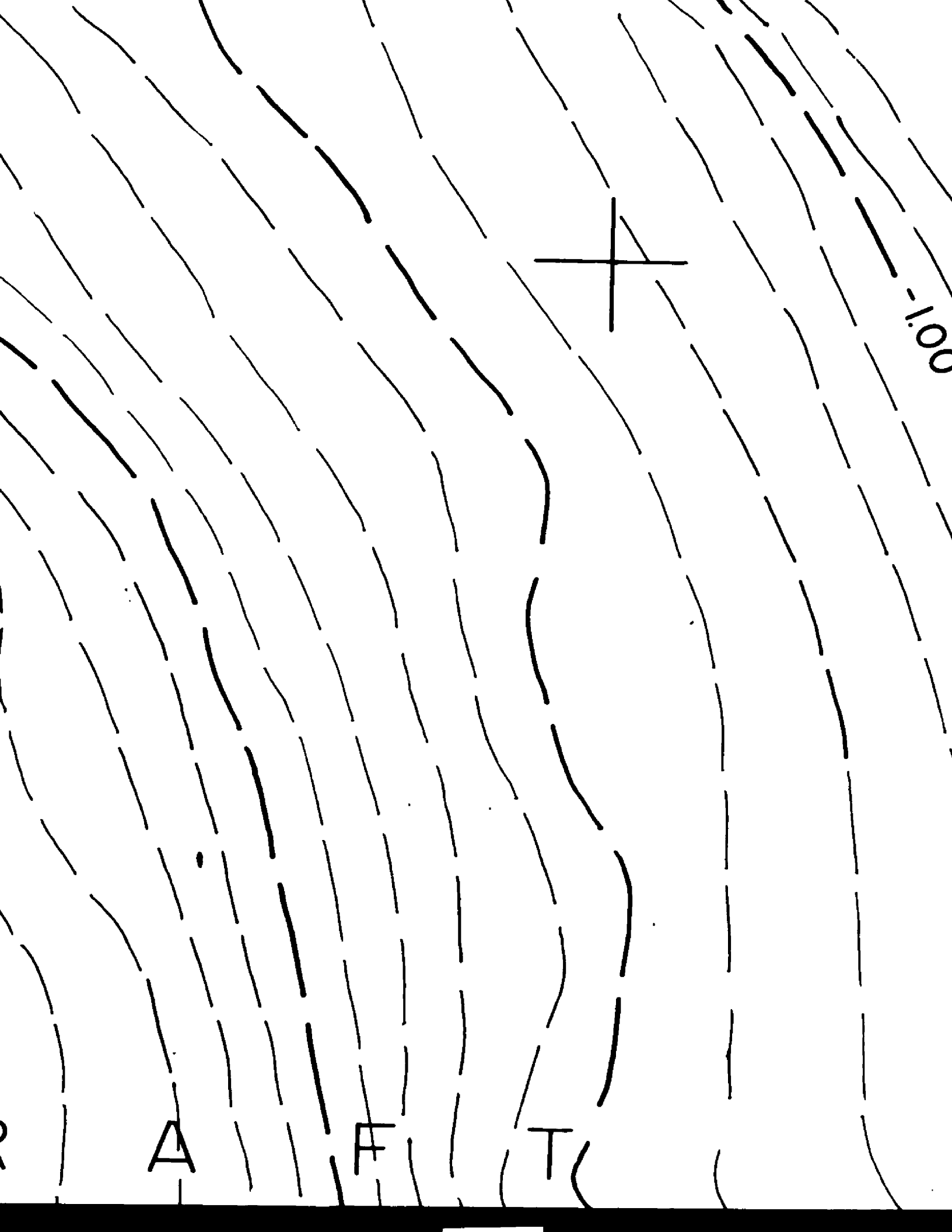
B

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X

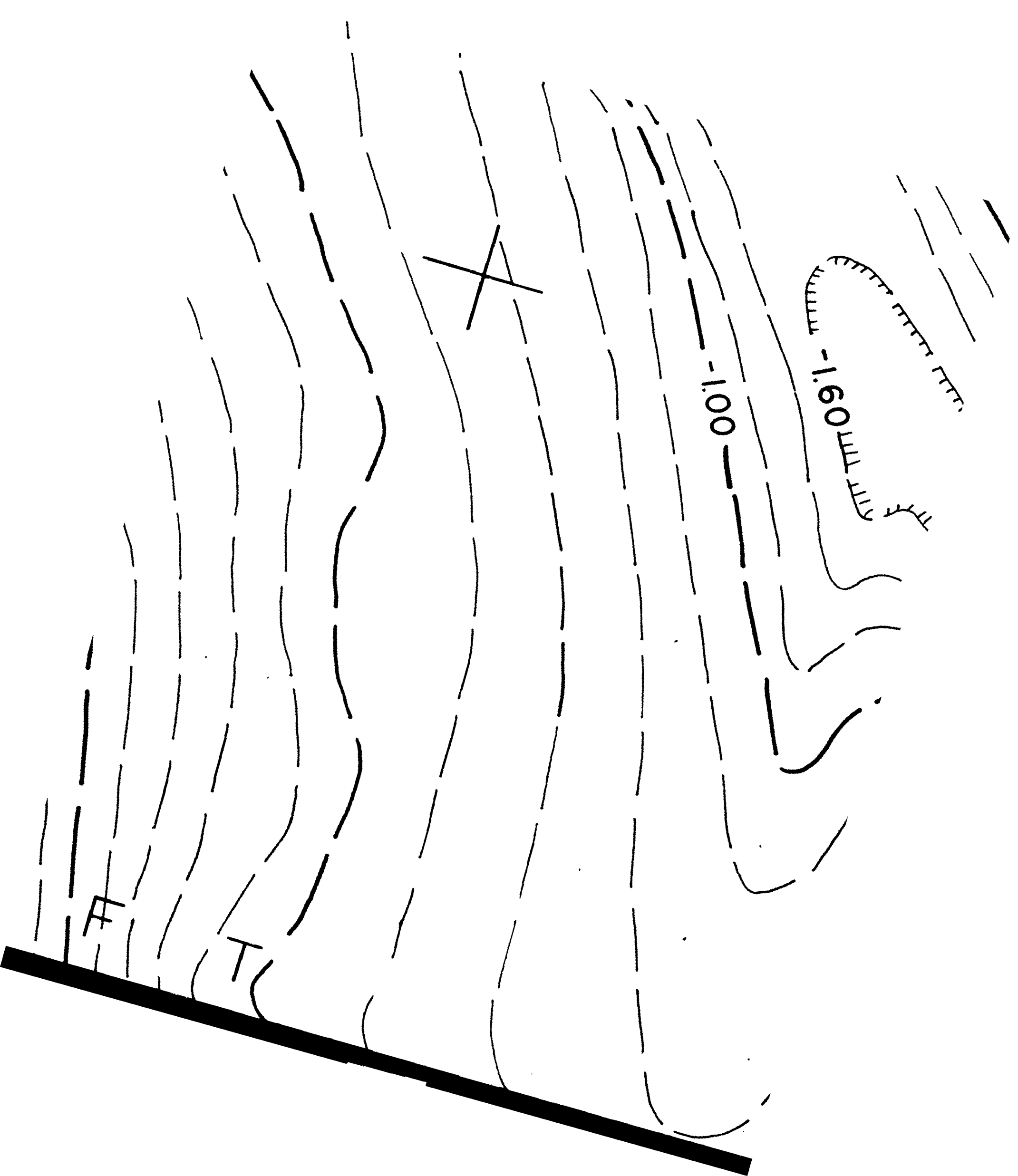


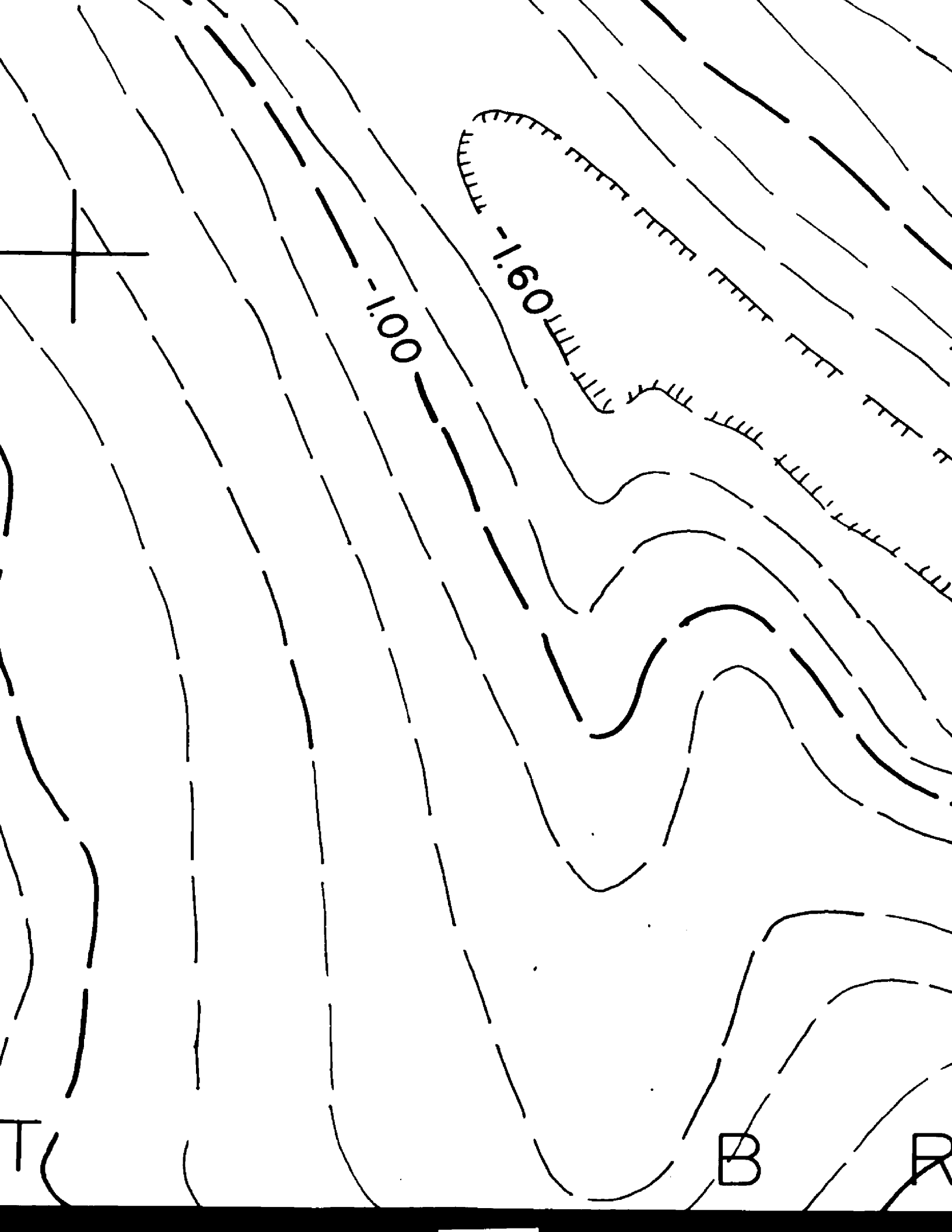
100-

A

F

T

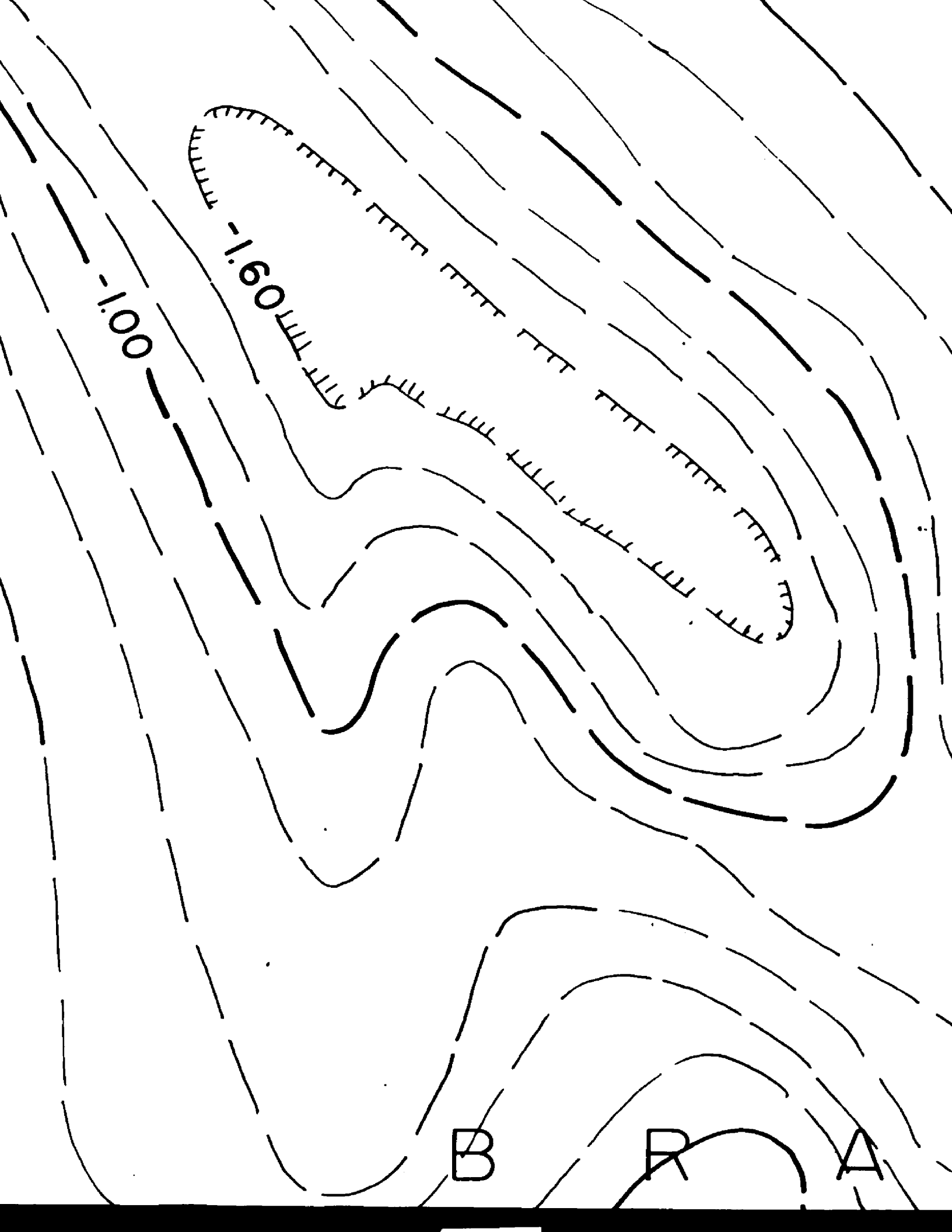


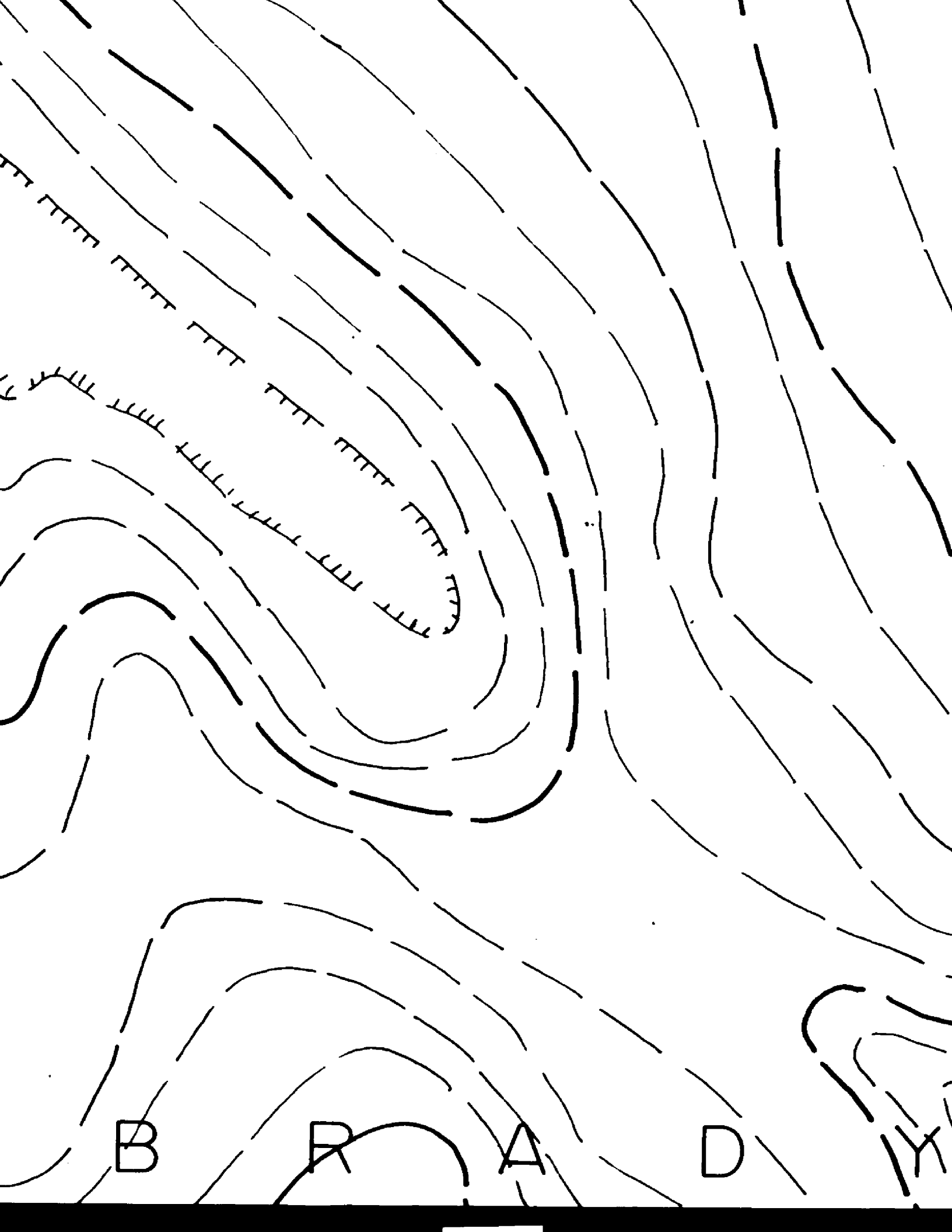


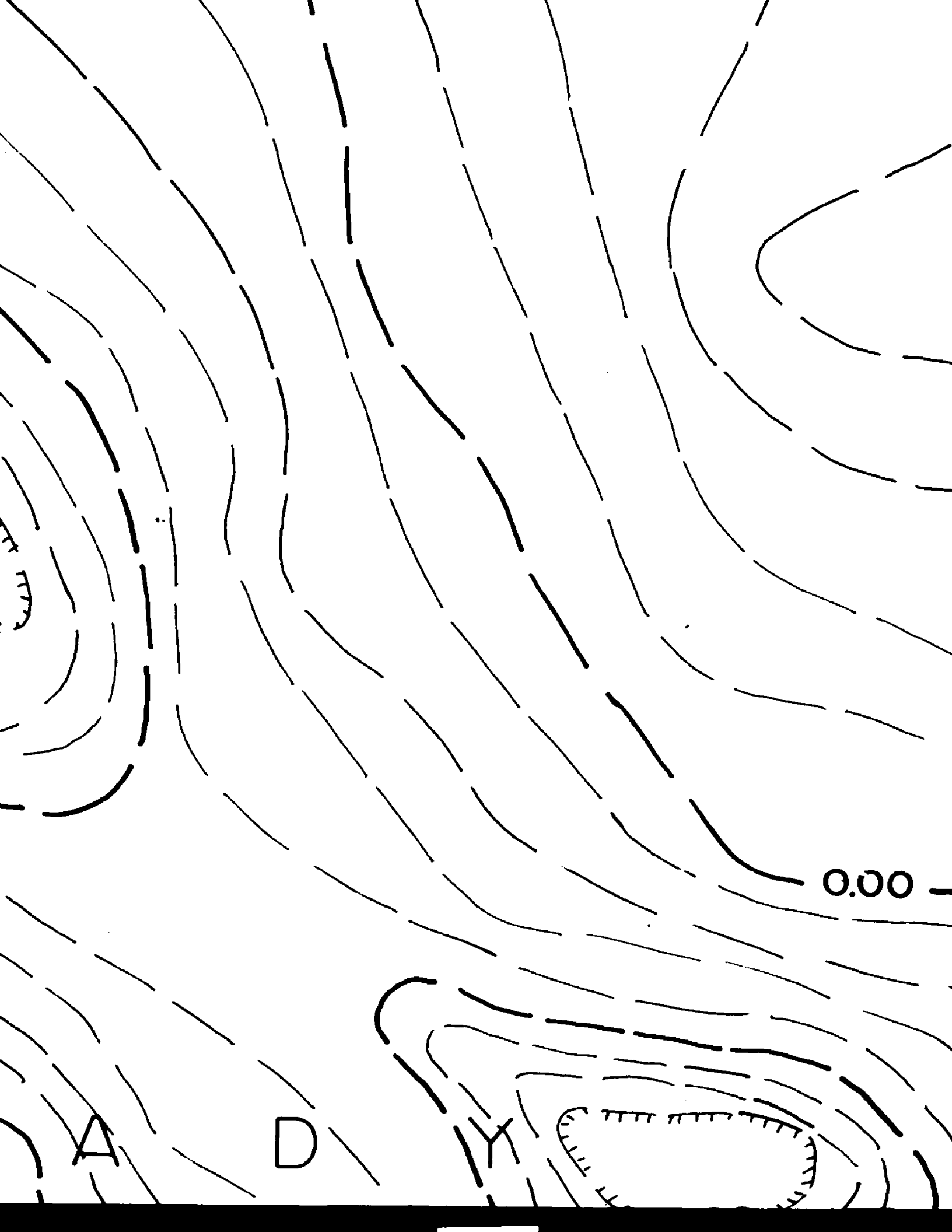
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B

R





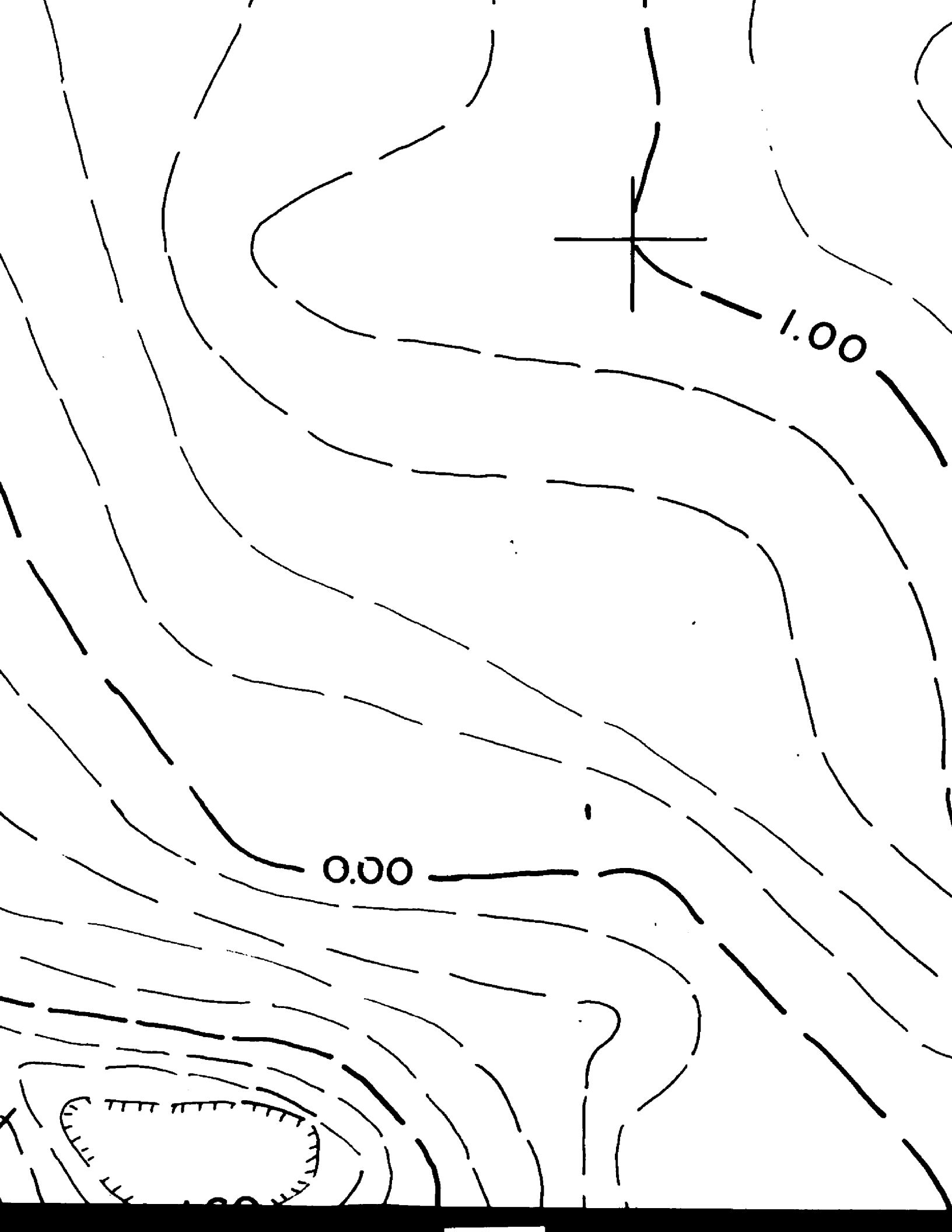


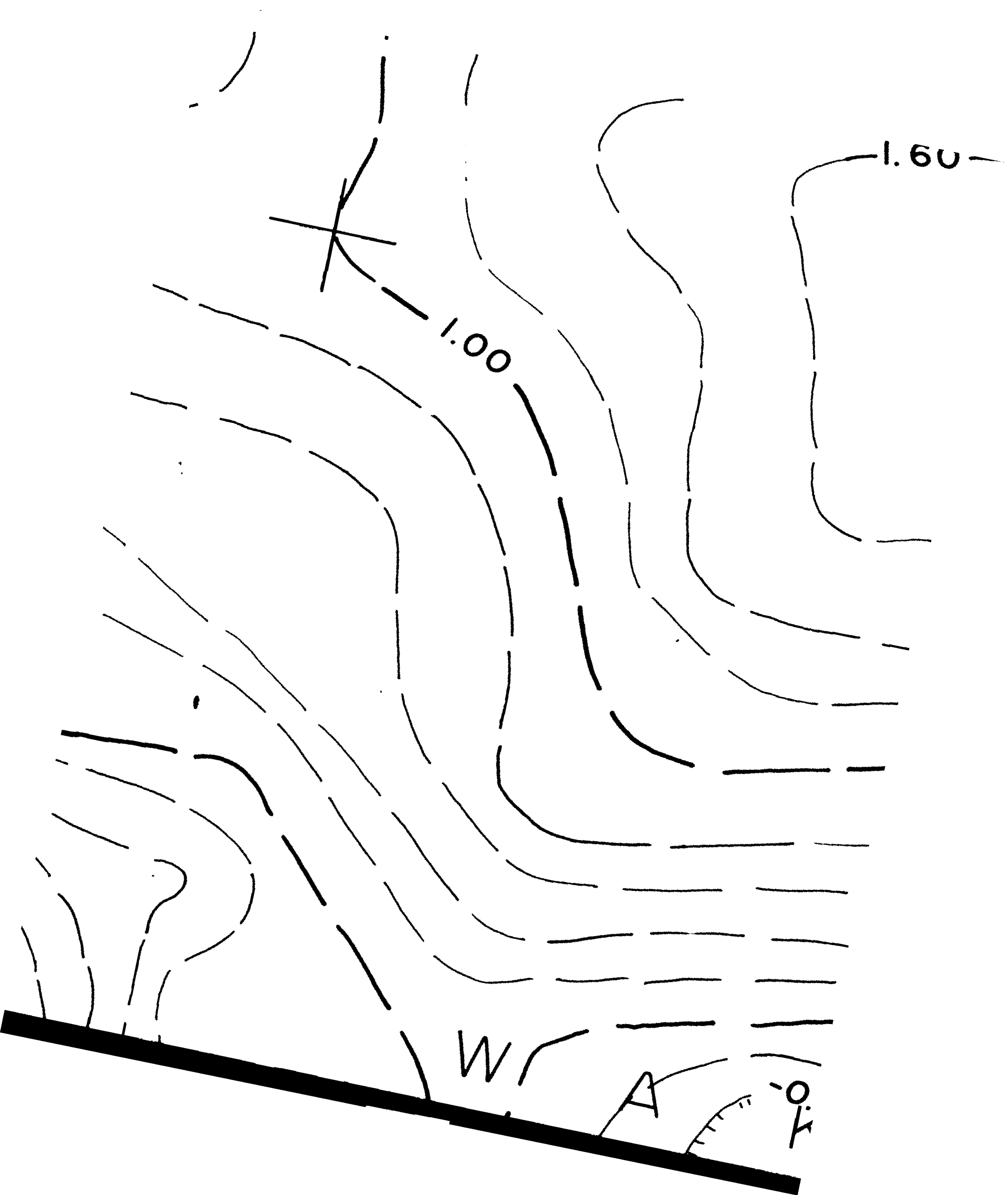
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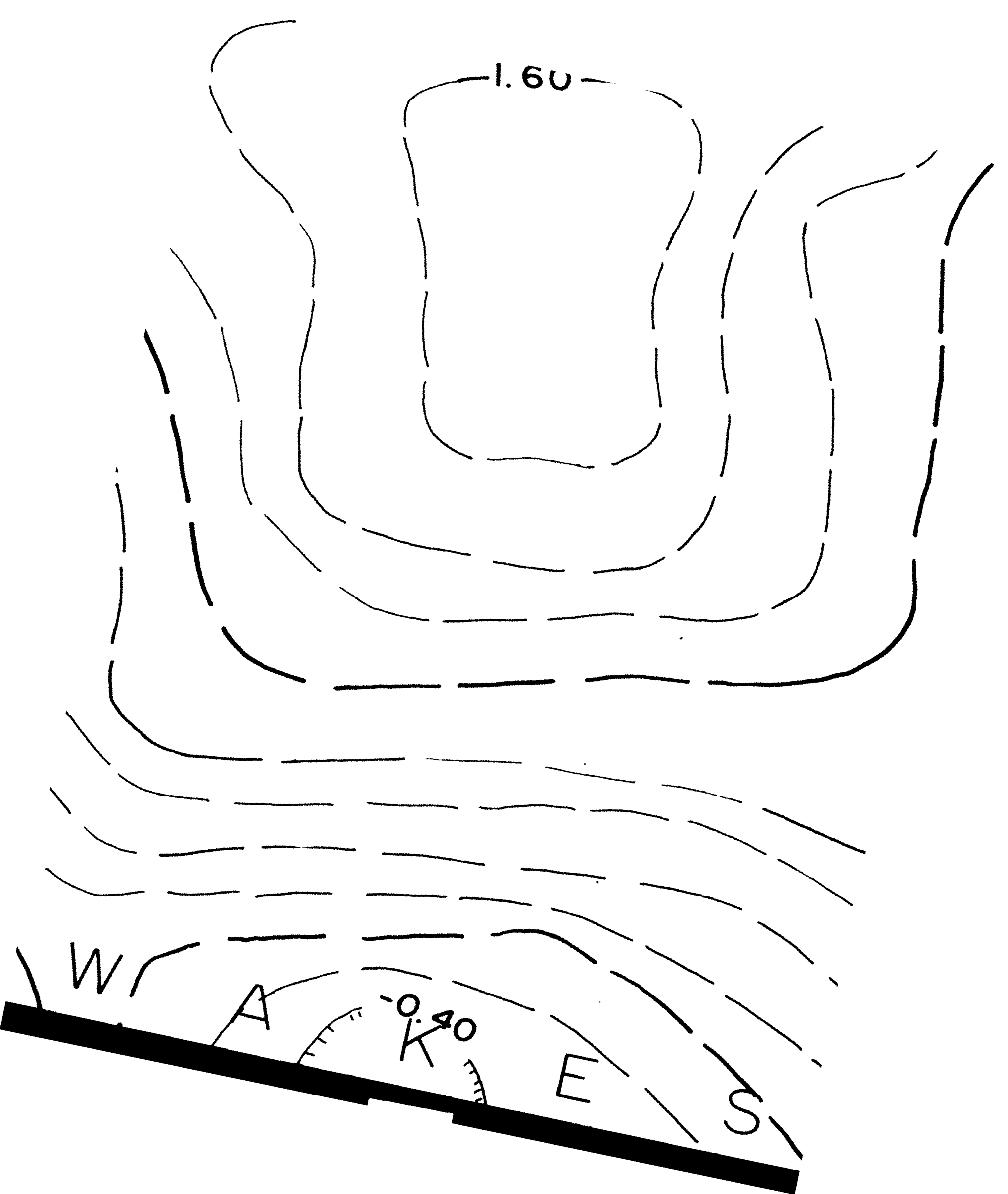
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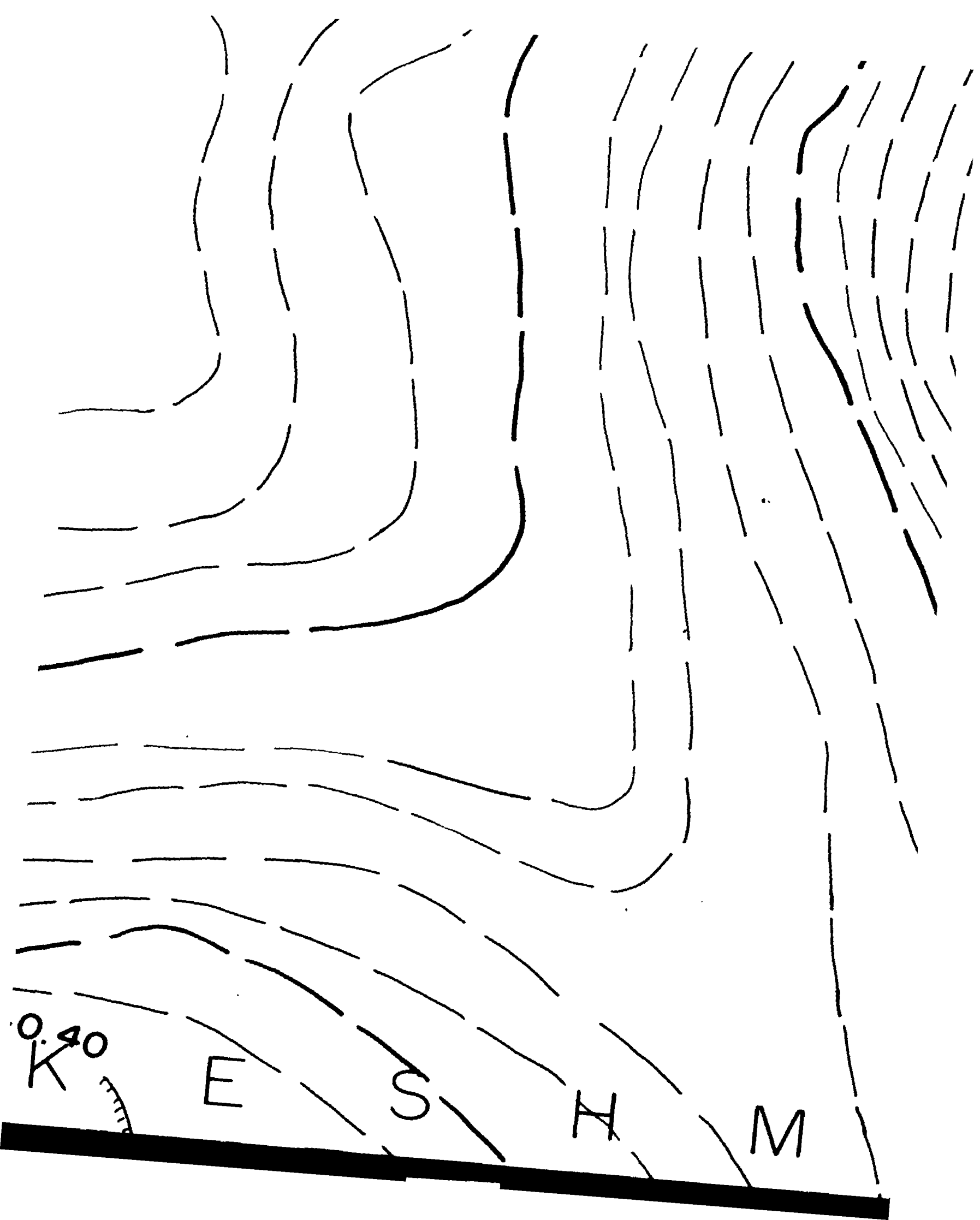
D

H









III

S

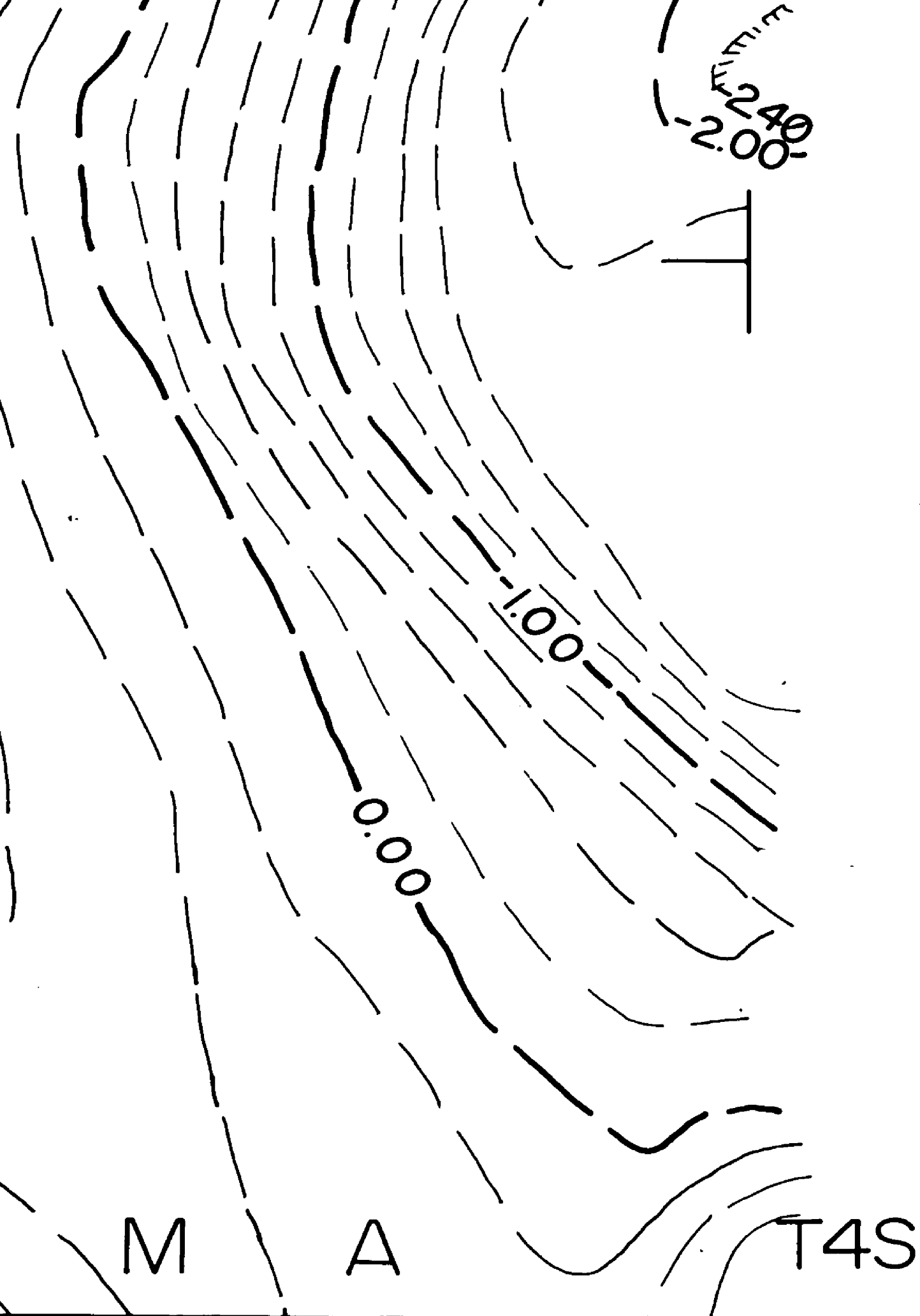
H

M

A

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ic



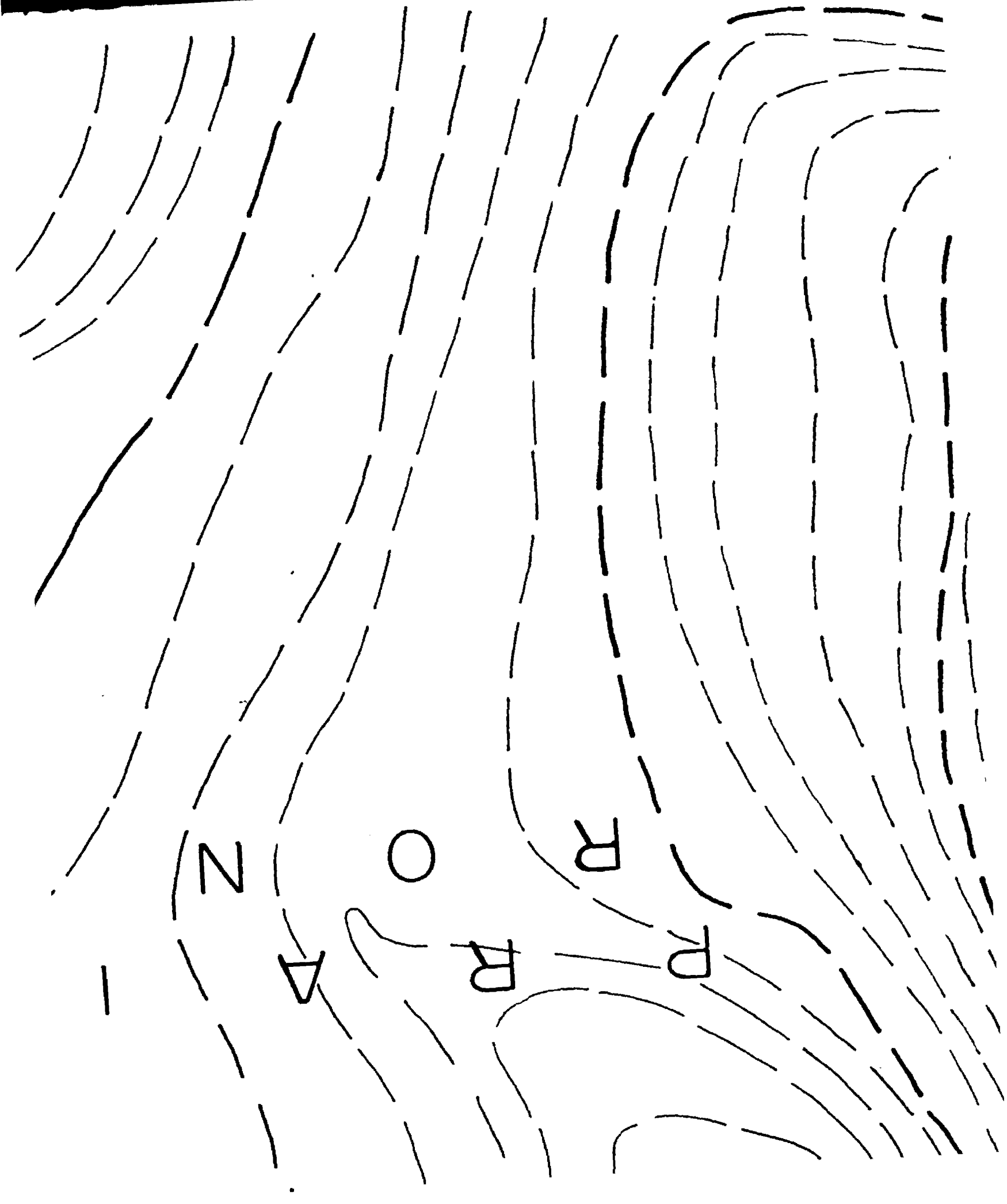
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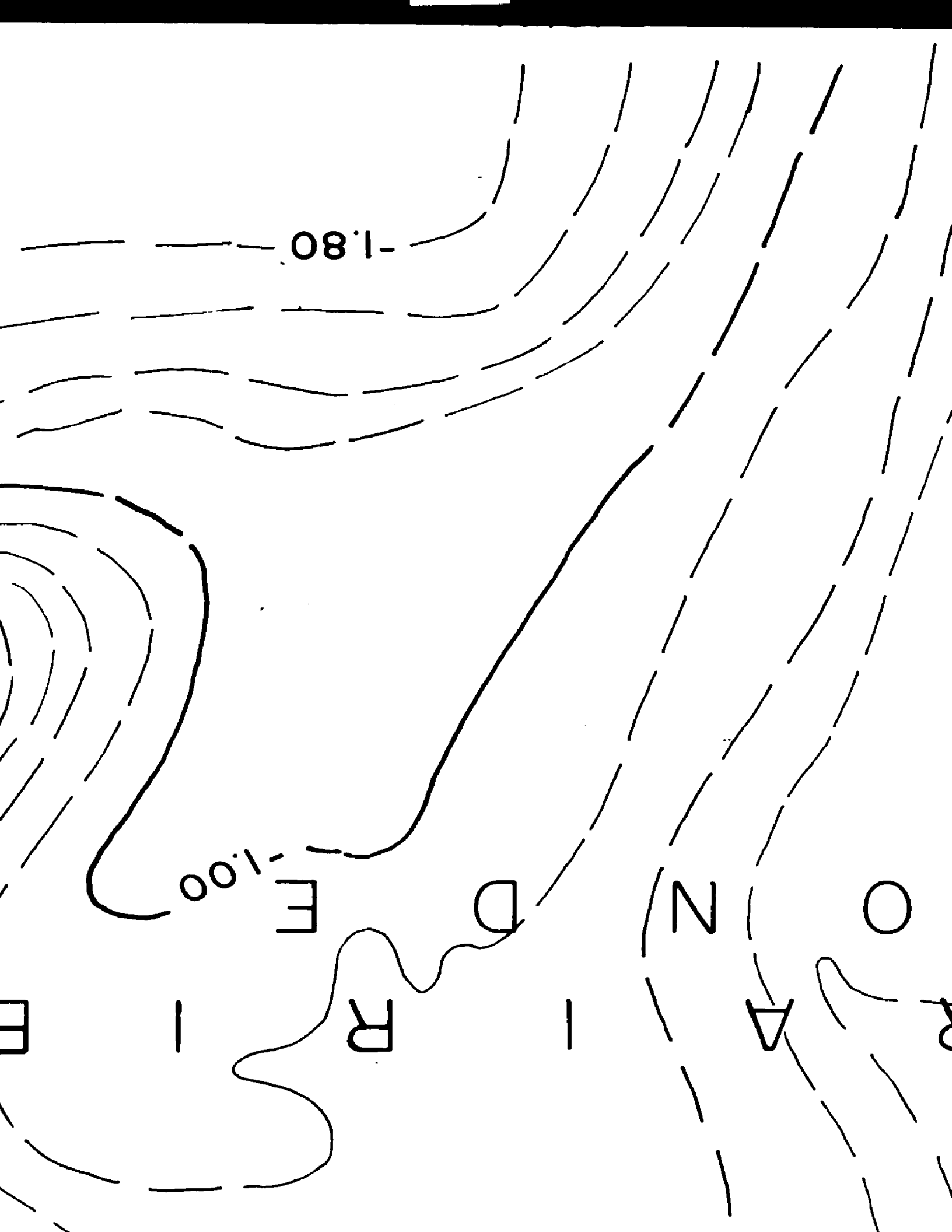
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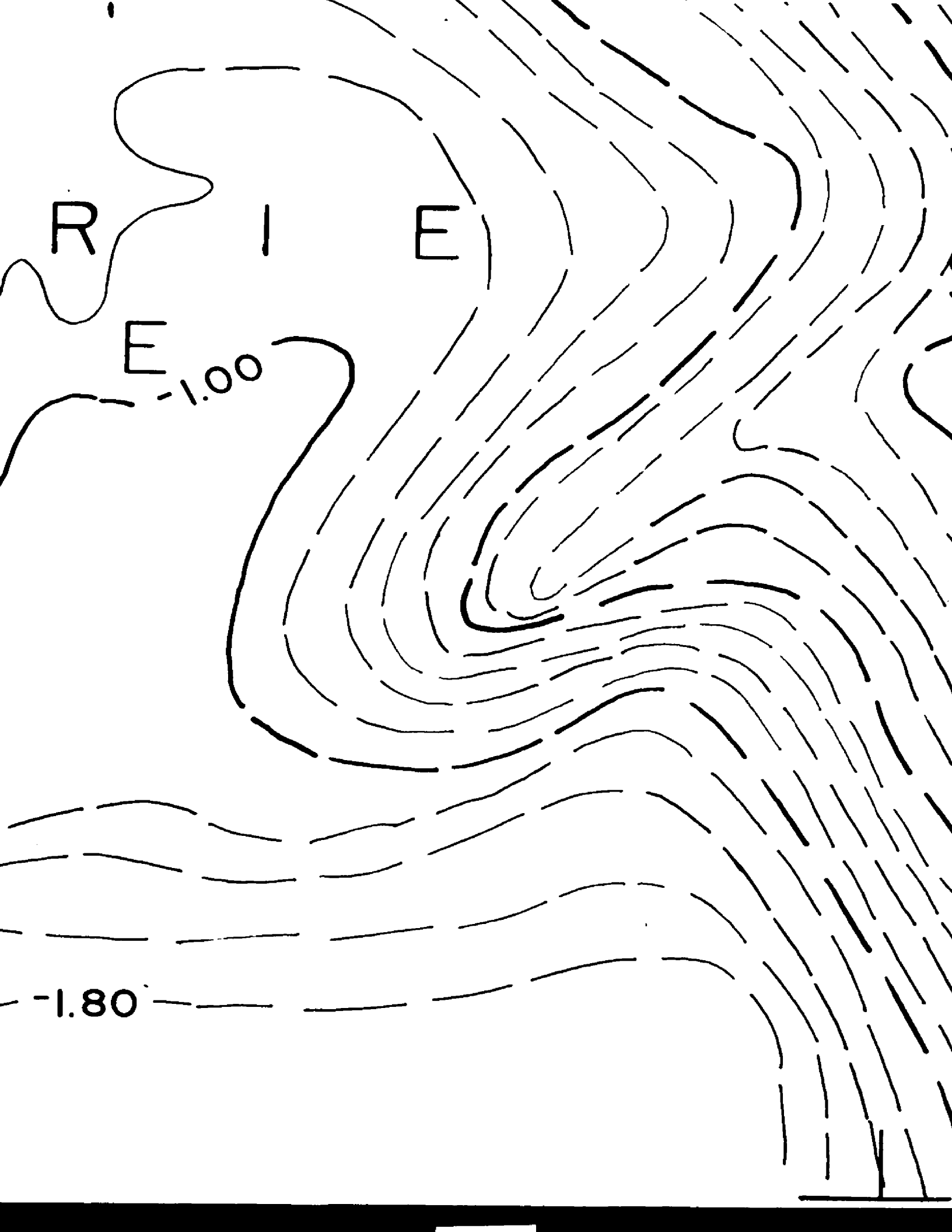
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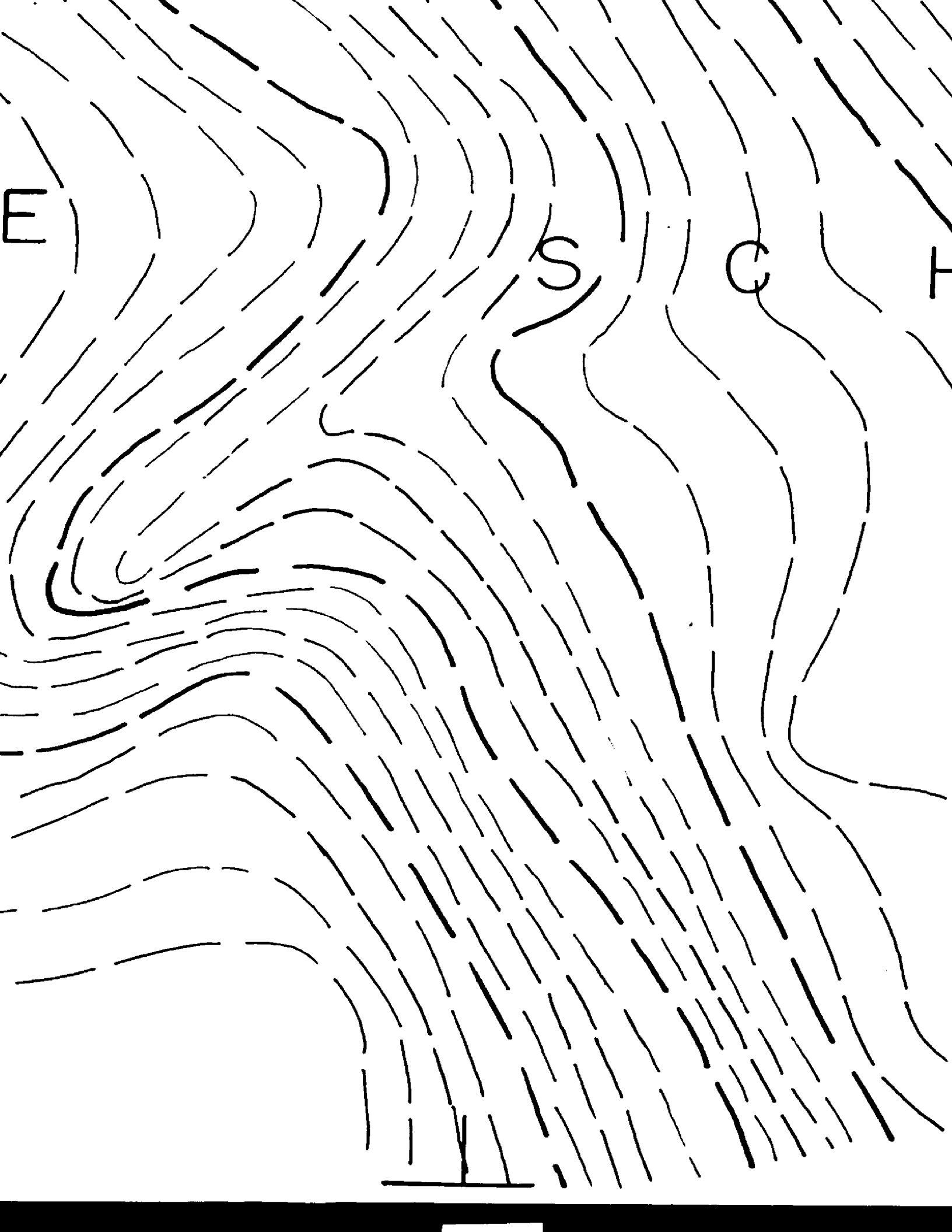
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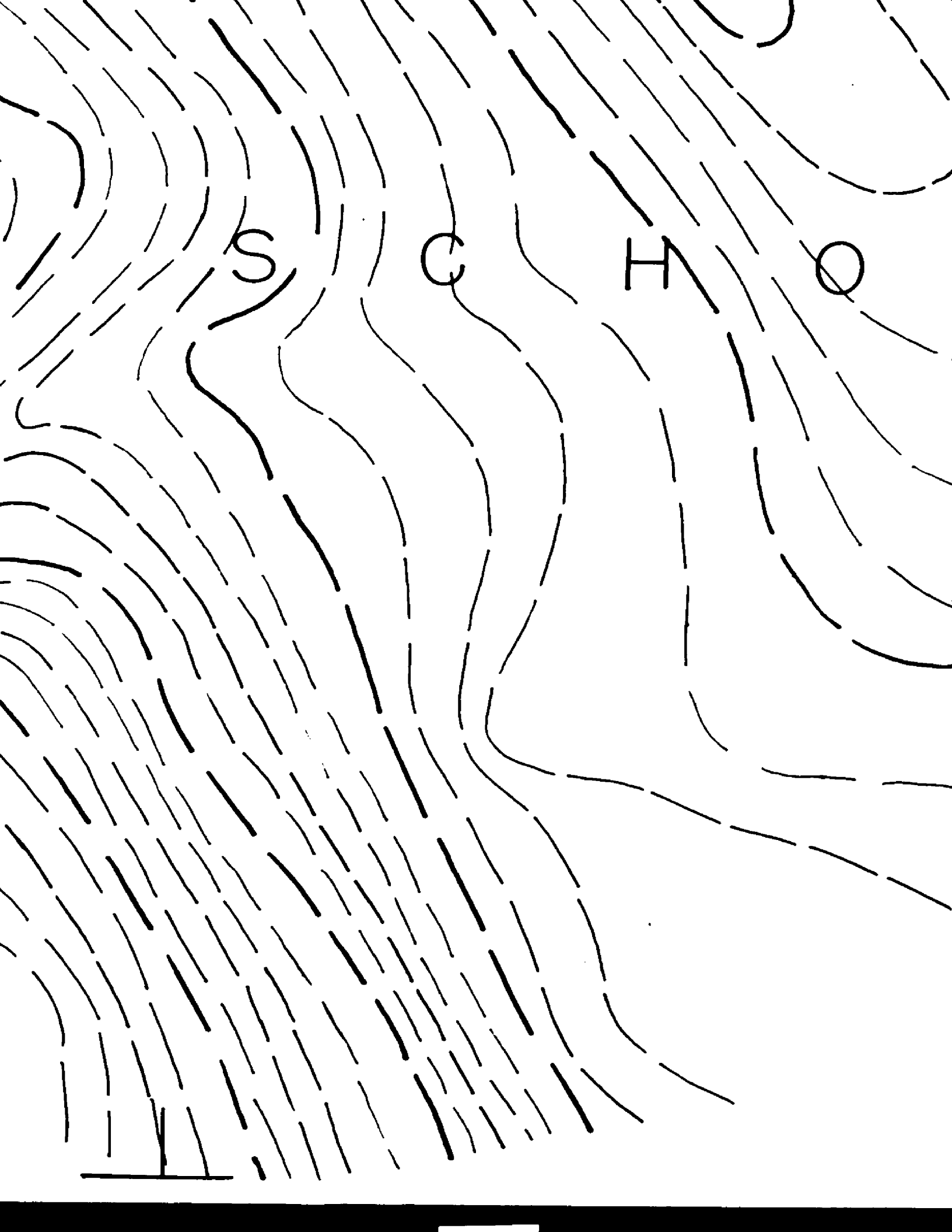
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42

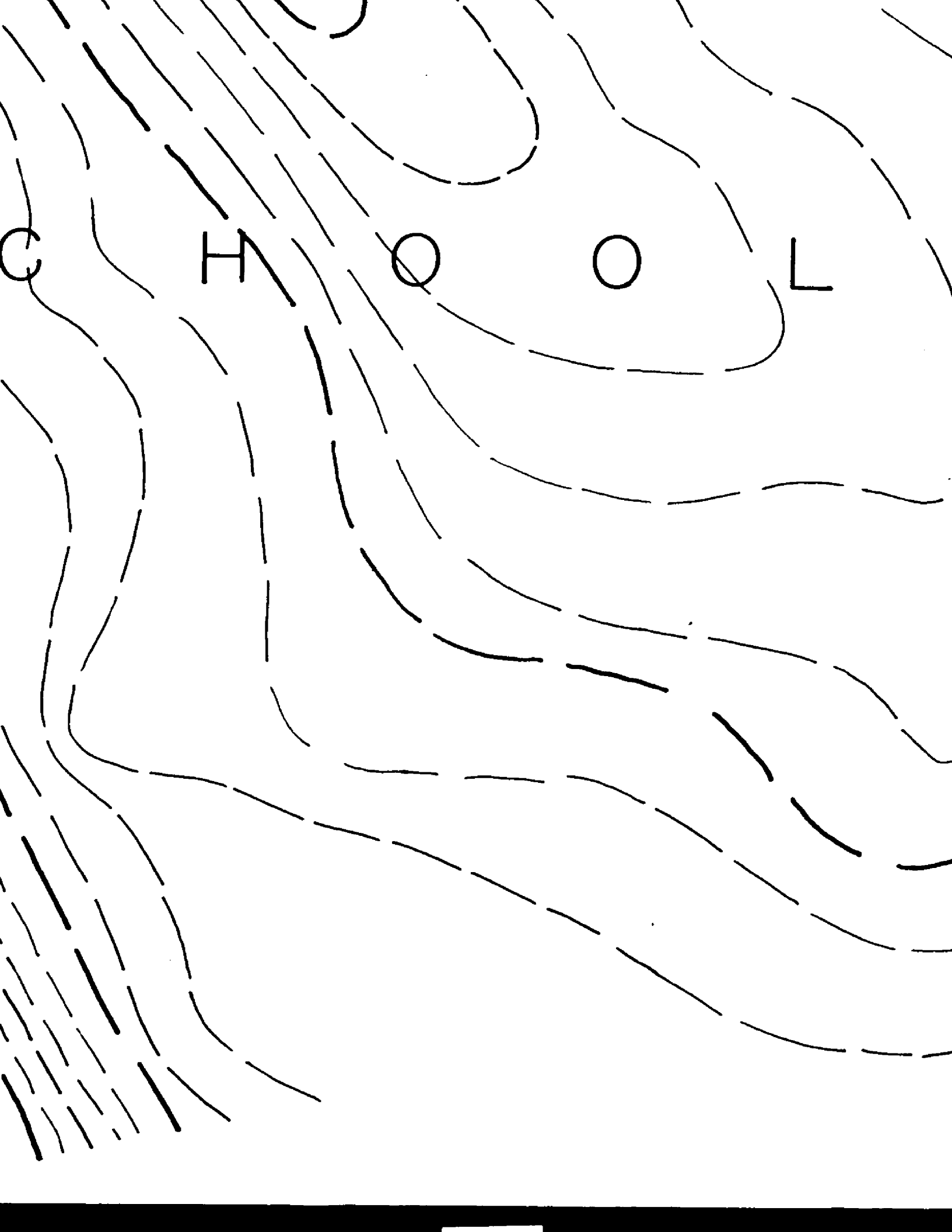


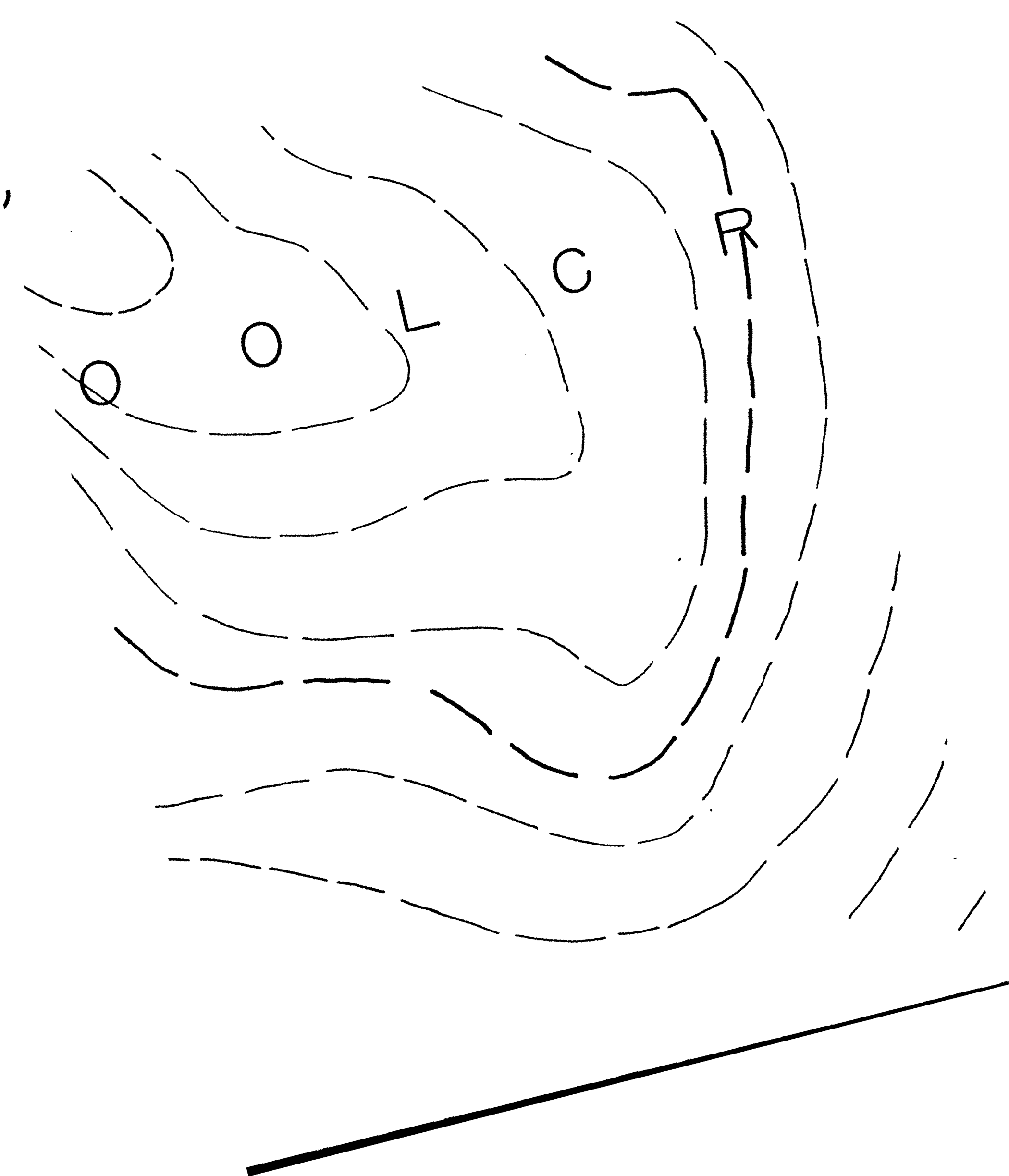


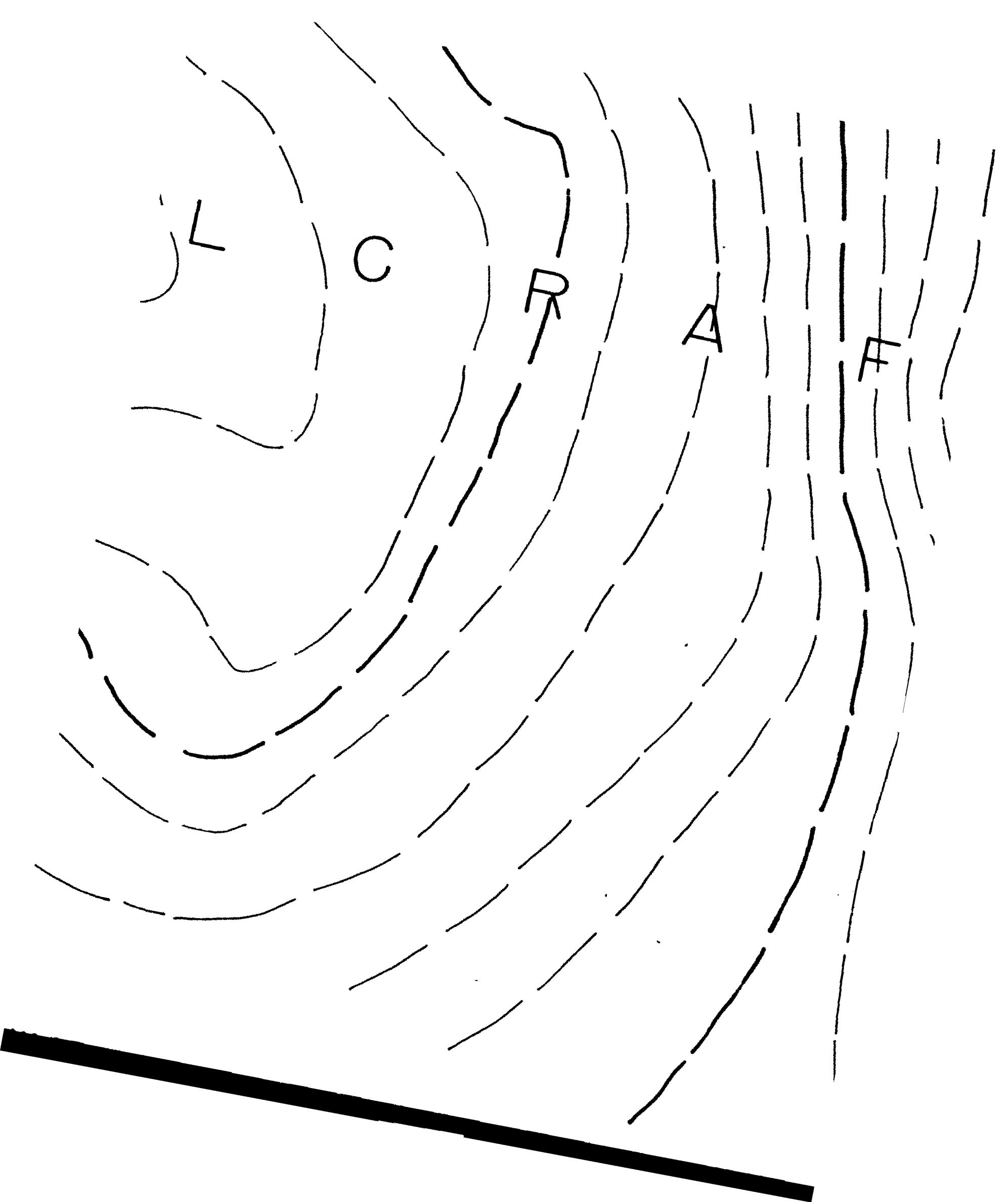










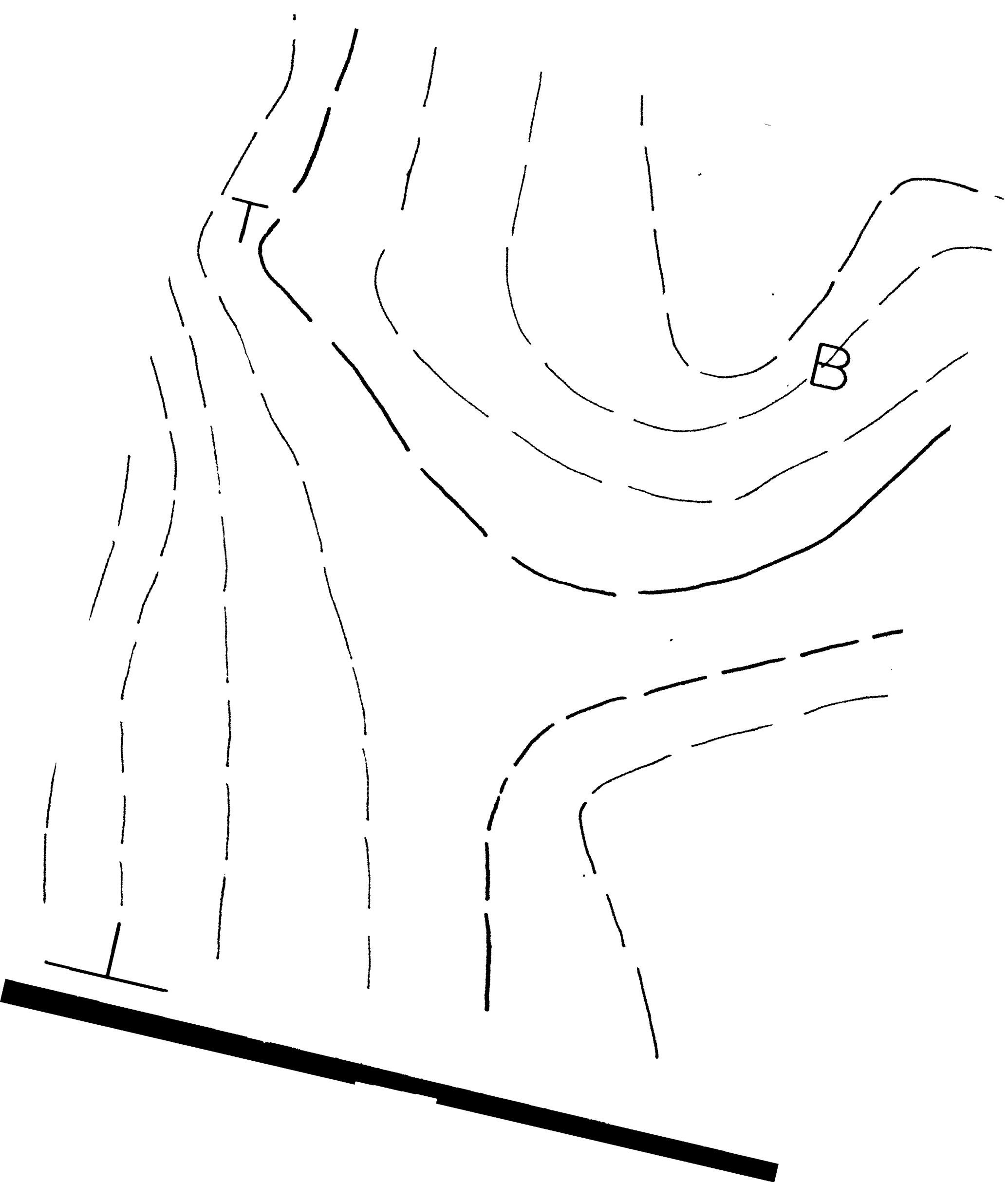


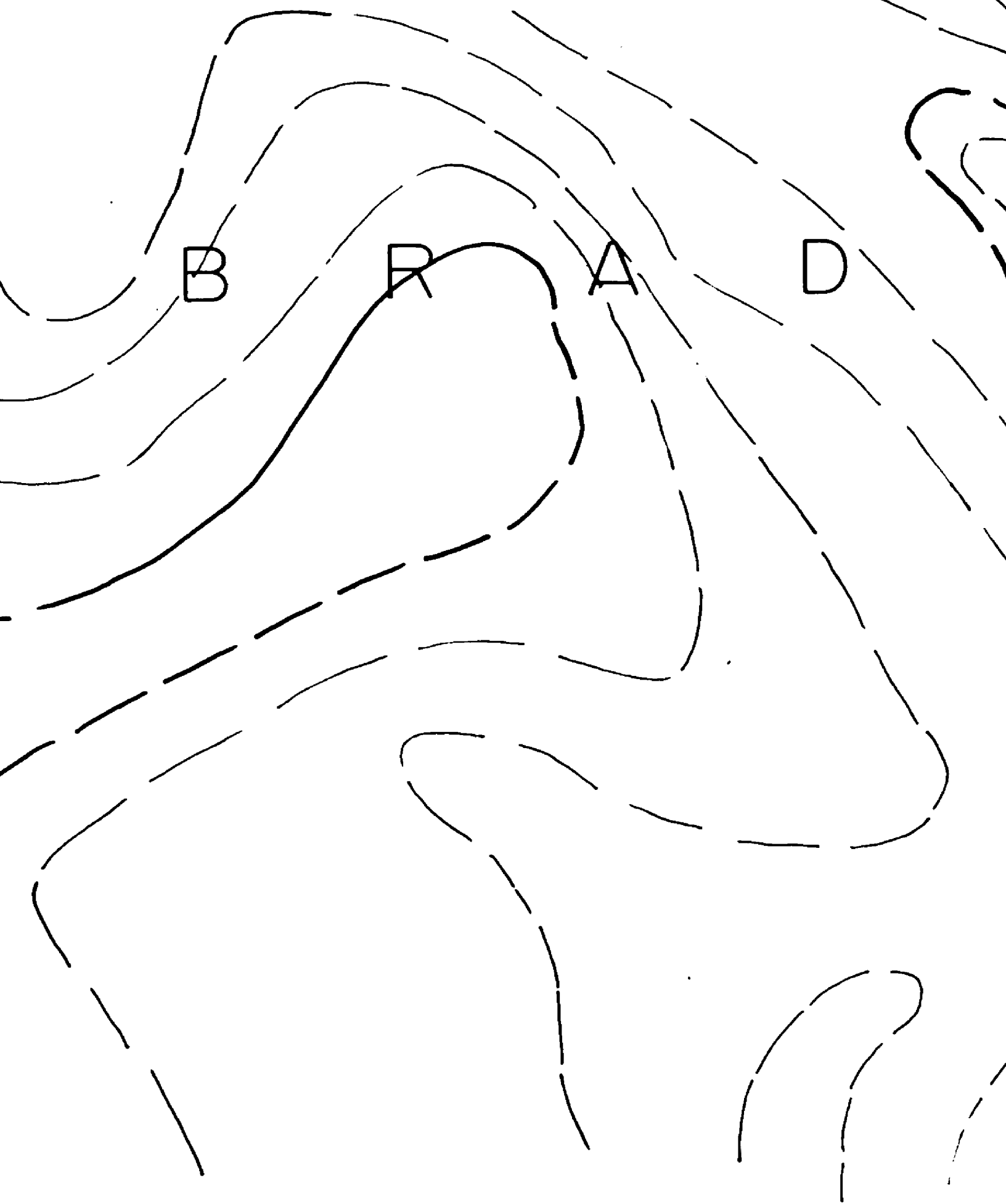
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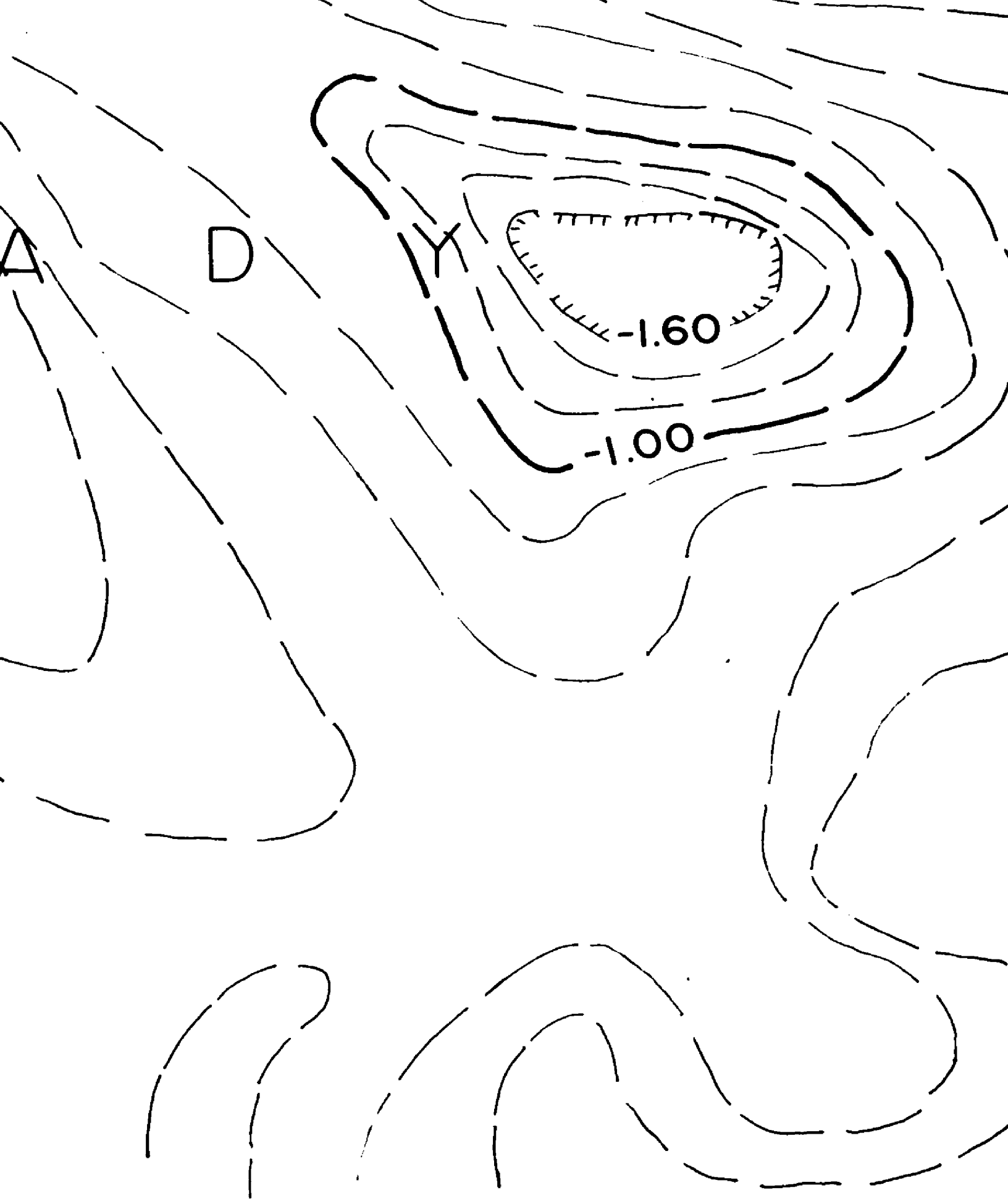
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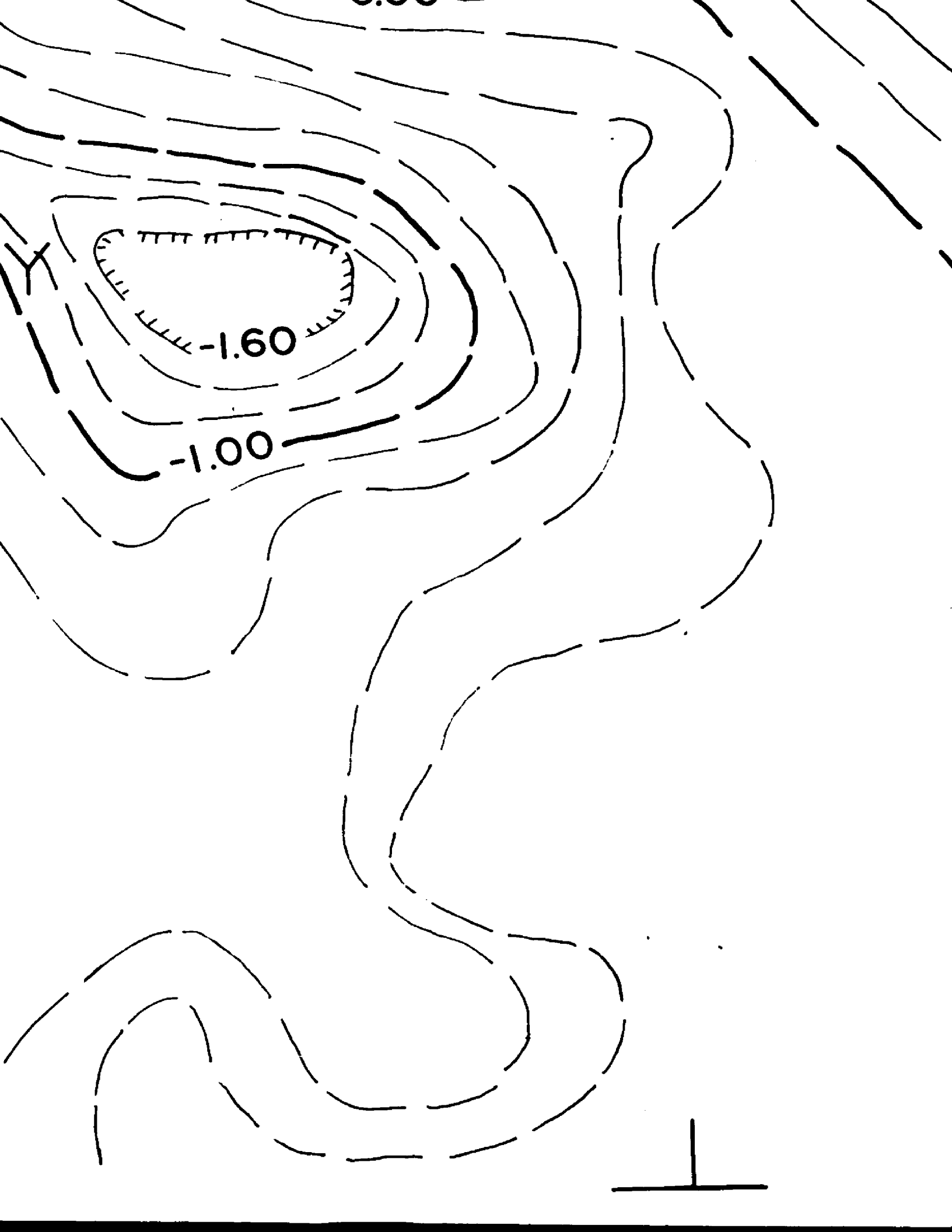




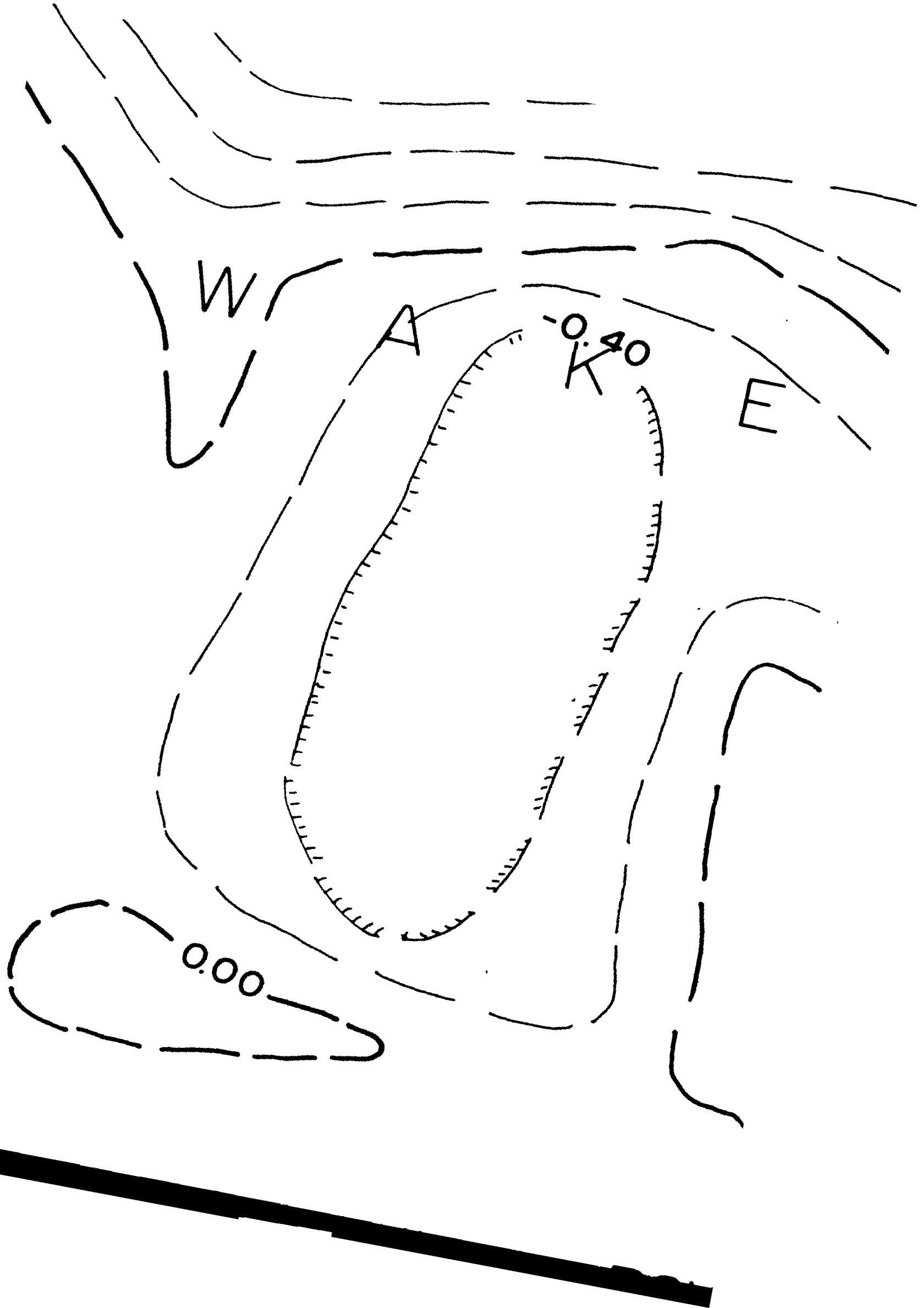
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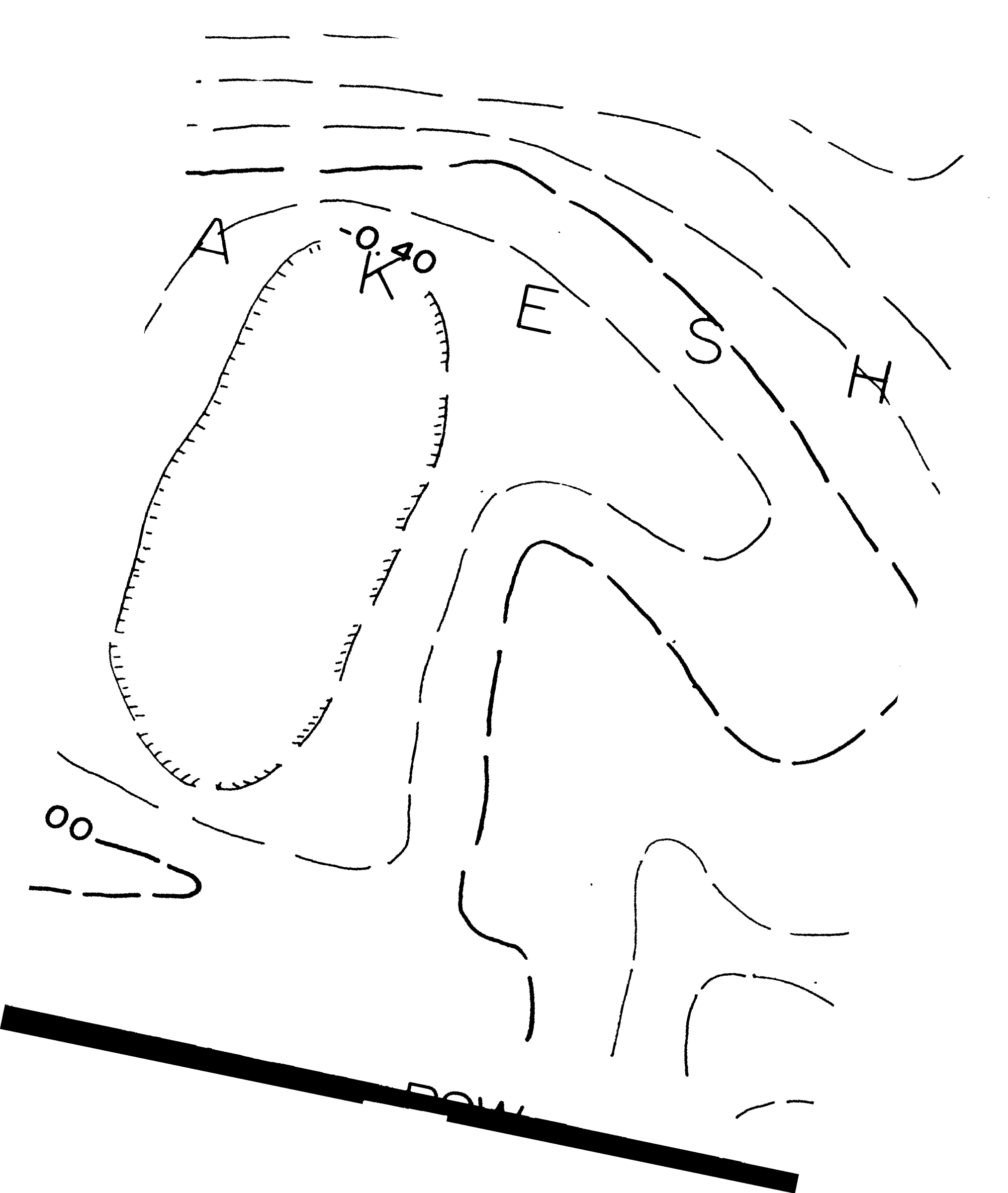


LOW

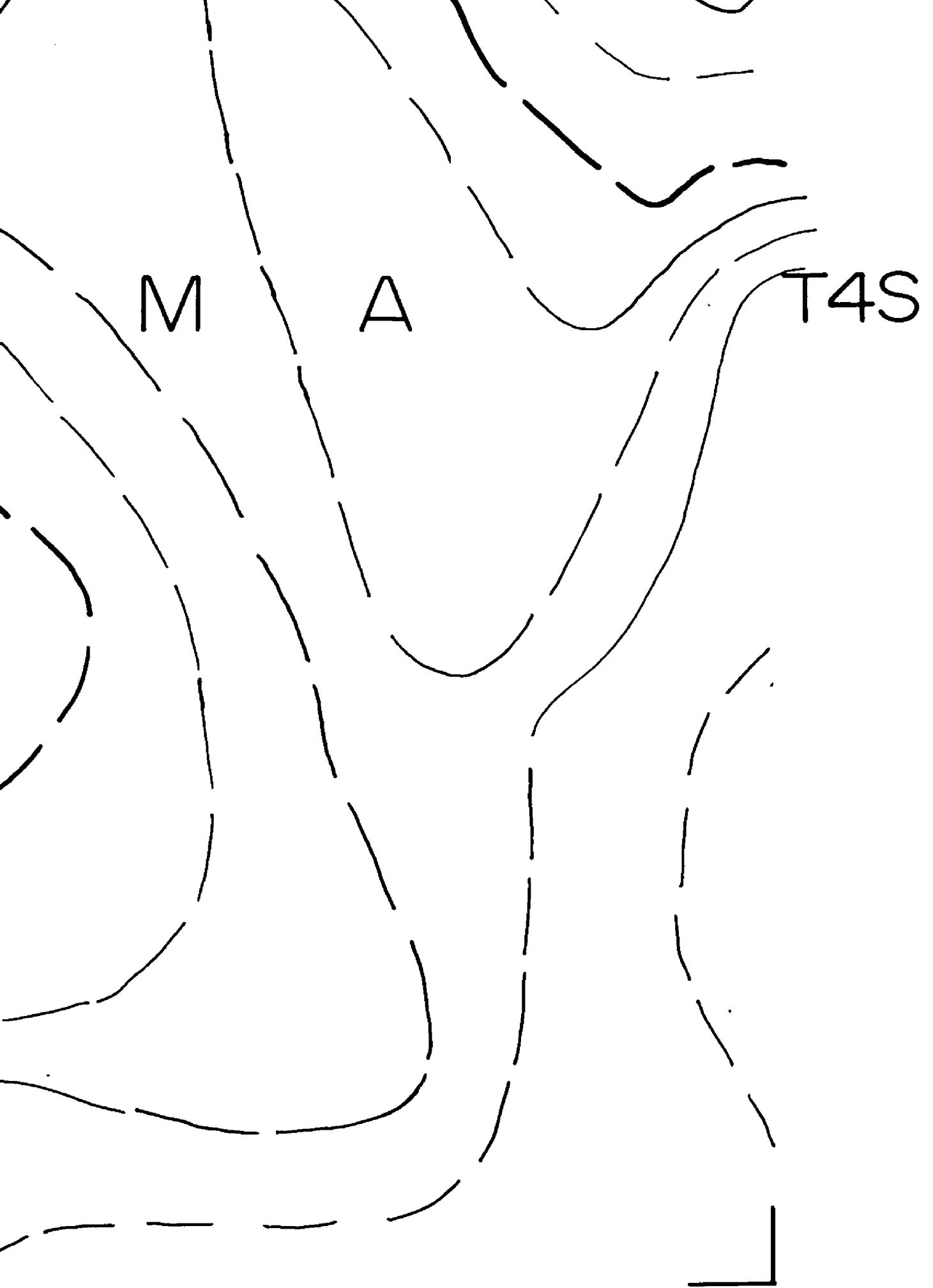










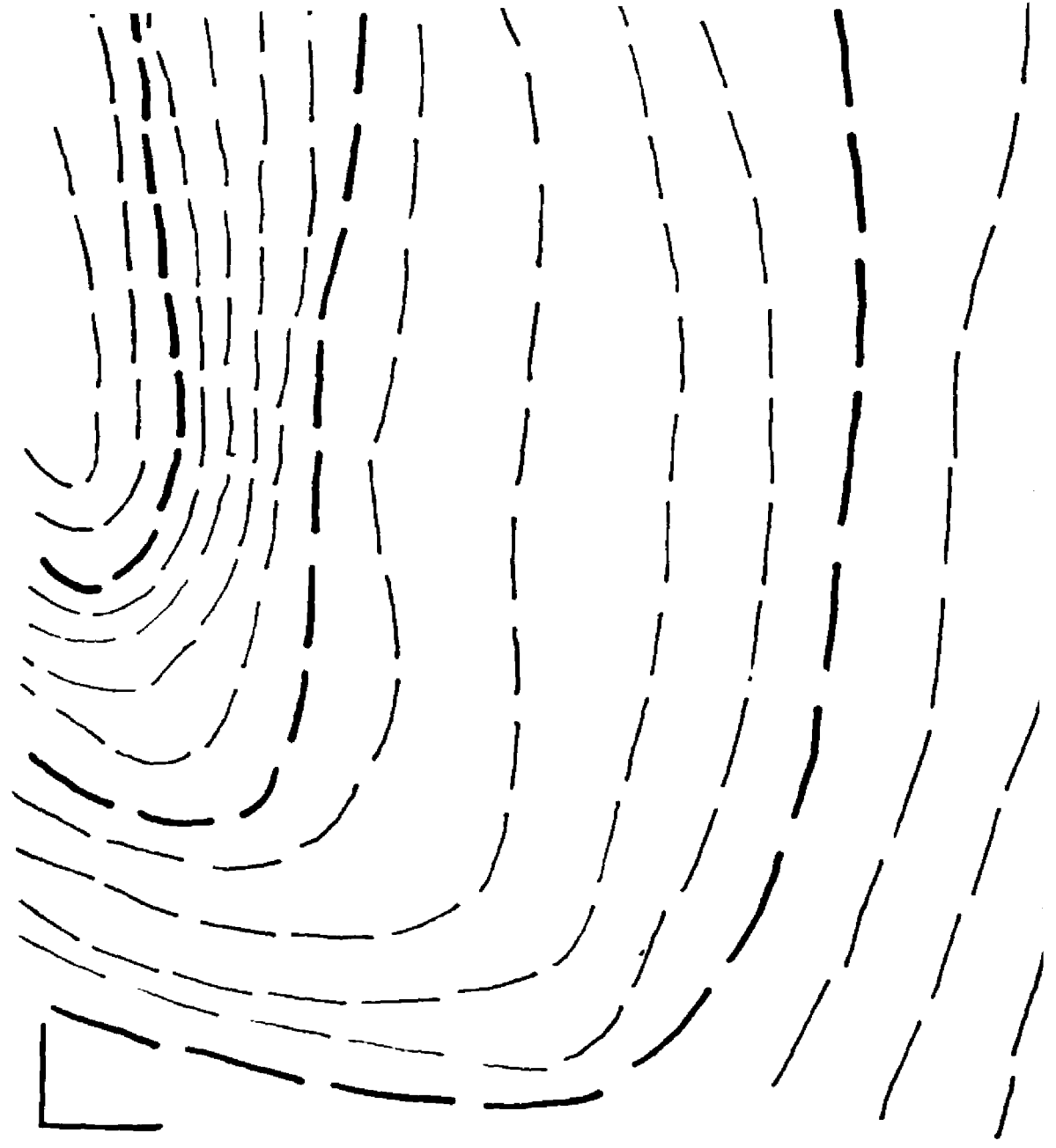


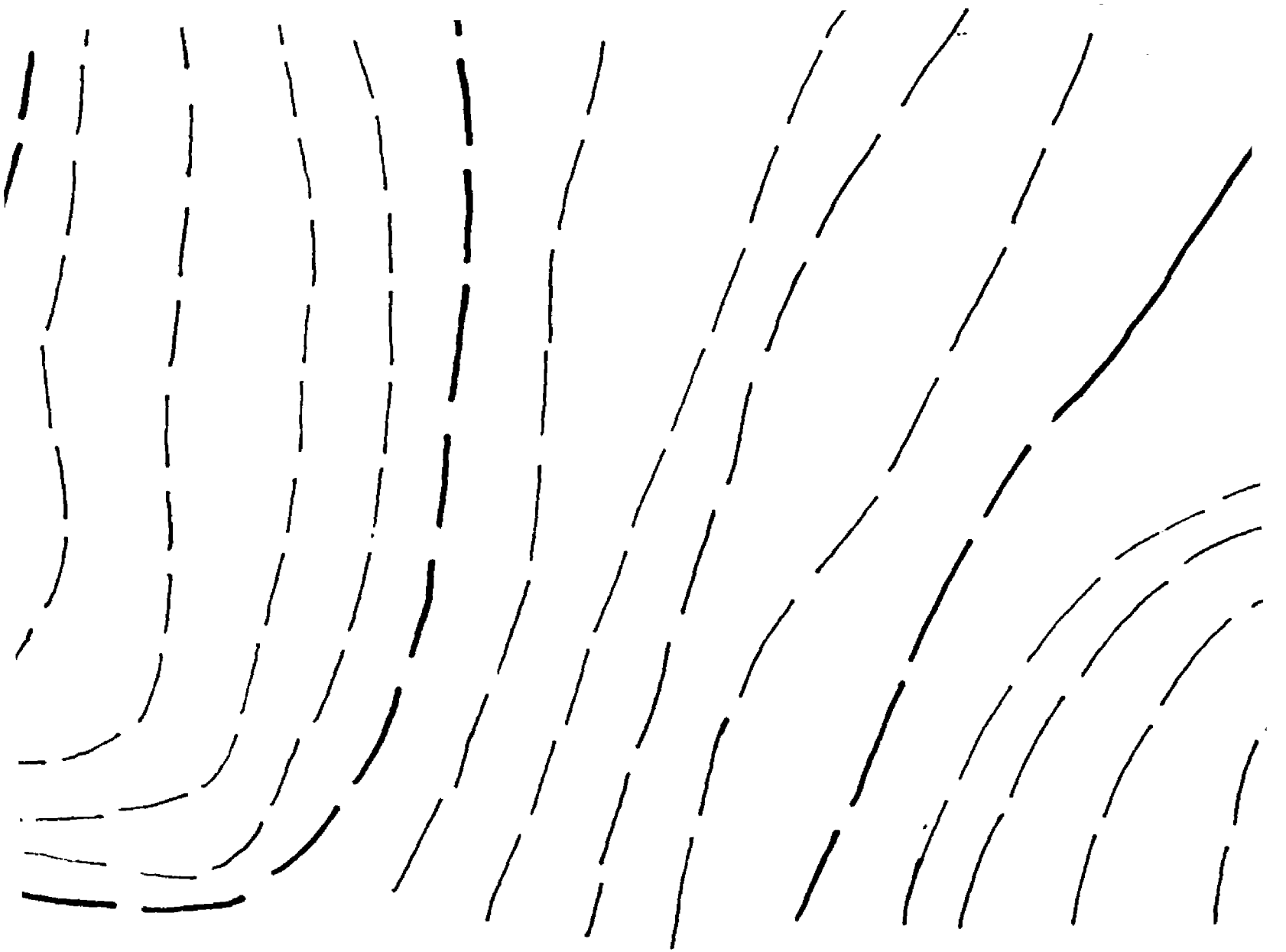
05.
42.

05.
42

45

P

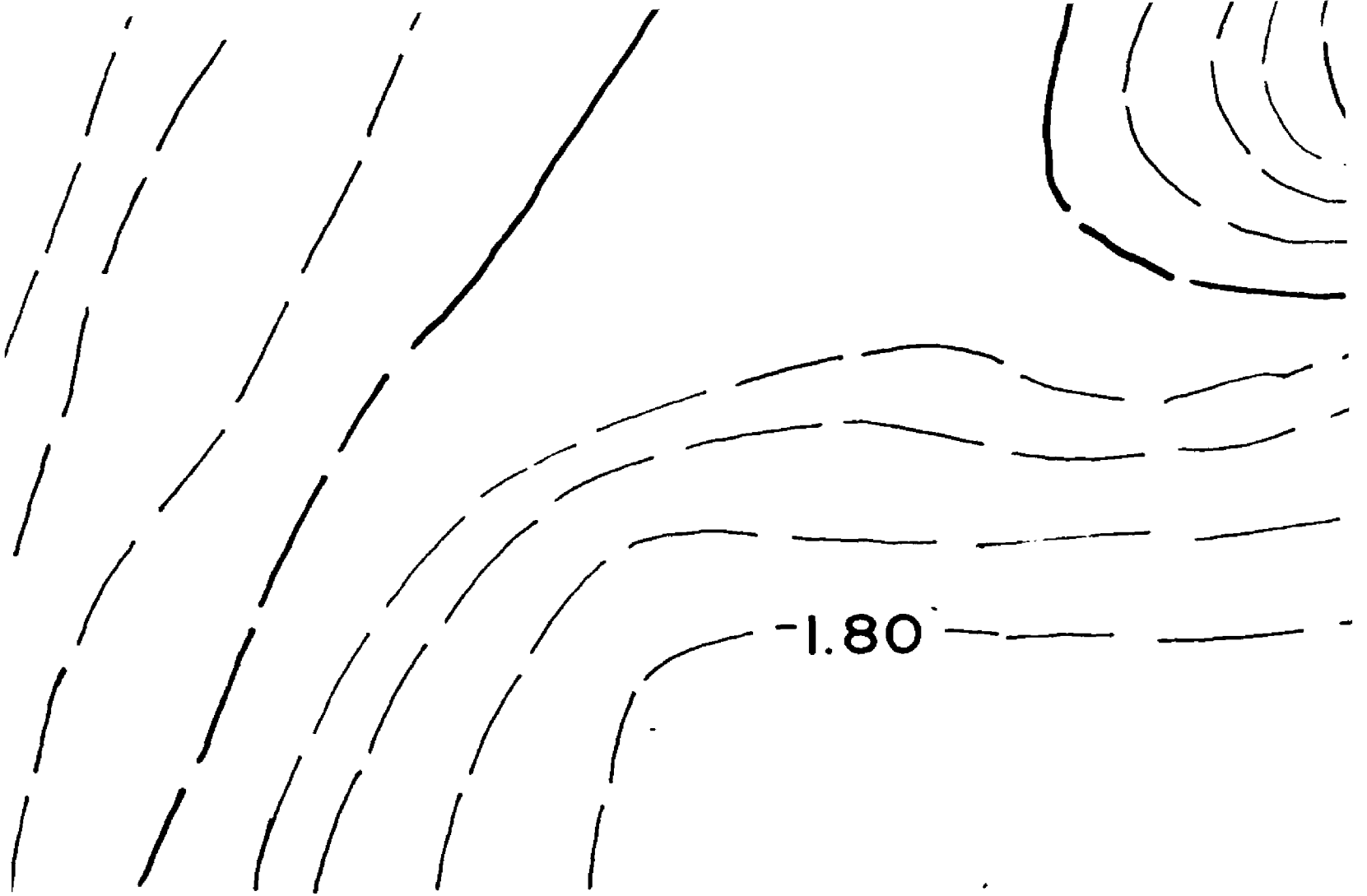




RI2W

45'

PLATE 7a



R12W

ATE 7a MAP OF THE
TO THE BOUG

SCALE 1 :



40

OF THE RESIDUAL VAL
E BOUGUER SURFACE

SCALE 1 : 24000



RESIDUAL VALUES FROM
SURFACE



RIIW

35

FROM 5TH DEGREE

SOUTHERN HALF OF
CONTOUR INTERVAL



RIIW

35

TH DEGREE POLYNOMIAL

SOUTHERN HALF OF KALAMAZOO

CONTOUR INTERVAL 0.20 MGALS



POLYNOMIAL

APPROXIMAT

OF KALAMAZOO COUNTY

L 0.20 MGALS



30'

APPROXIMATION

COUNTY



RIOW

30'

ON



RIOW

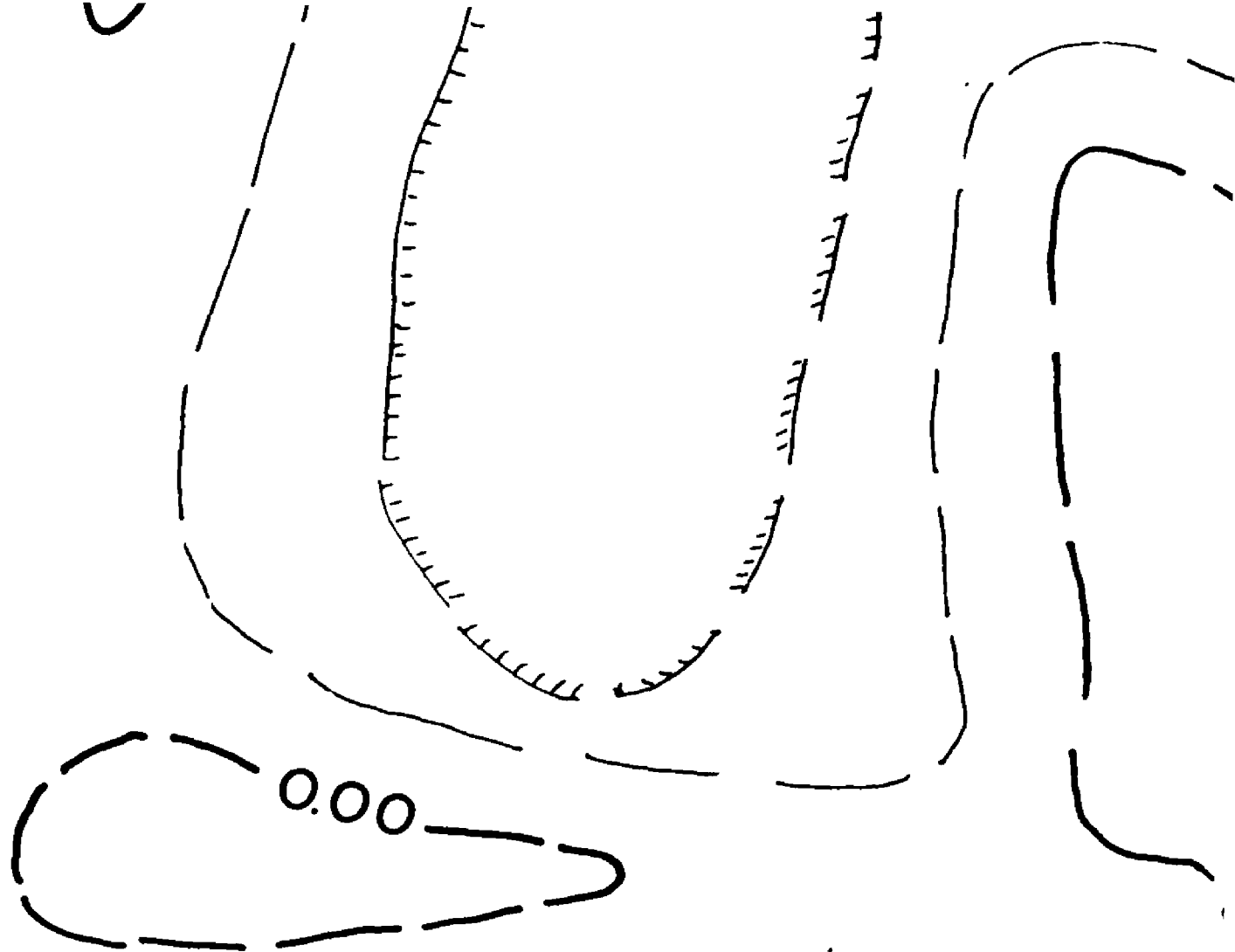




25'



25'



R9V



R9W

85° 20'



N

85° 20'



05-
42

ó

45'

42°
- 25

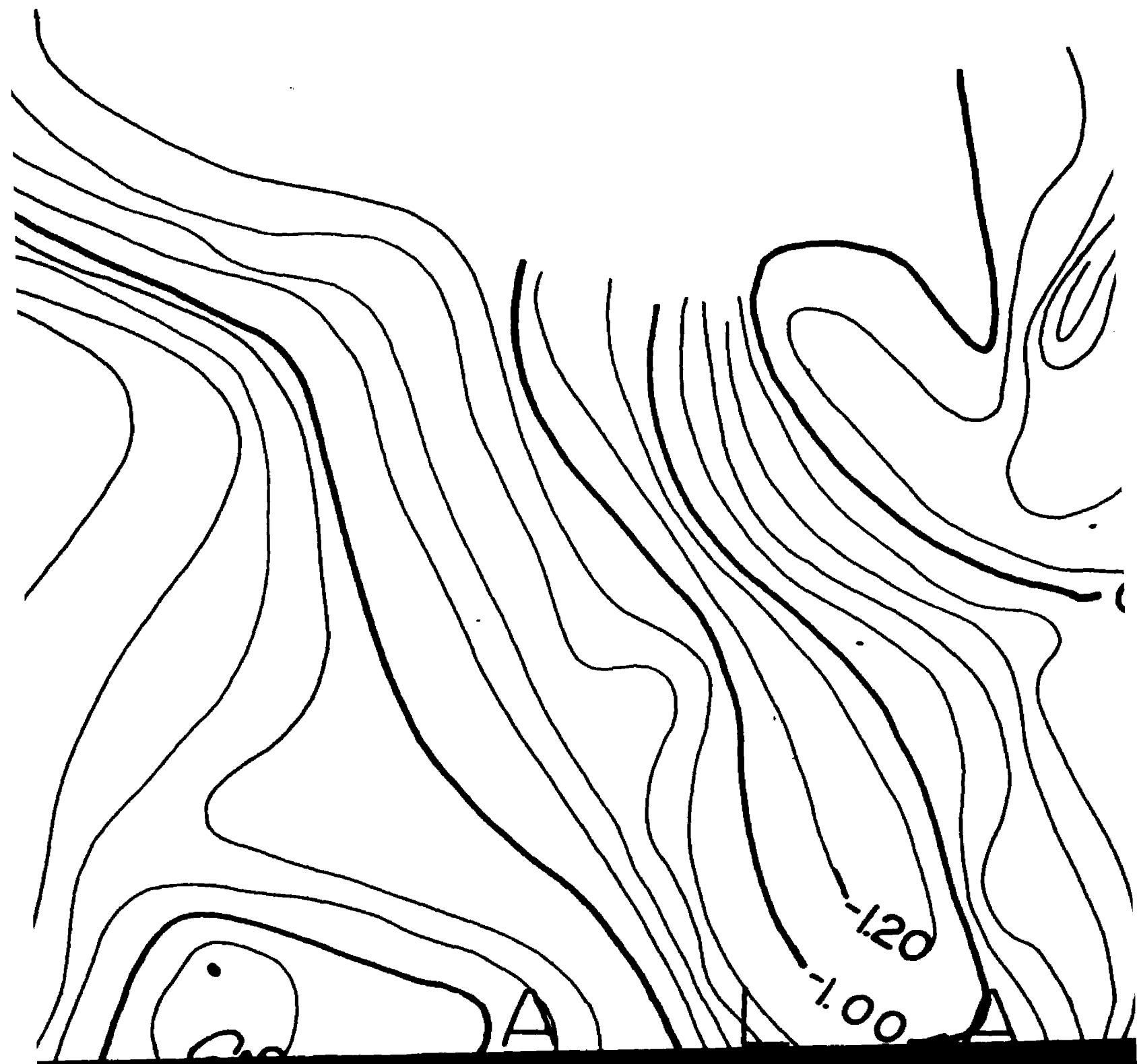


TIS

A

45'

R12W



R12W



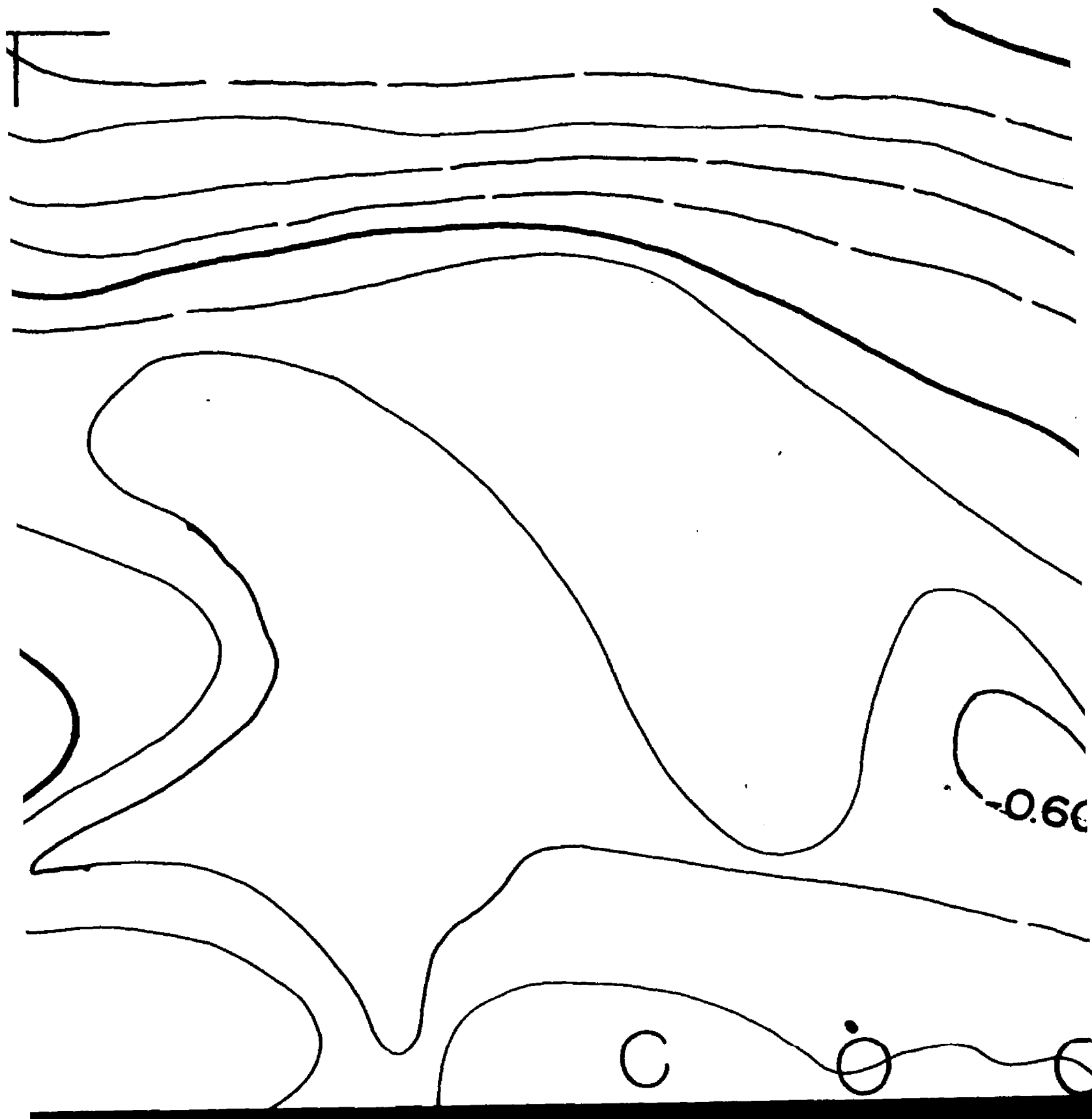
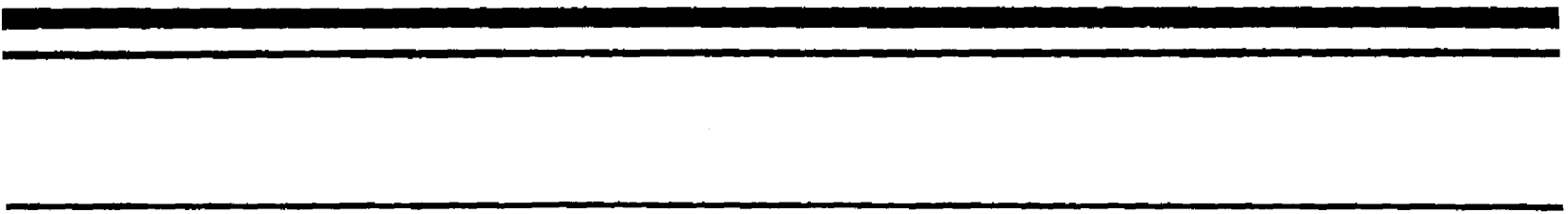
40'

0.40



40'





35'

RIIW

1.00

0.00

-0.60

C

0

0

P

F

5th

35'

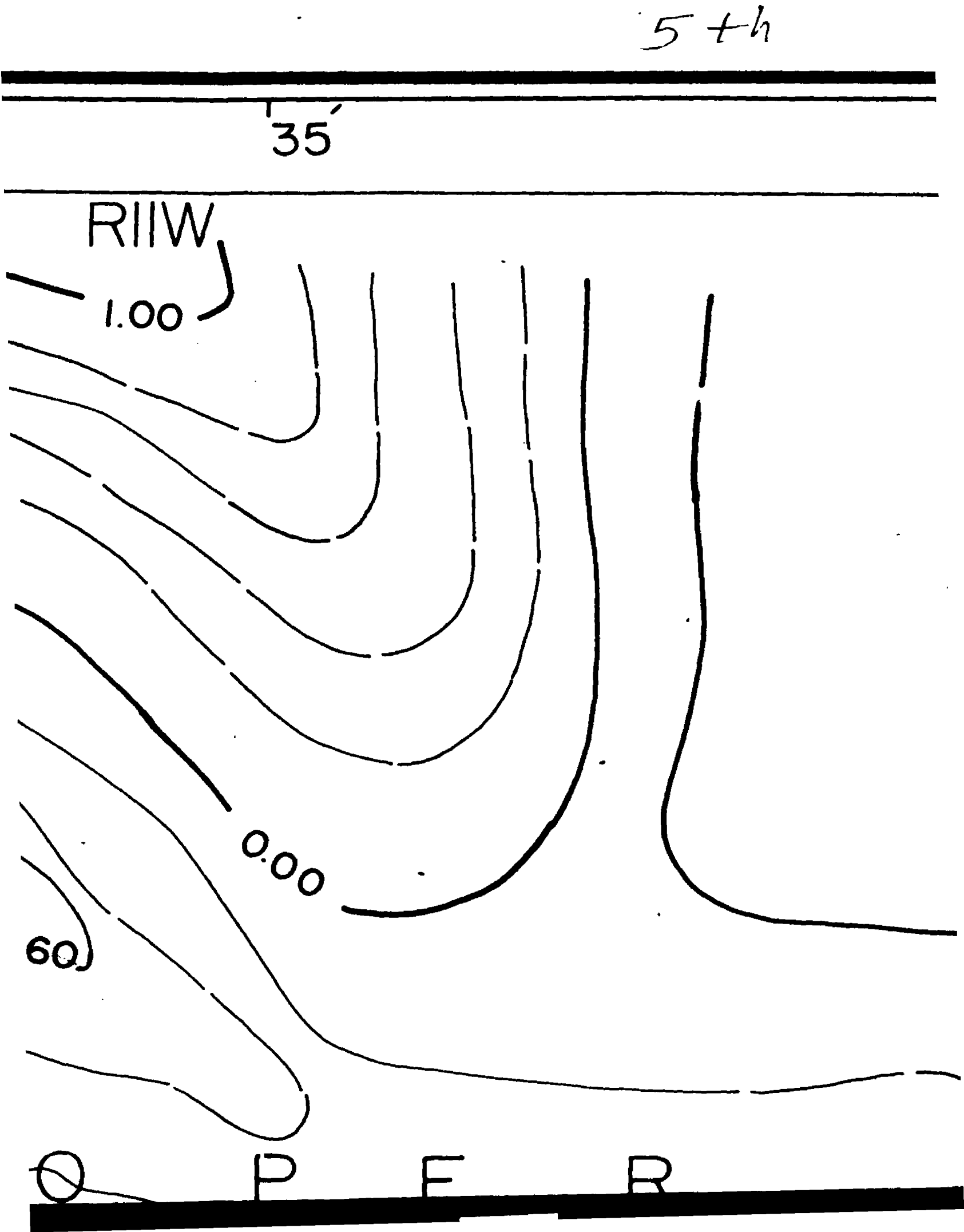
RIIW

1.00

0.00

60)

O P F R



5th

T

0.00

R

4

T

0.00

0.40

0.00

R

30'

0.00

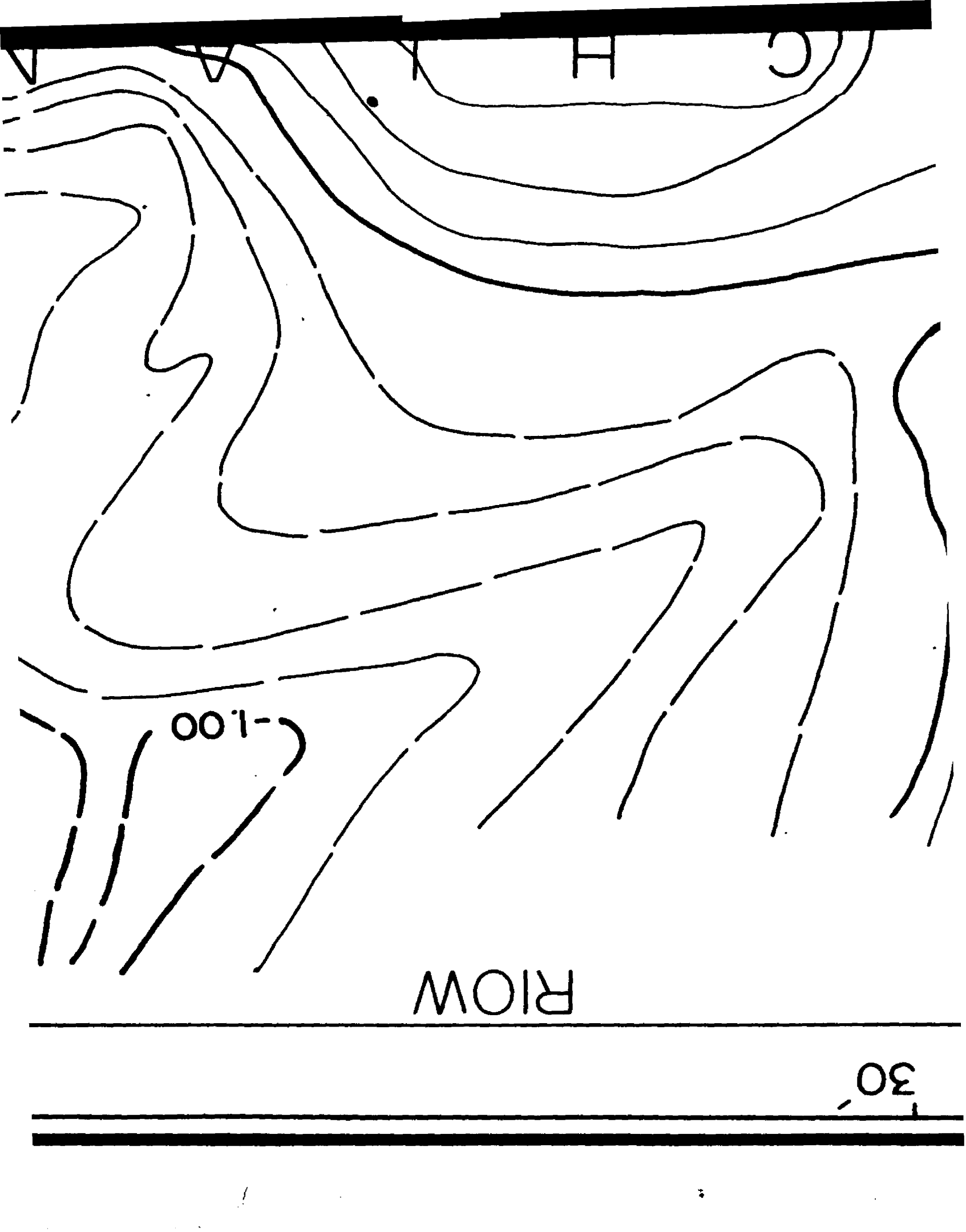
0.40

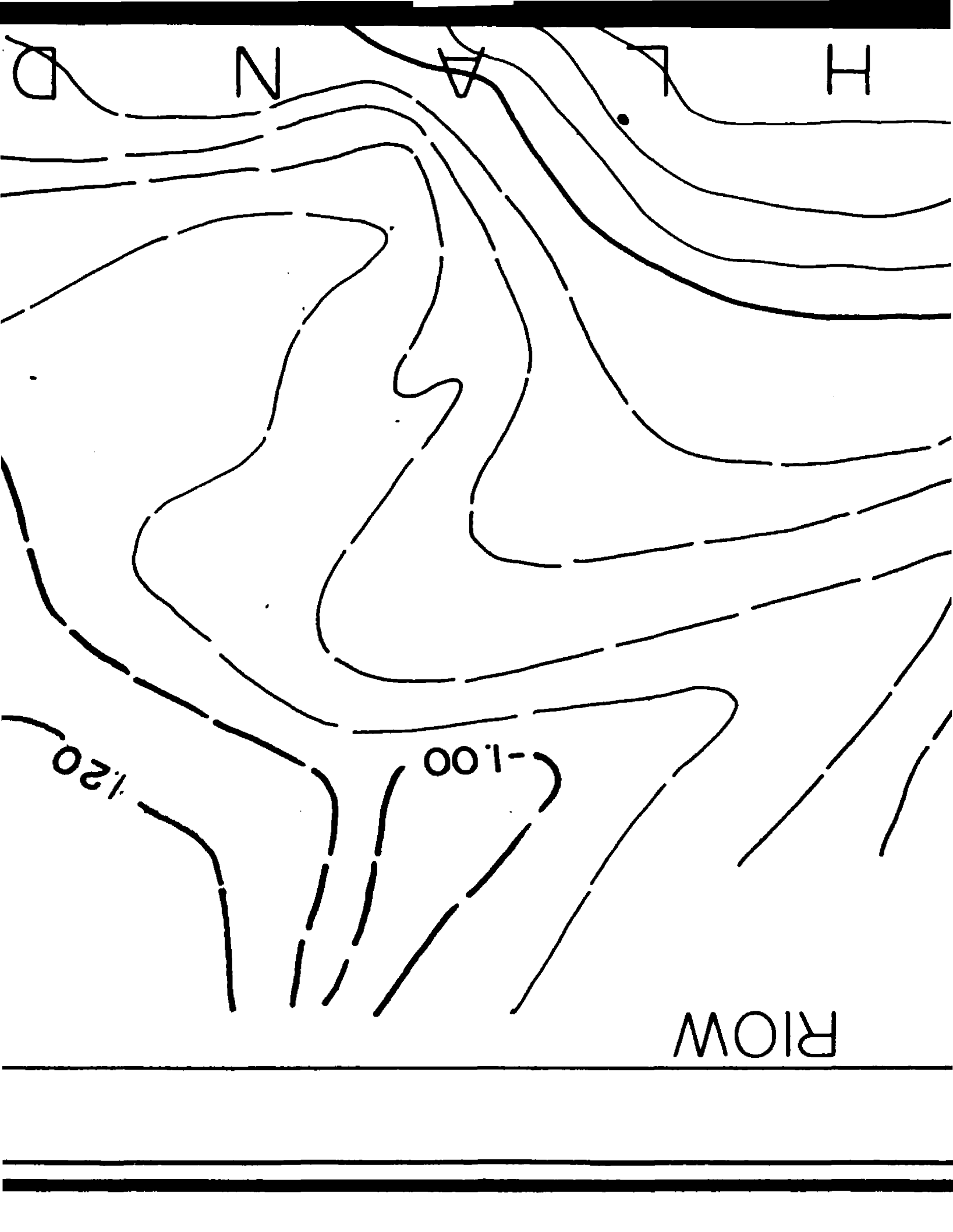
0.00

R

C

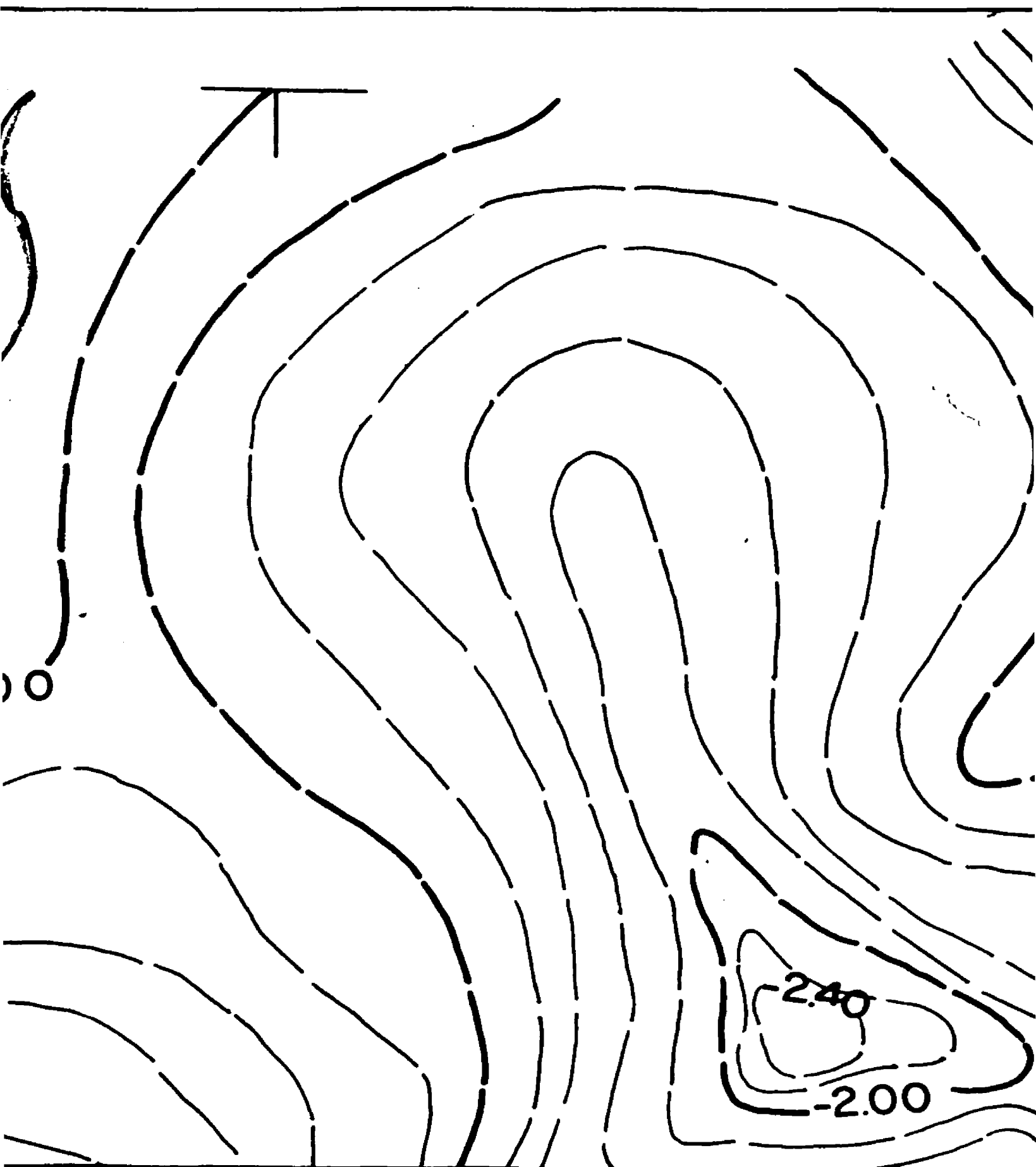
H







25'



R9W

-2.40

-2.00

R

O

85° 20'

R9W

0° R O S S

85° 20'

R9W

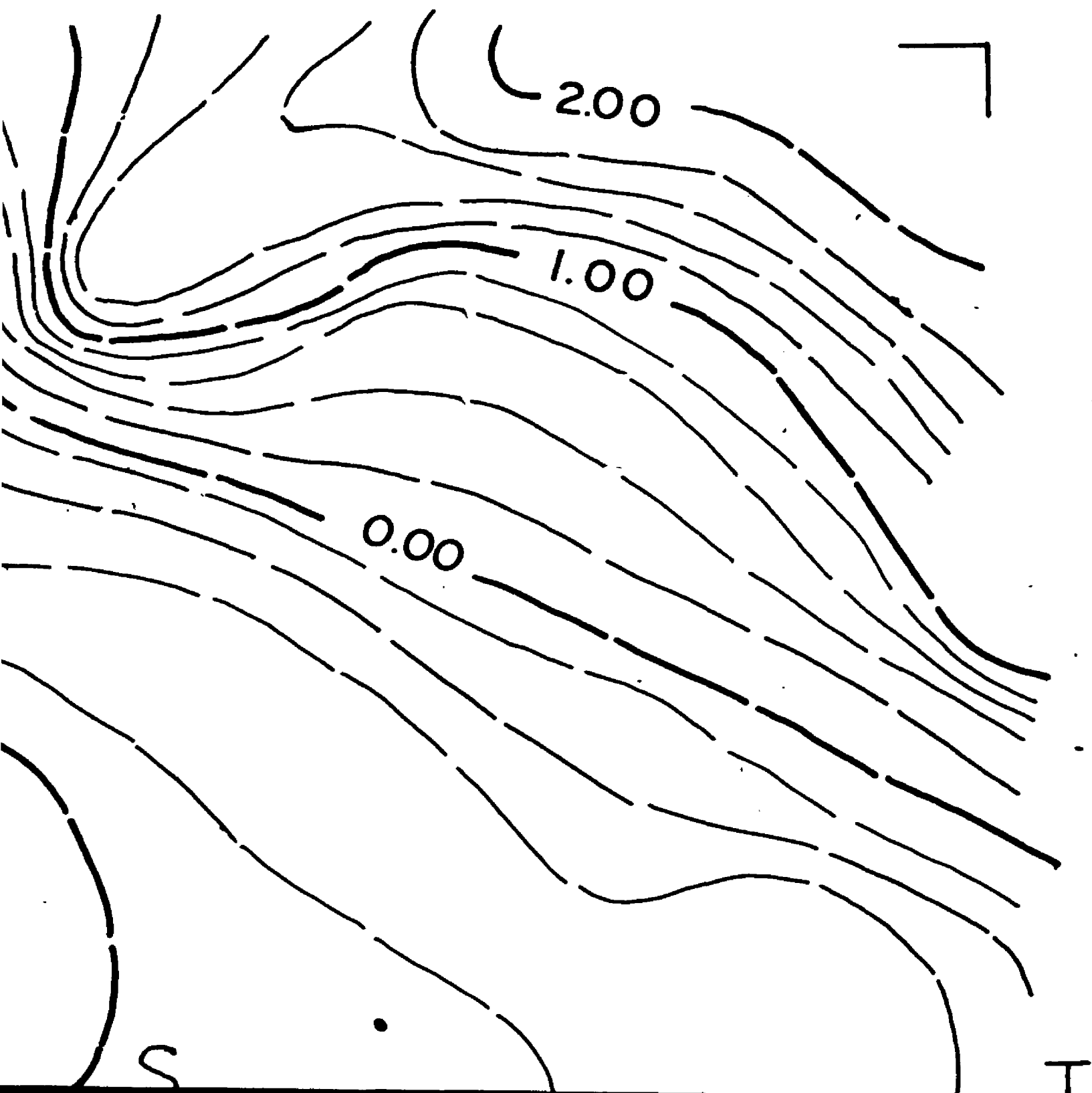
2.00

1.00

0.00

S

85°20'



20'

42°
25'

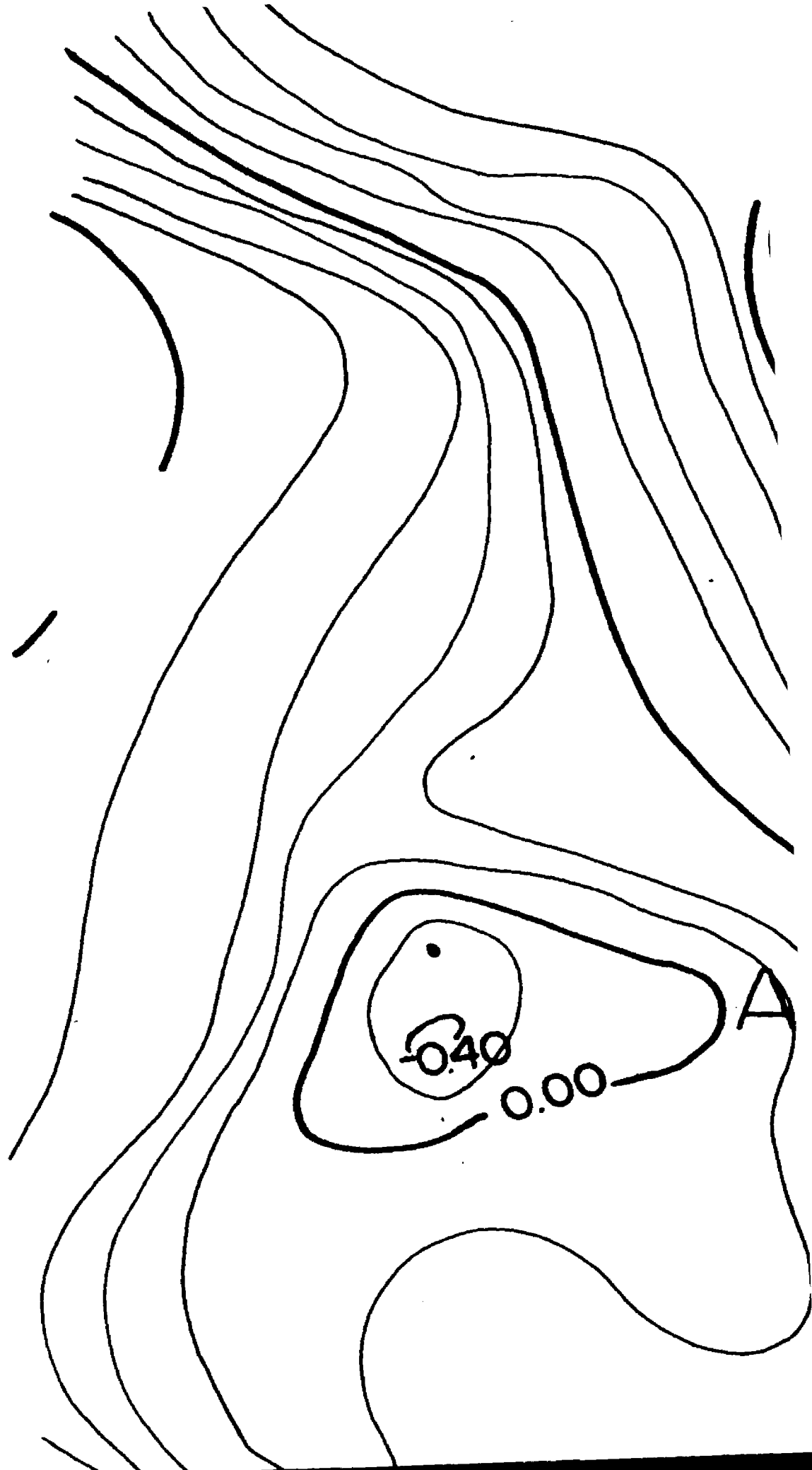
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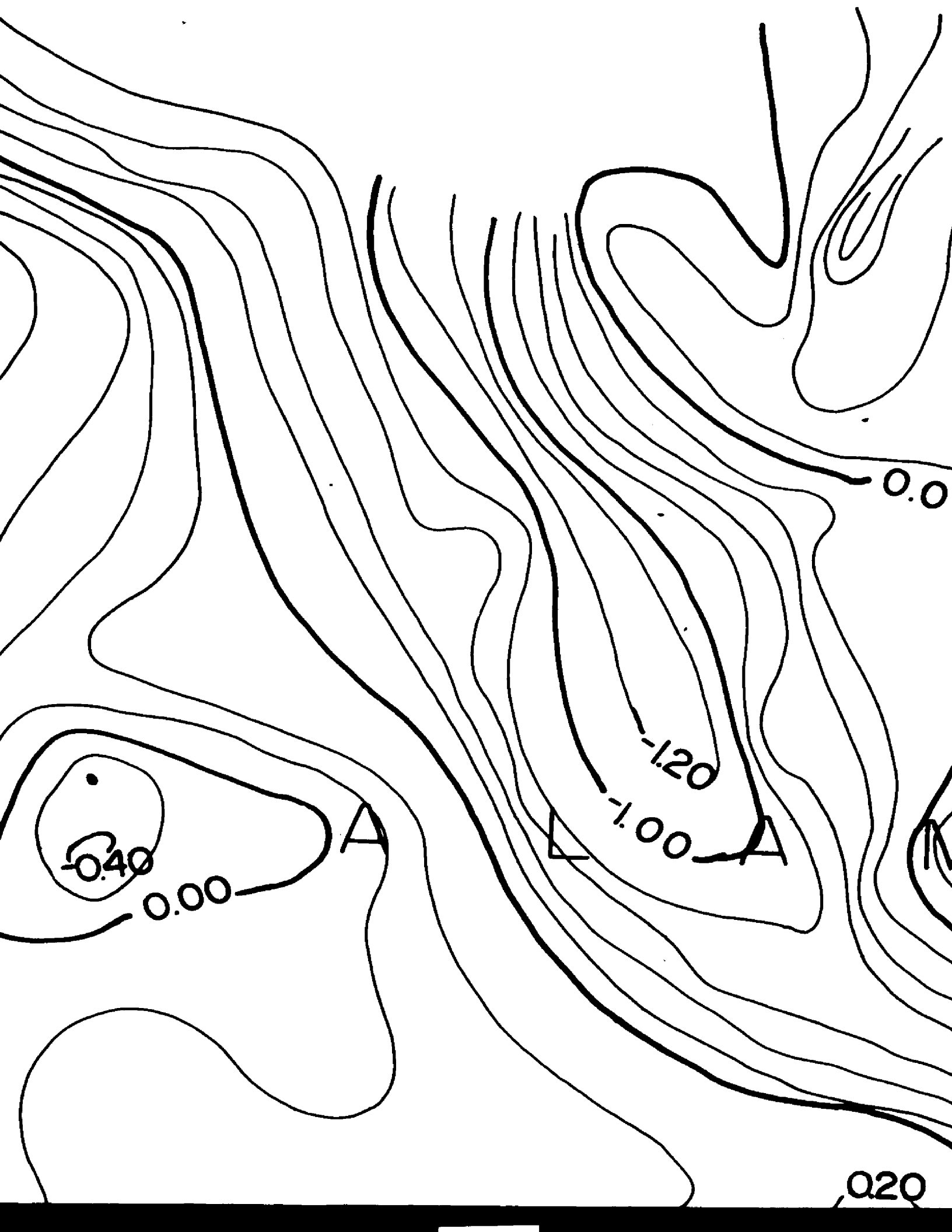
1.00

0.00

TIS

TIS









0.00

0.40

M

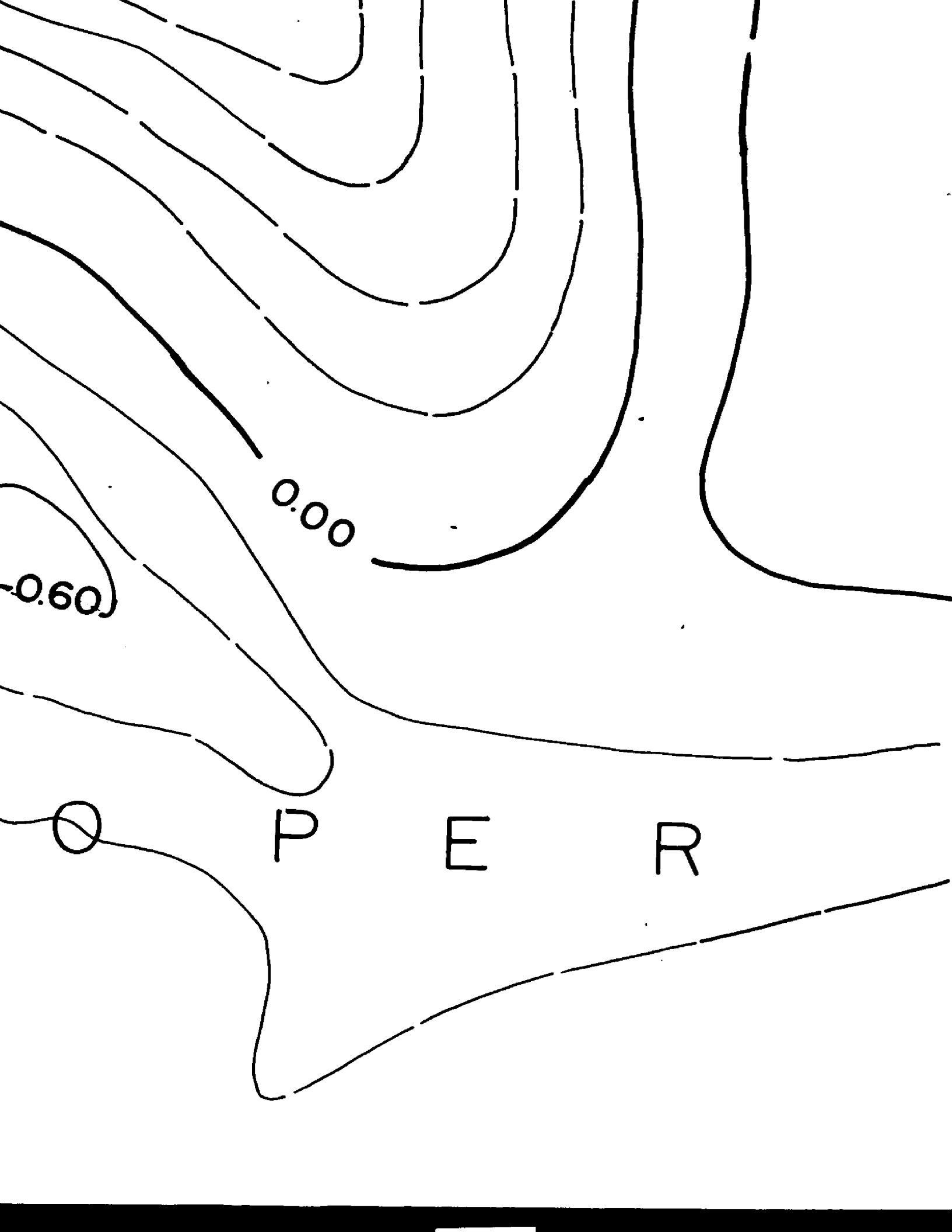
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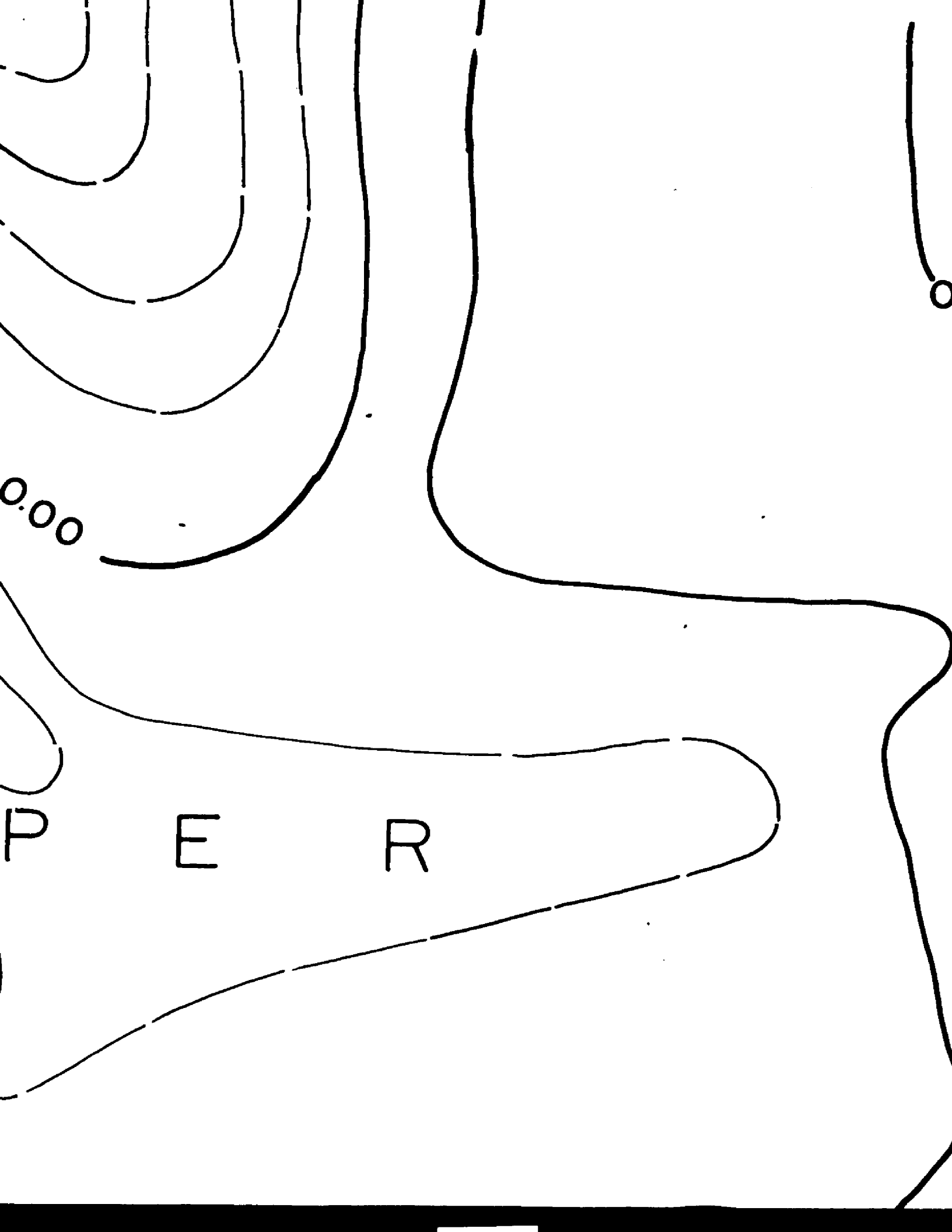




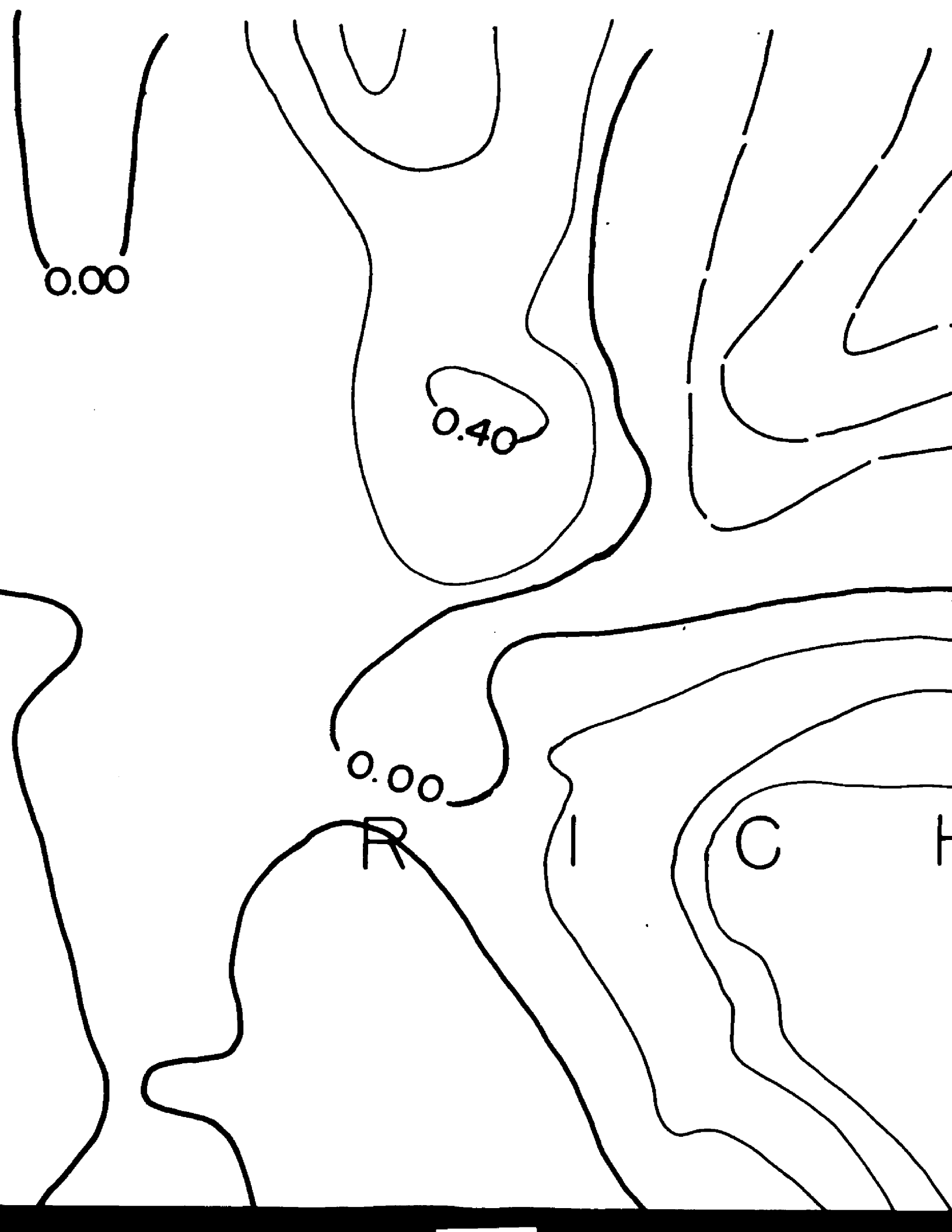


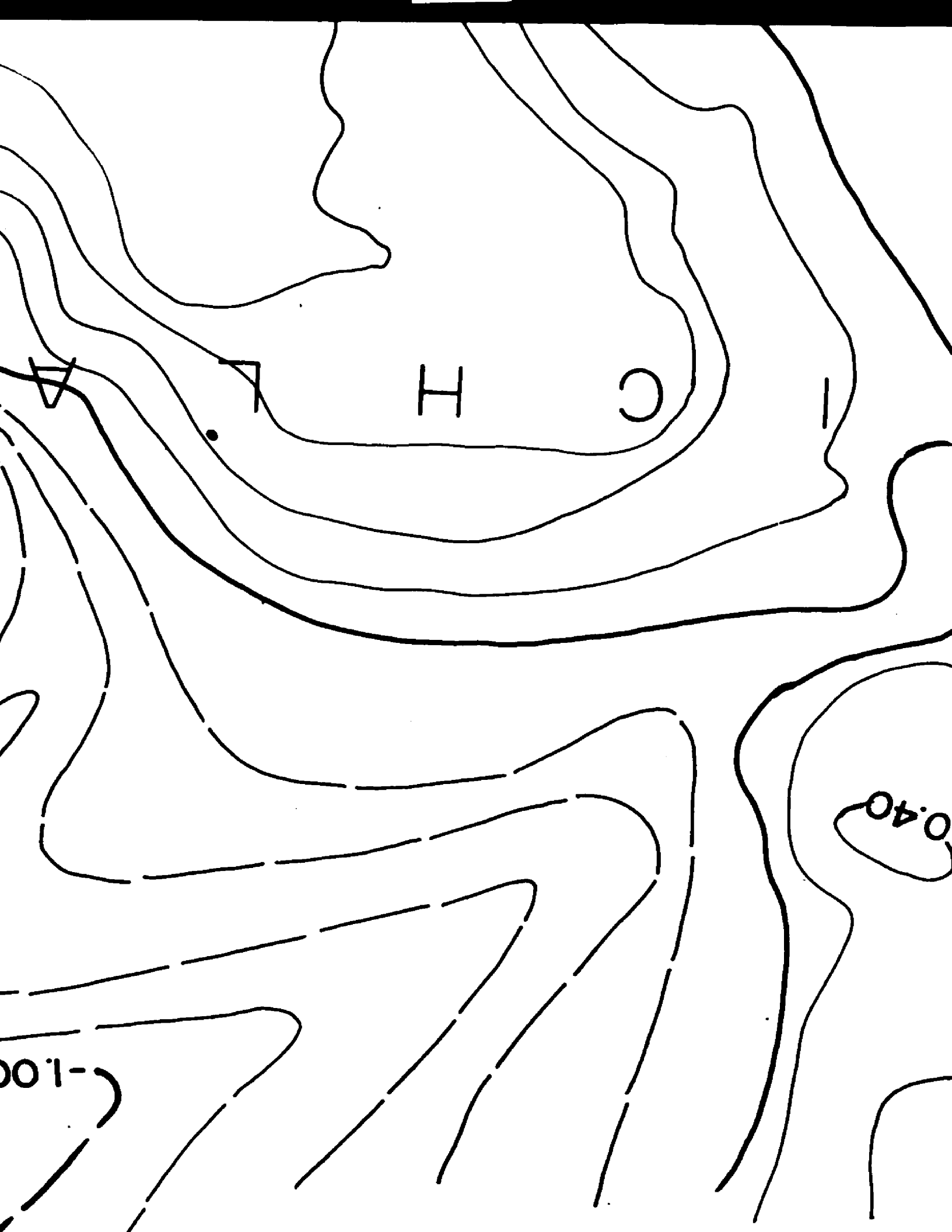


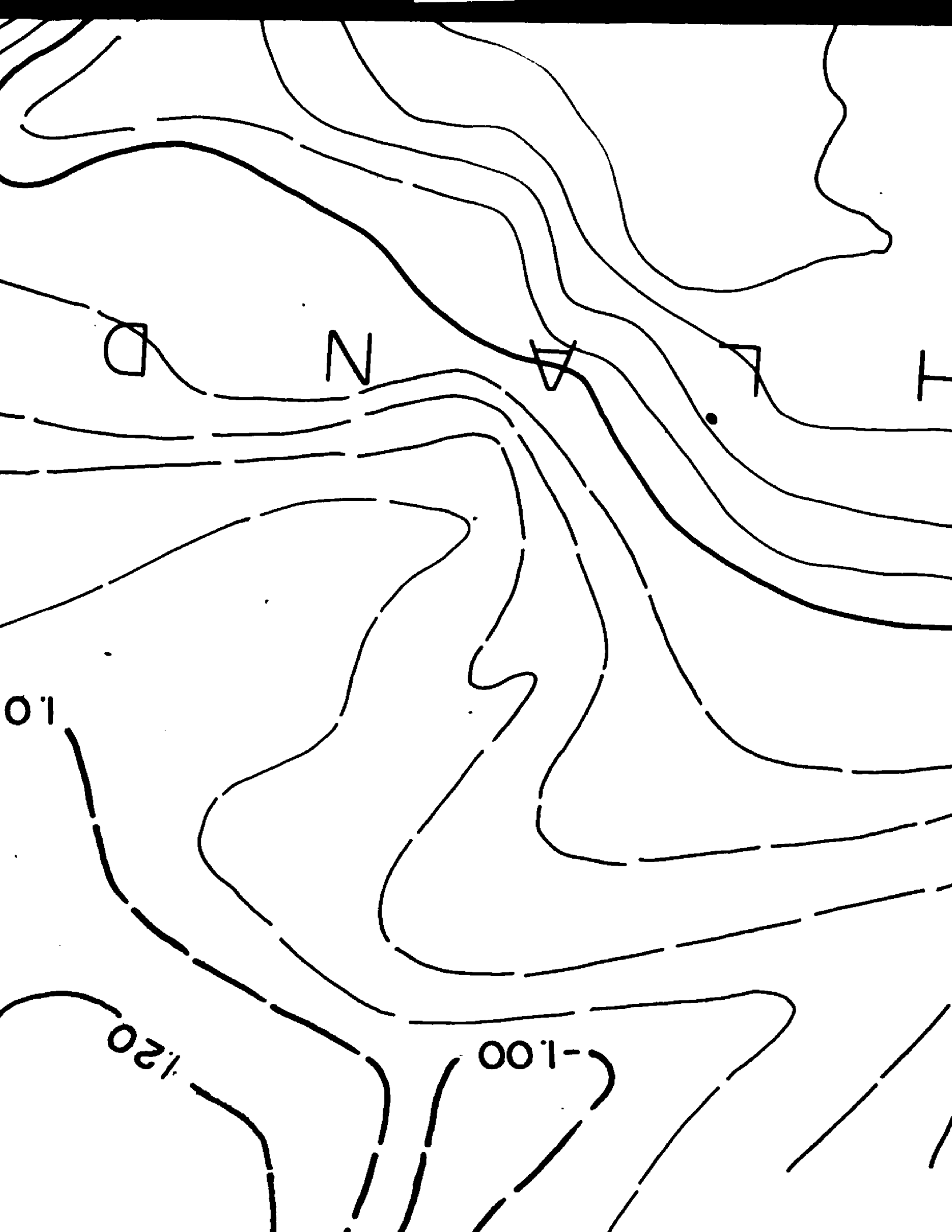




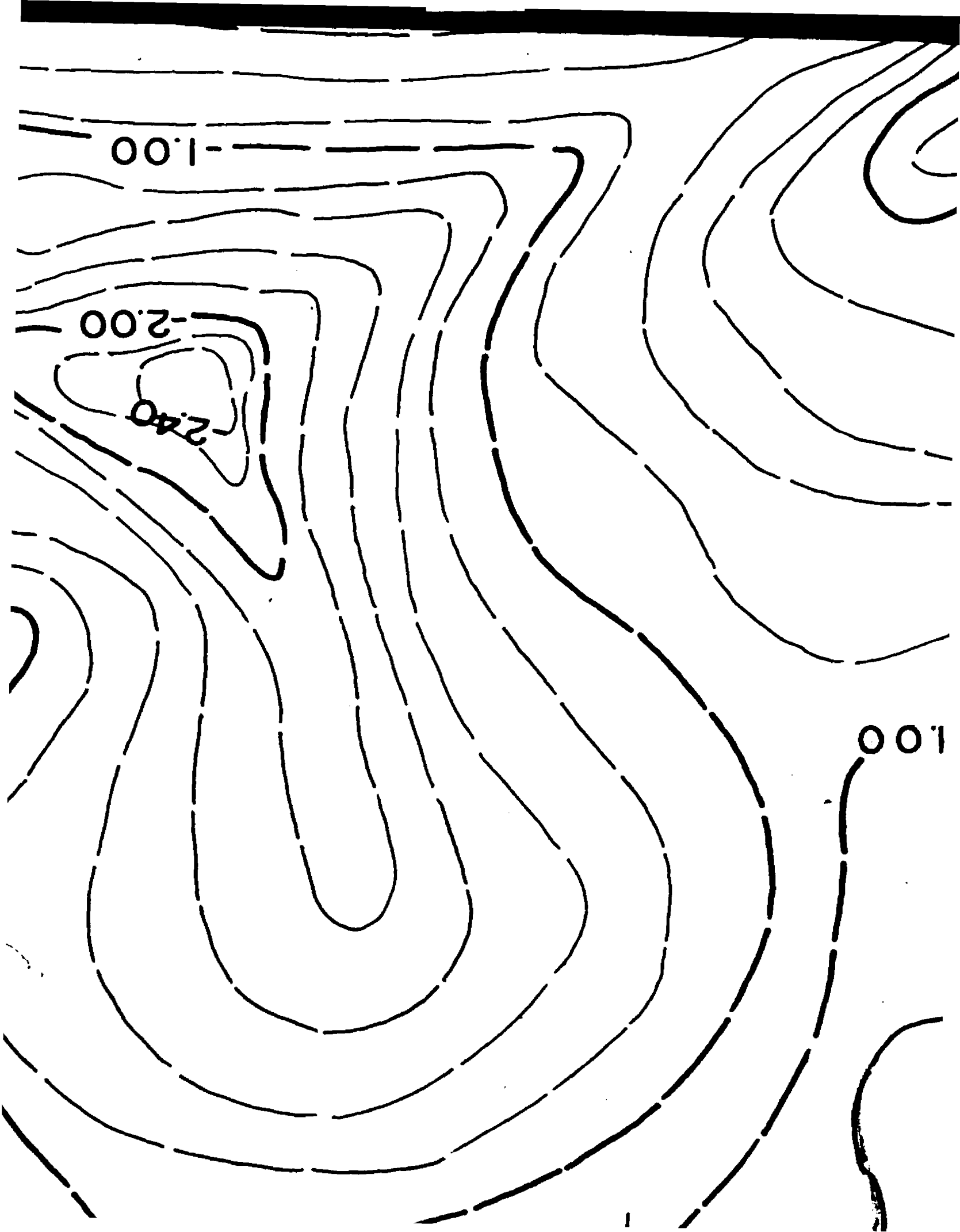


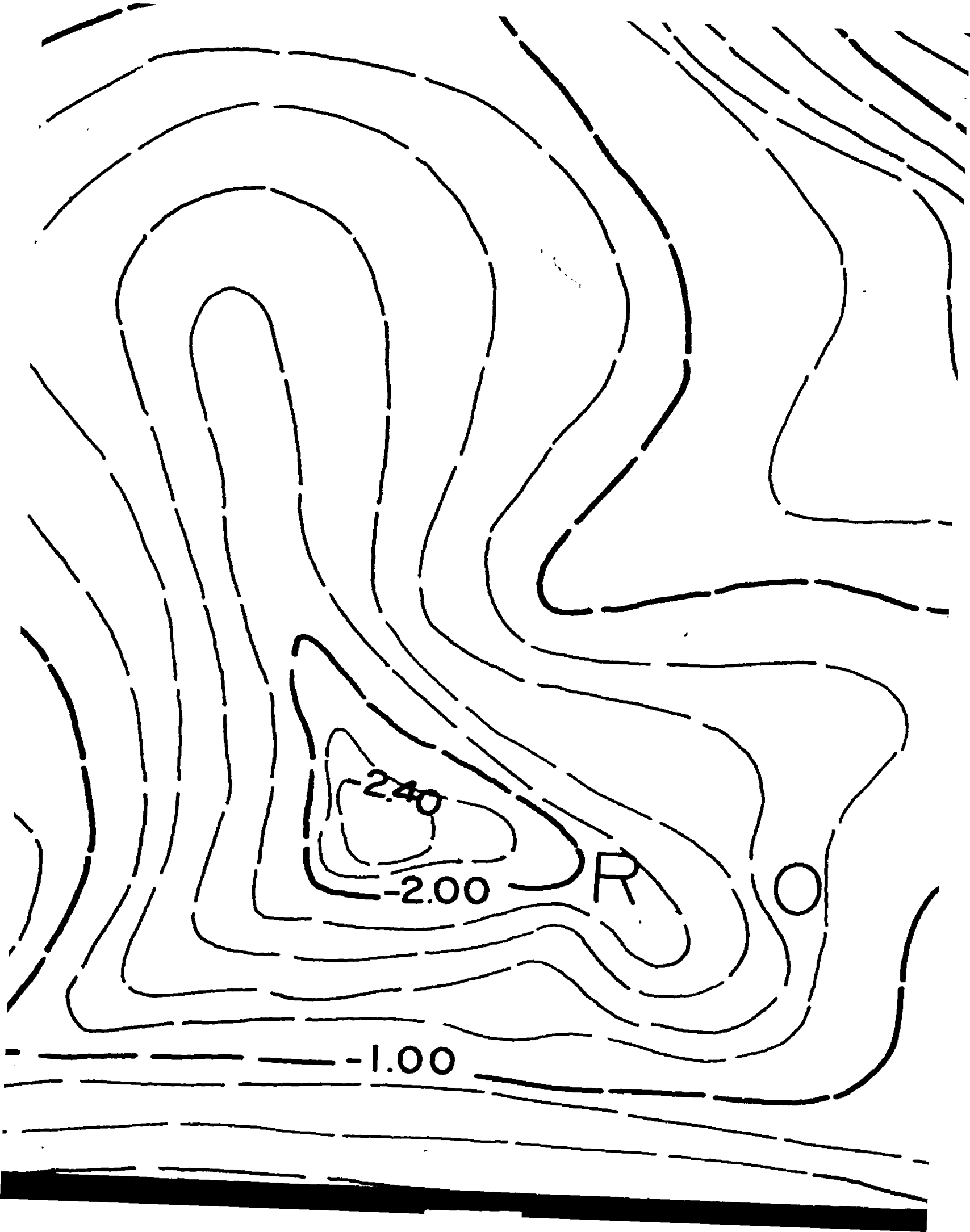


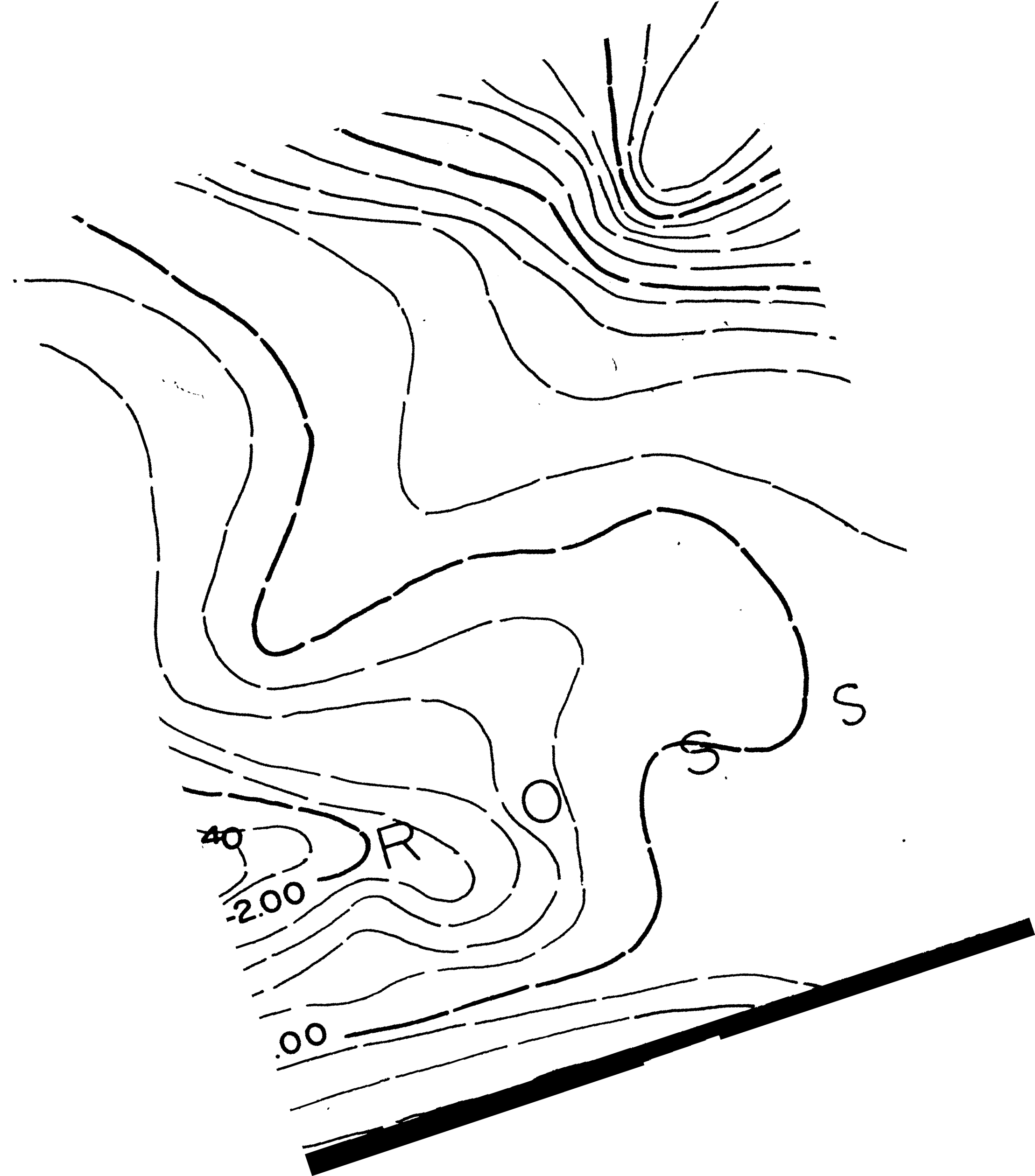


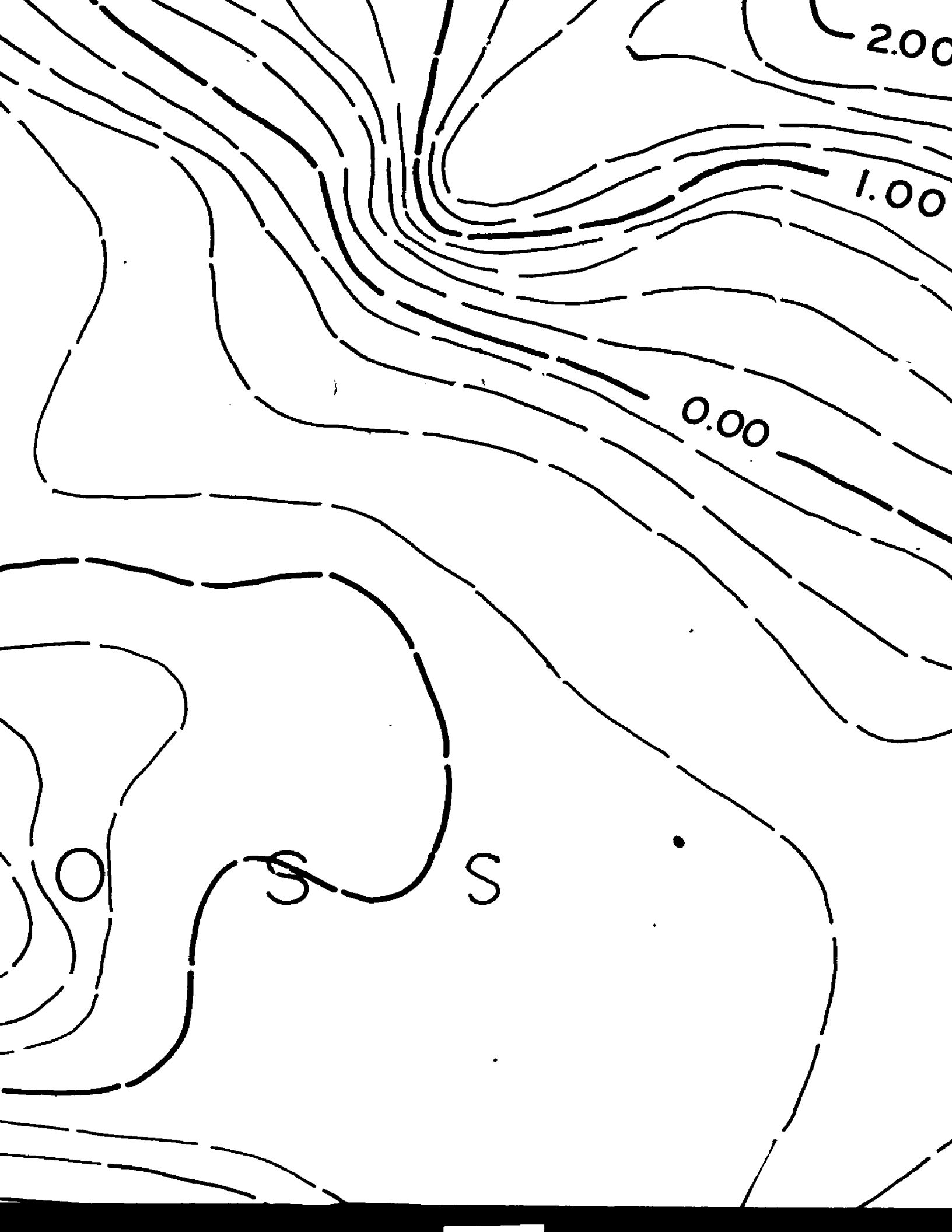


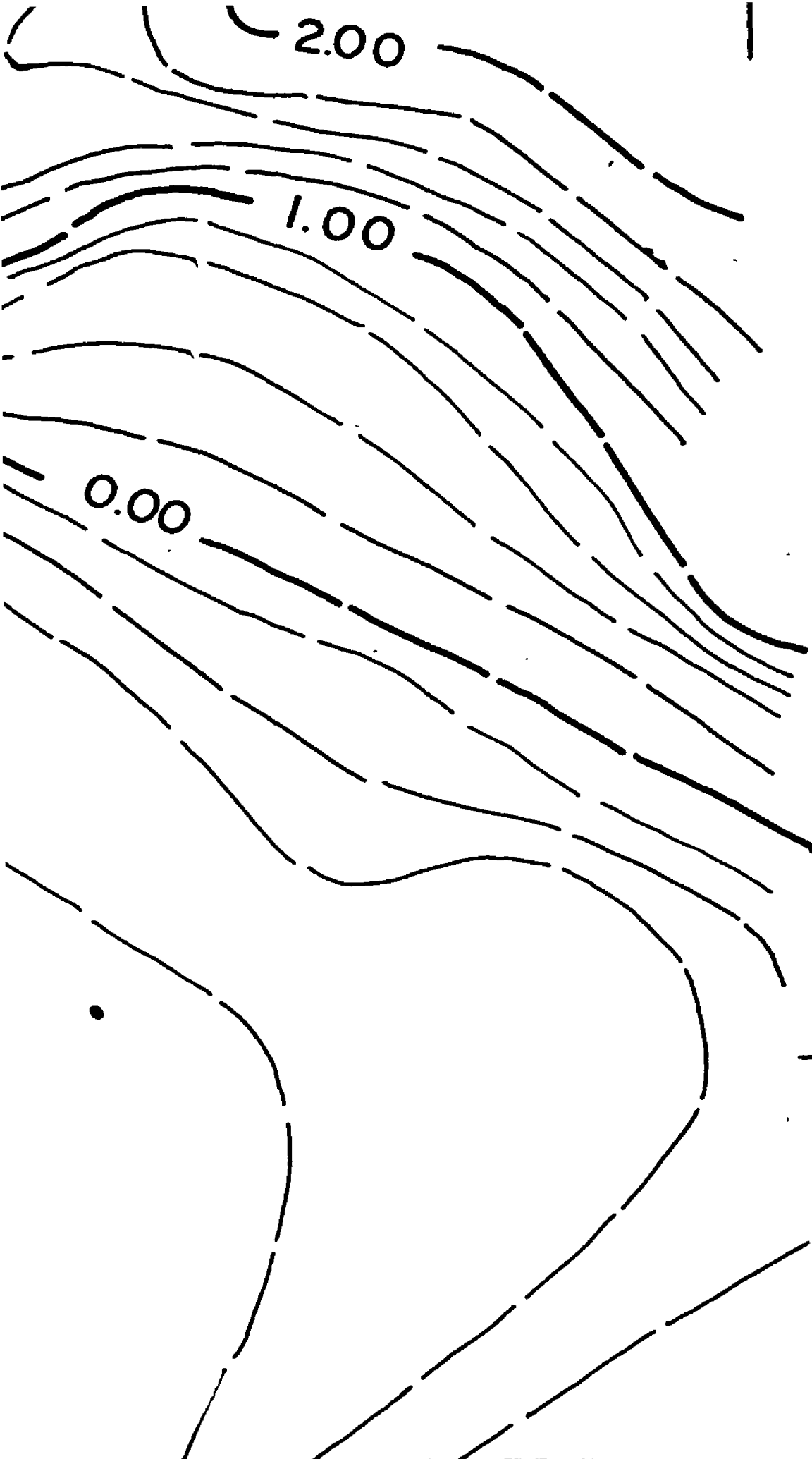










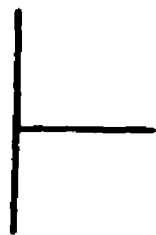


TIS

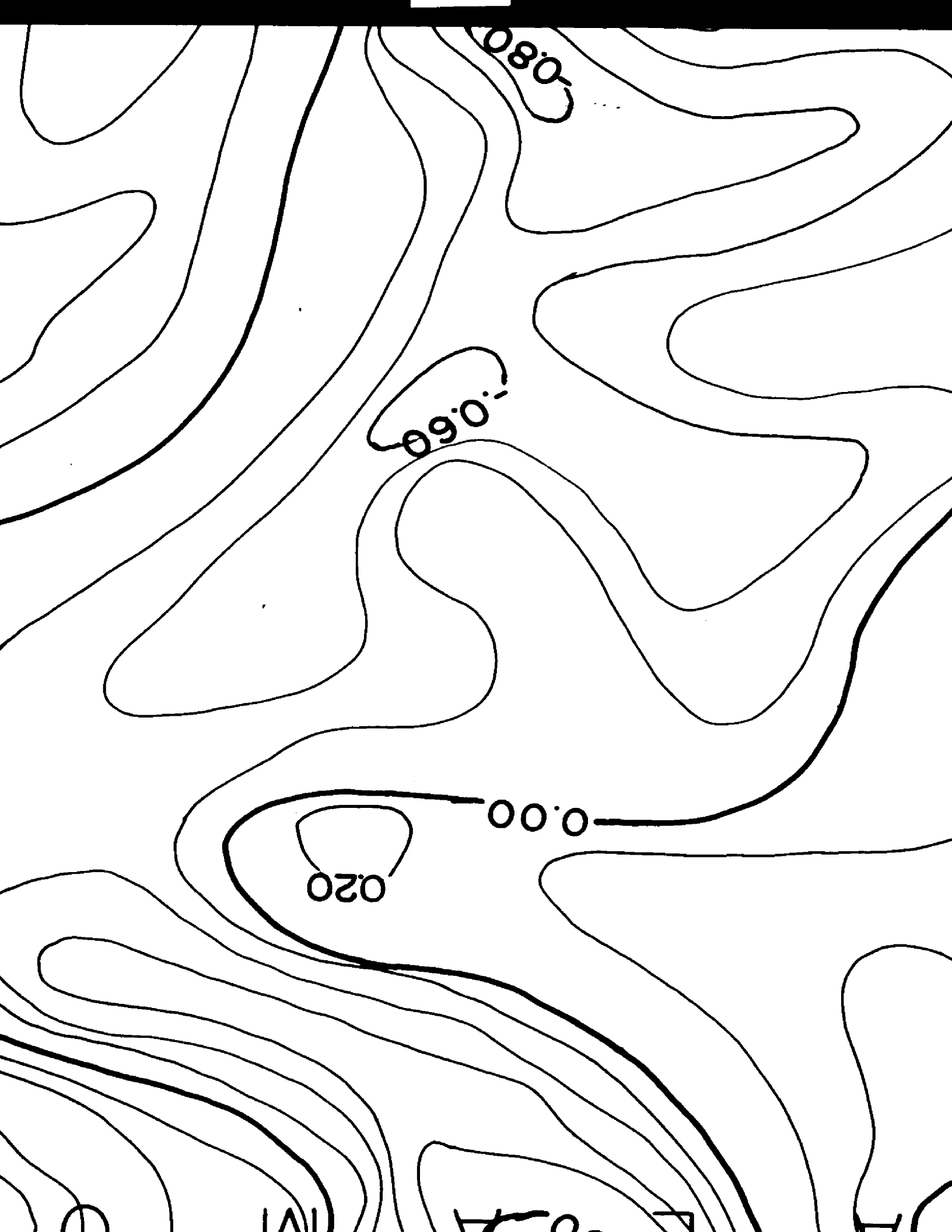
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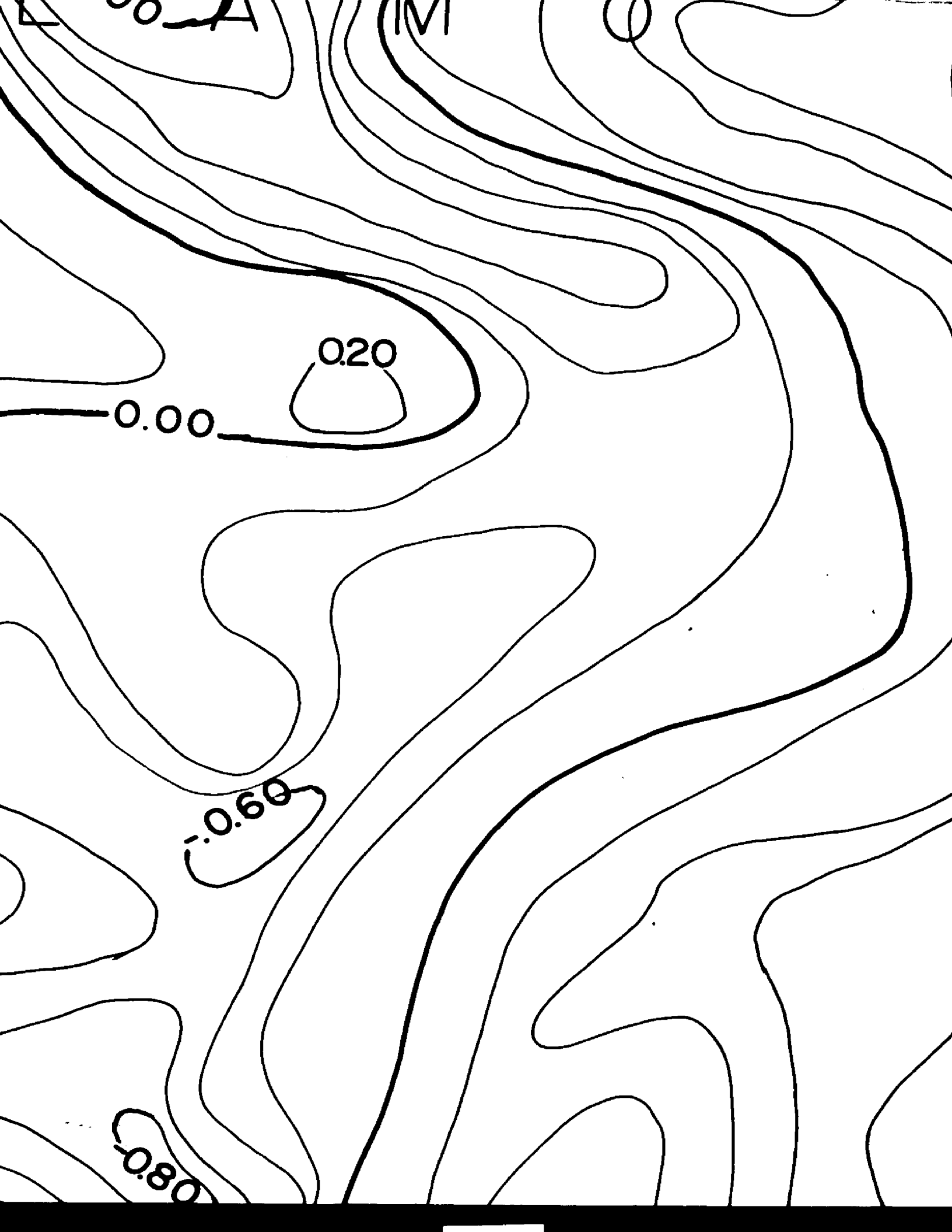
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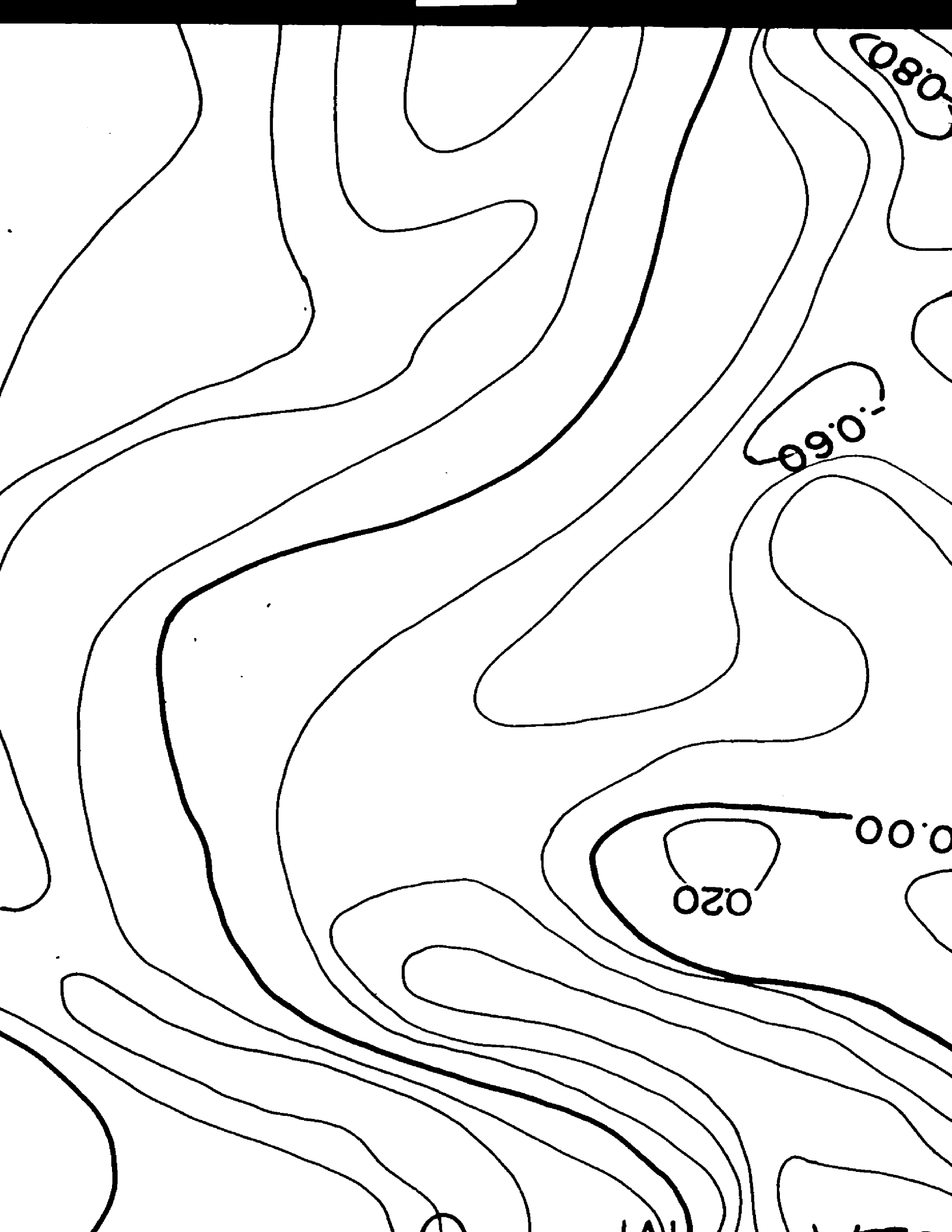
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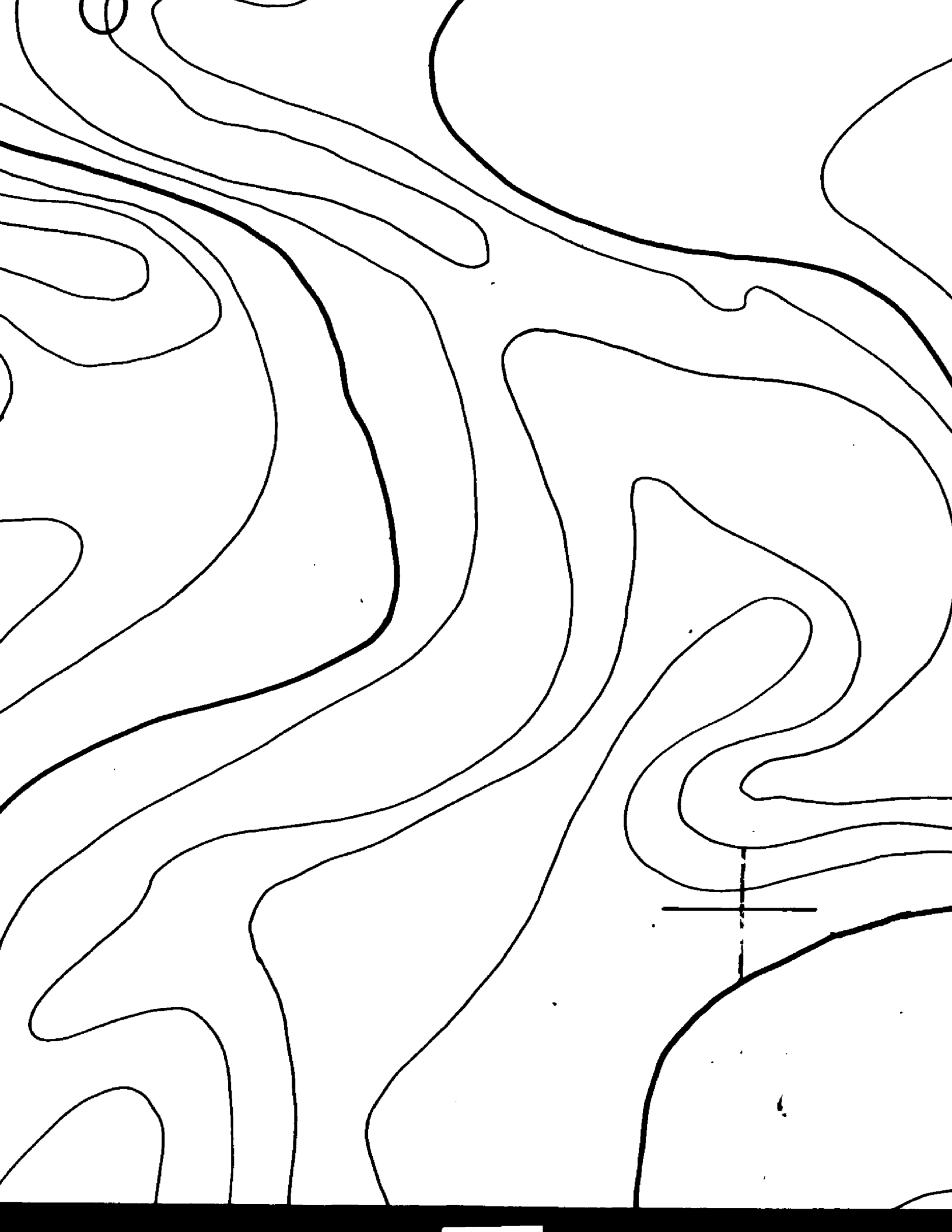


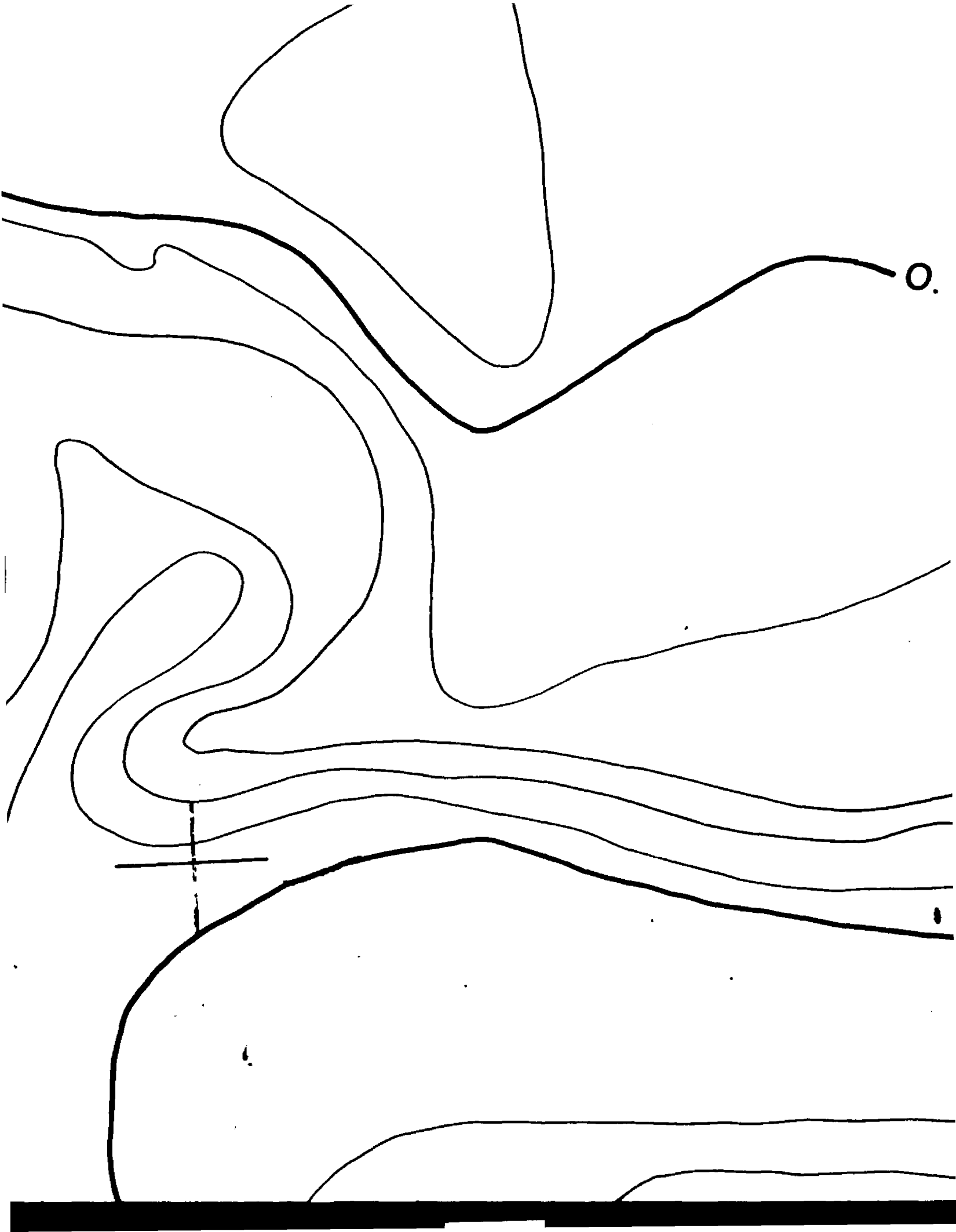


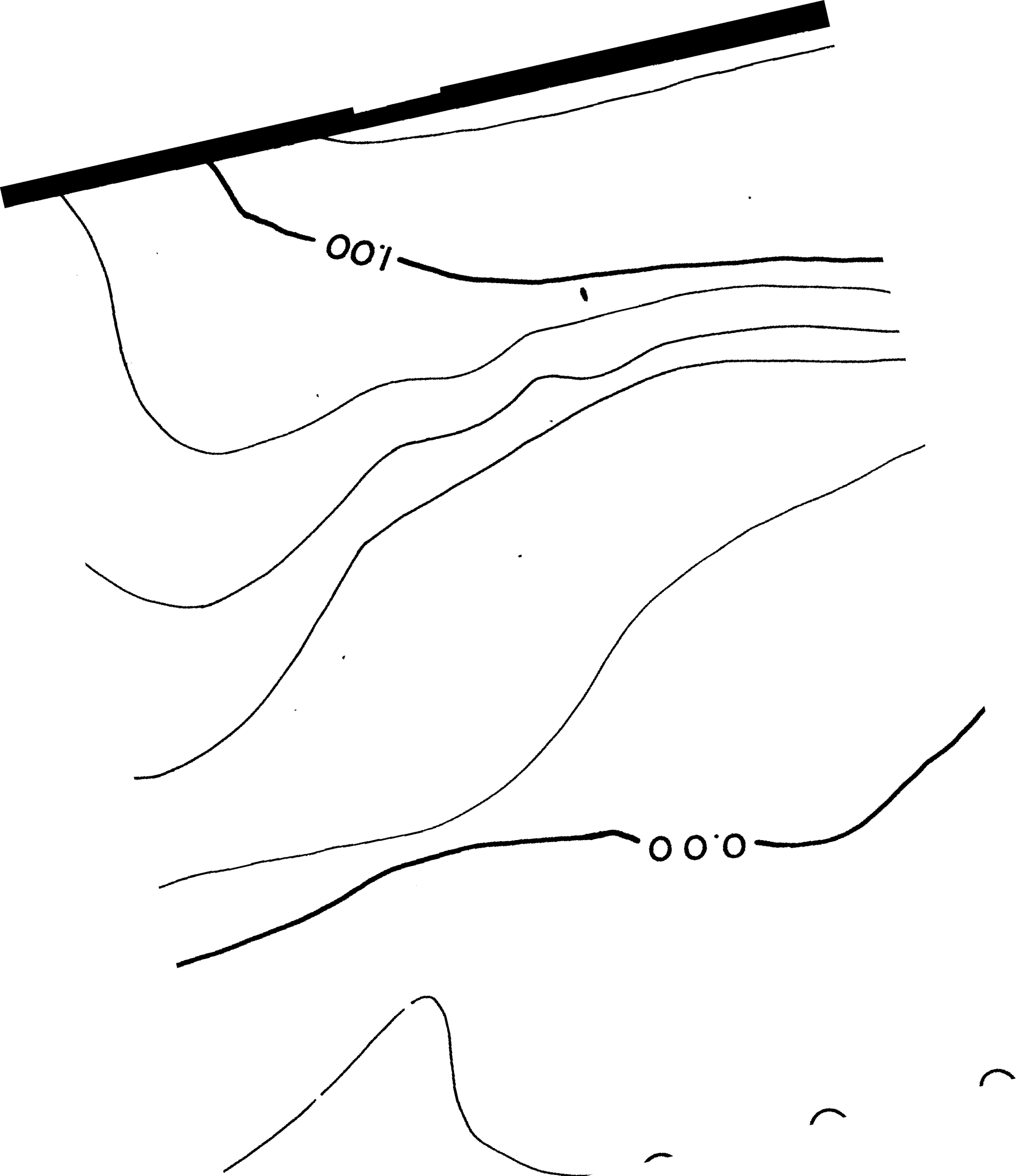








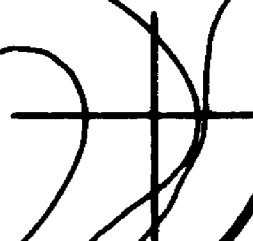


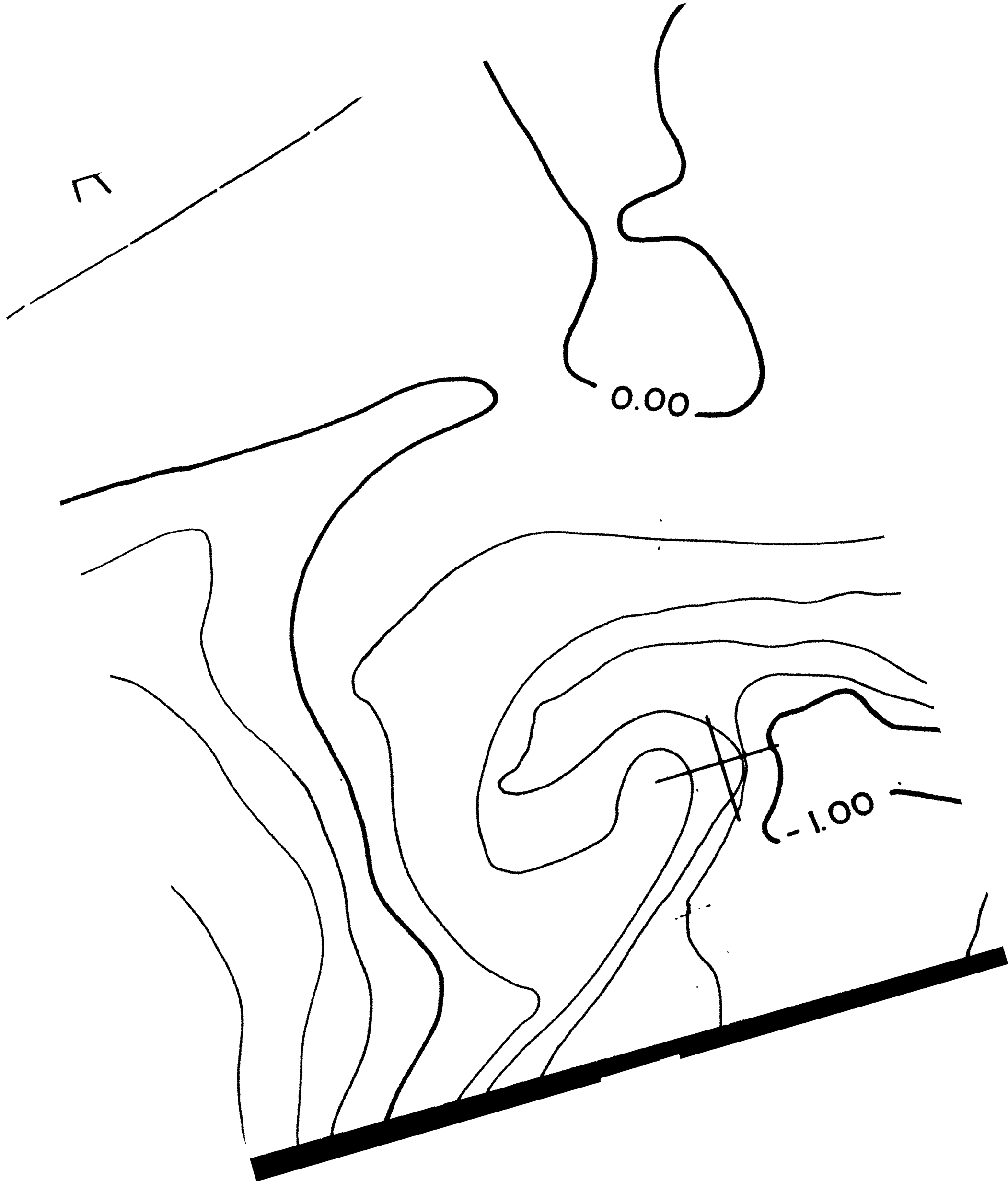


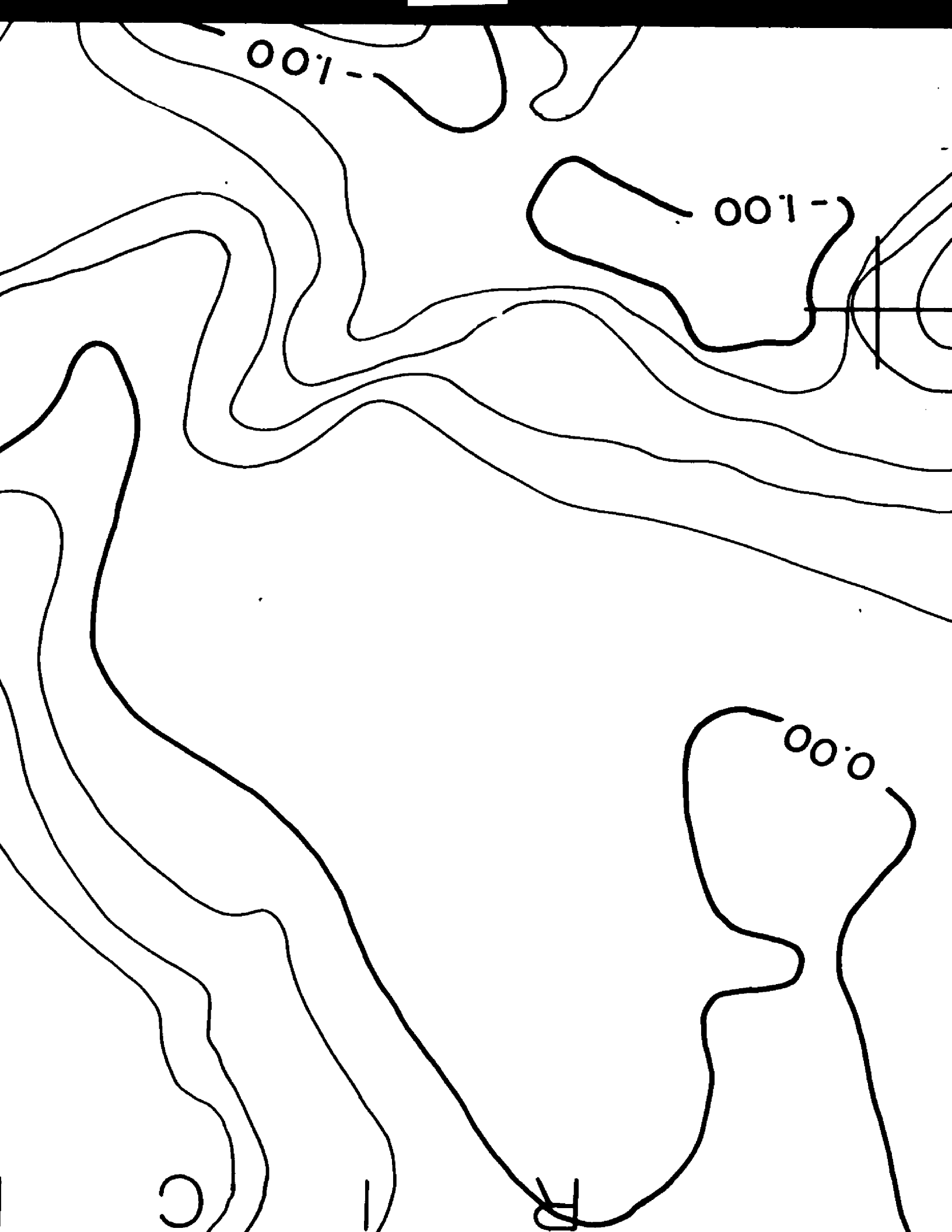


E R

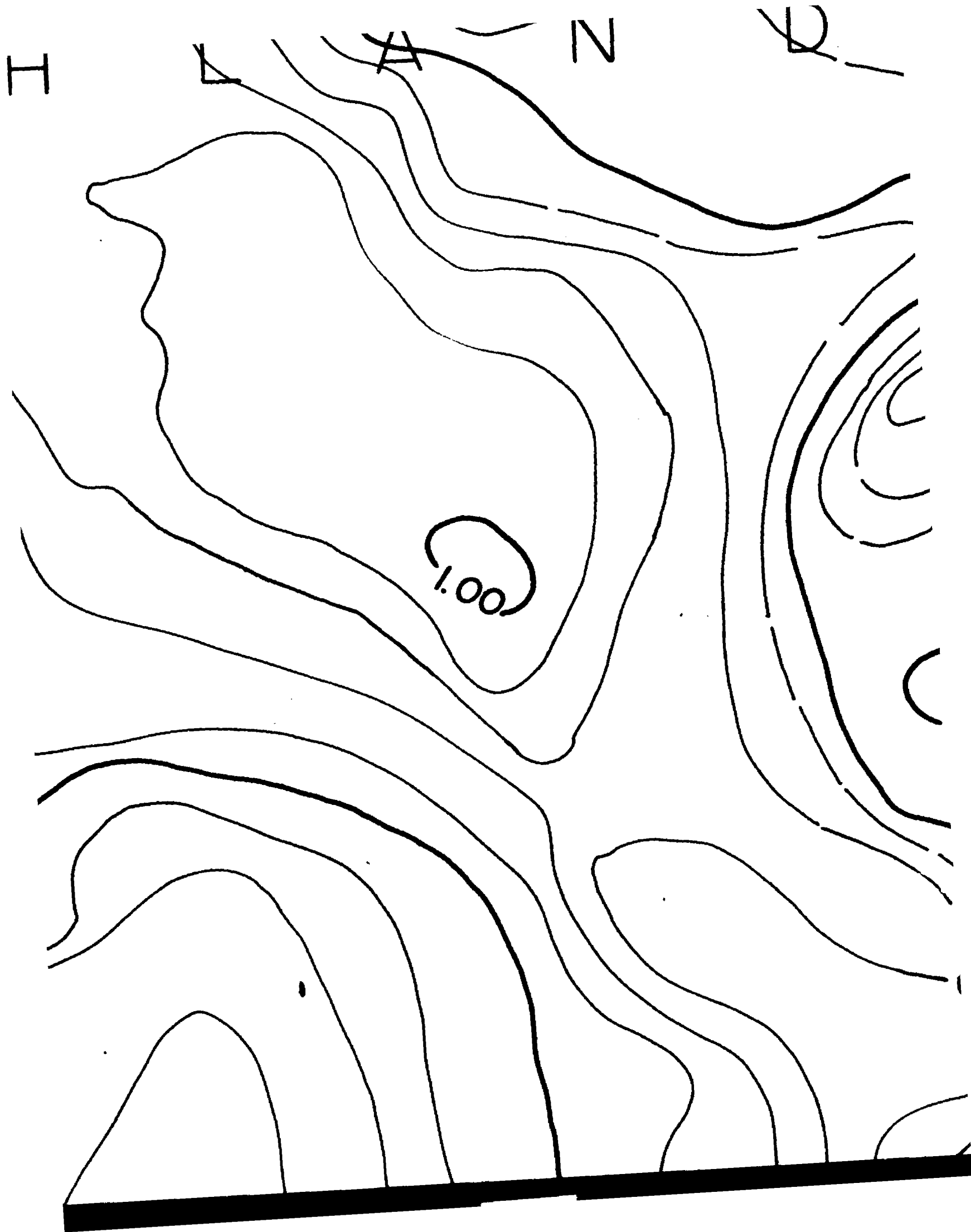
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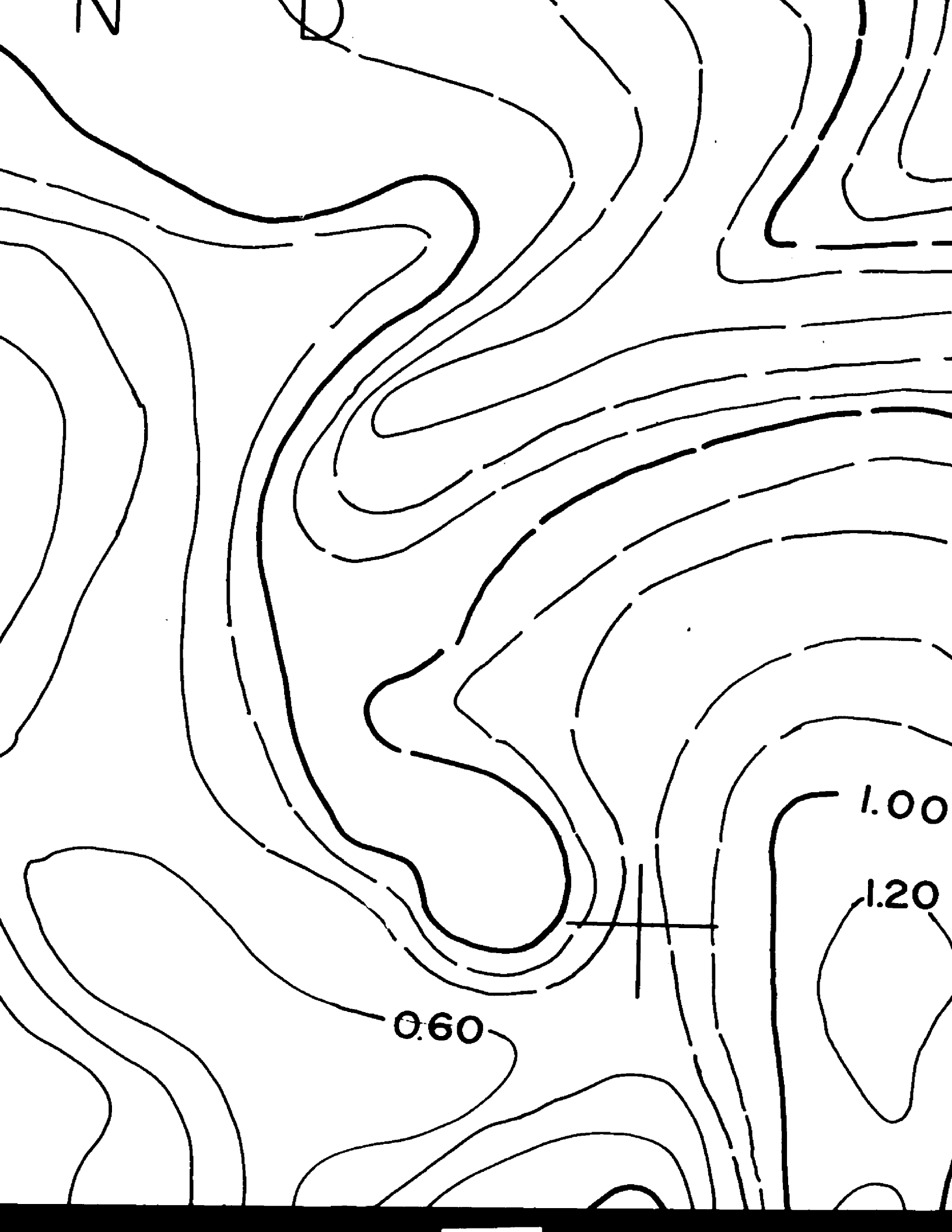












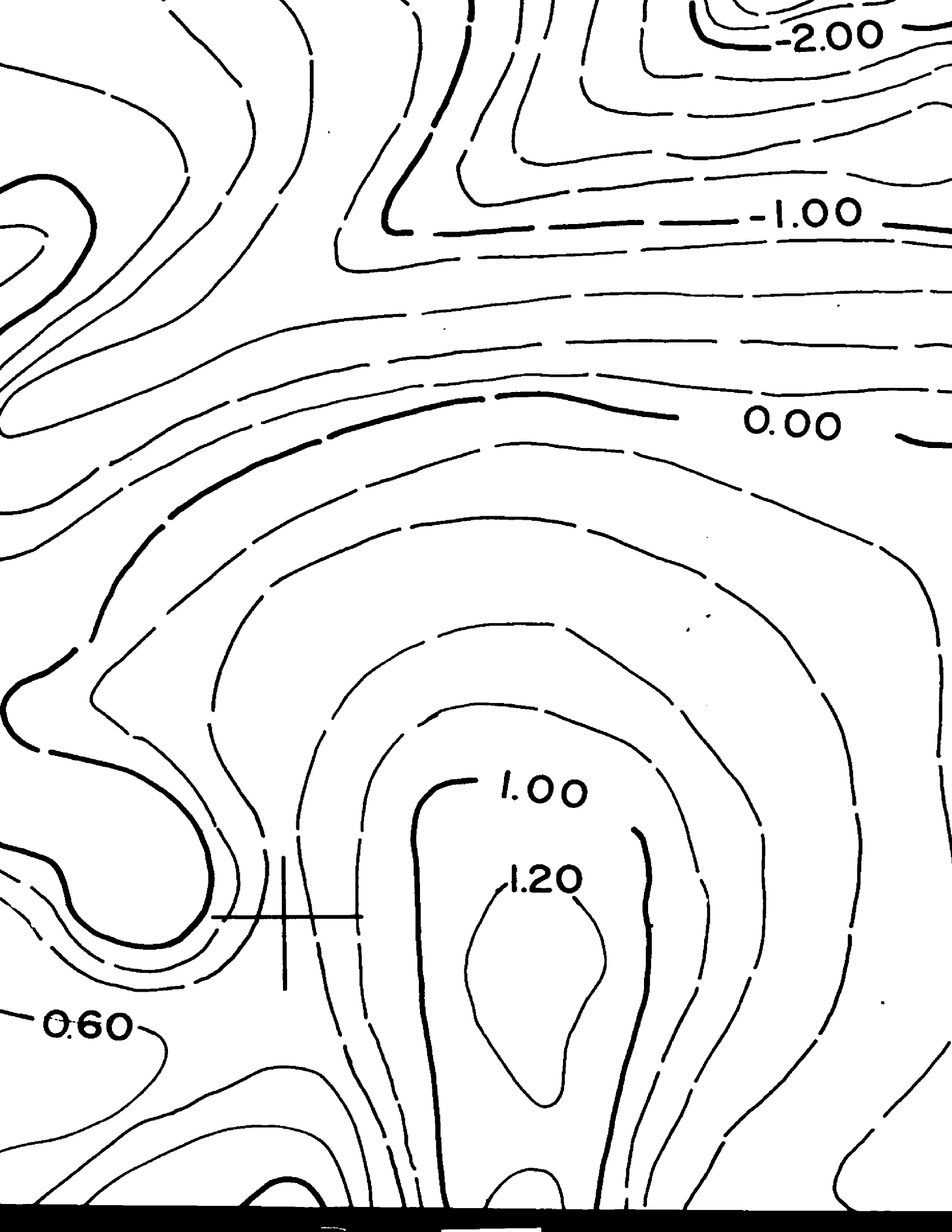
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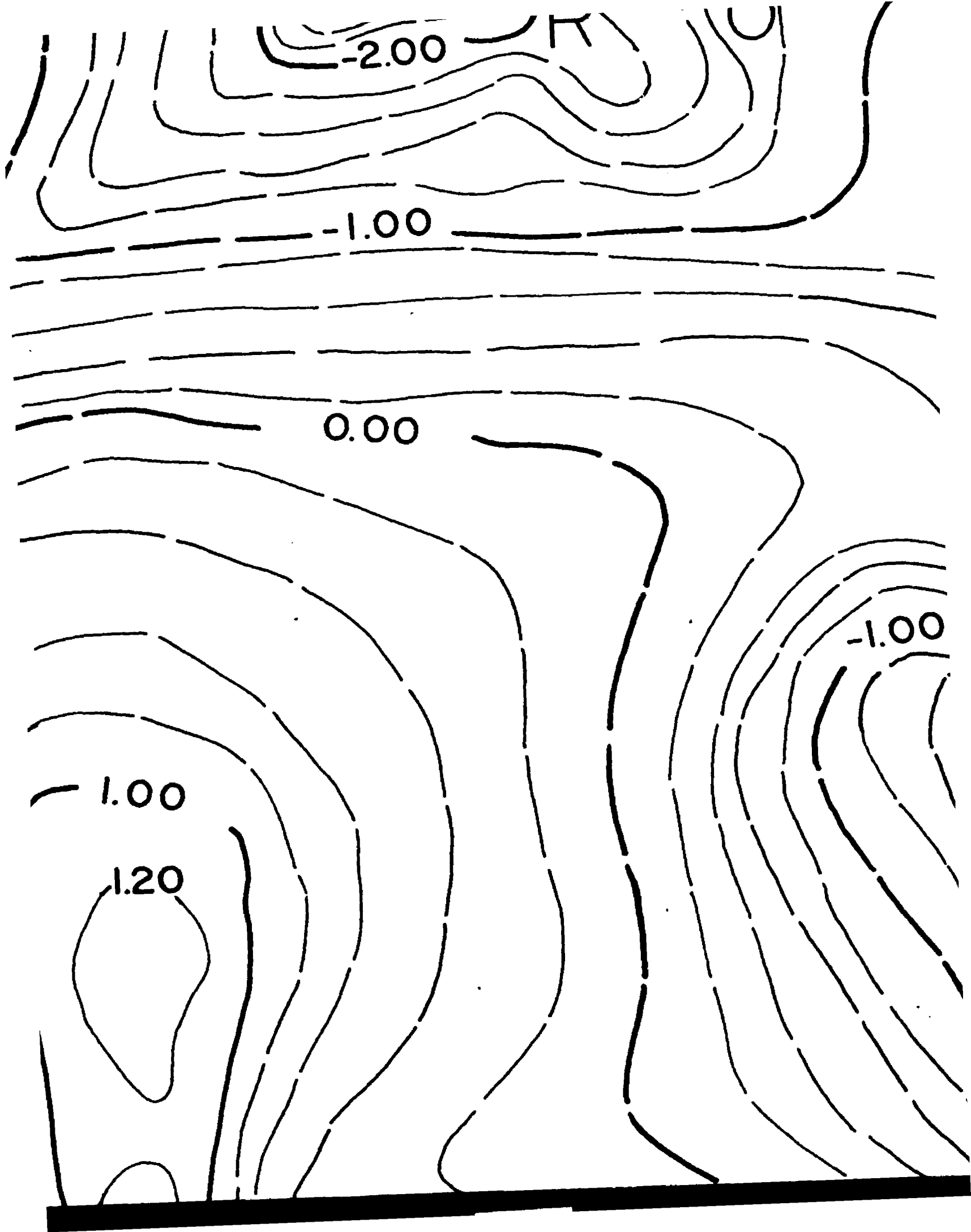
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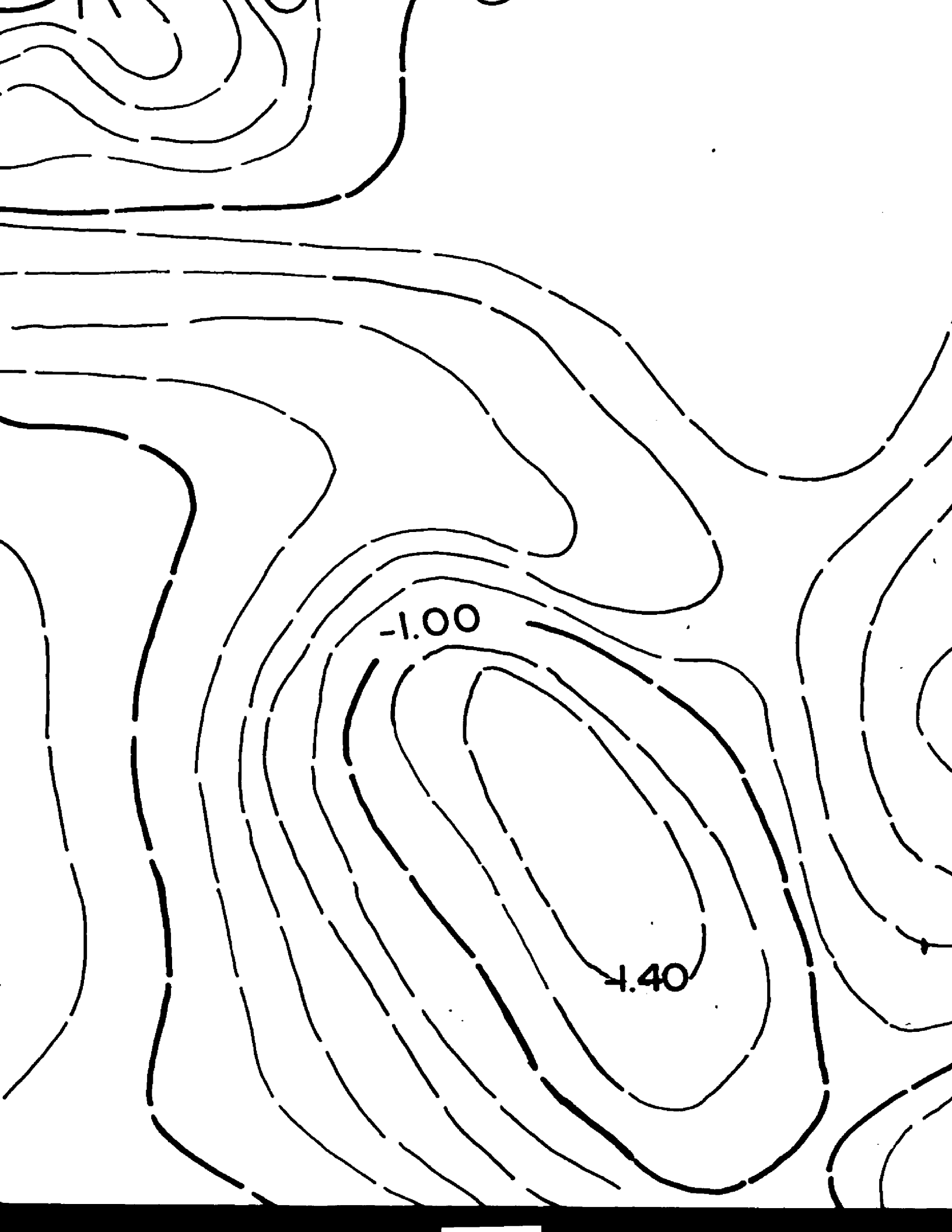
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1.00

1.20

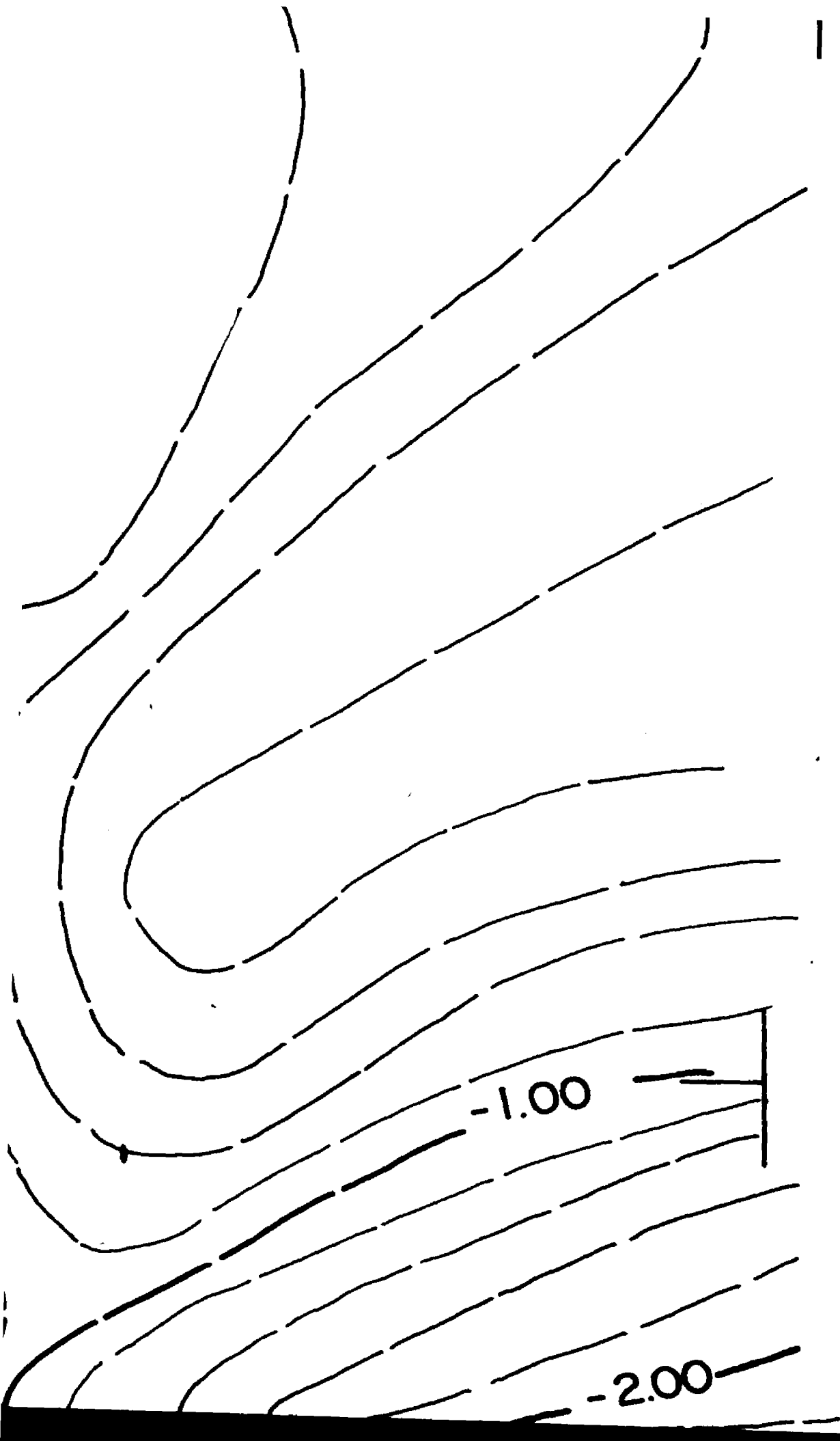








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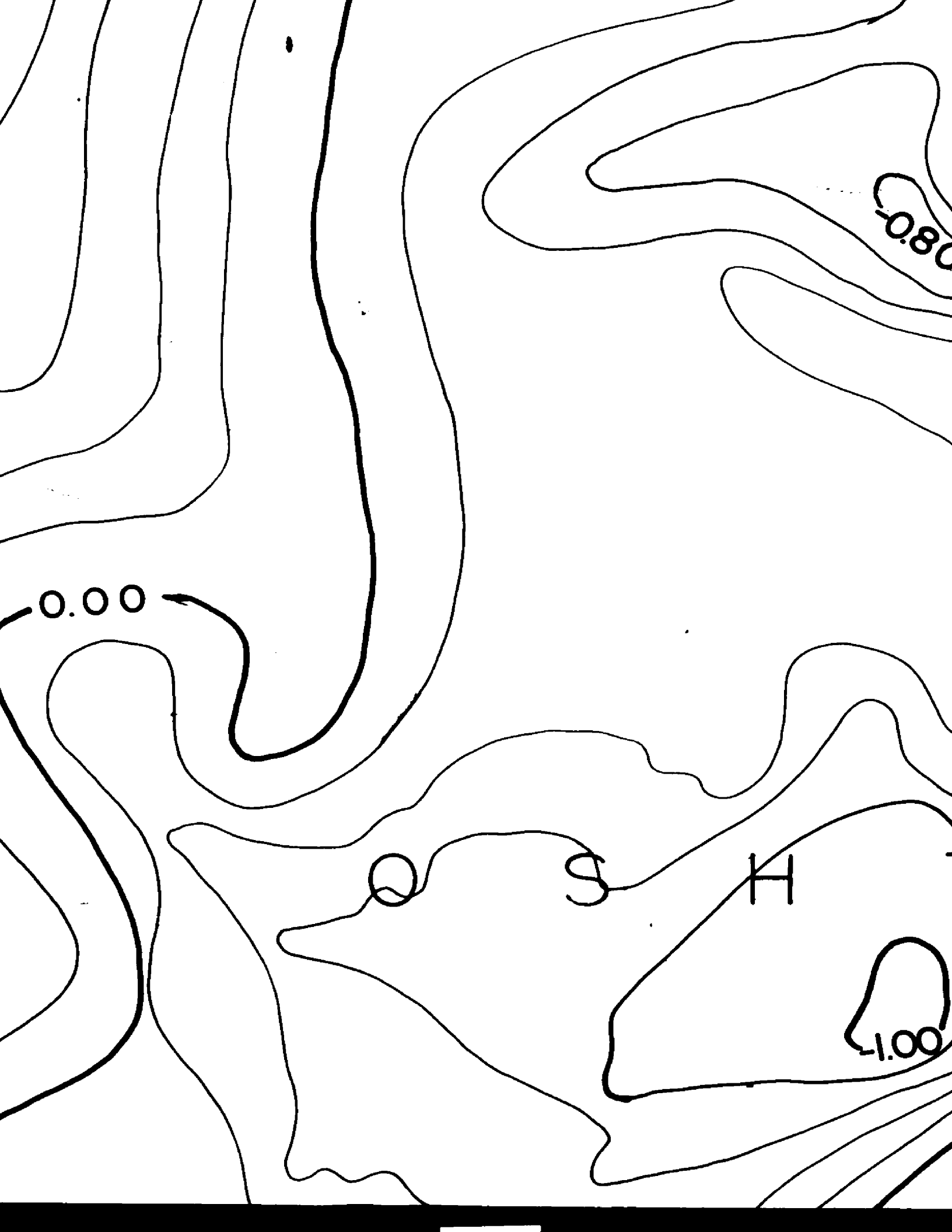


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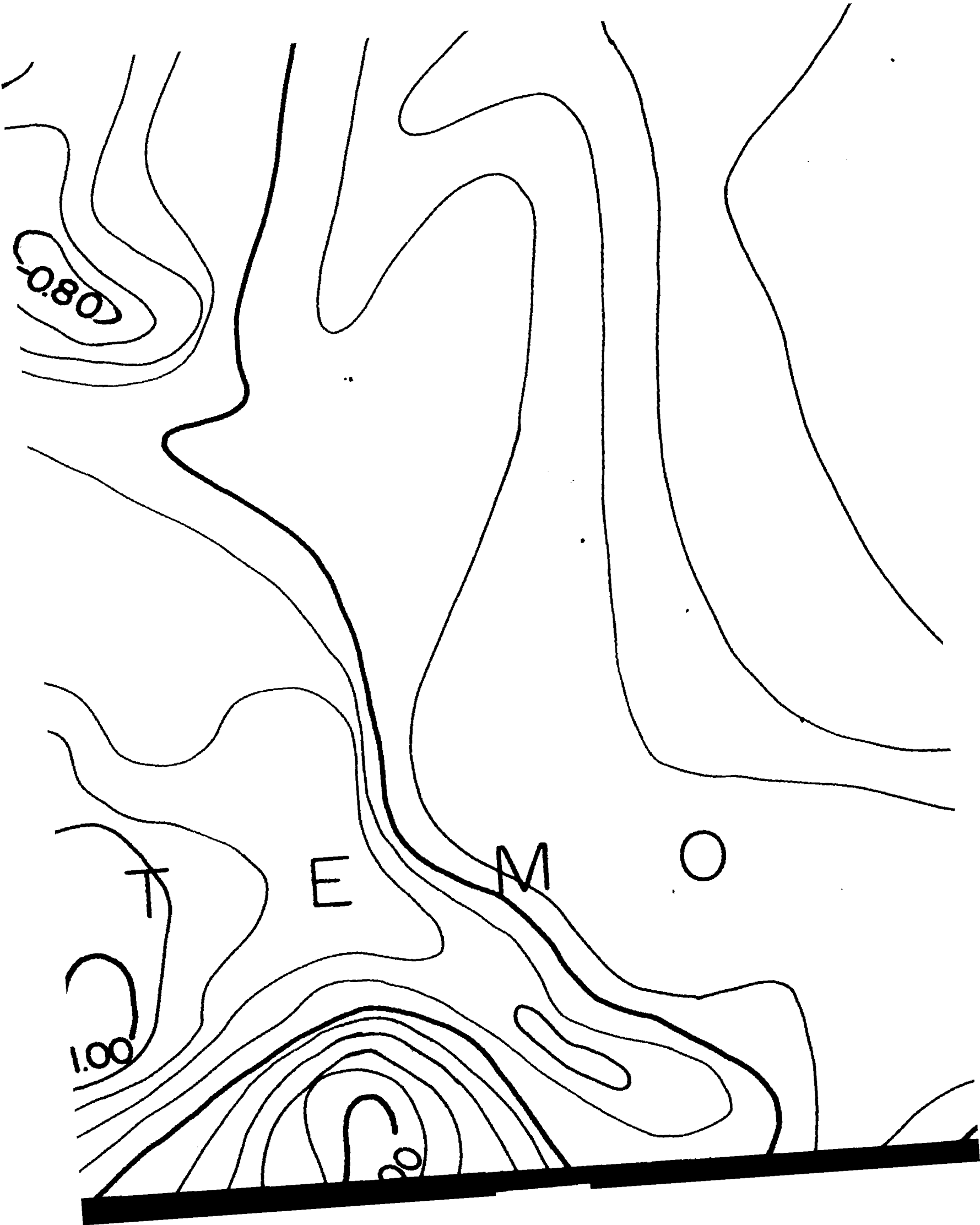
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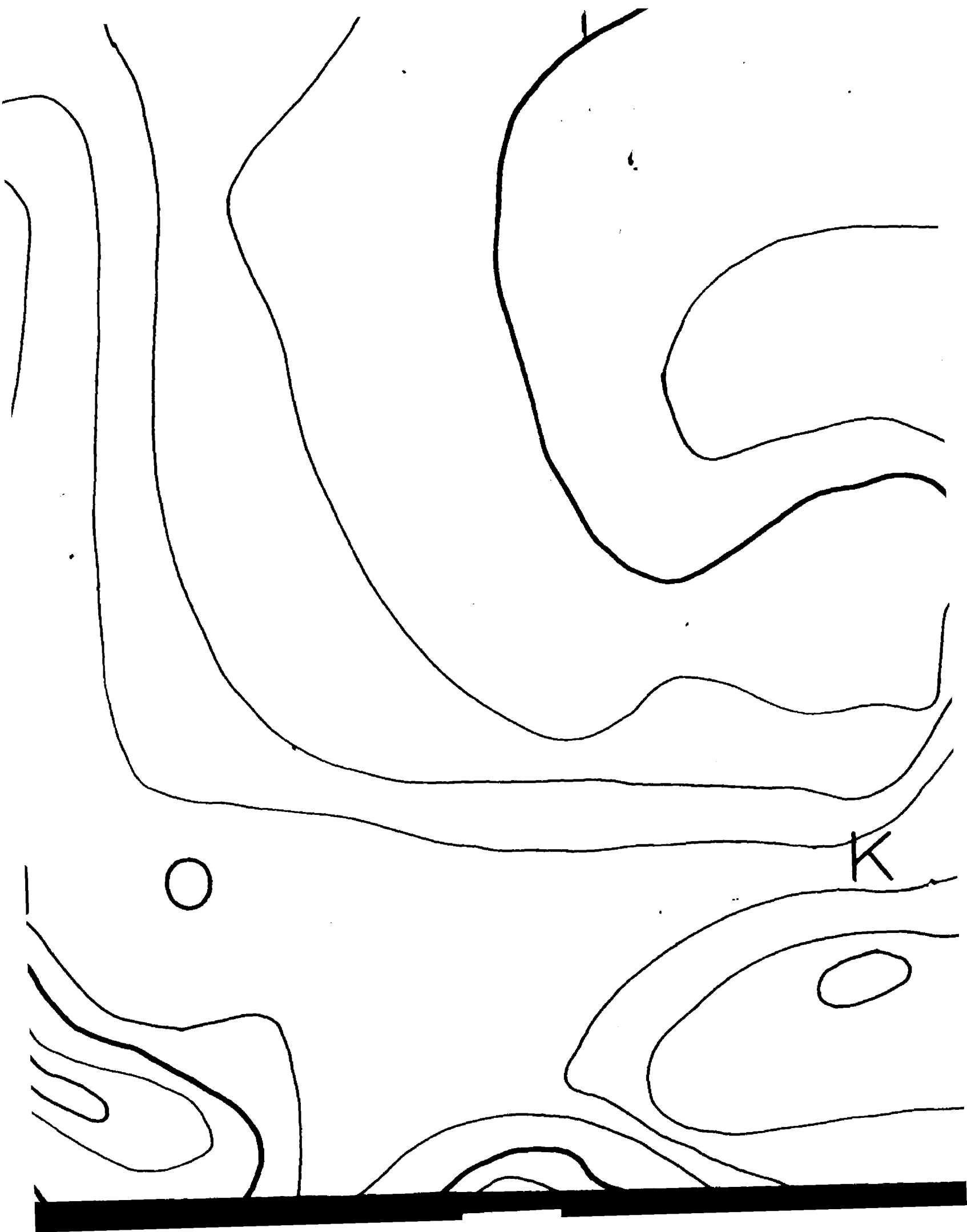
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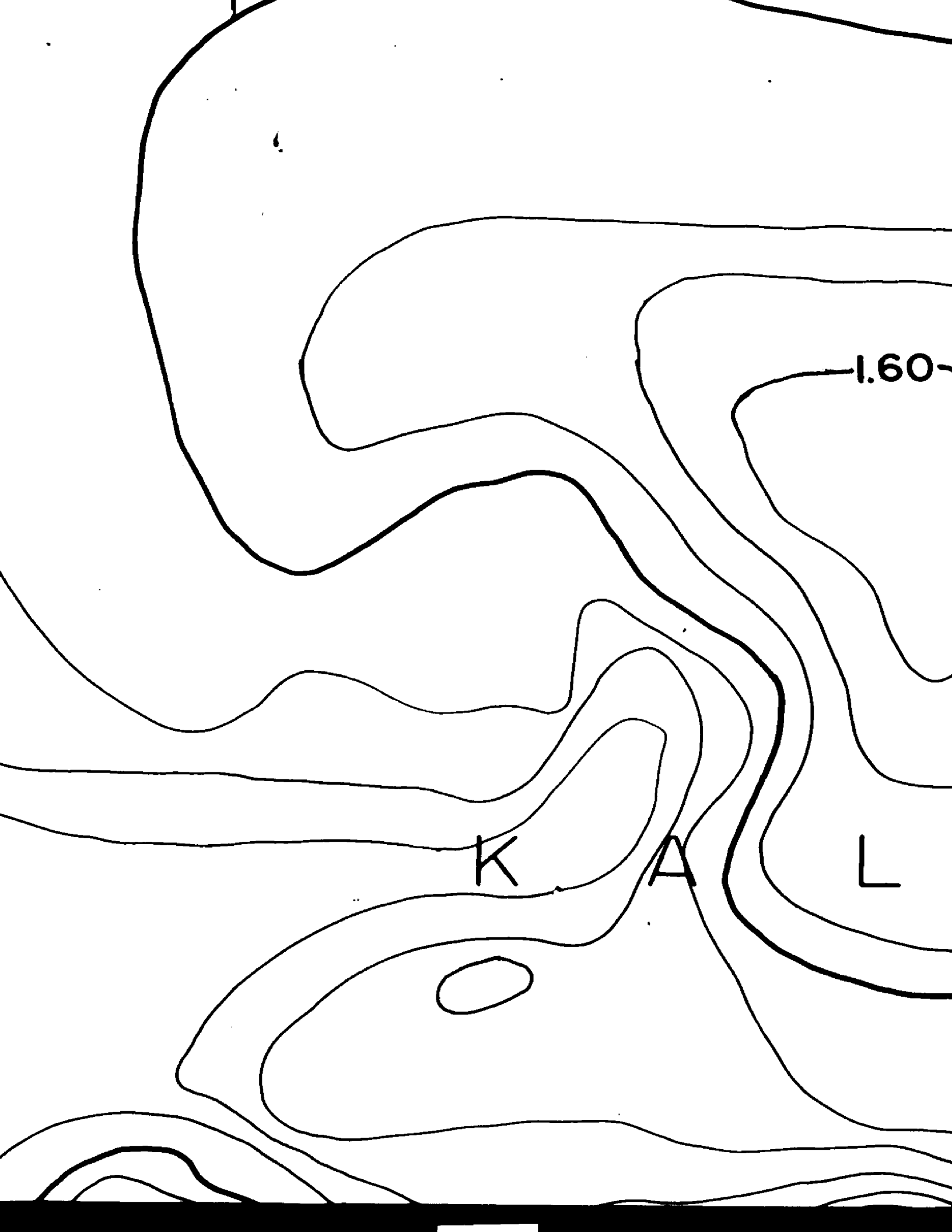
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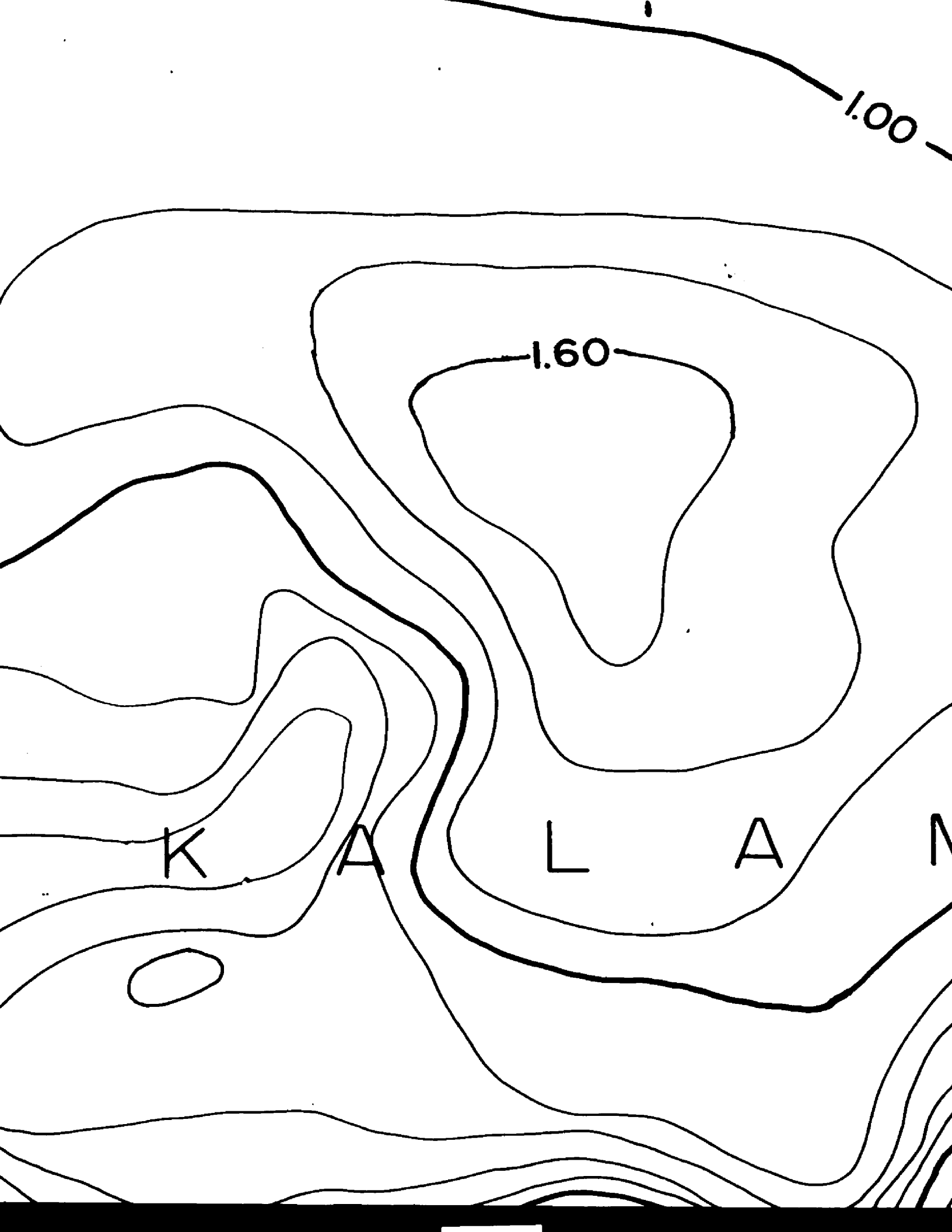


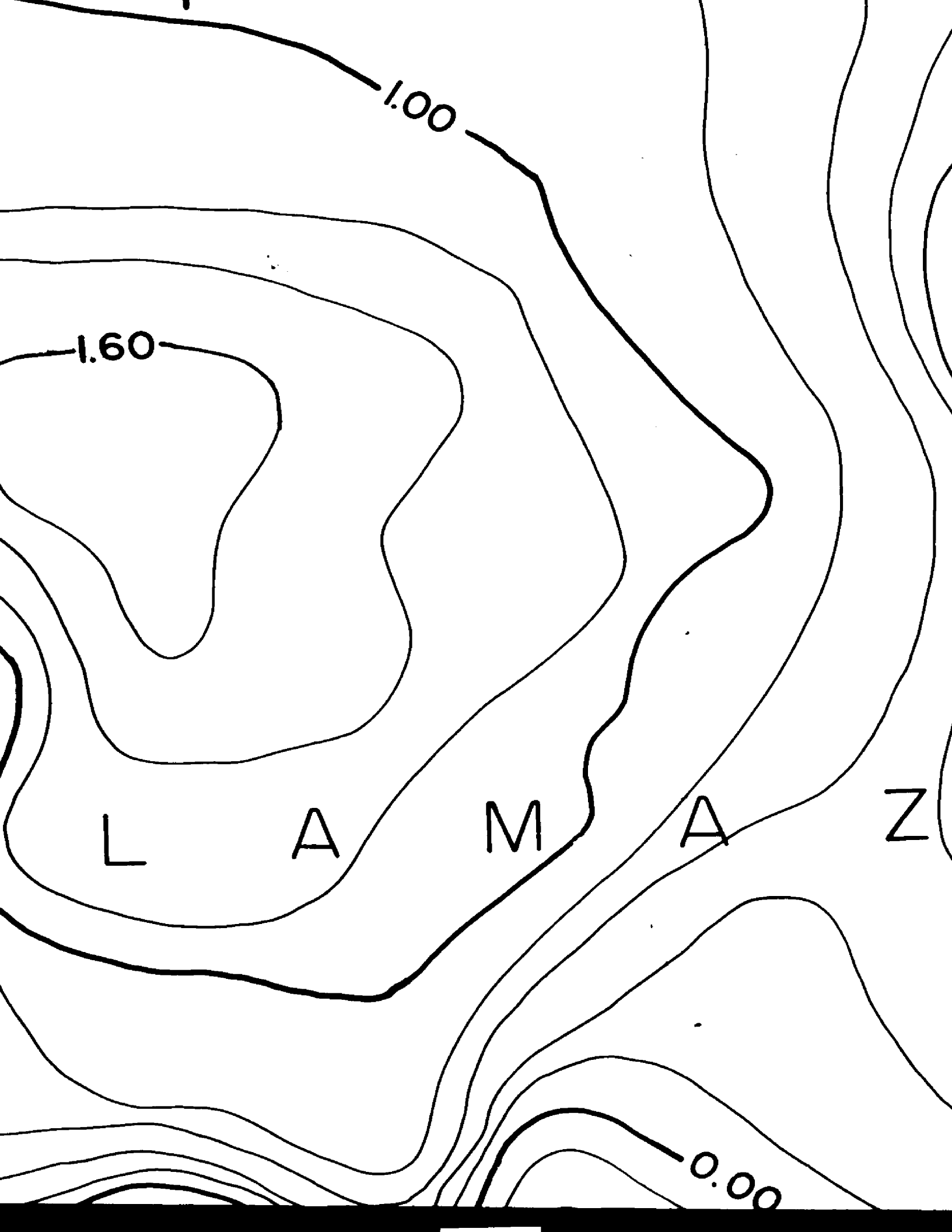


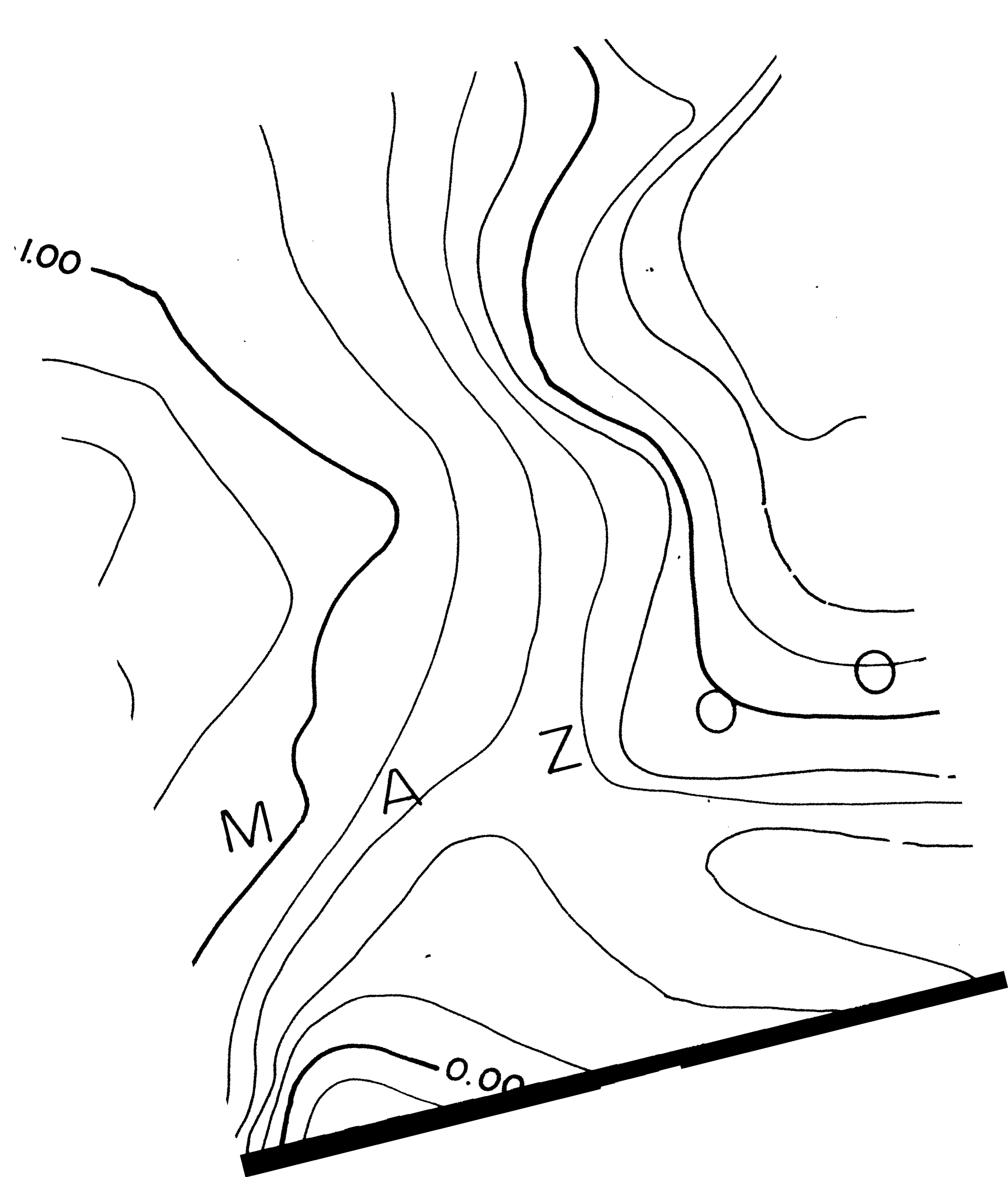




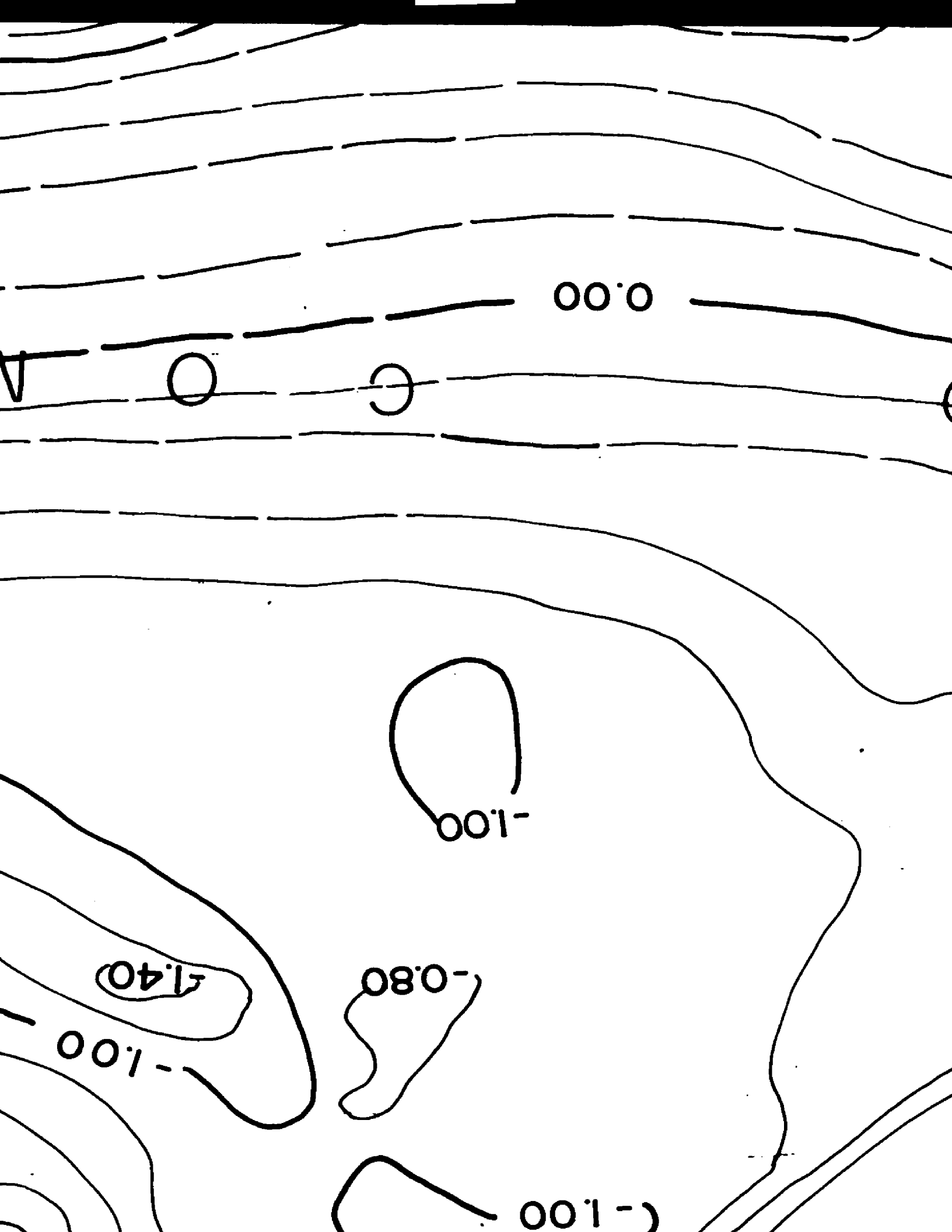


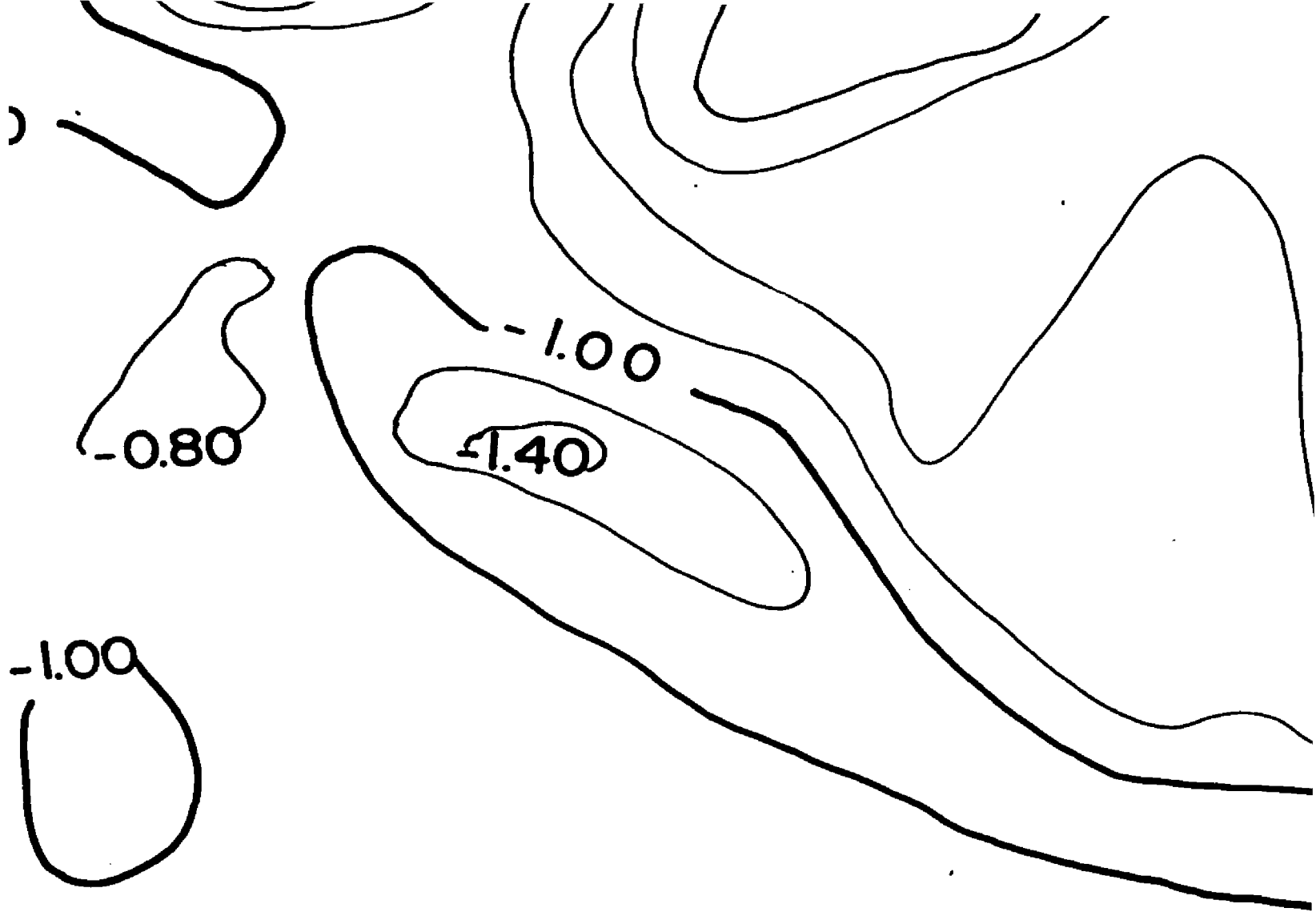




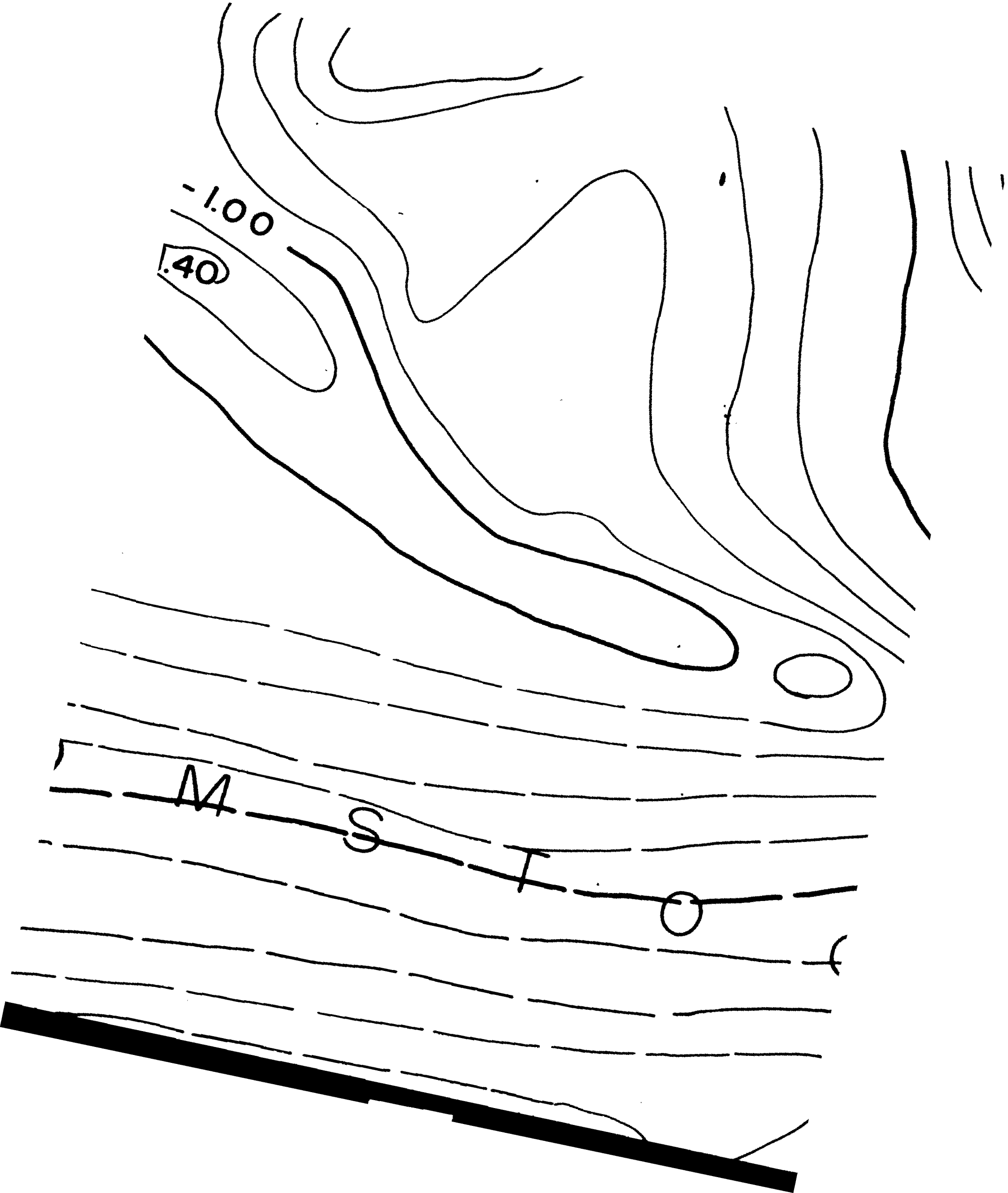






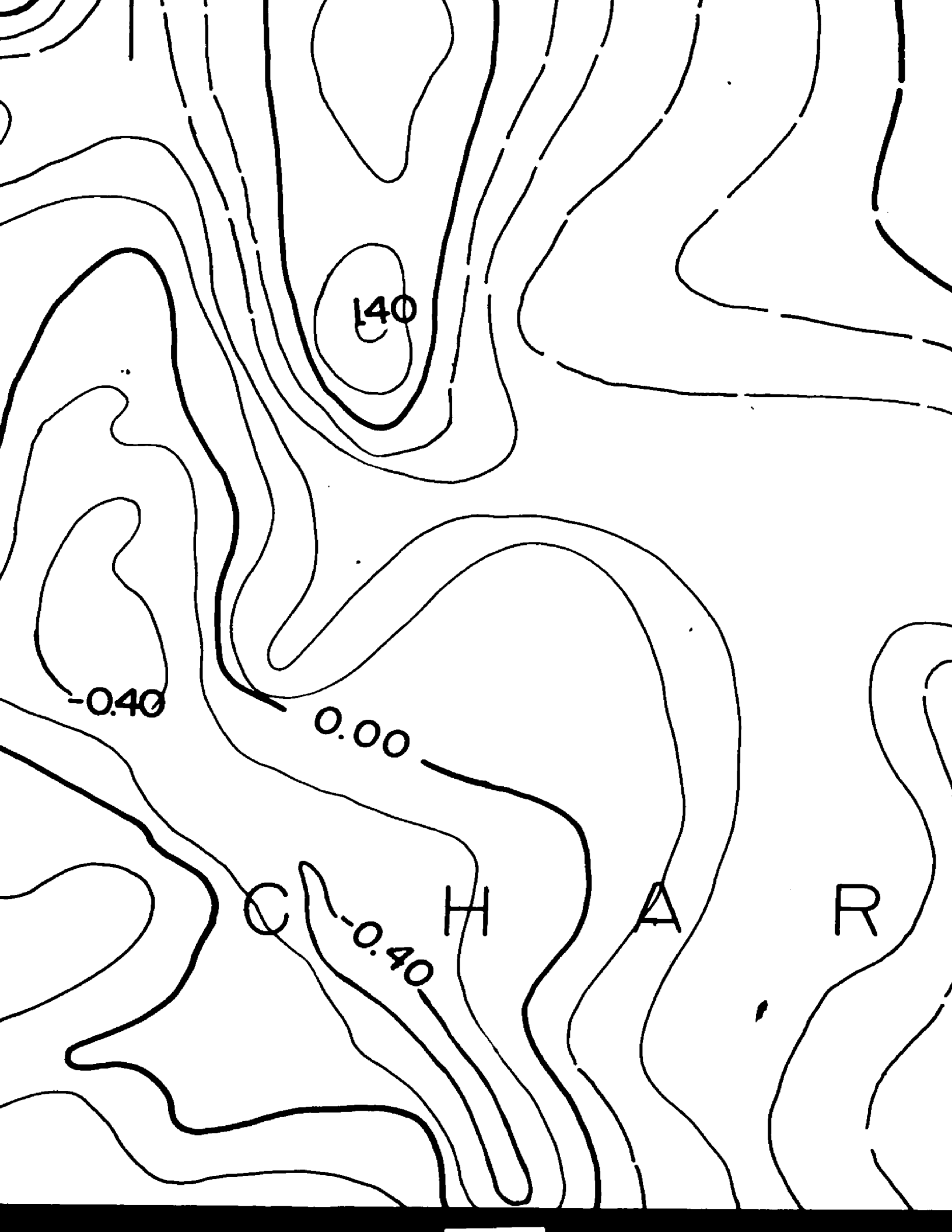


C O M S I

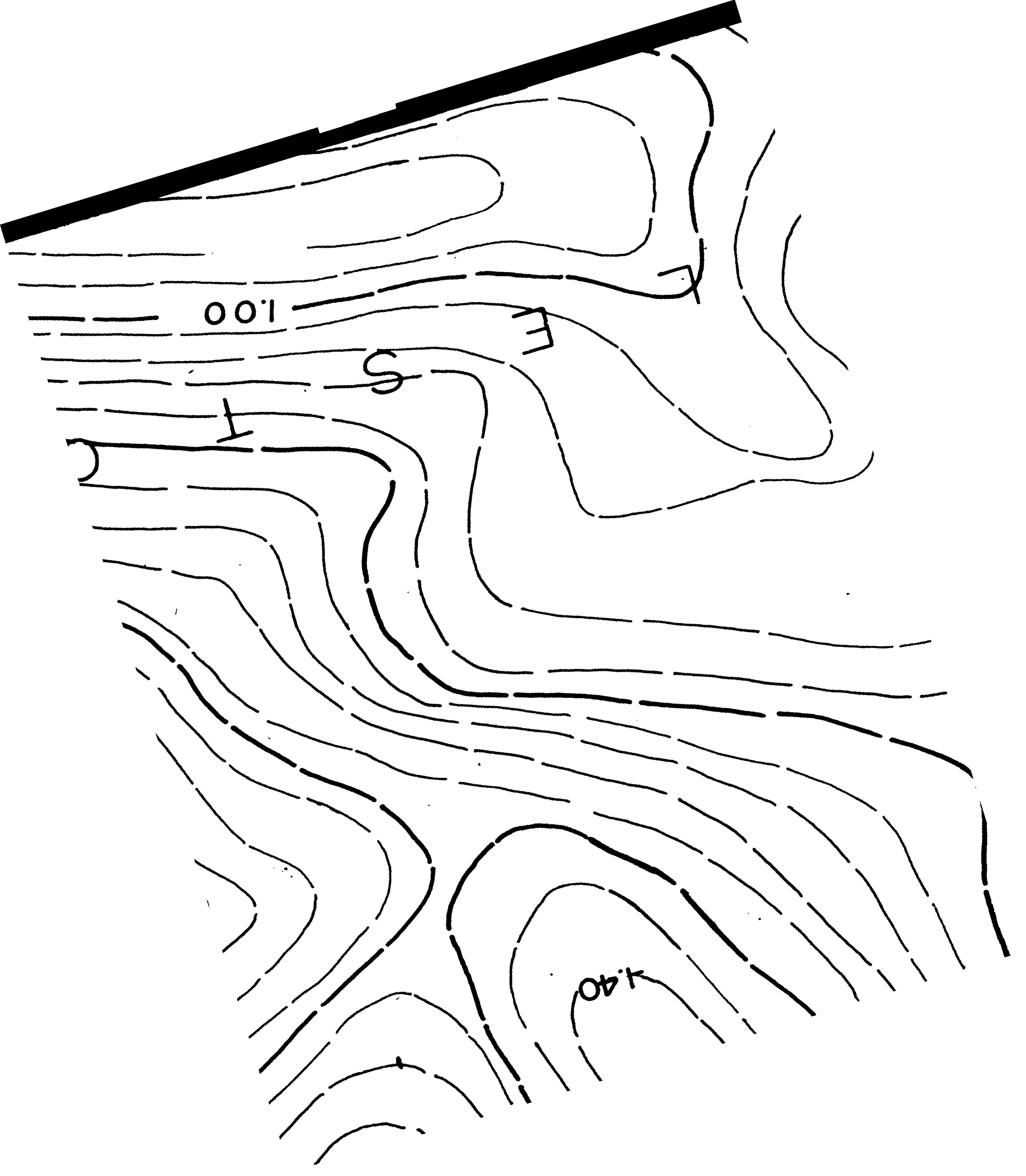


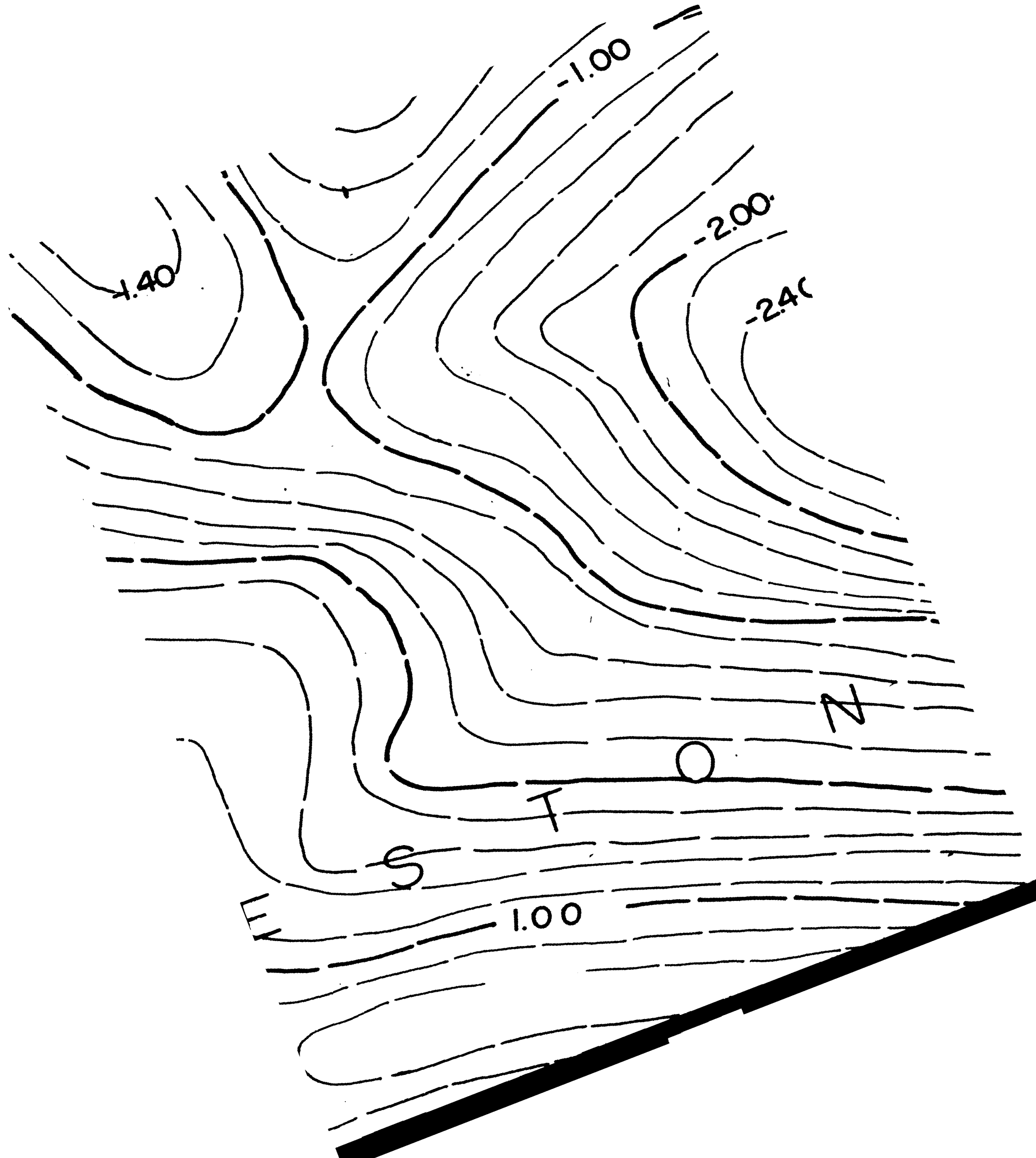


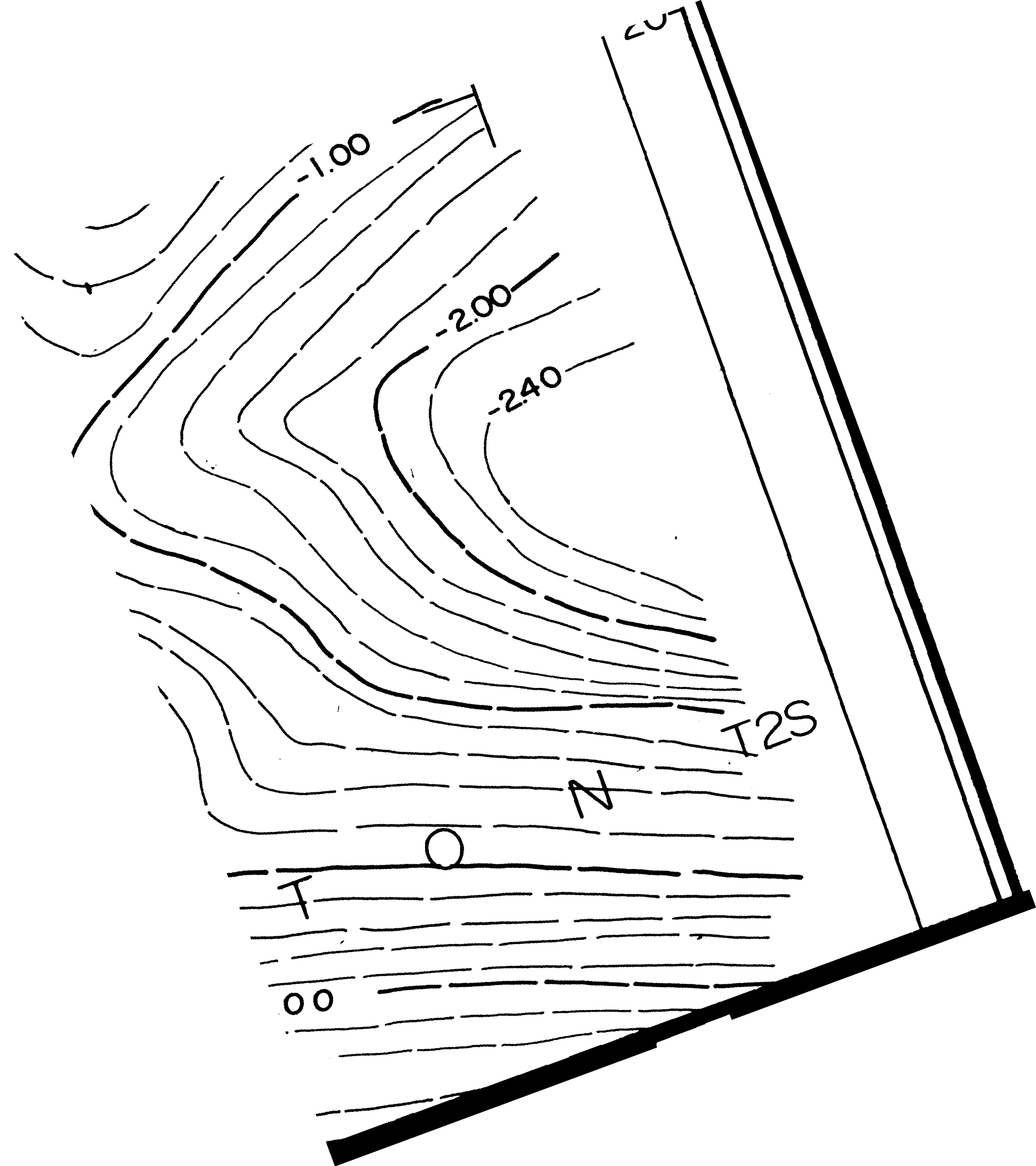


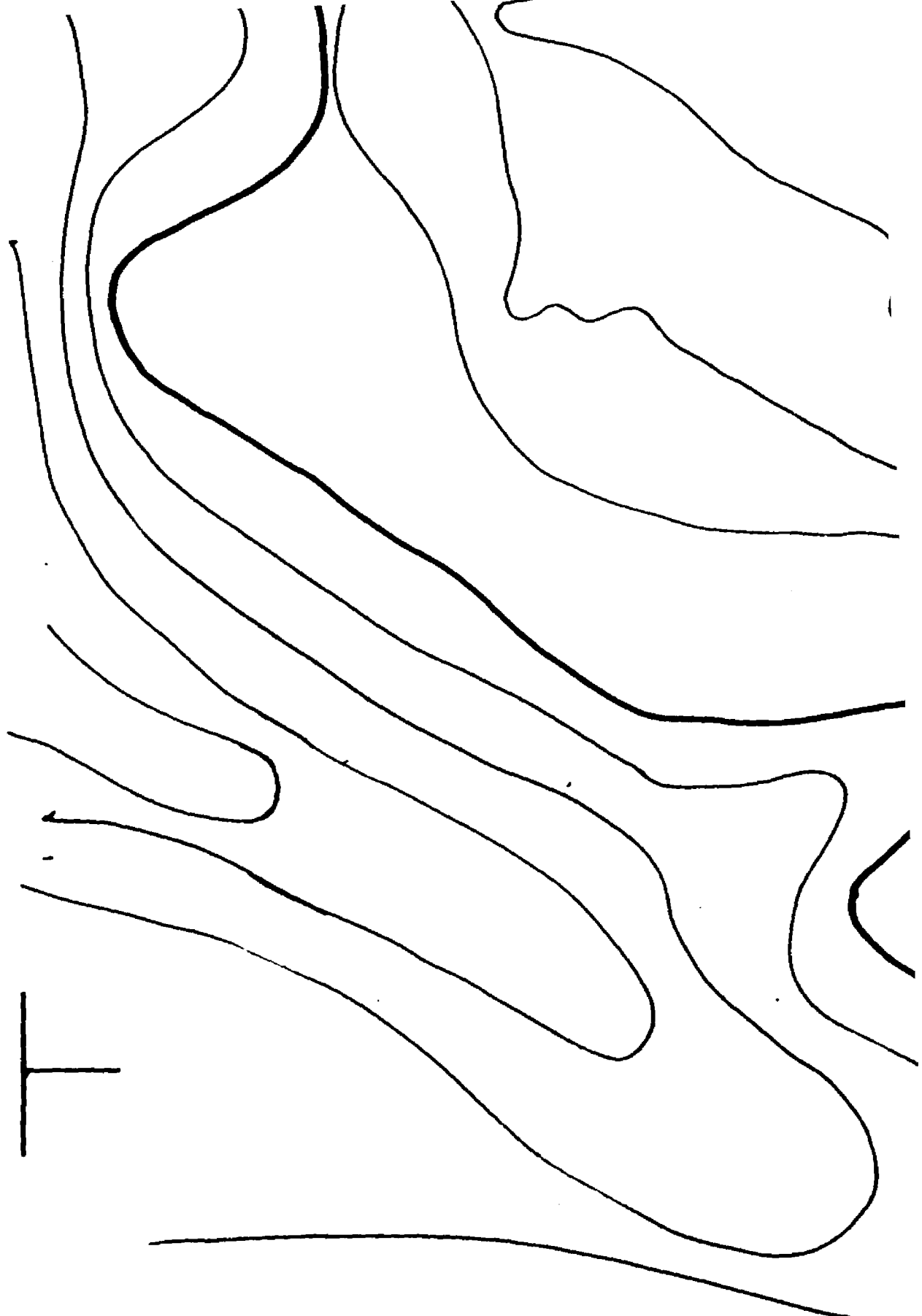










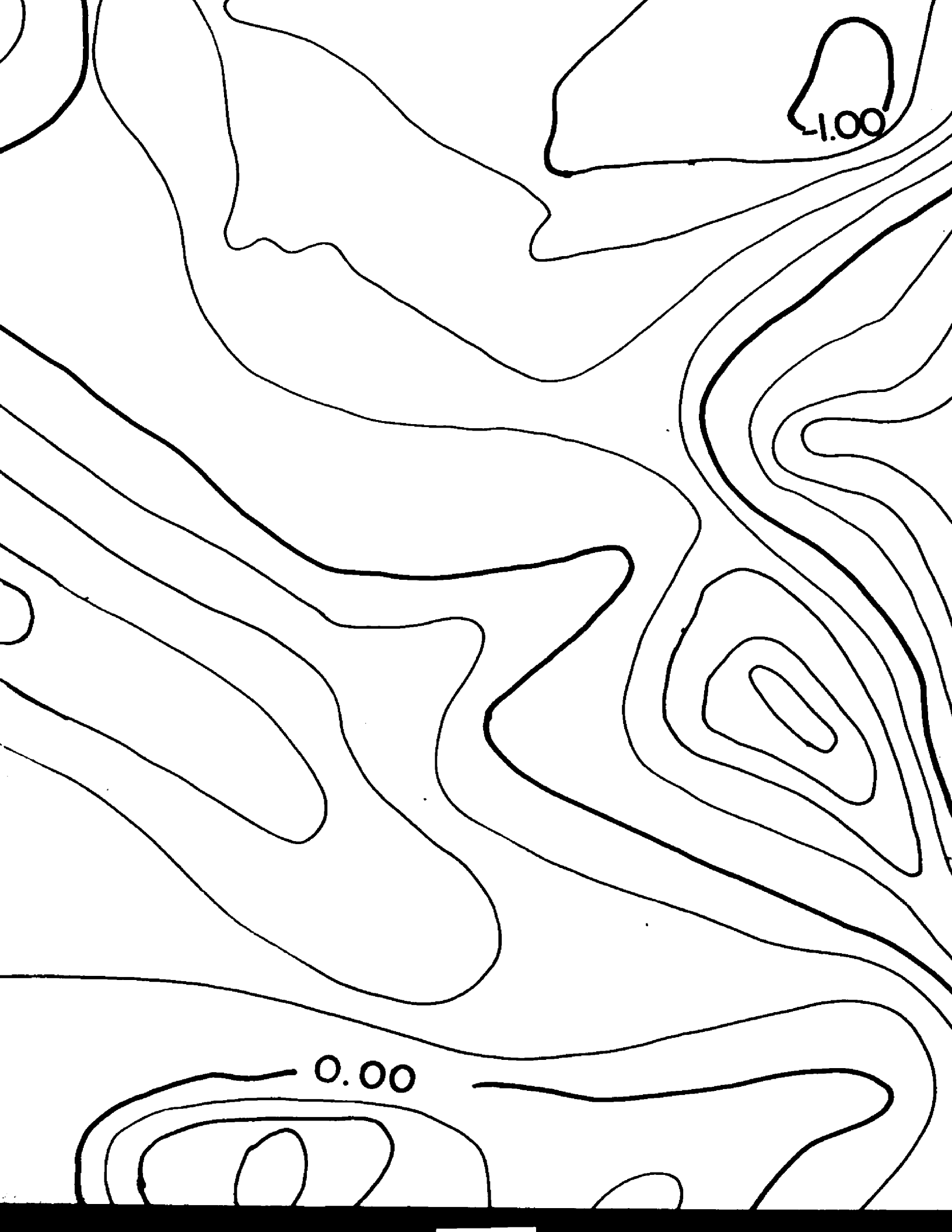


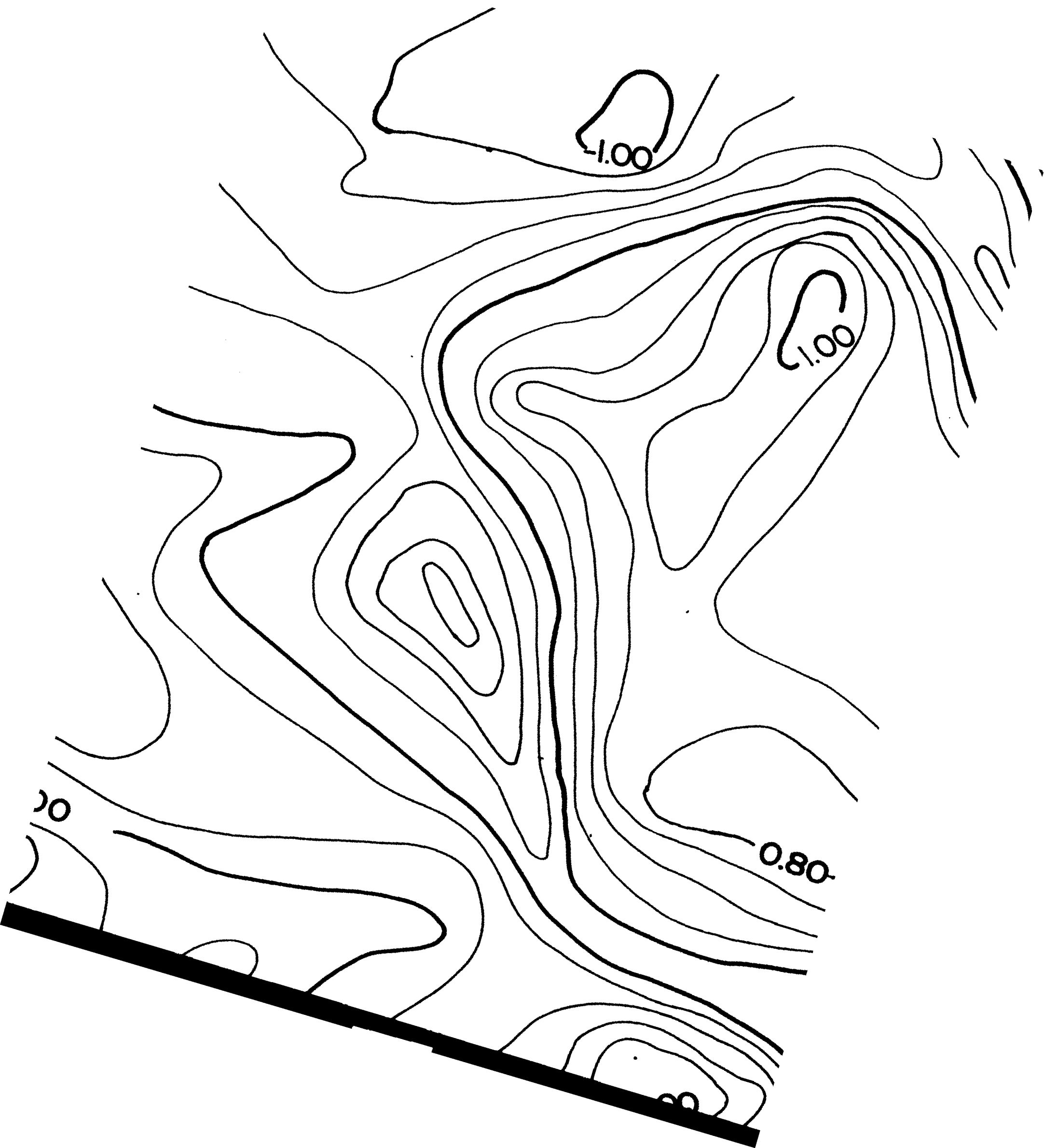
15'

T

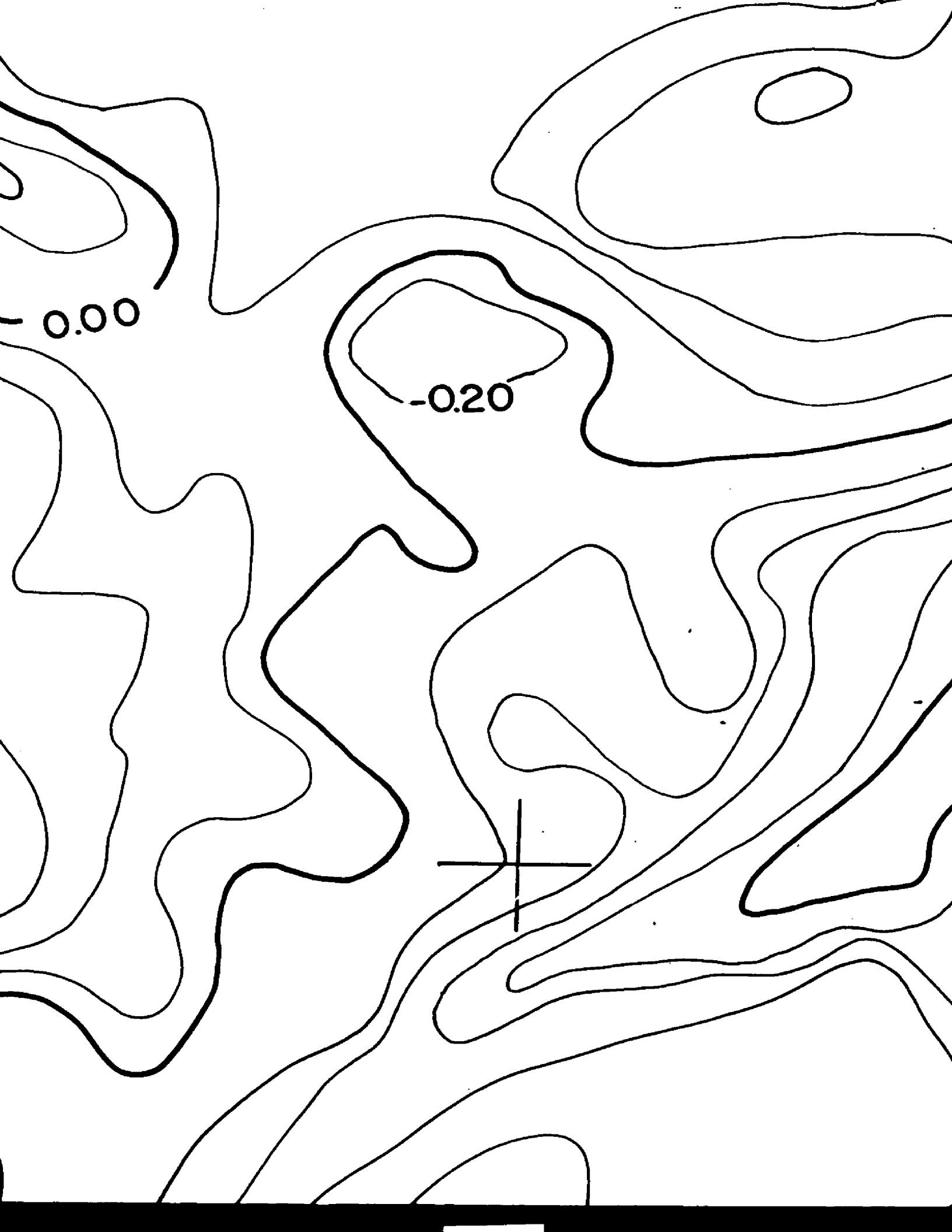
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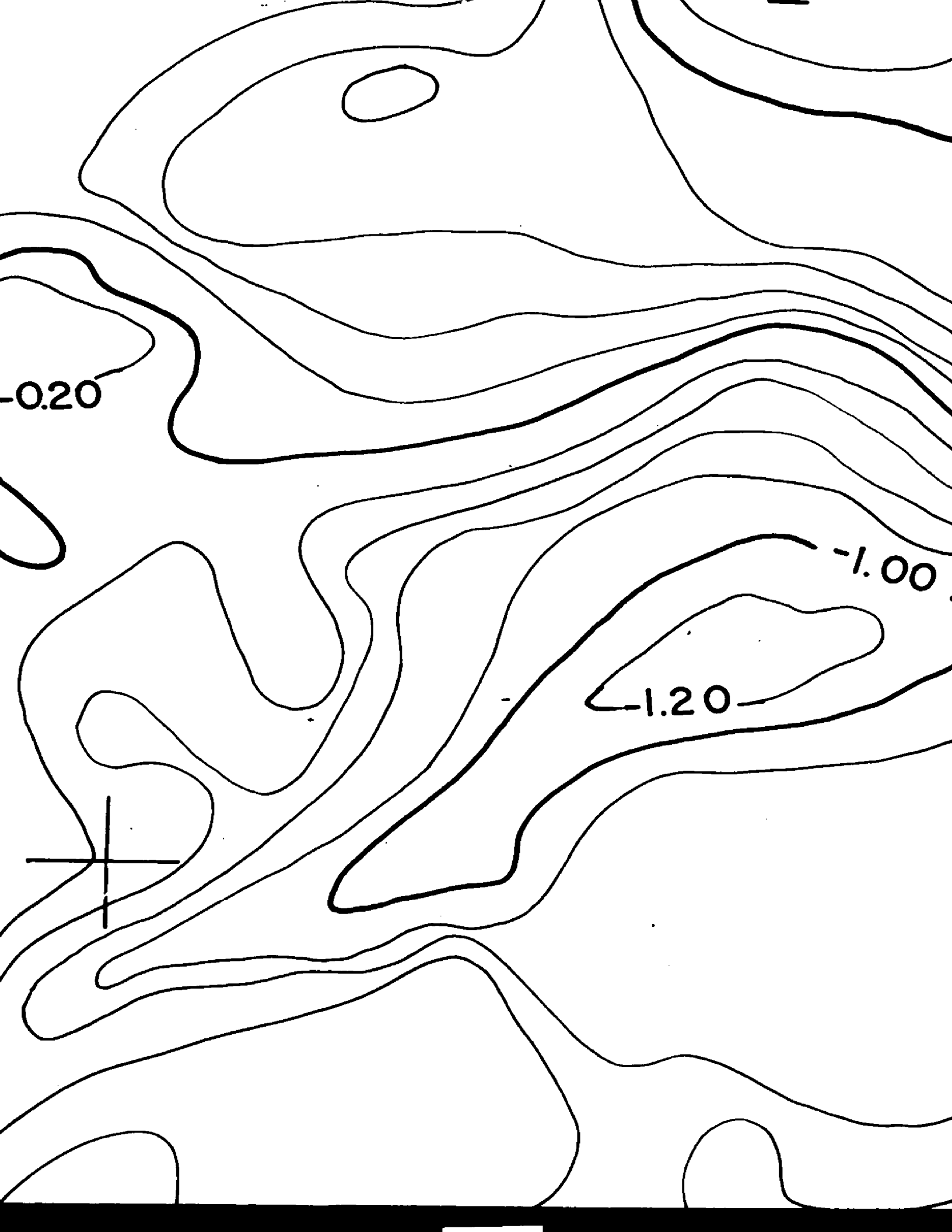






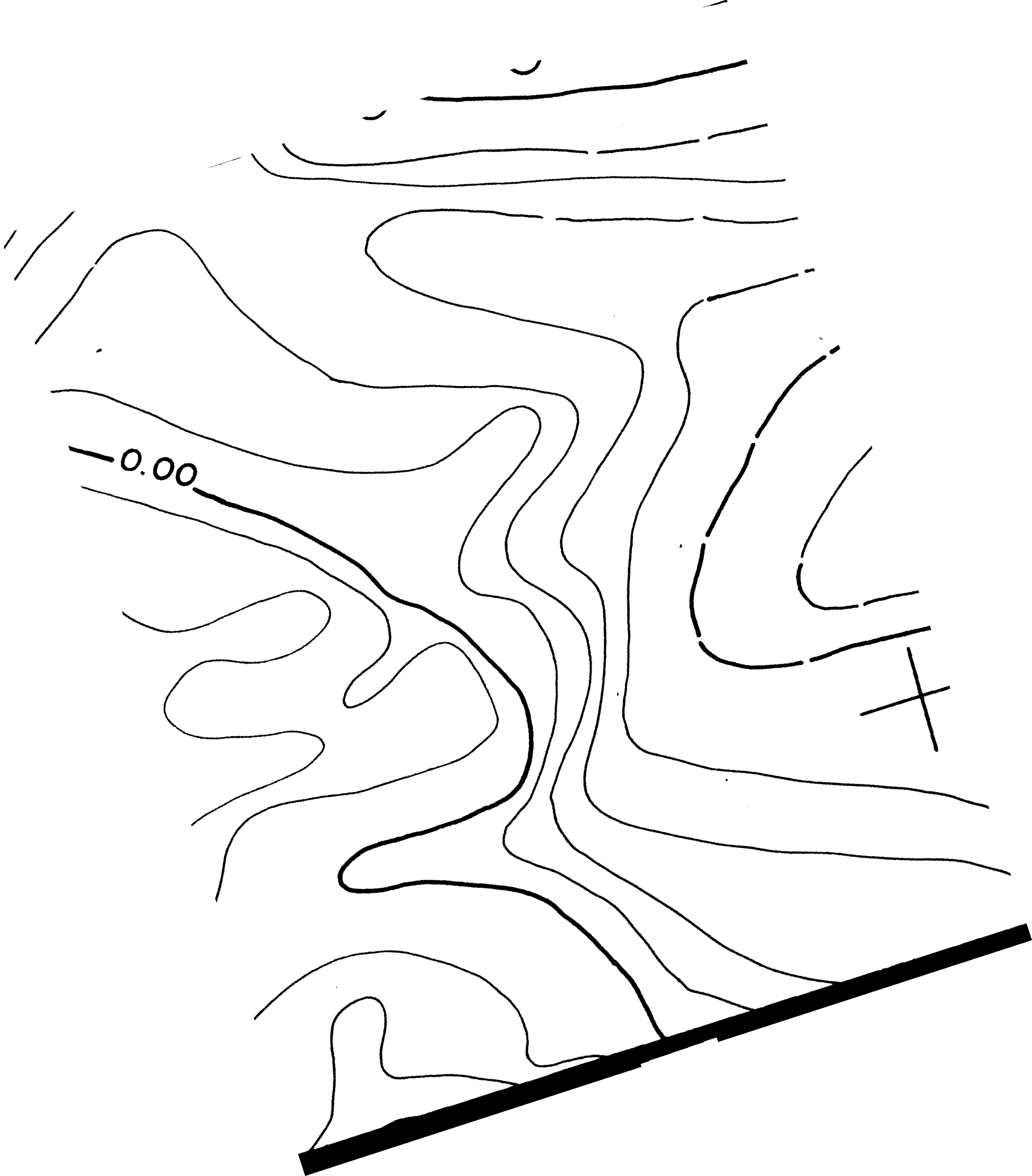






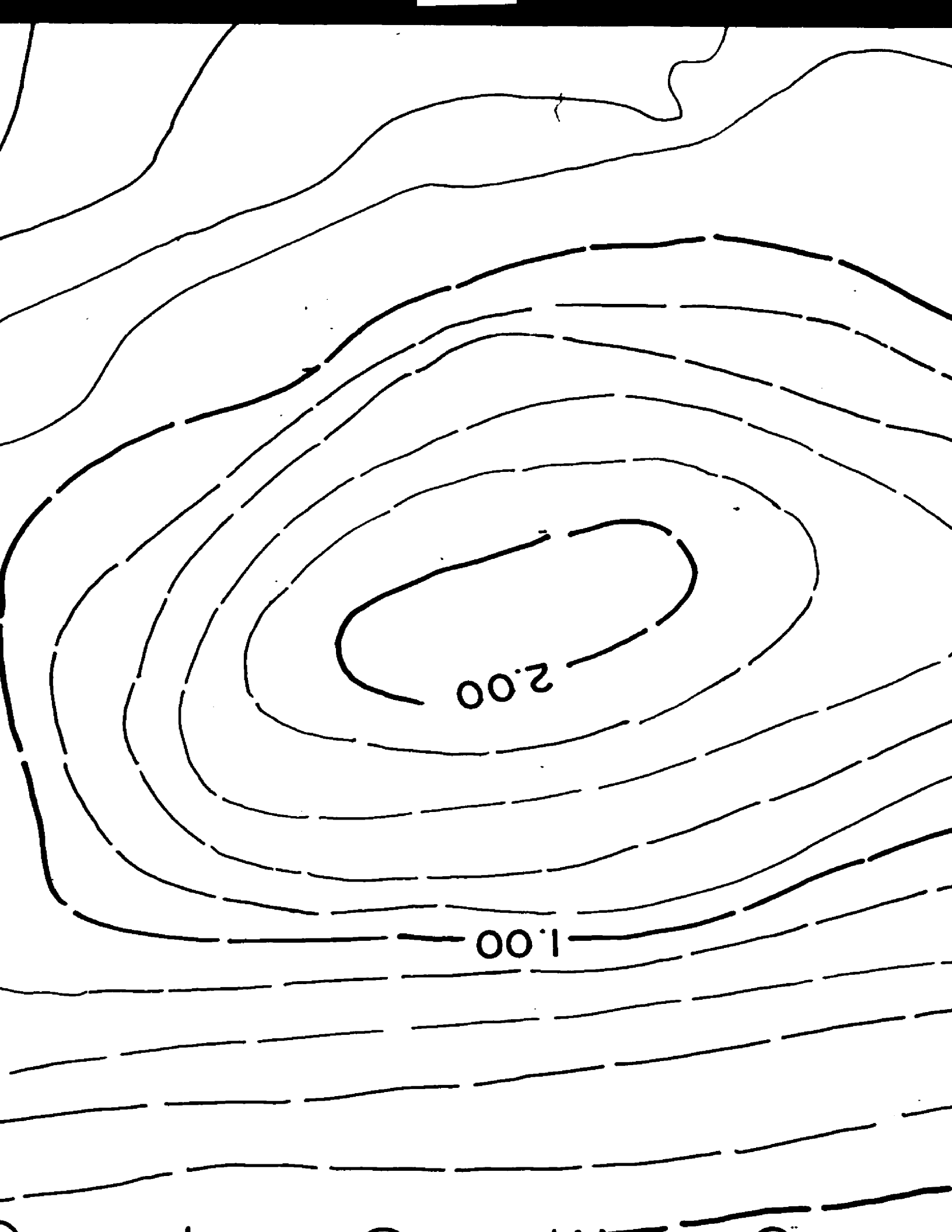


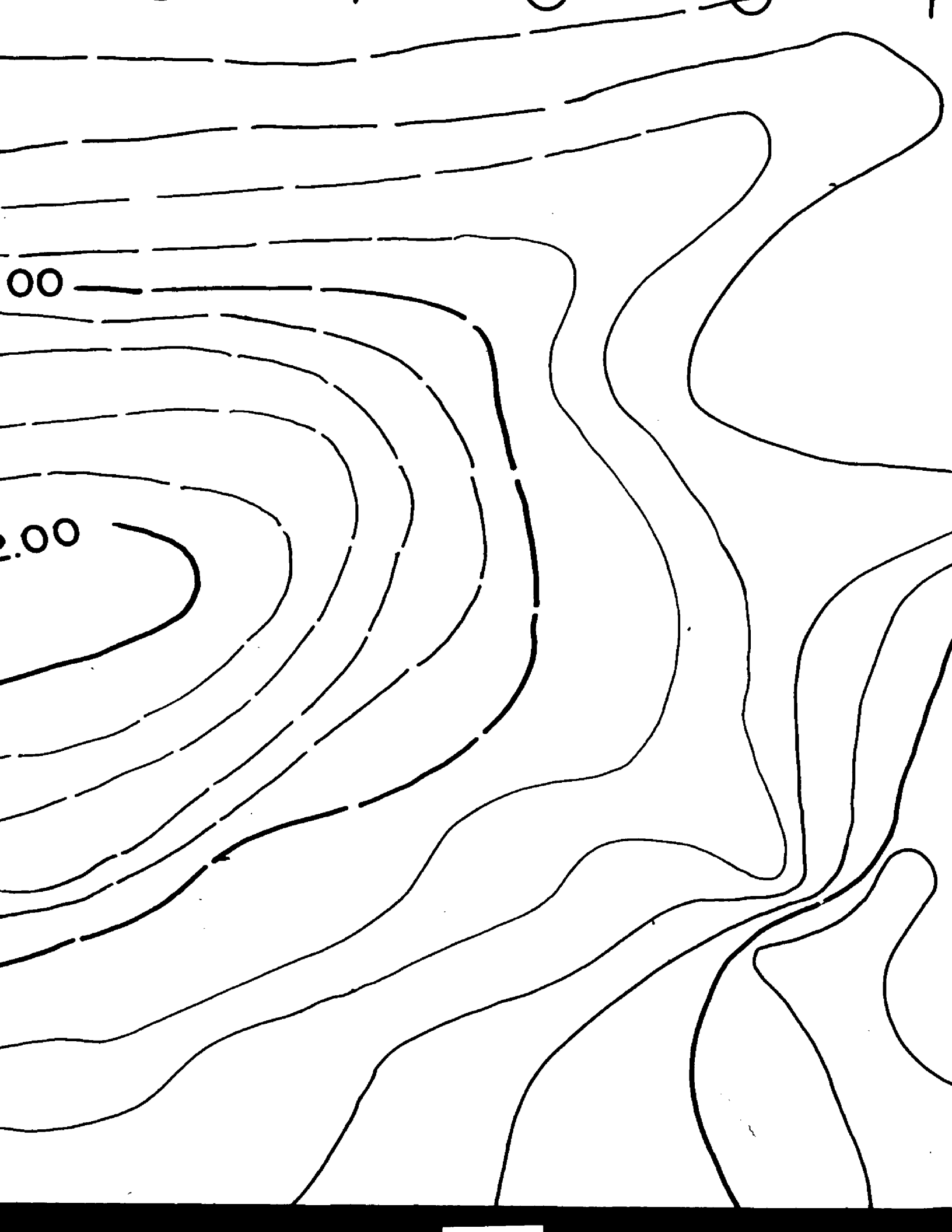




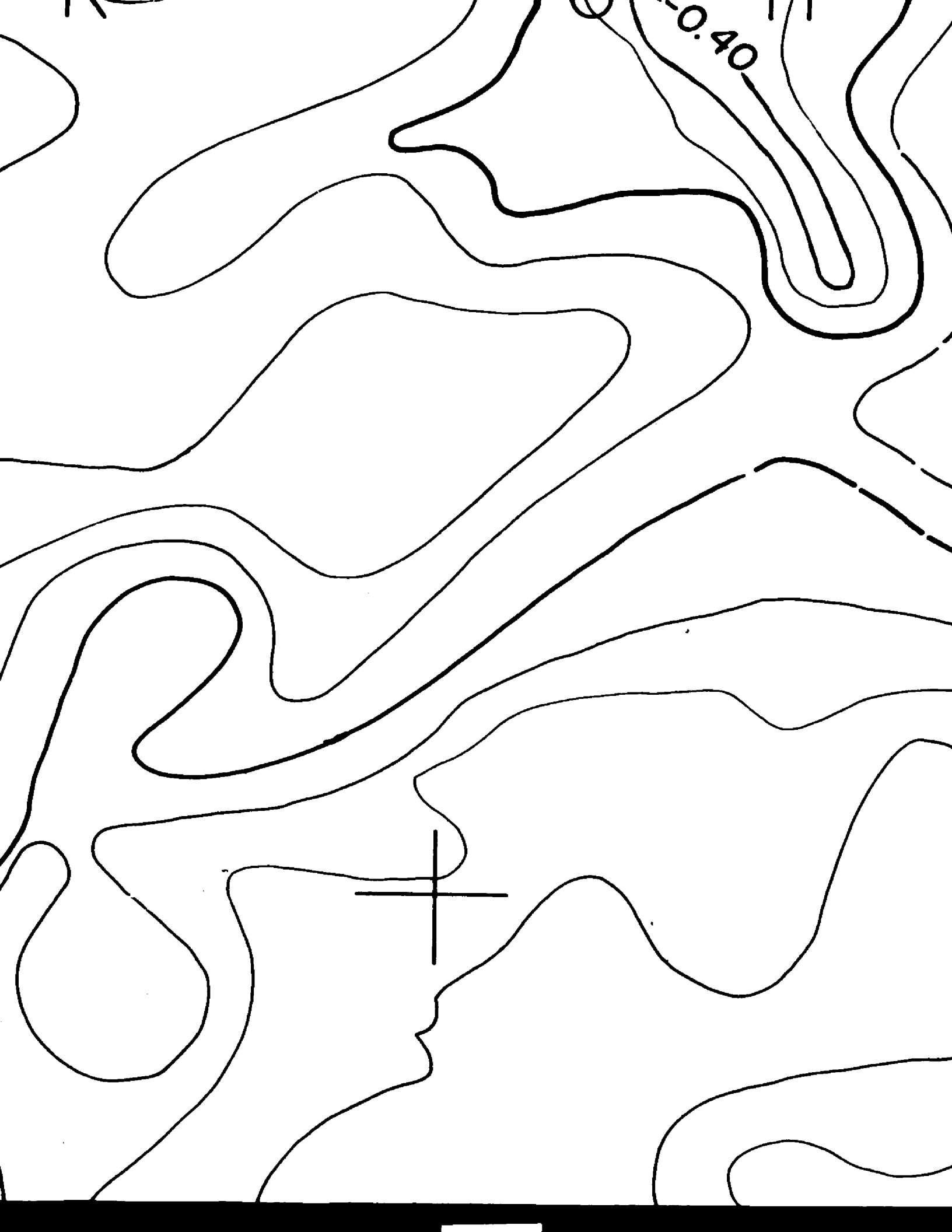


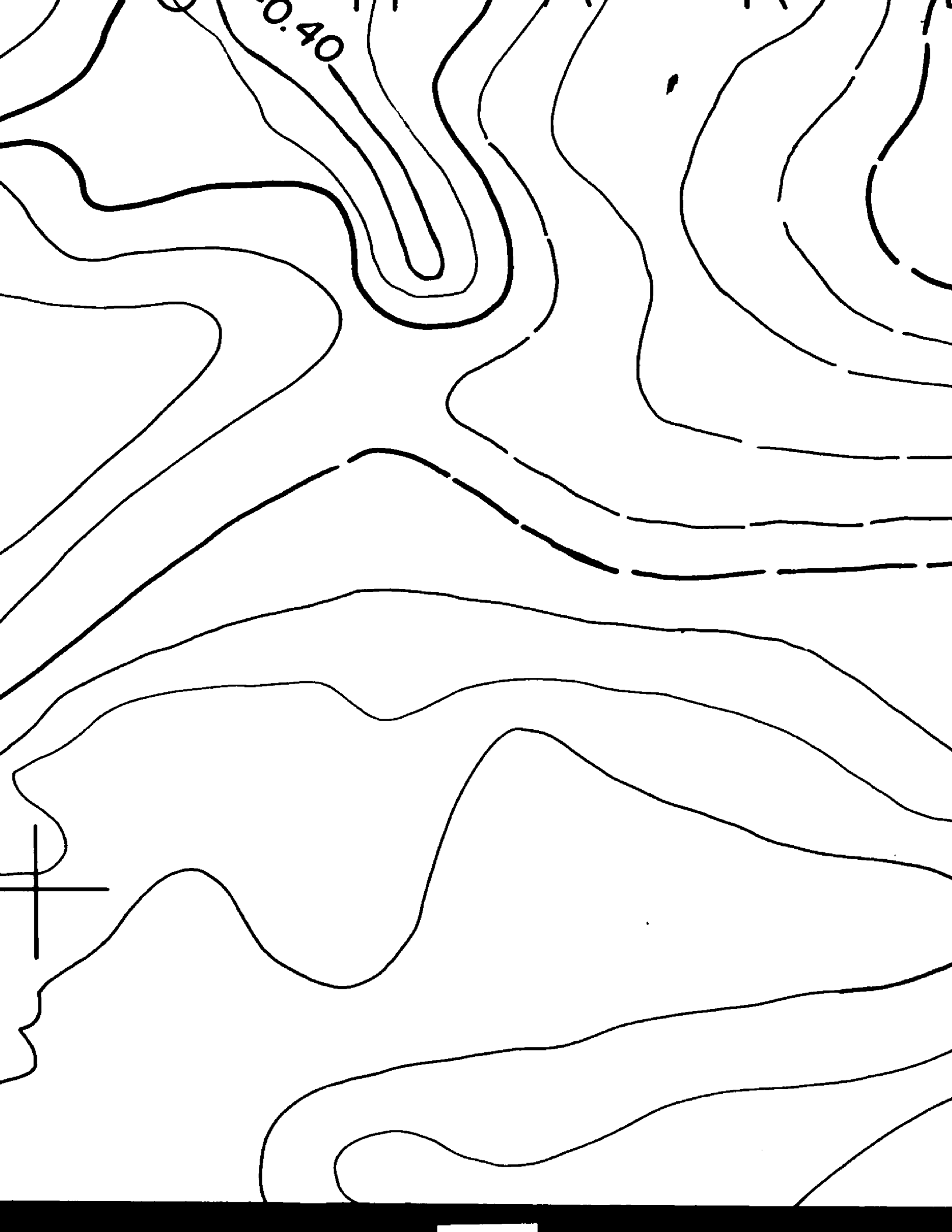




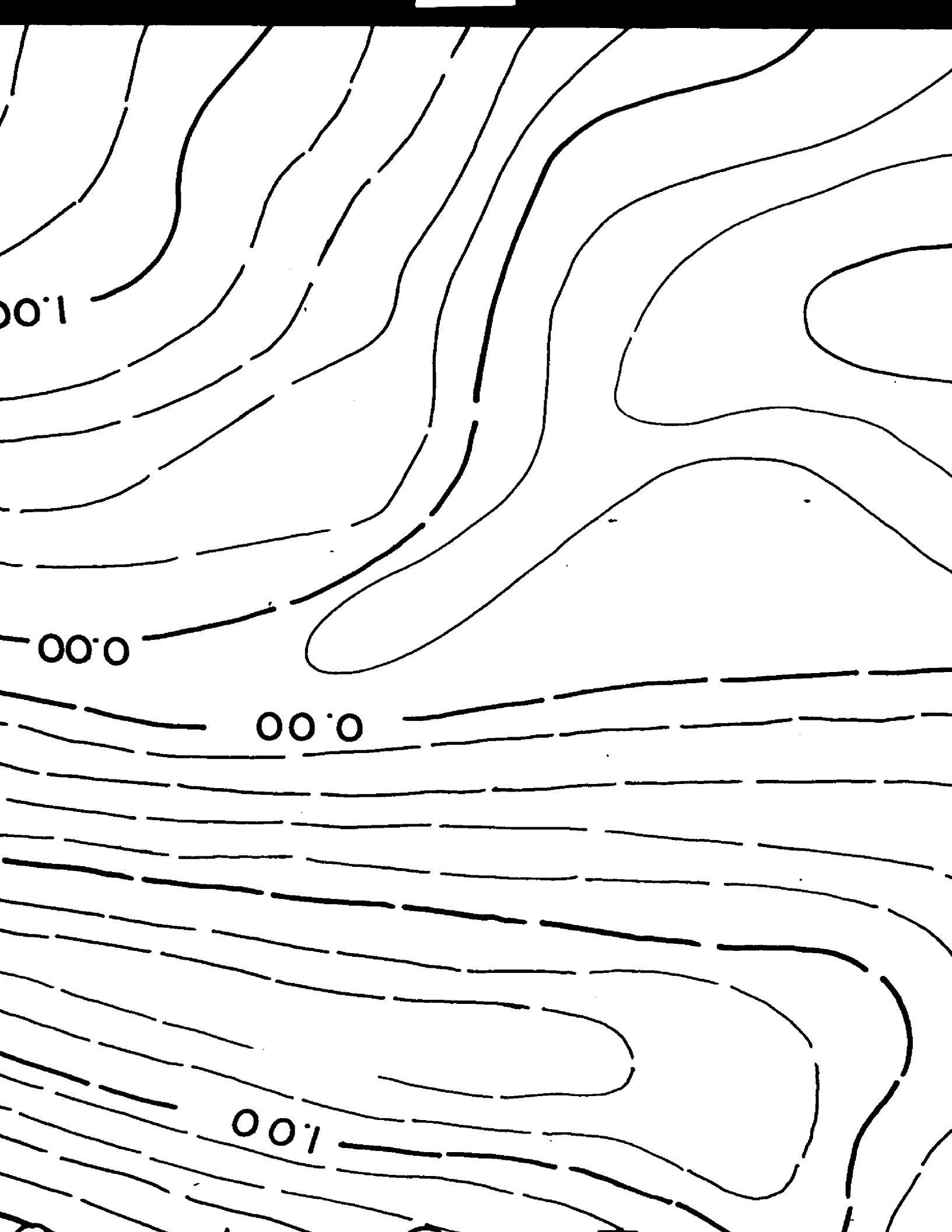


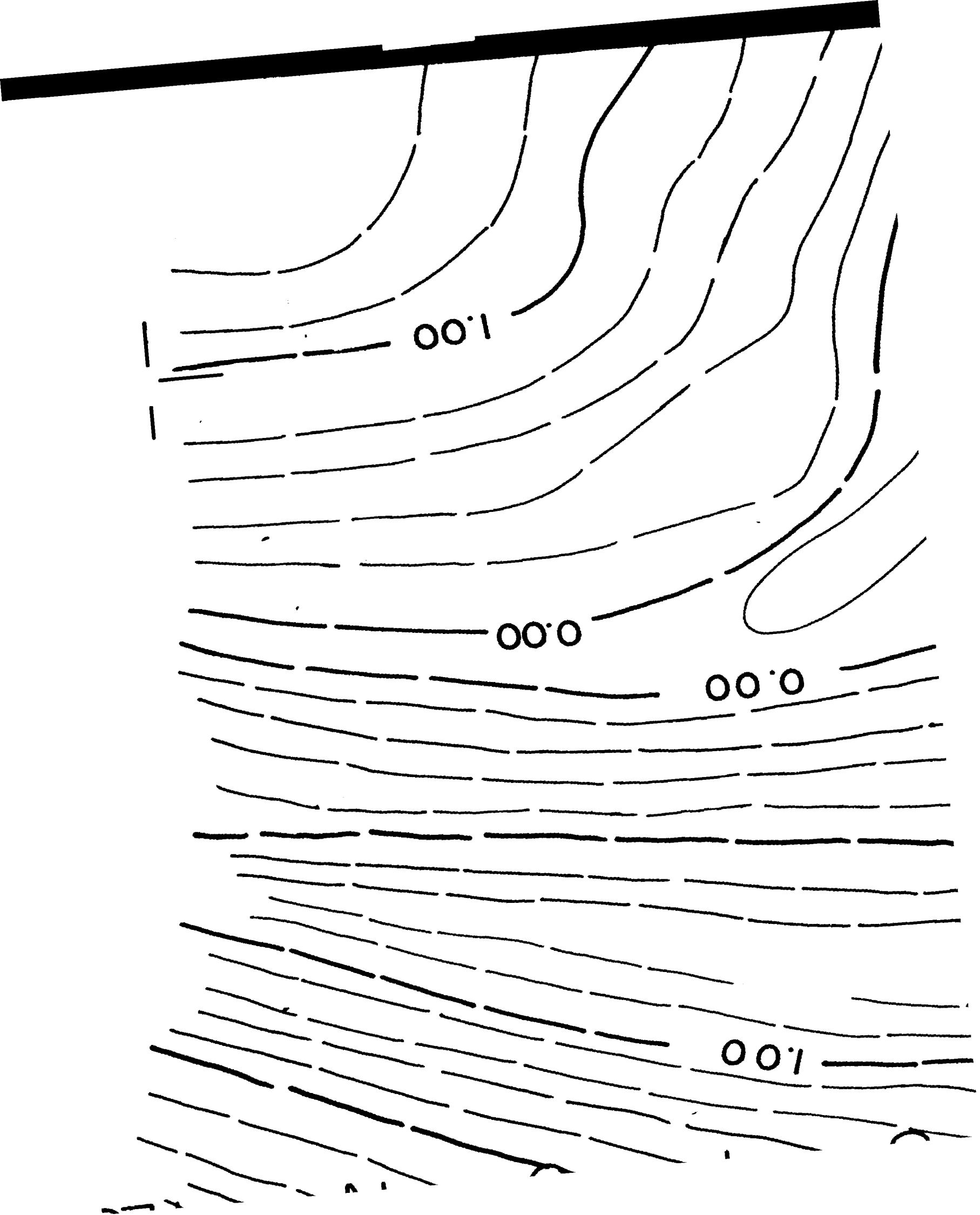


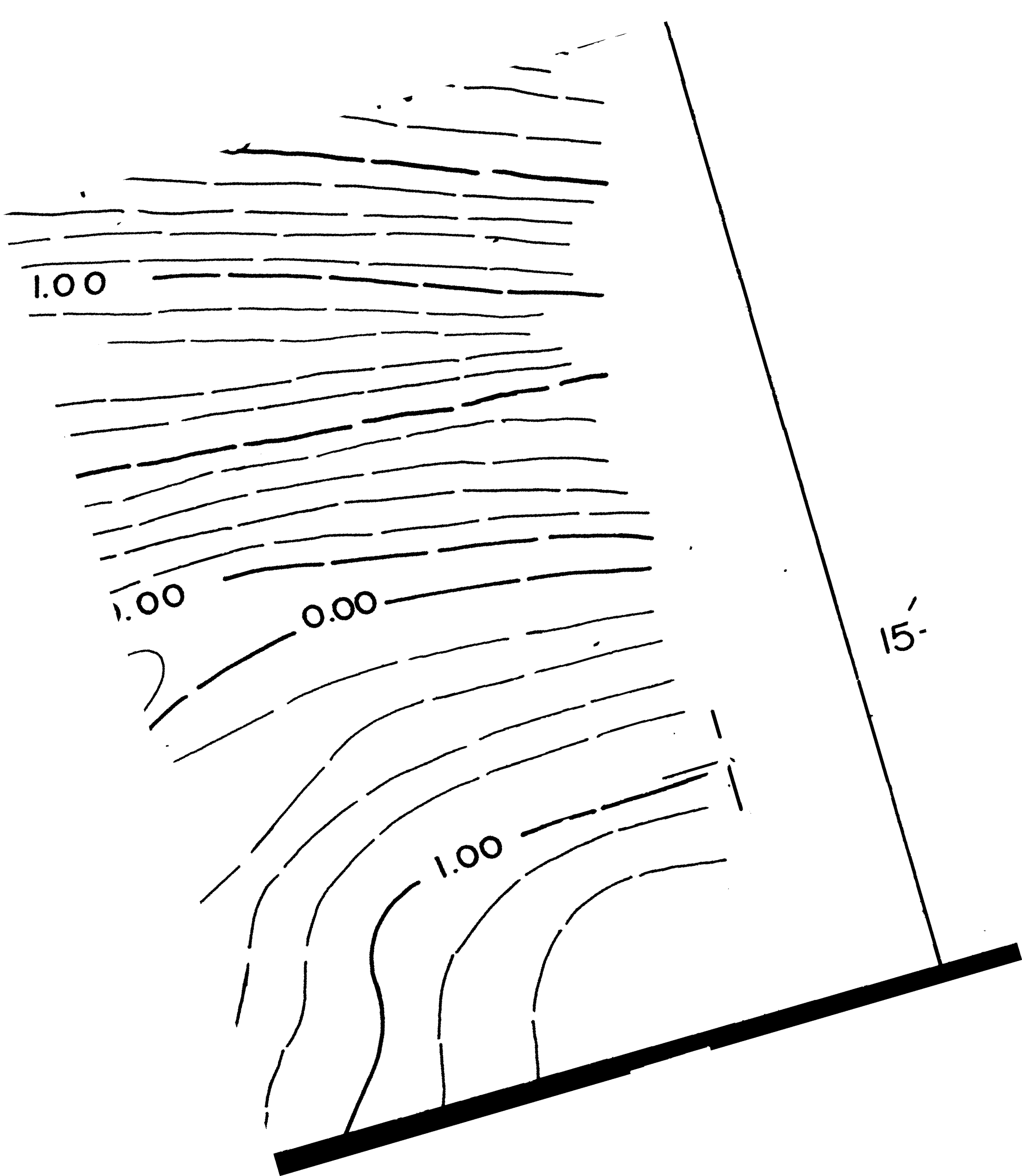




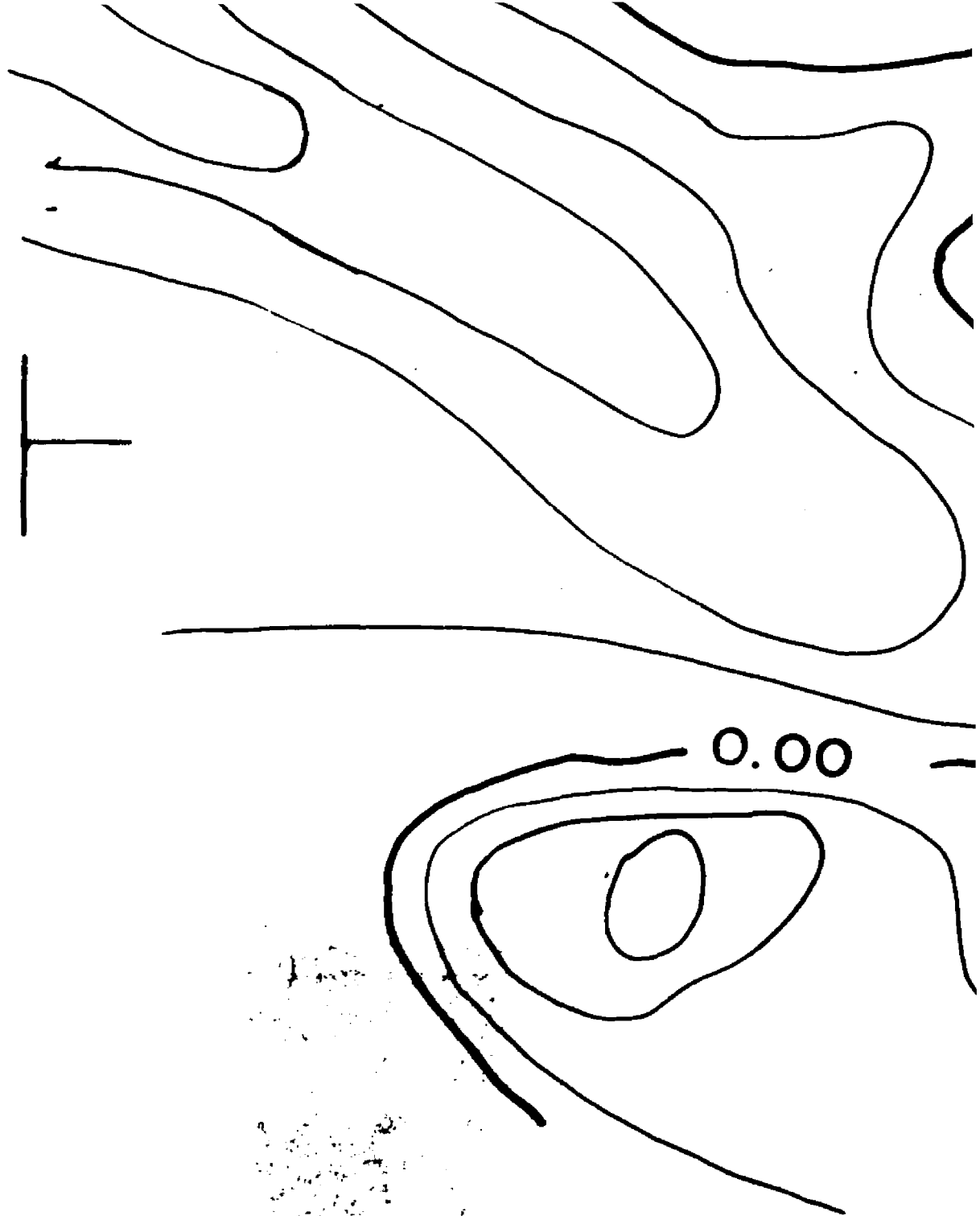




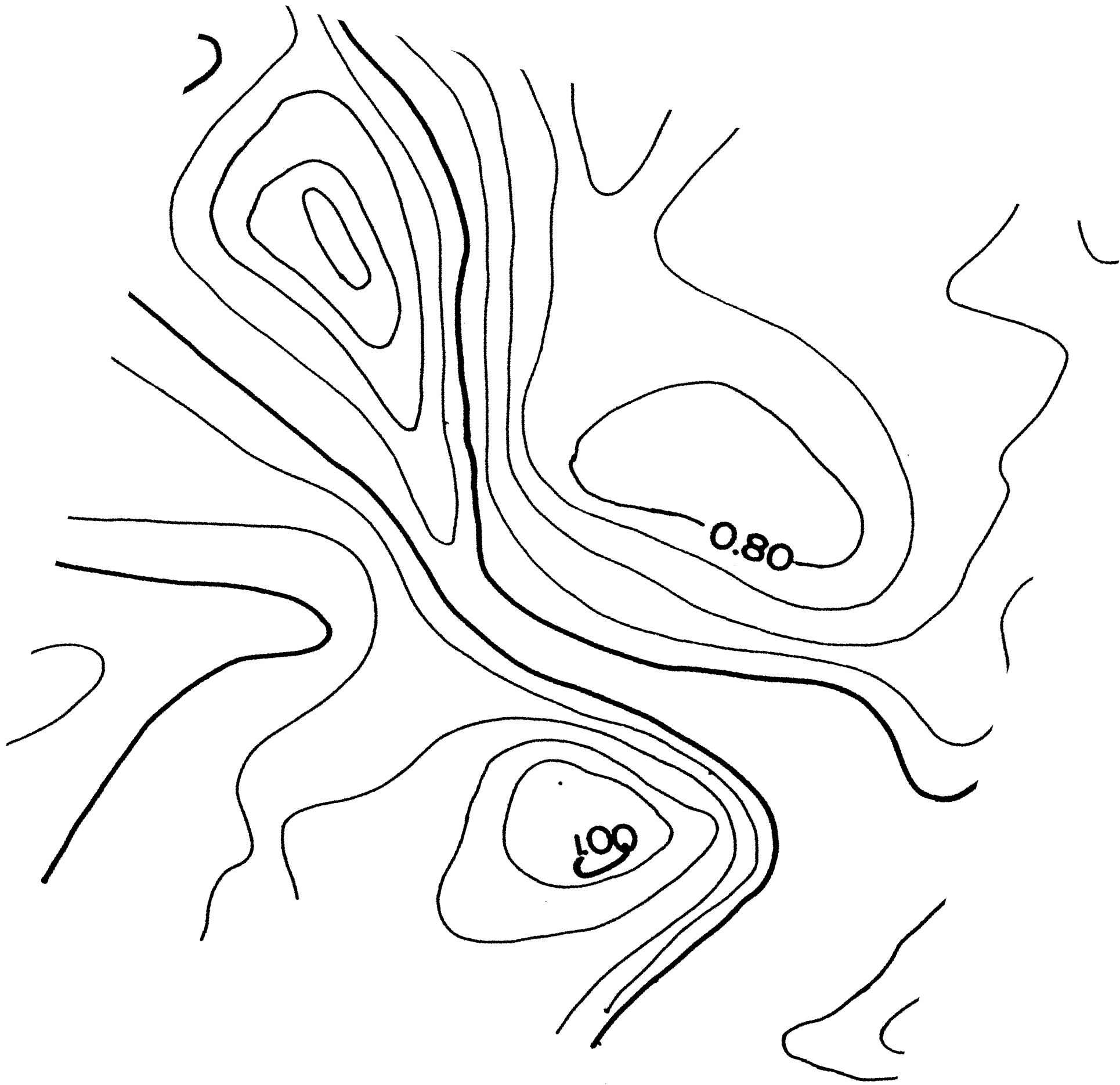




15







PLATE

7b



PLATE 7b

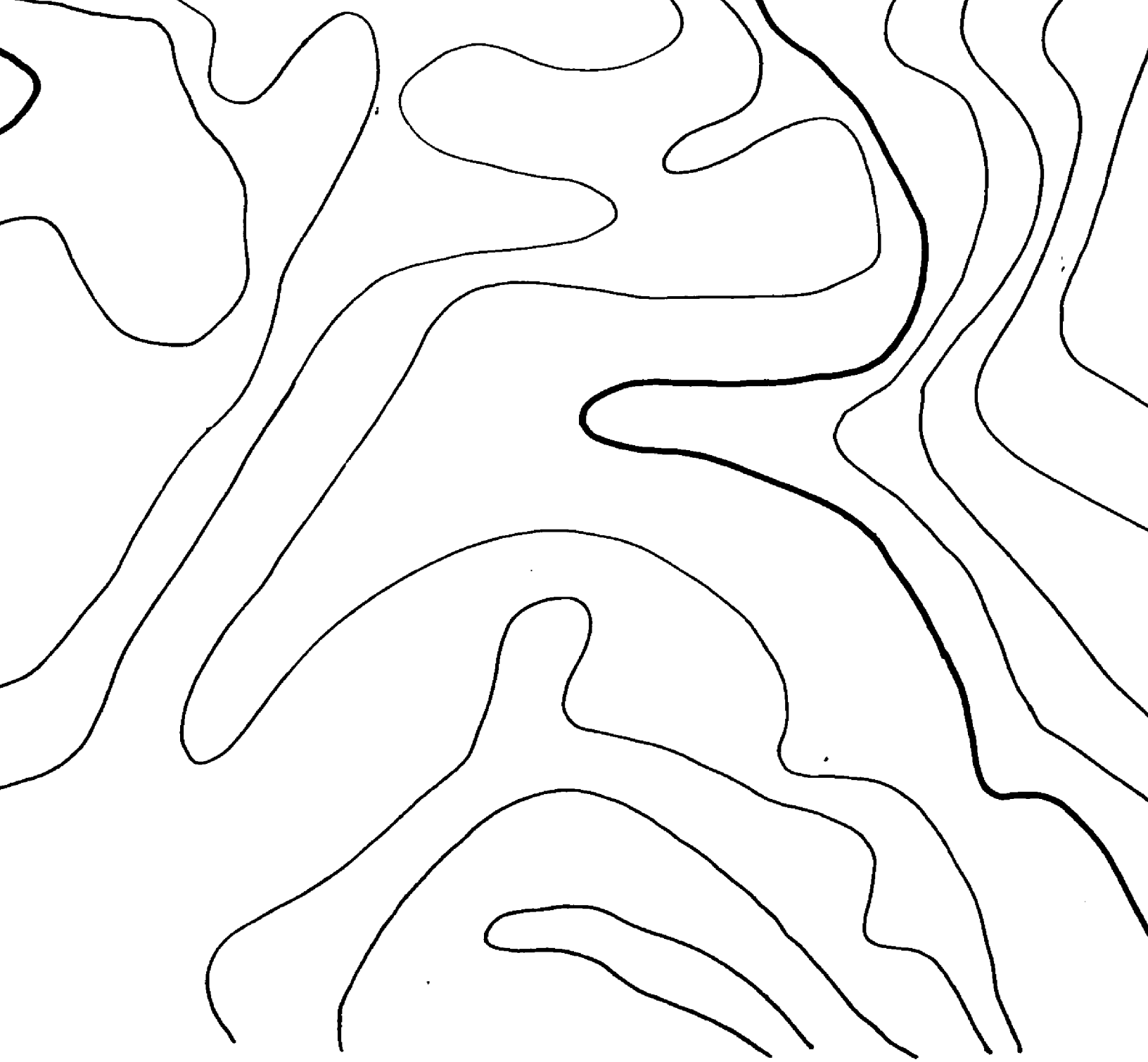
MAP OF
TO BOUGU



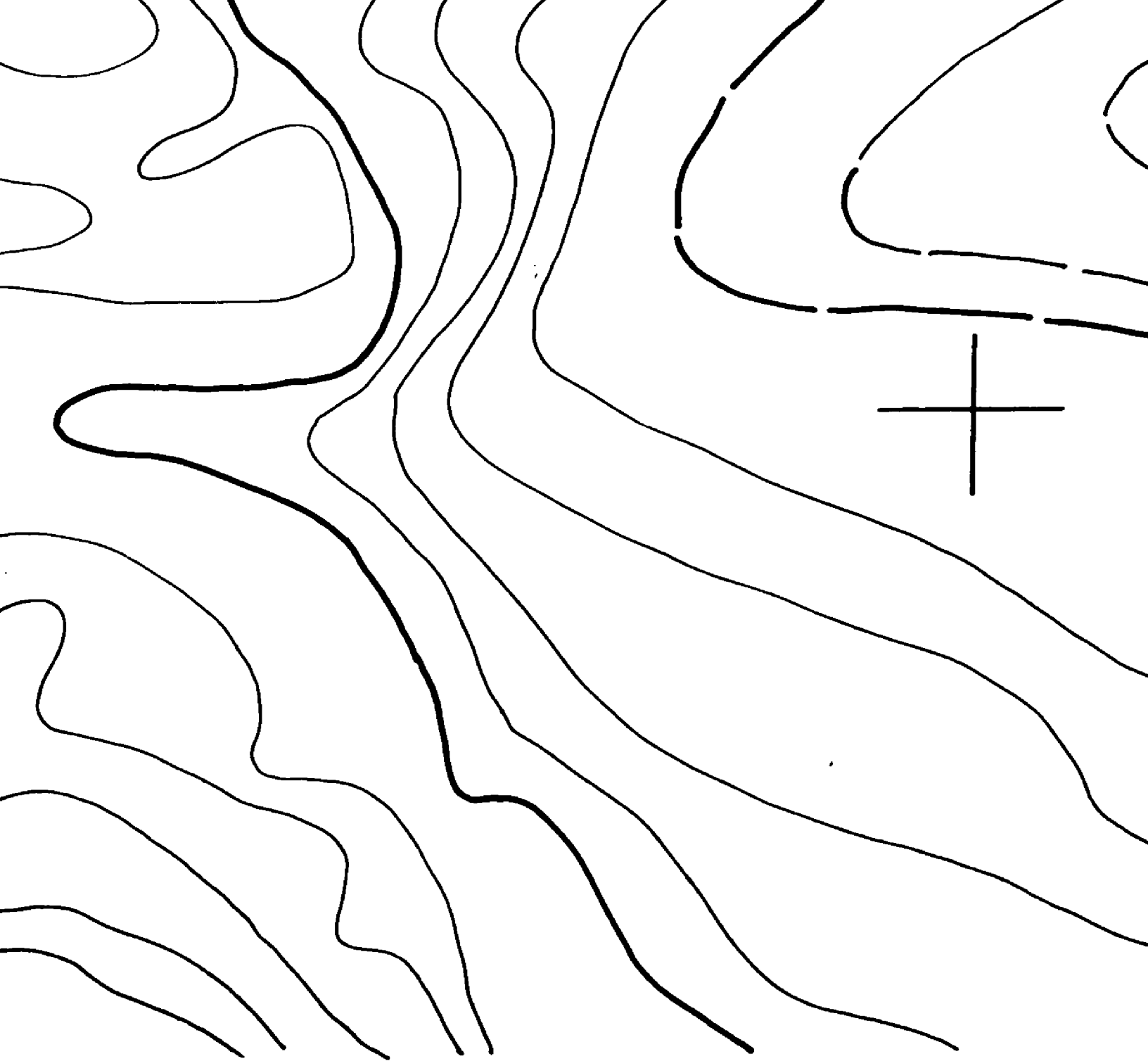
MAP OF THE RESIDUAL
TO BOUGUER SURFACE



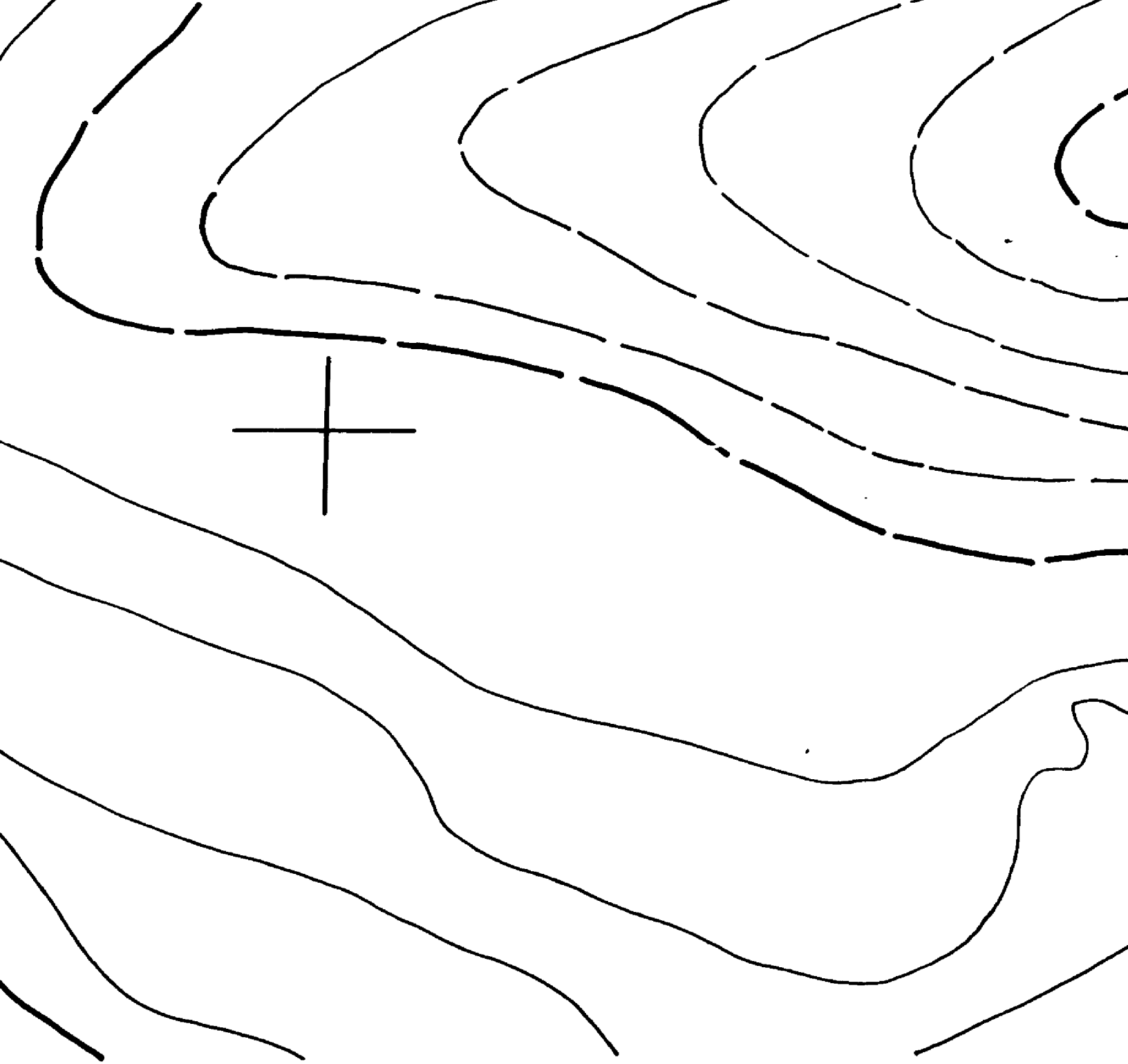
THE RESIDUAL VALUES FOR SURFACE



VALUES FROM 5TH DEG



DM 5TH DEGREE POLYNOM

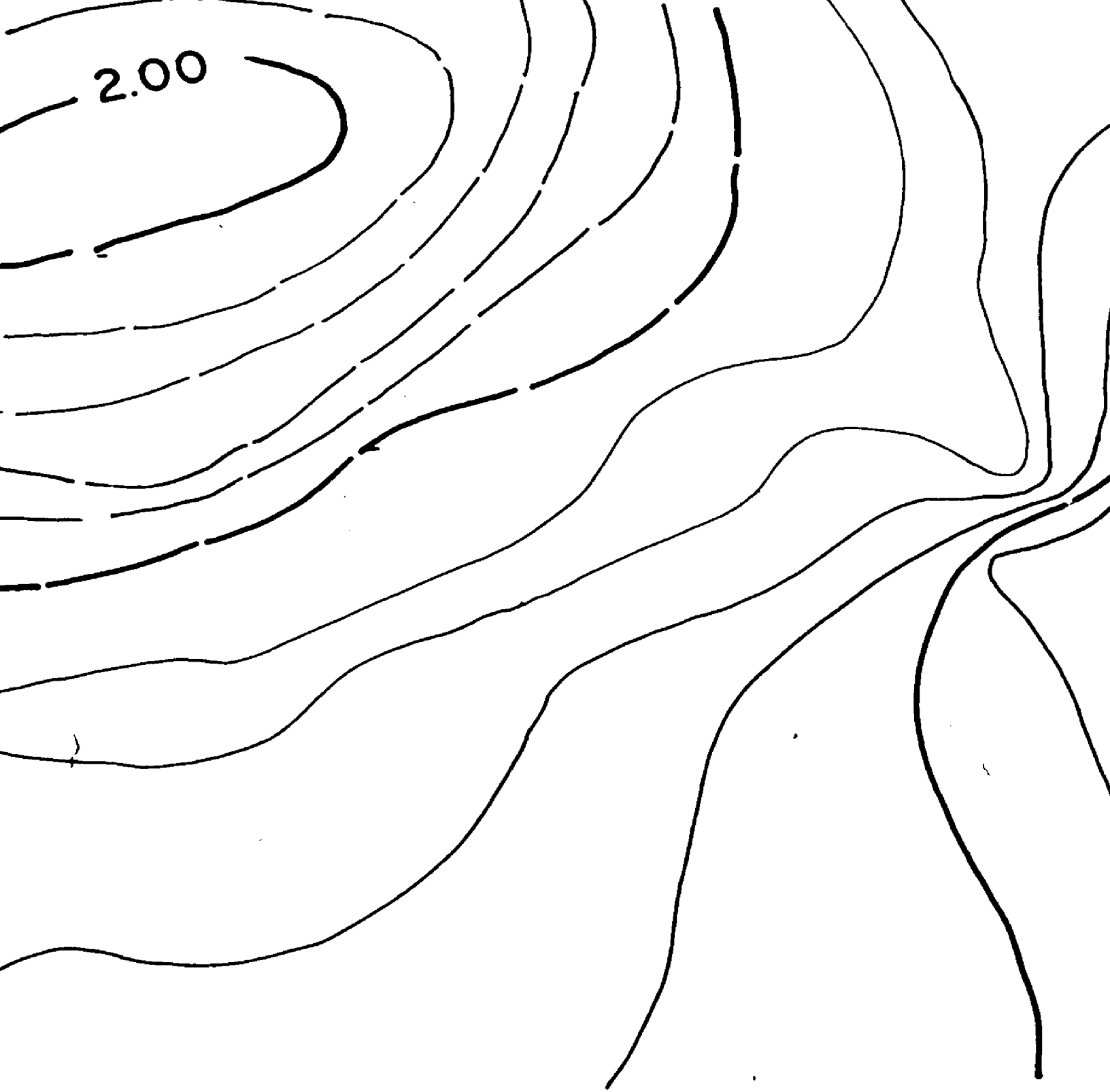


FREE POLYNOMIAL APPROXIMAT



IAL APPROXIMATION

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ON

NORTHERN

HALF

OF



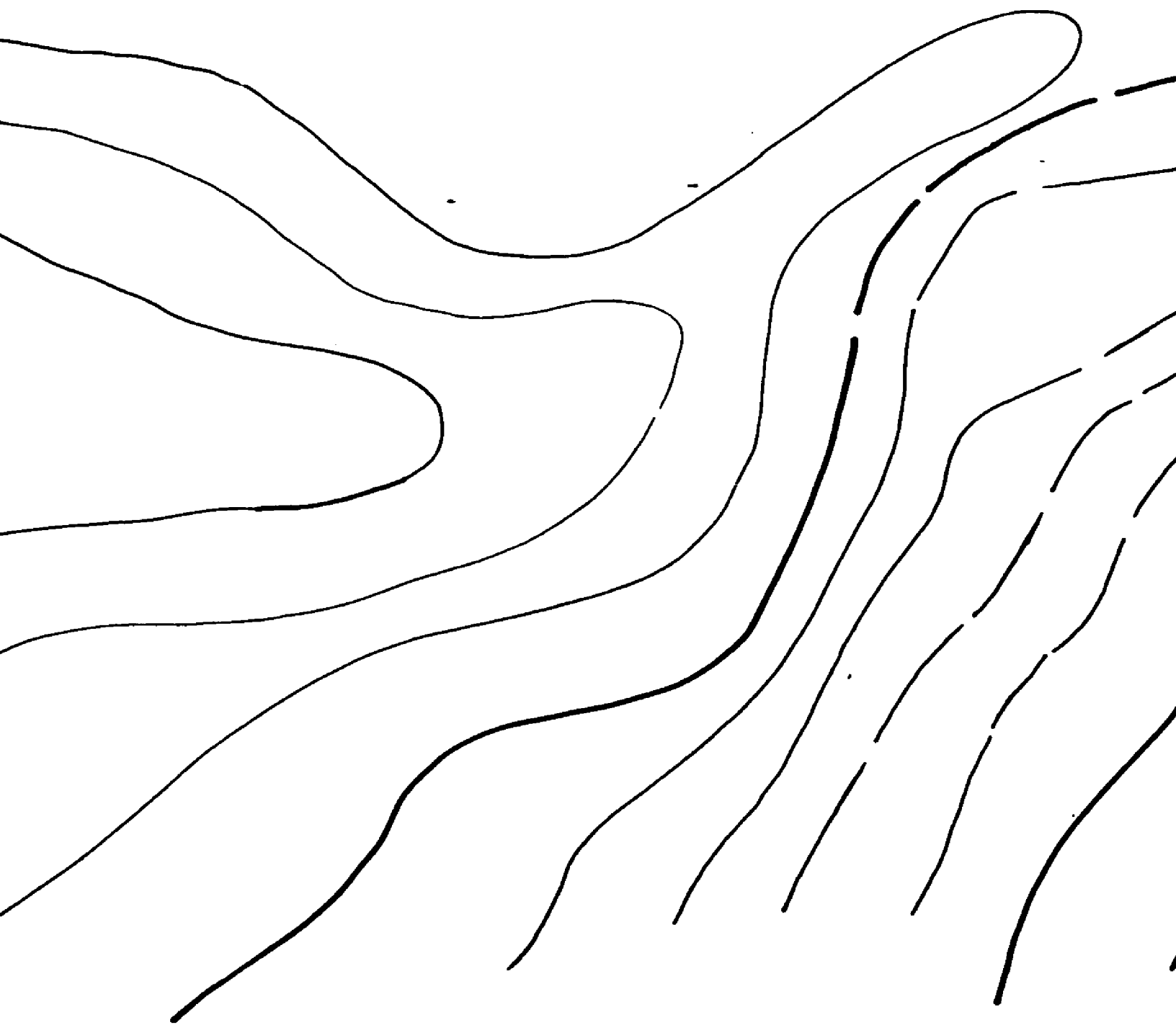
N HALF OF KALAMAZOO COUNTY

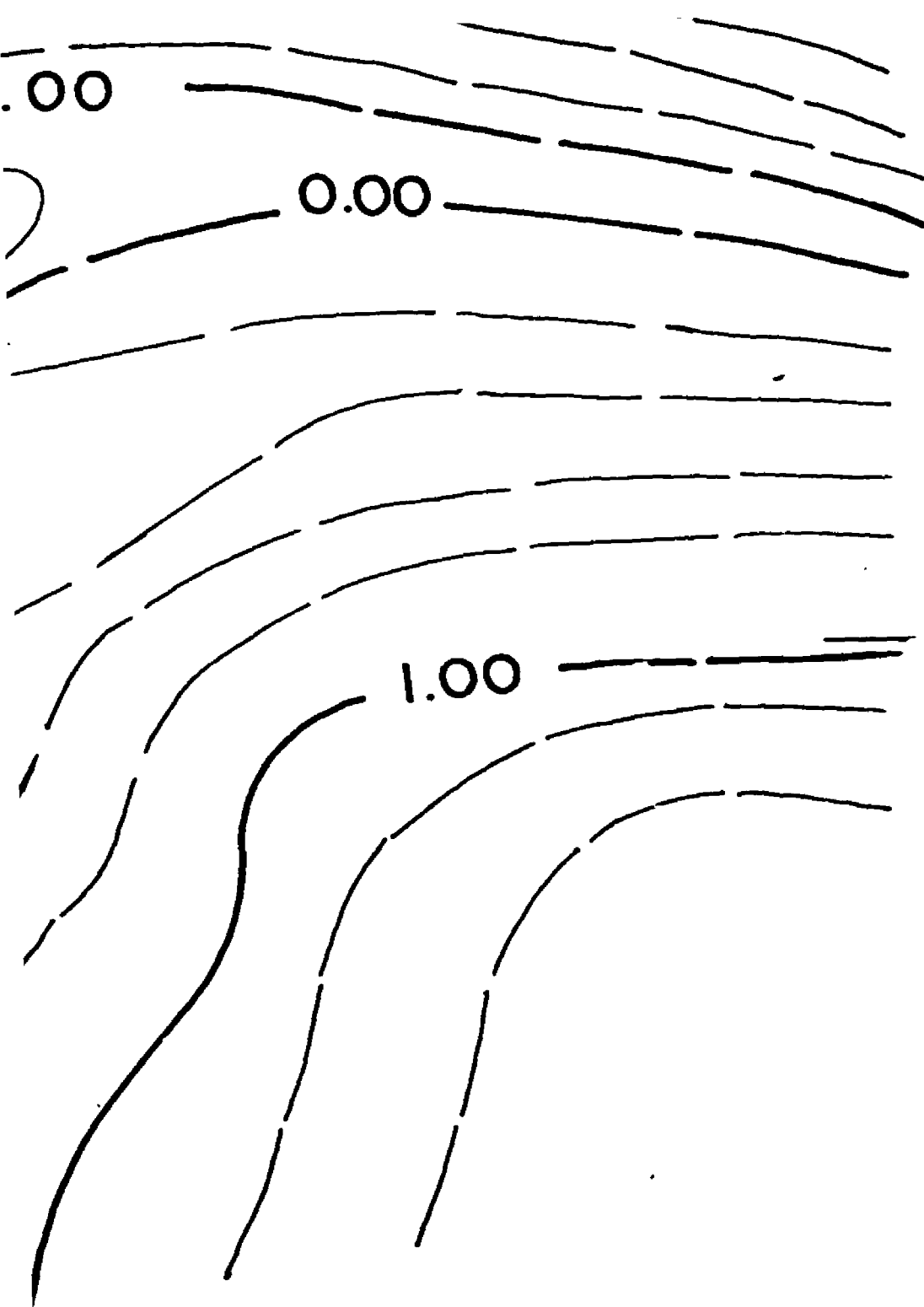


KALAMAZOO COUNTY



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T3S

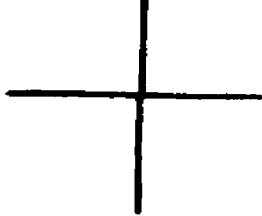
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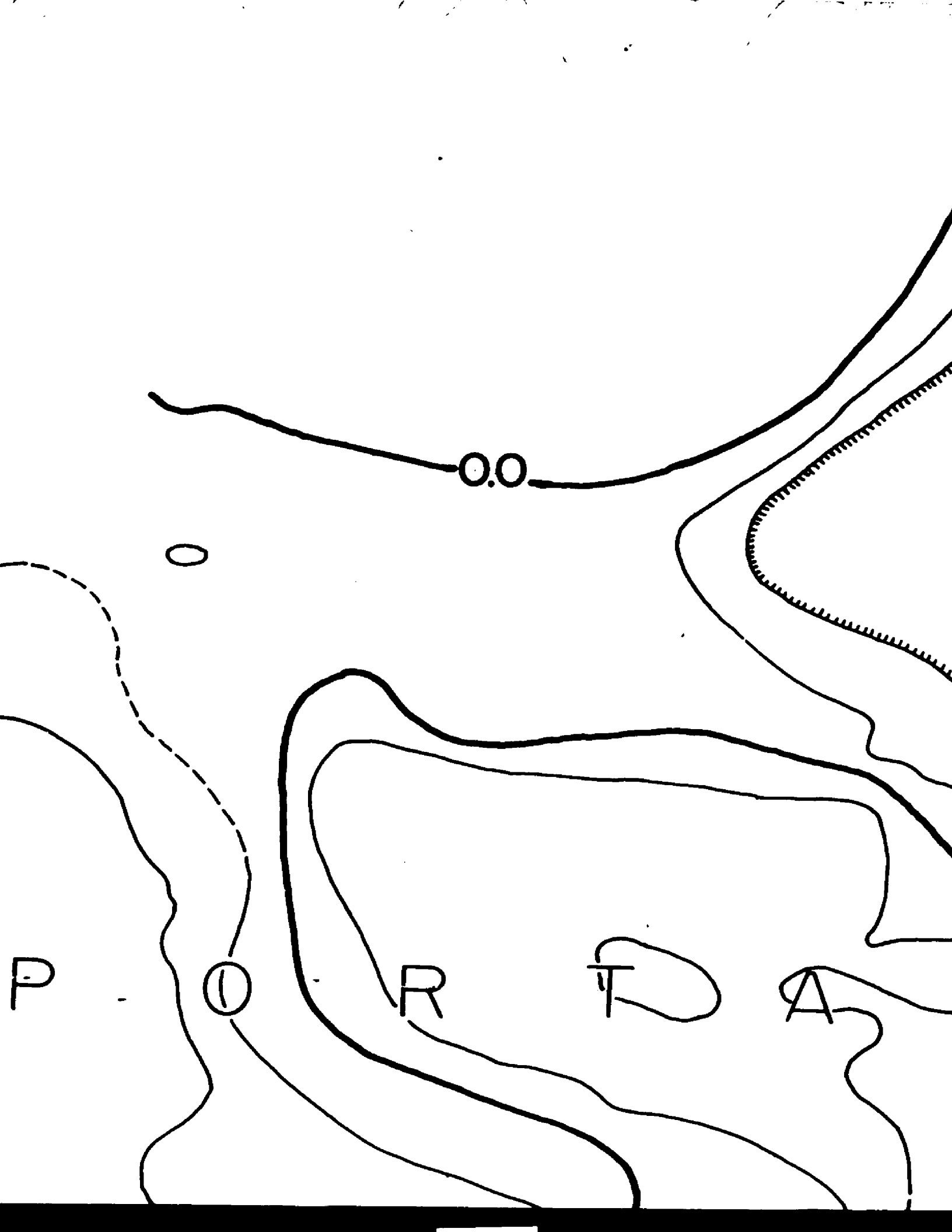




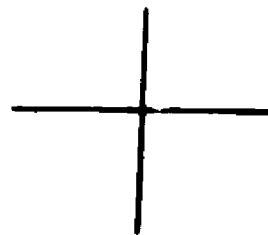


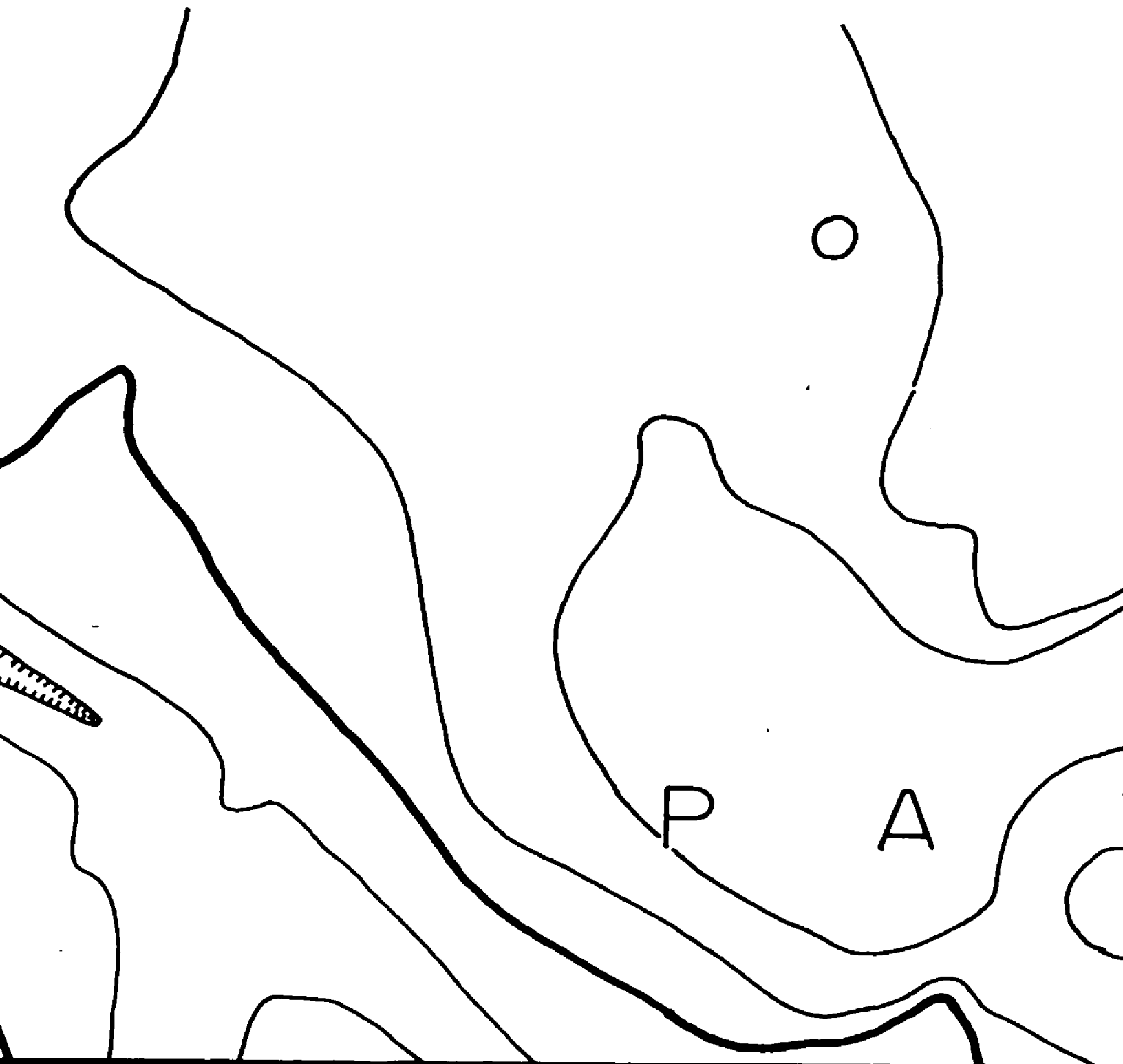
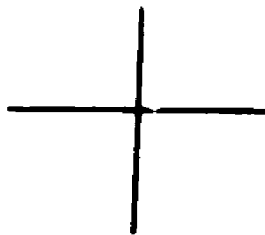


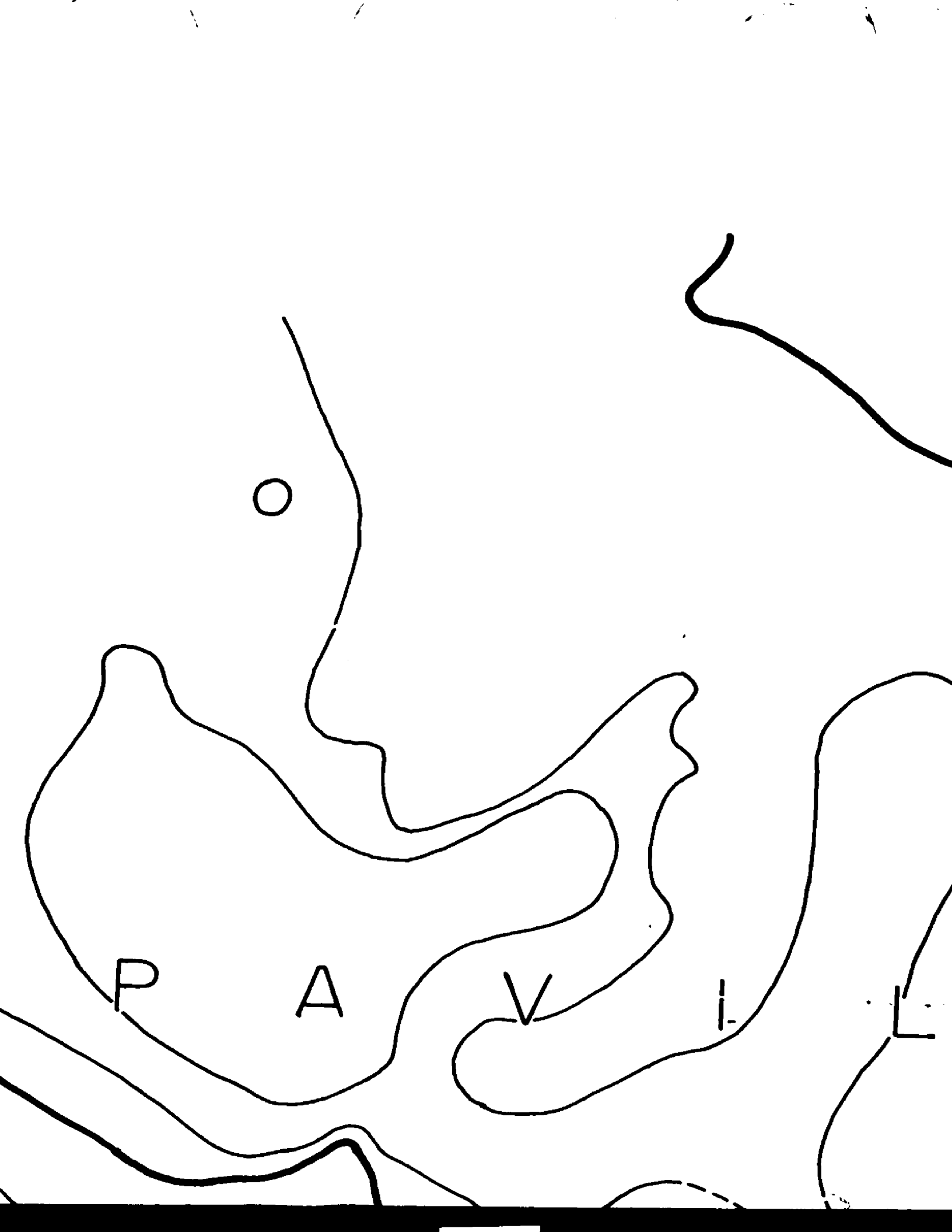






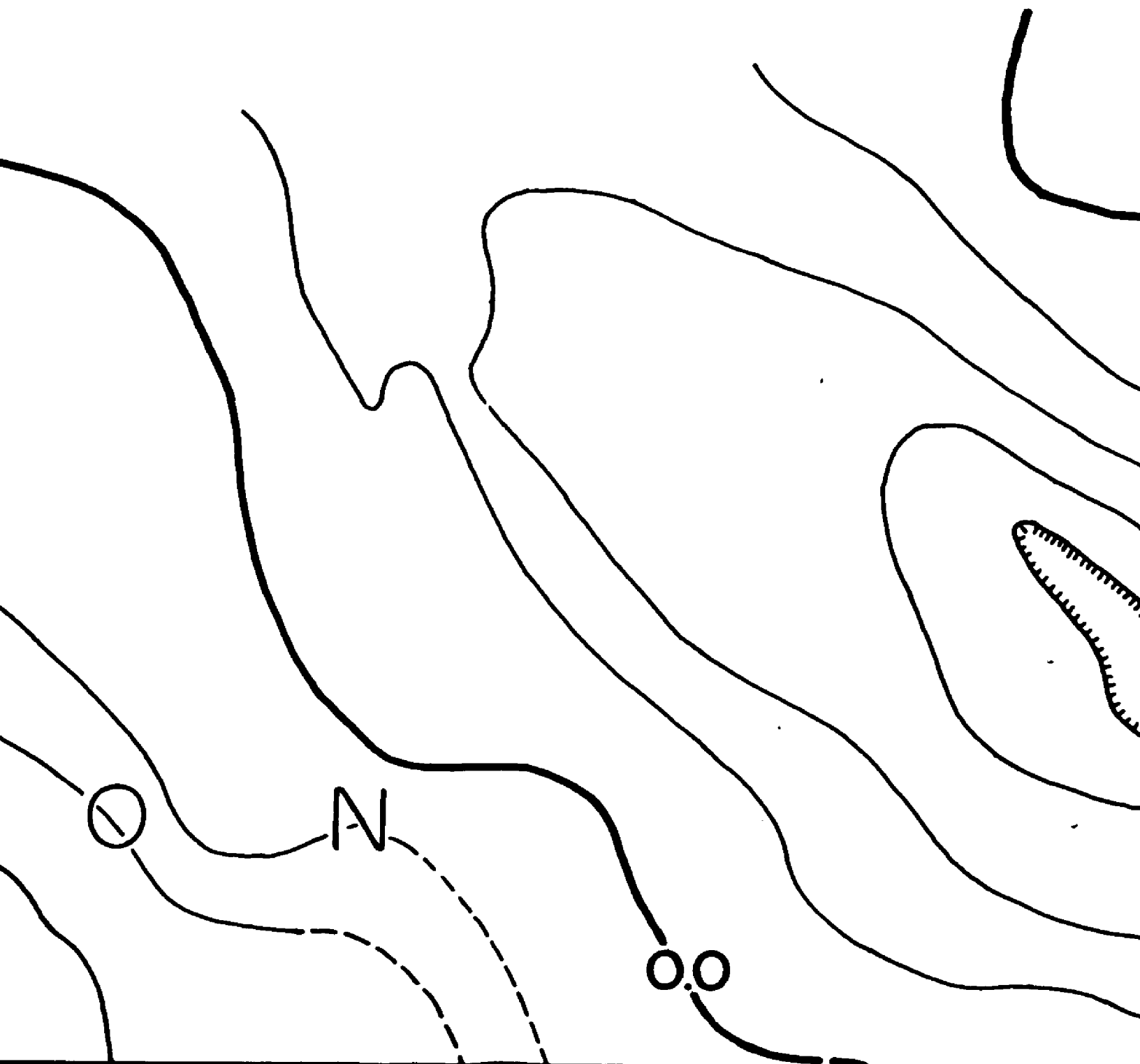
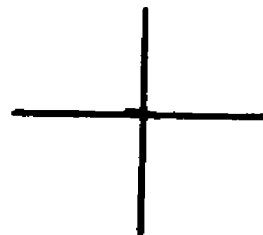


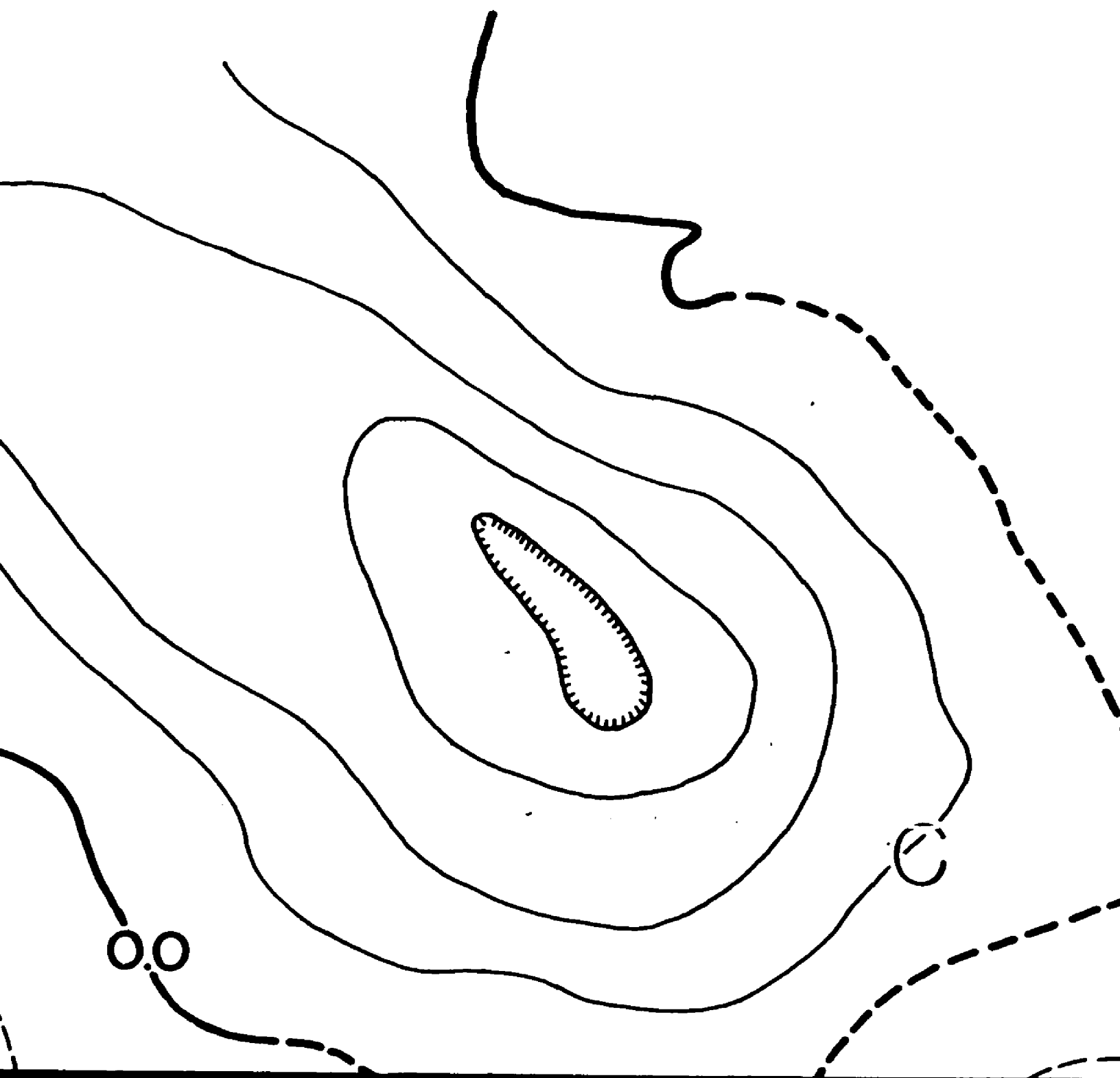
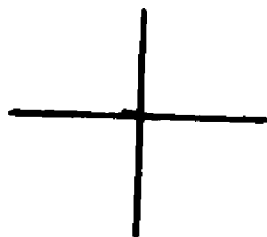


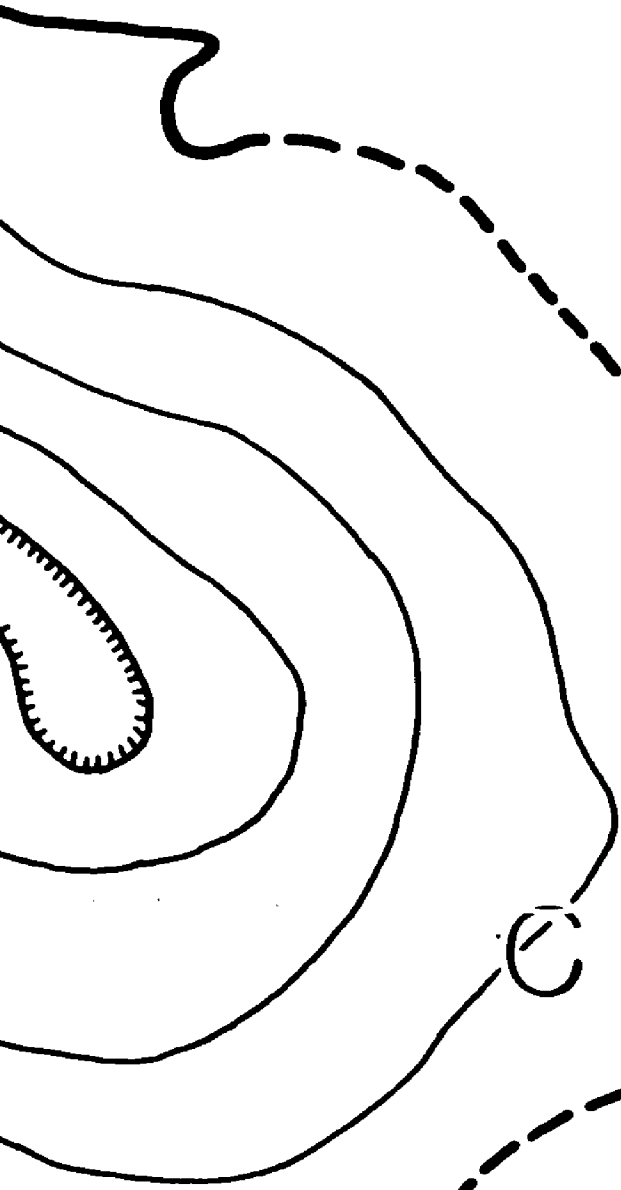










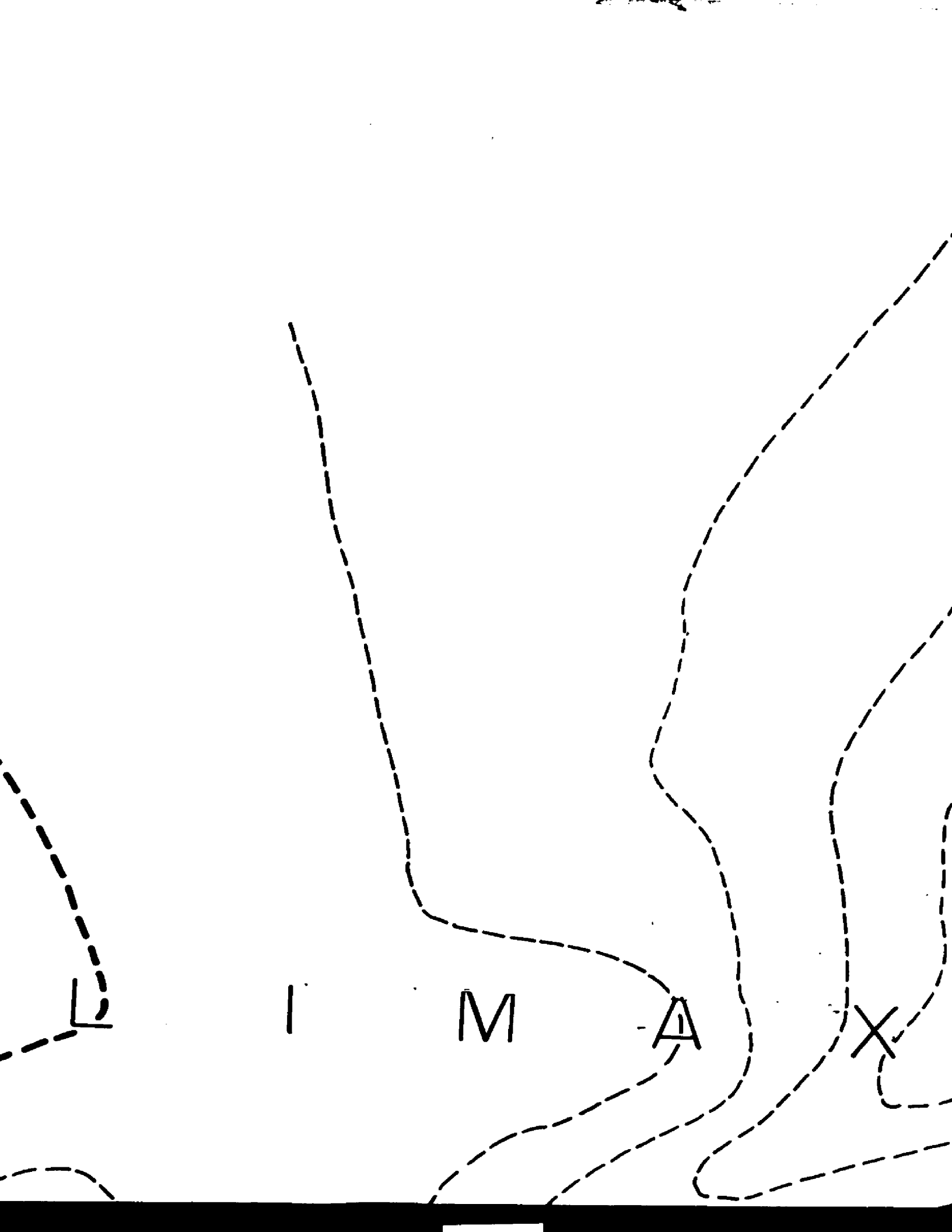


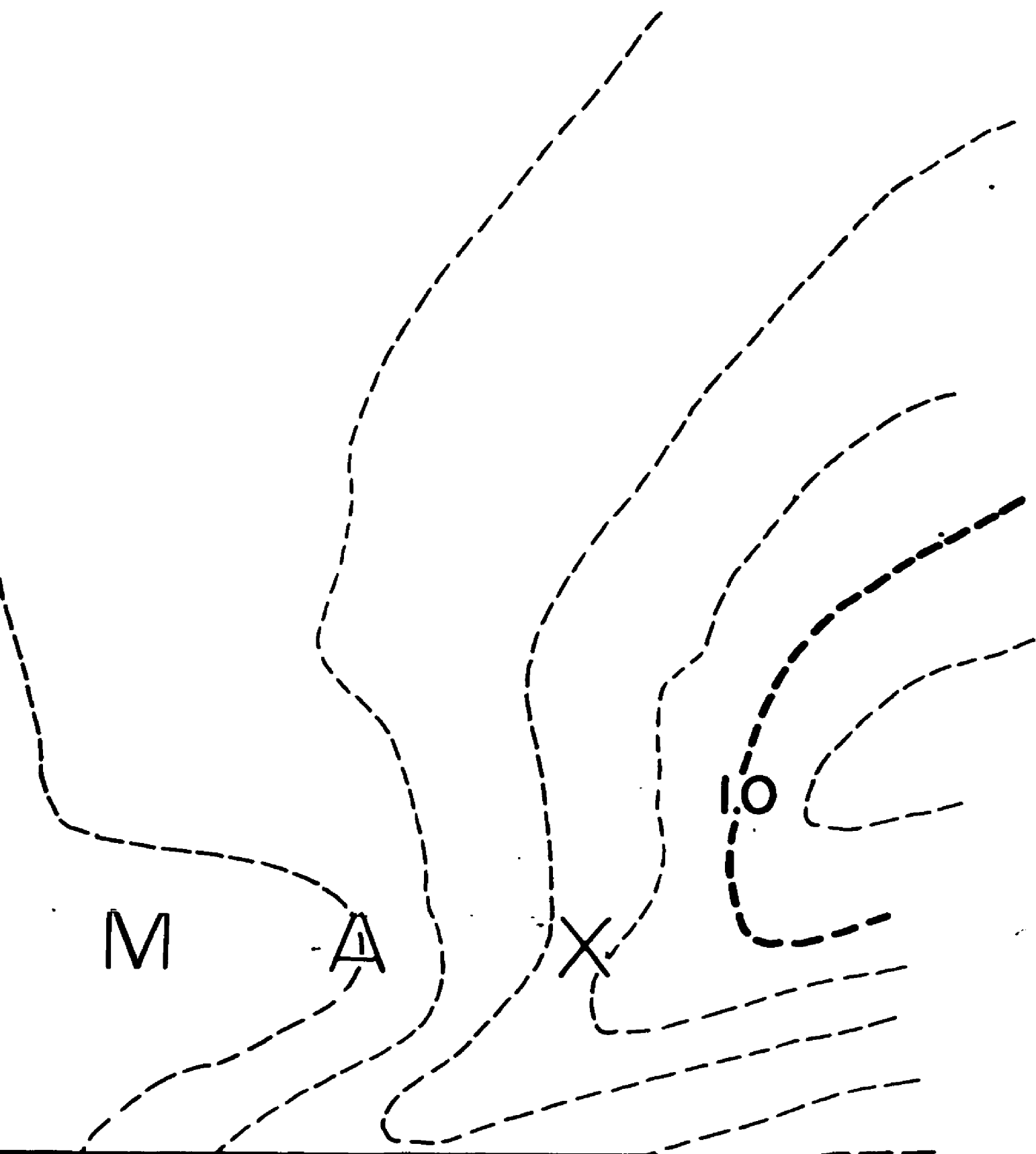
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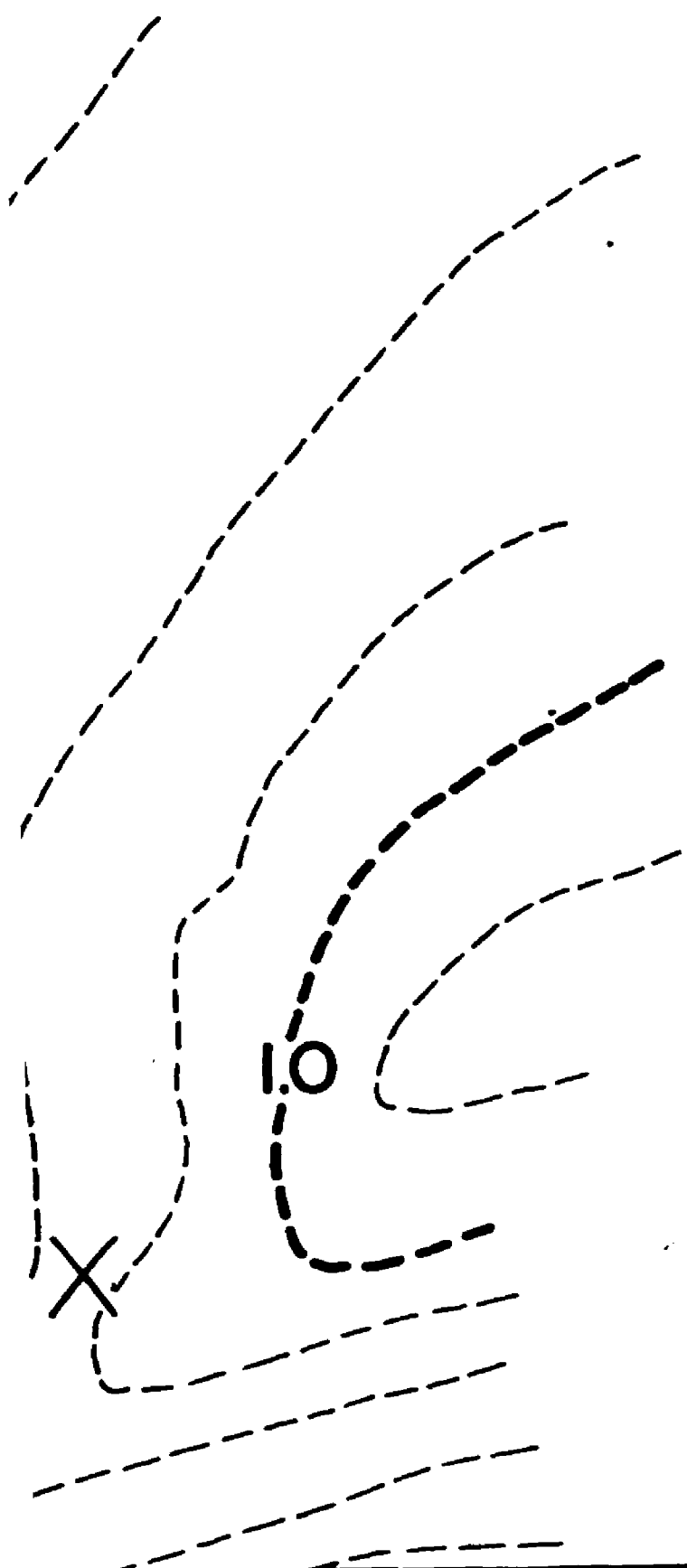
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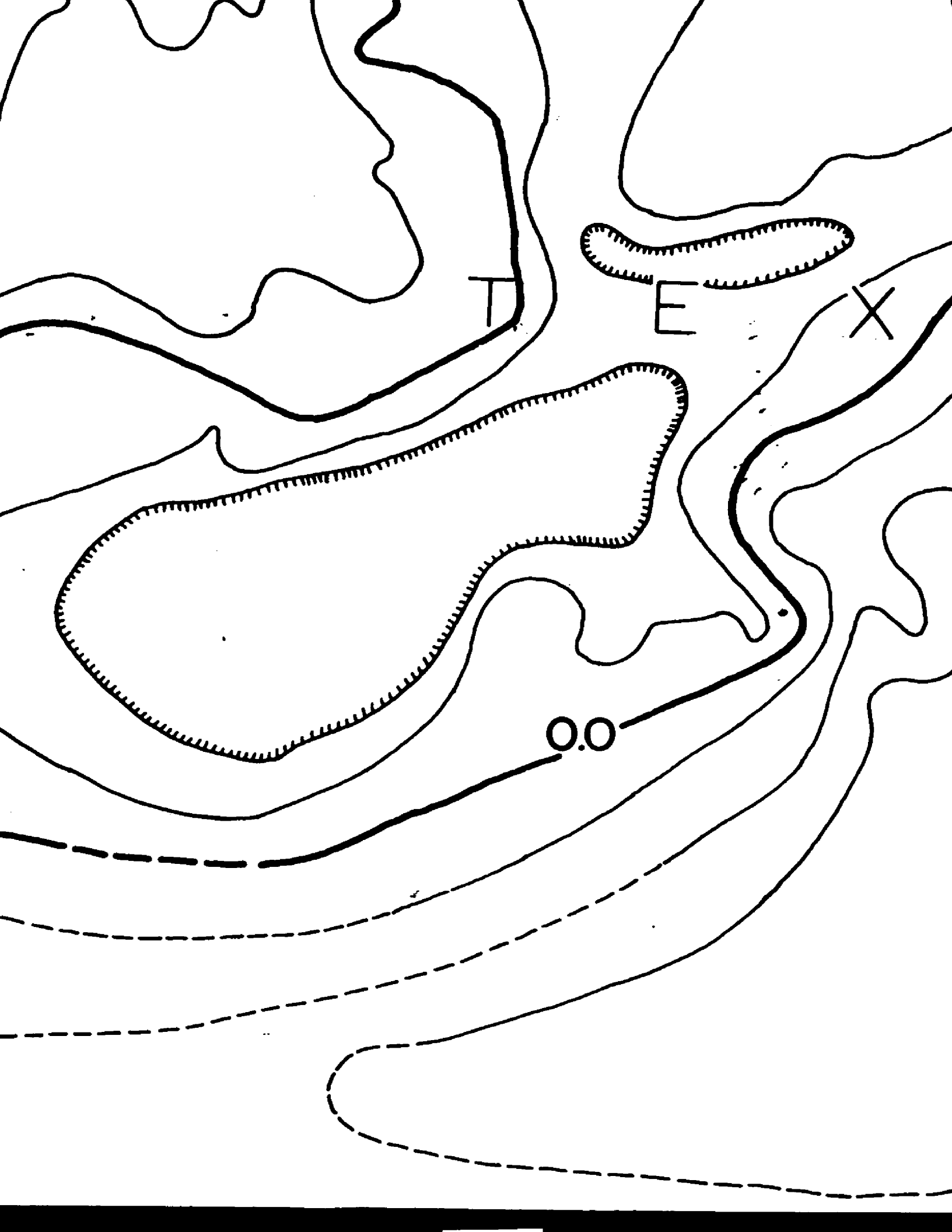
T3S

T3S

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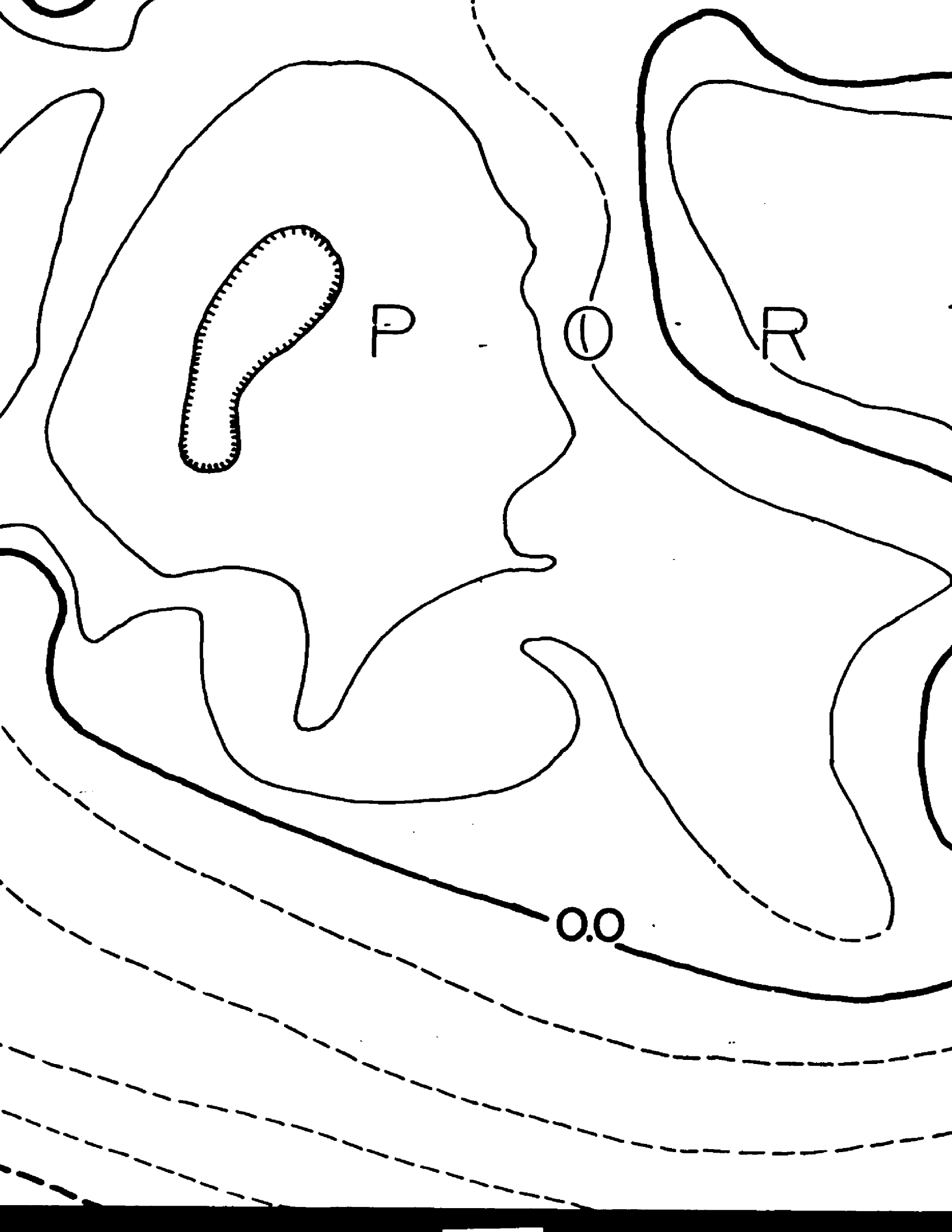


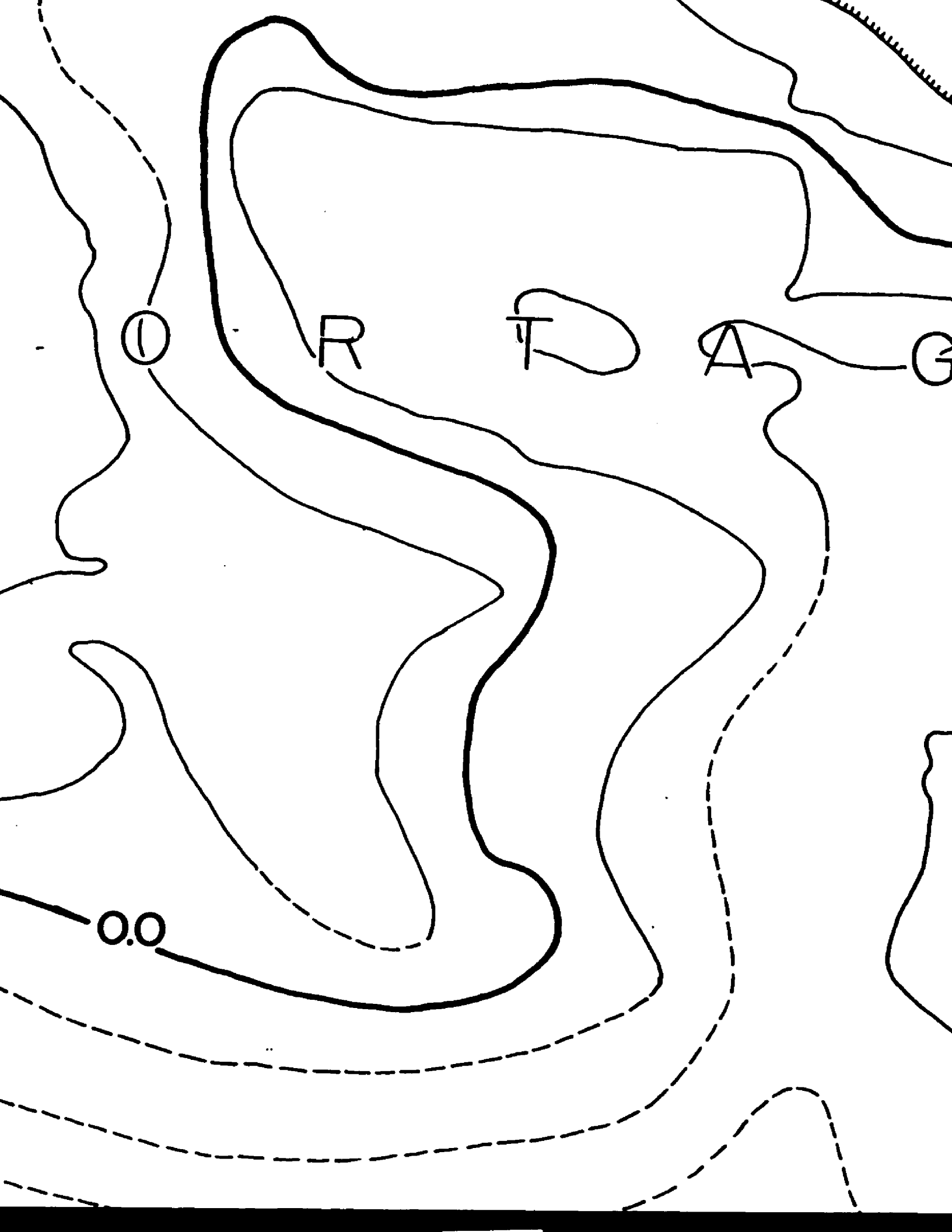






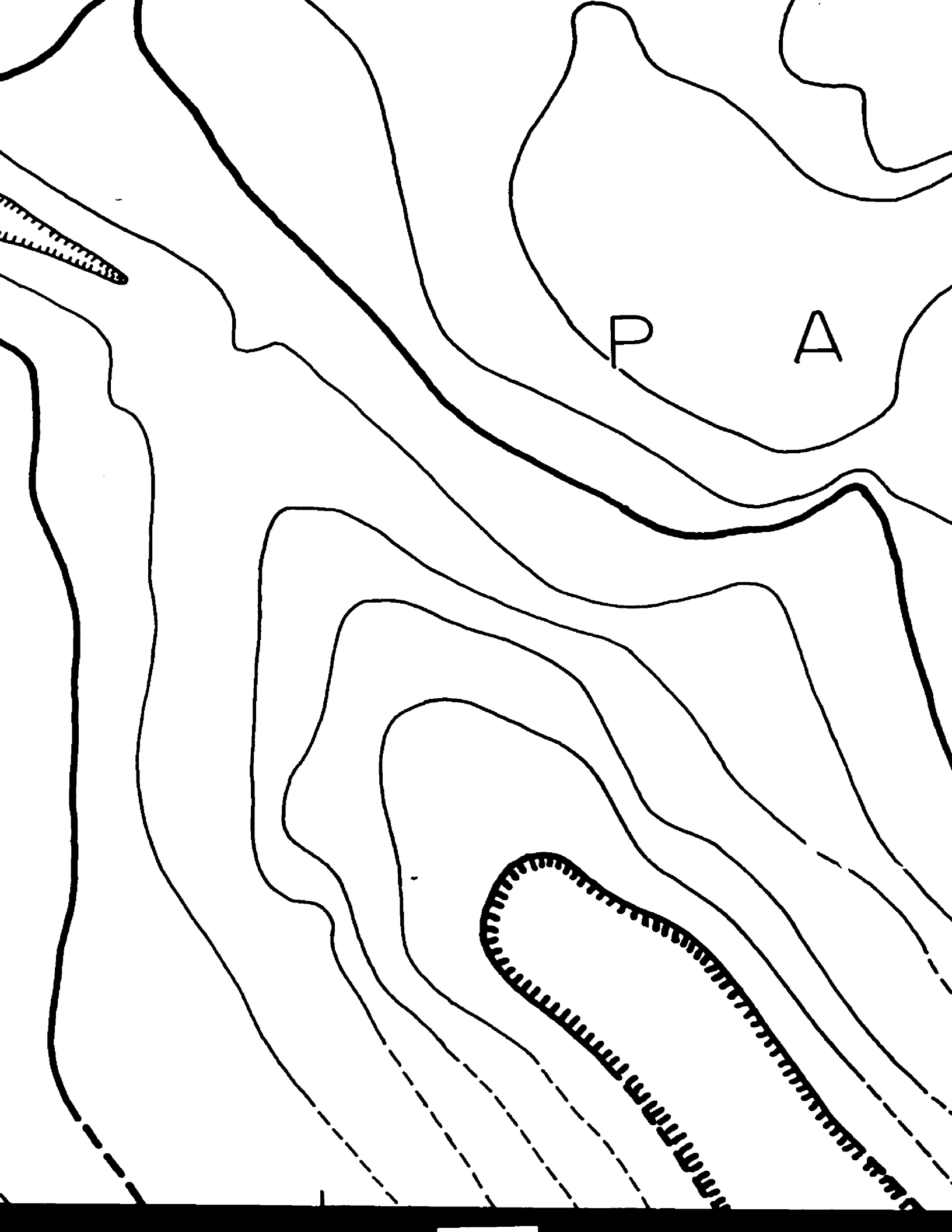


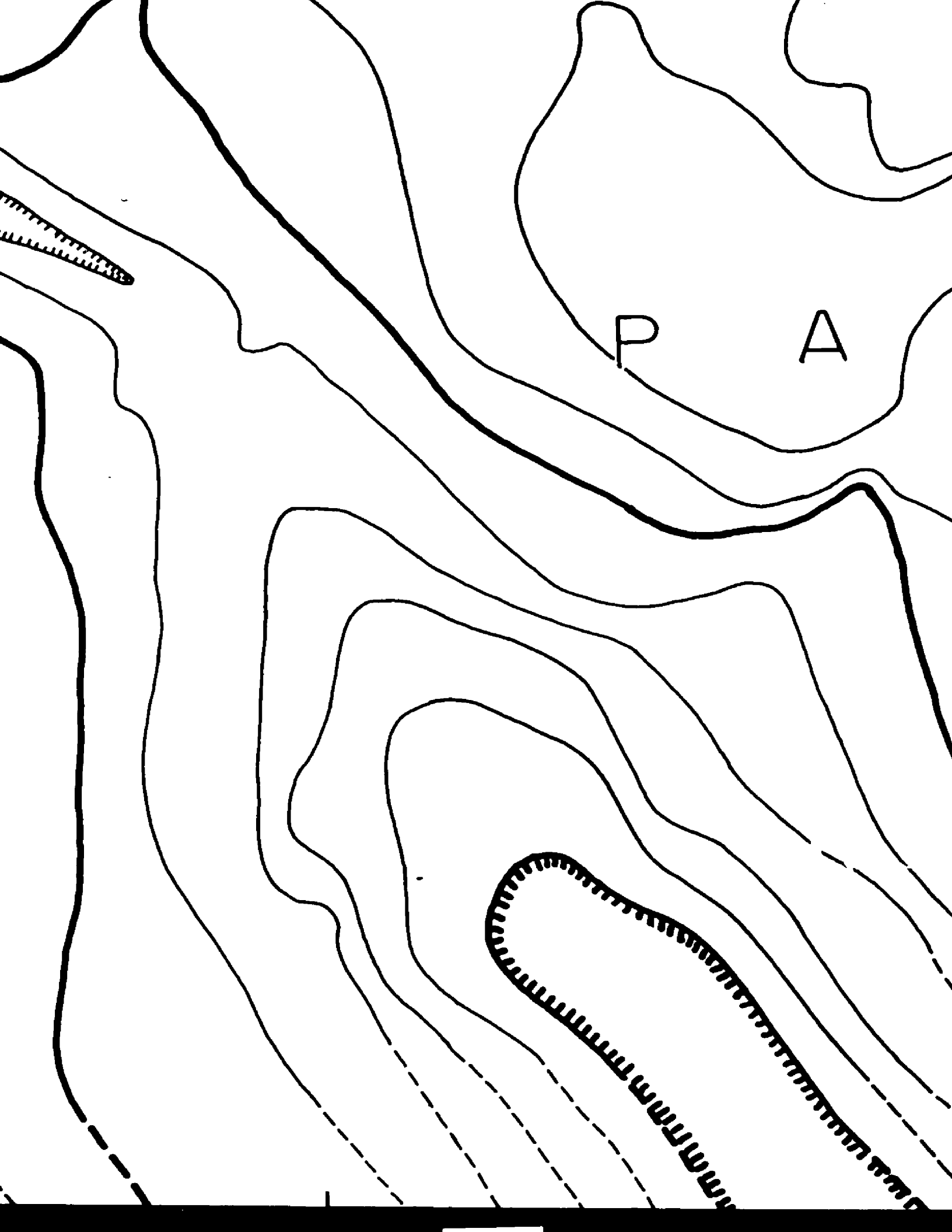






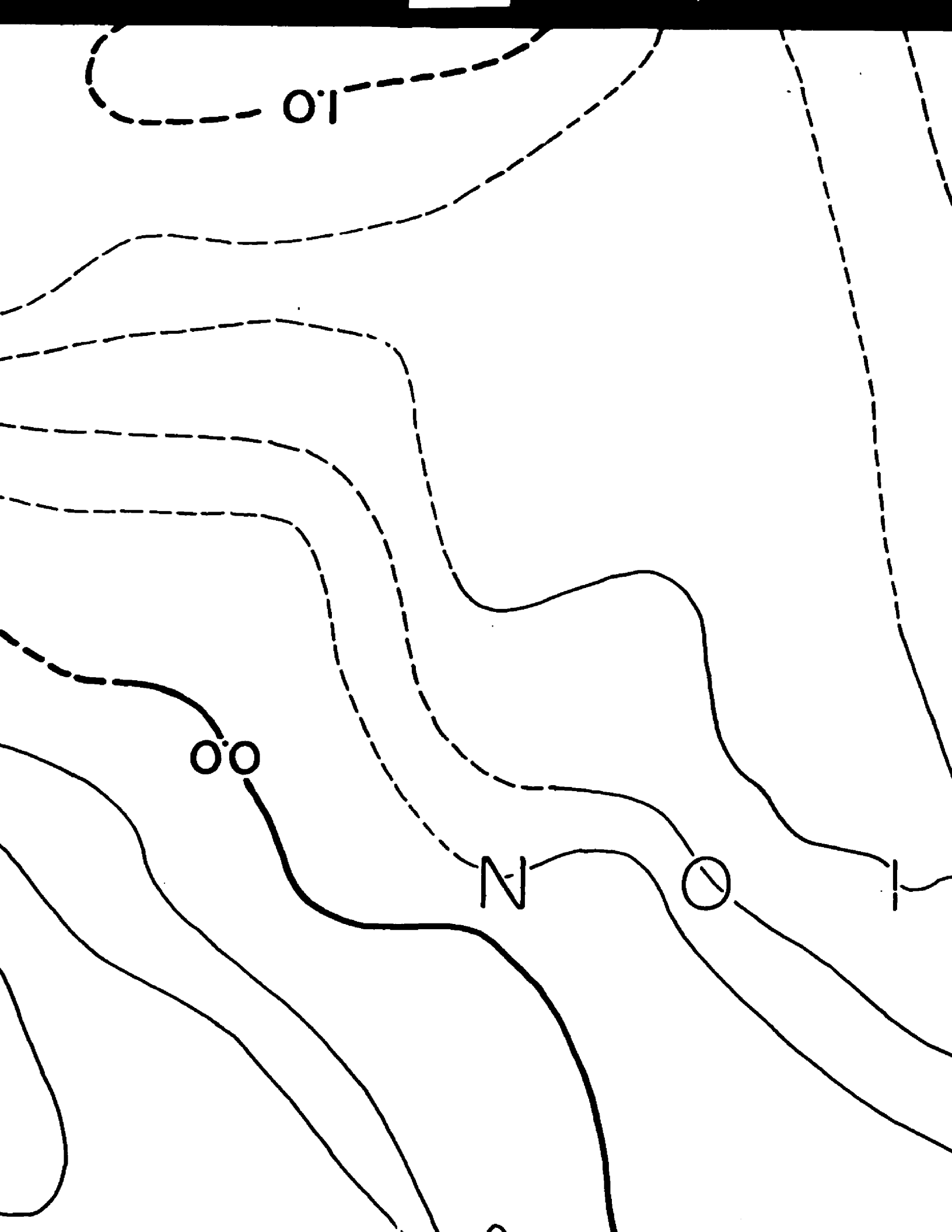


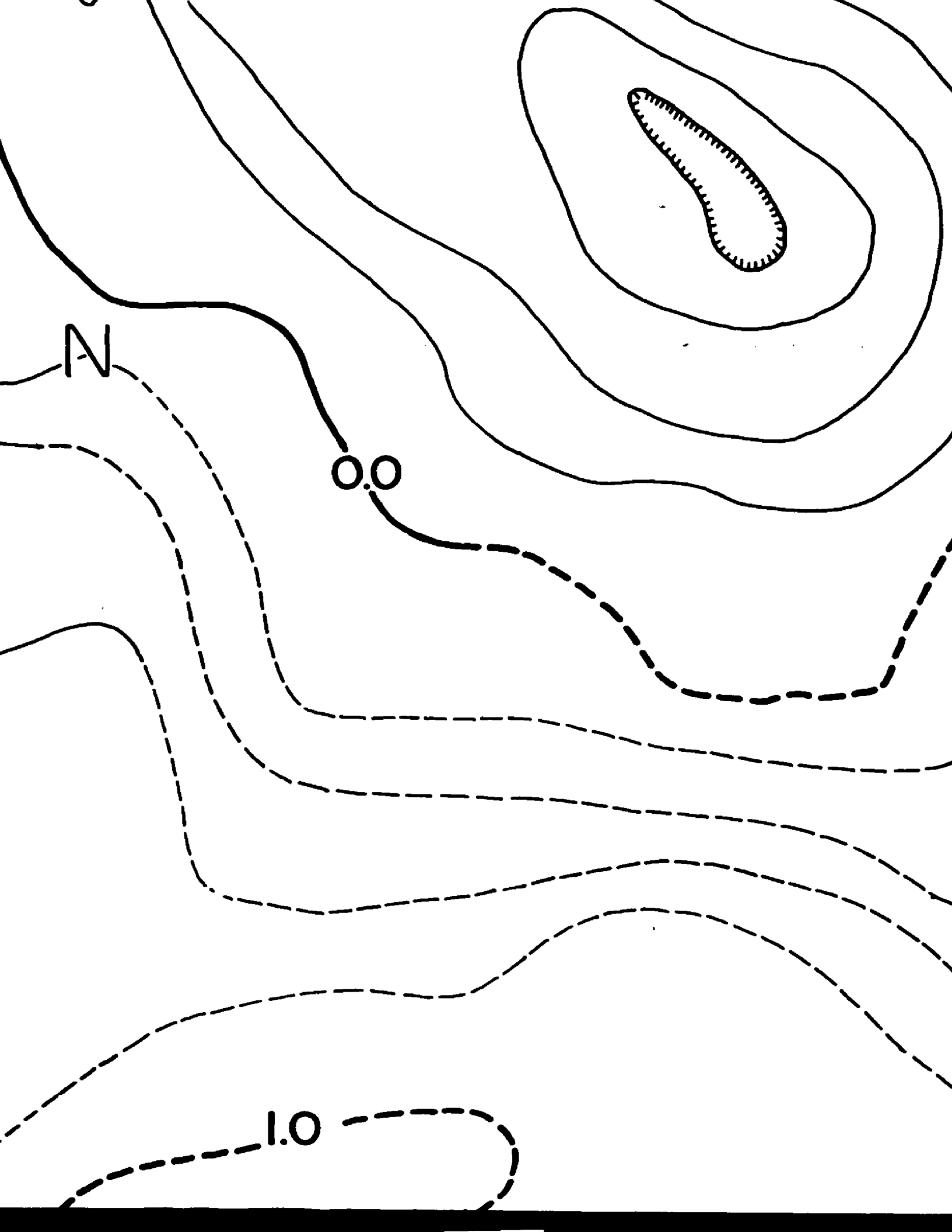


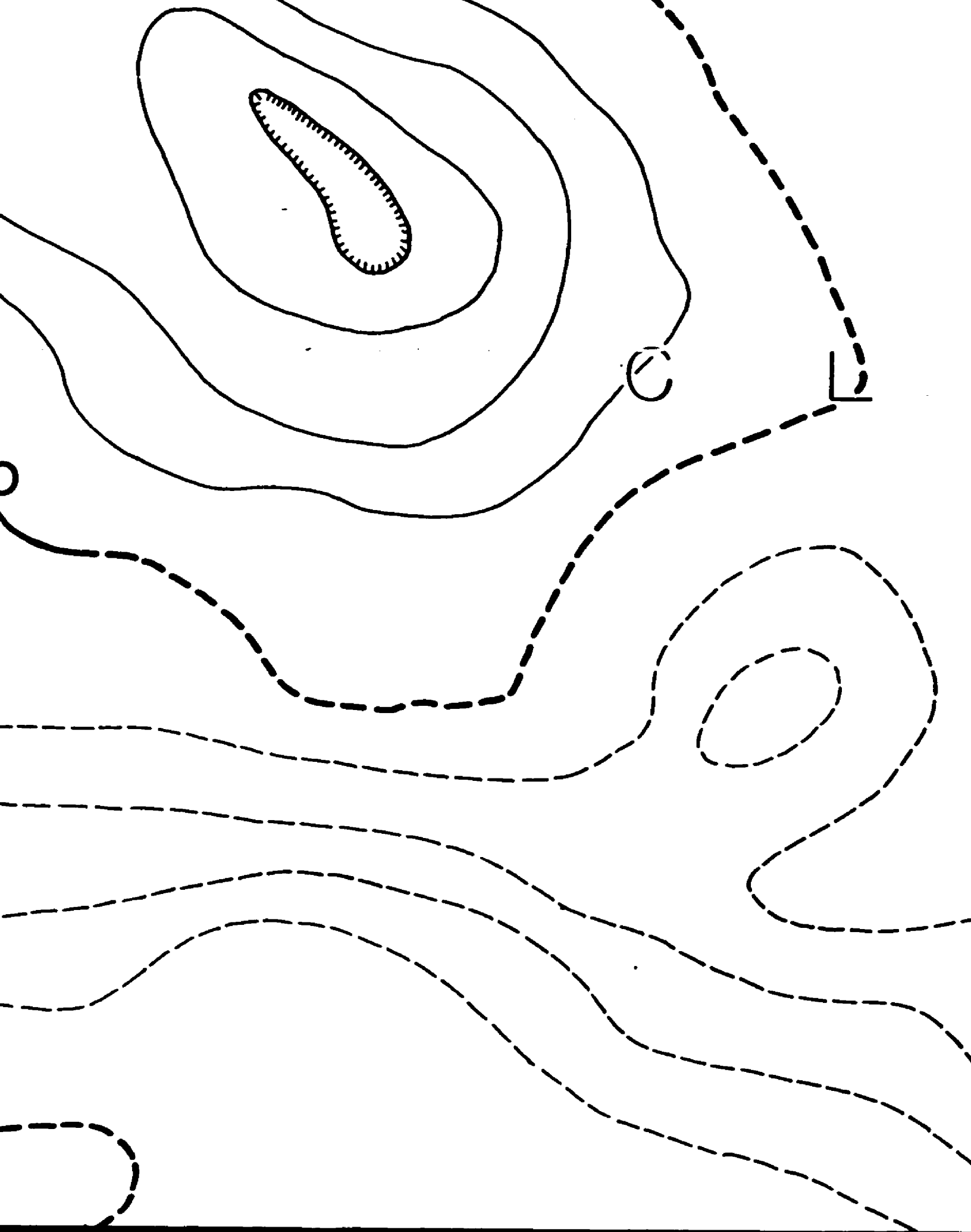


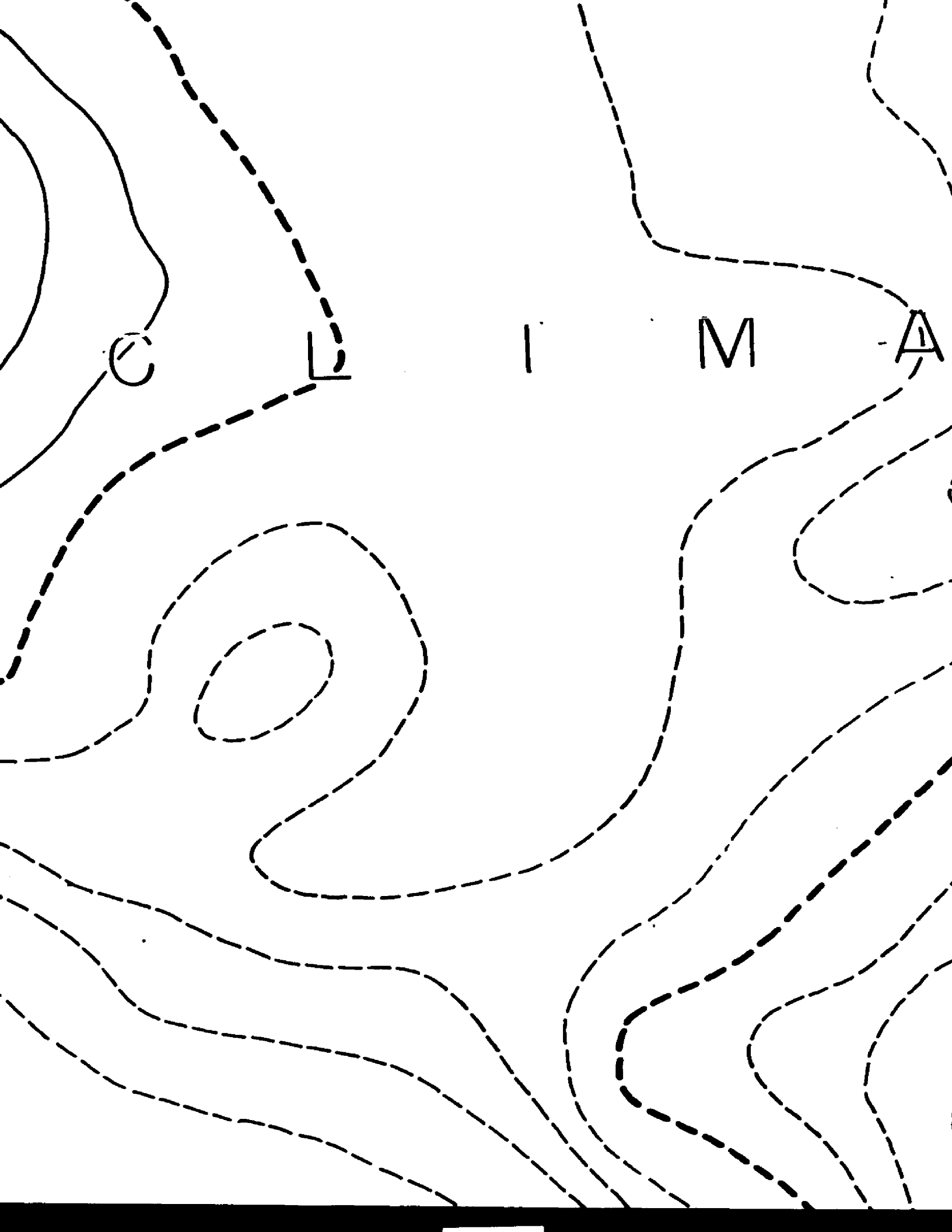


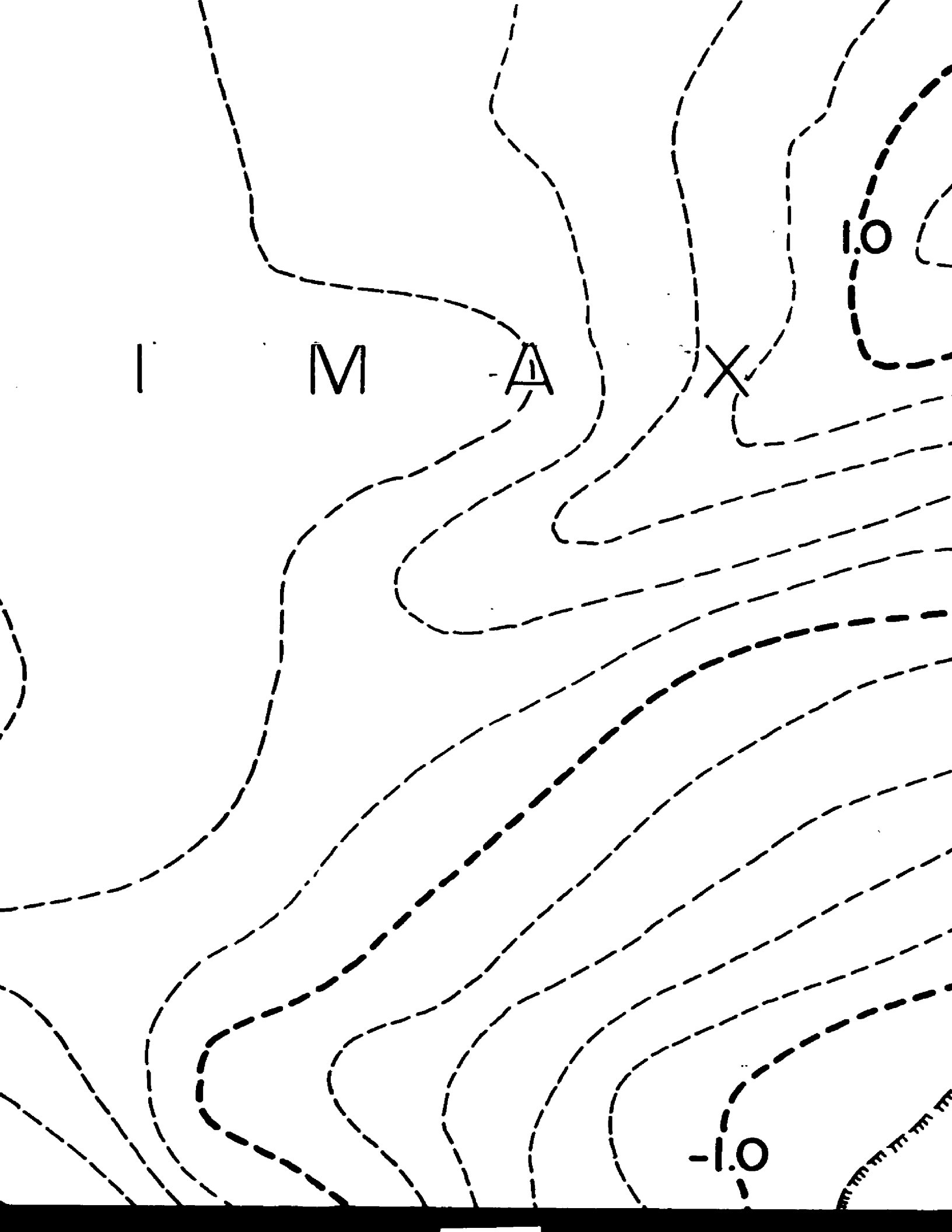


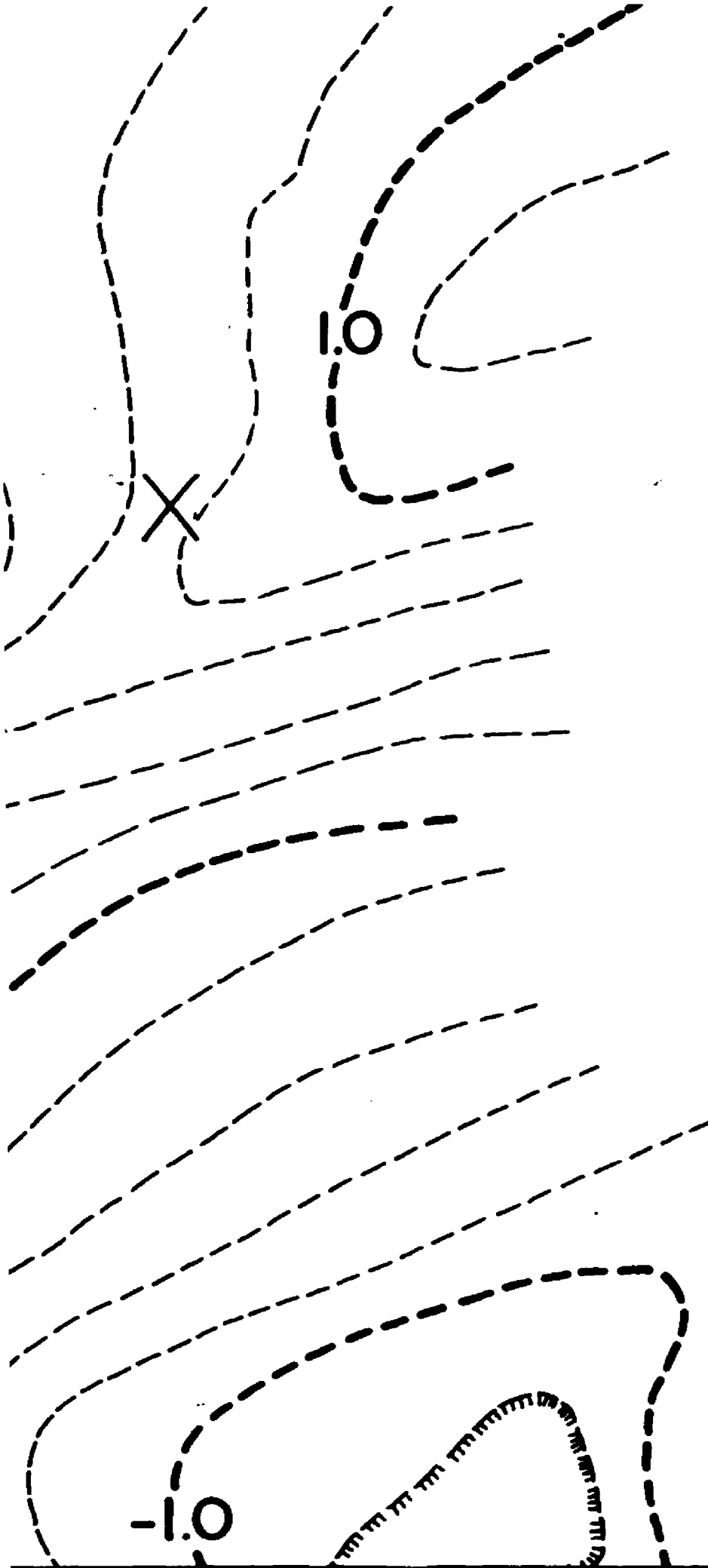






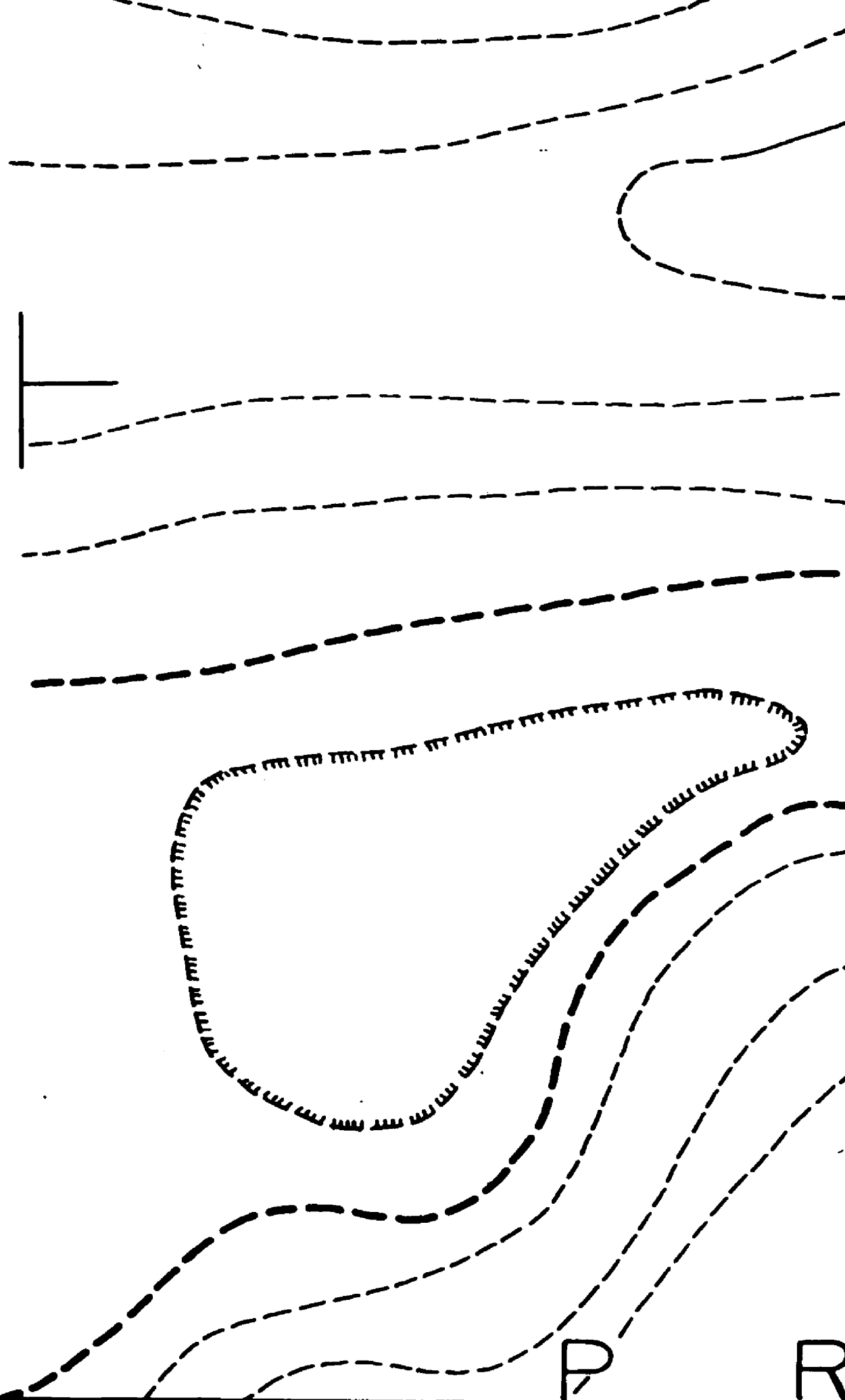






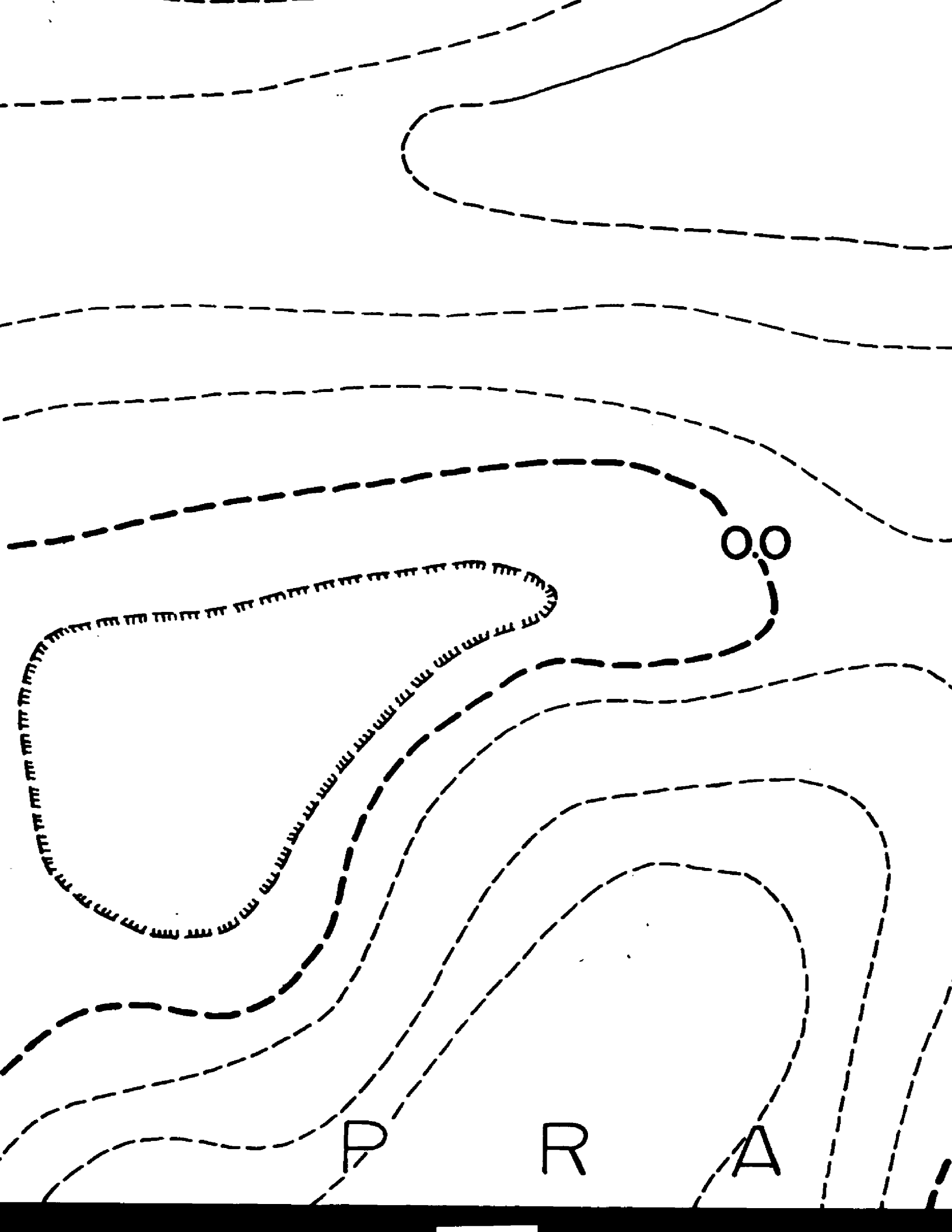
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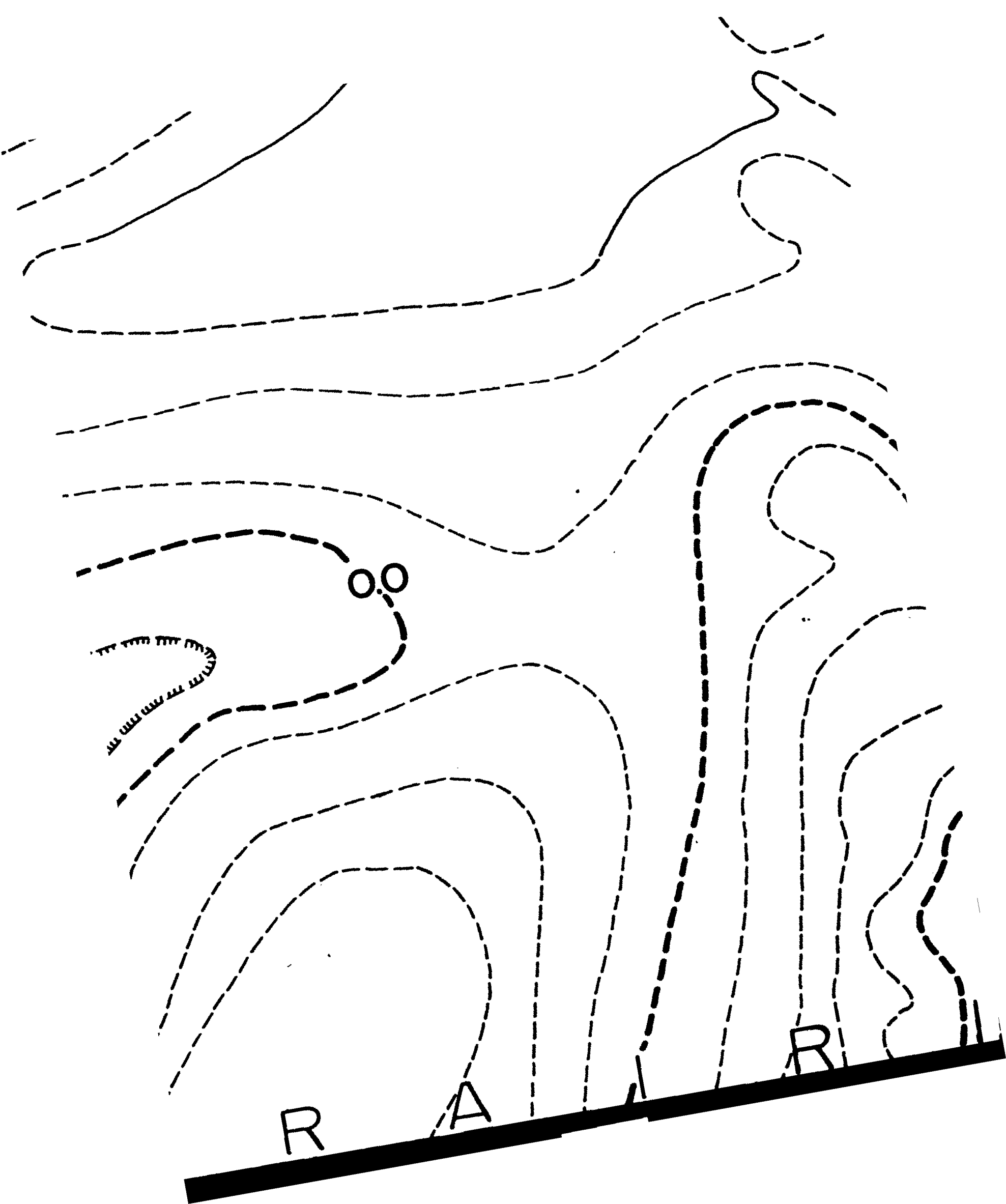
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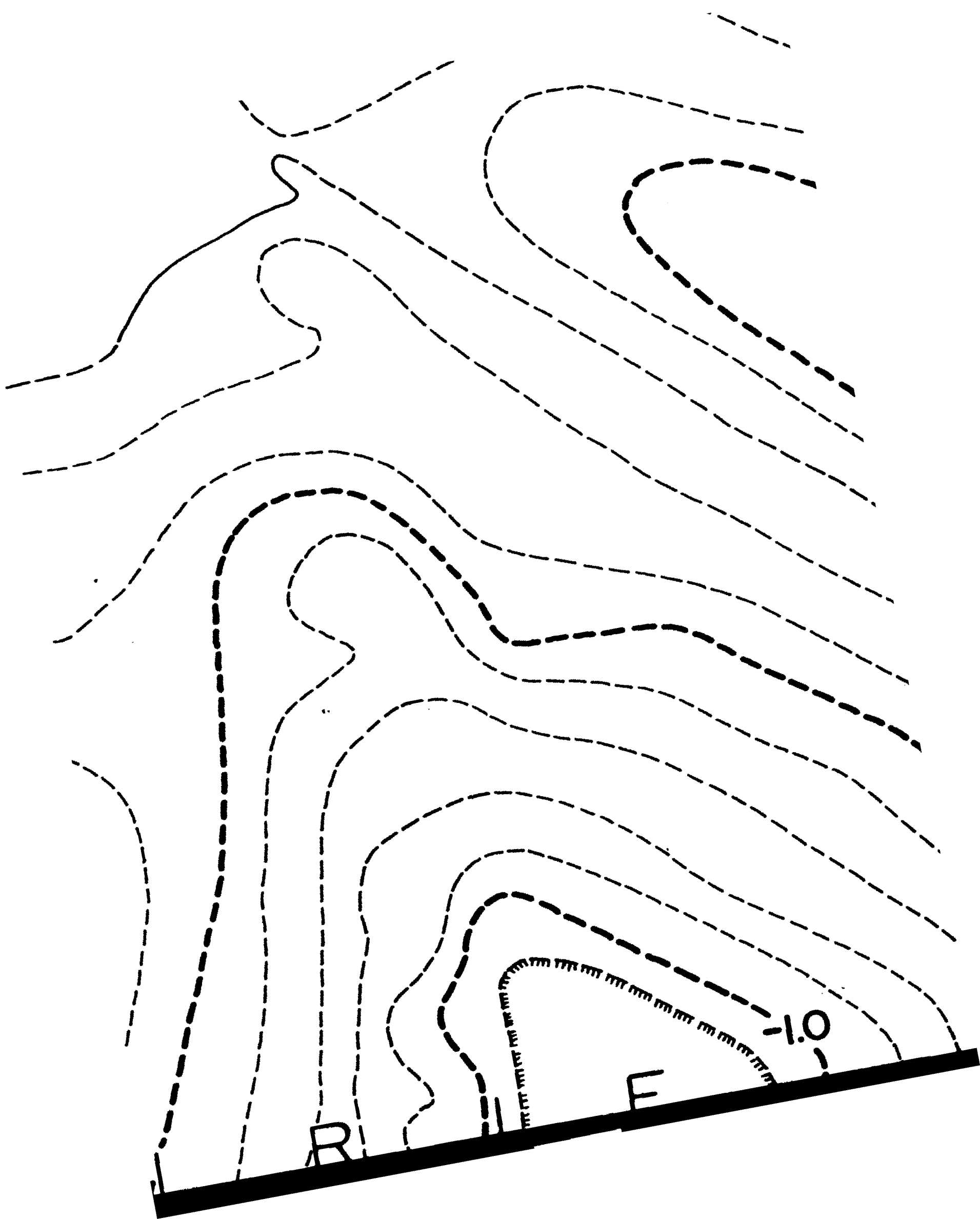


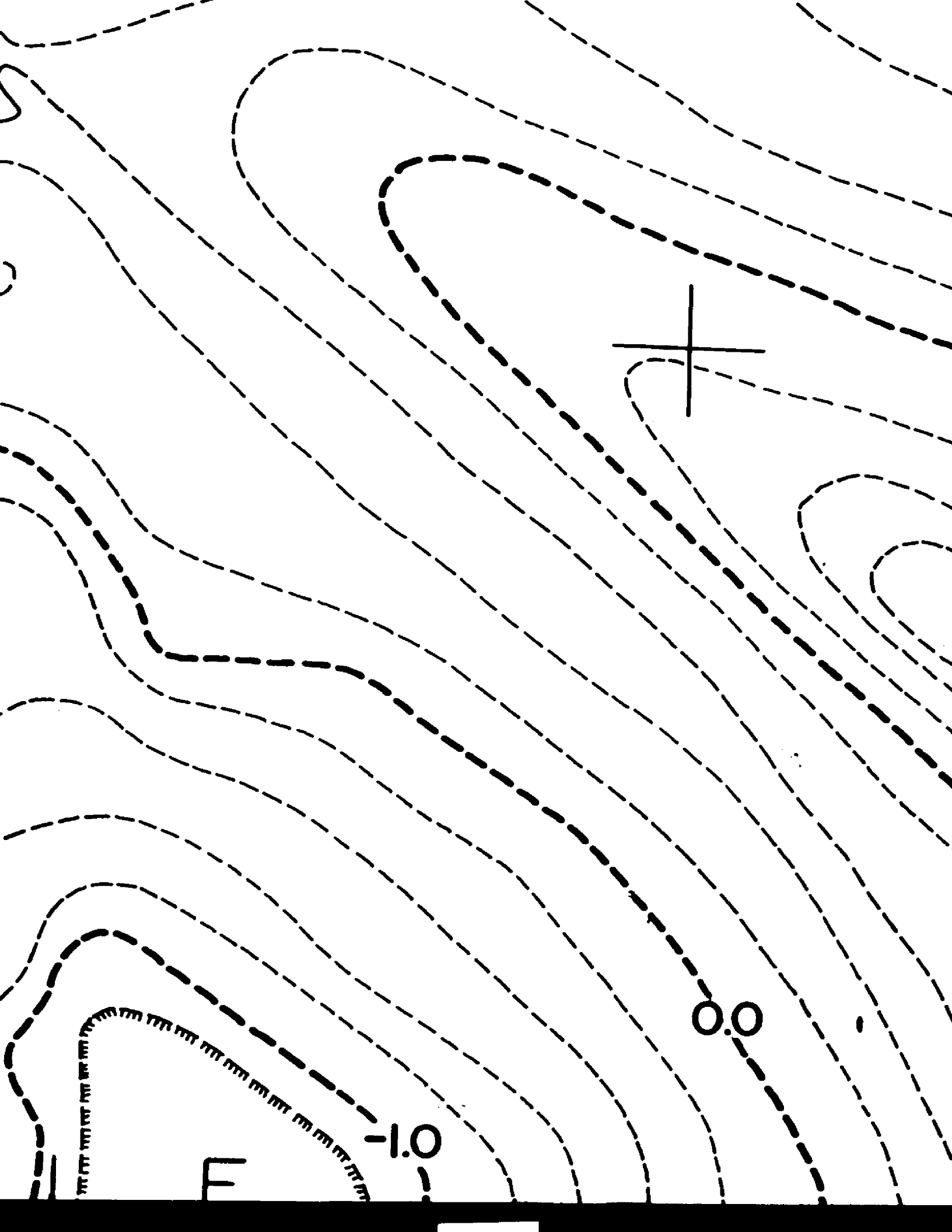
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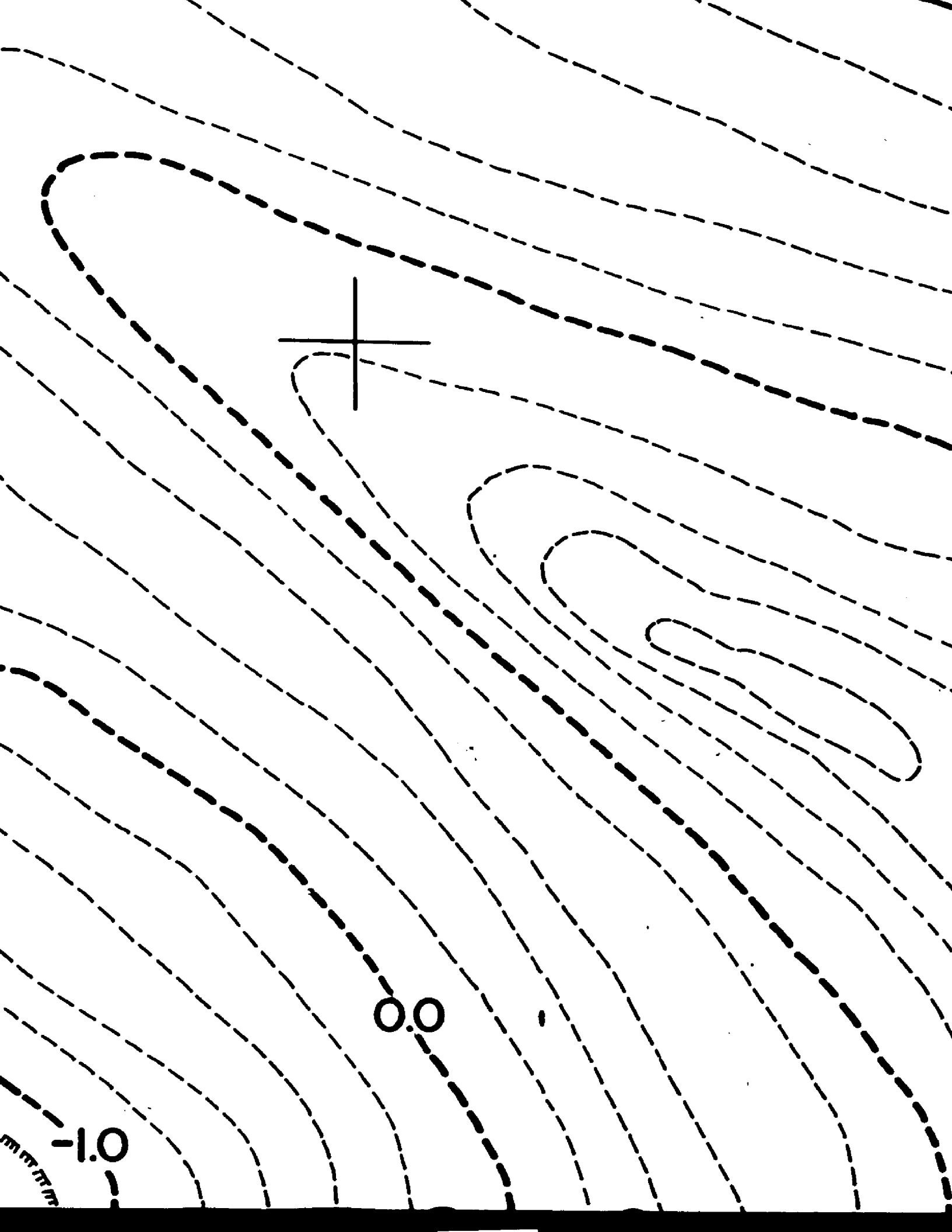
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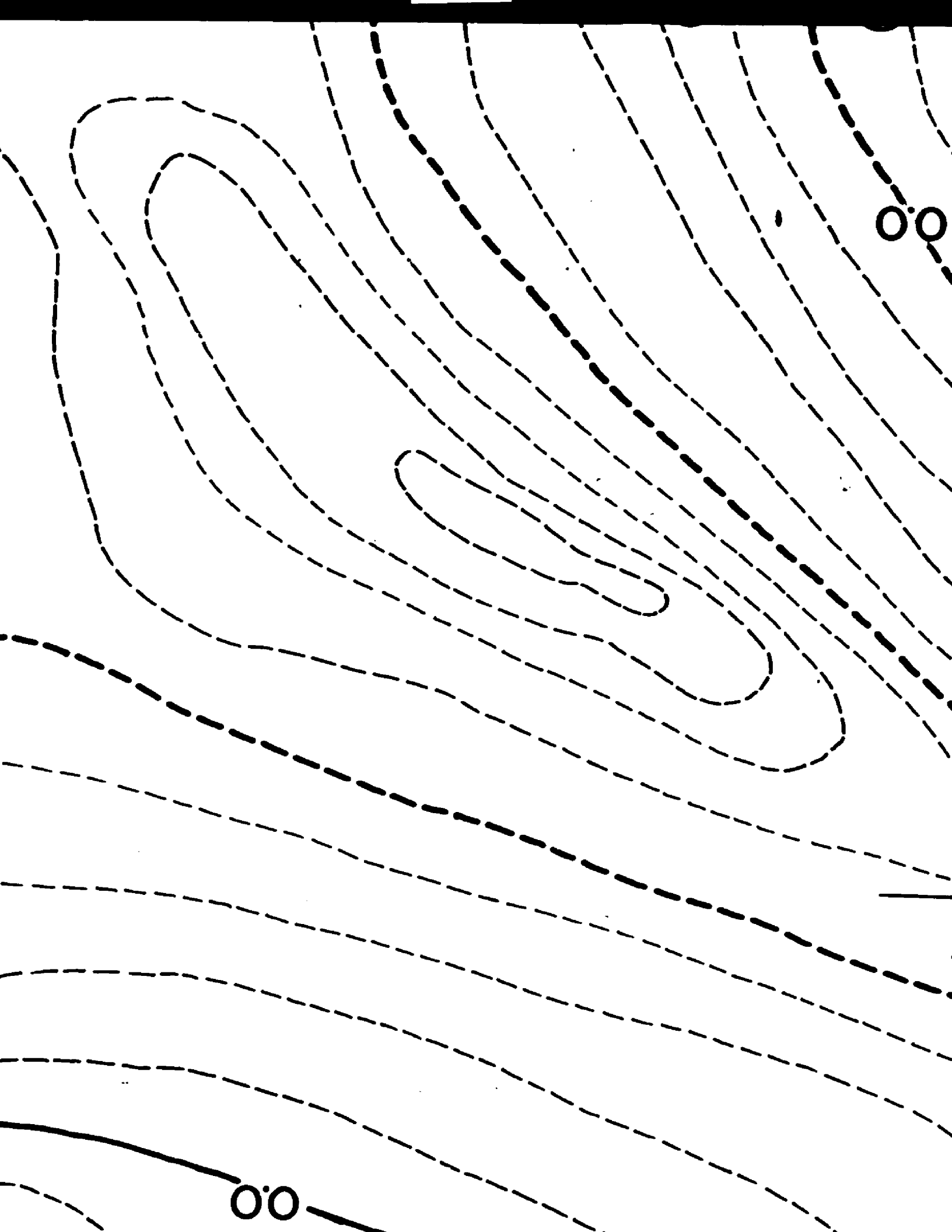


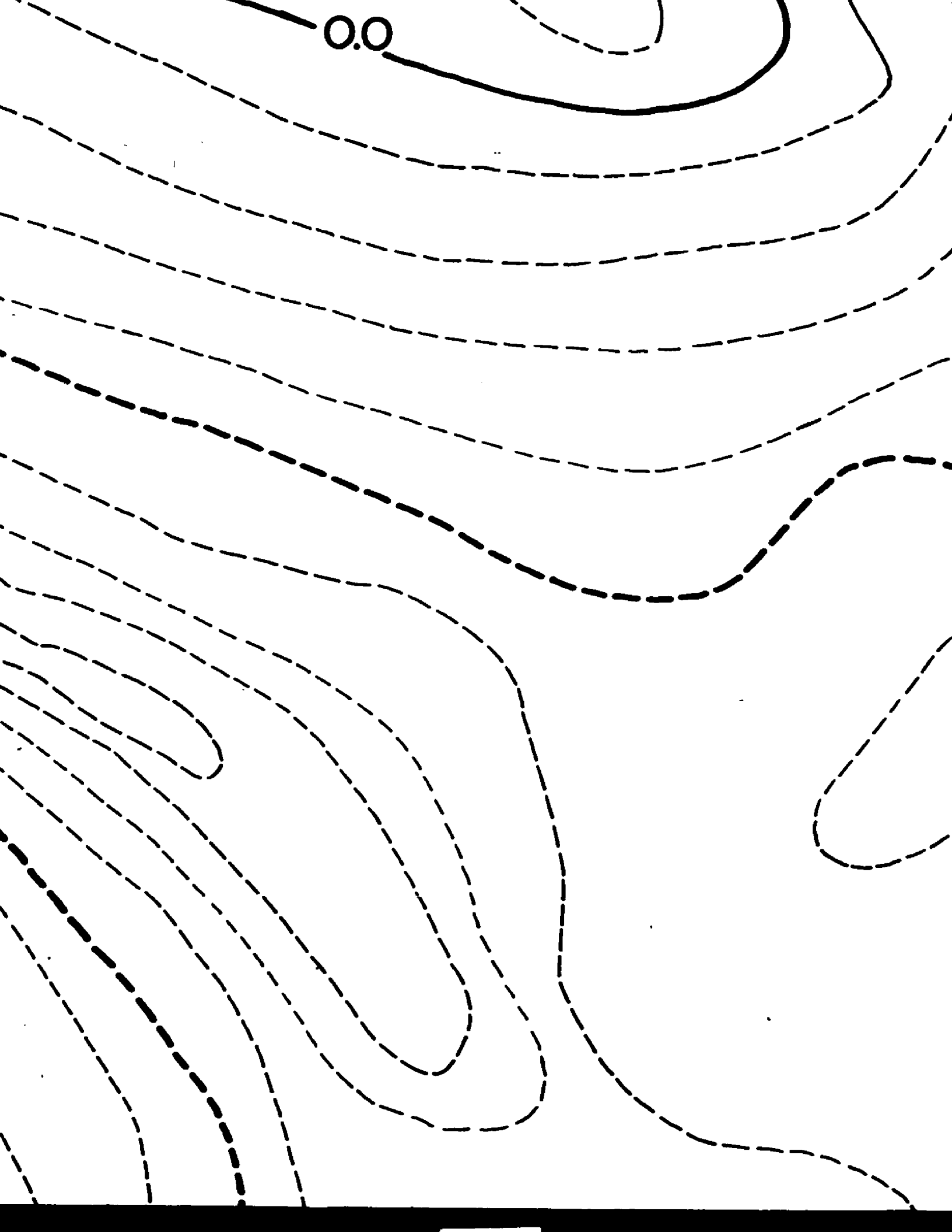


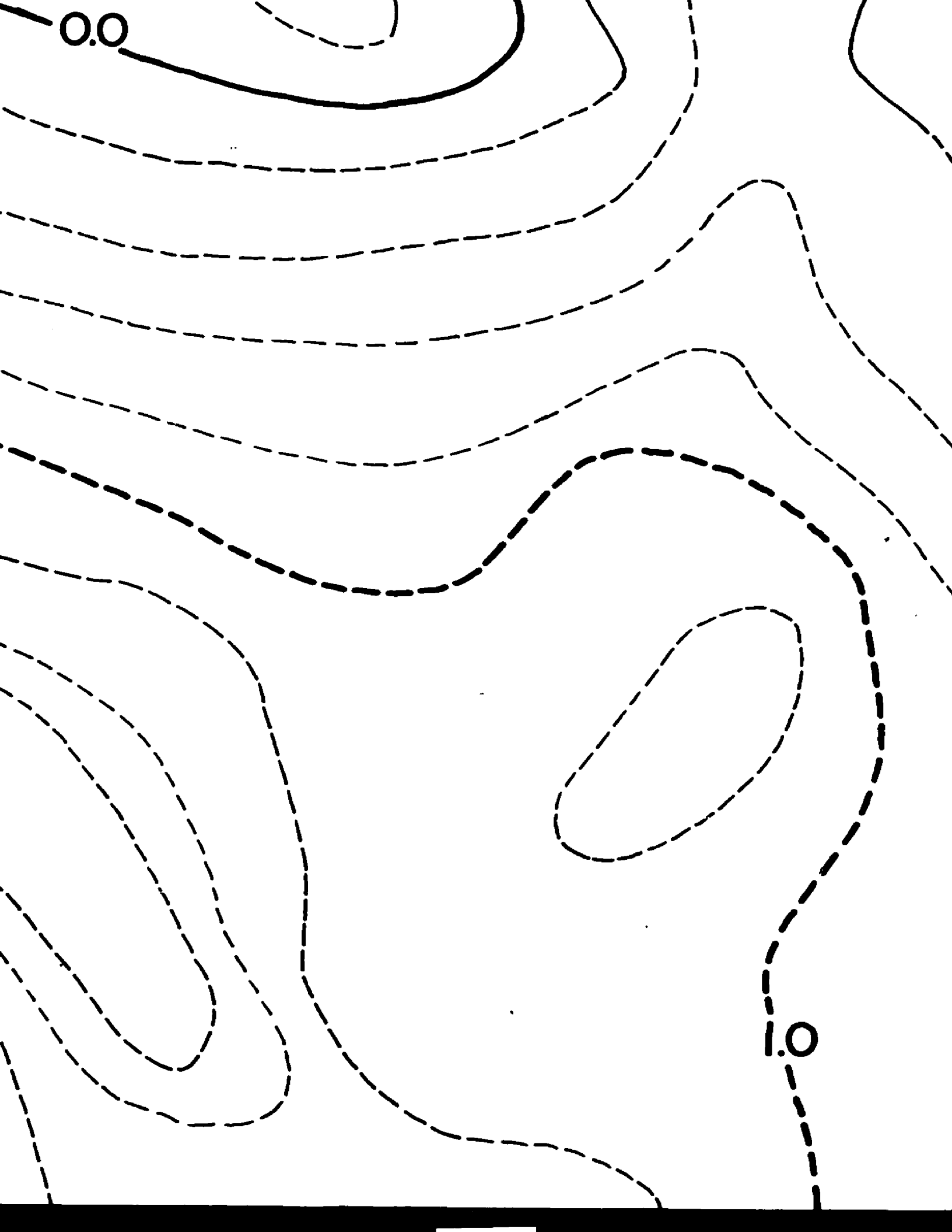


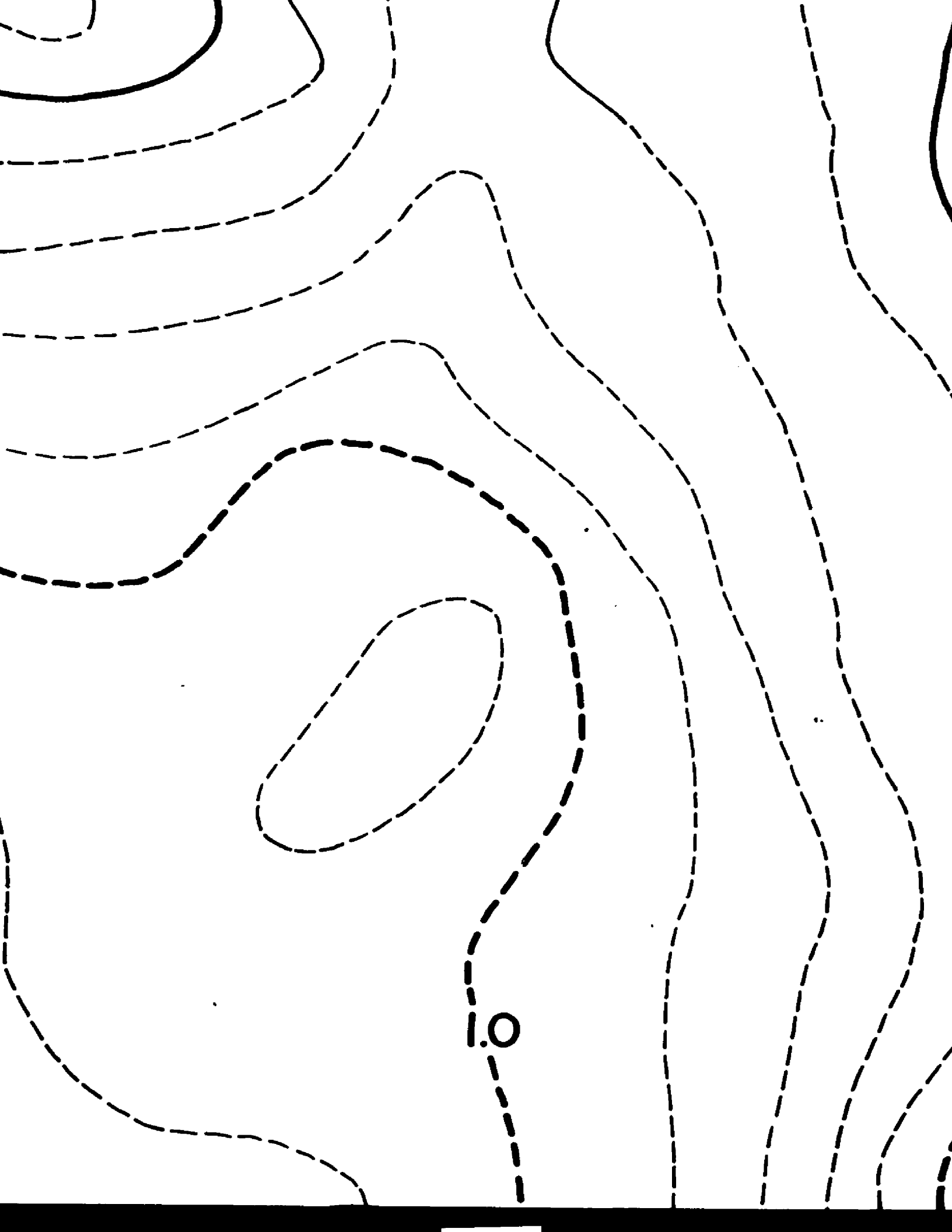




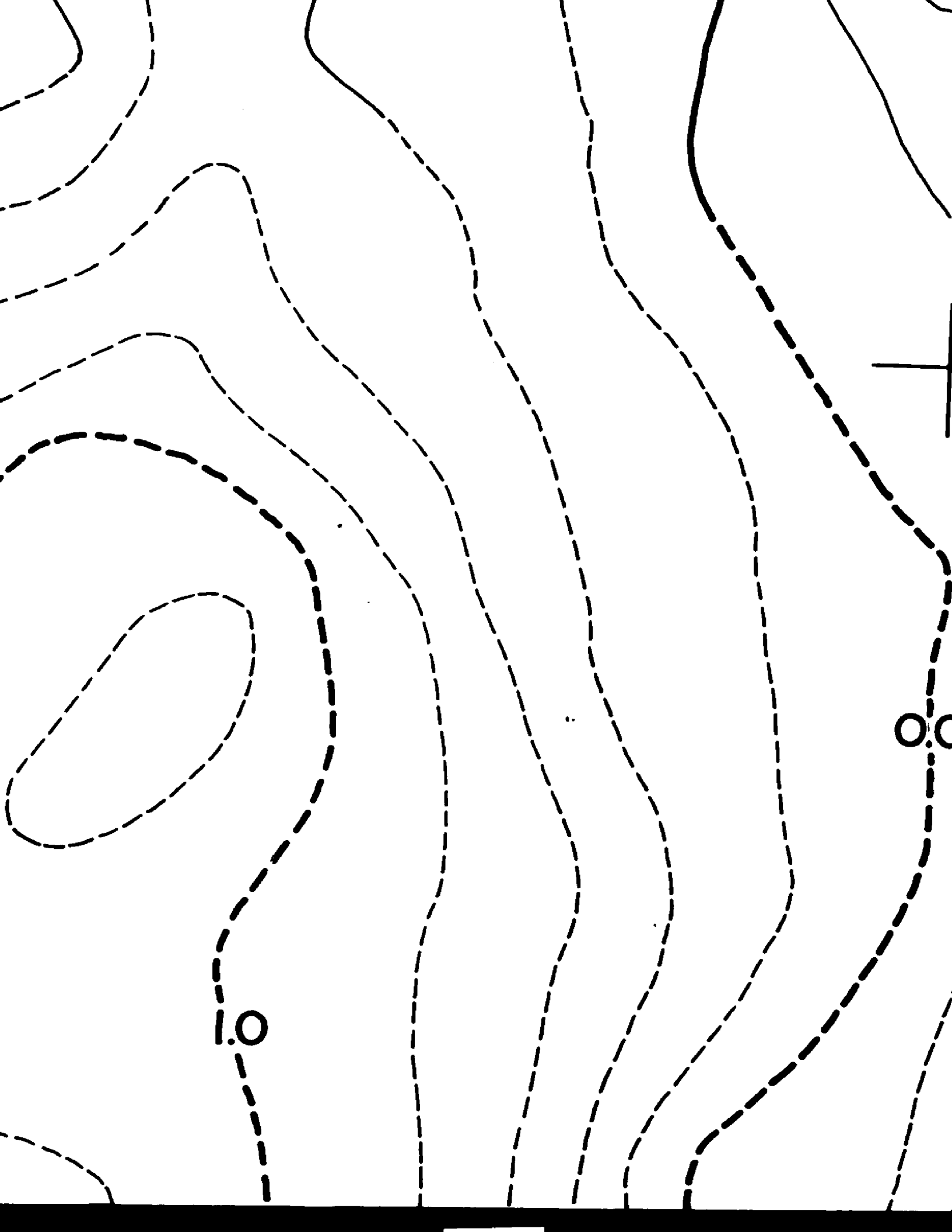


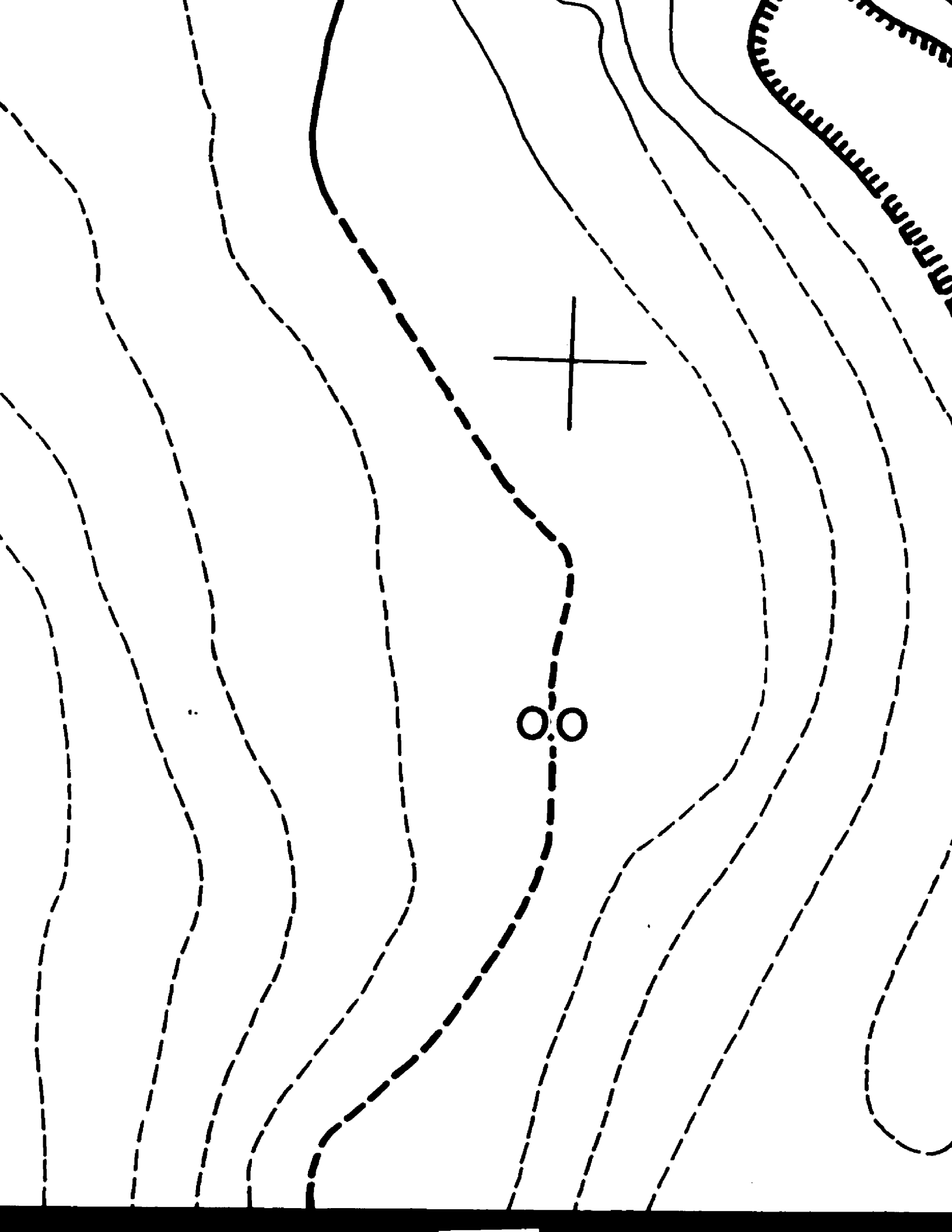


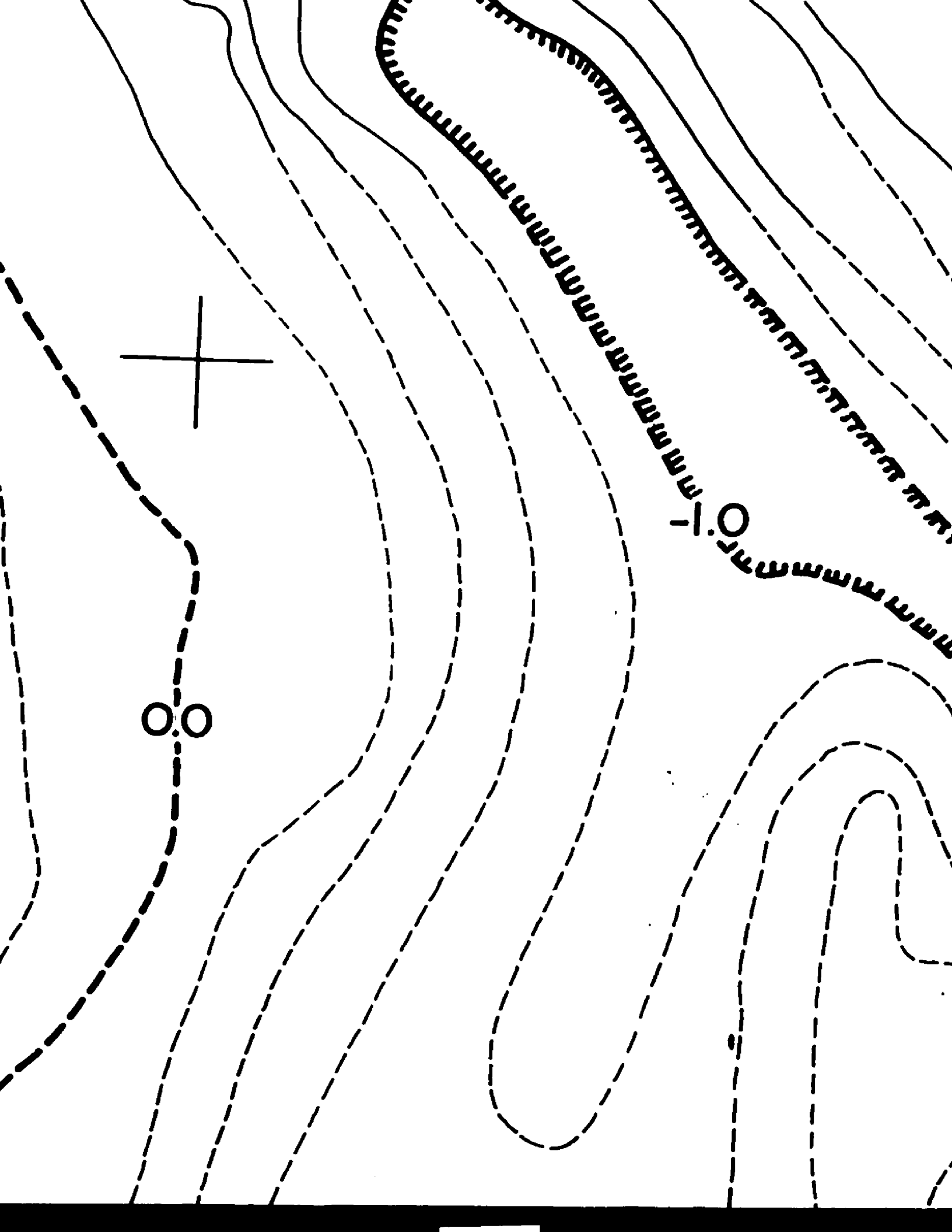


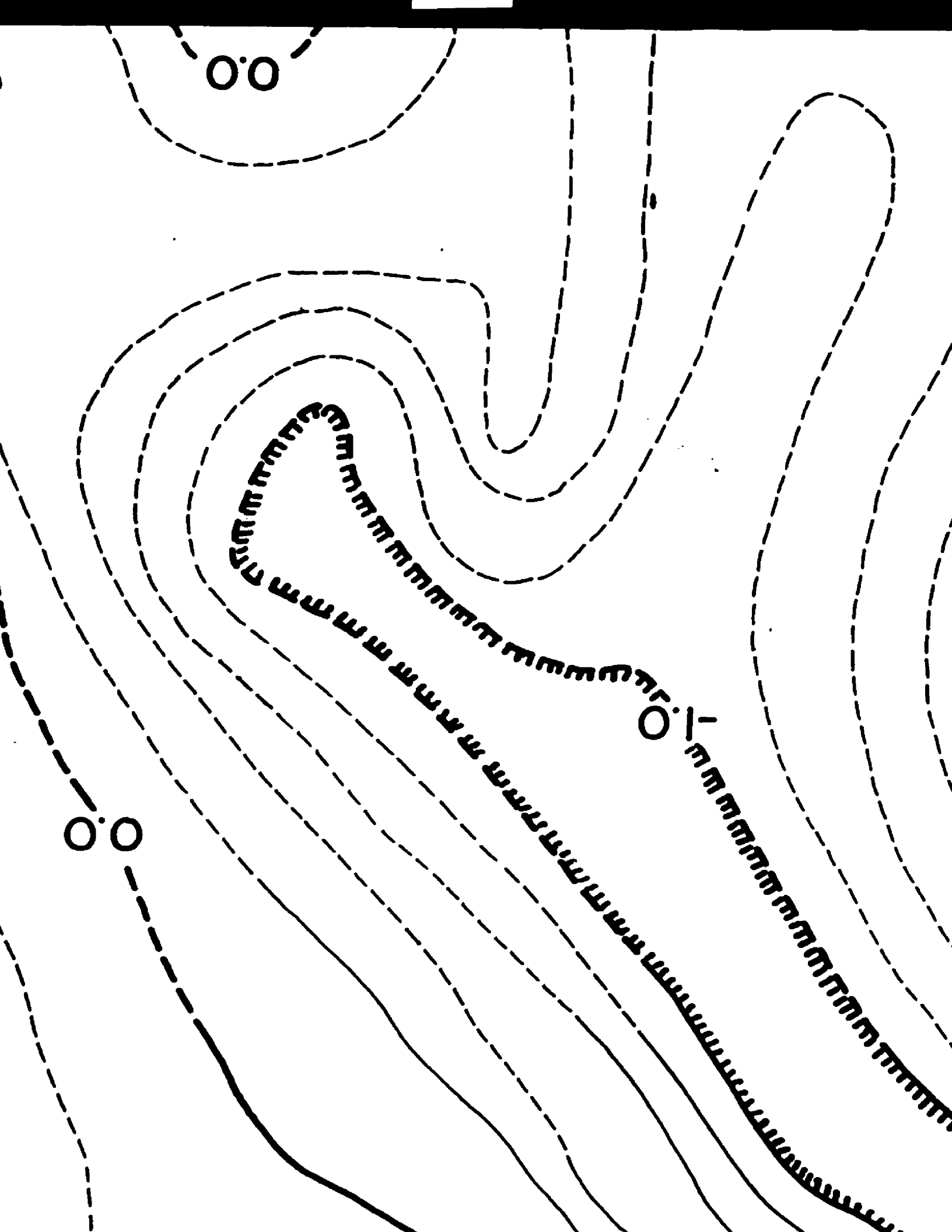


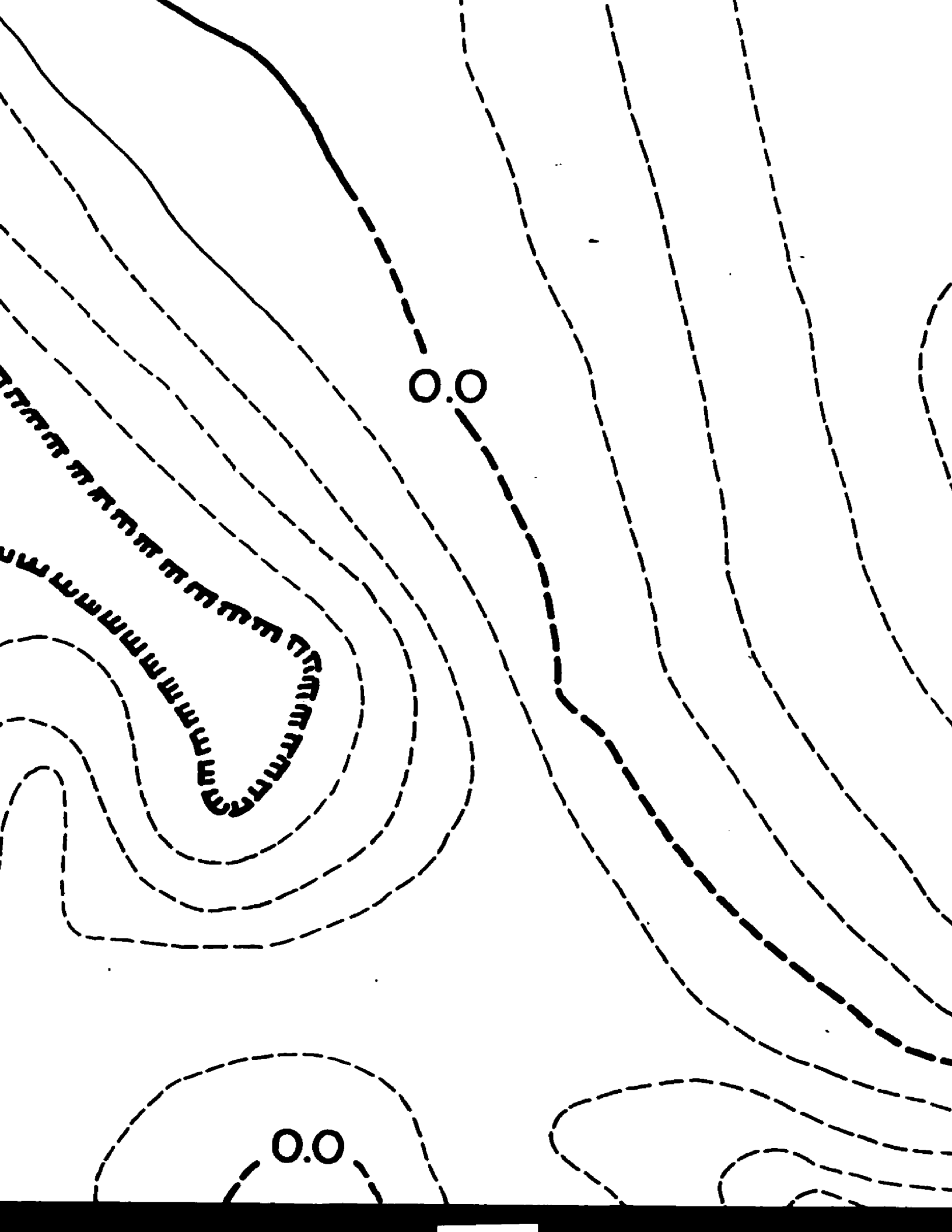
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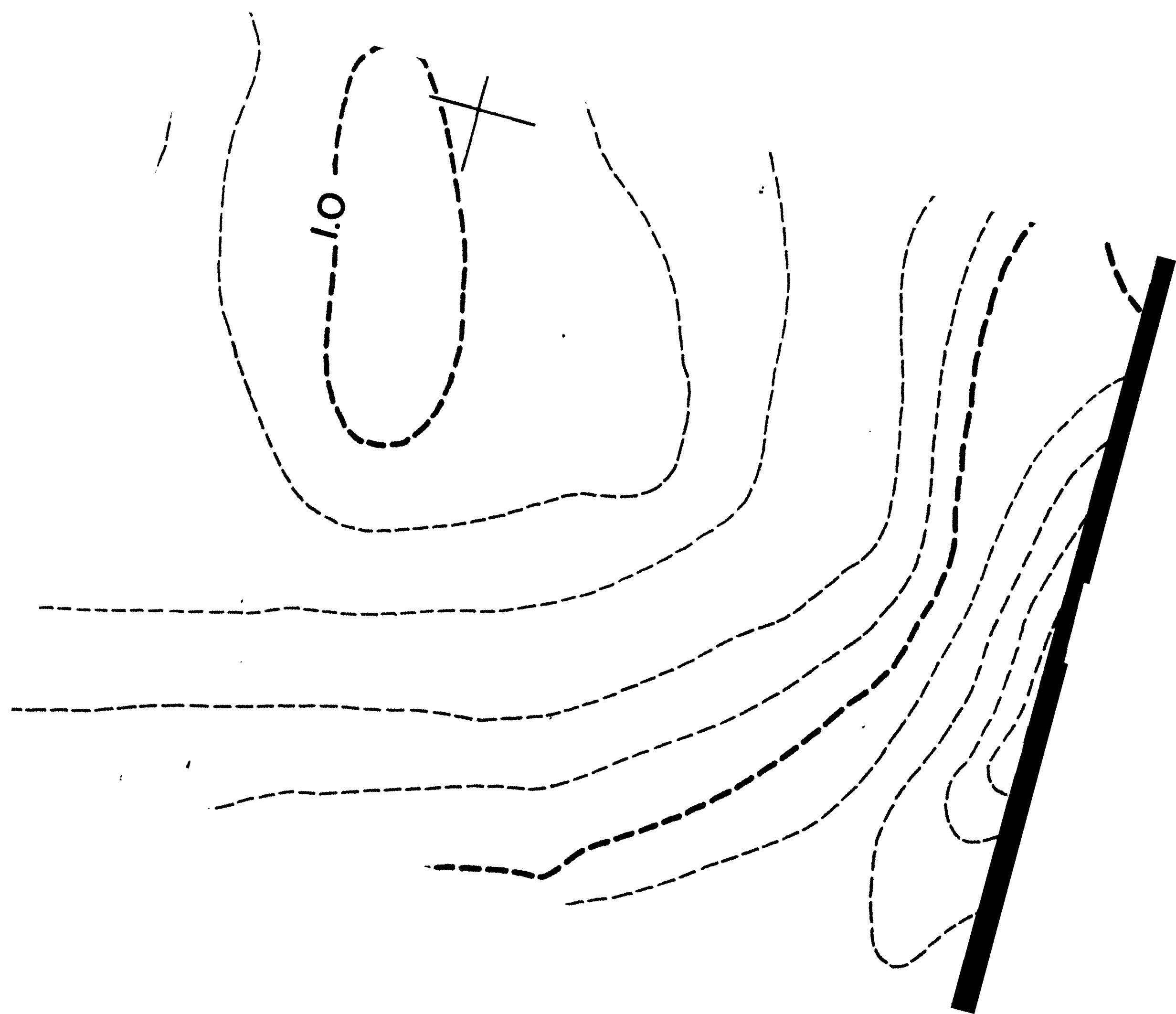


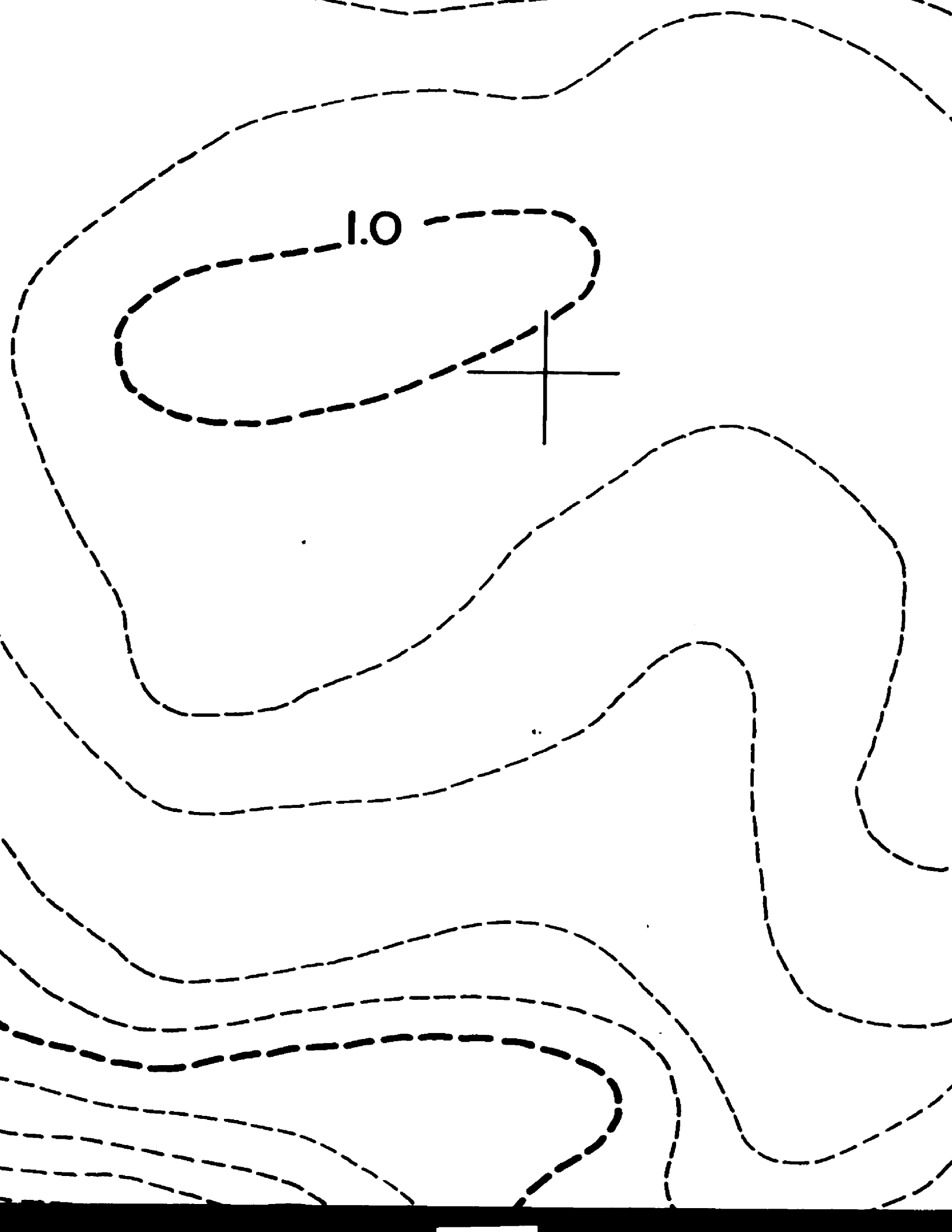


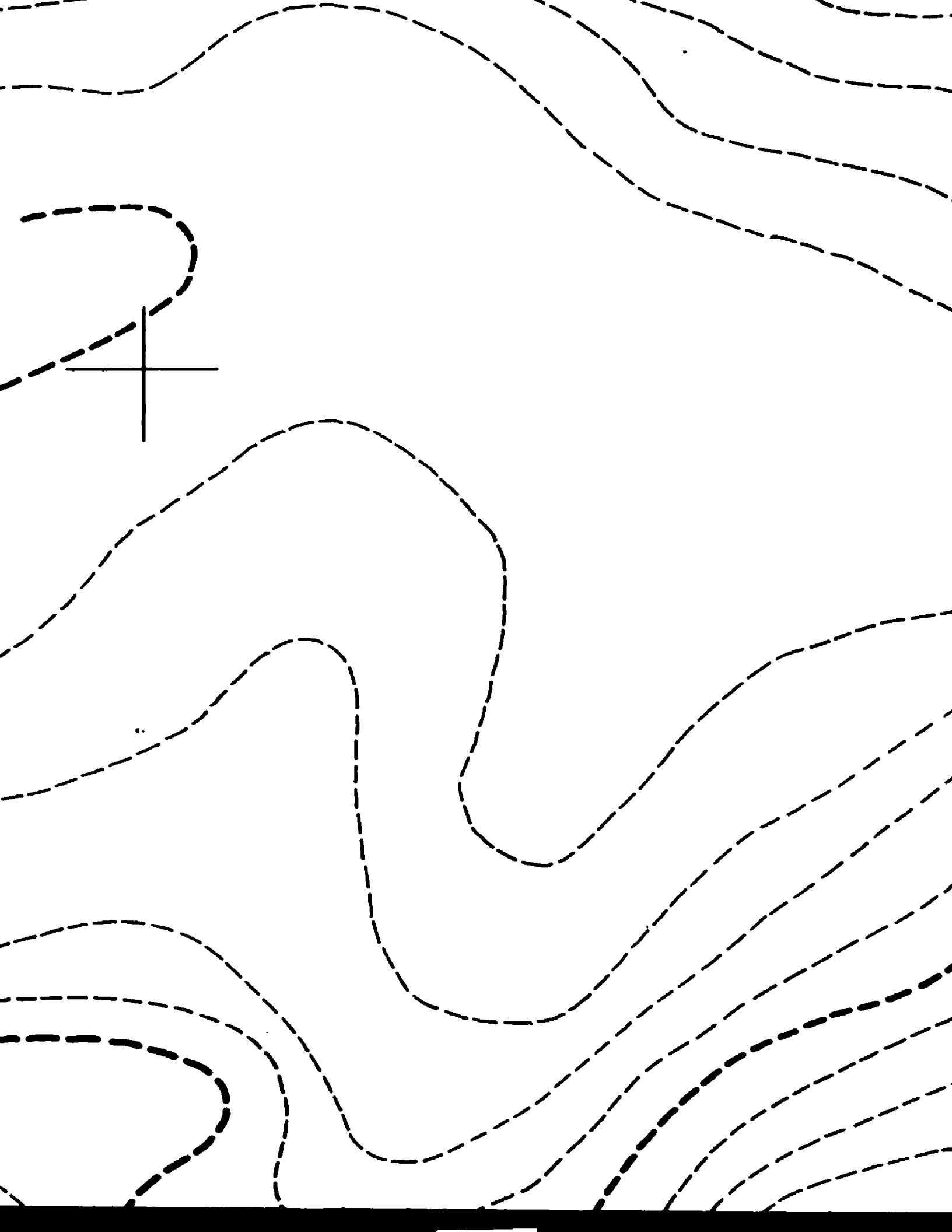


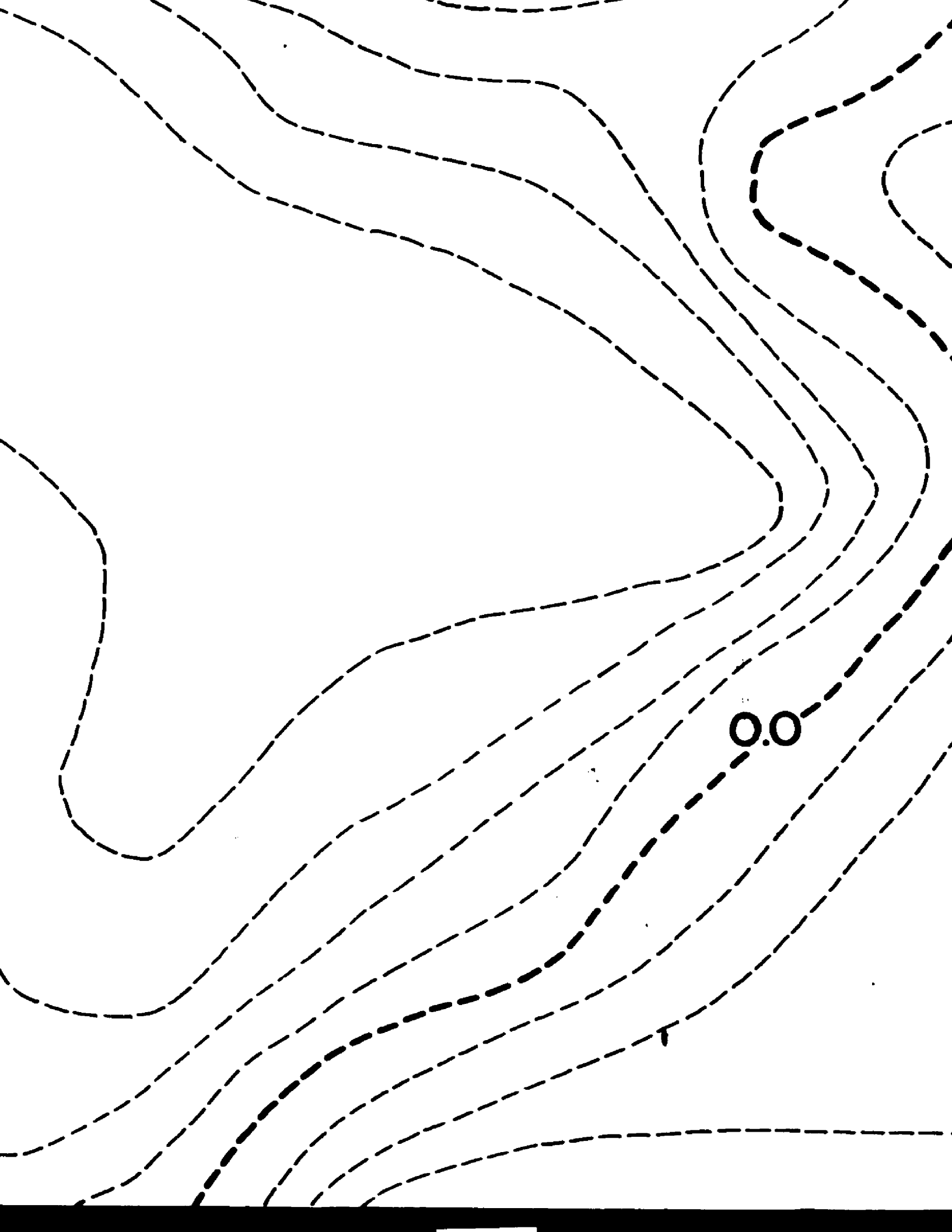


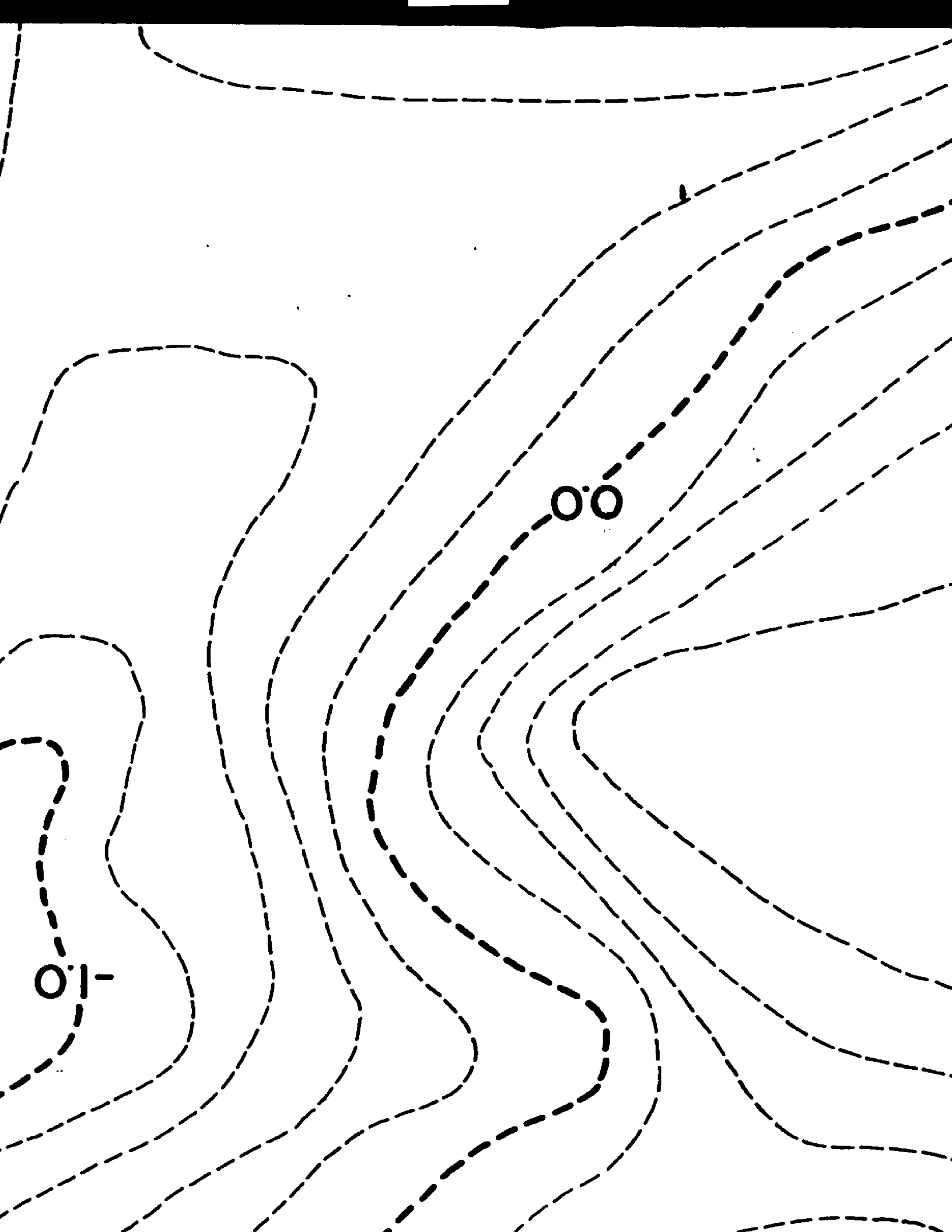


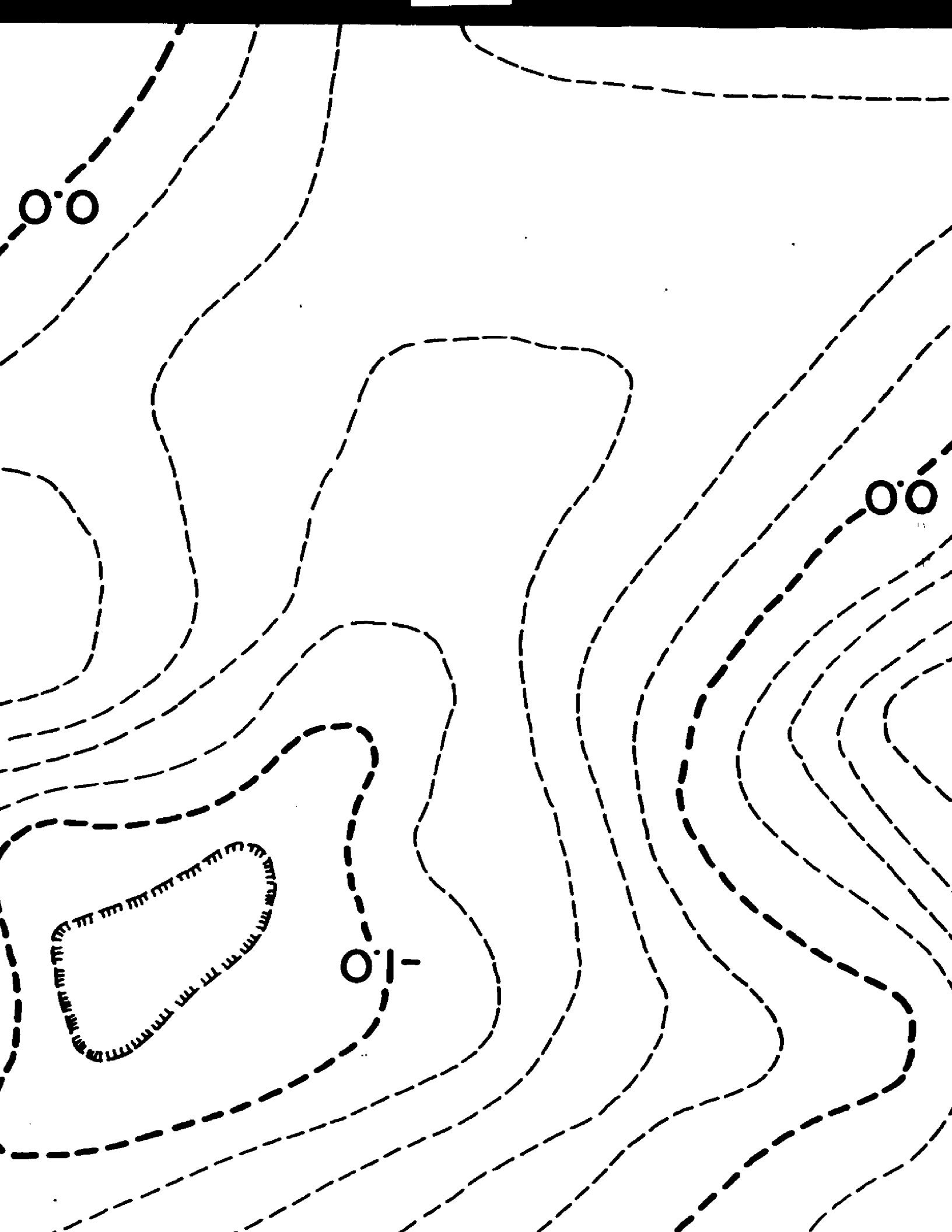


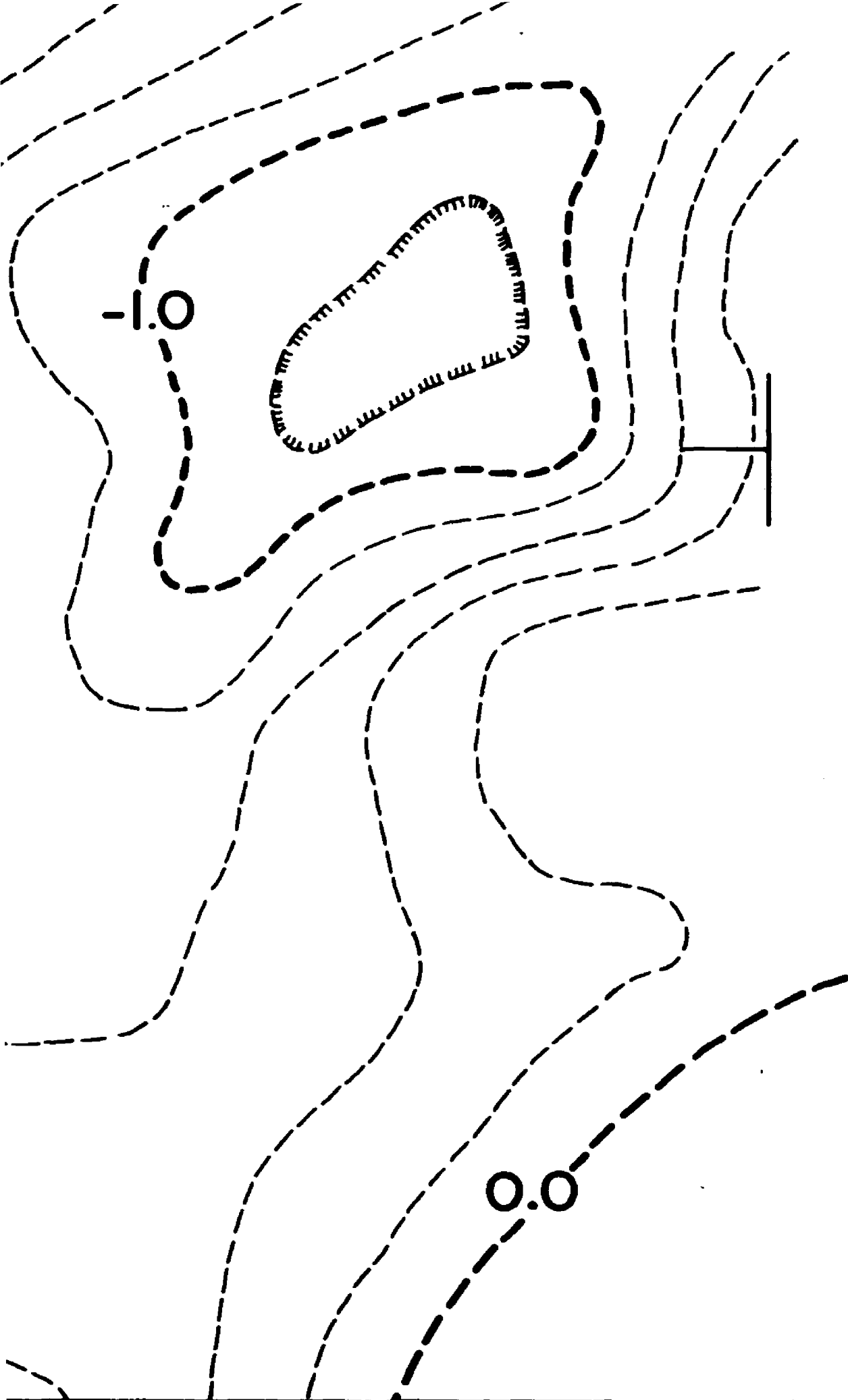












10'

T4S

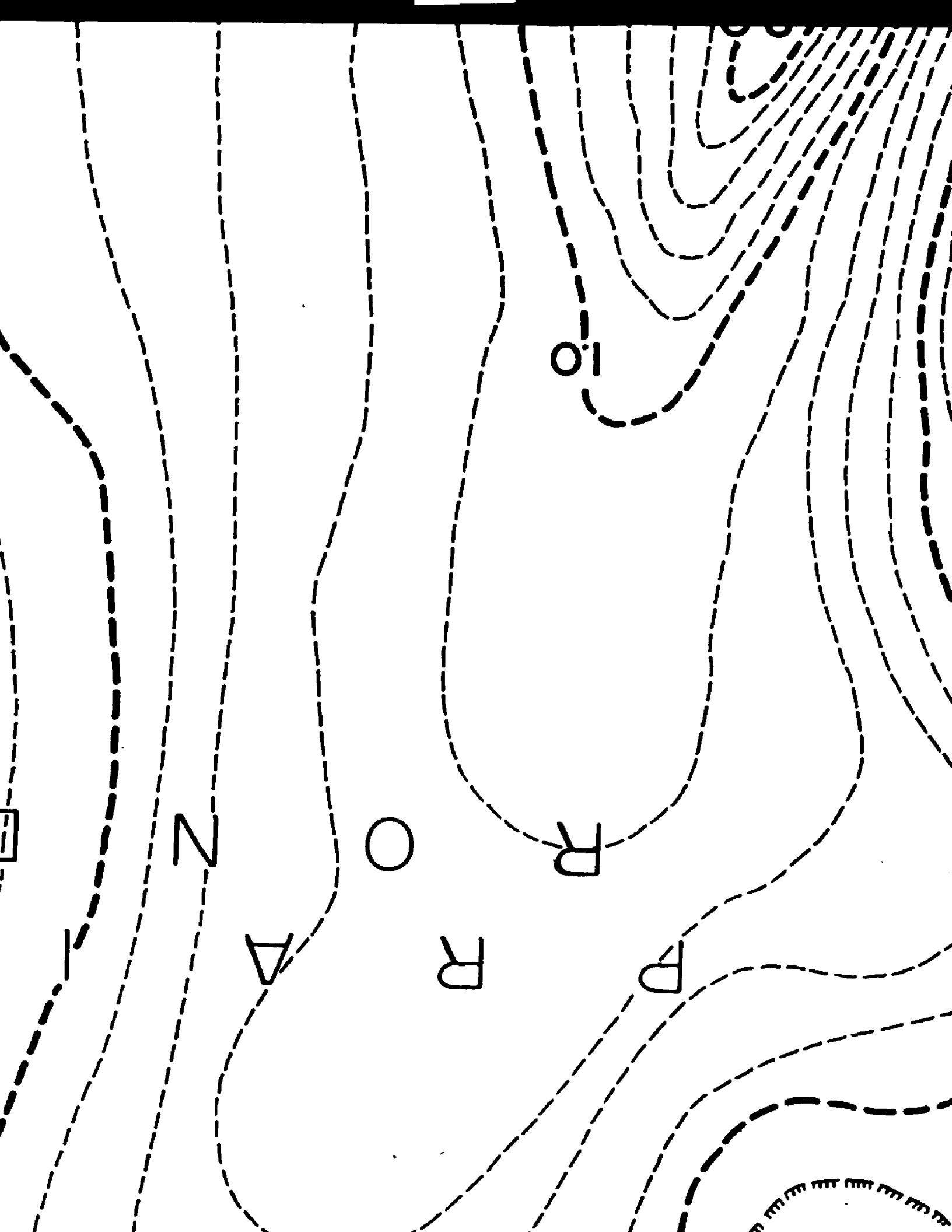
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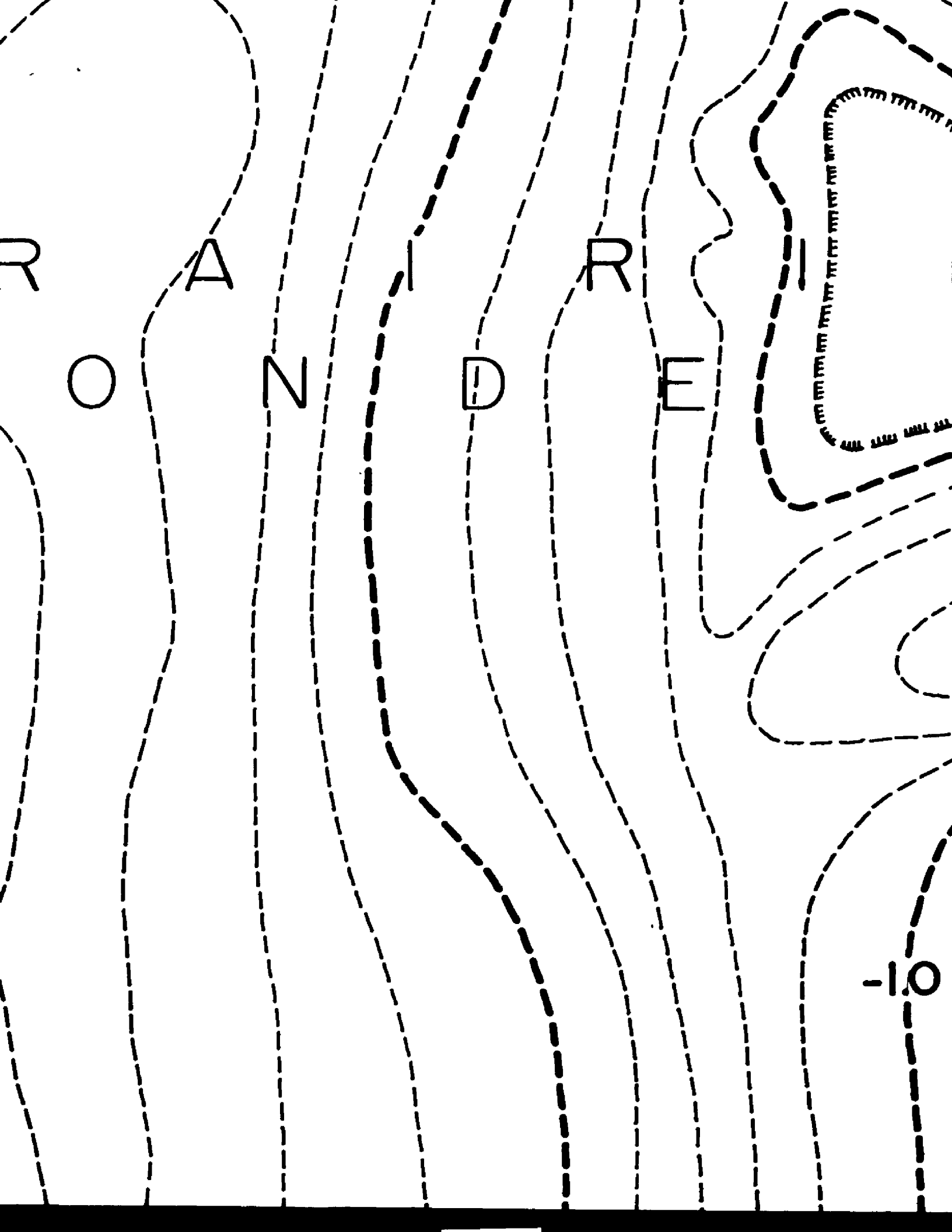
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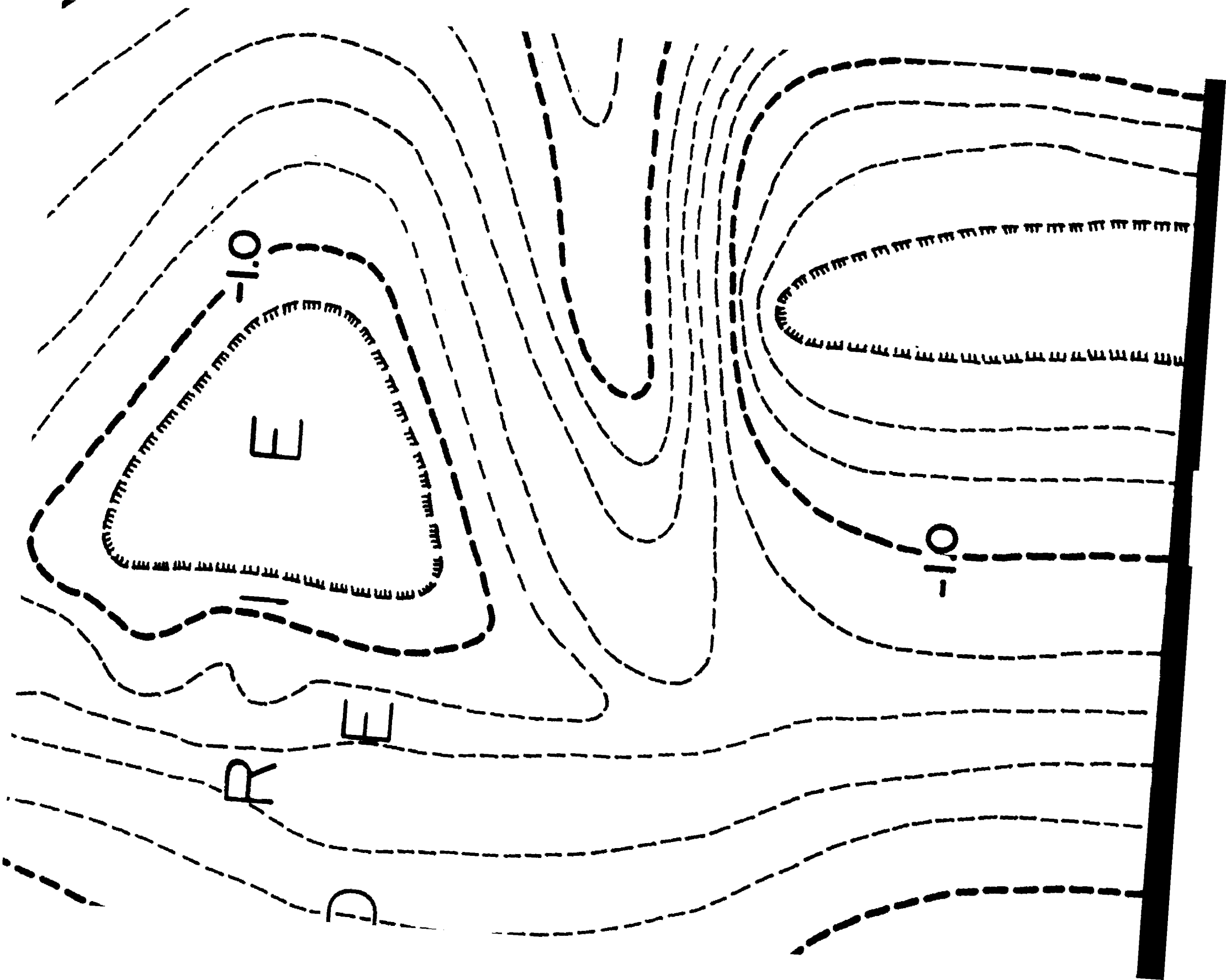
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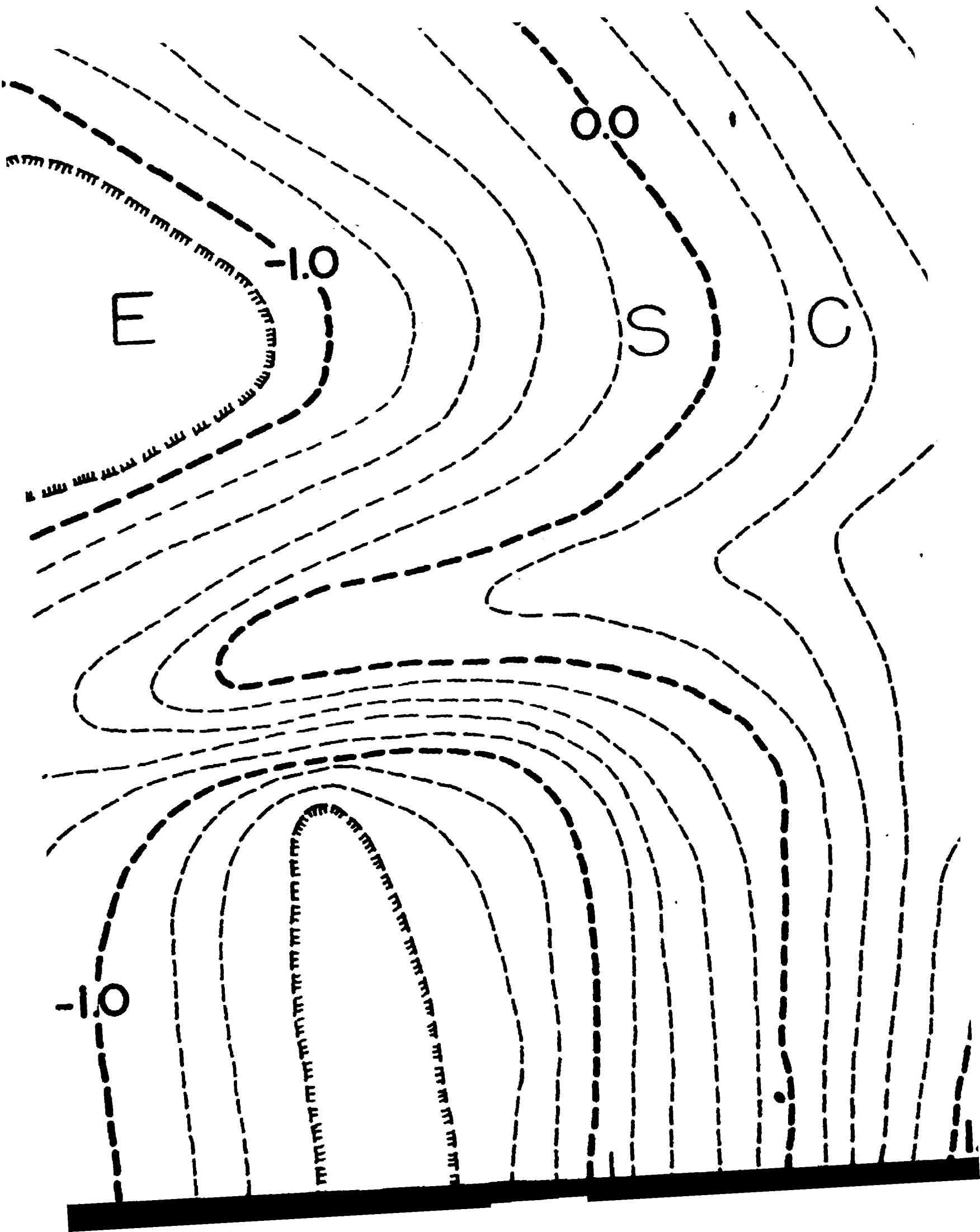
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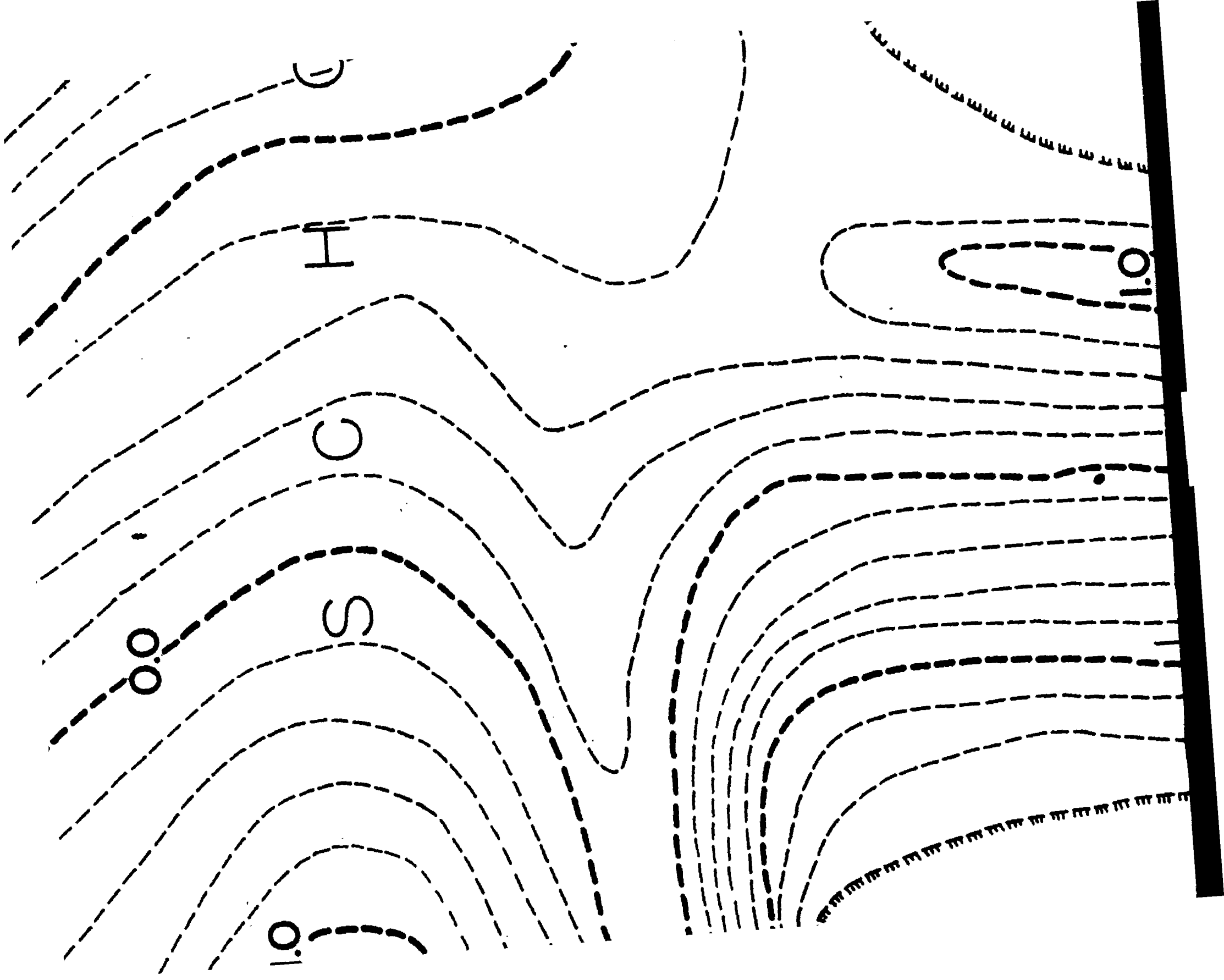
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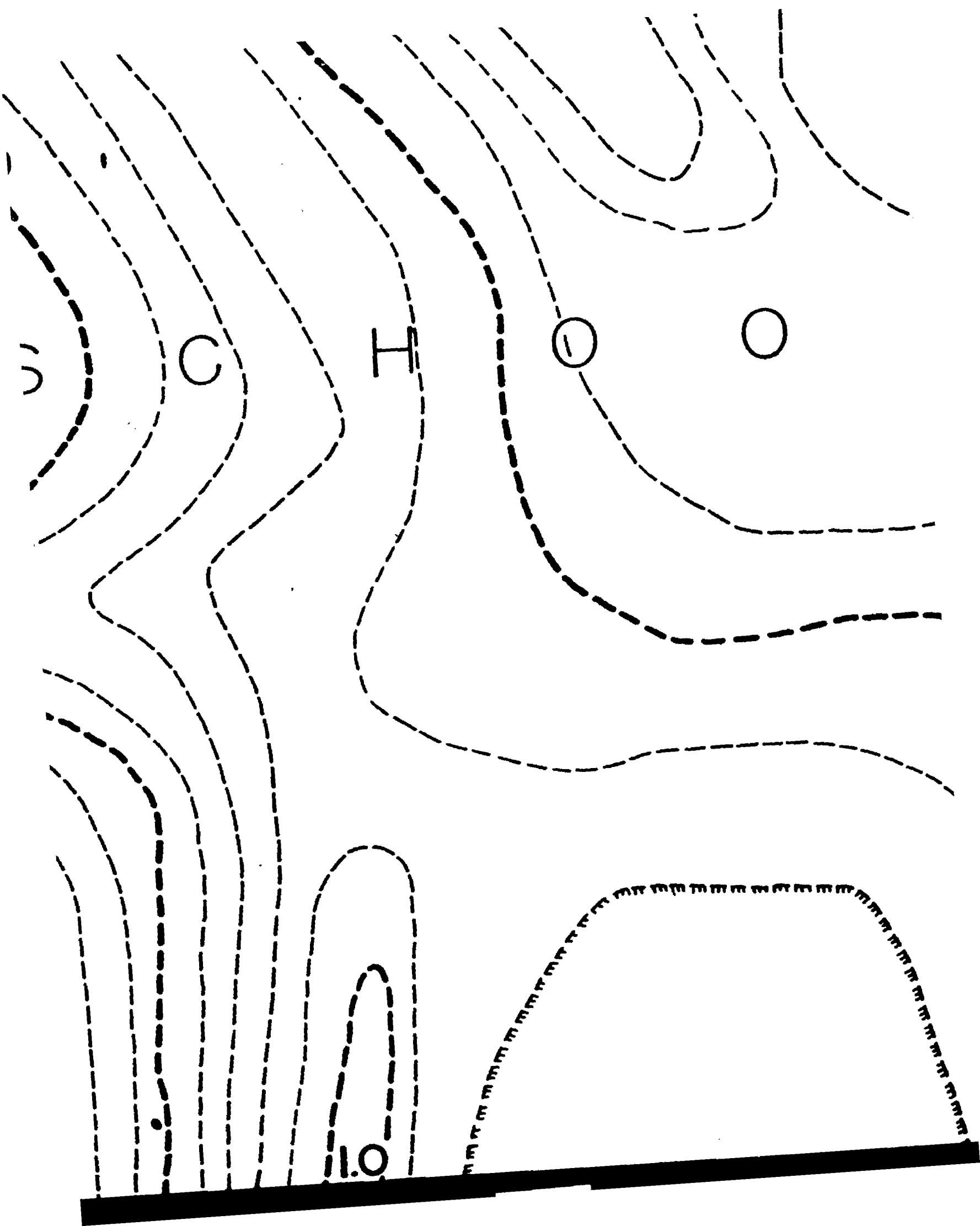
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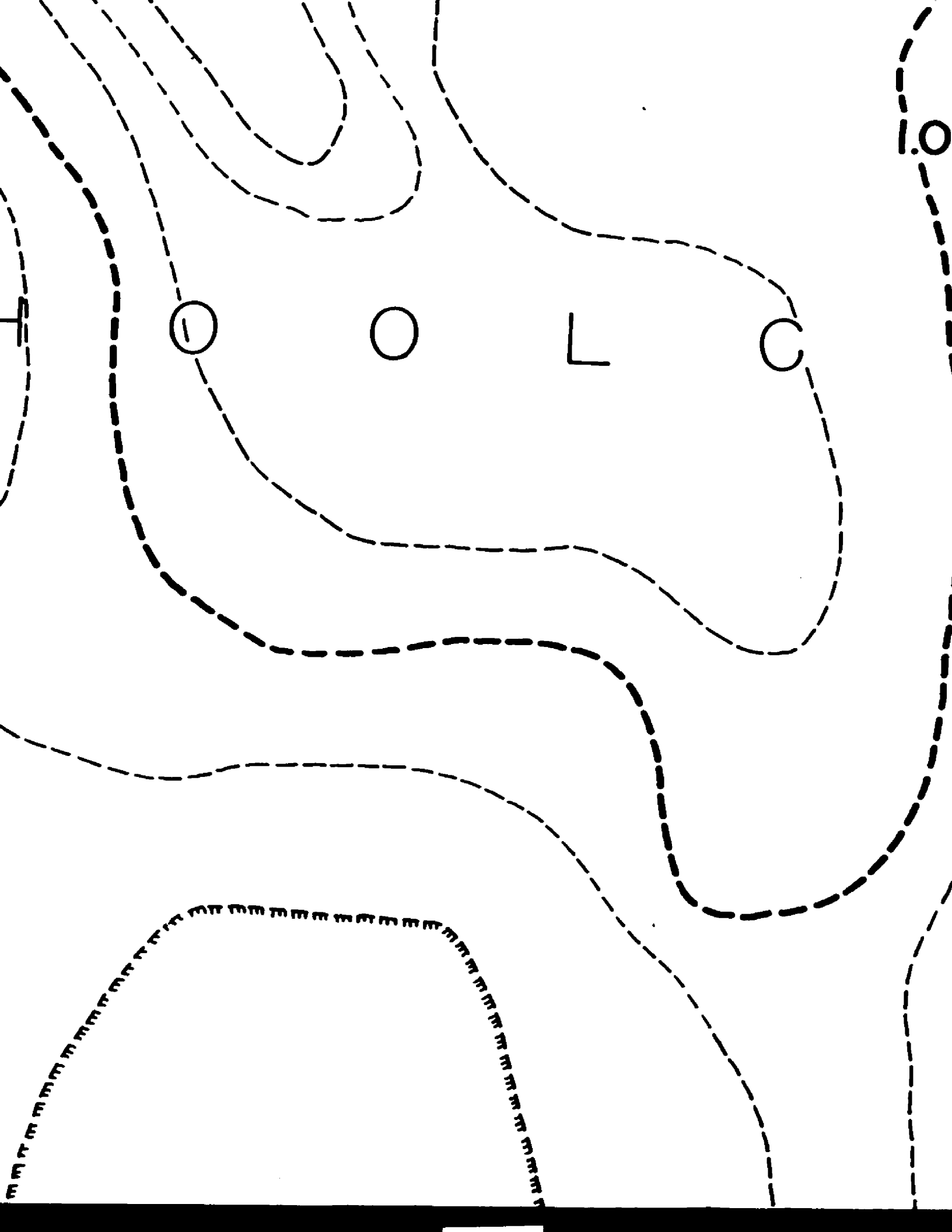
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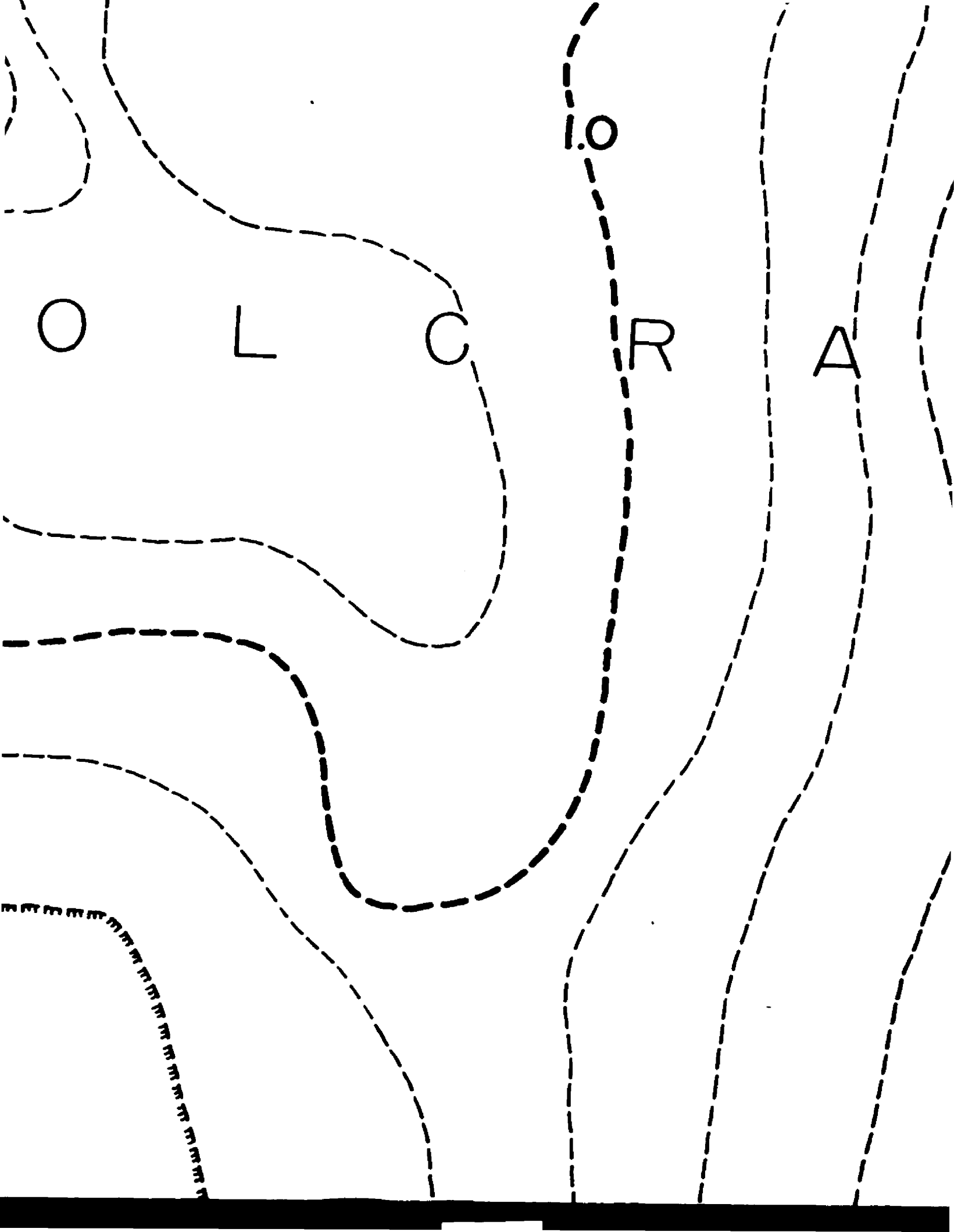


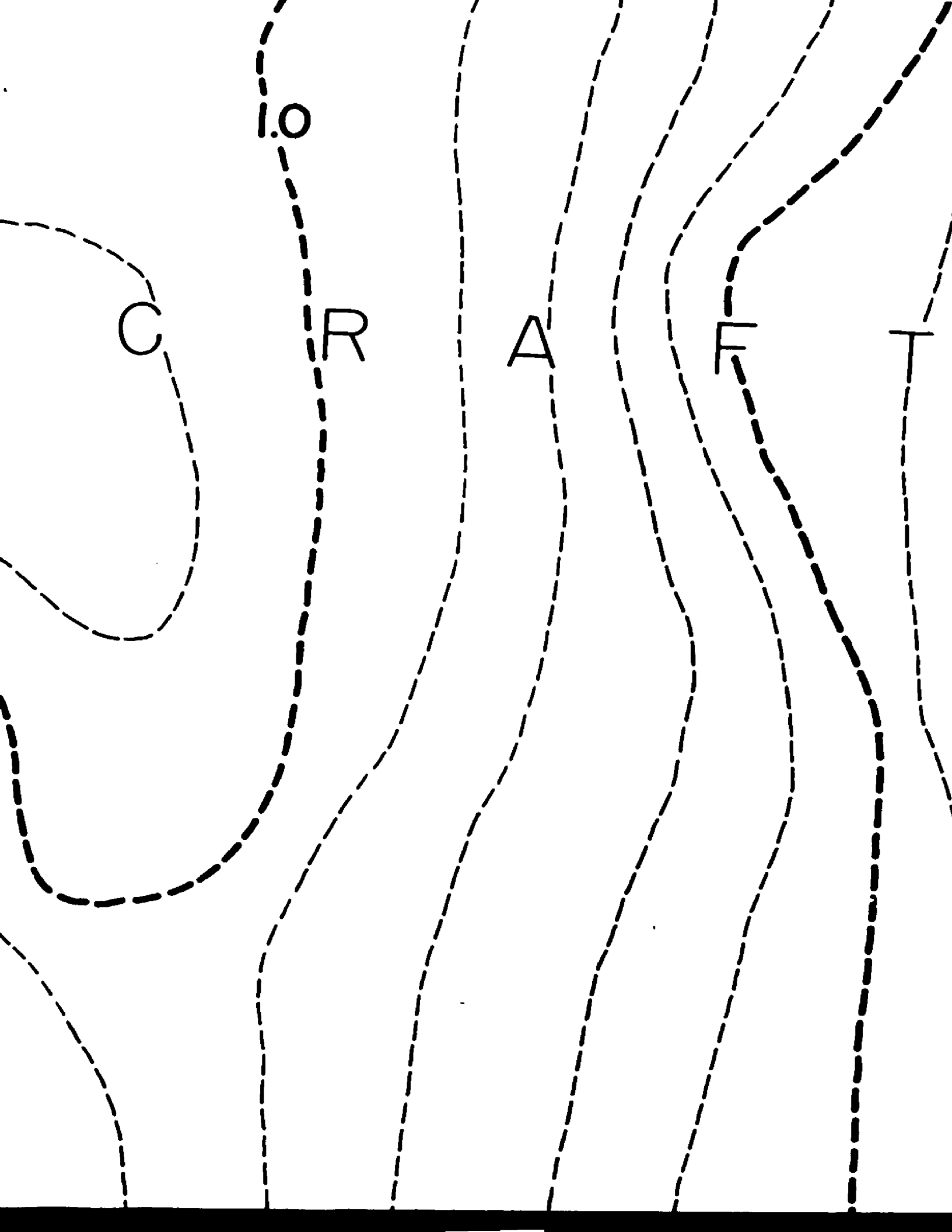












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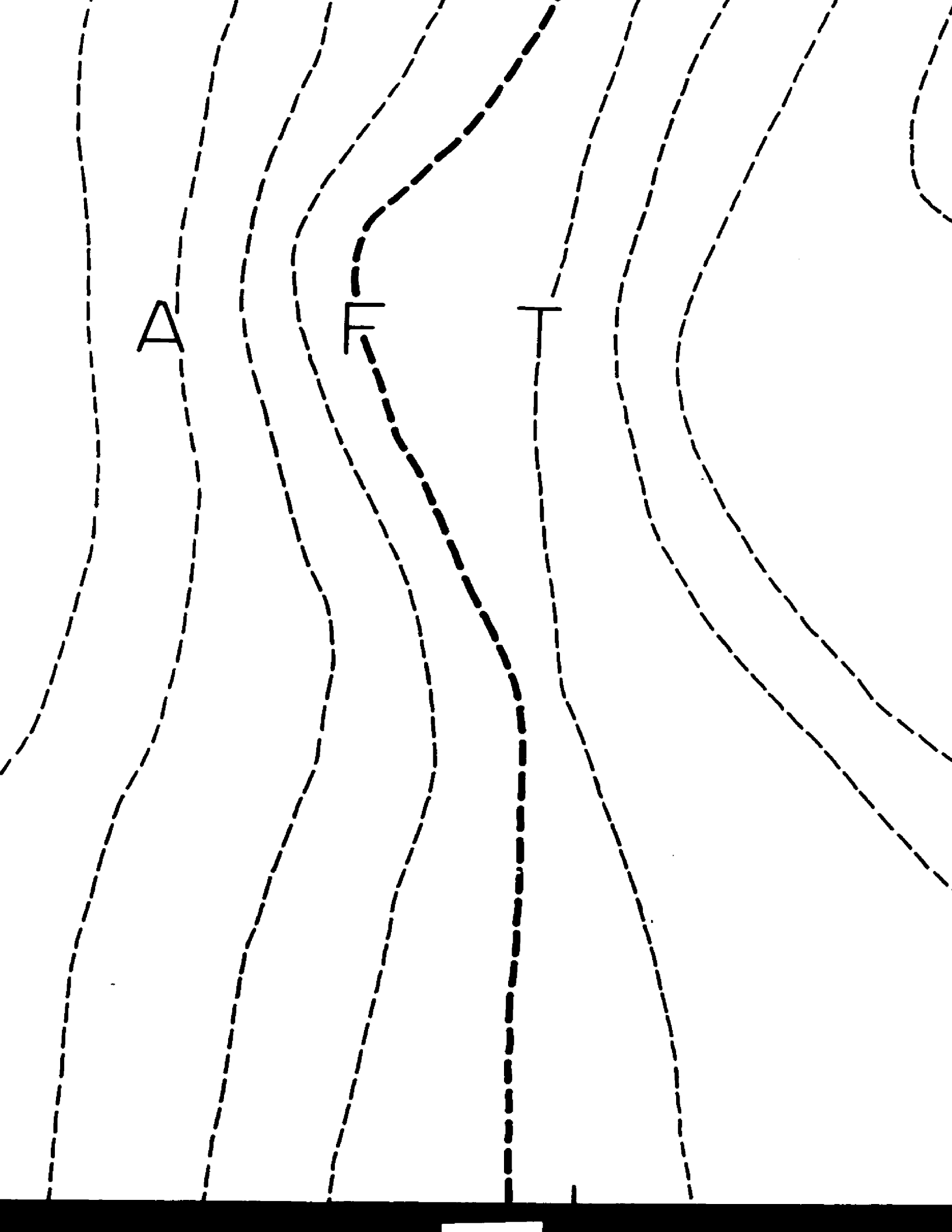
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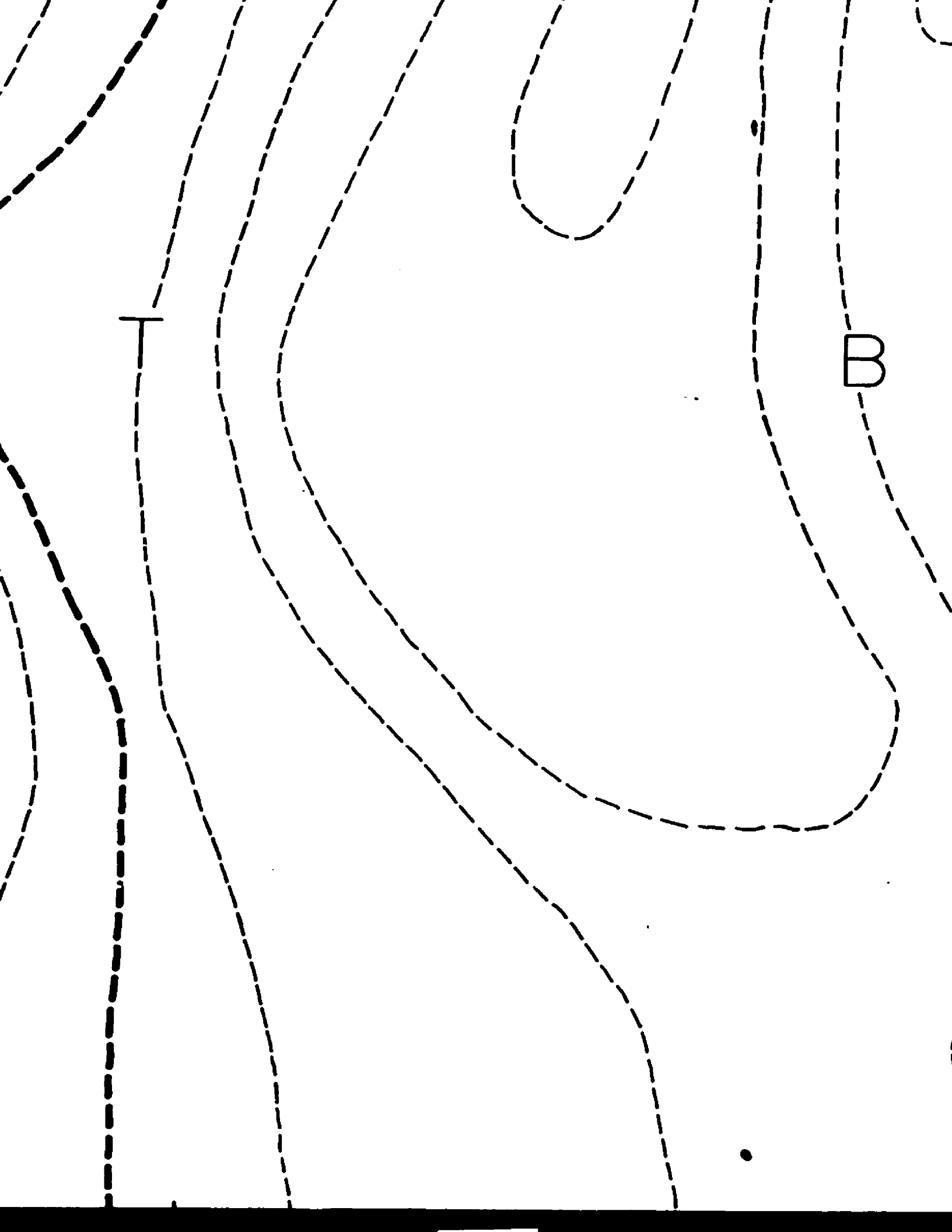
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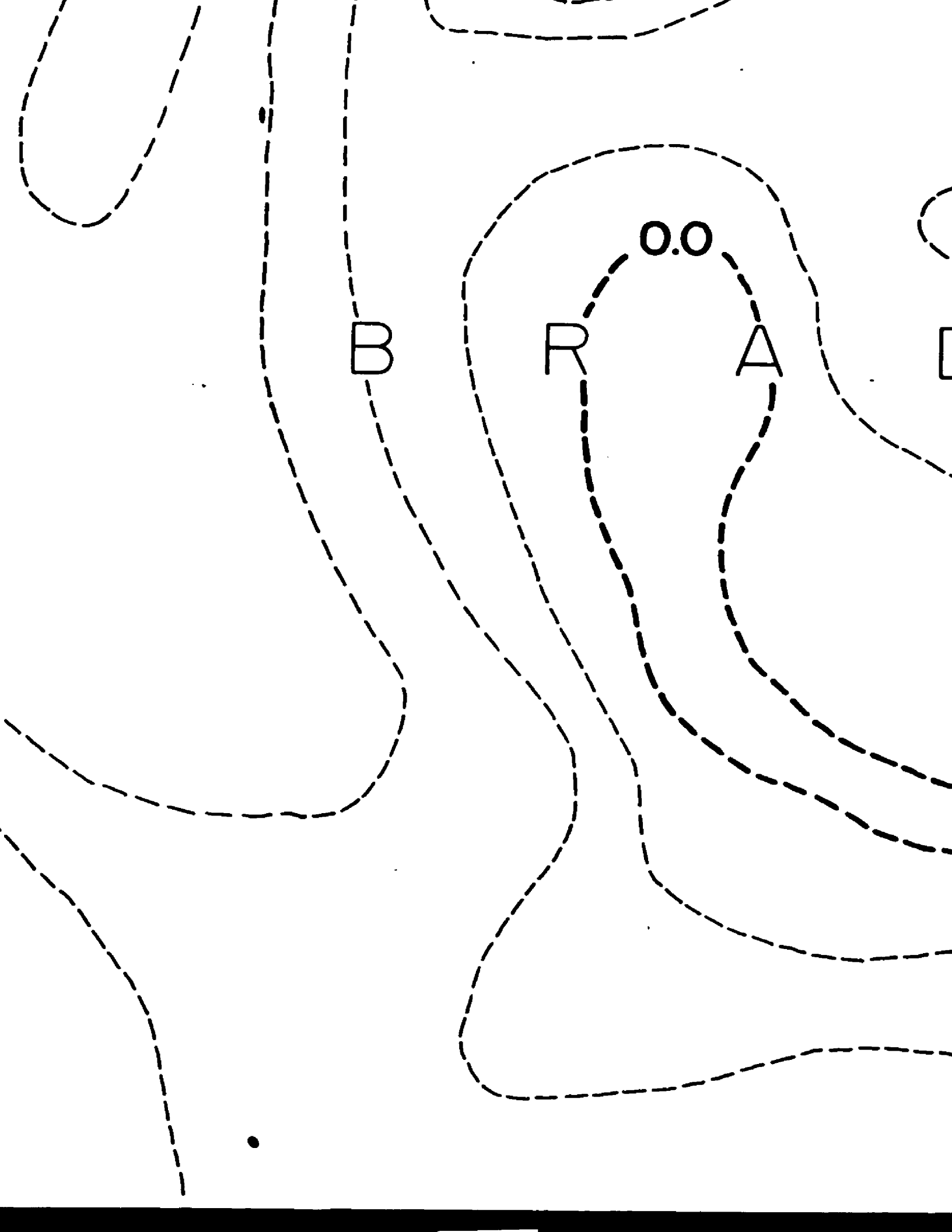


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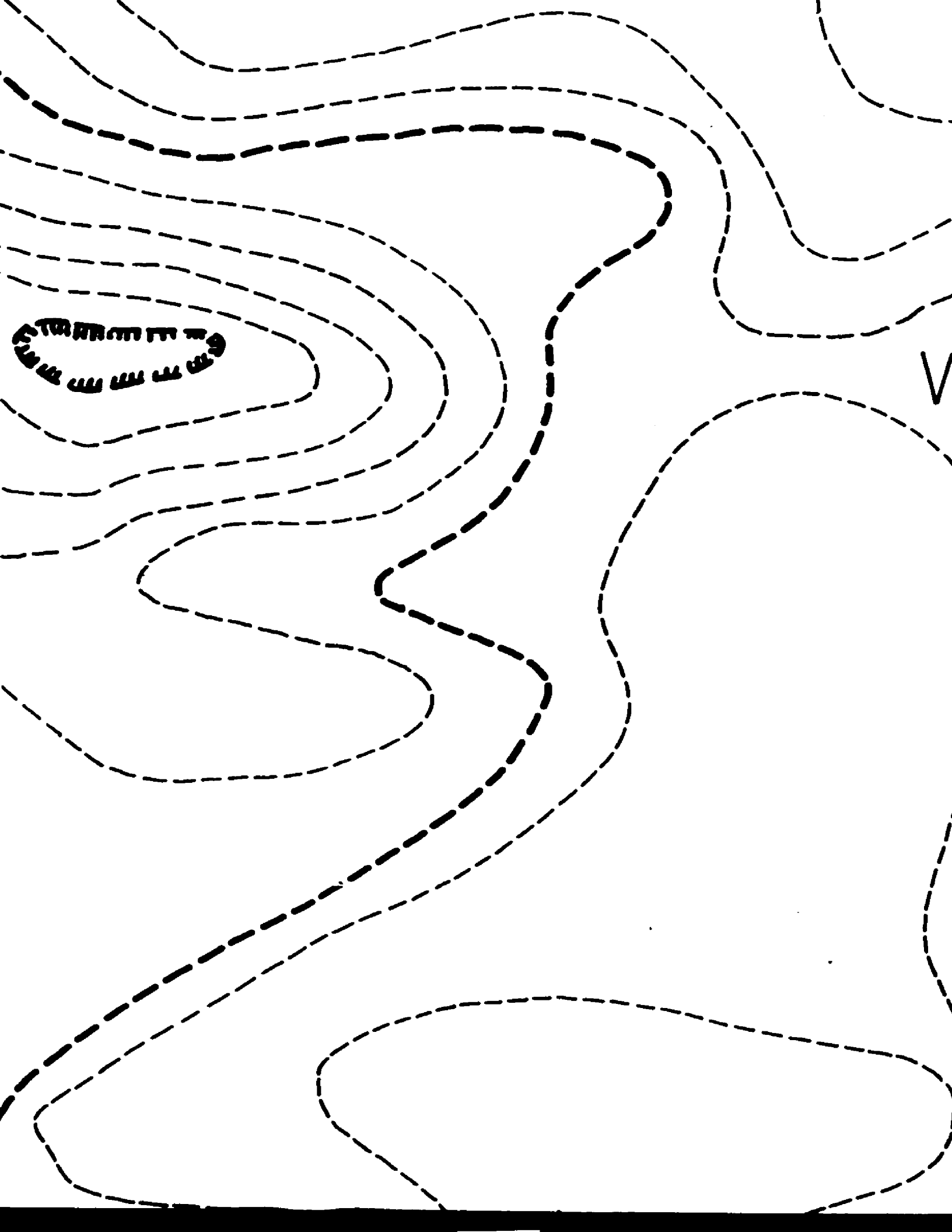
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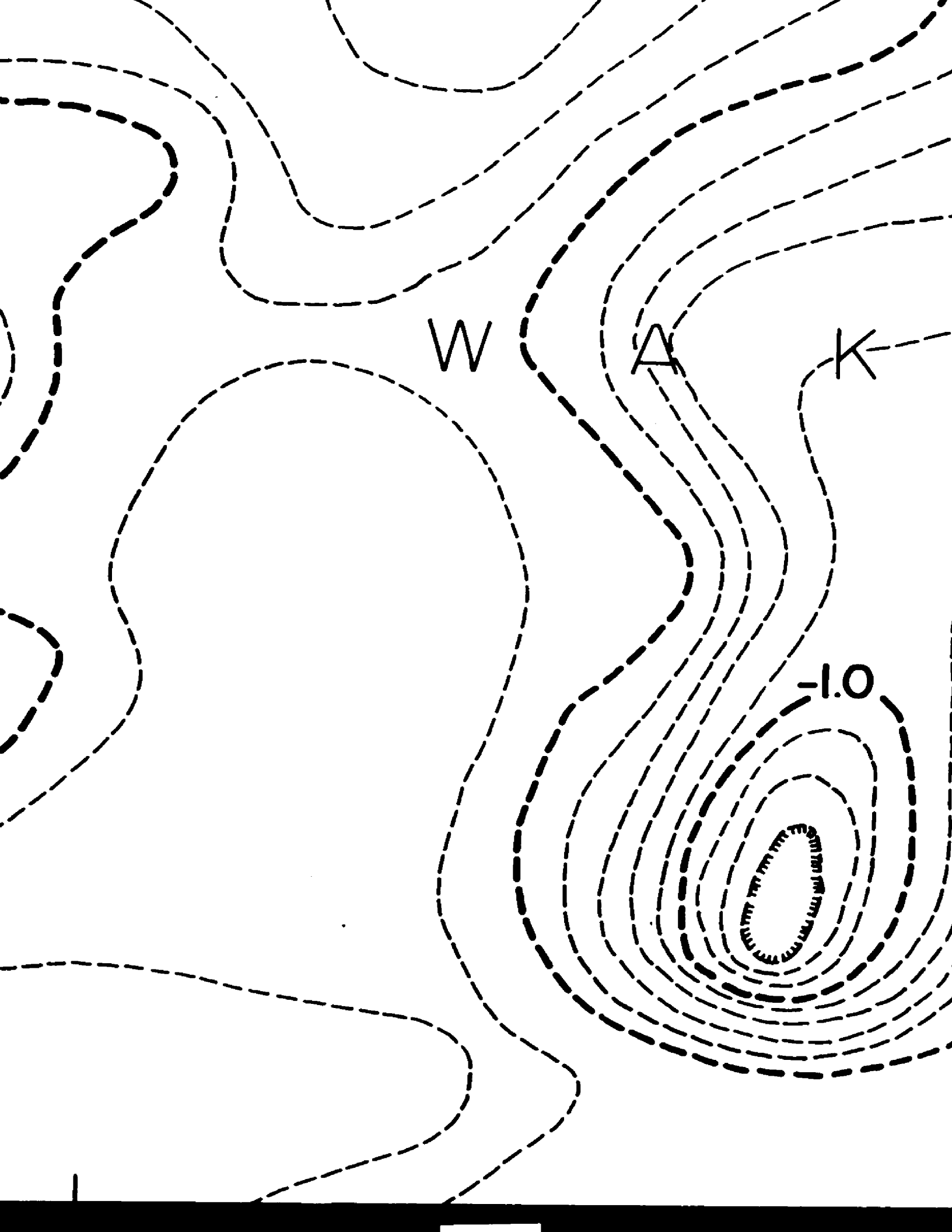


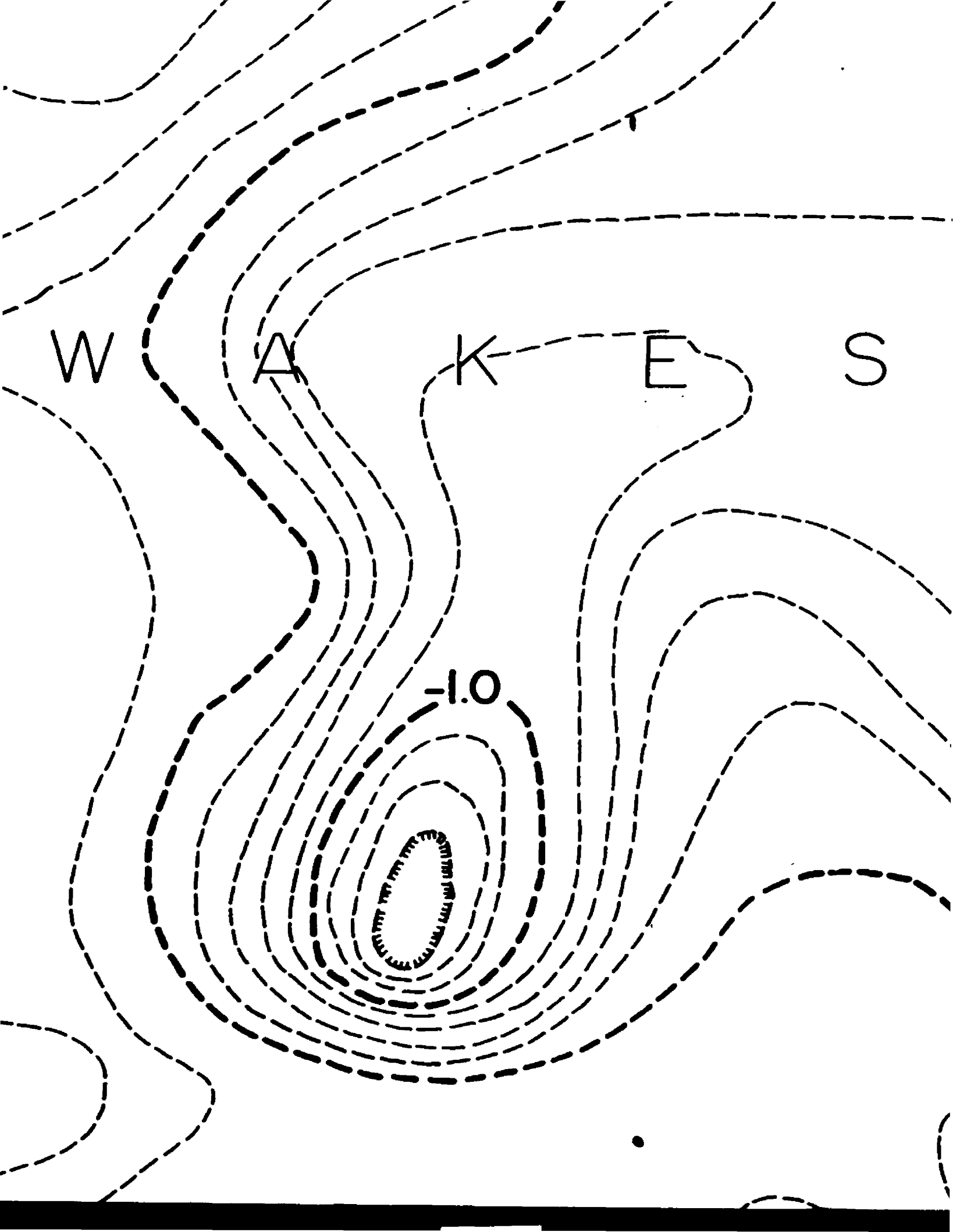


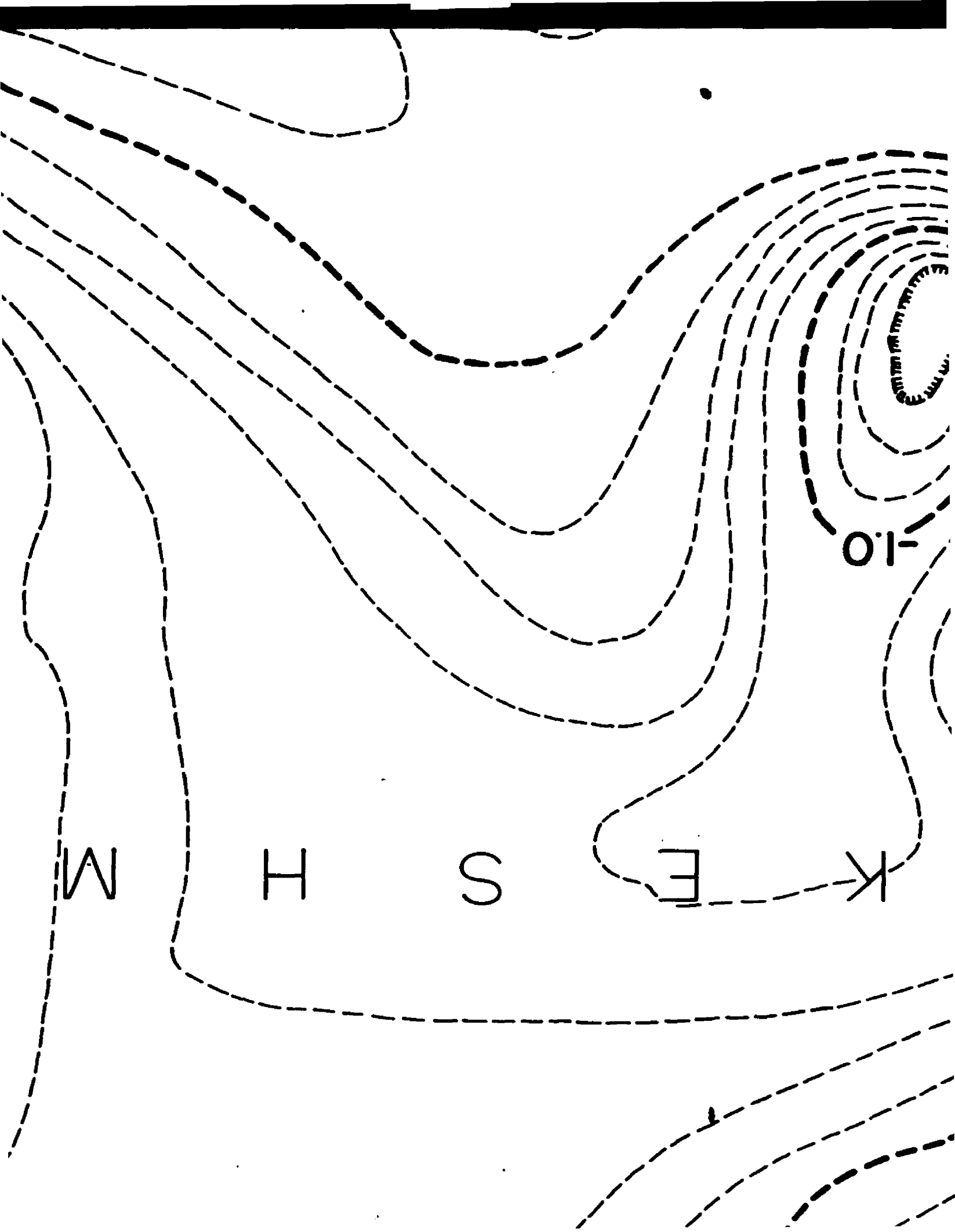


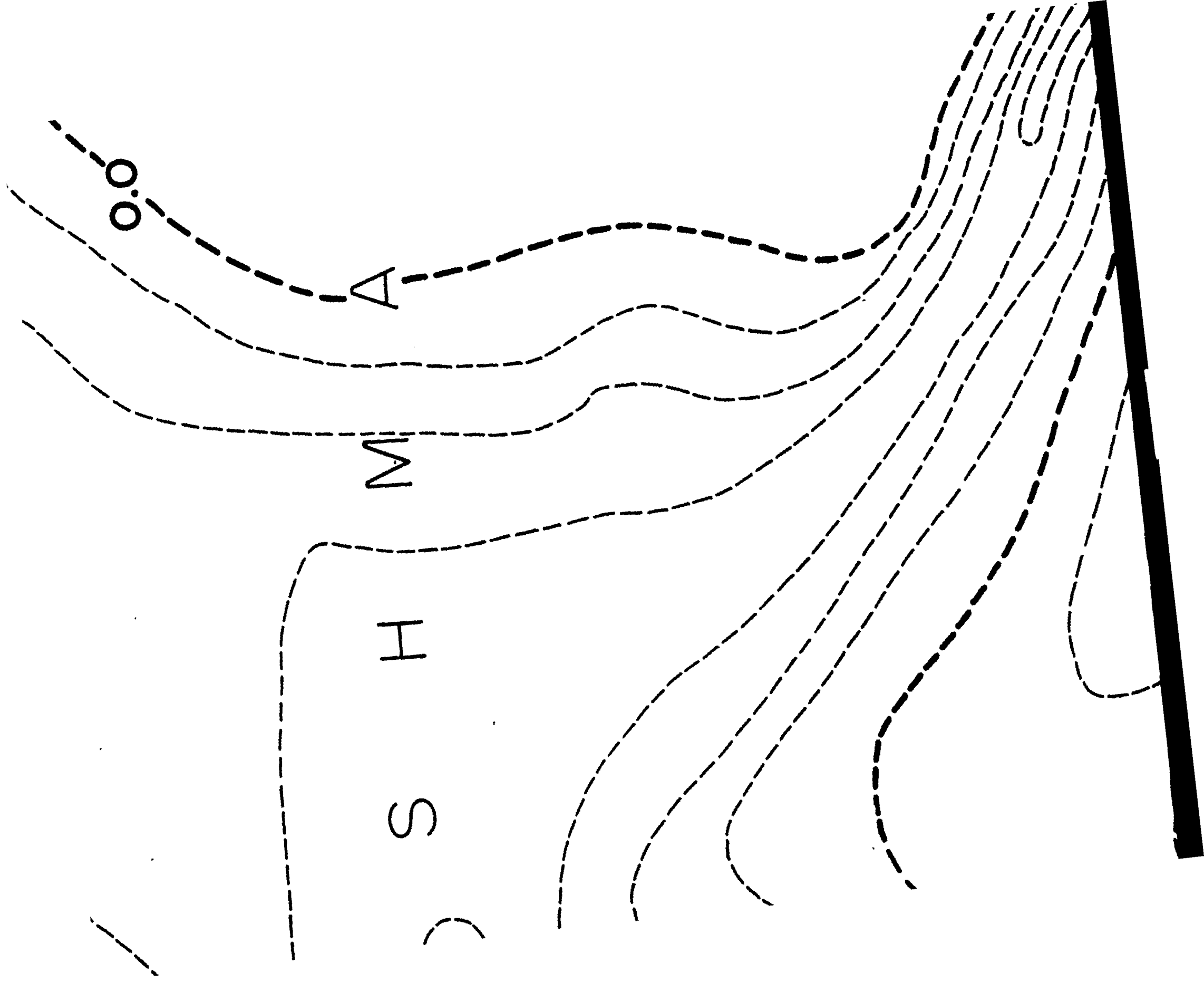


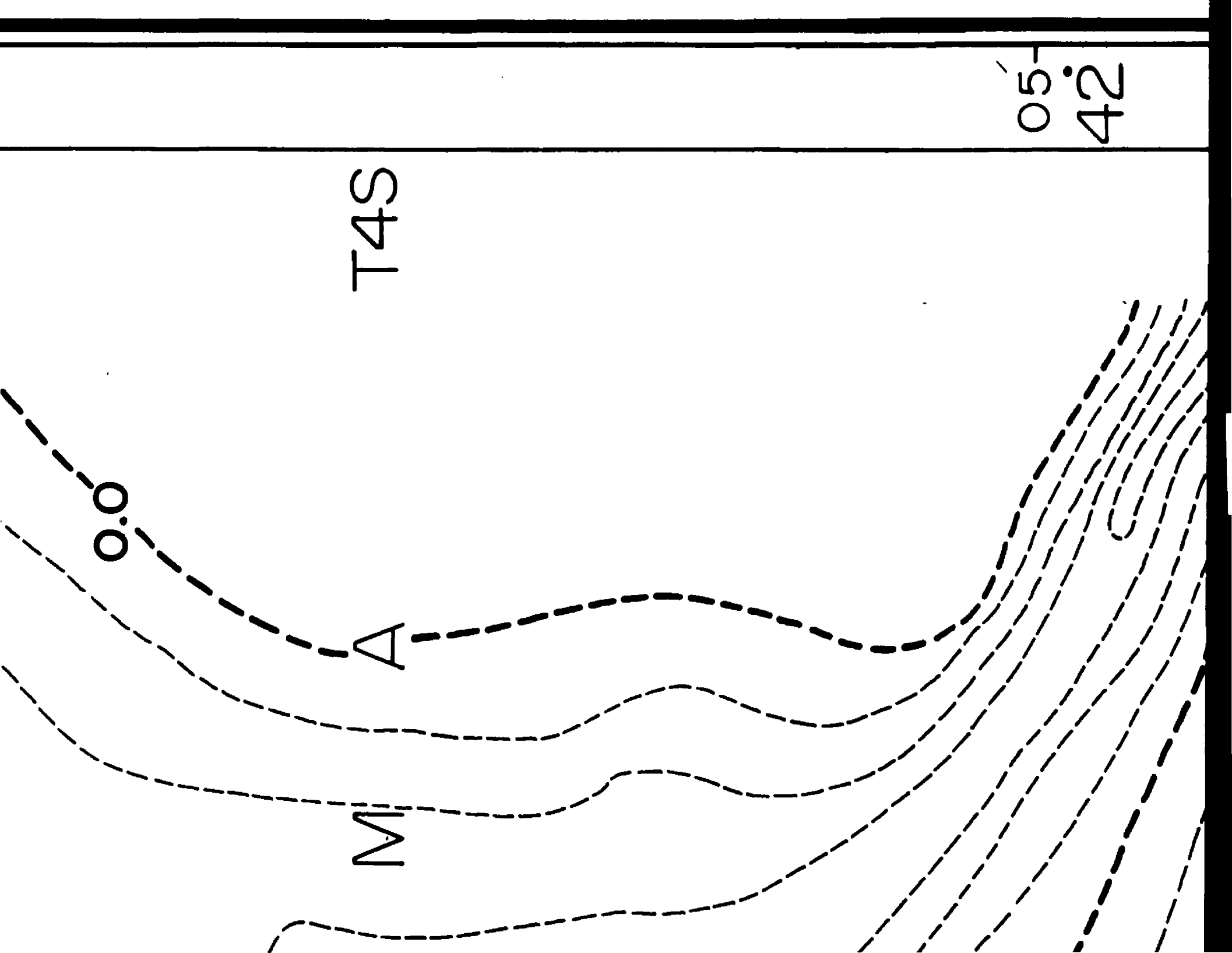












T4S

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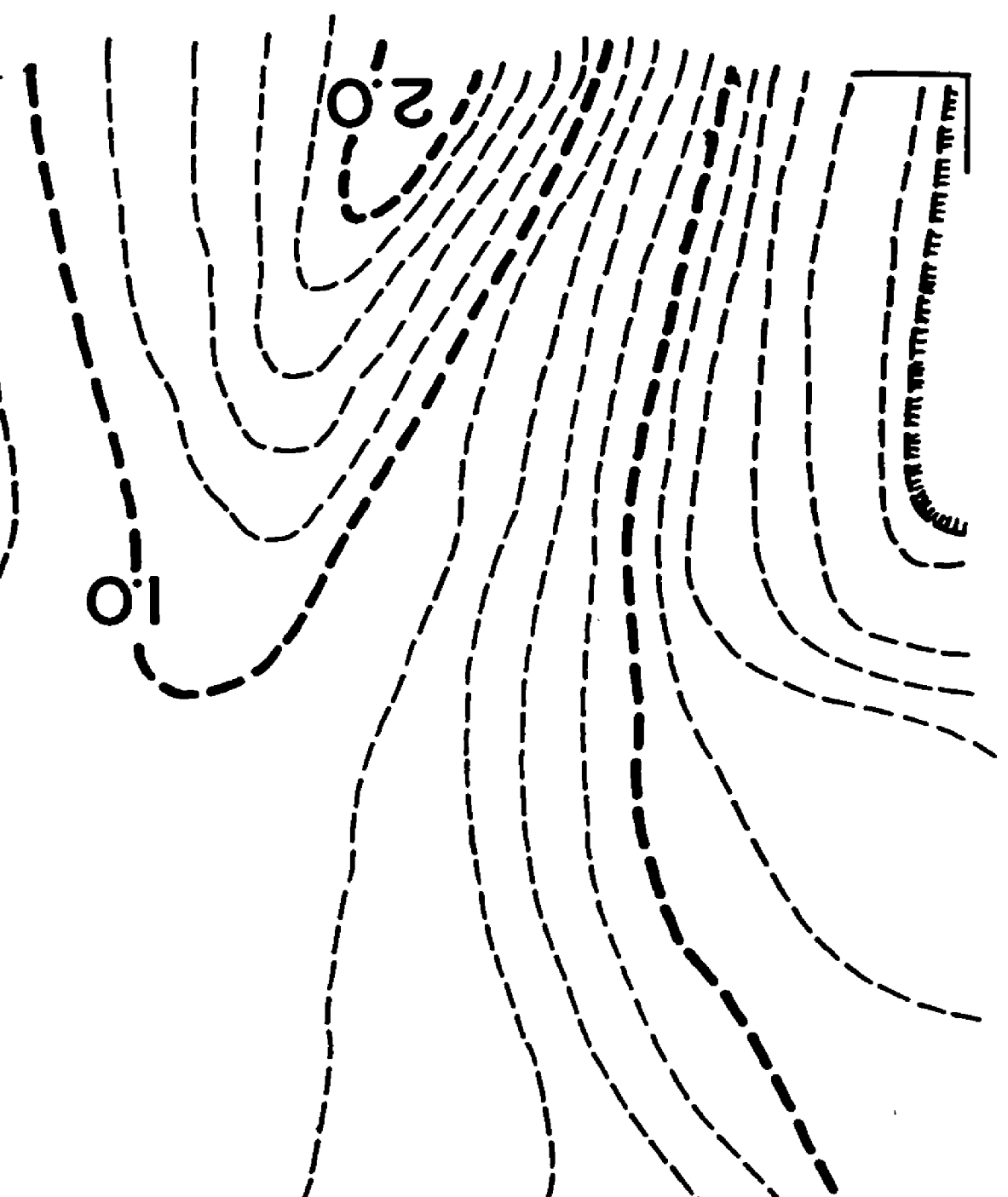
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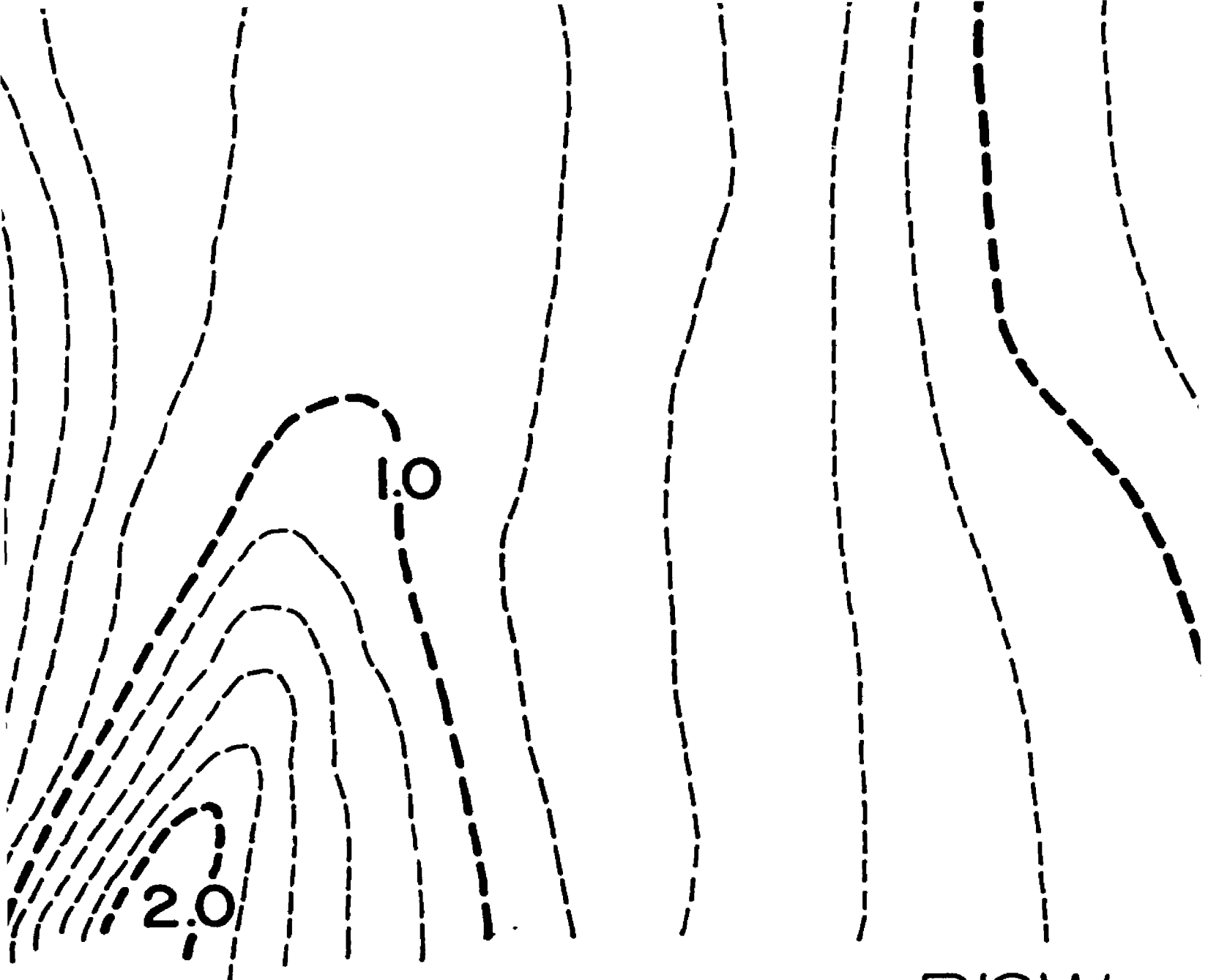
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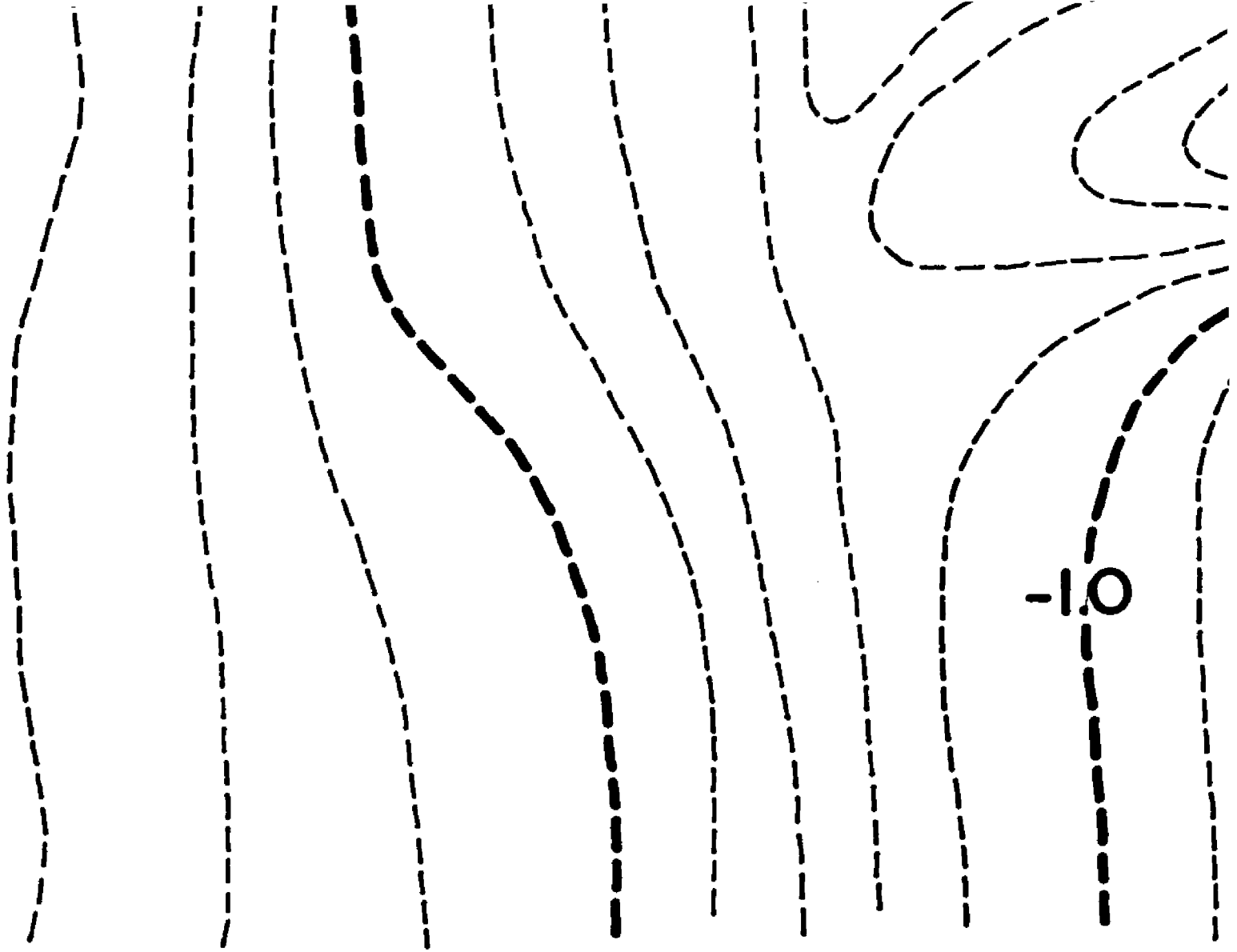




R12W

PLATE

8a



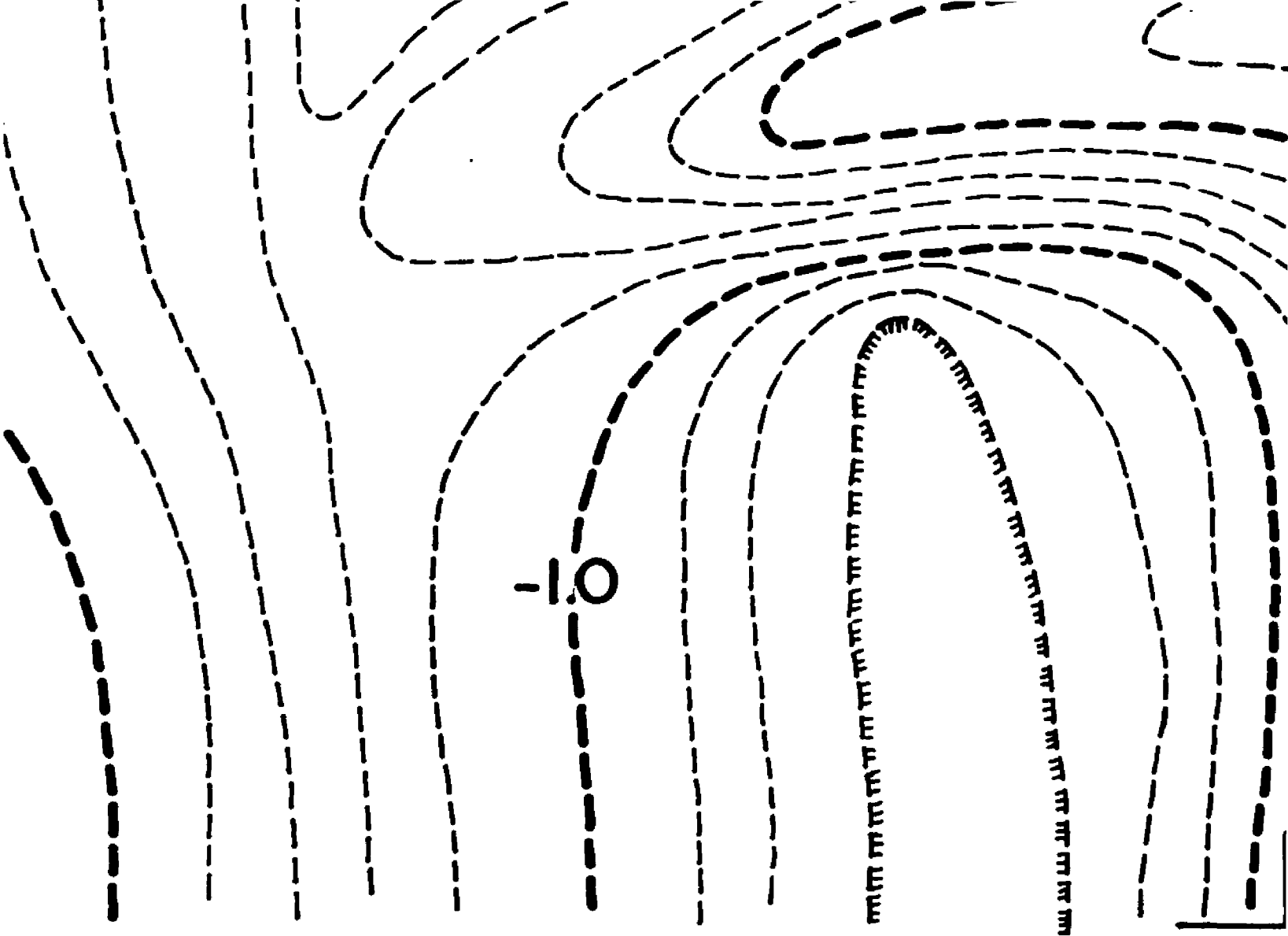
R12W

PLATE

8a

MAP OF THE

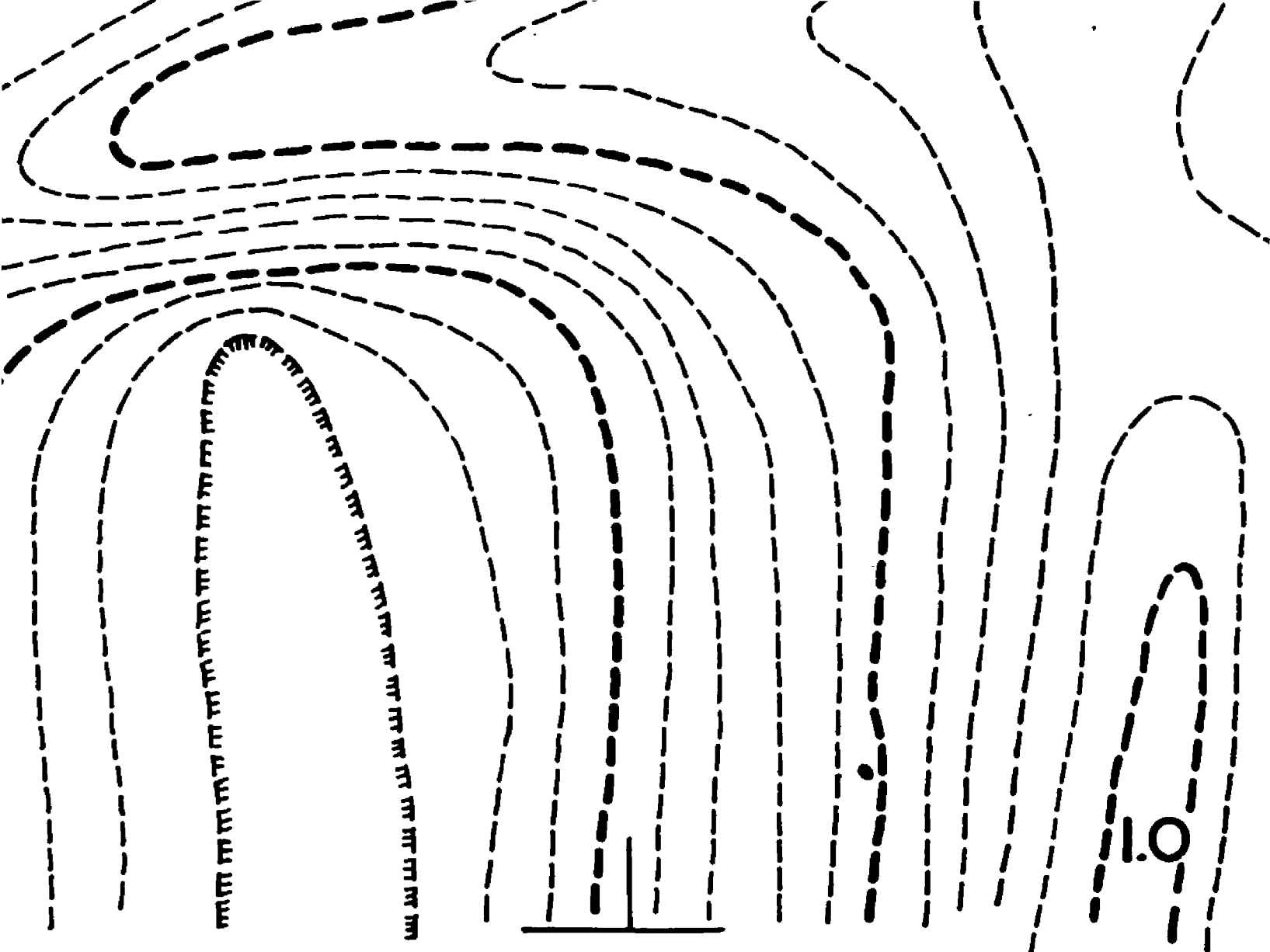
THE BOUGL



40'

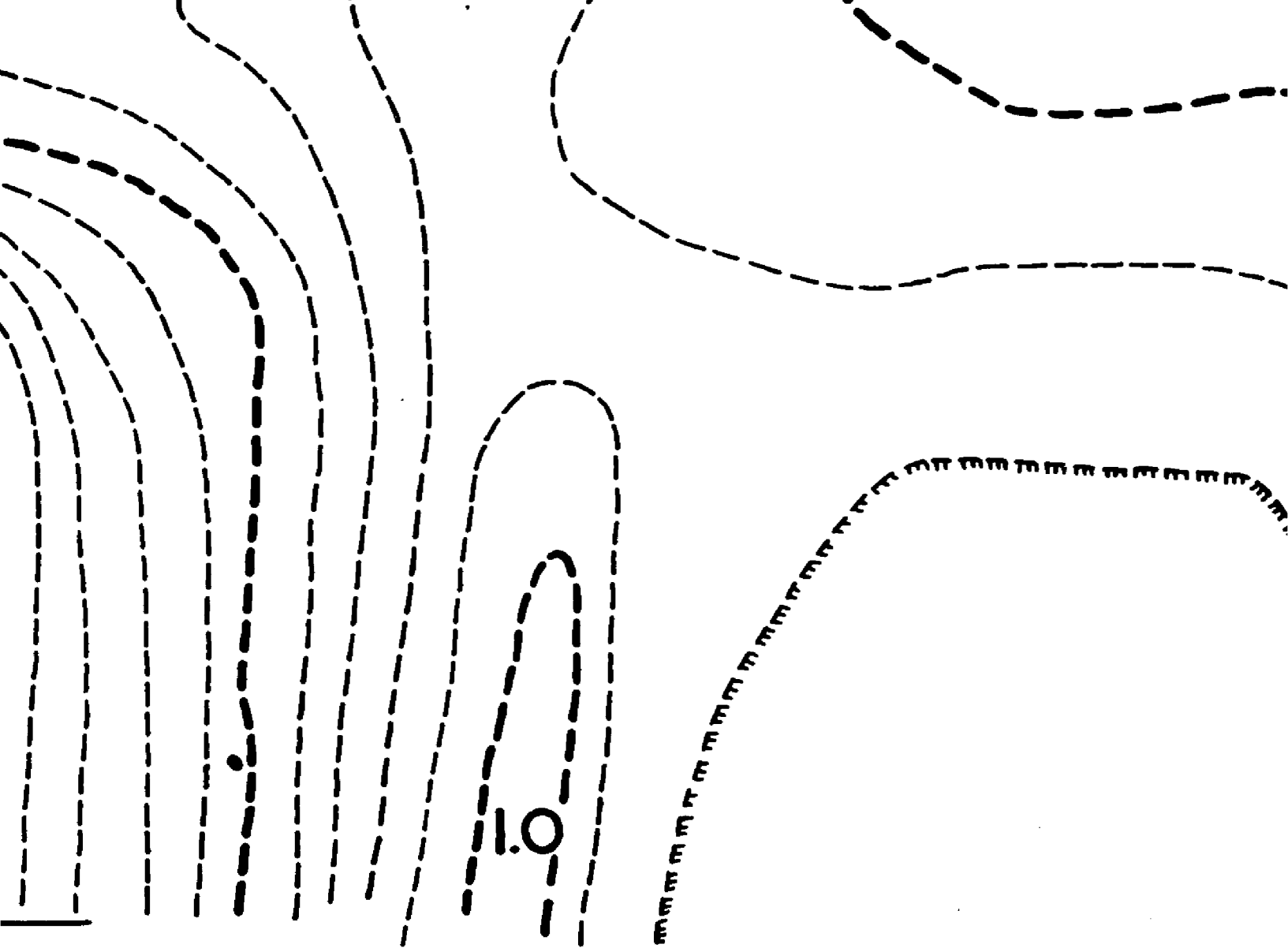
3a

MAP OF THE RESIDUAL
THE BOUGUER SURFAC

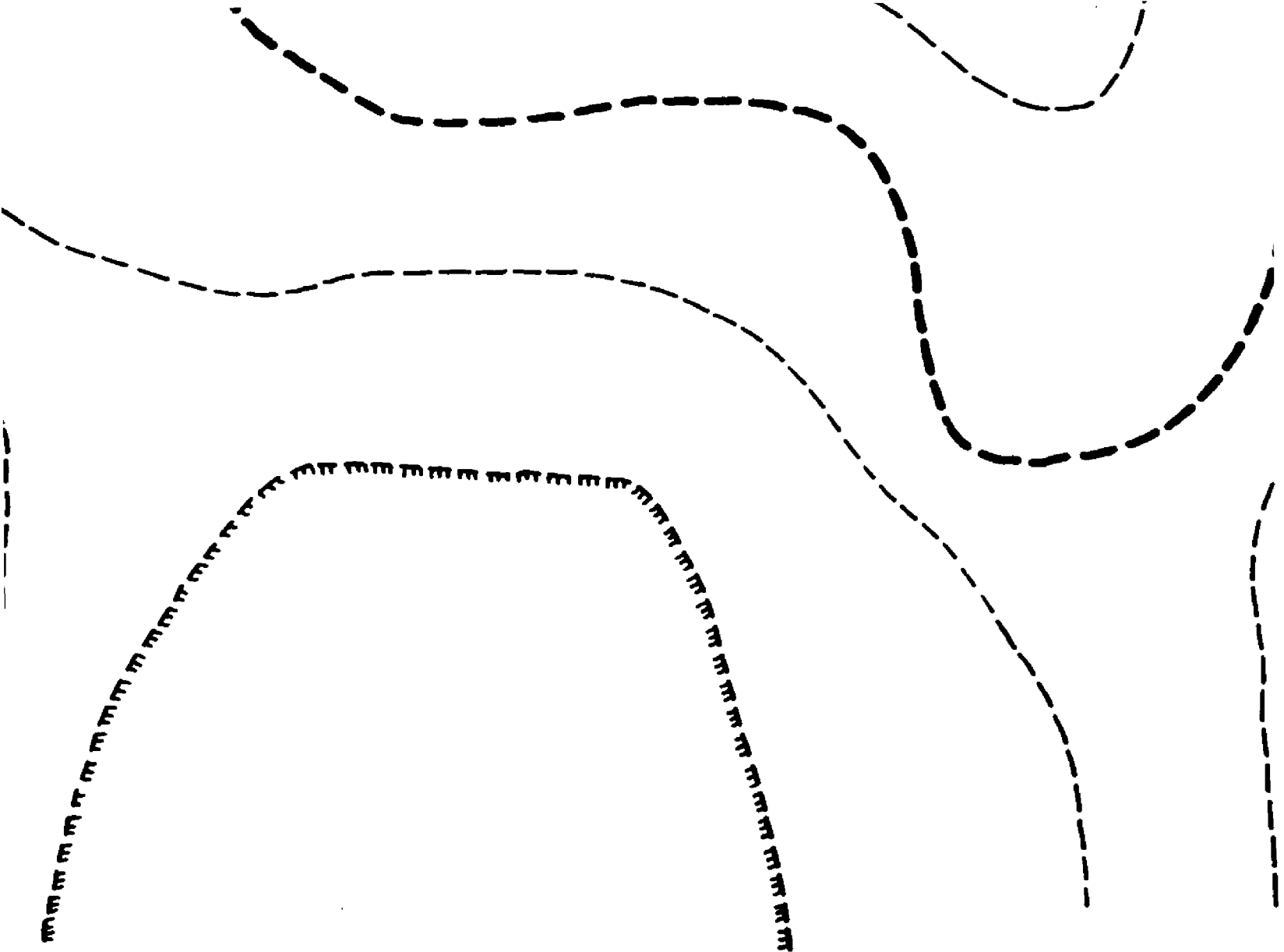


40'

THE RESIDUAL VALUES FROM
THE SURFACE



VALUES FROM 7TH DE
E SCA

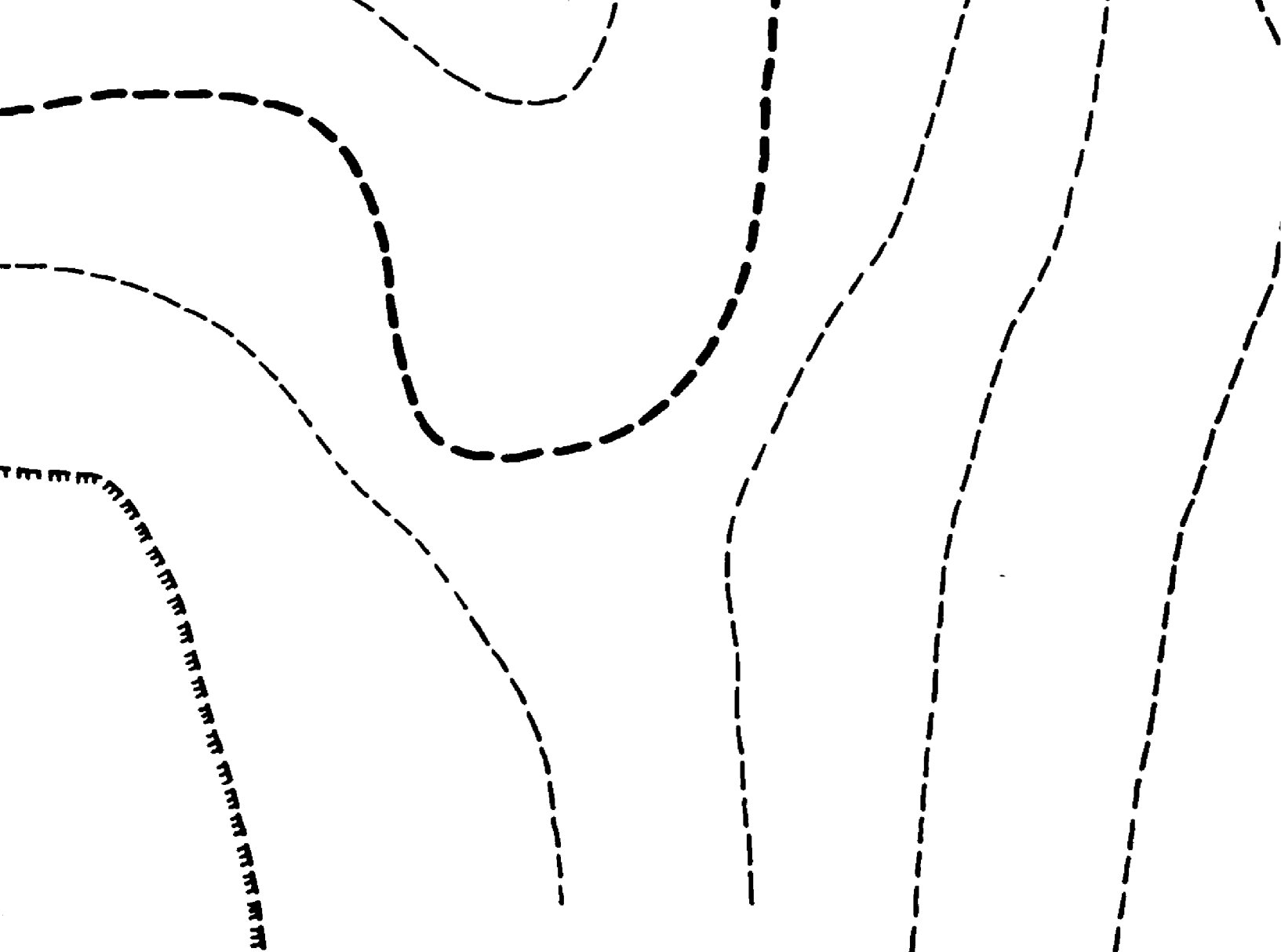


RIIW

35'

FROM 7TH DEGREE POLYN

SCALE 1: 24000



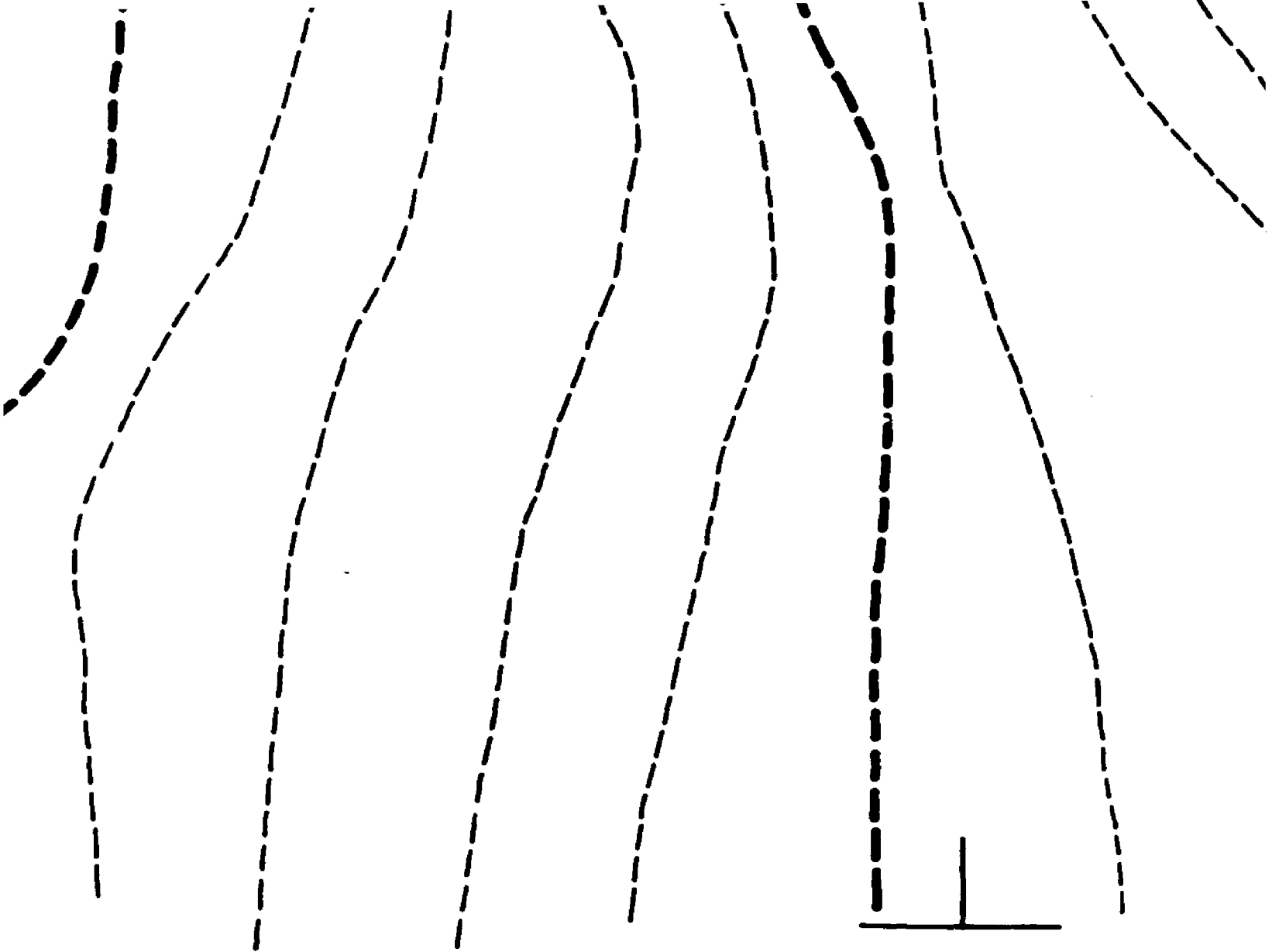
RIIW

35'

DEGREE POLYNOMIAL APP

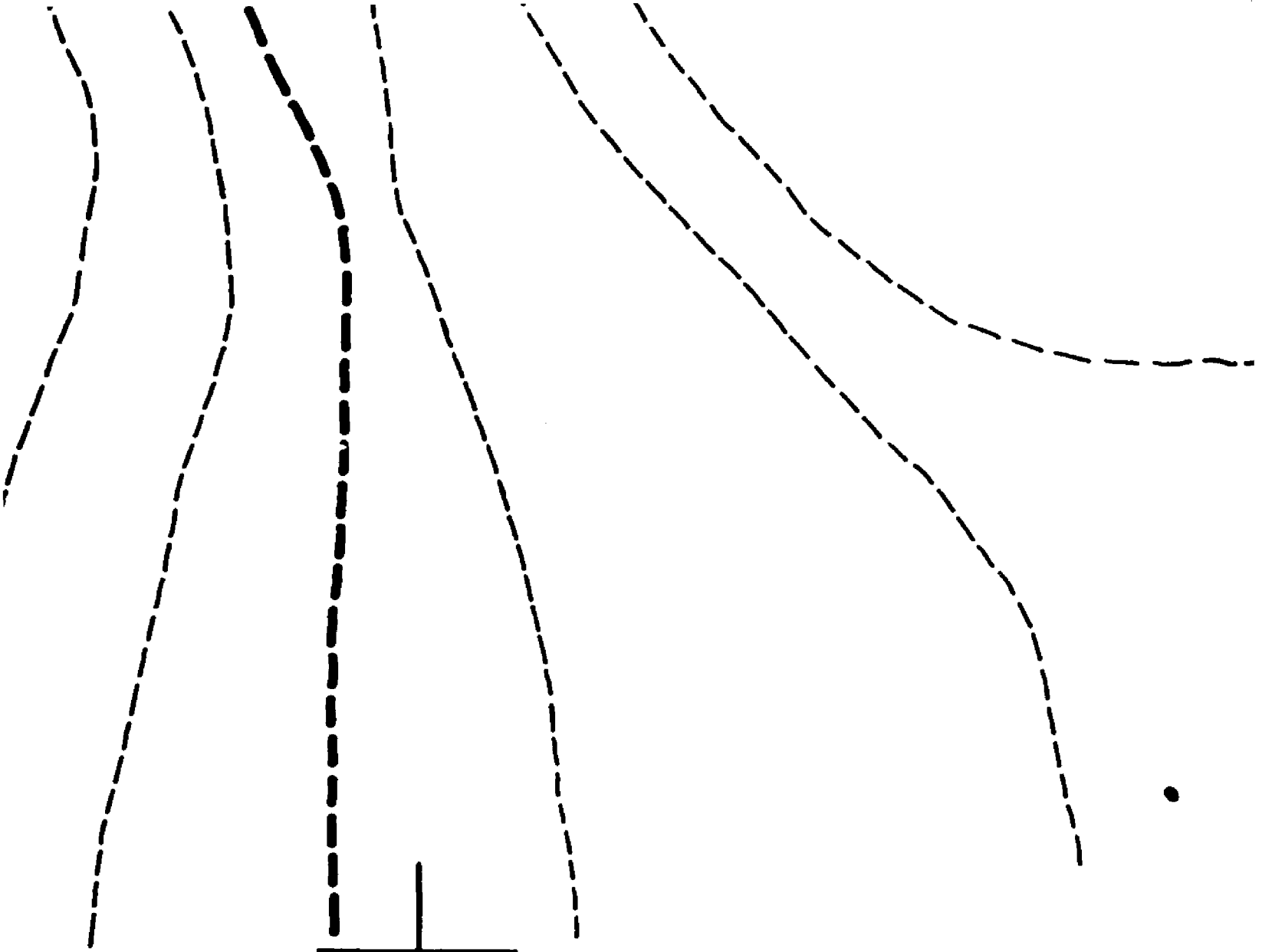
SCALE 1: 24000

CONTO



YNOMIAL APPROXIMATION

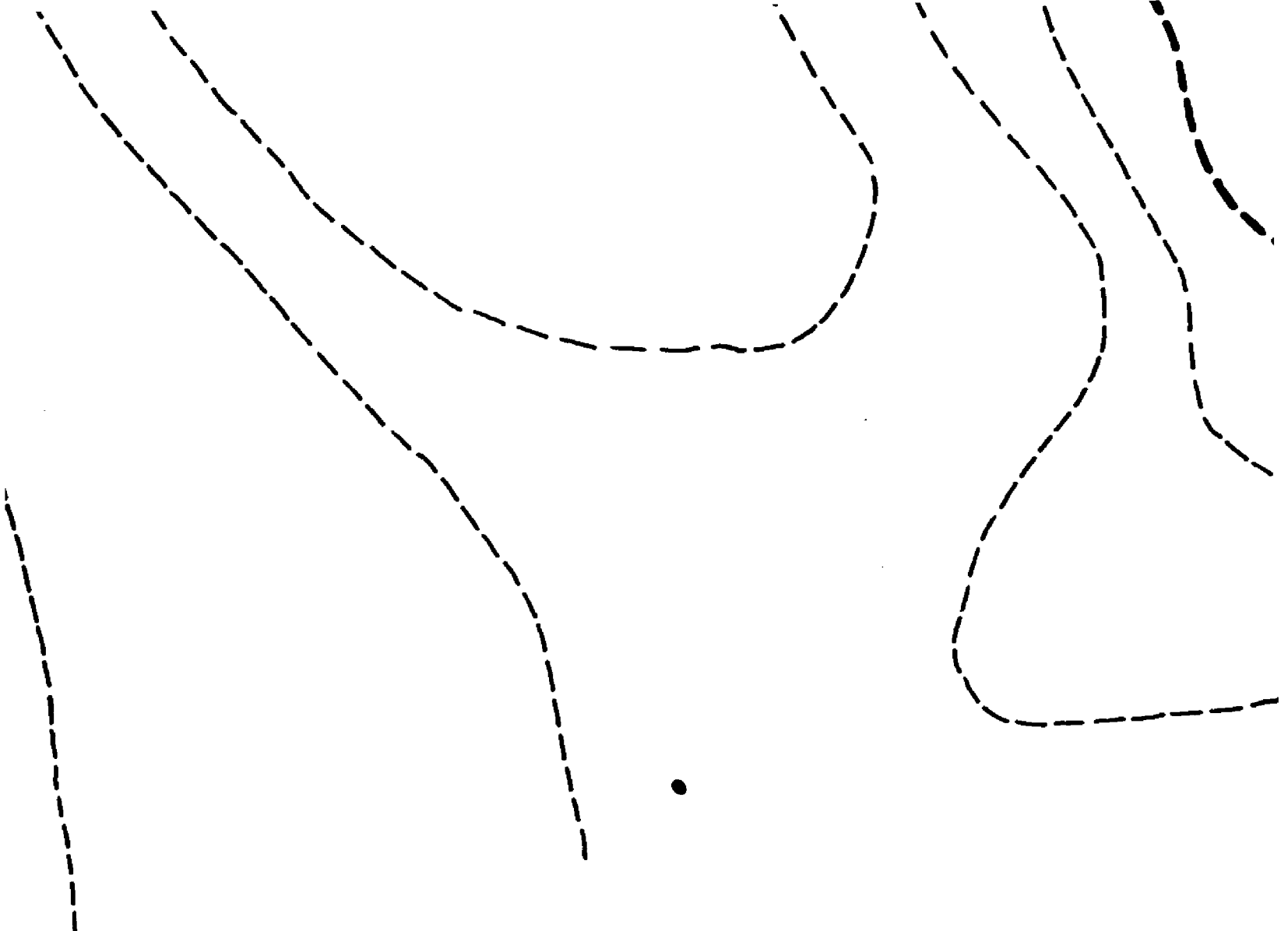
CONTOUR INTERVAL 0.20 M



30'

APPROXIMATION TO

TOUR INTERVAL 0.20 MGALS

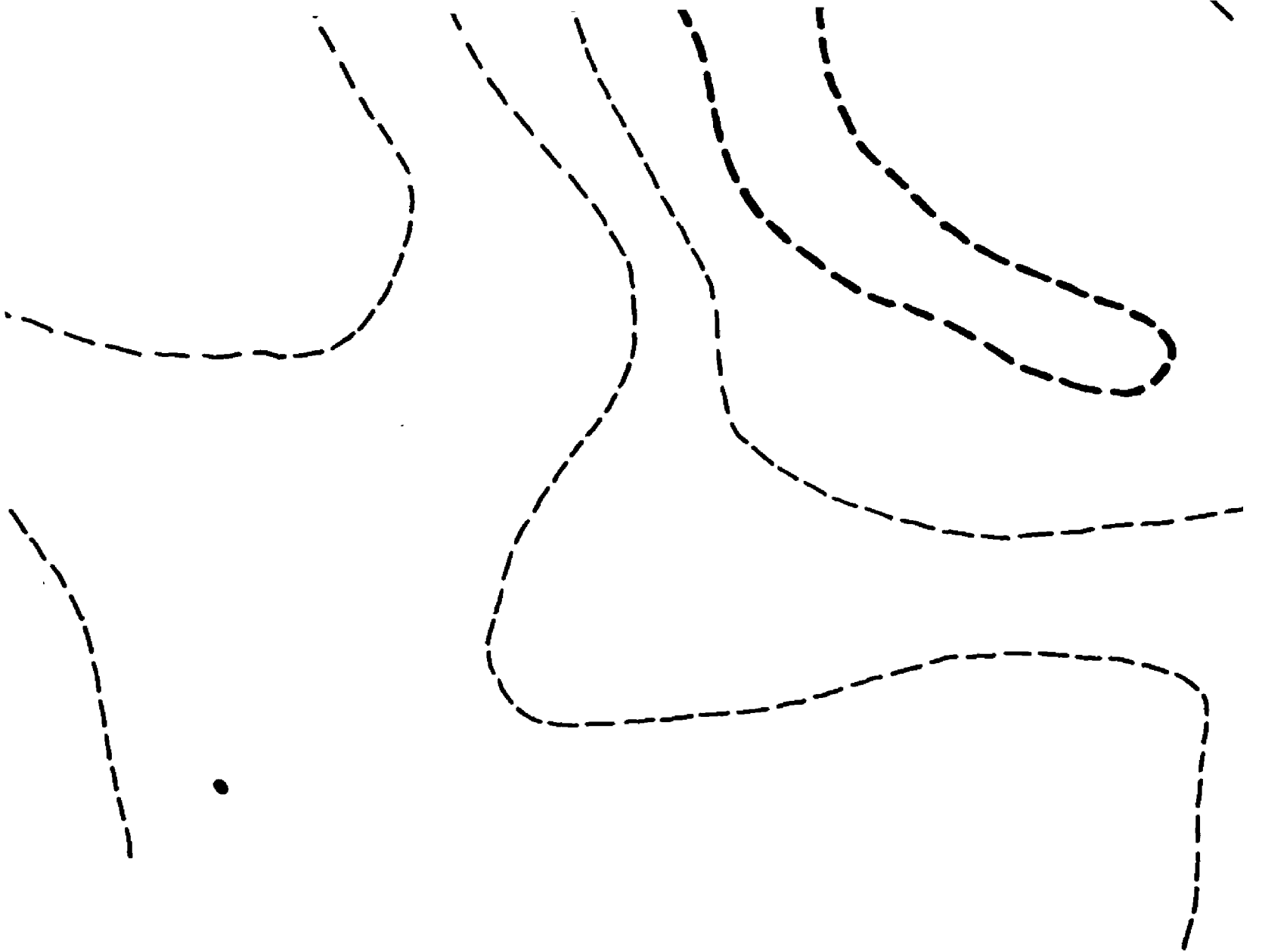


F

30'

ON TO

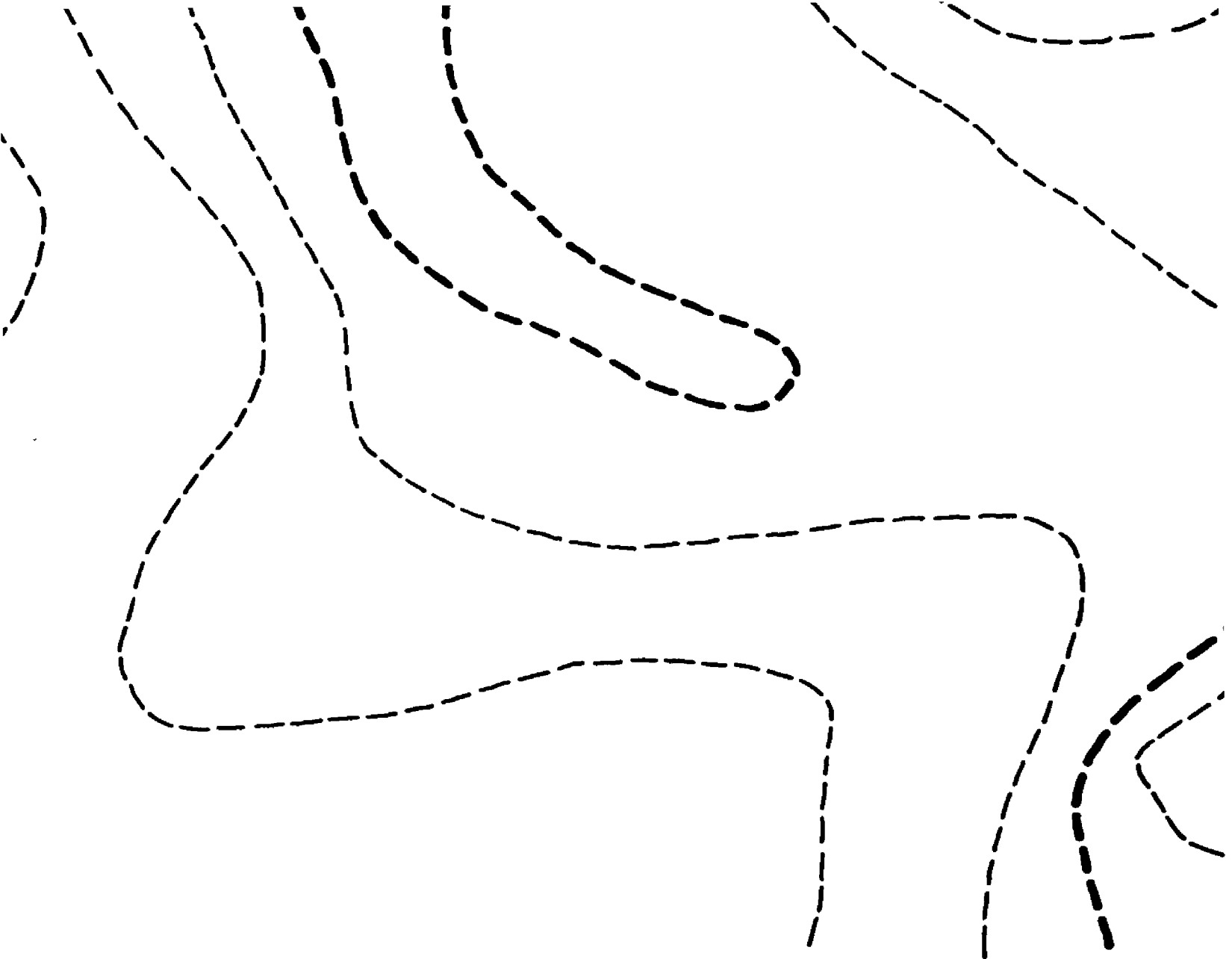
0.20 MGALS



RIOW

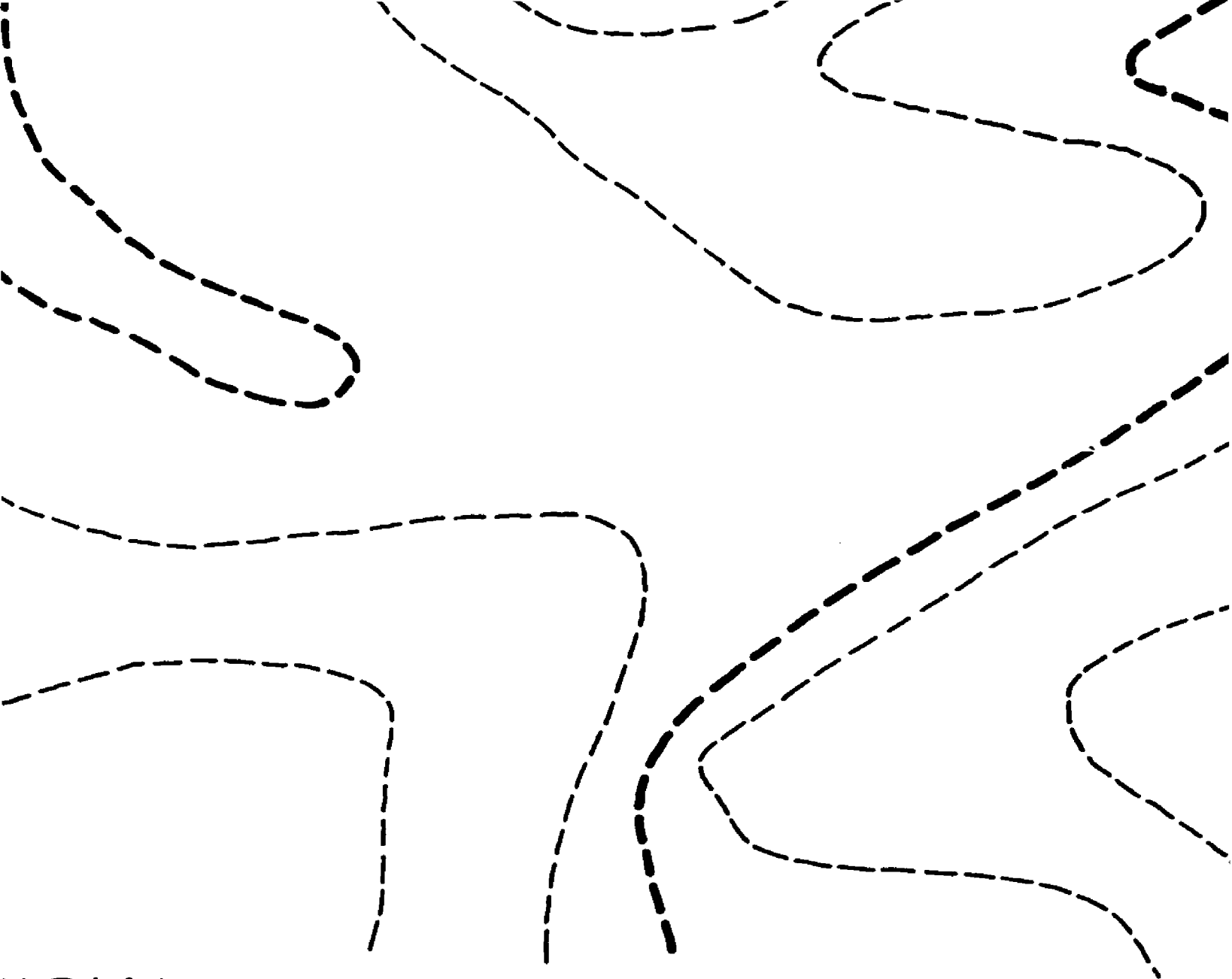
30'

SOUTH



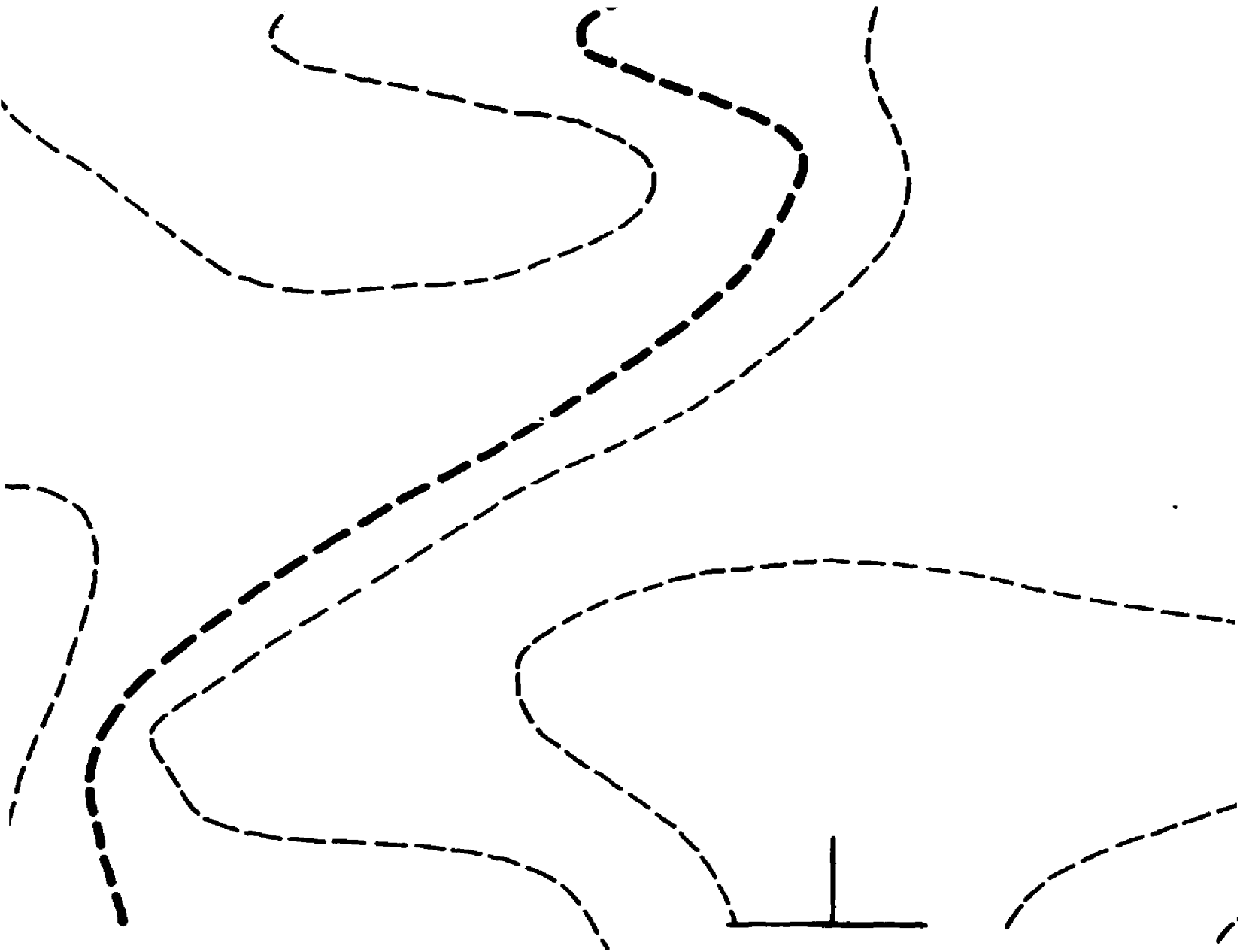
RIOW

SOUTHERN HALF



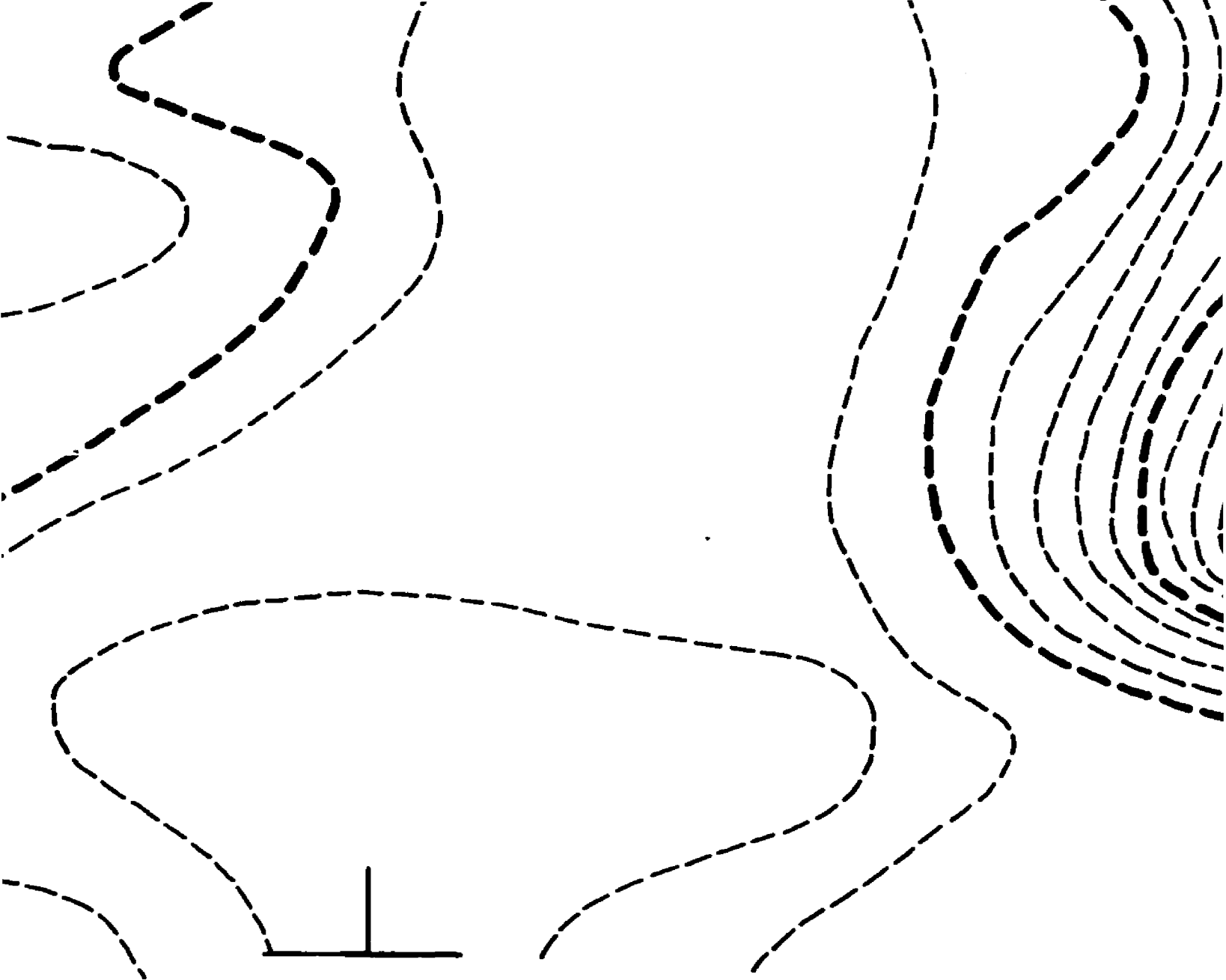
RIOW

SOUTHERN HALF OF KALAM



25

HALF OF KALAMAZOO COUNTY

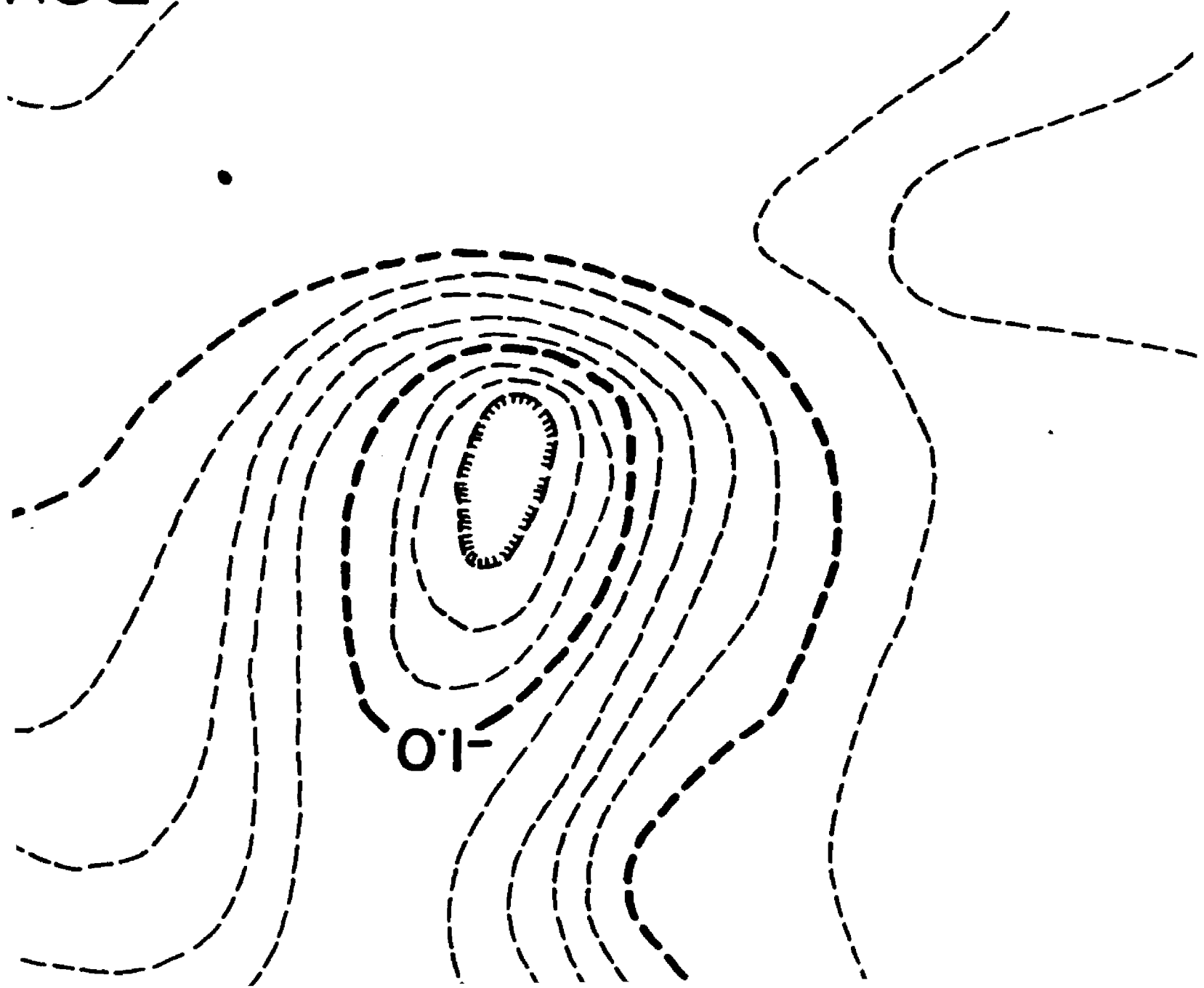


25'

KALAMAZOO COUNTY

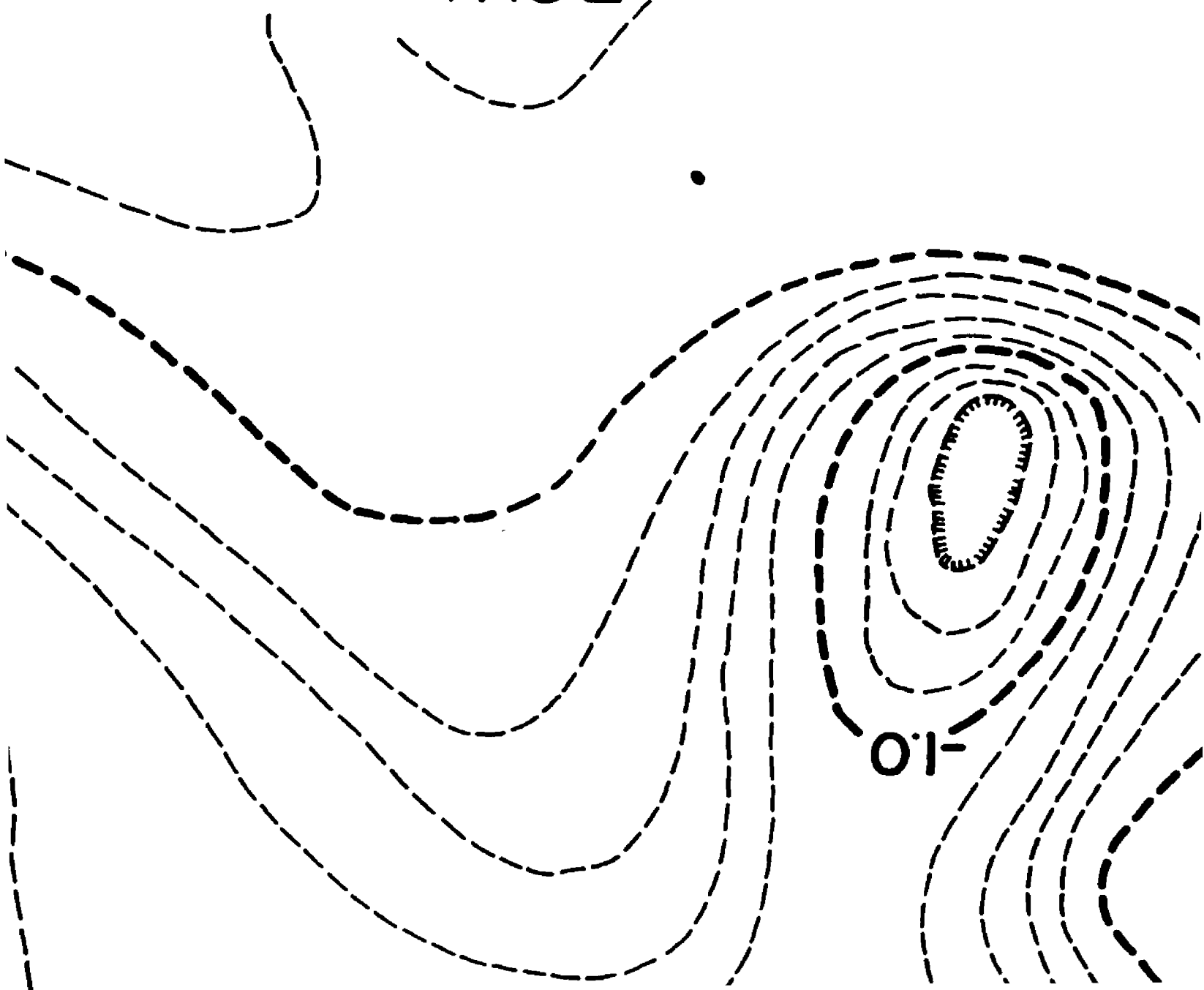
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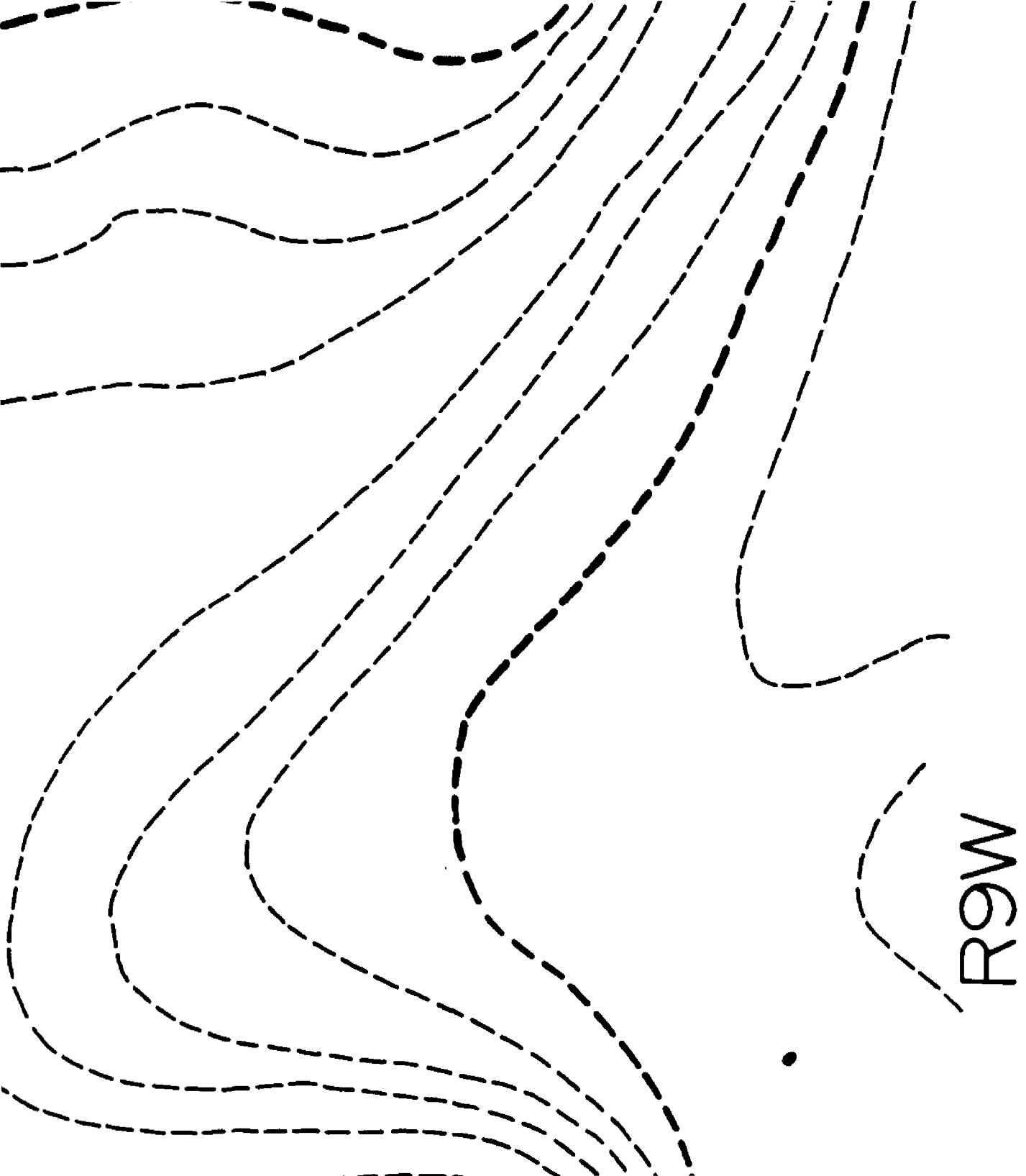
R9V



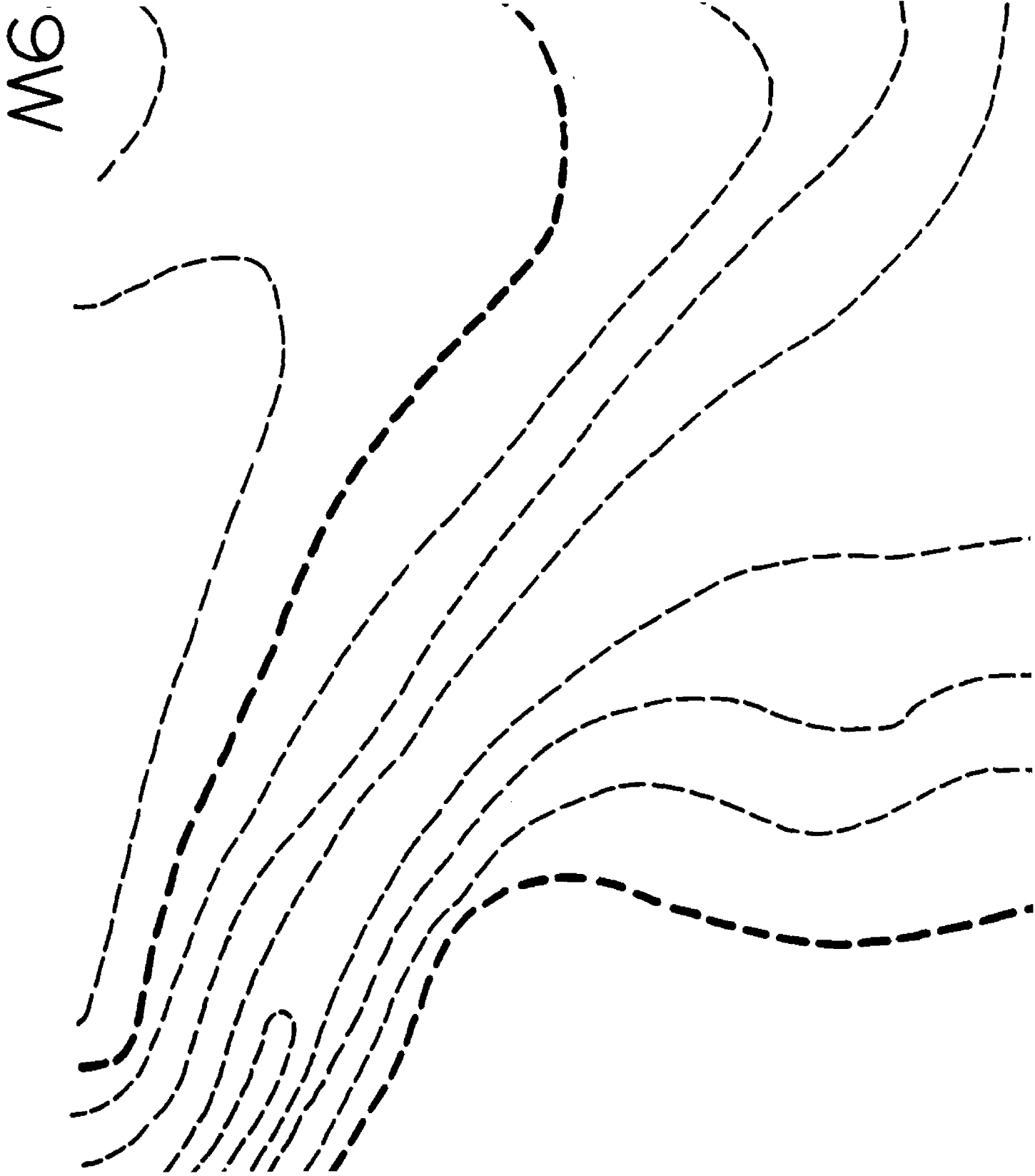
85.20

R9W



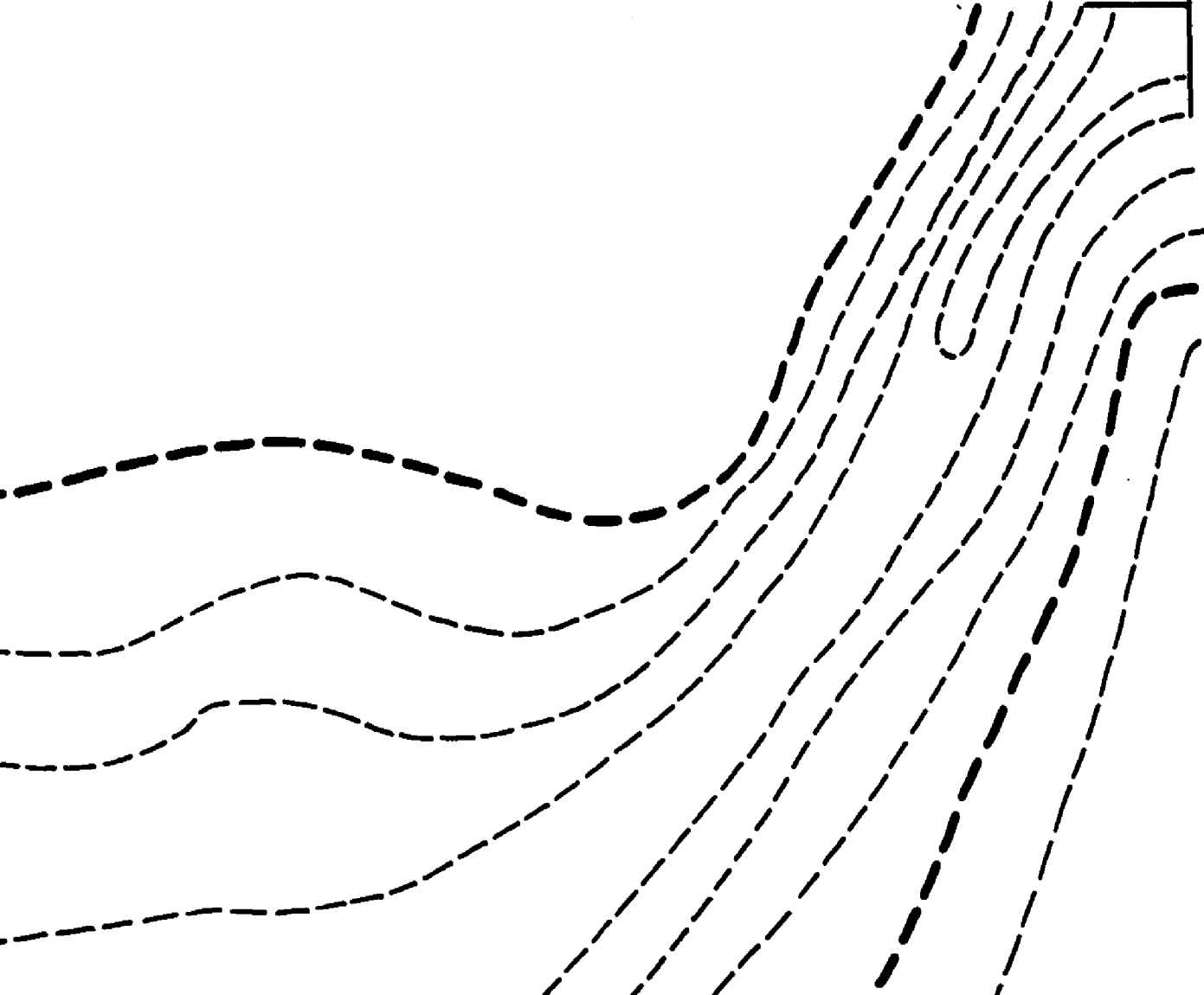


85° 20'



85° 20'

05-
42



05

45'

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TIS

AO



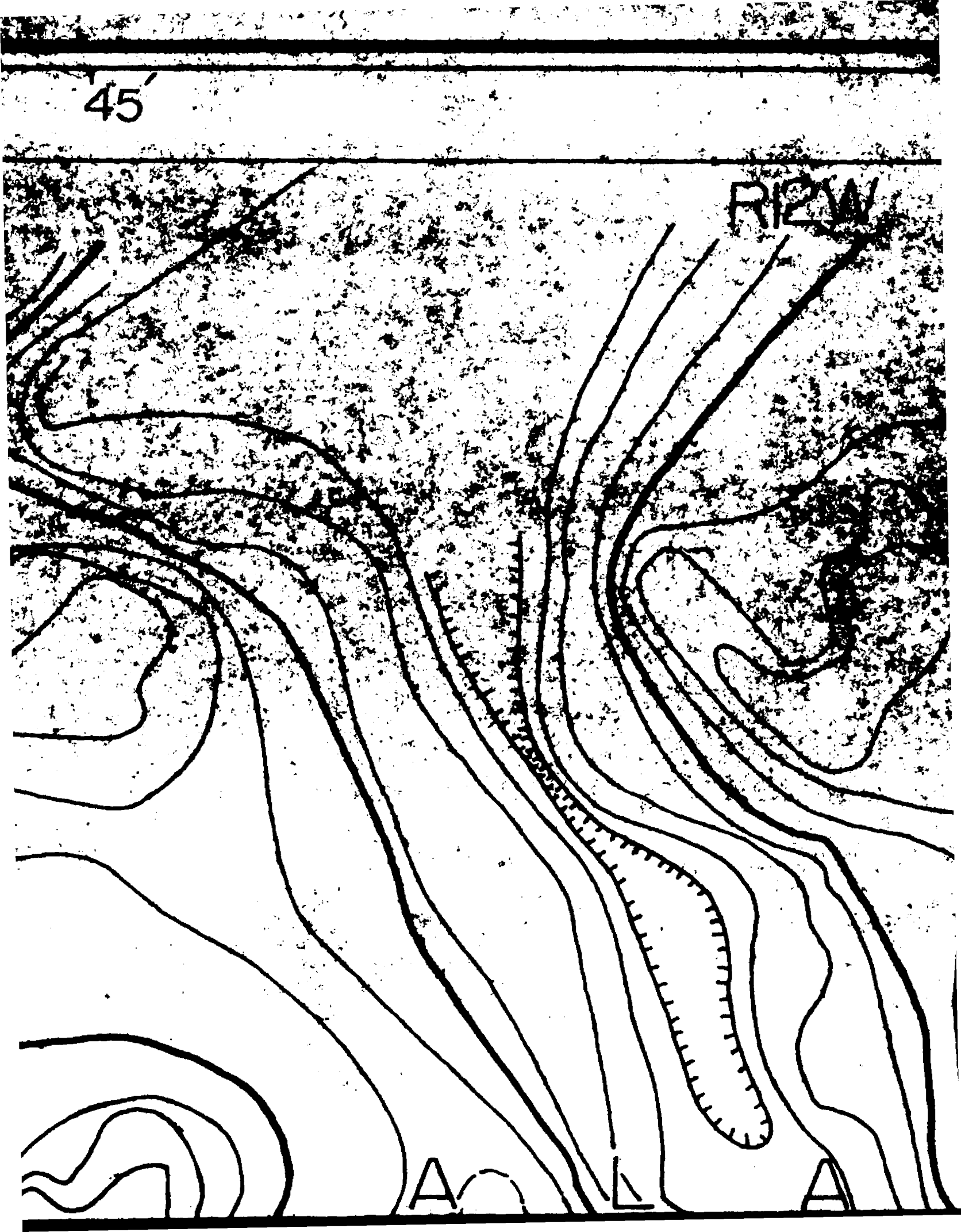
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R12W

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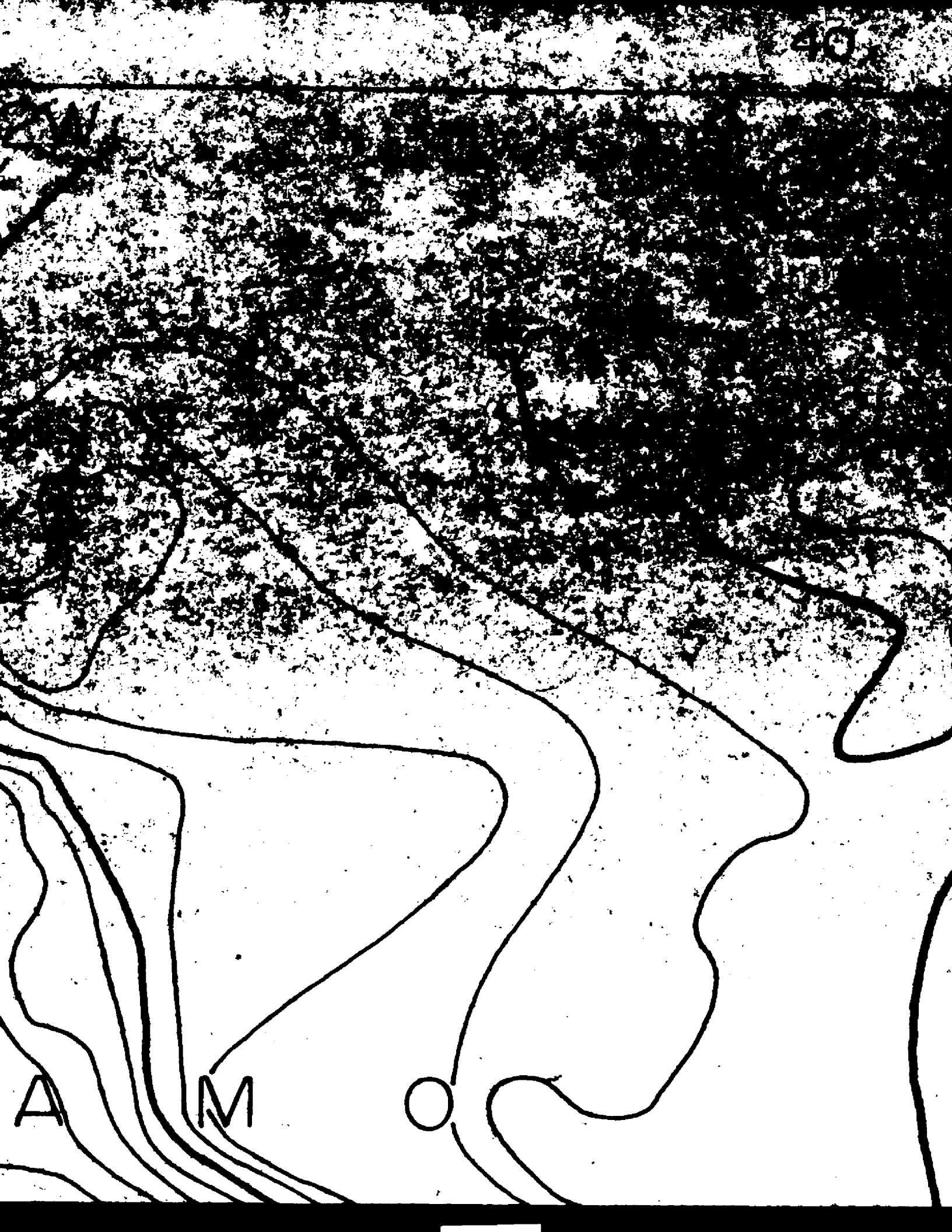
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R12W





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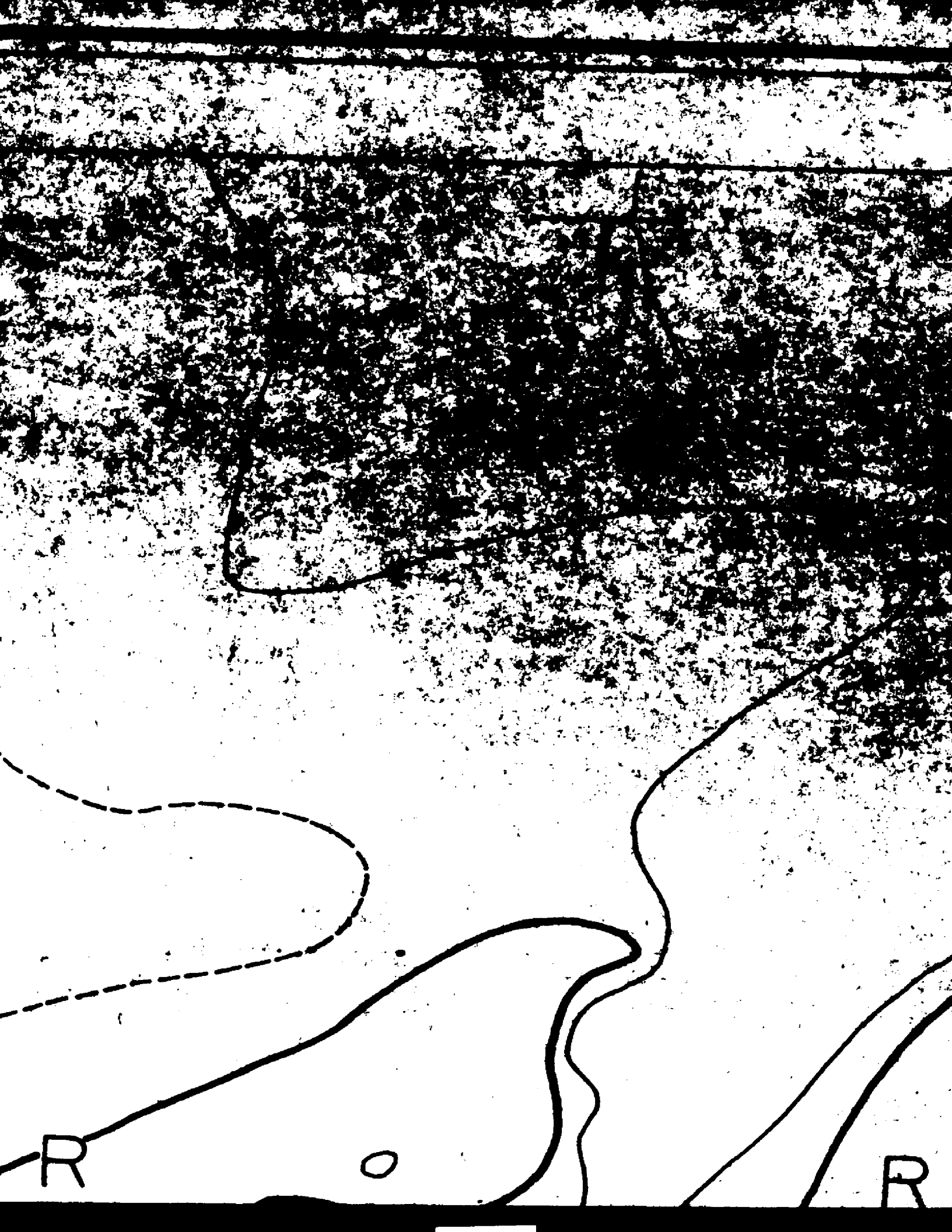


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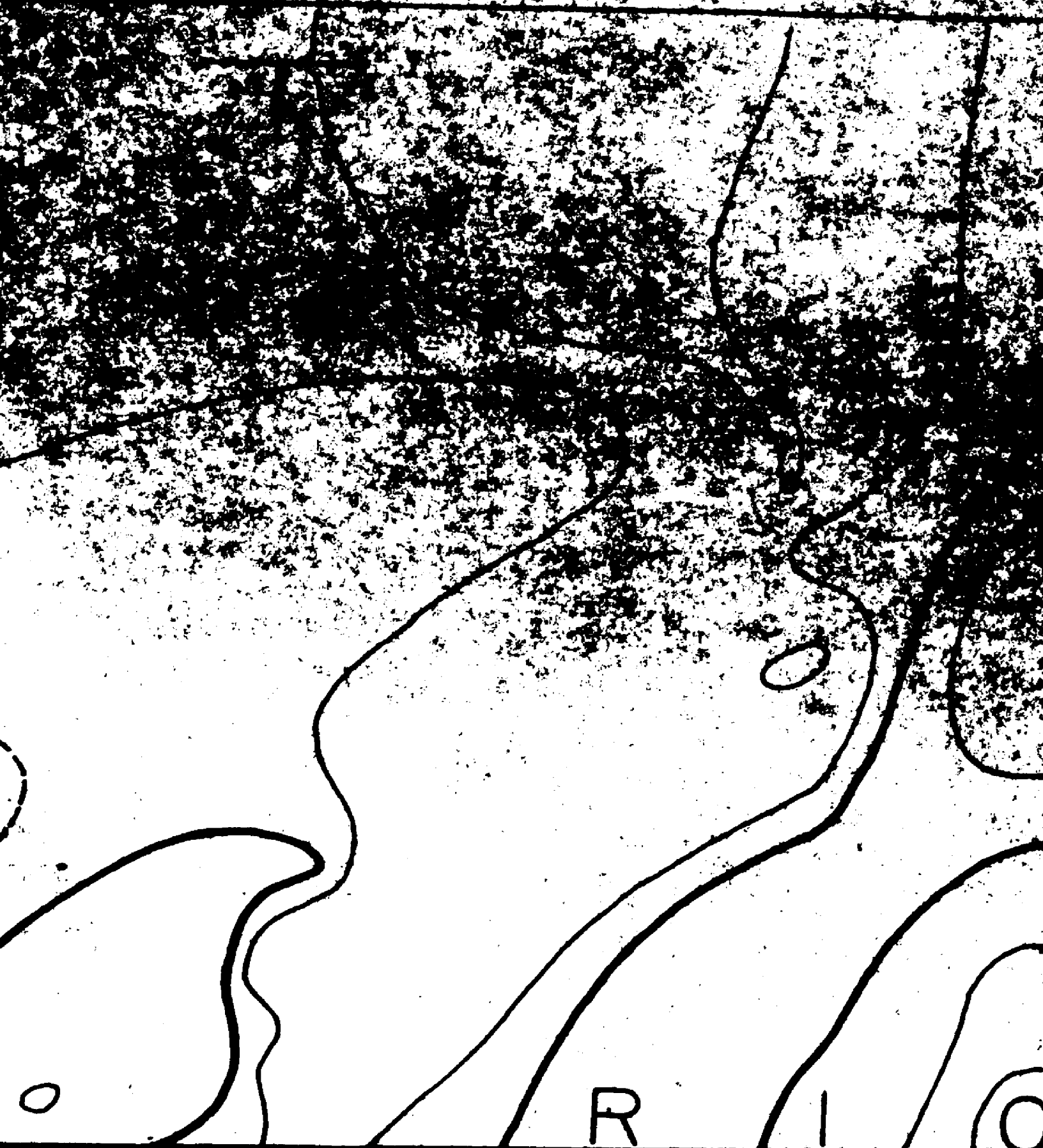


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8

ROW

R O S E

85° 20'

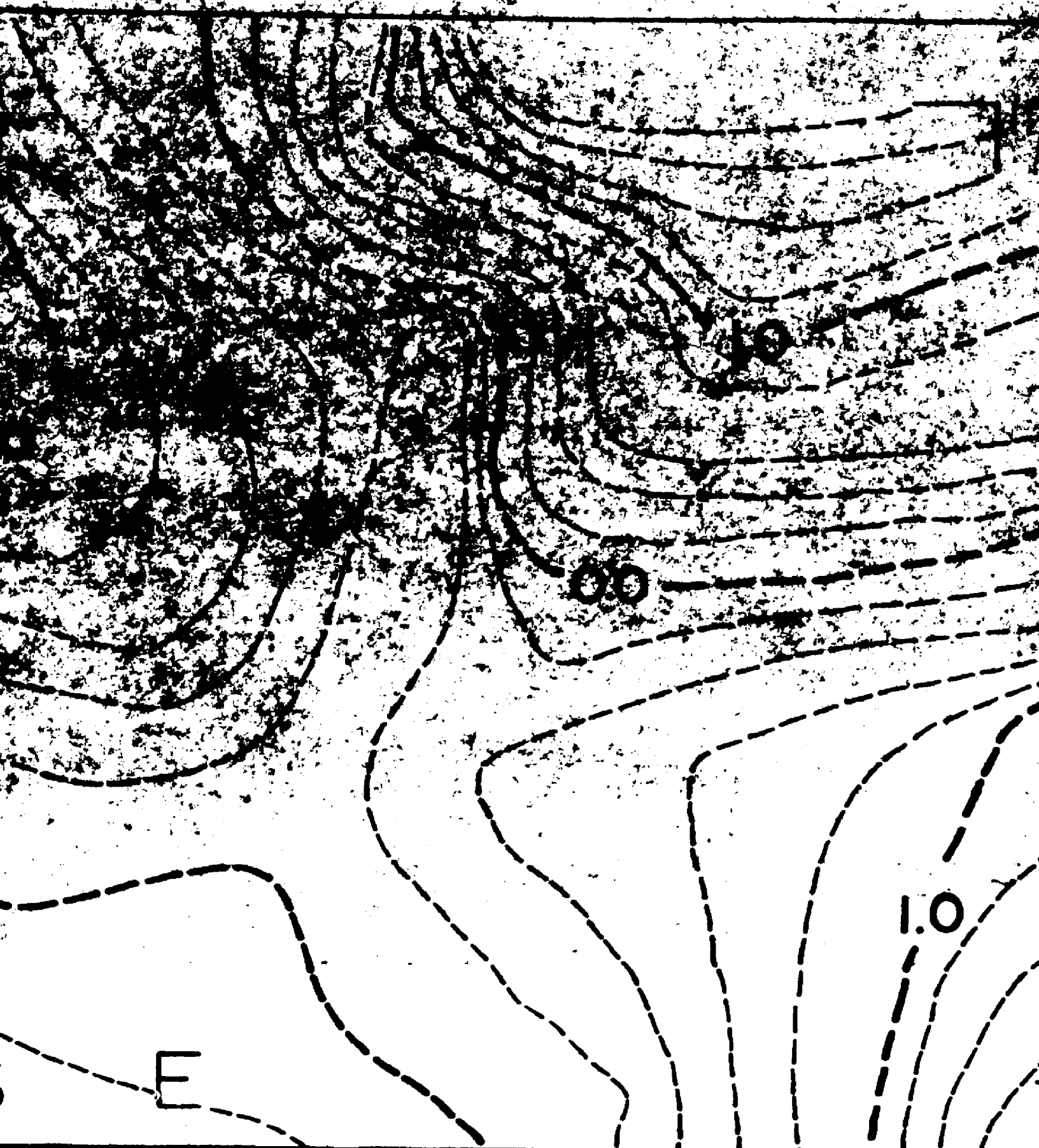
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MAN

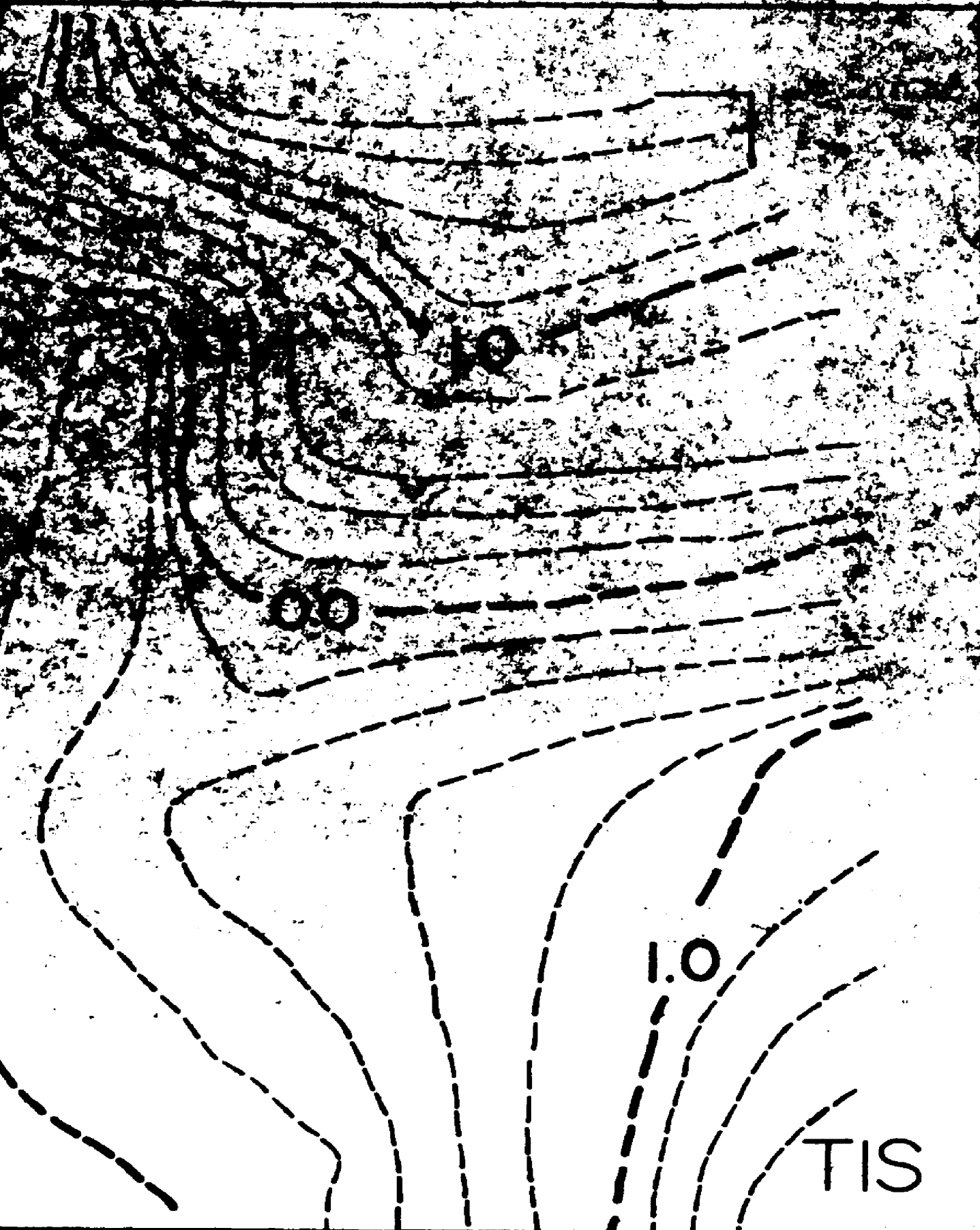
05

O S E

85°20'

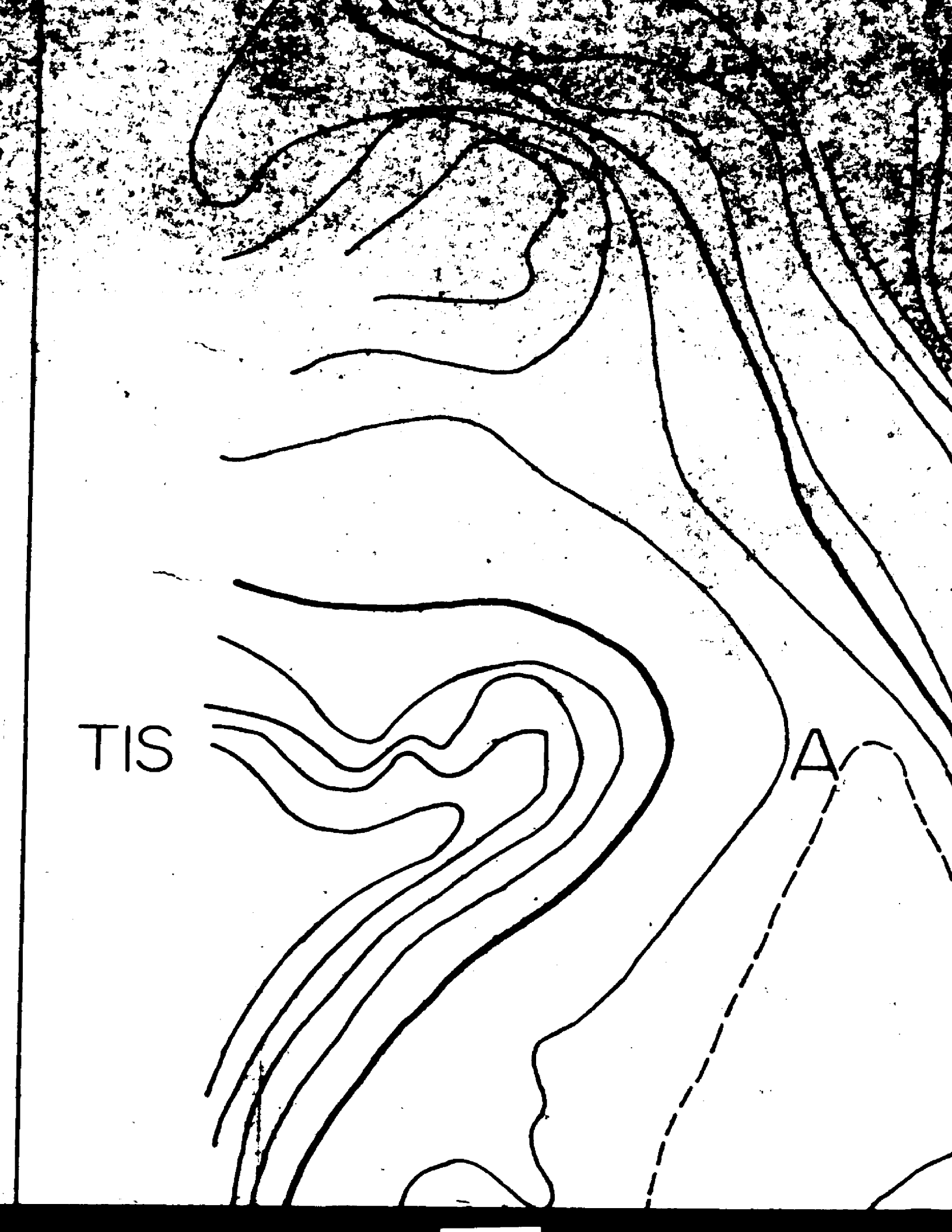


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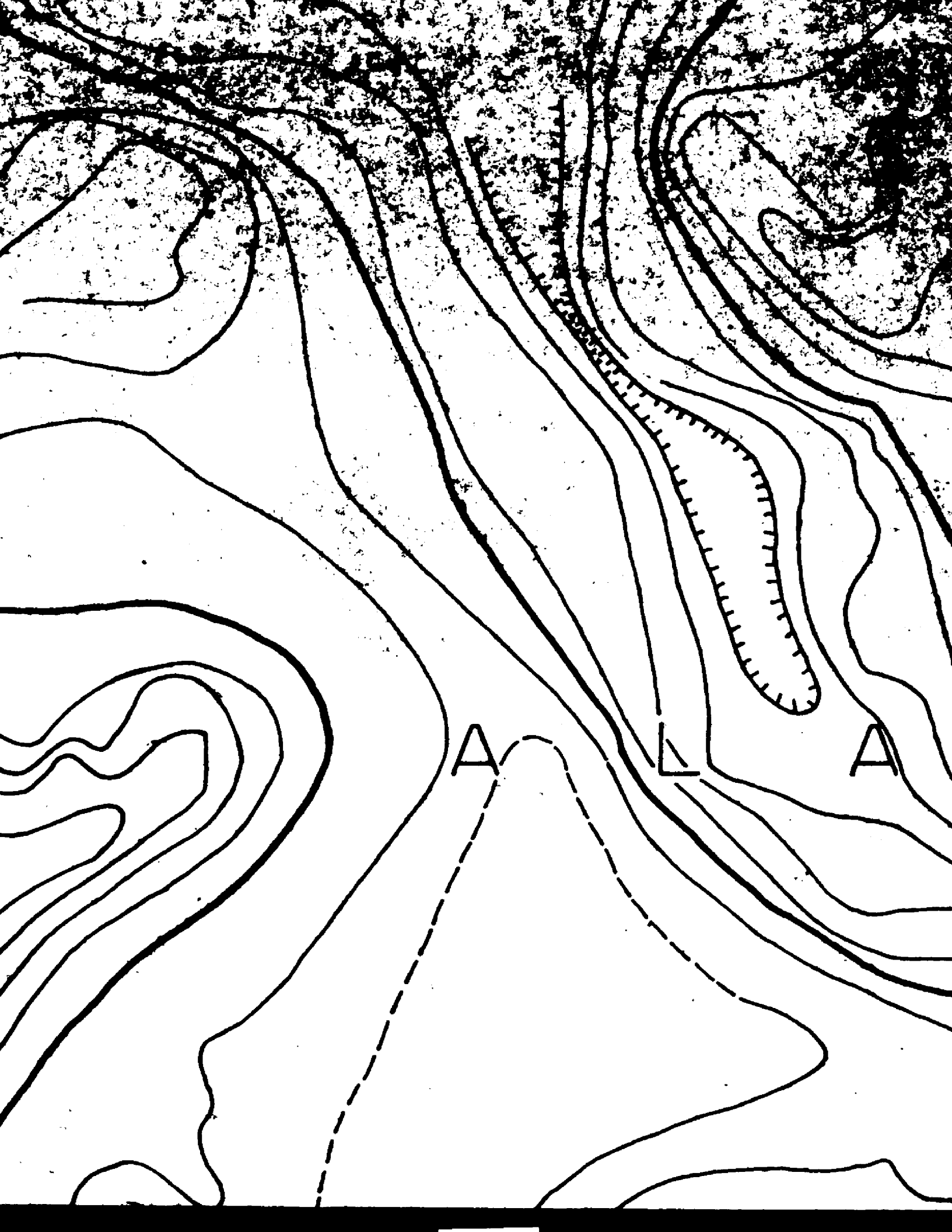
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TIS



TIS

A





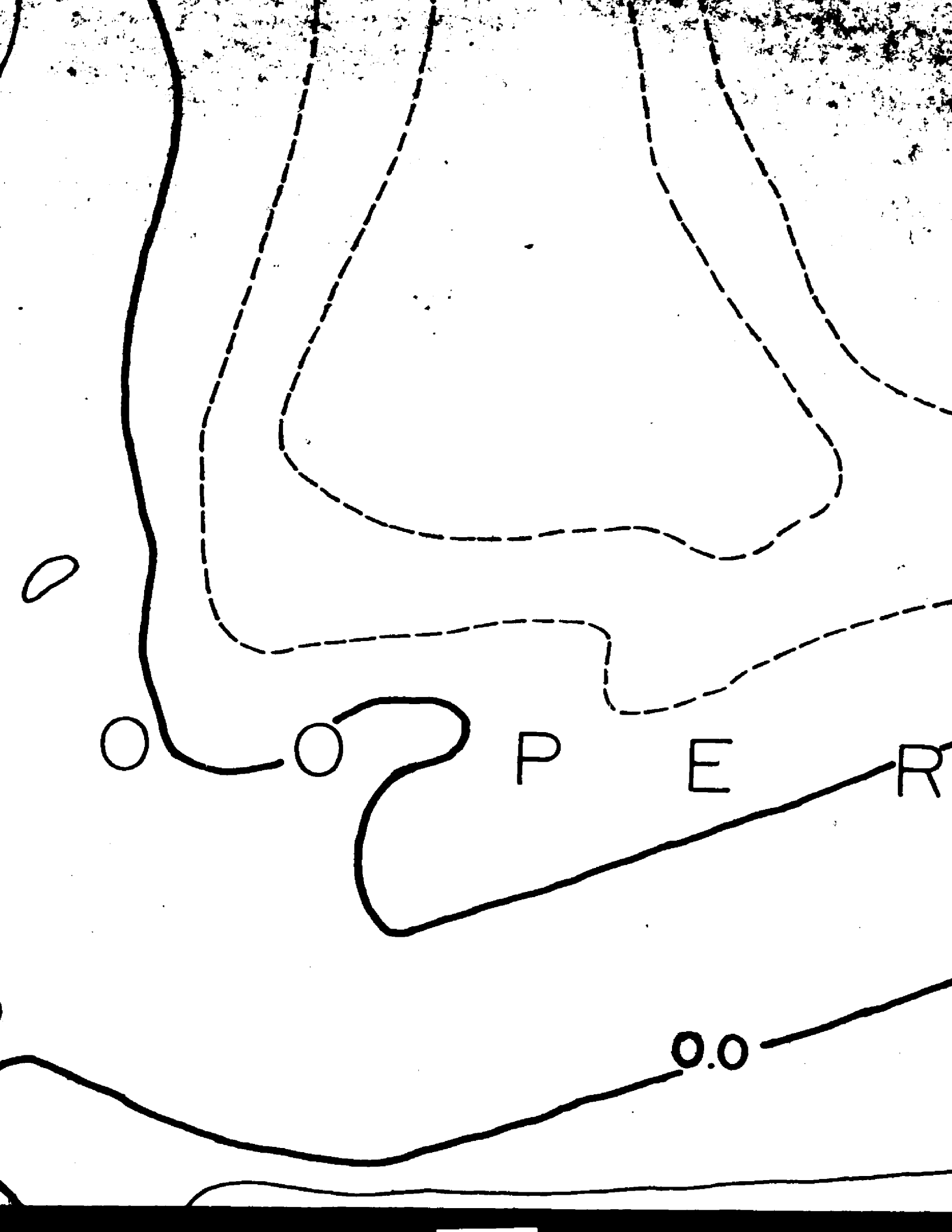


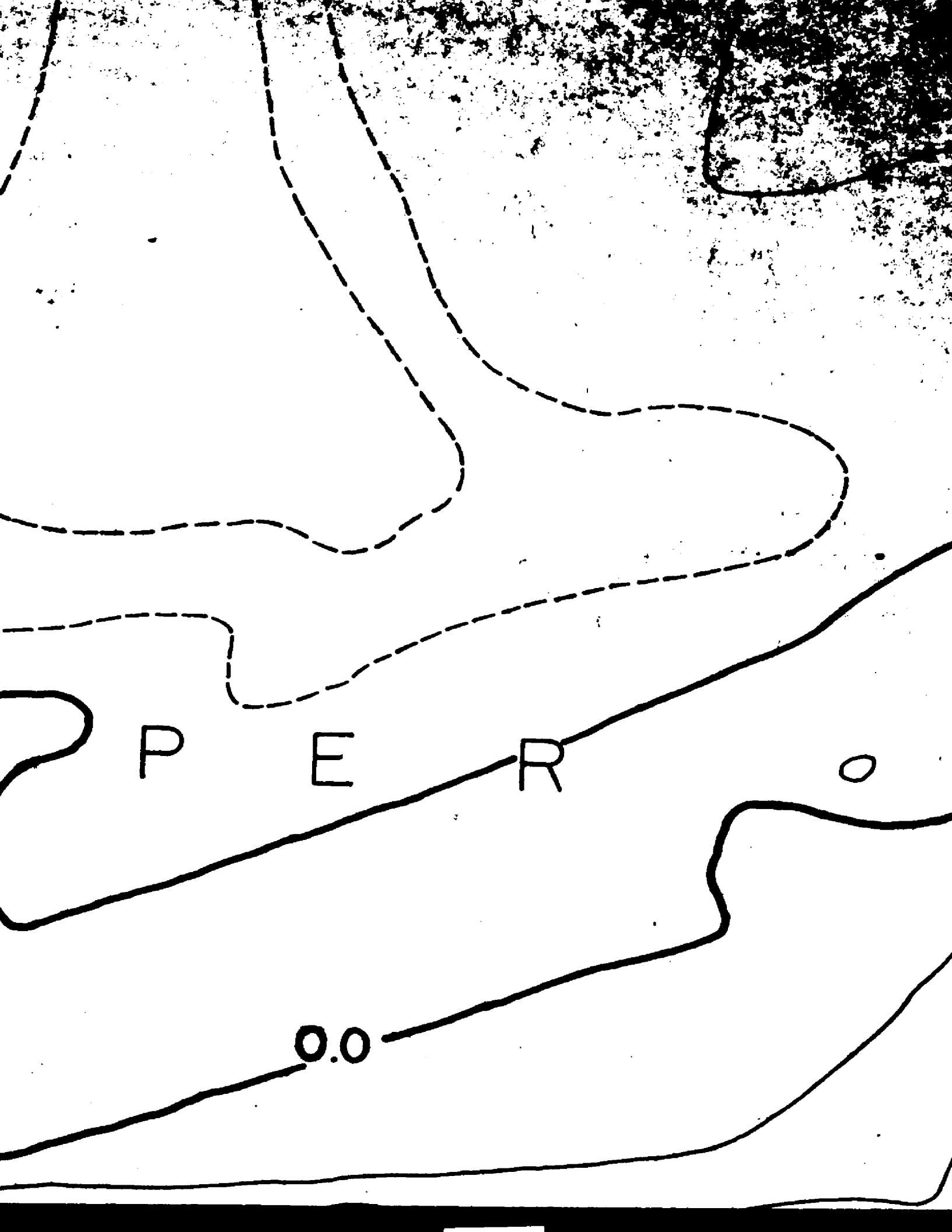




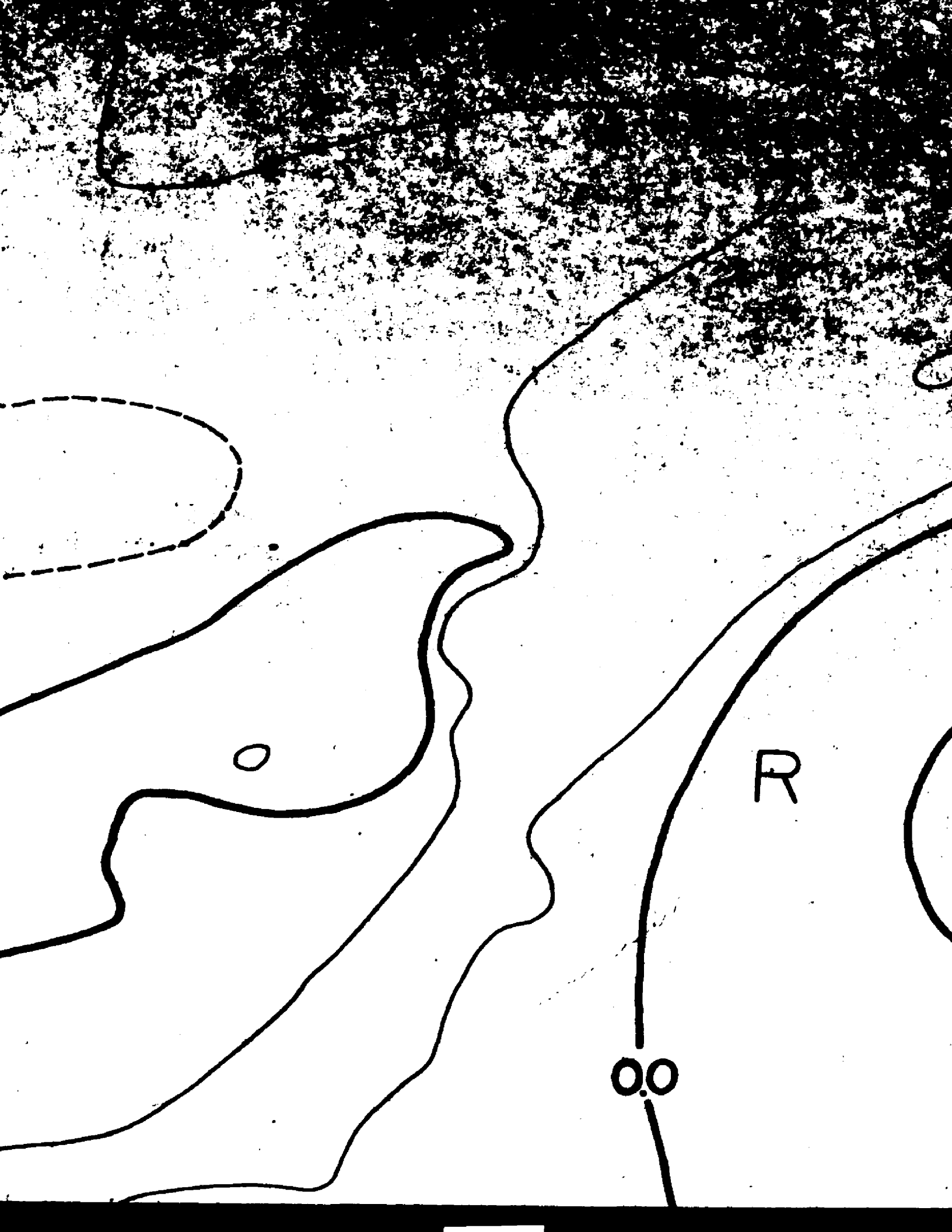


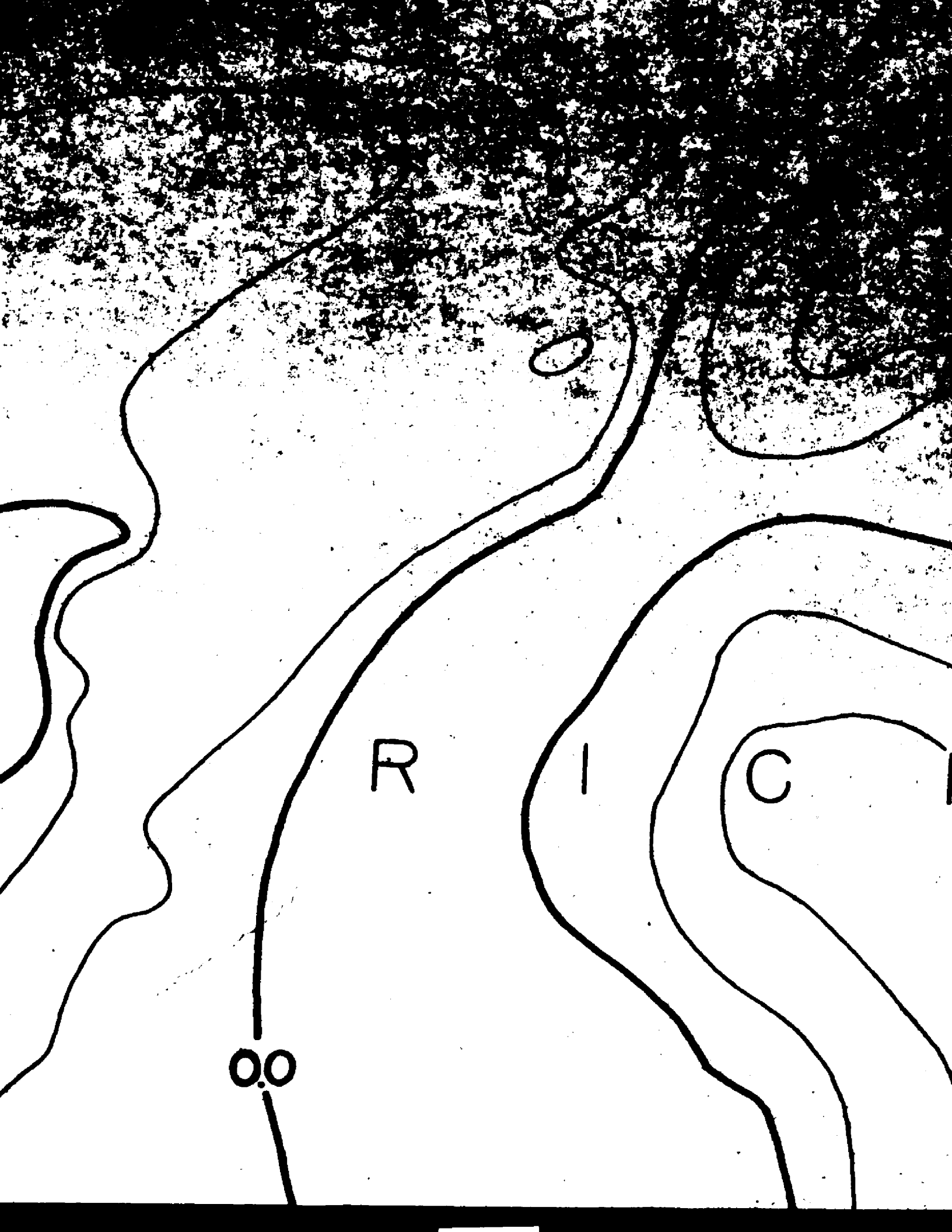


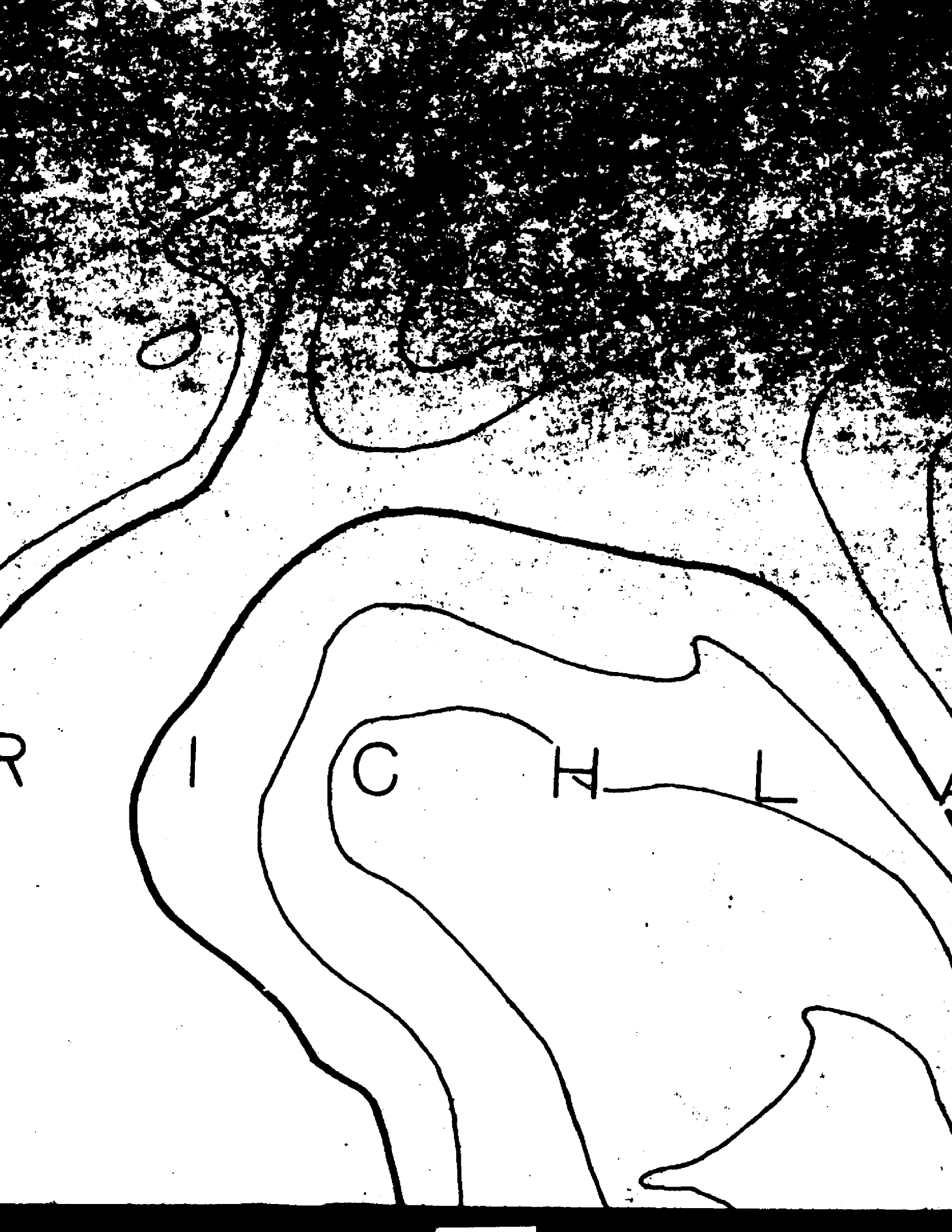














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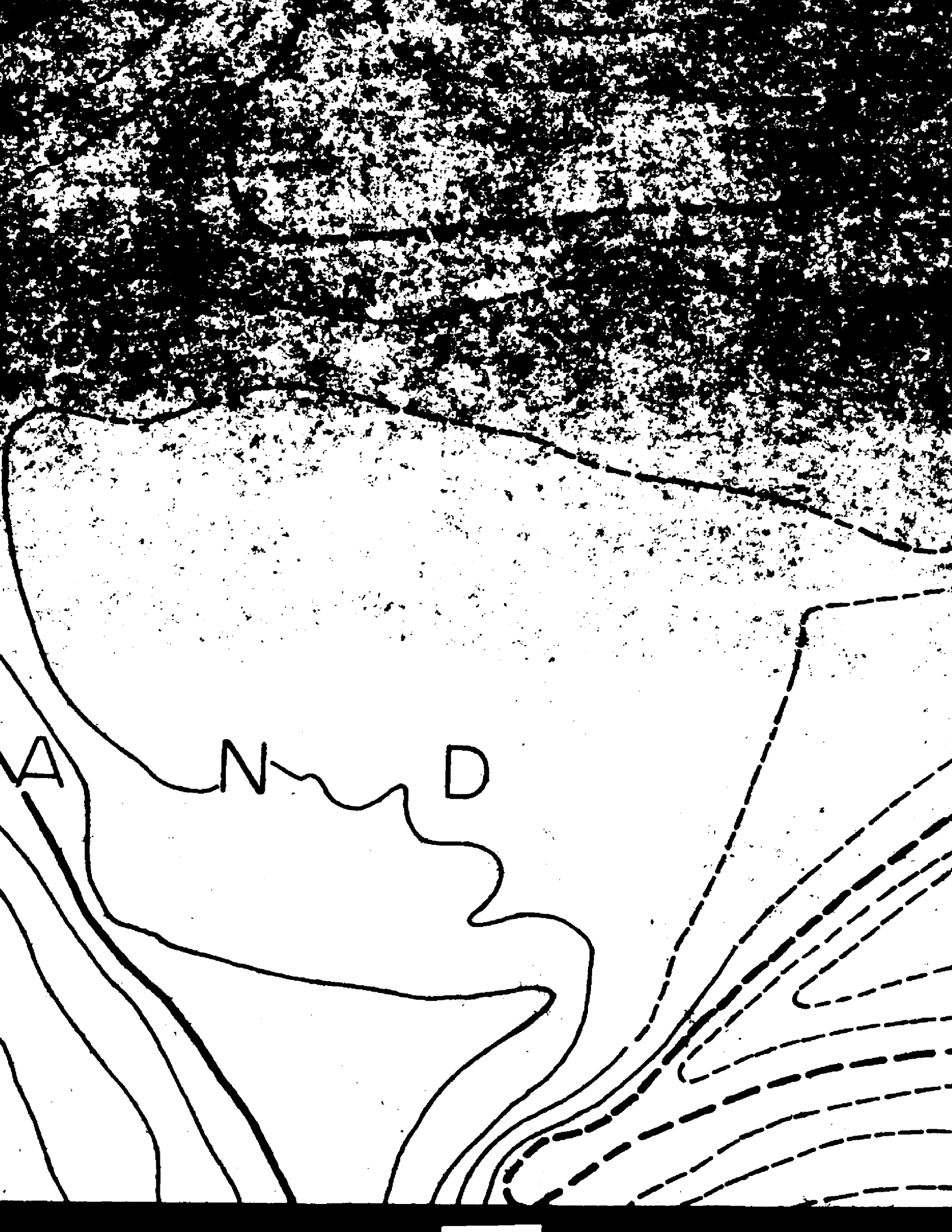
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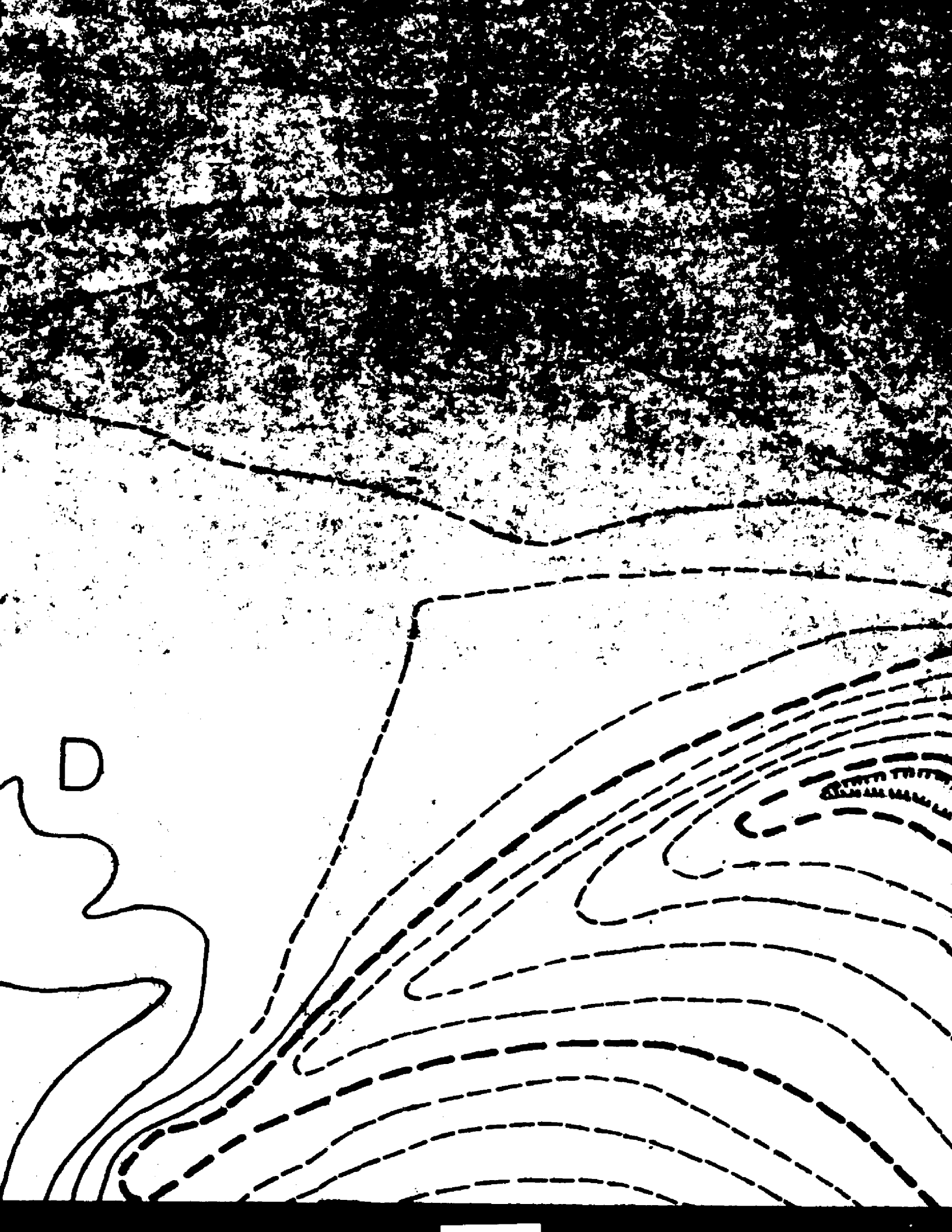
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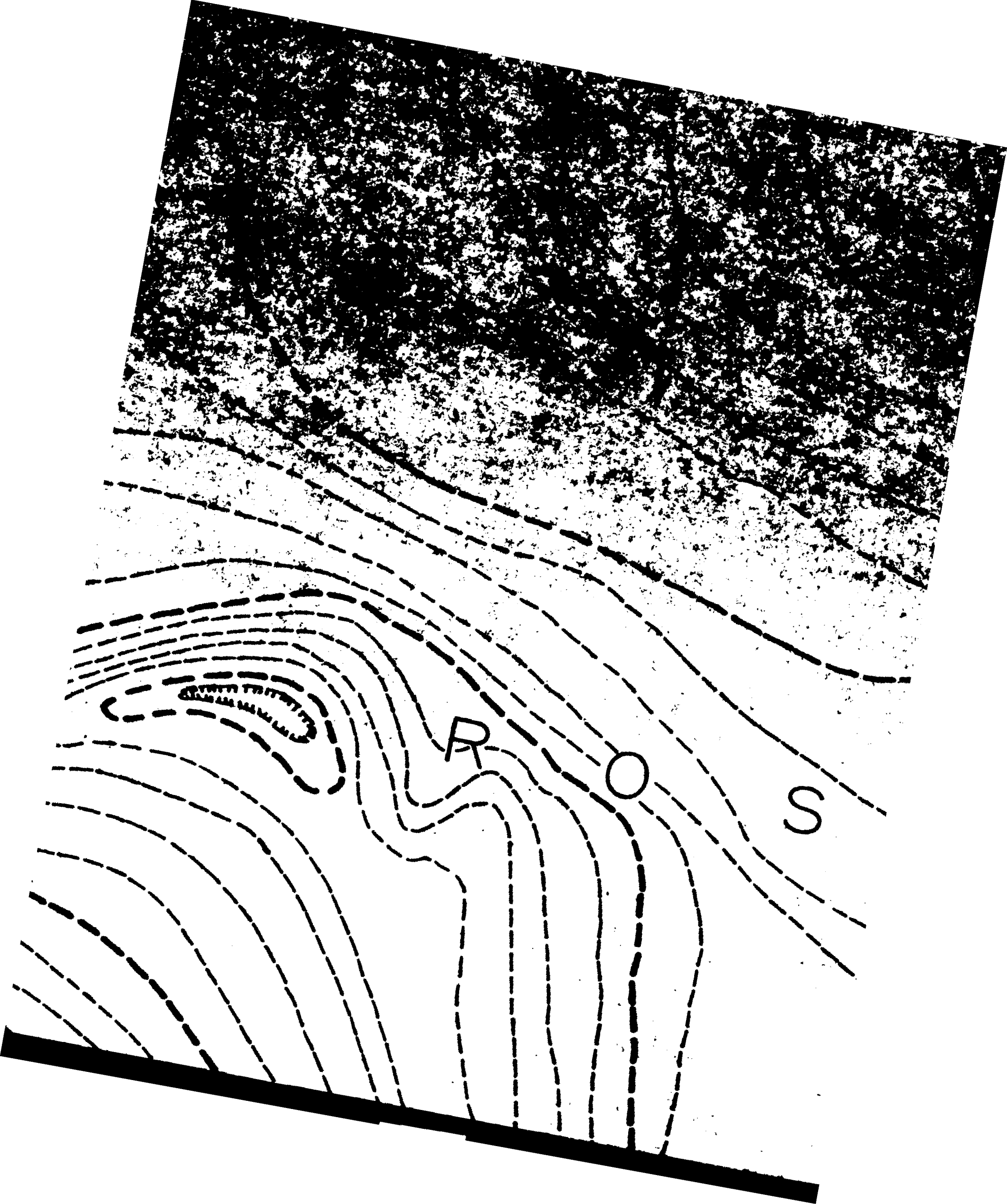
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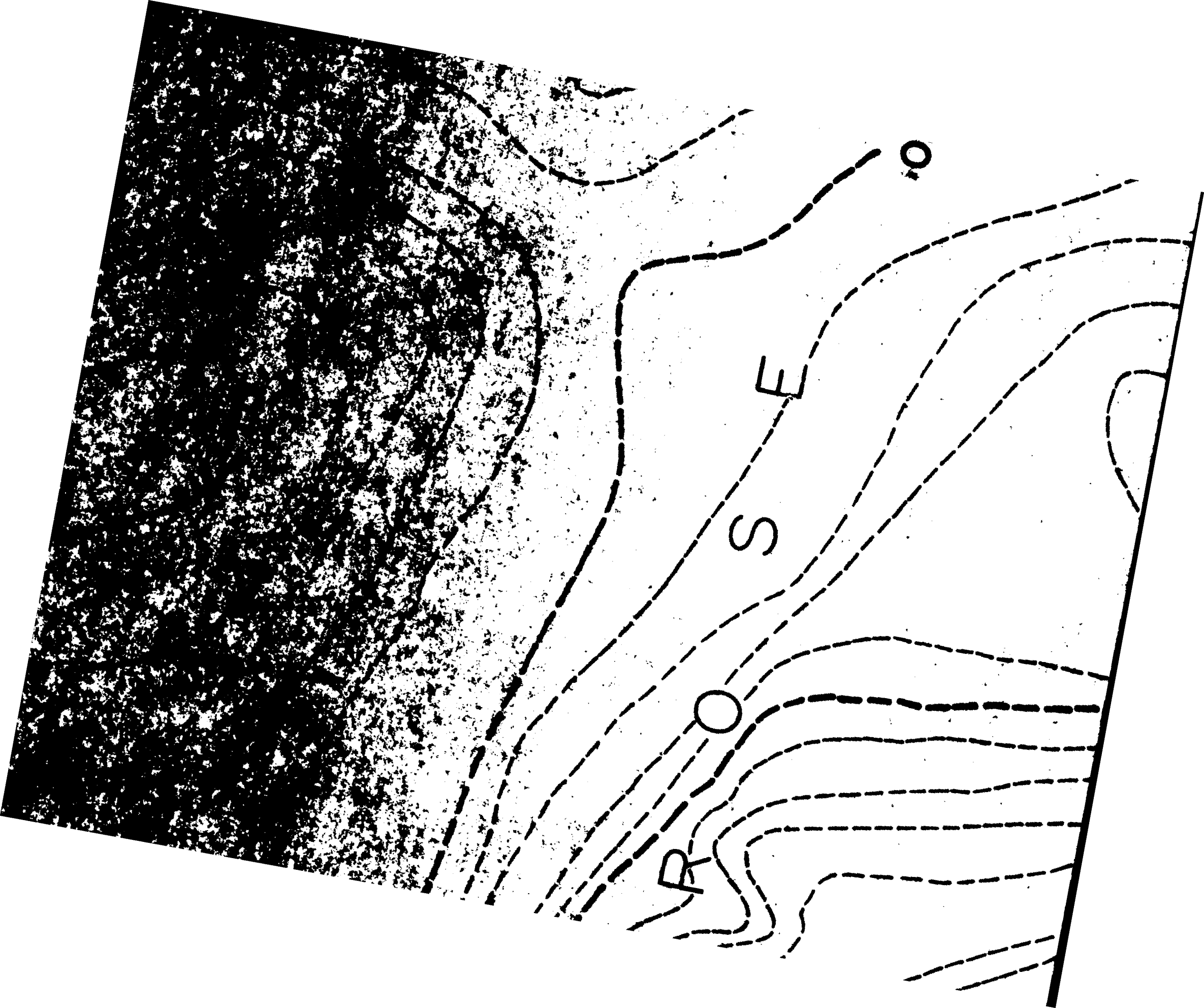


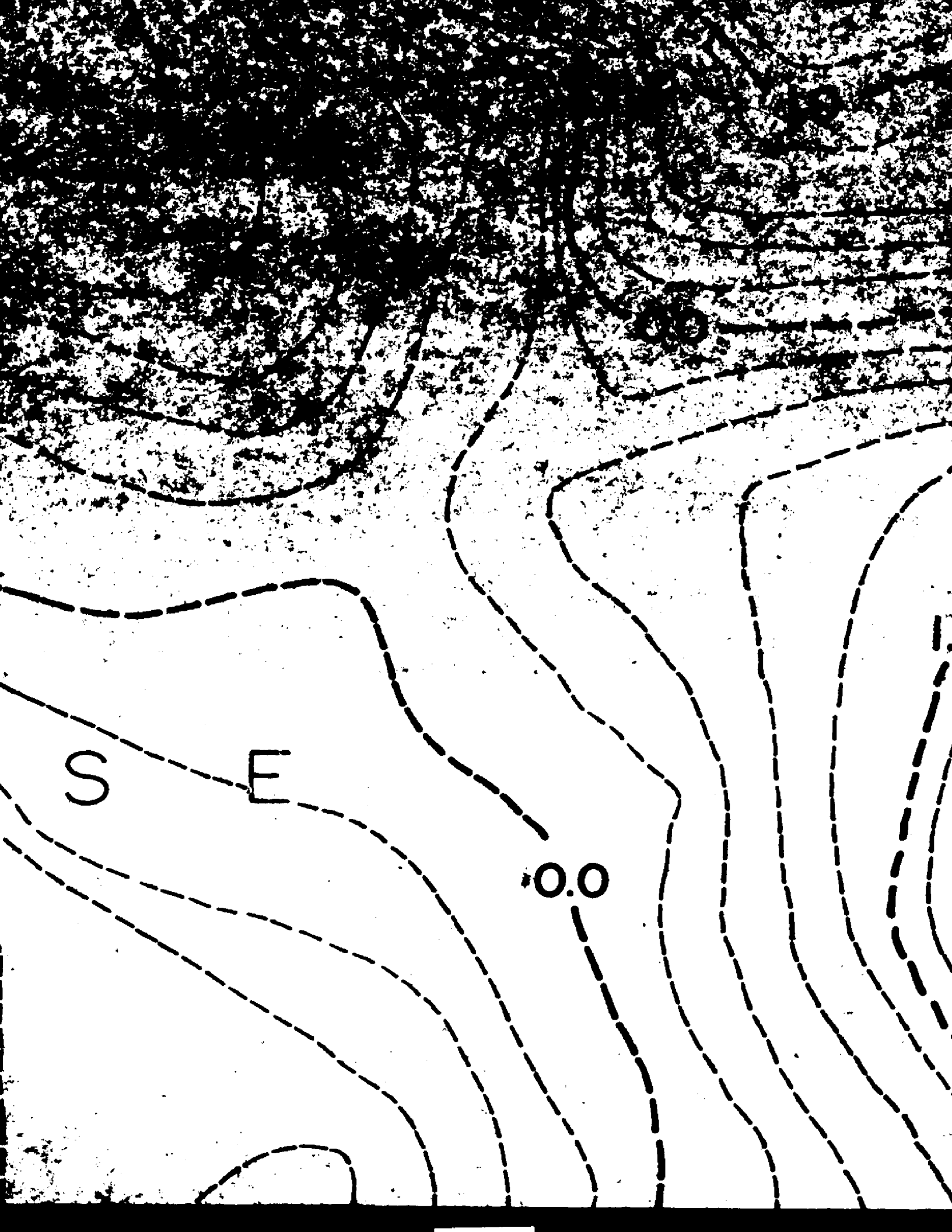


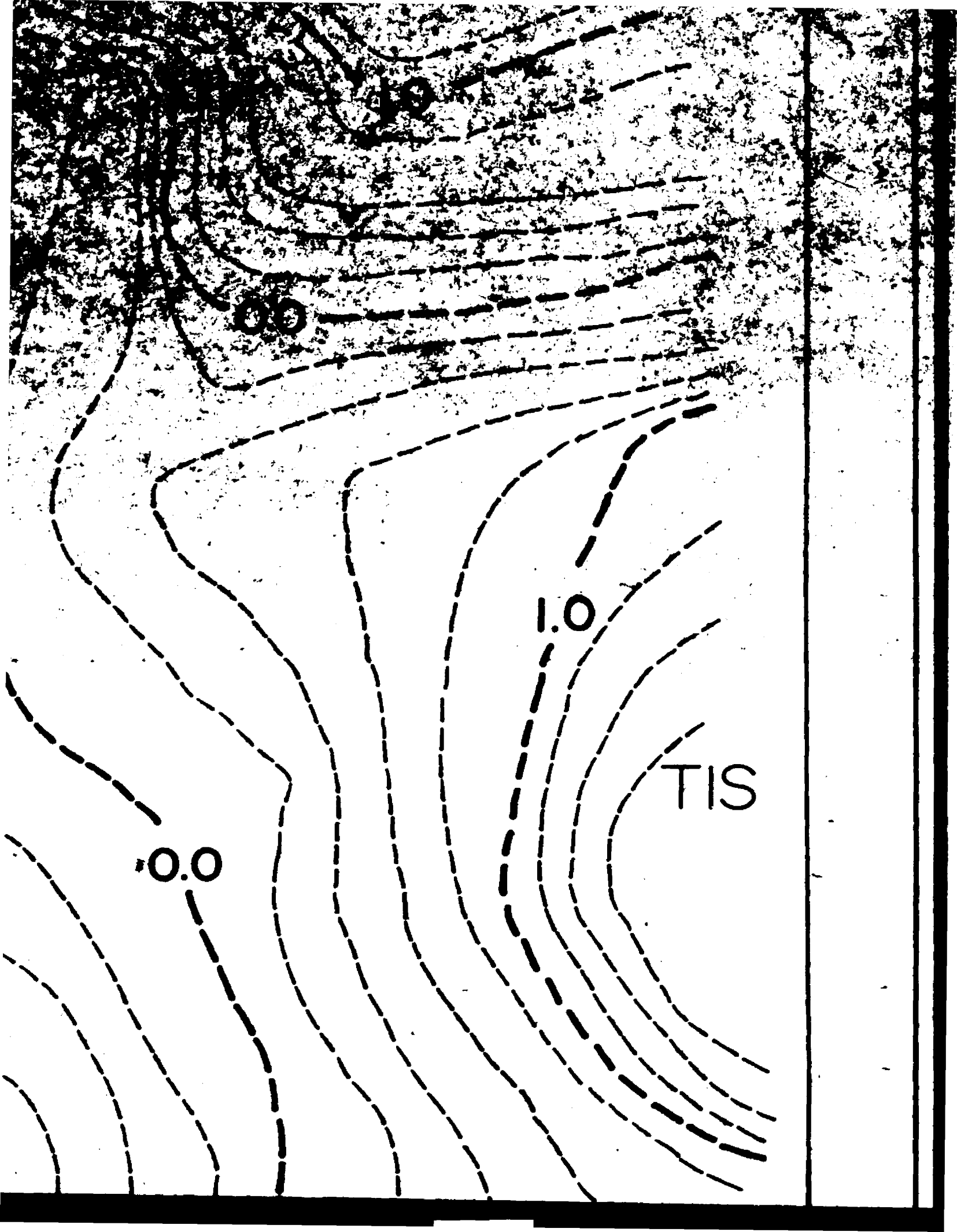












20'

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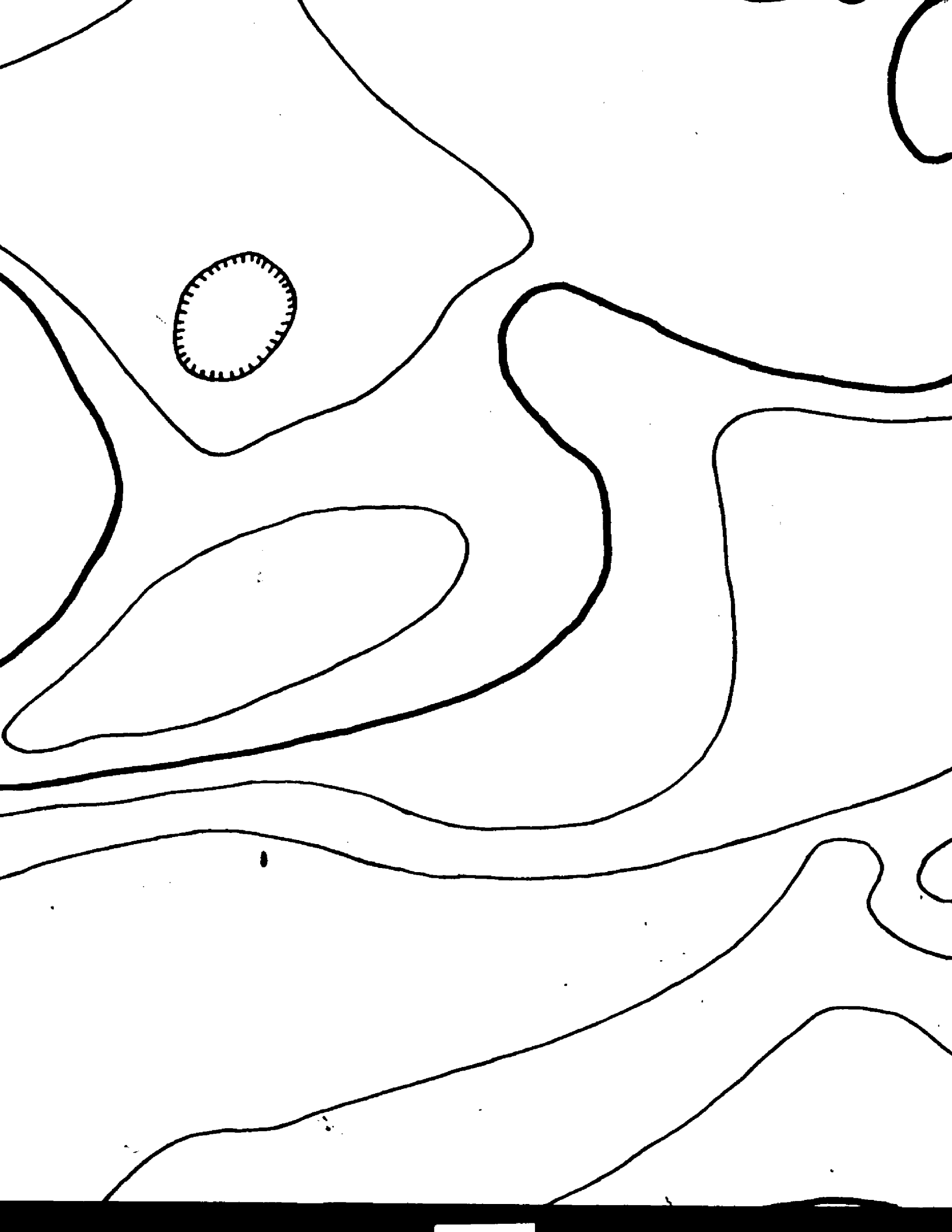




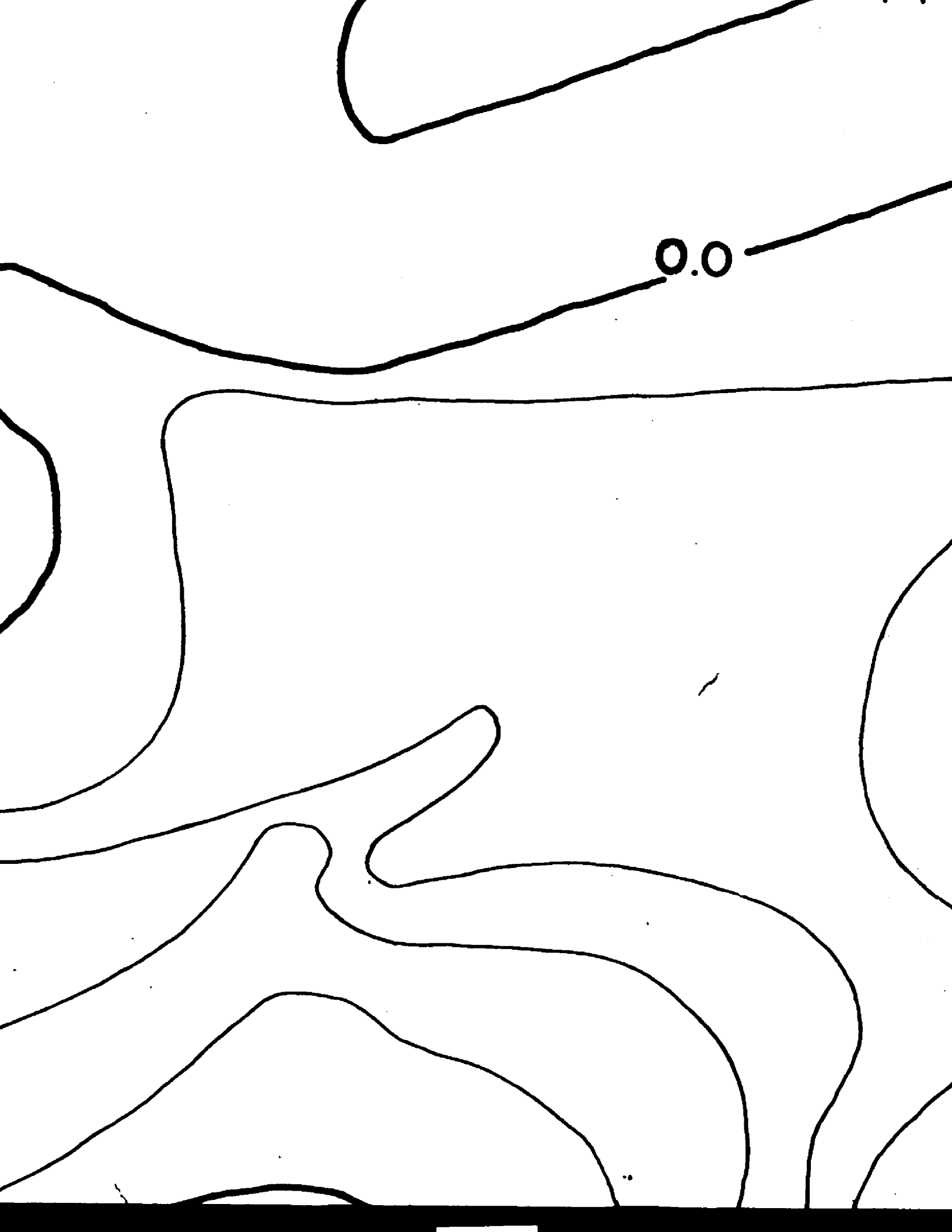


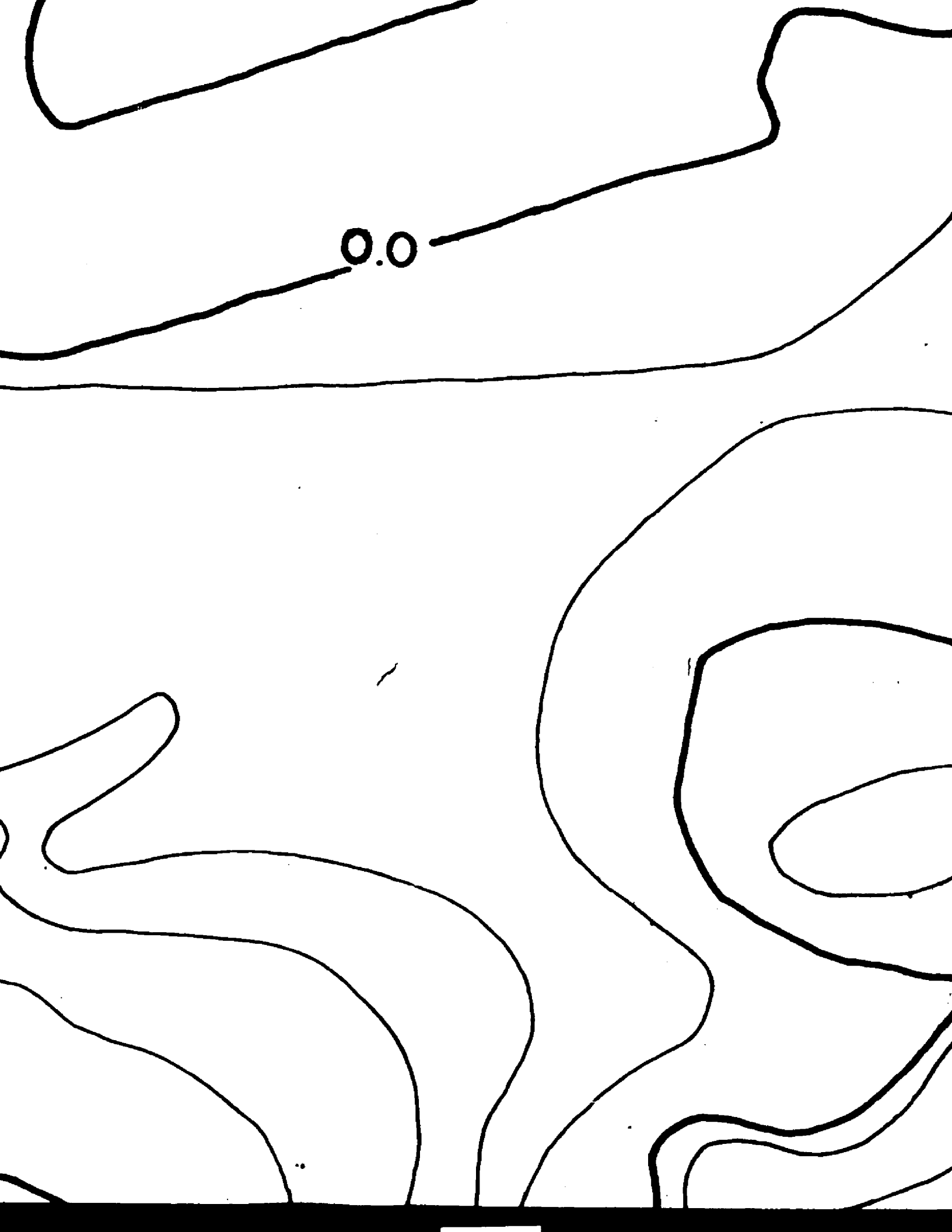


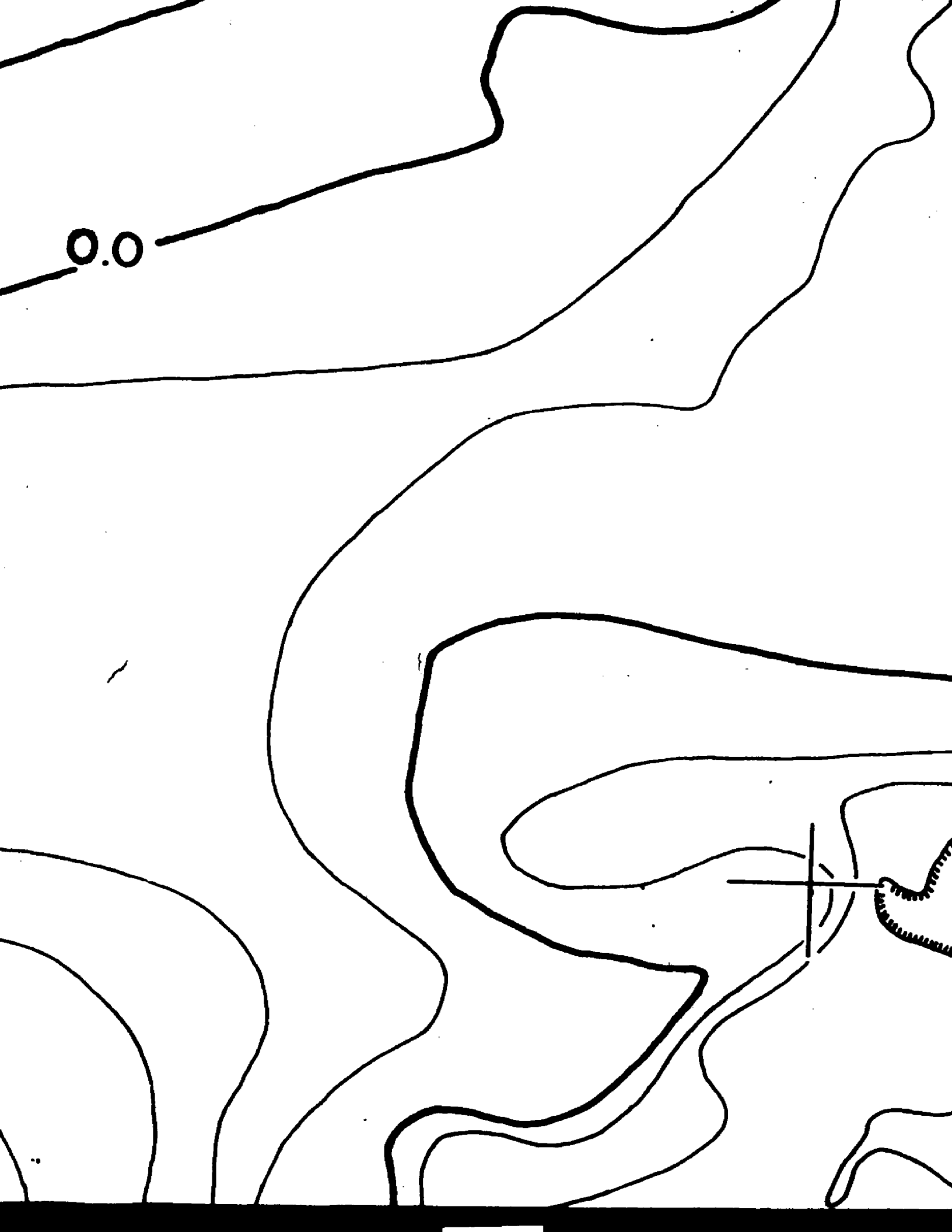




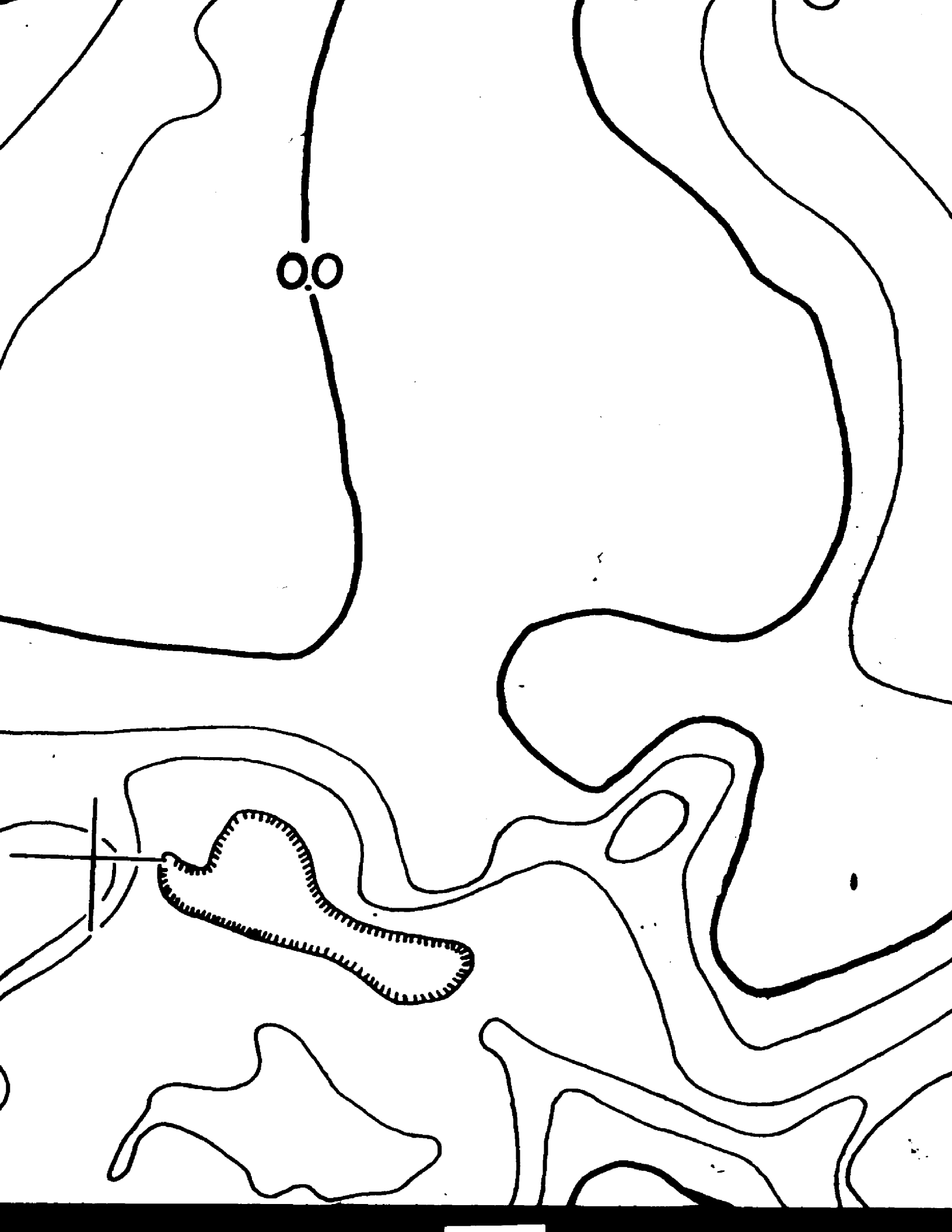








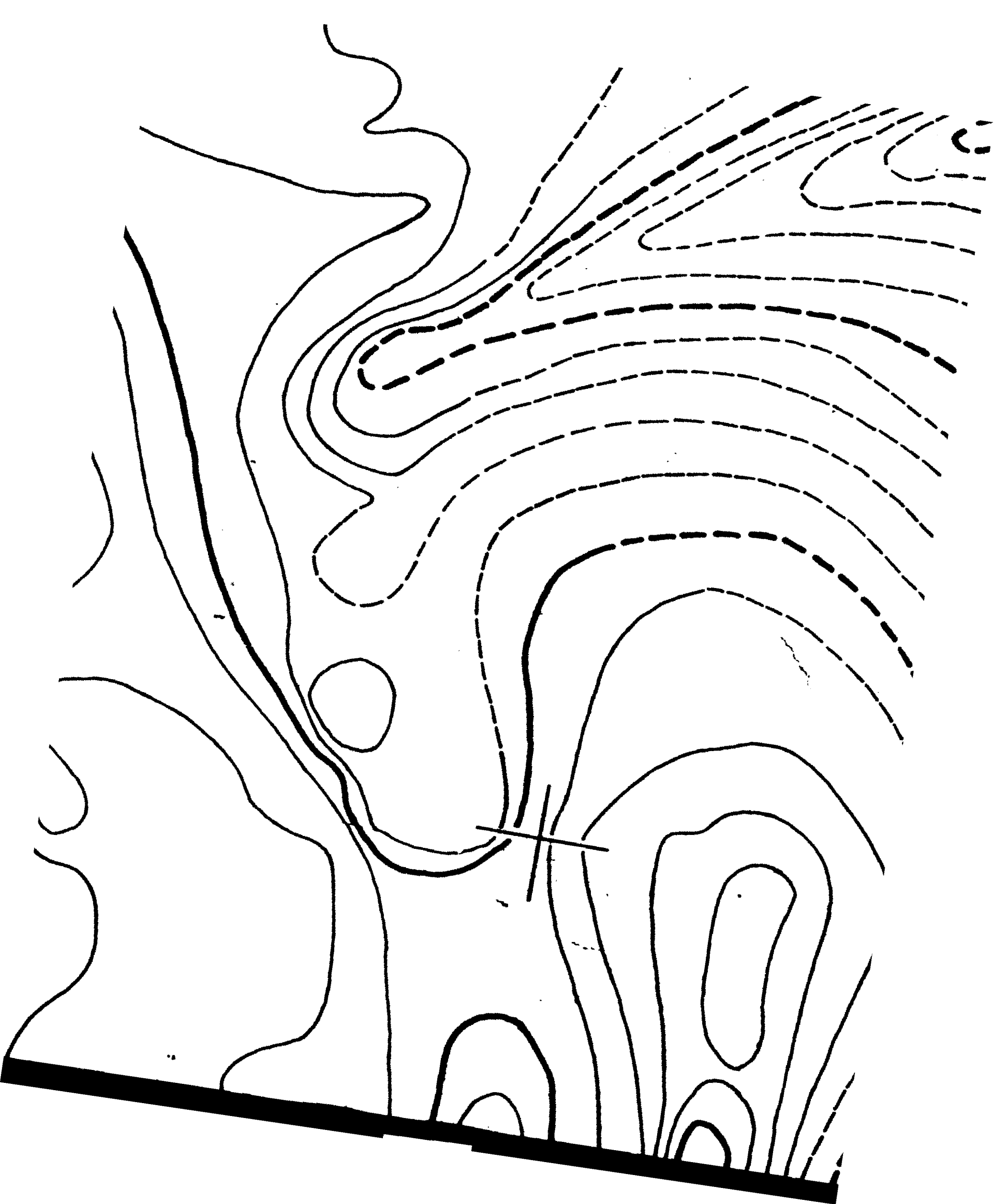


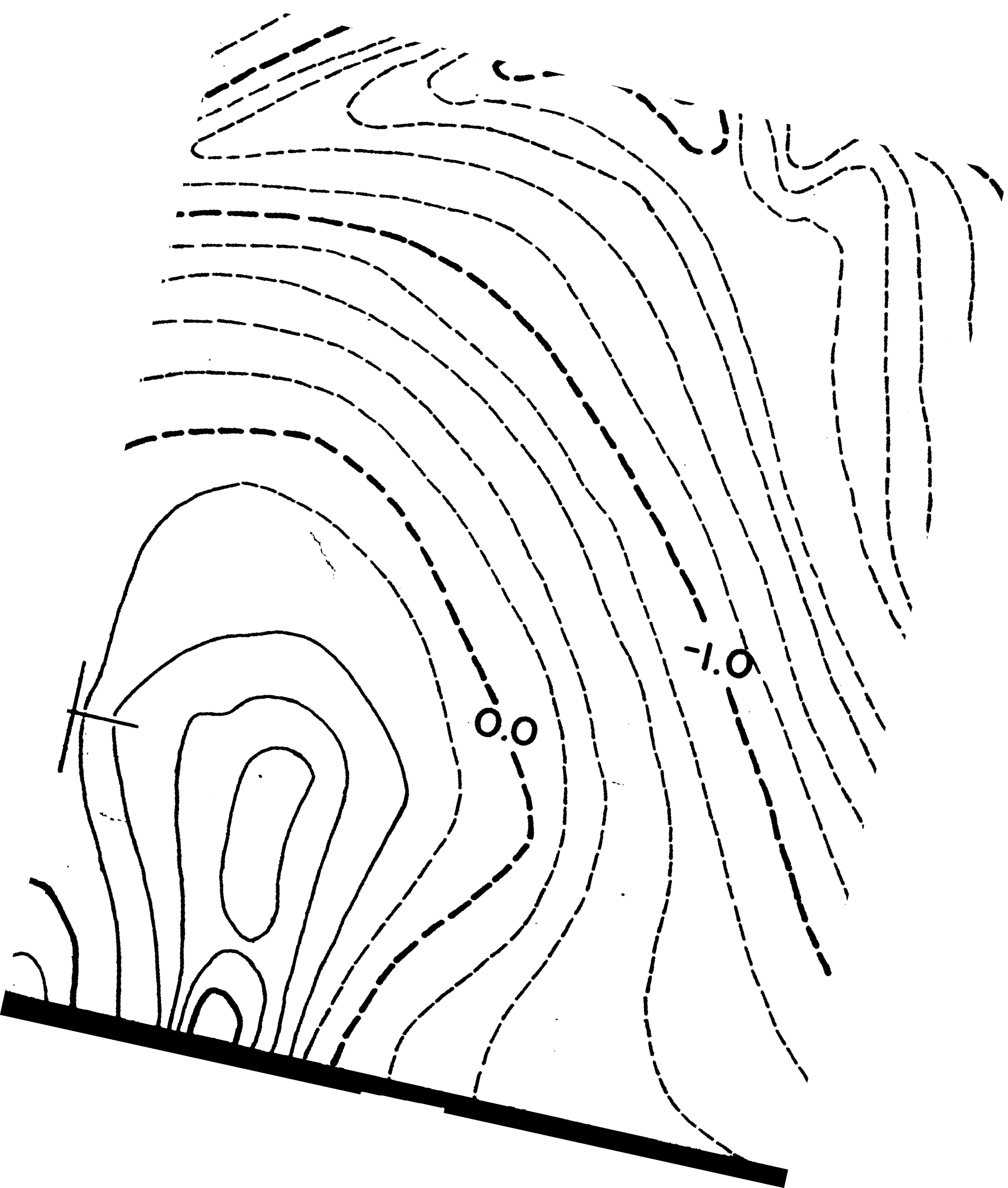


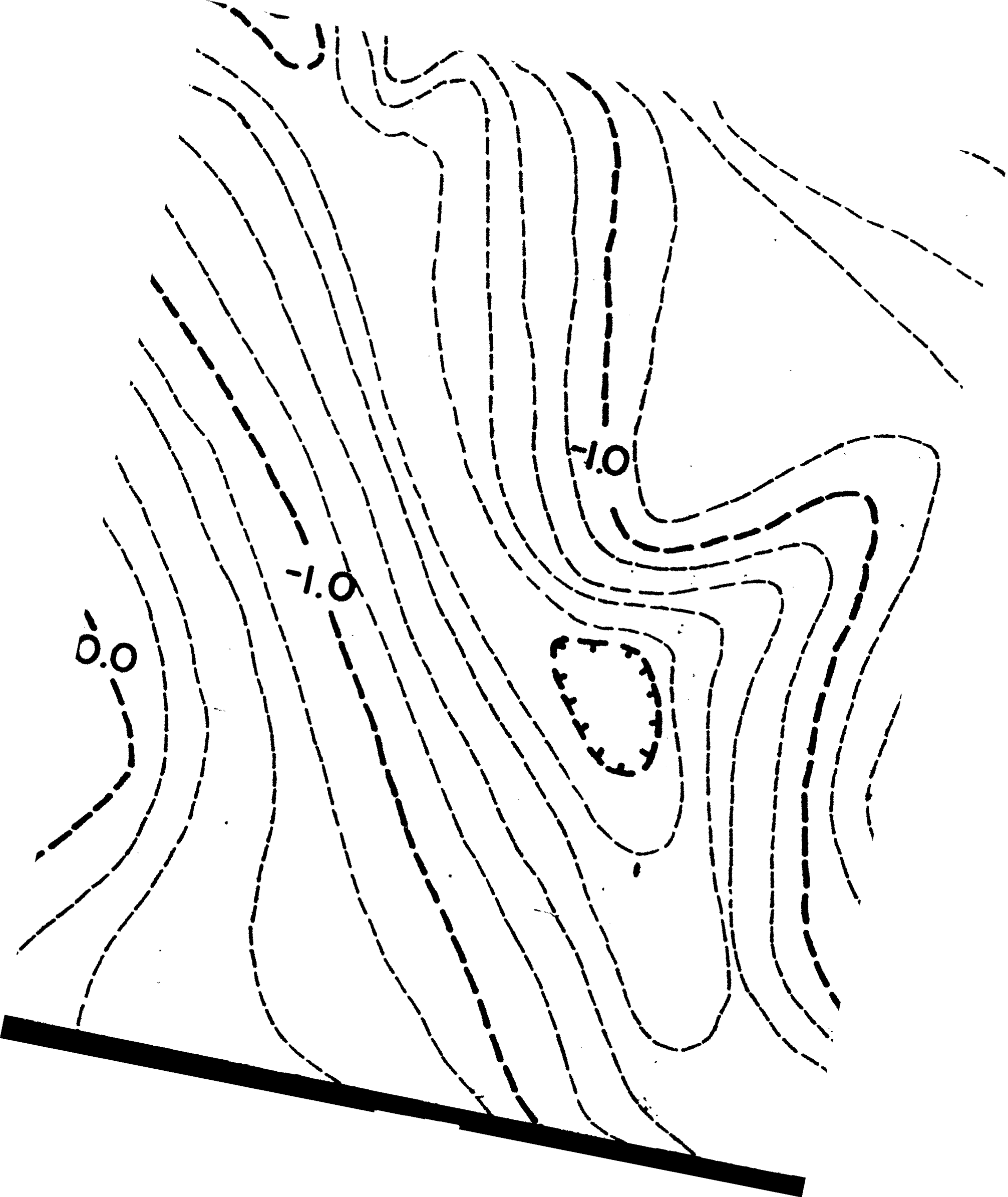


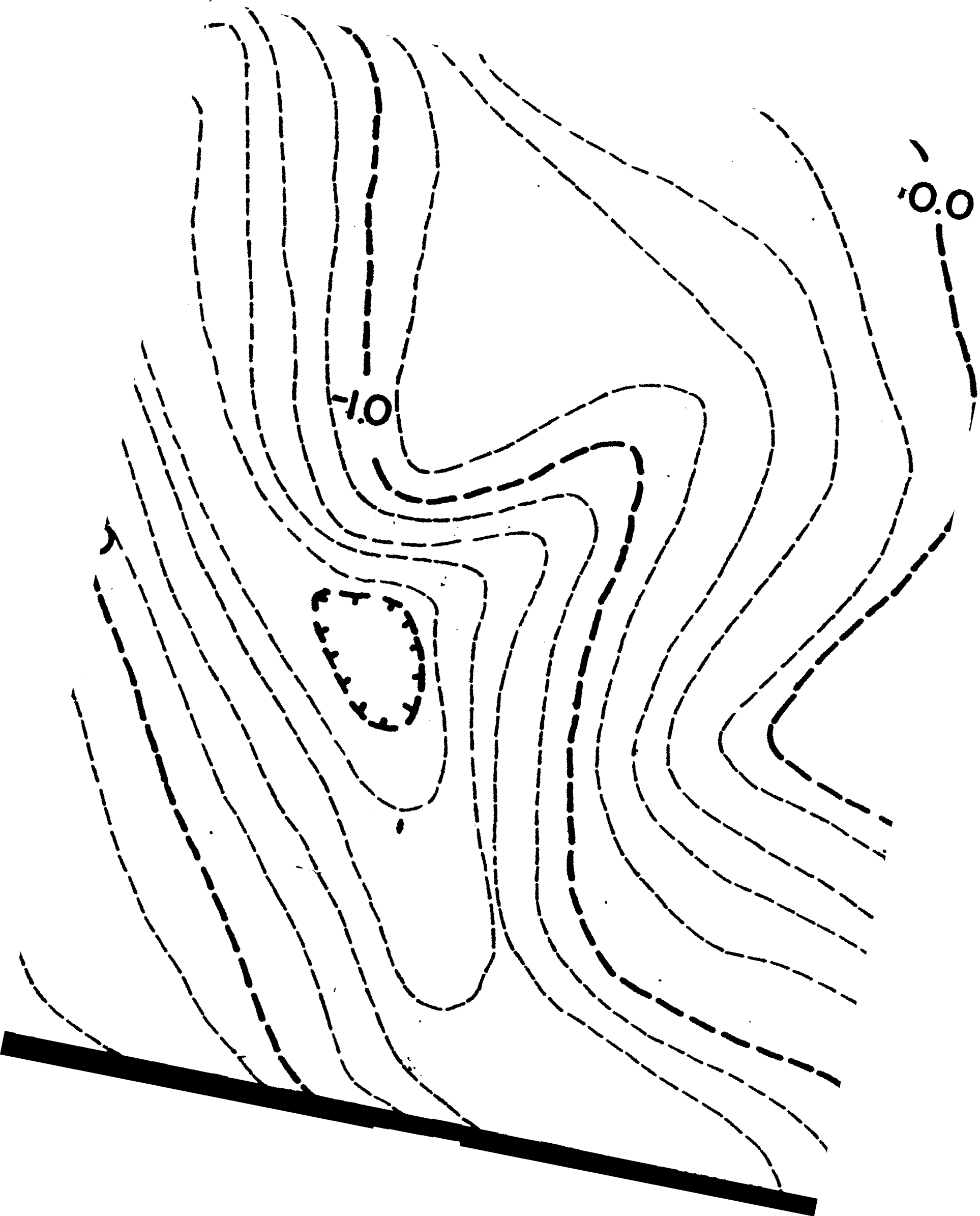


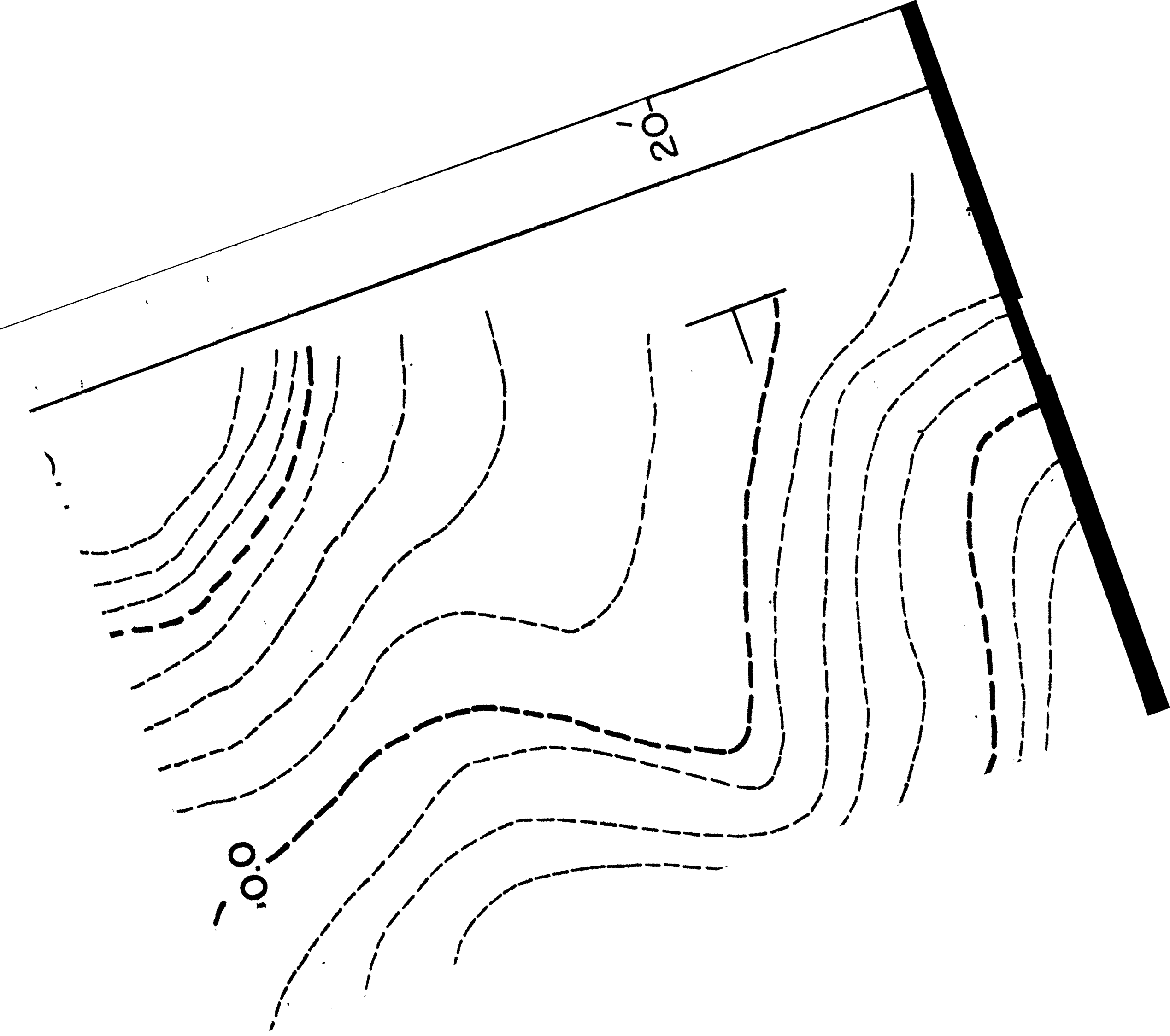








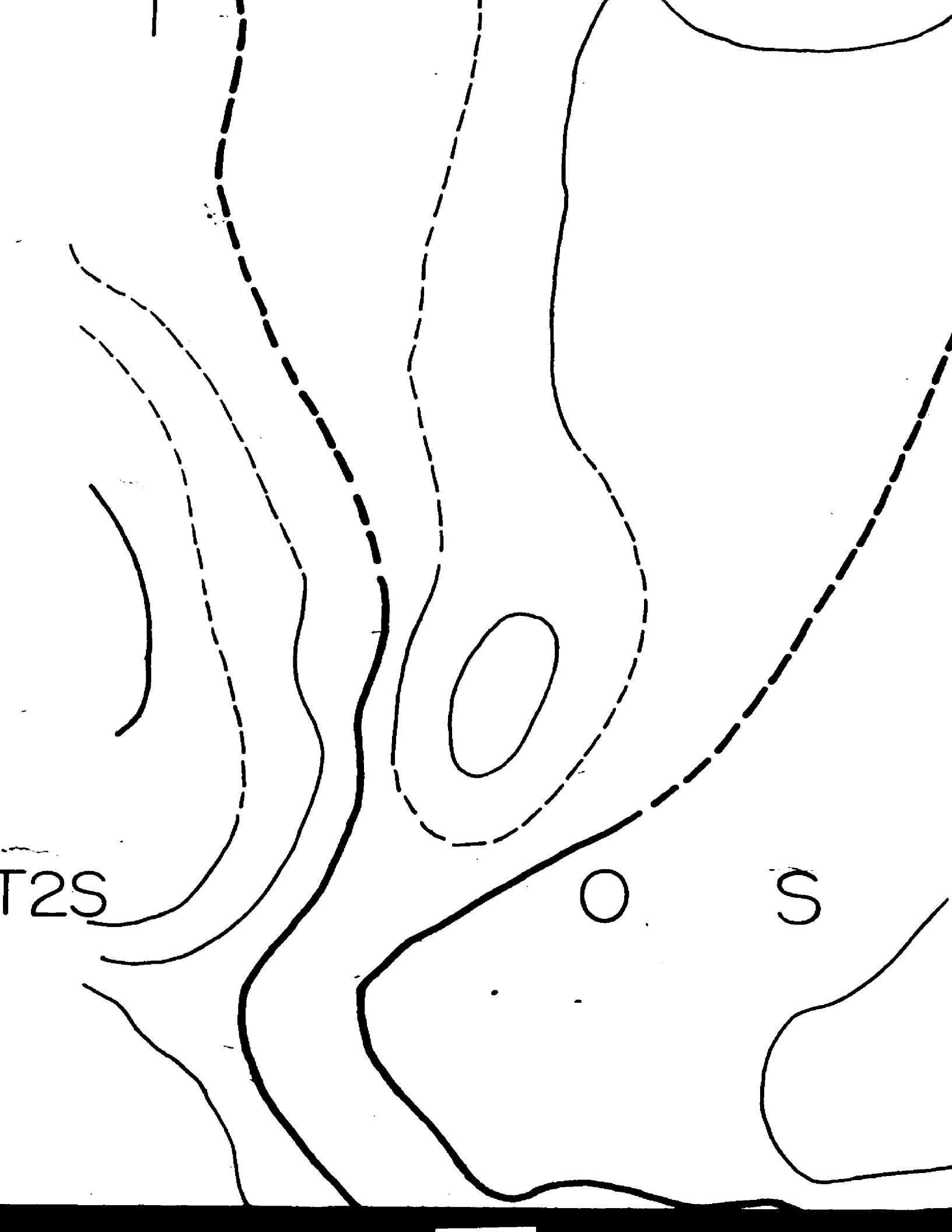


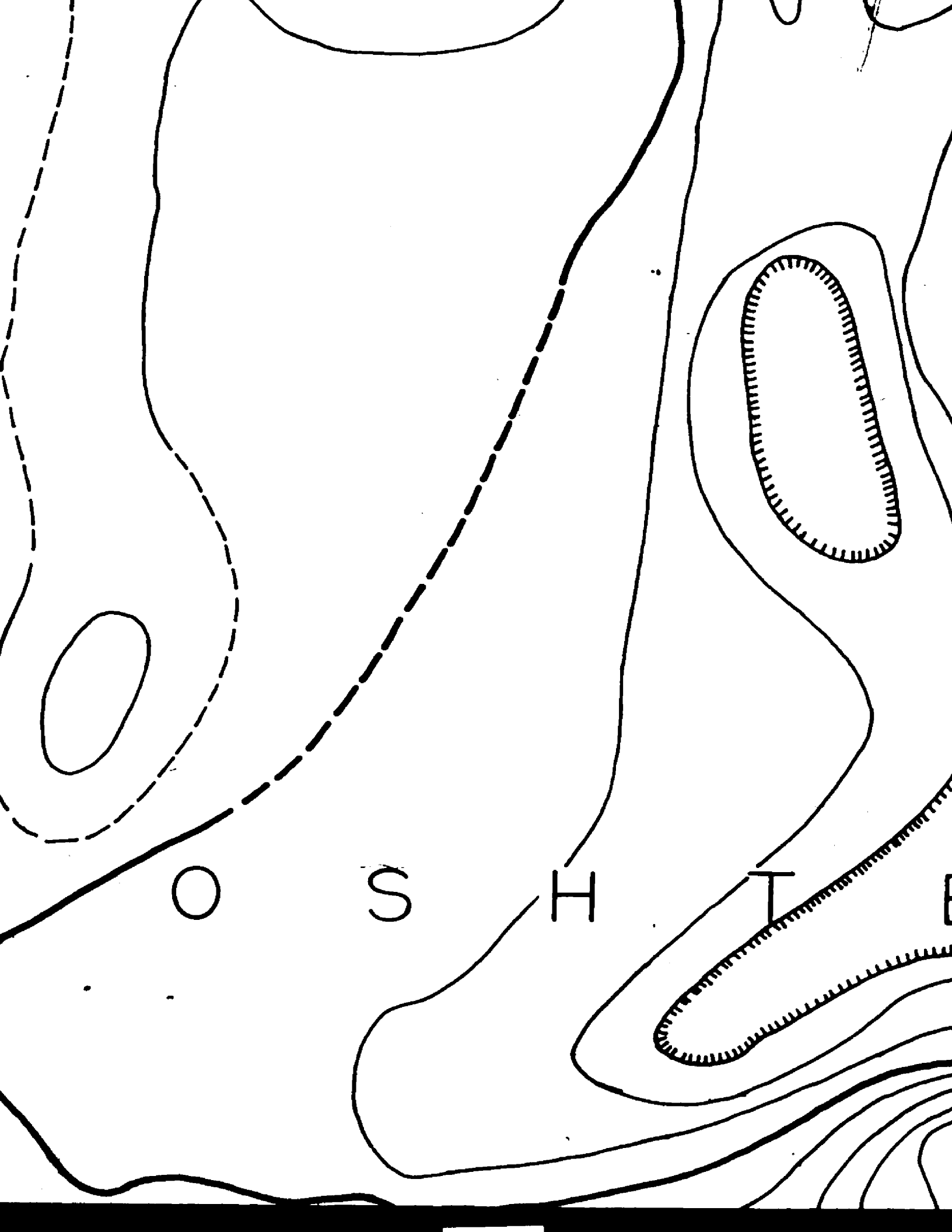


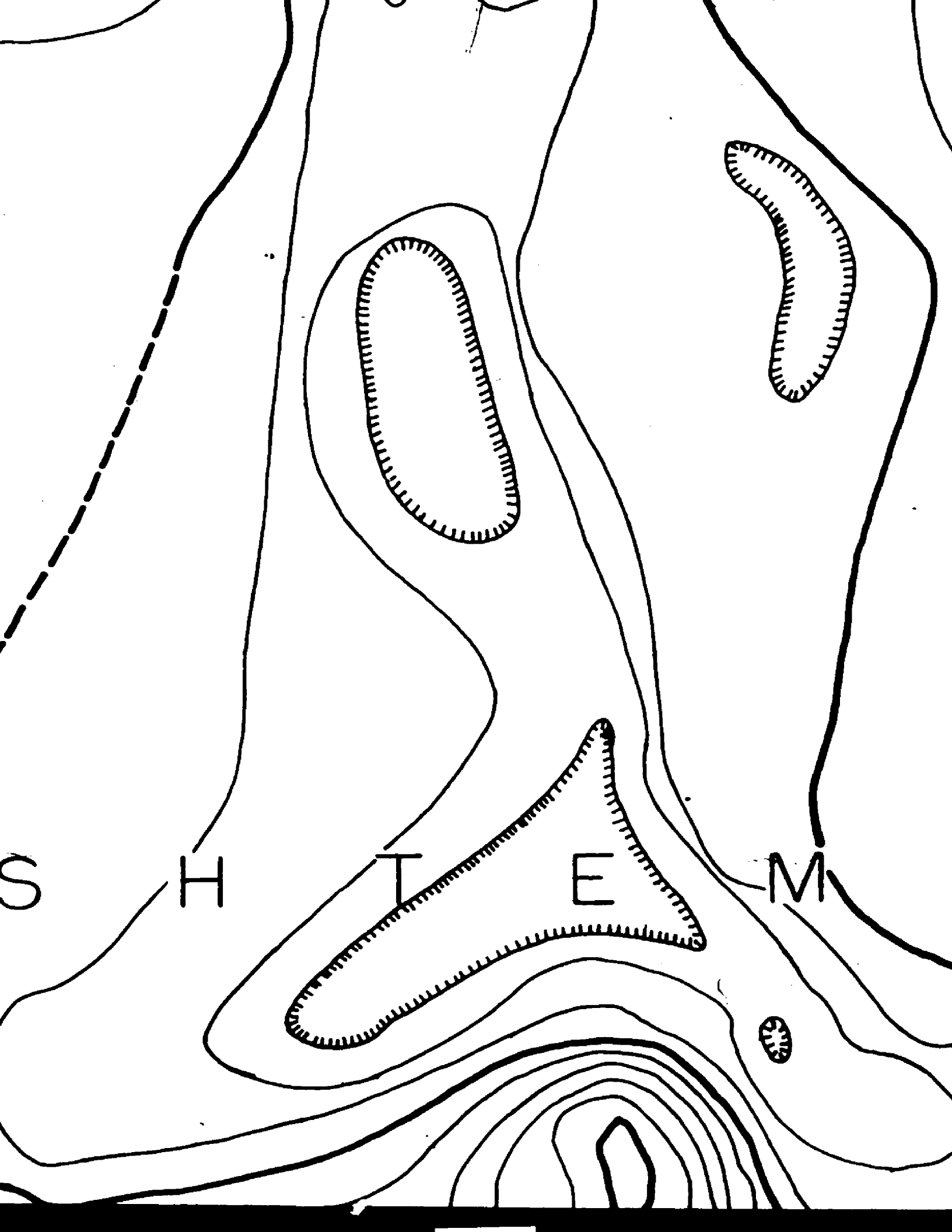
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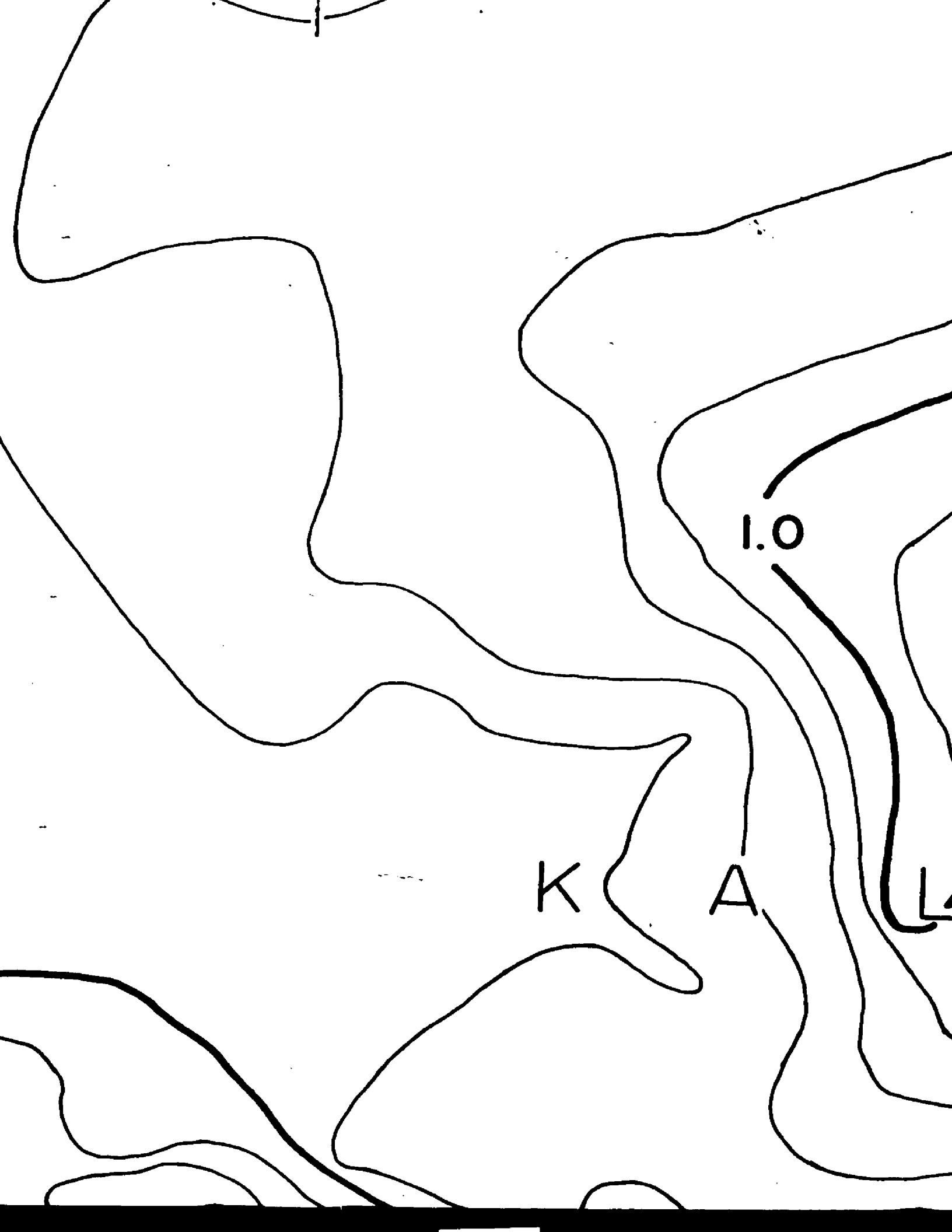


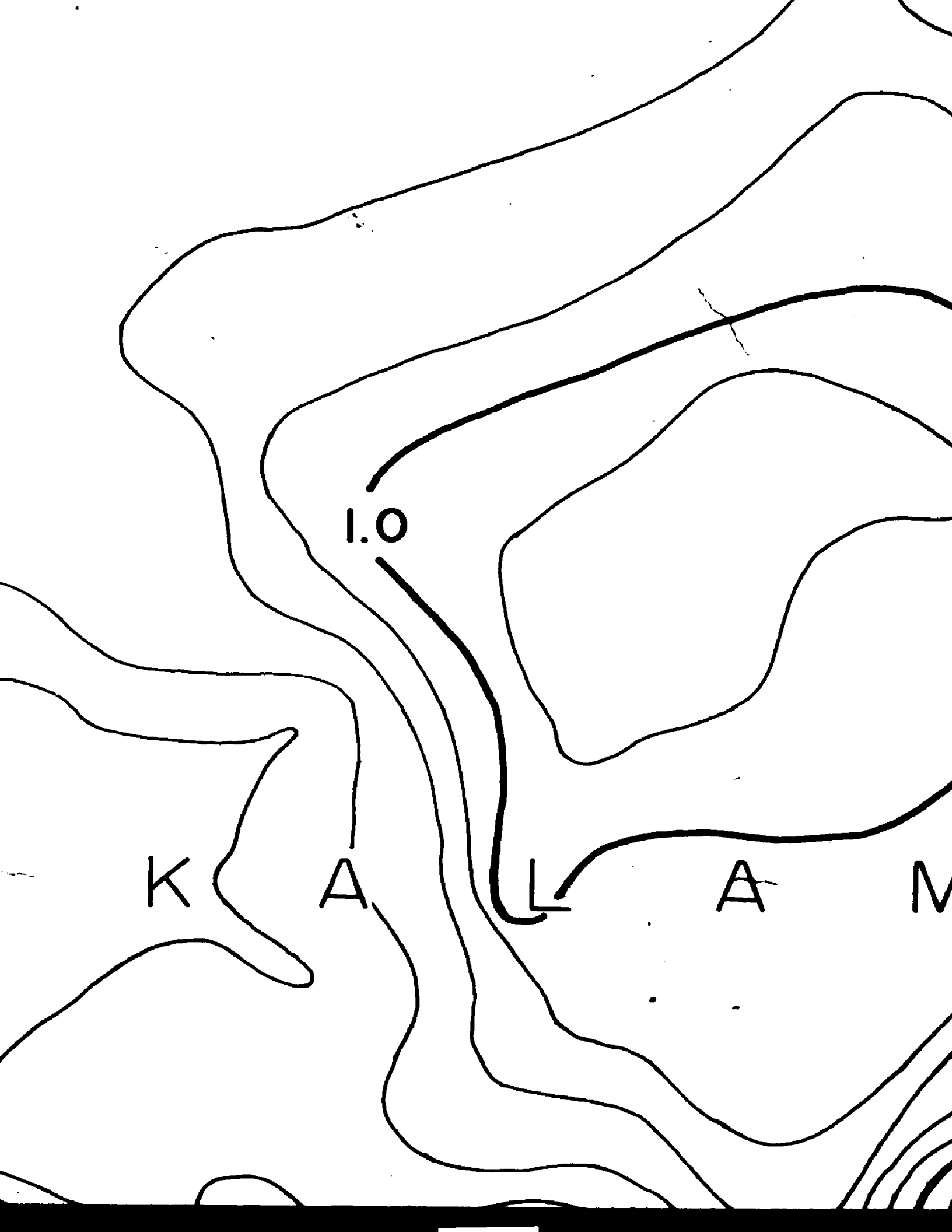


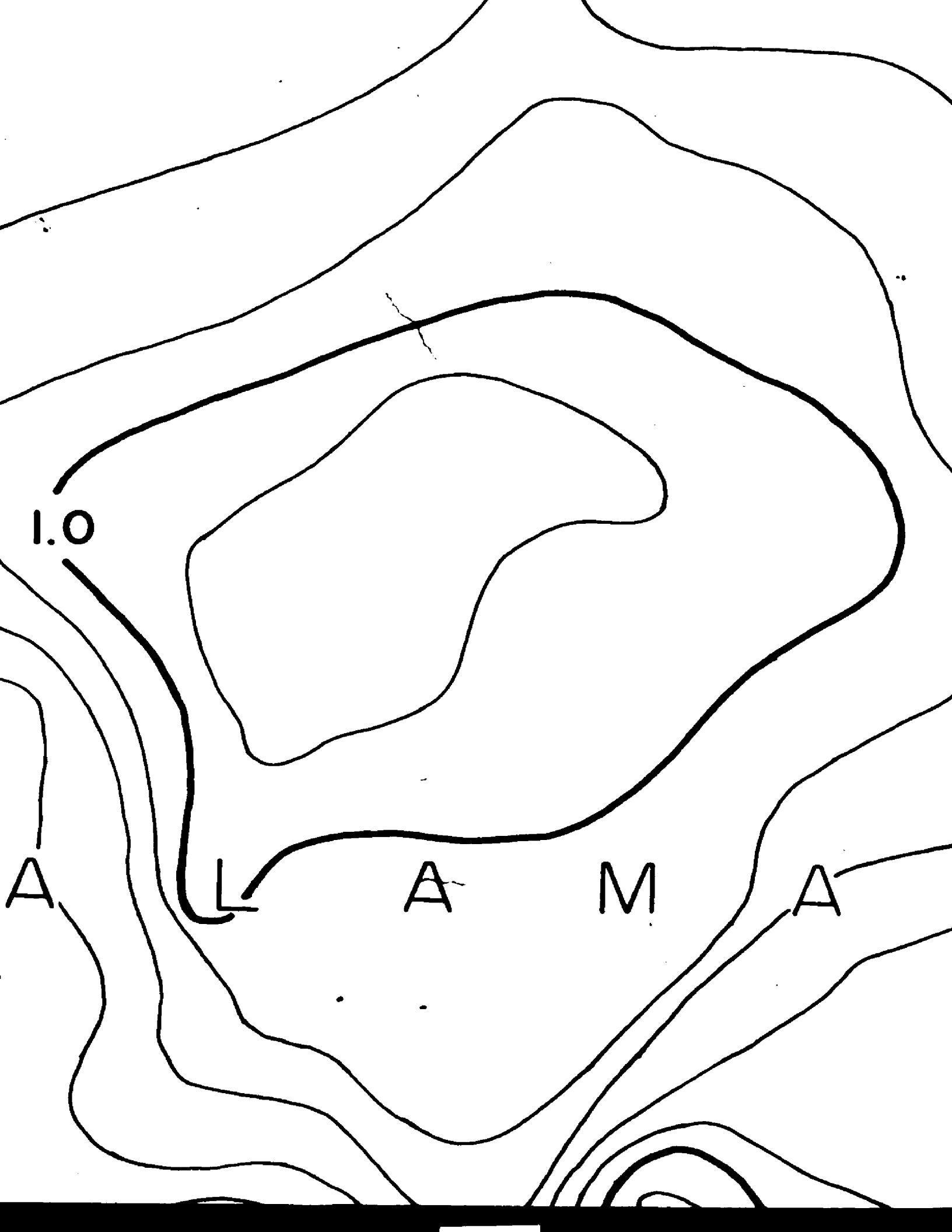


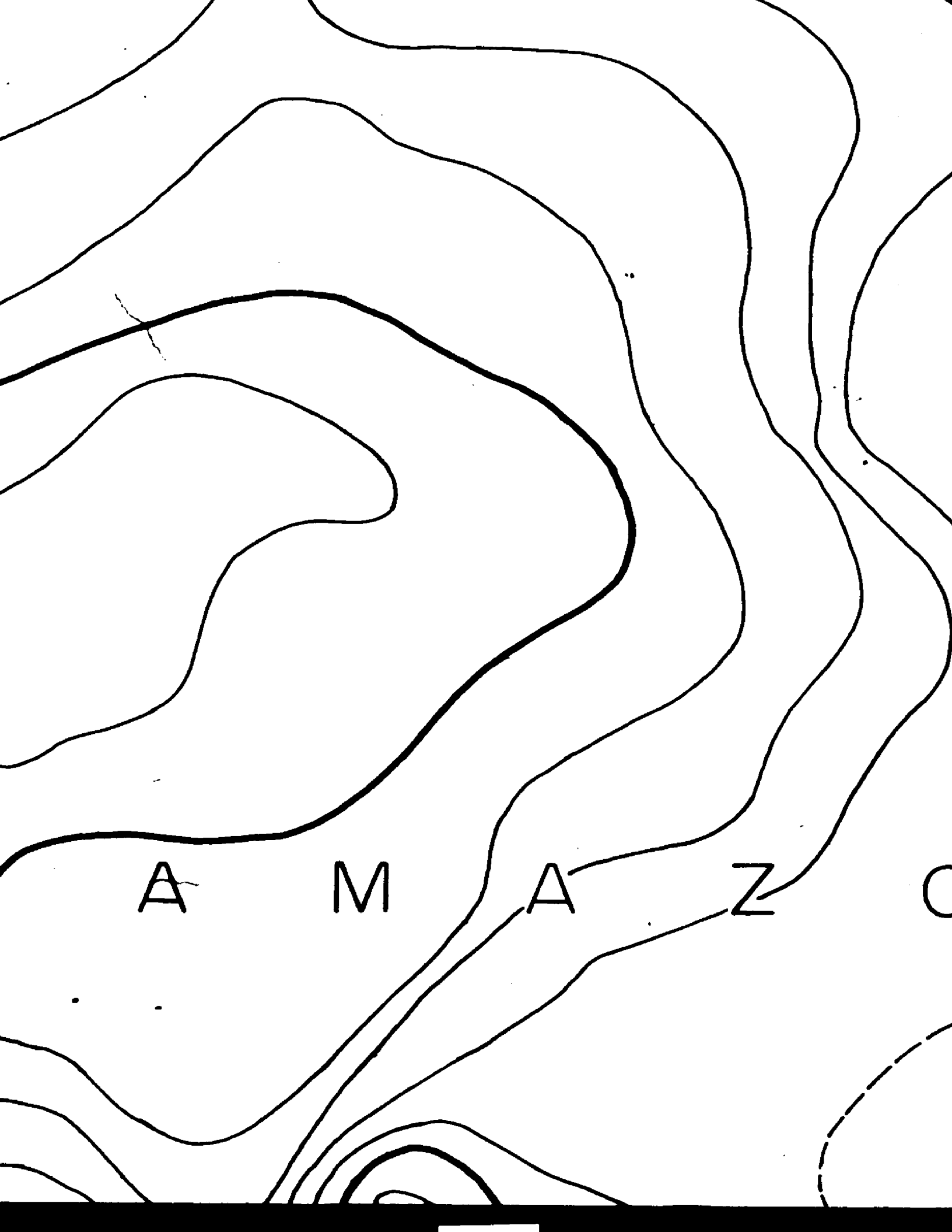












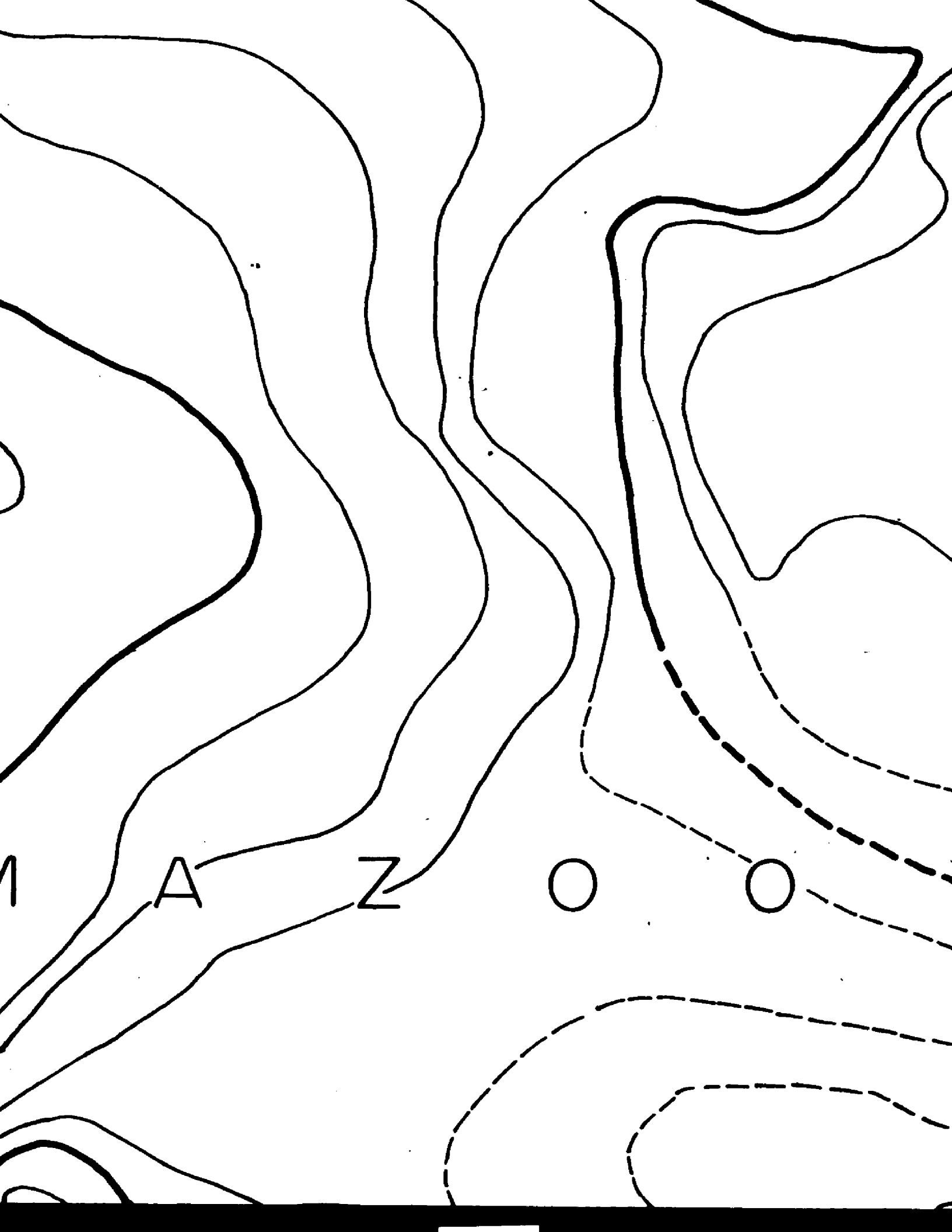
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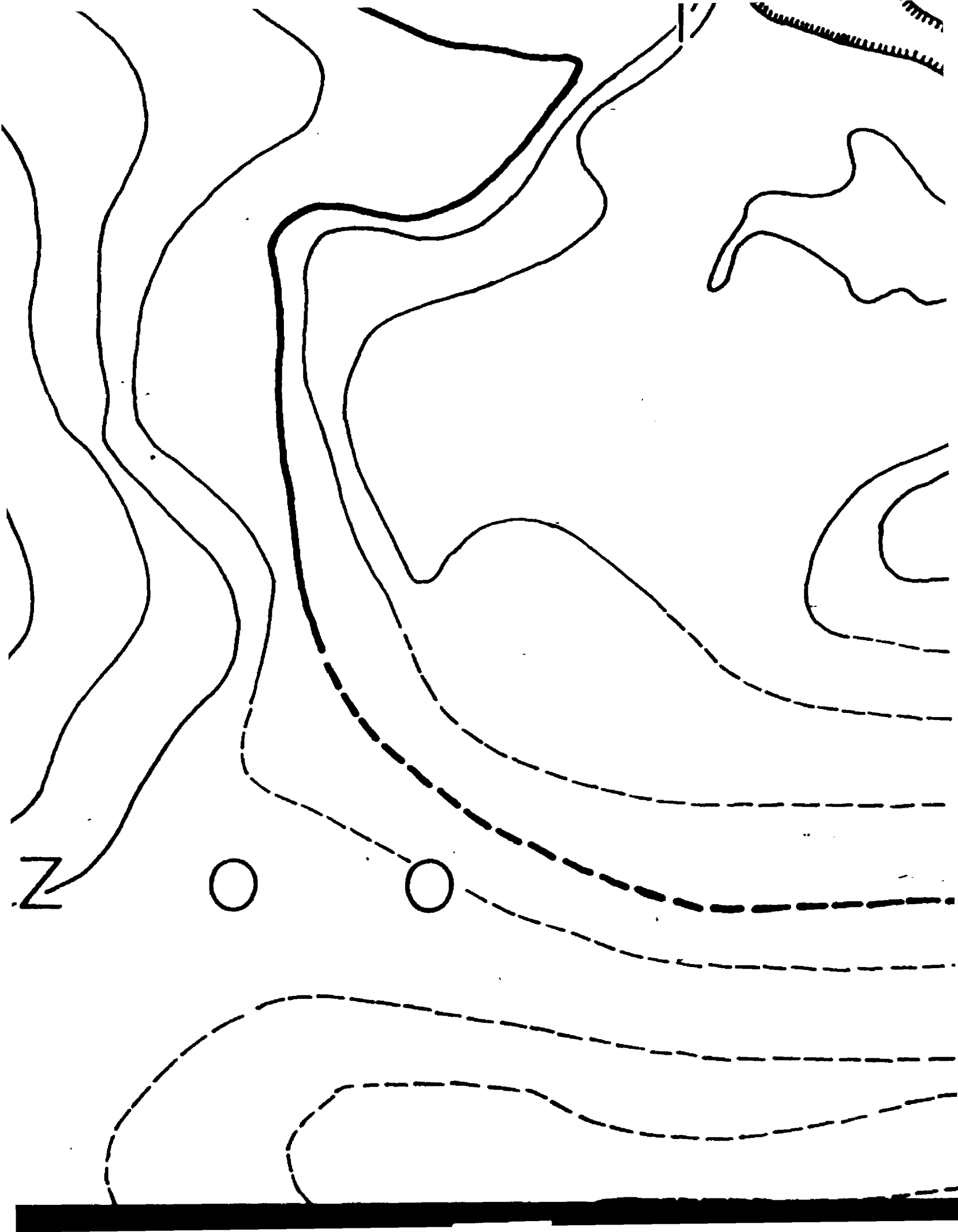
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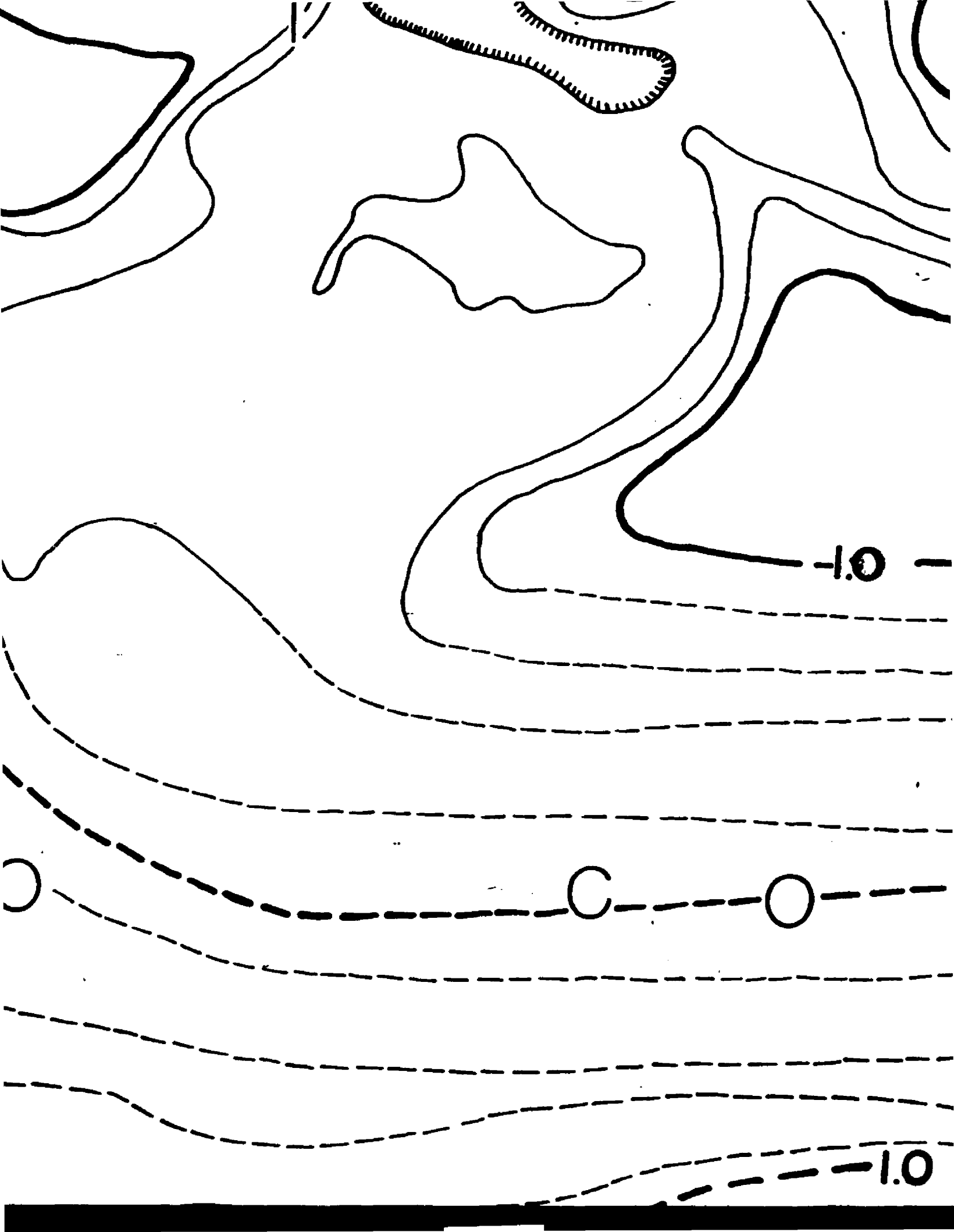
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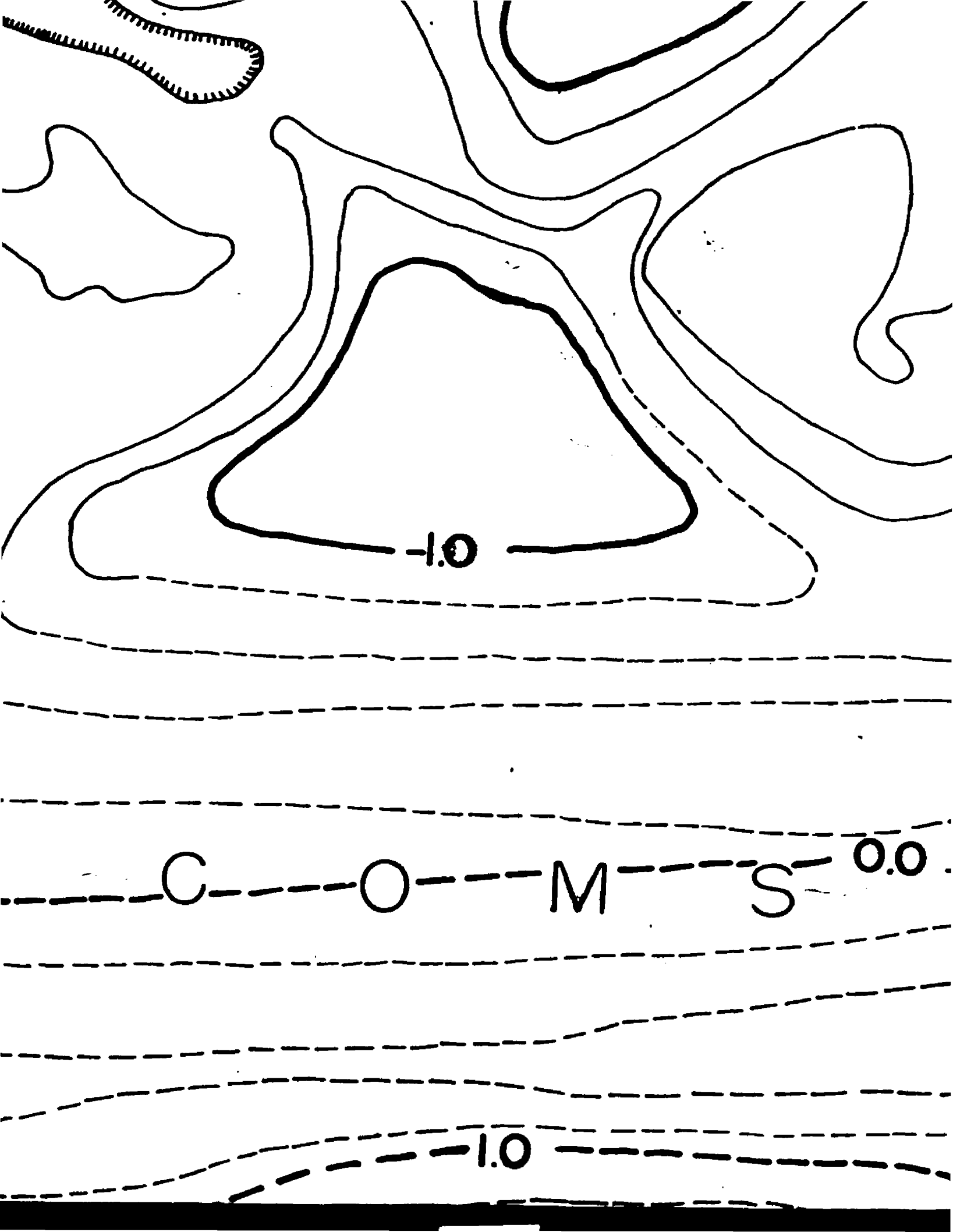
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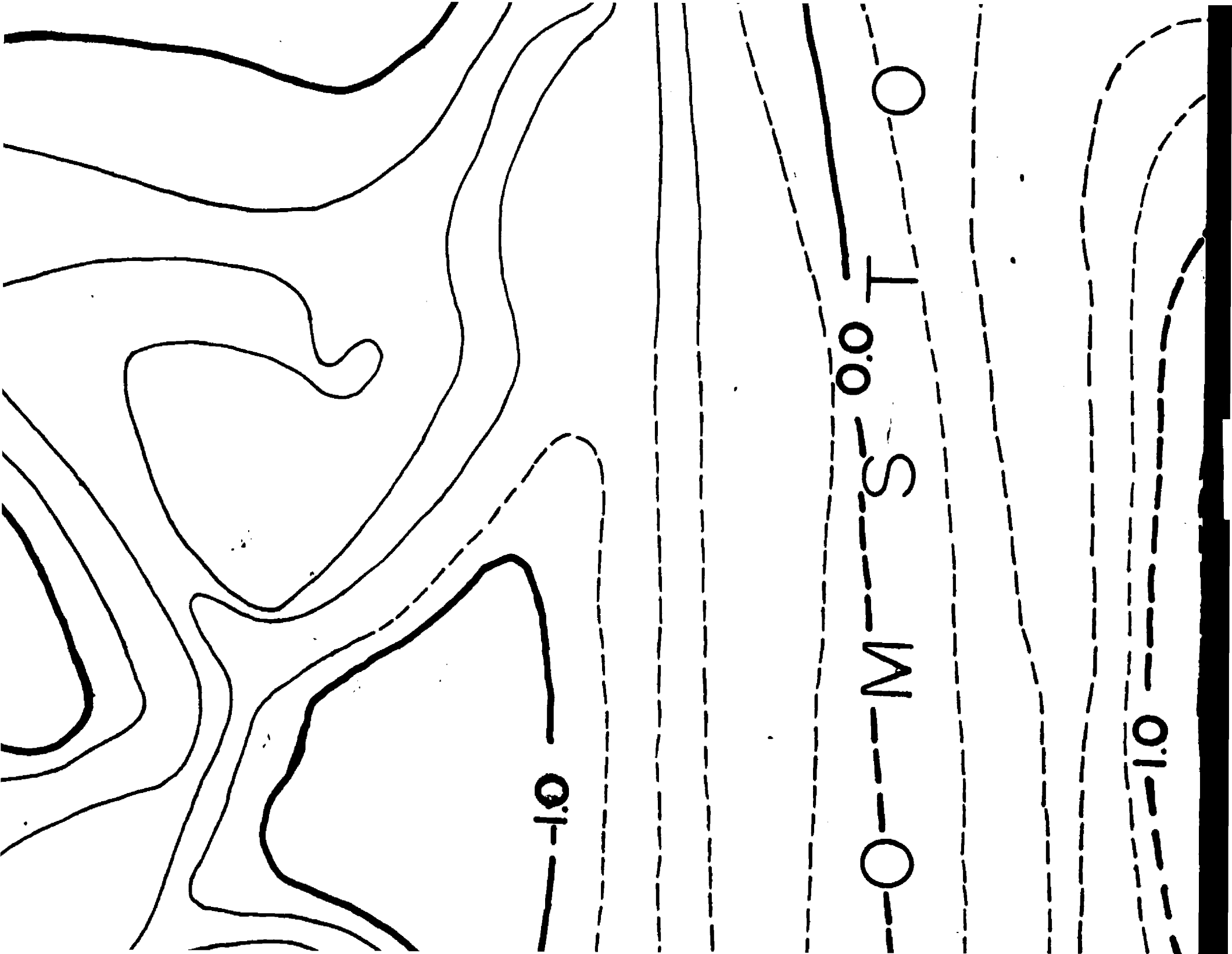
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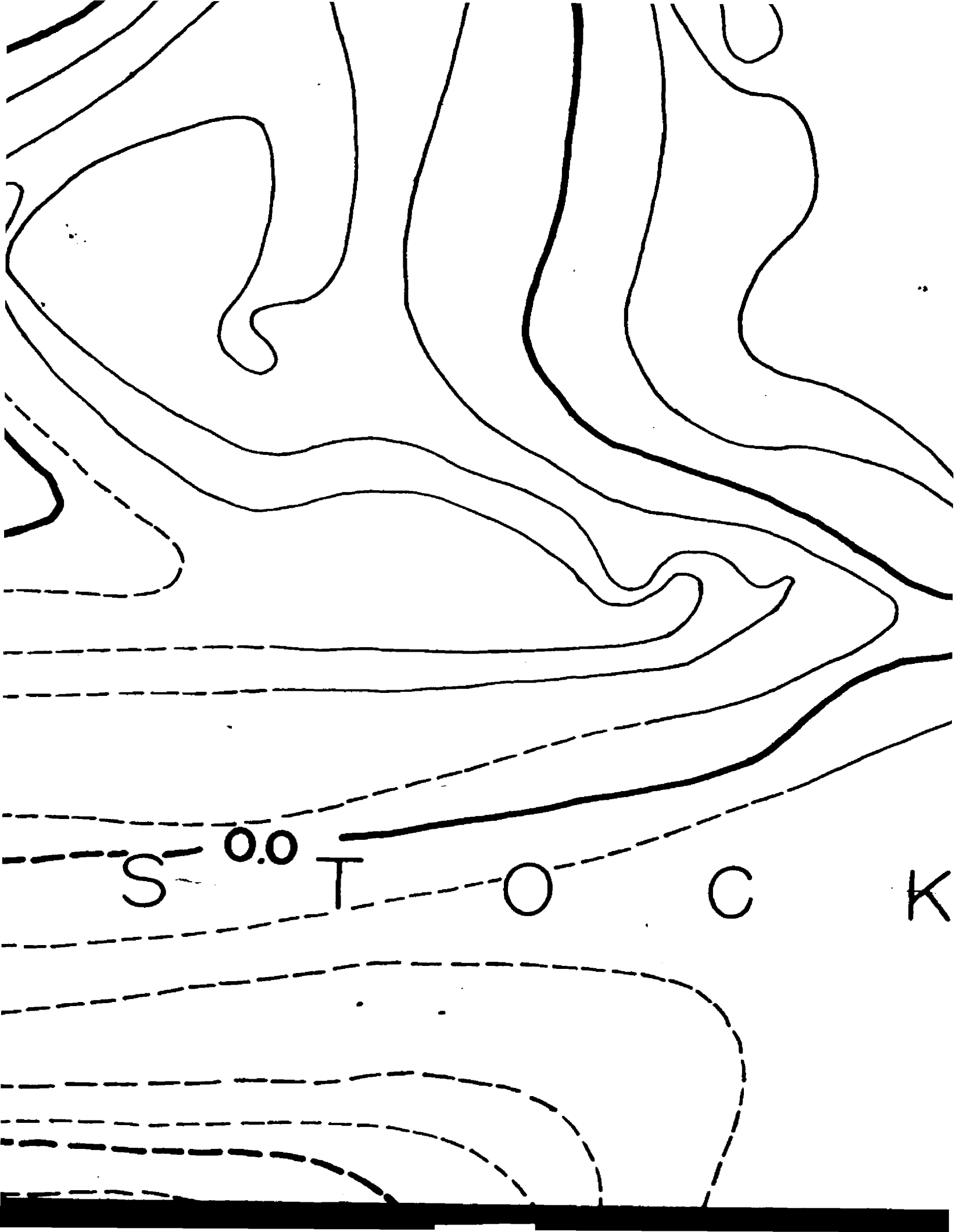












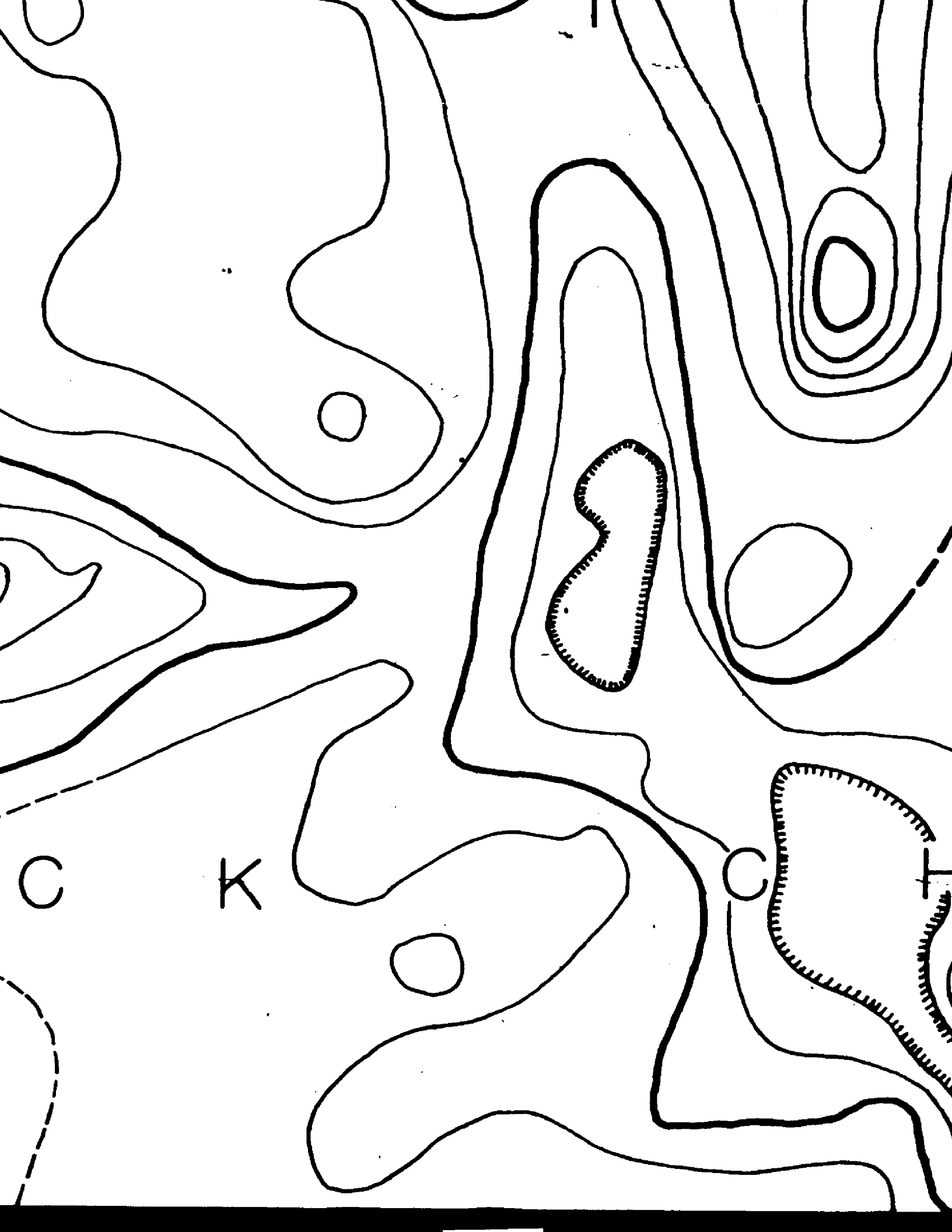


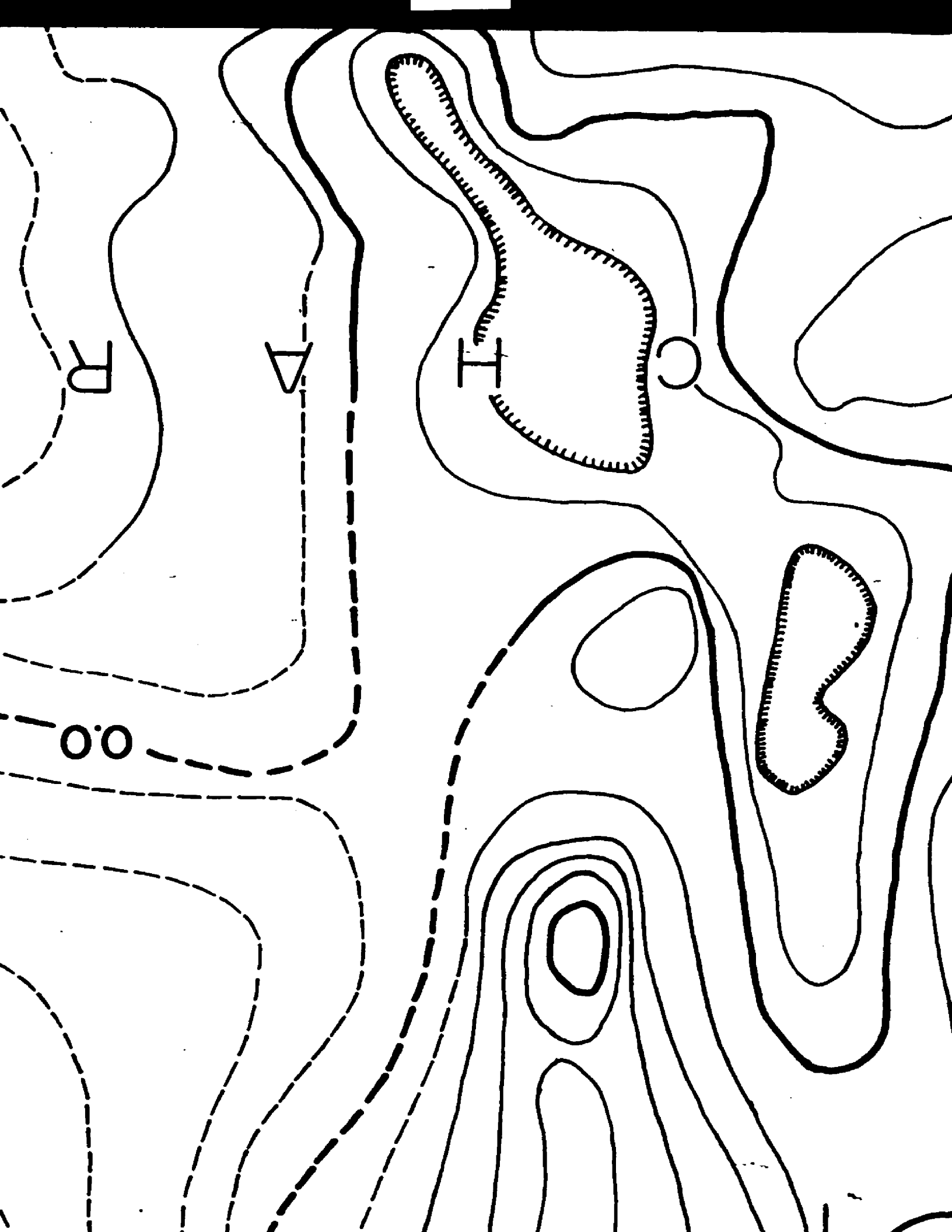
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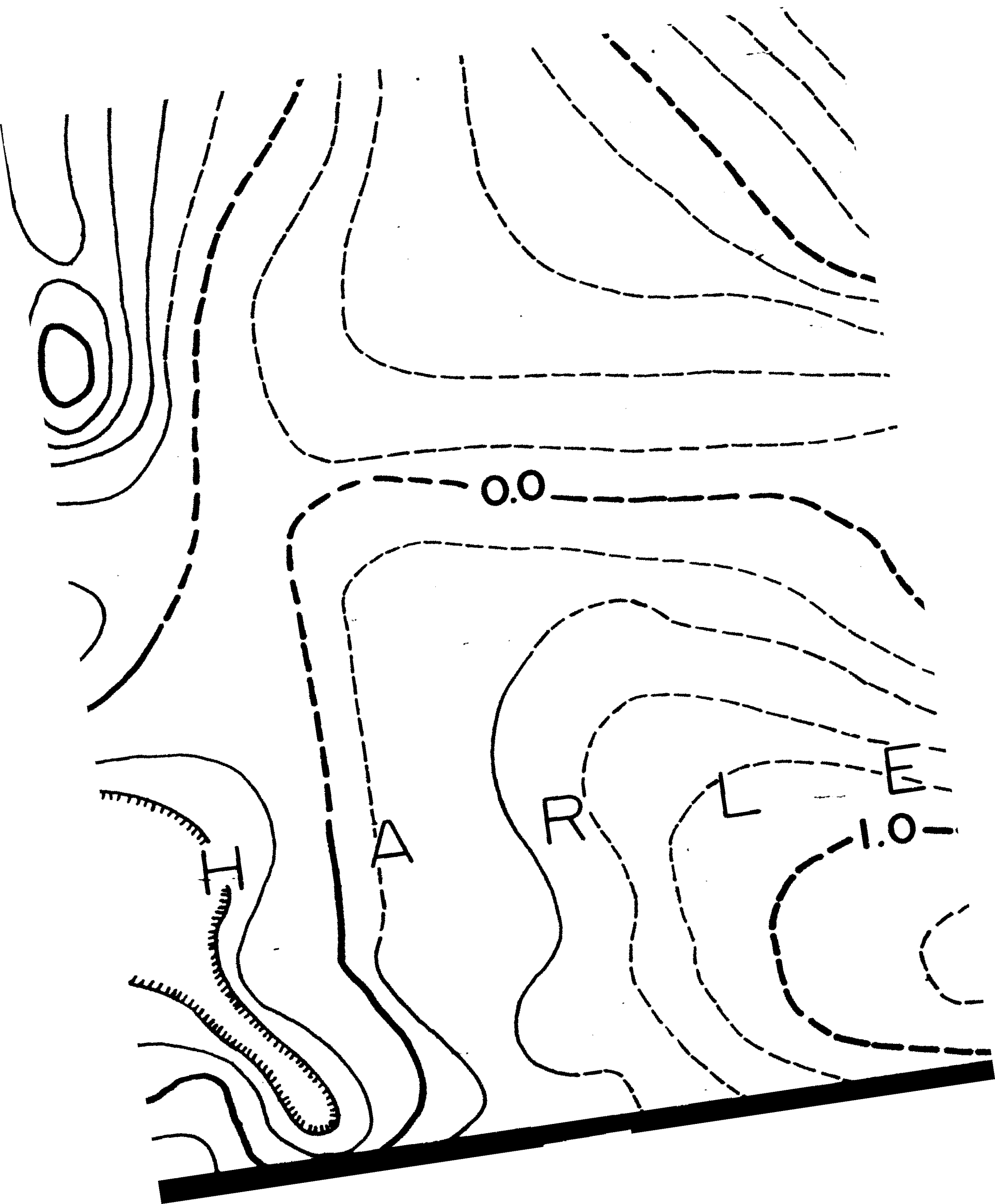
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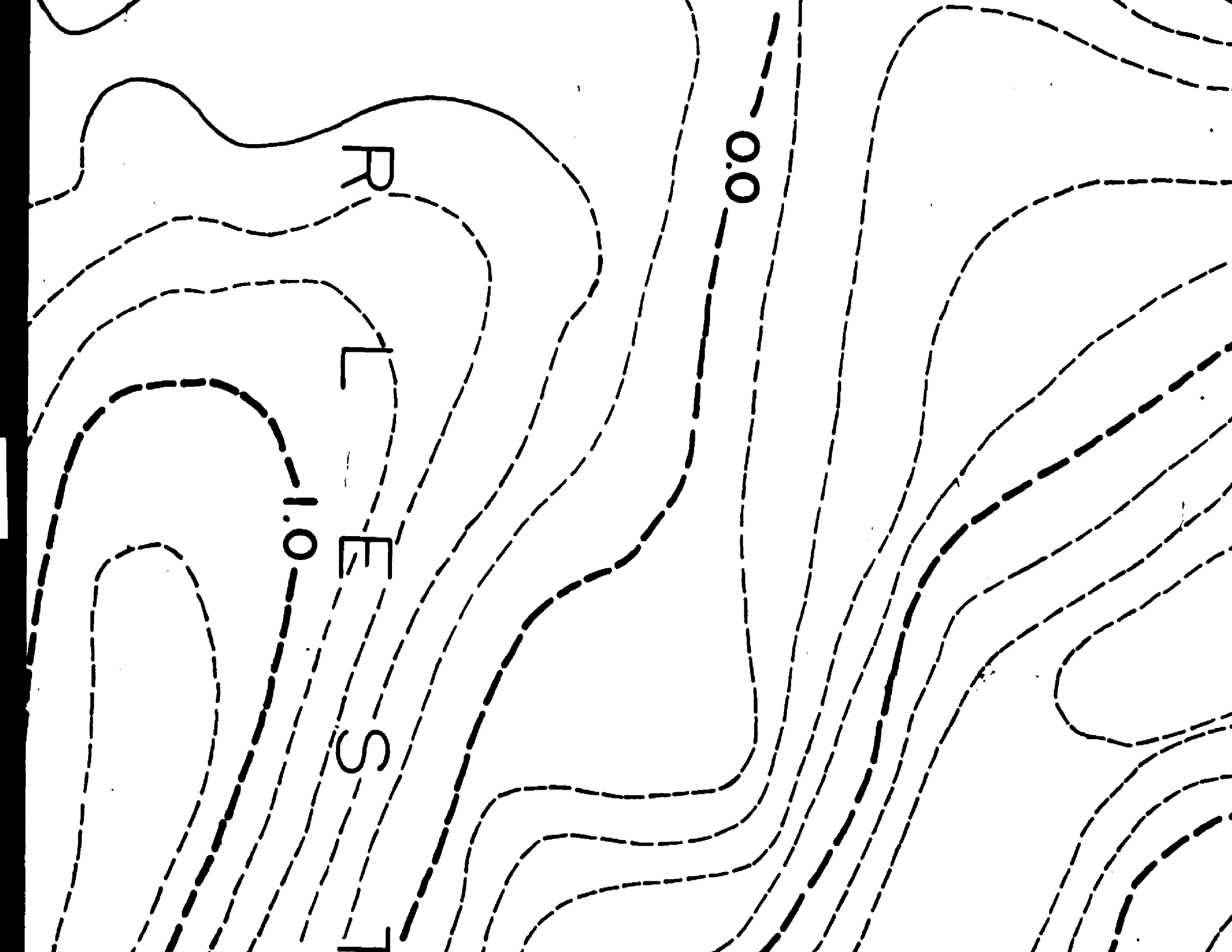
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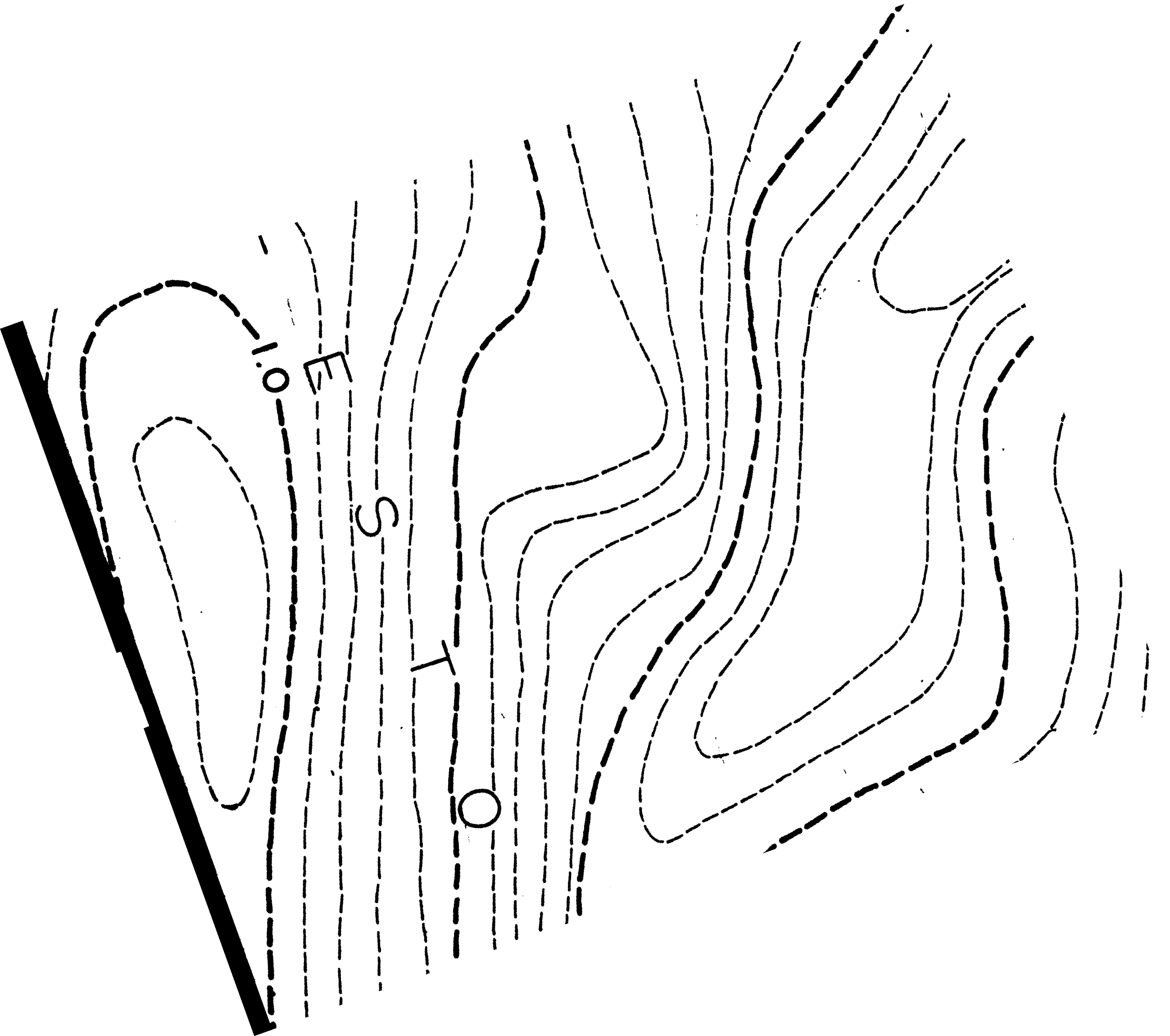
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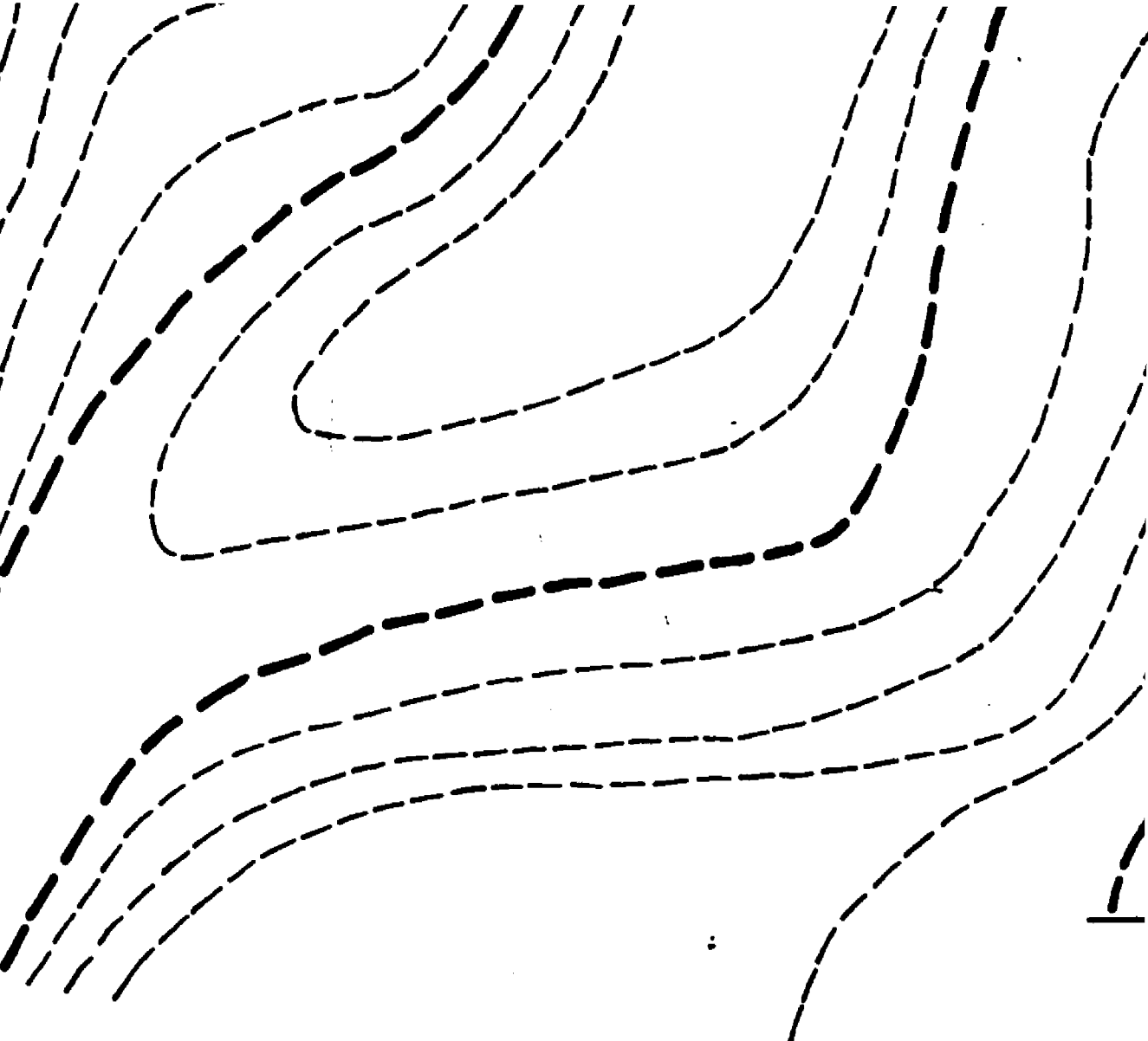








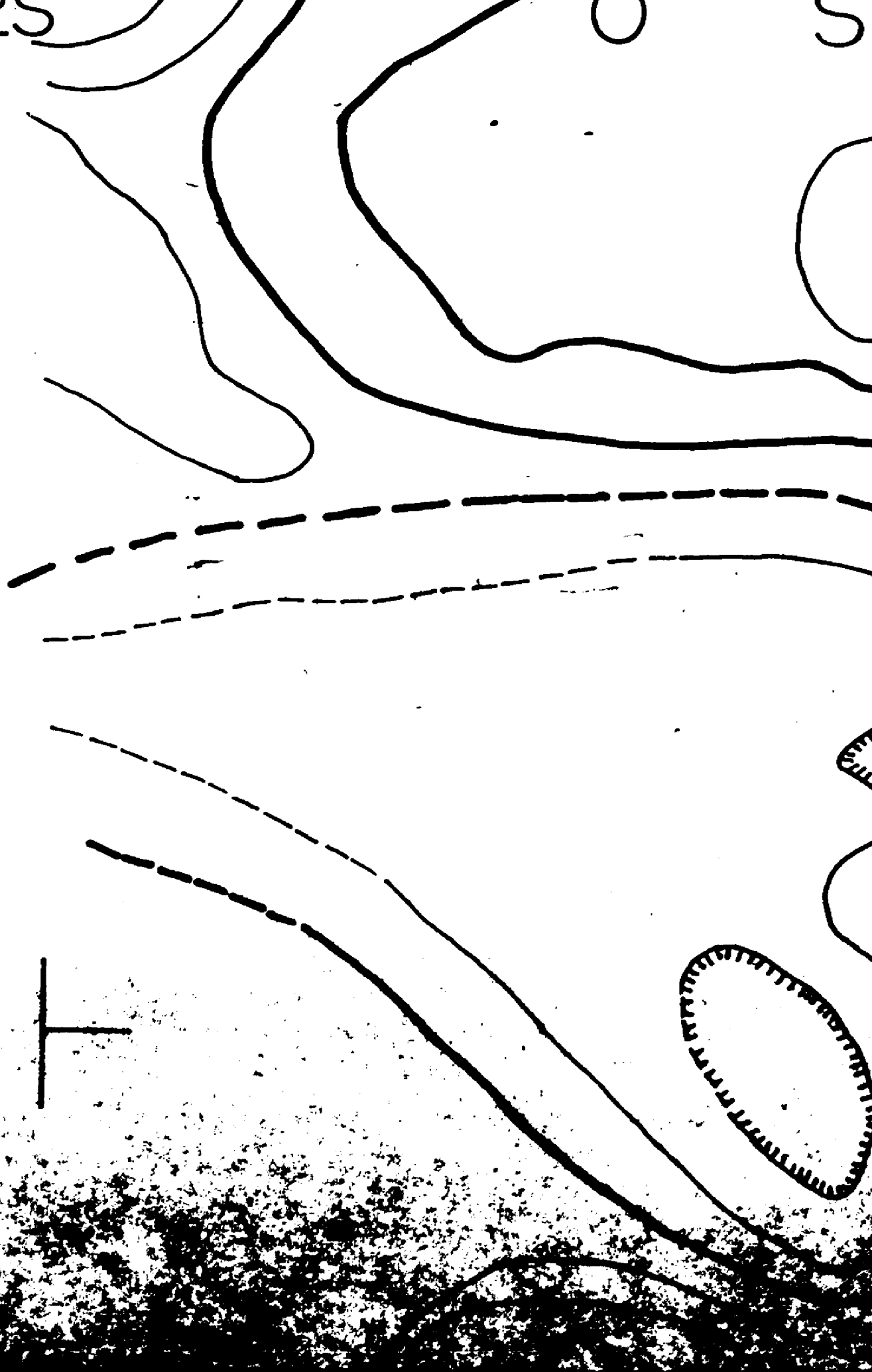
T
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T2S



125

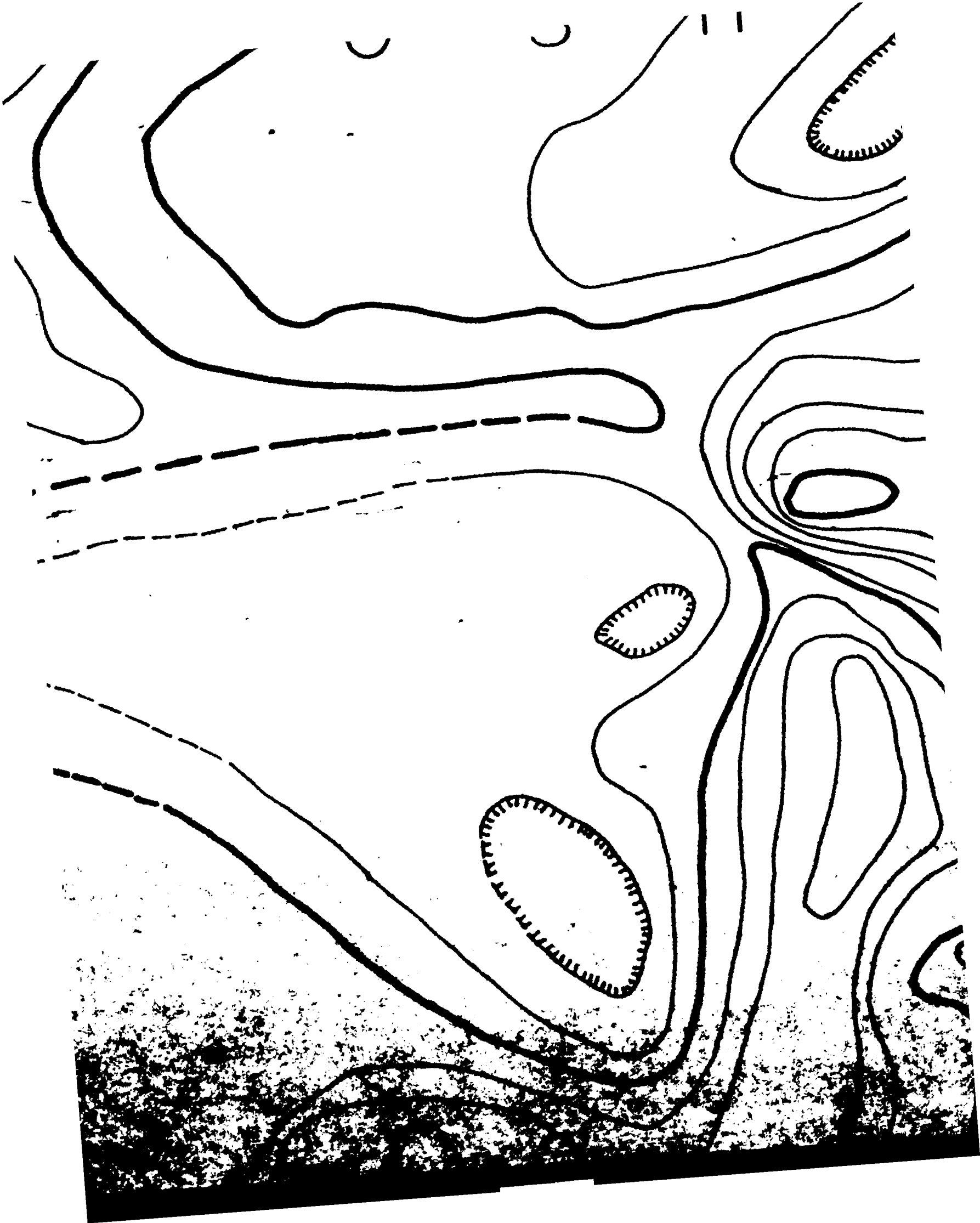
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5



15'

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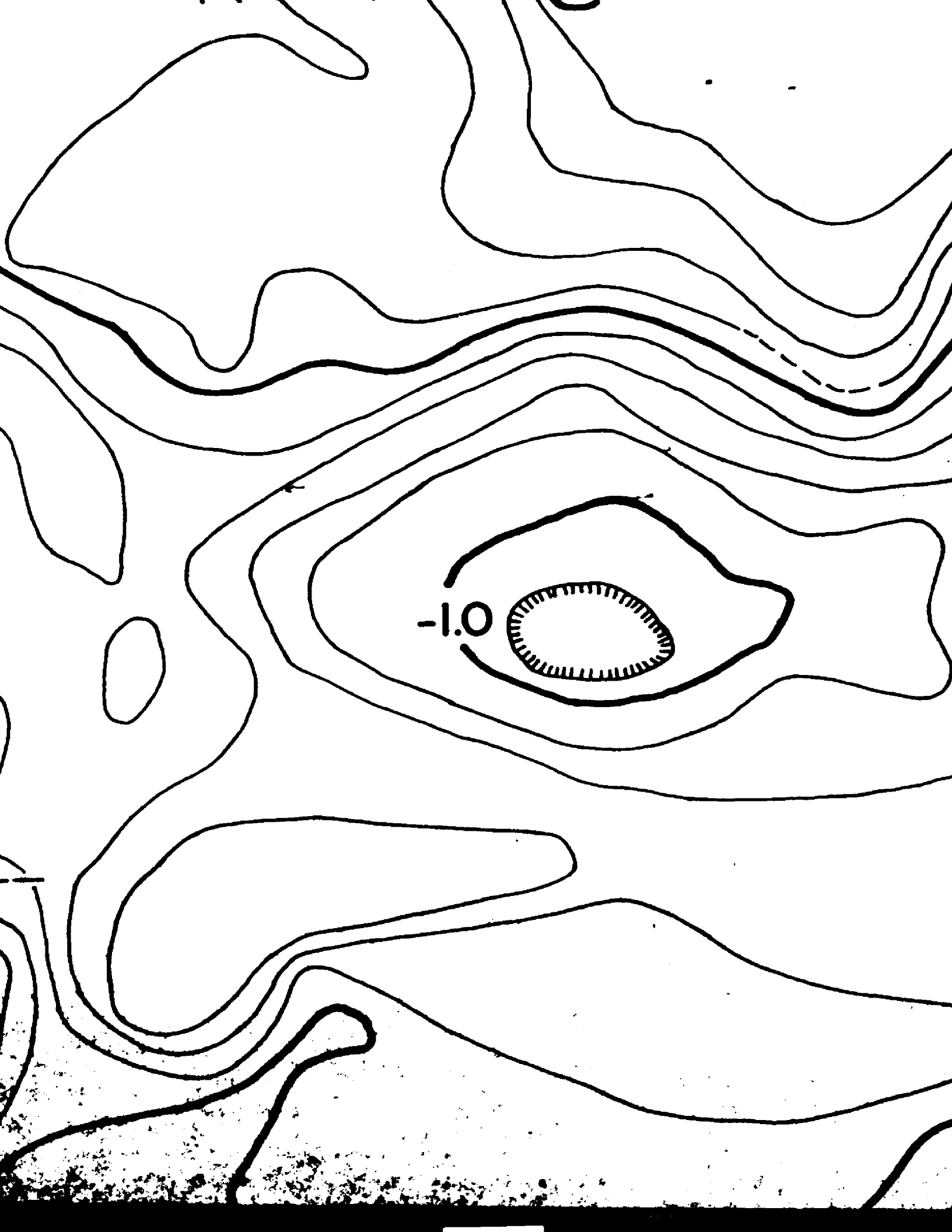


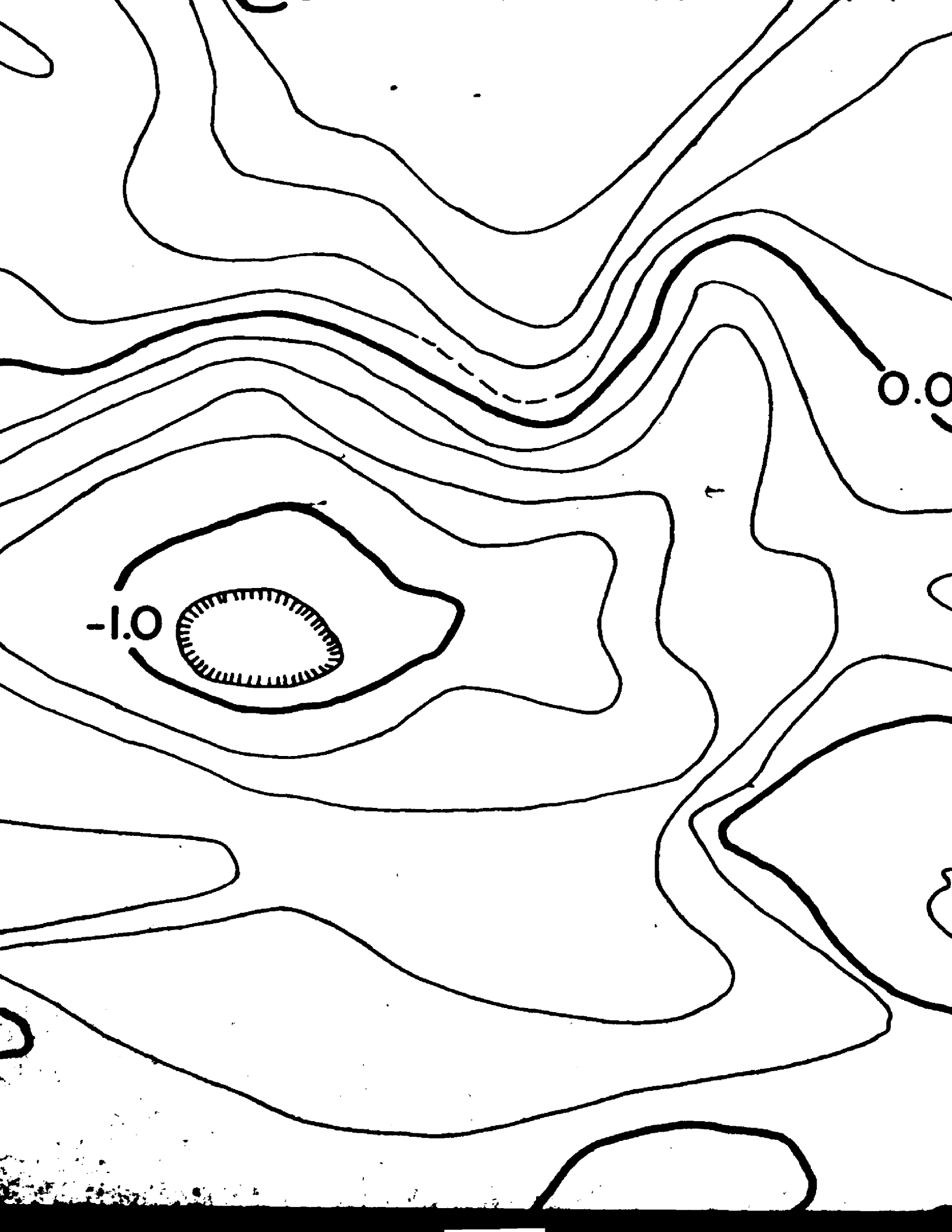






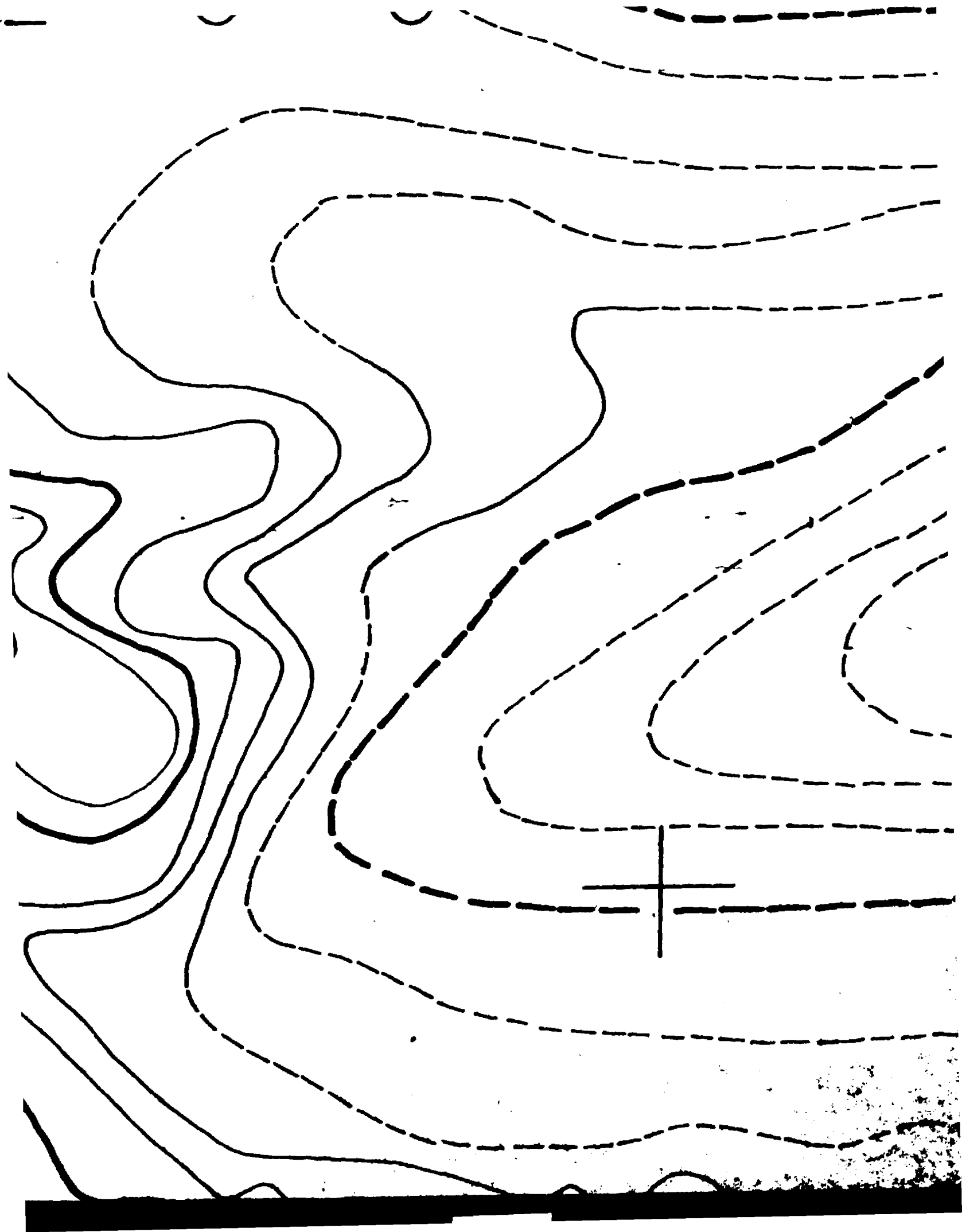


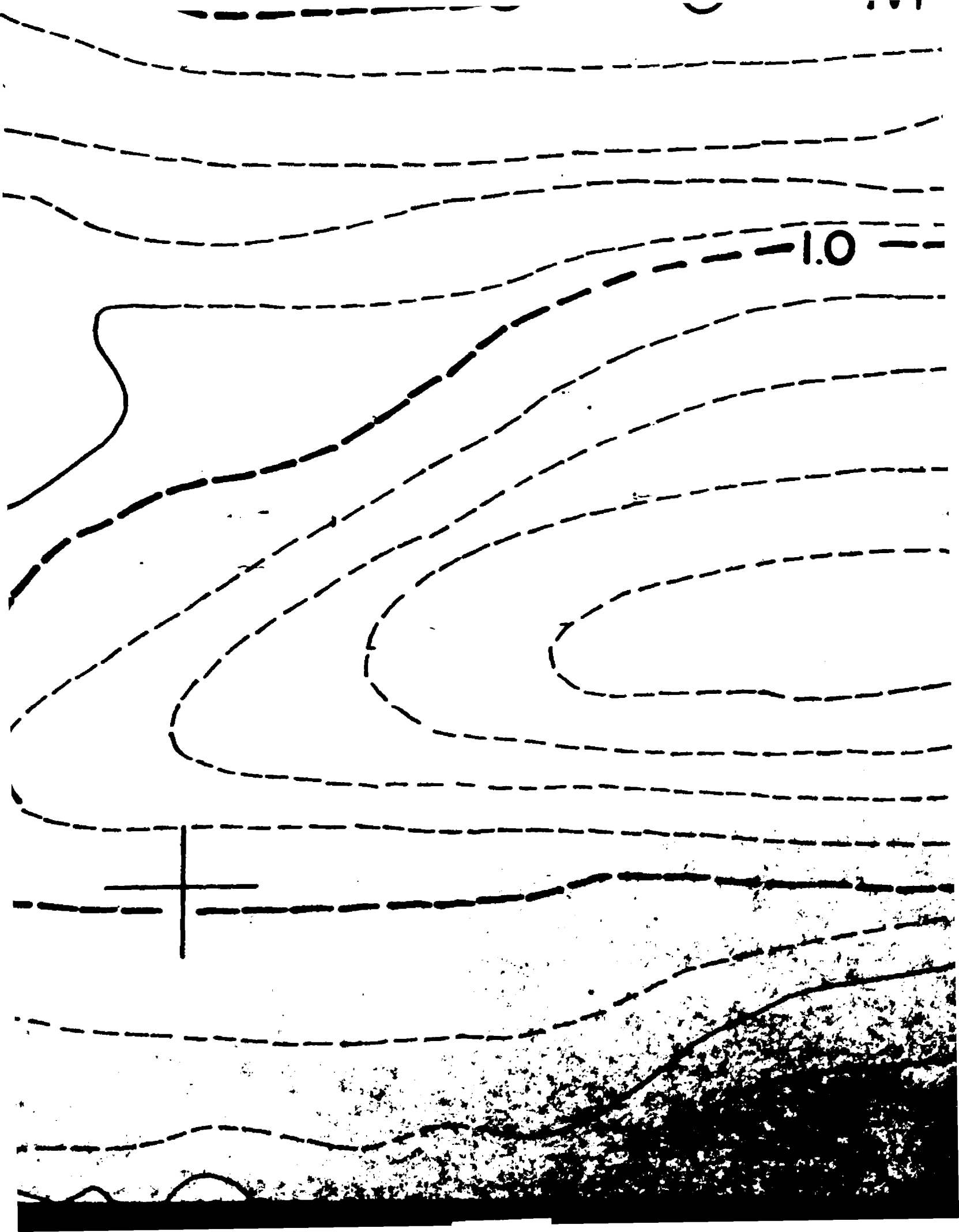


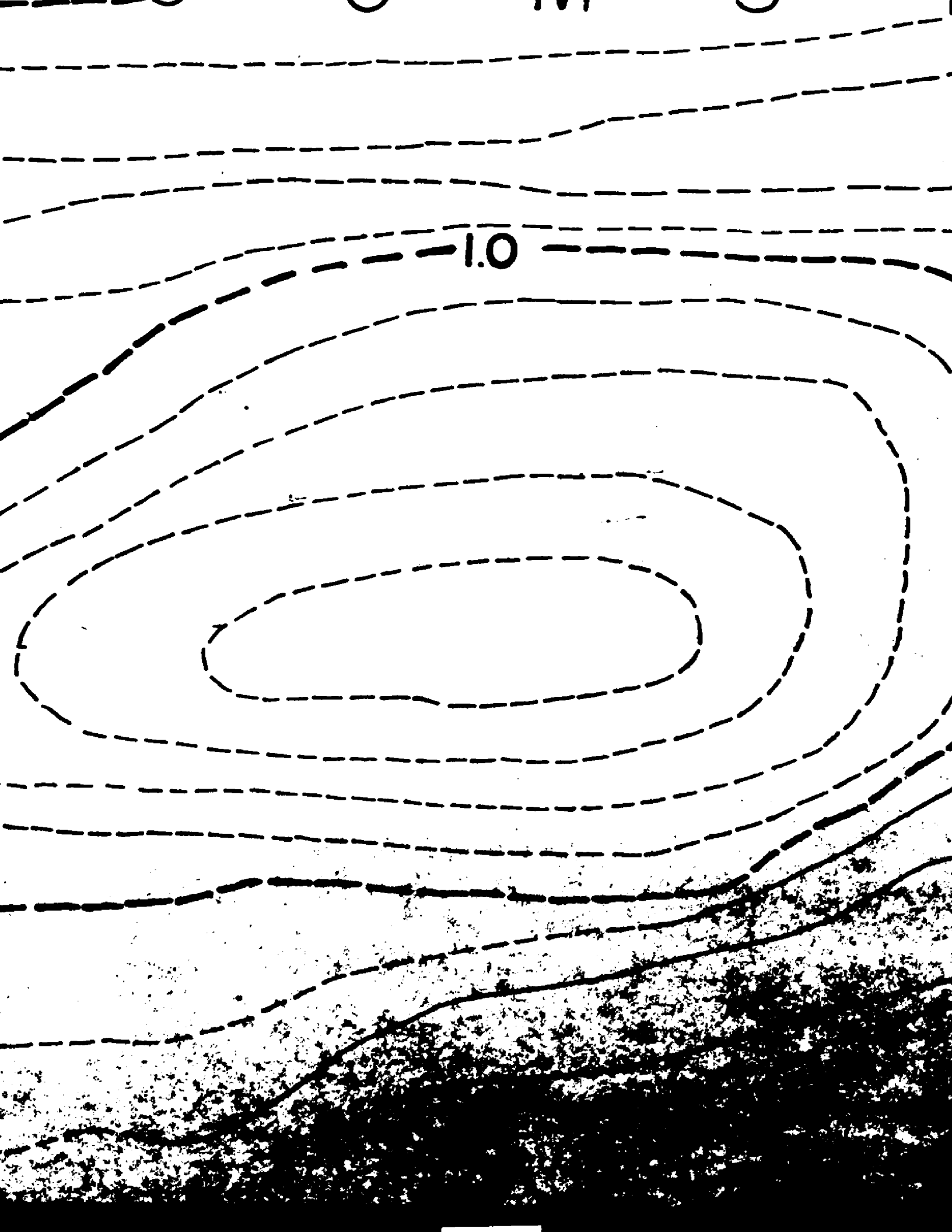


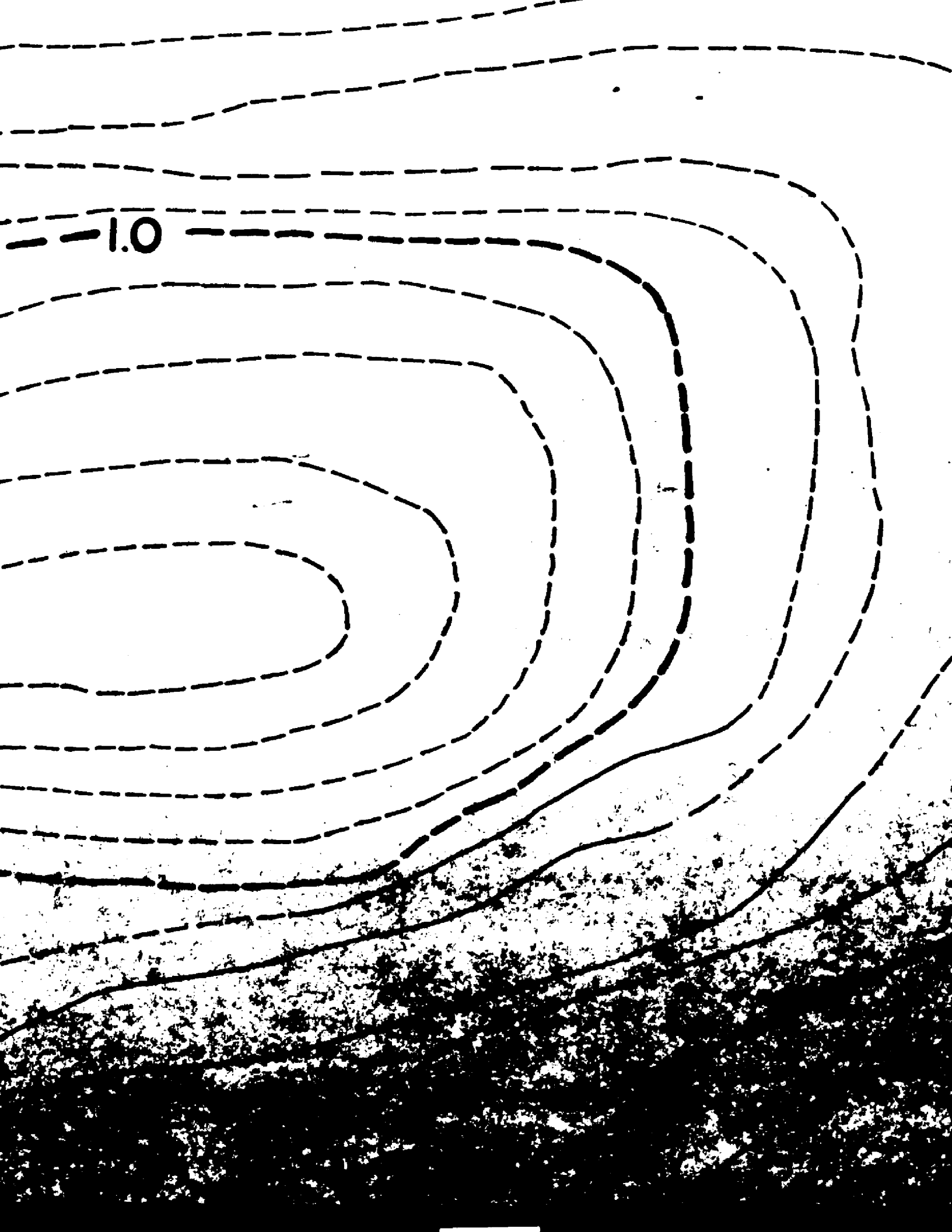




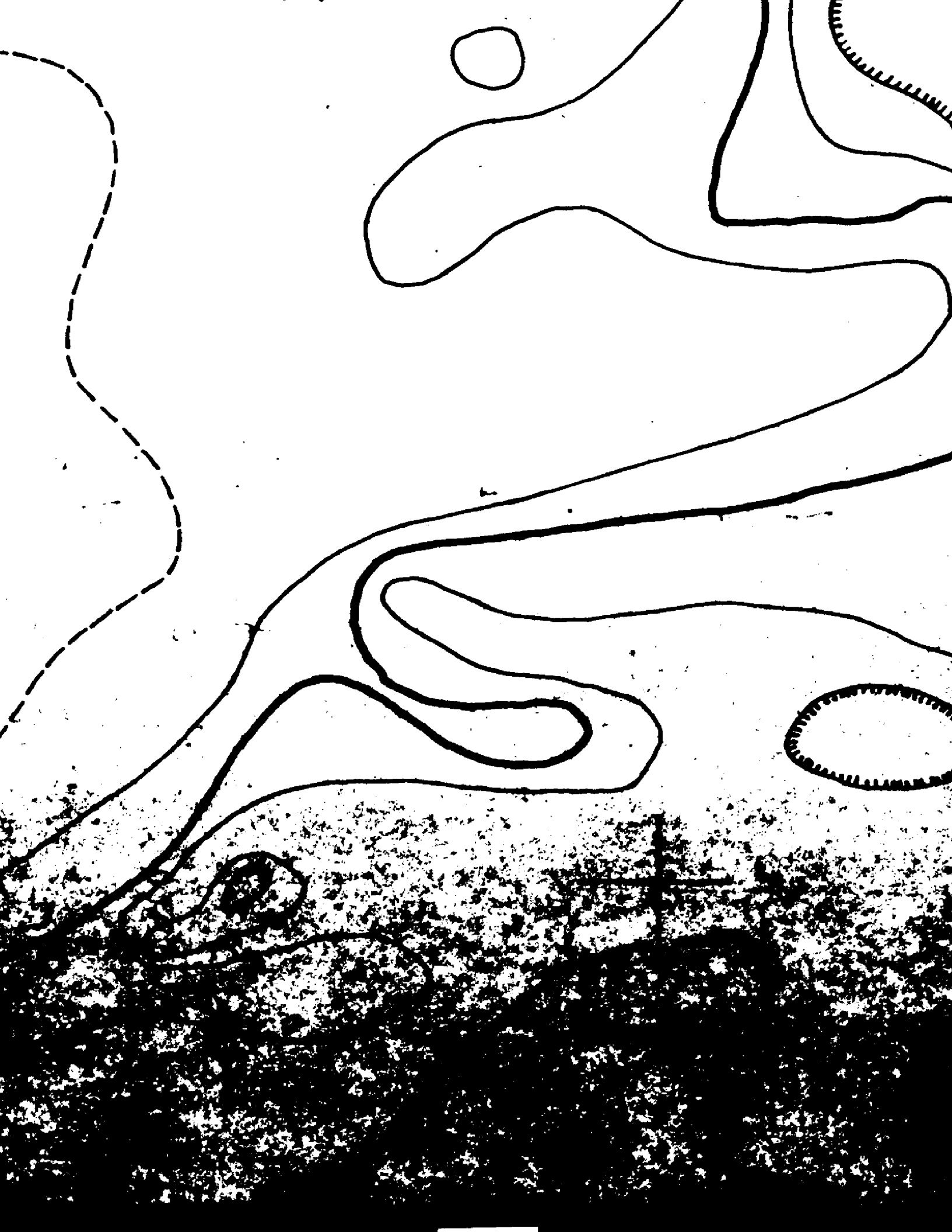












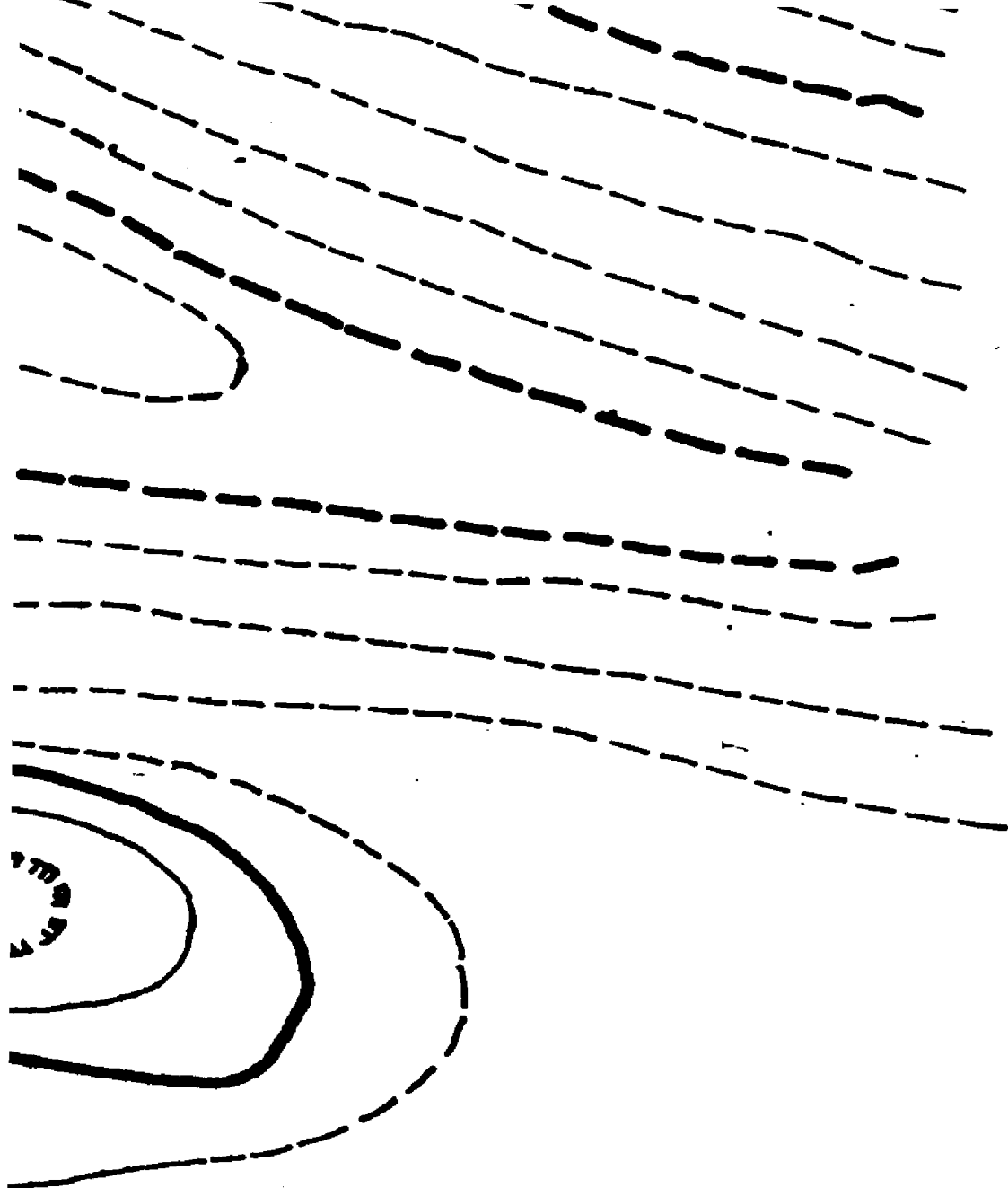








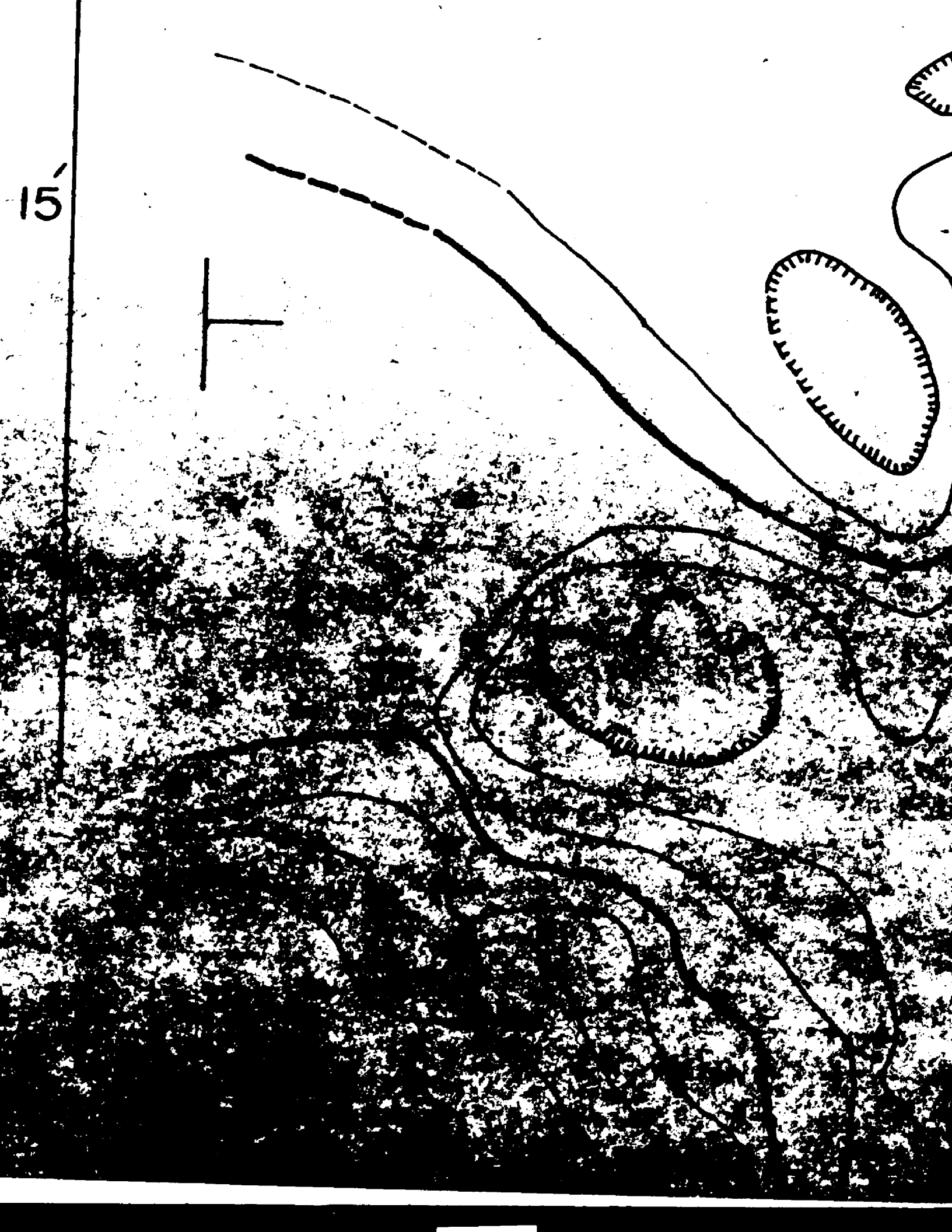


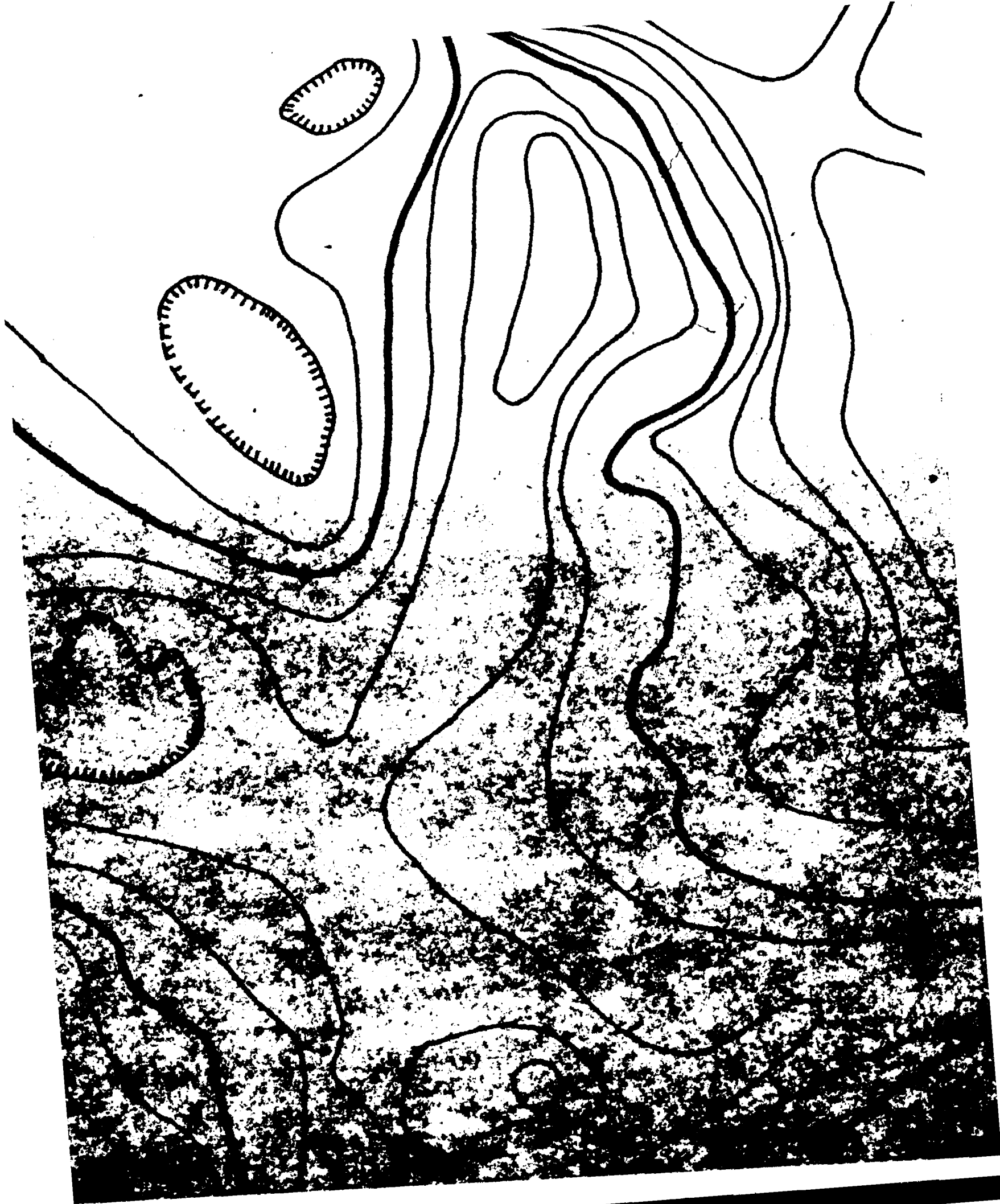


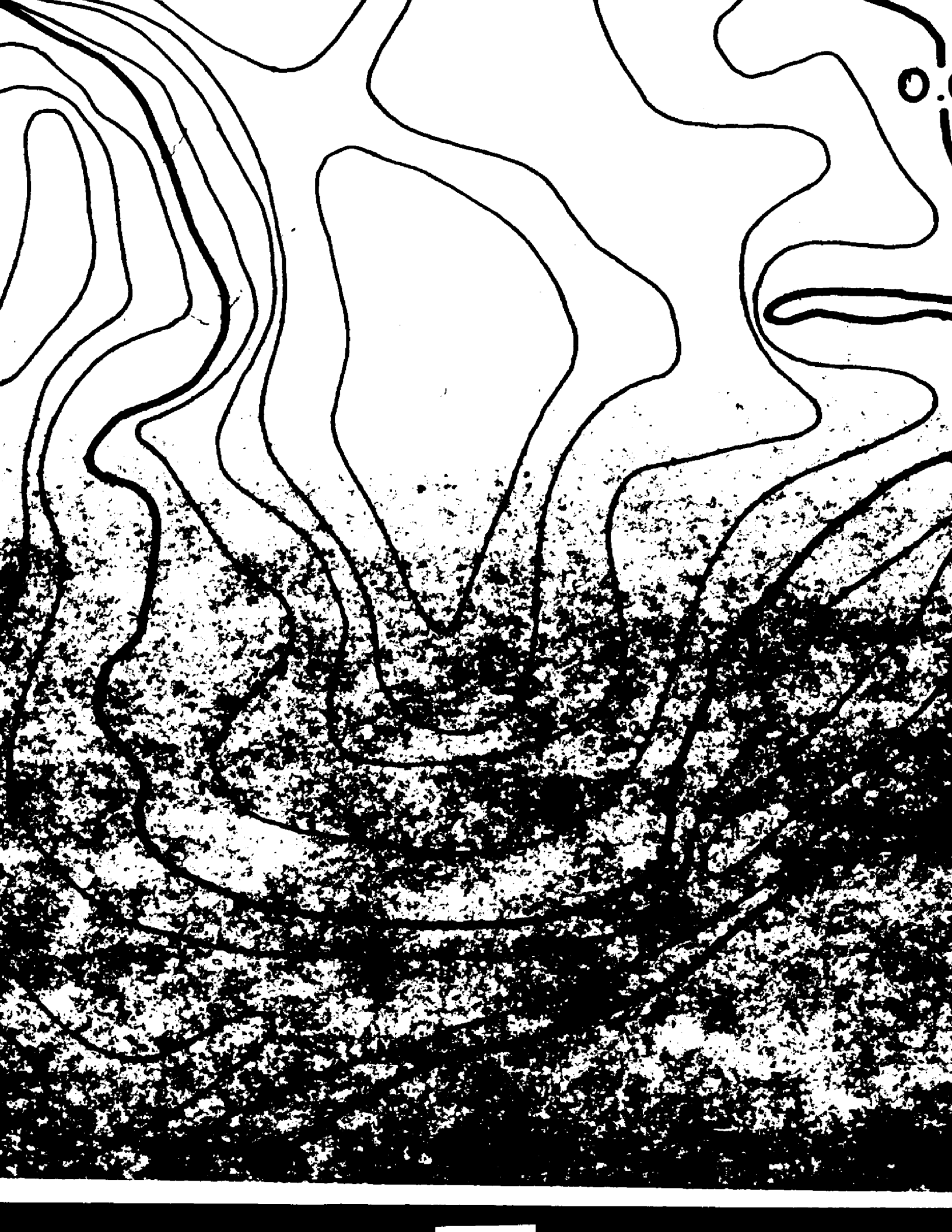
15'

15'

H



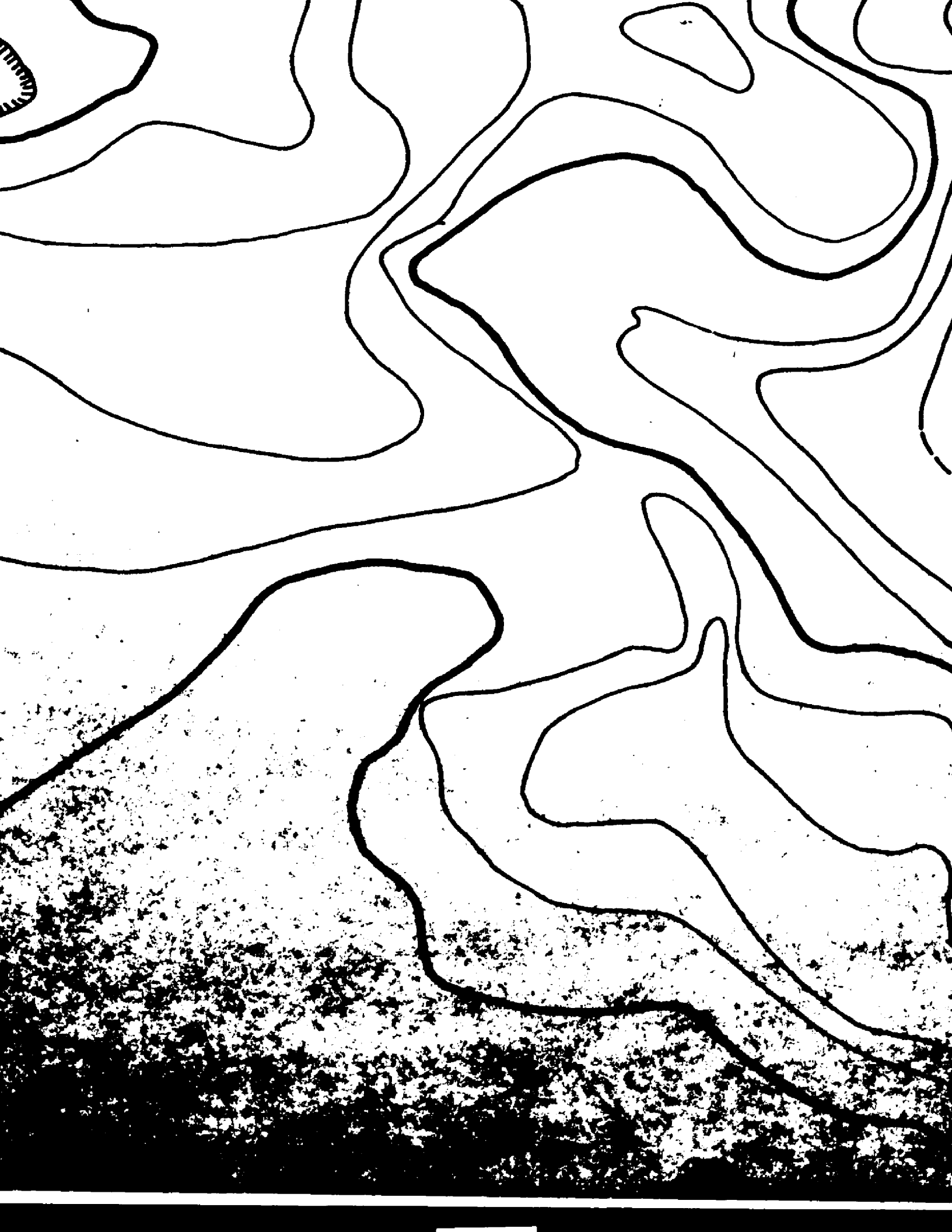








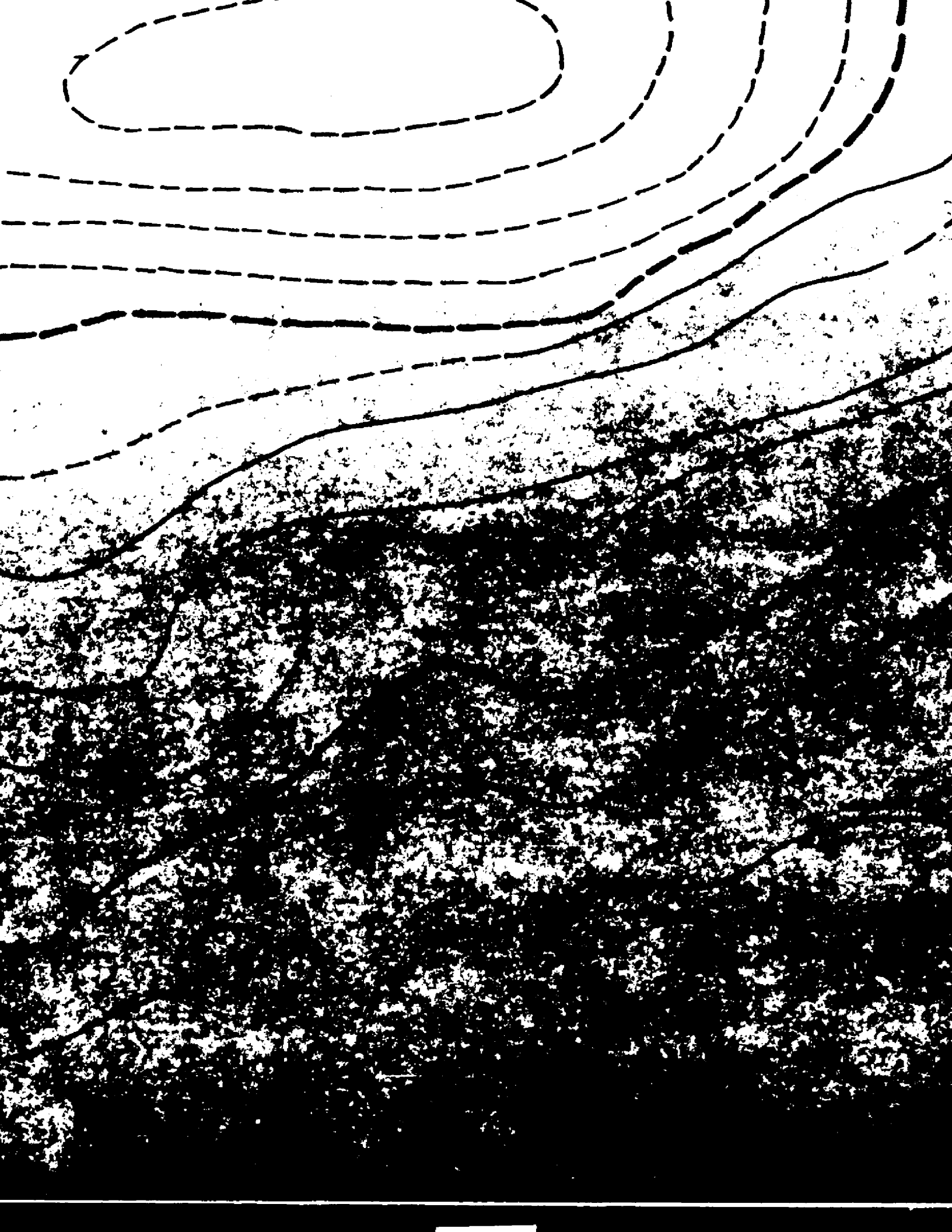


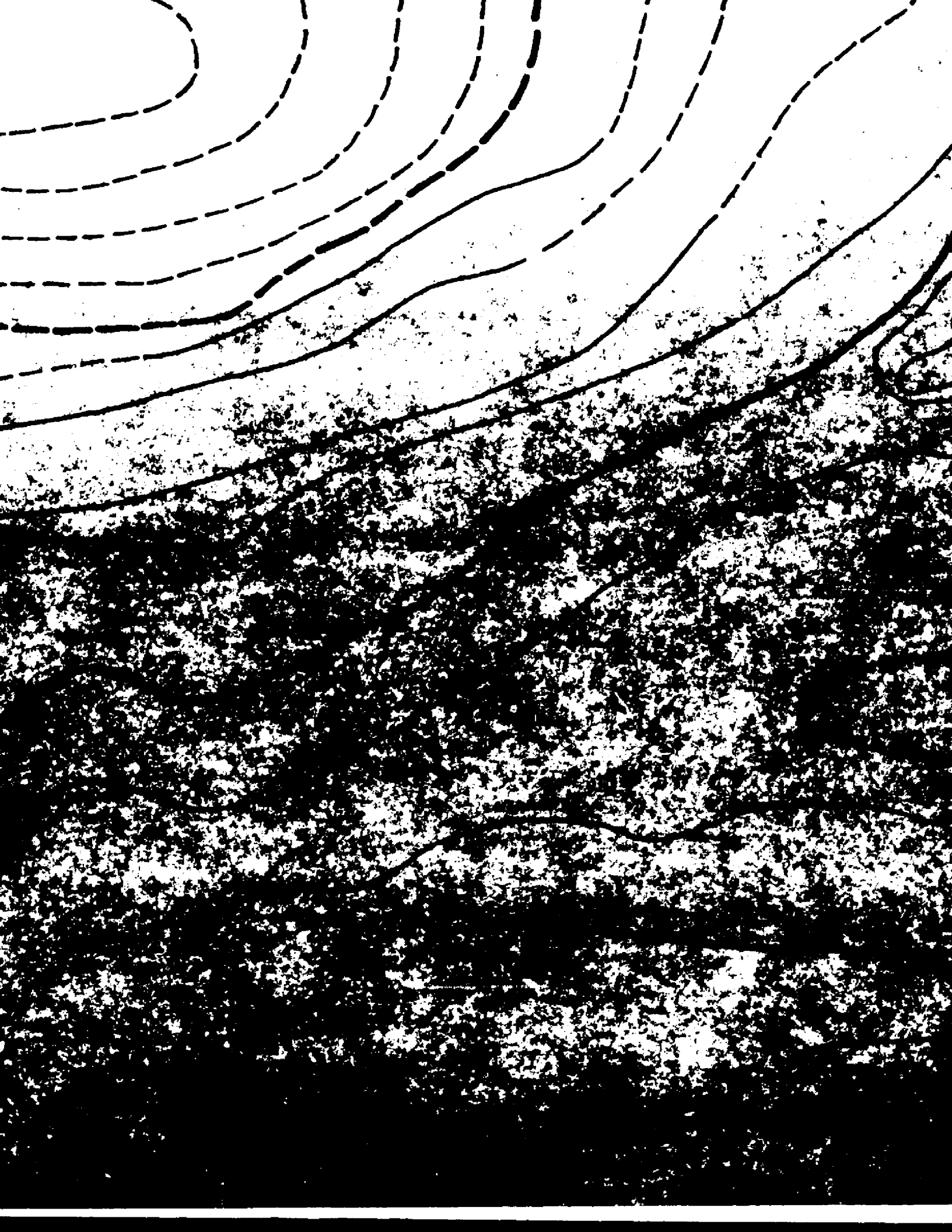
















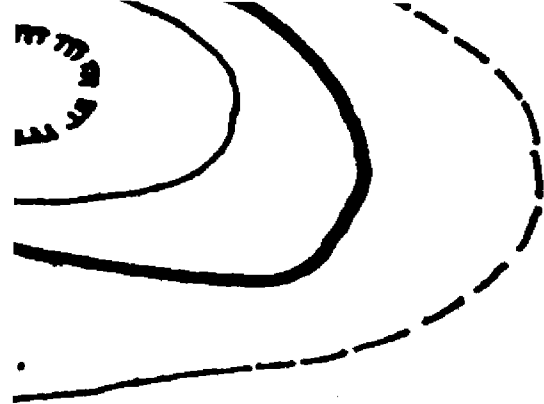


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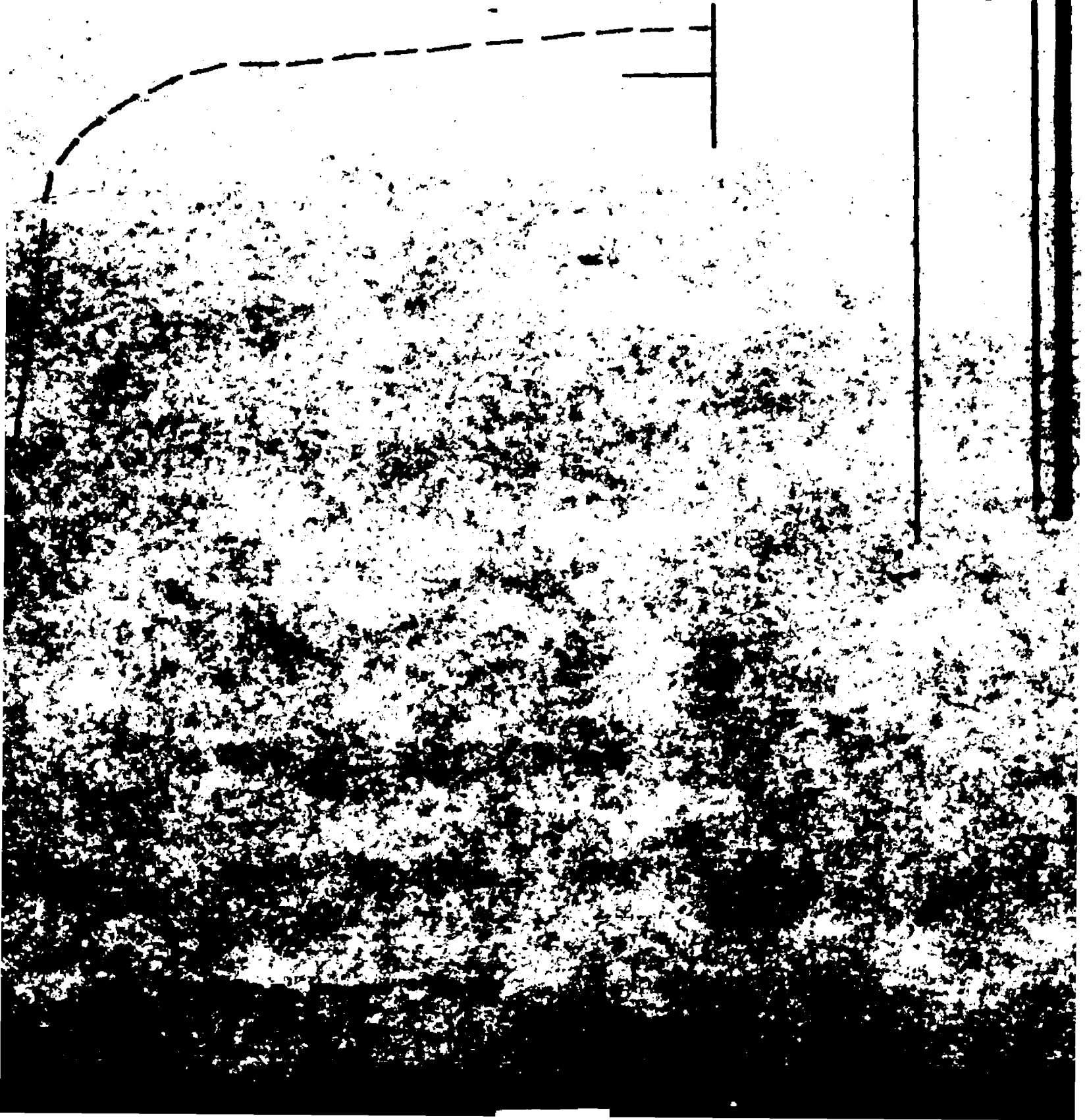
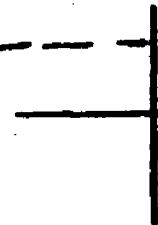


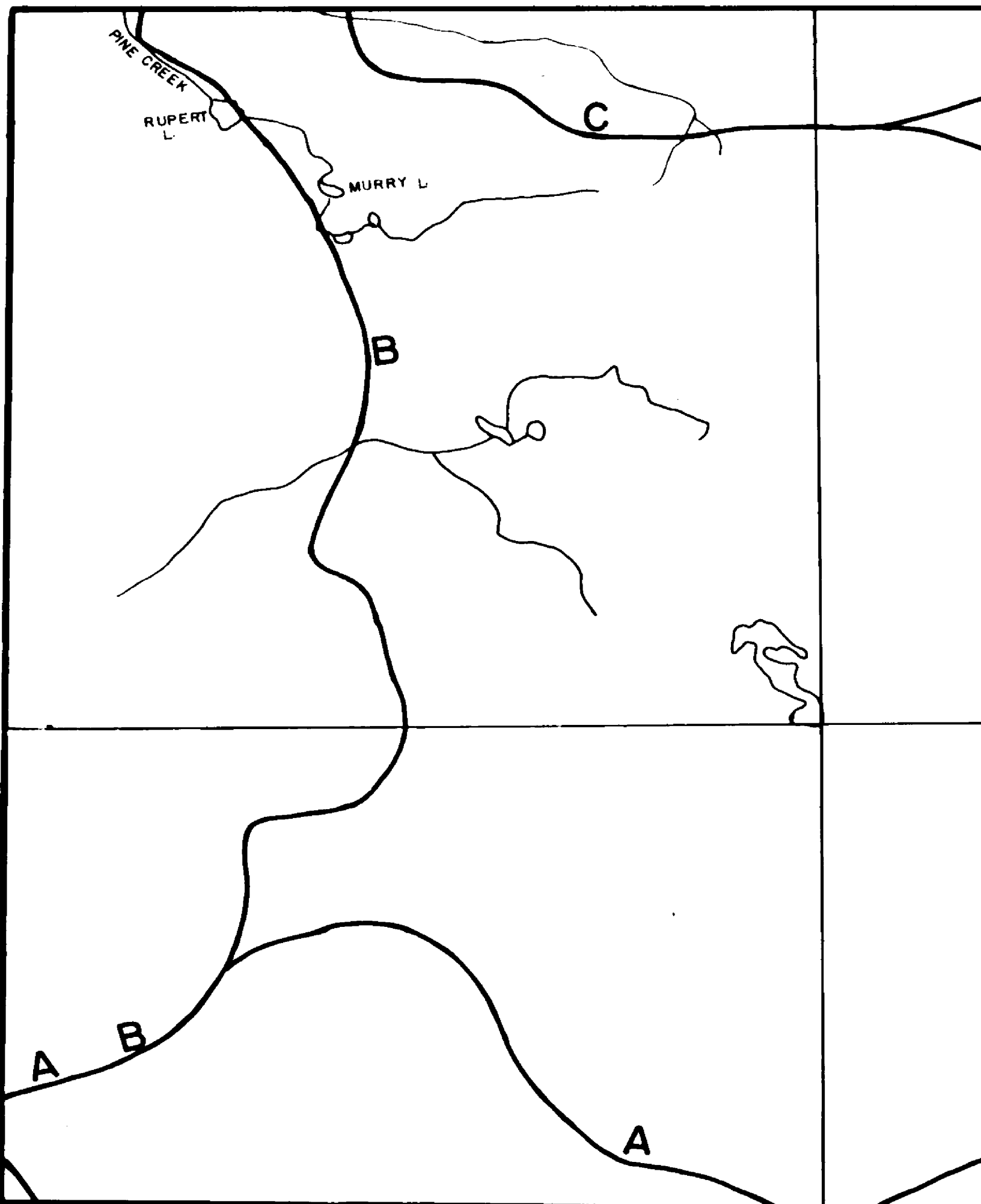




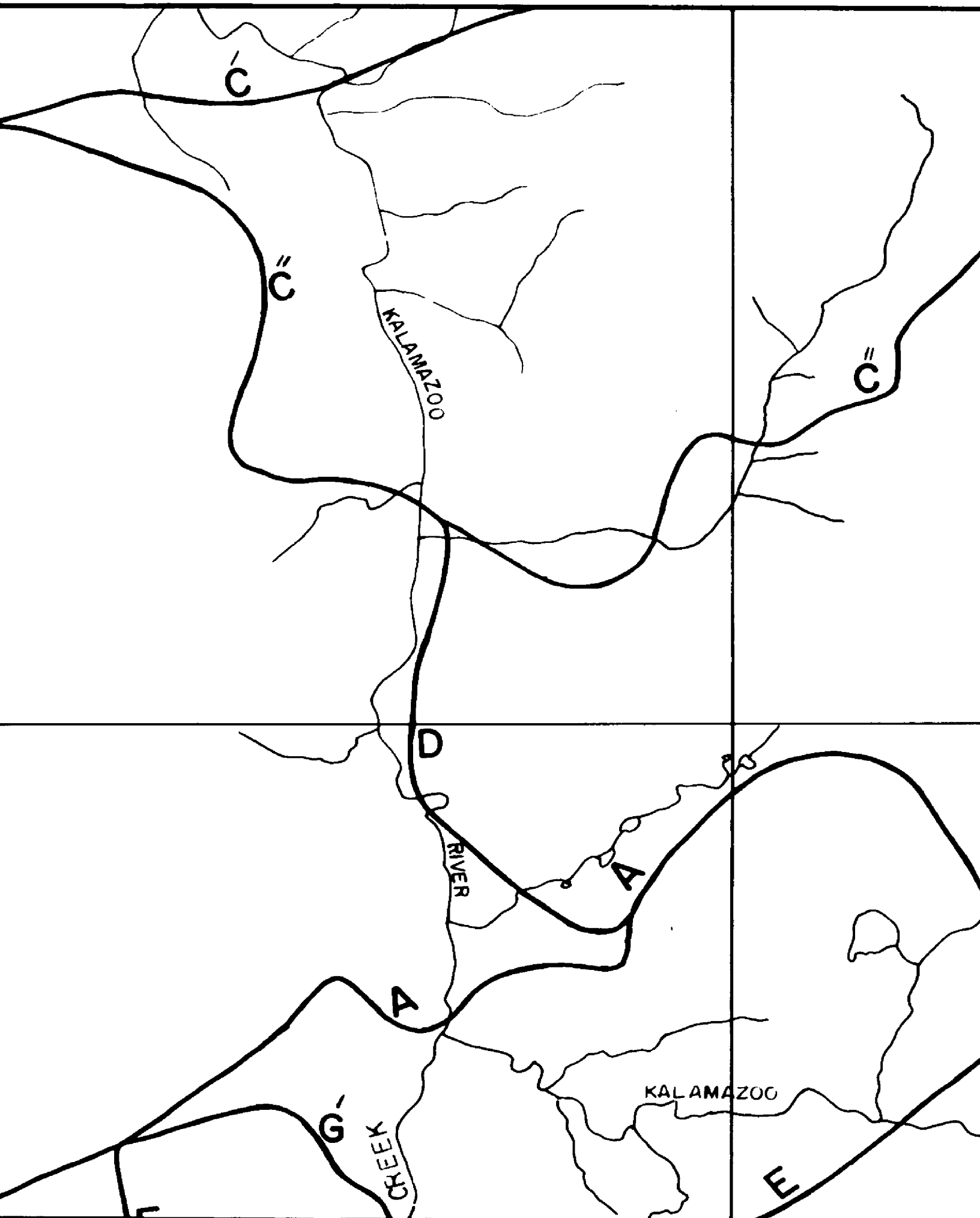


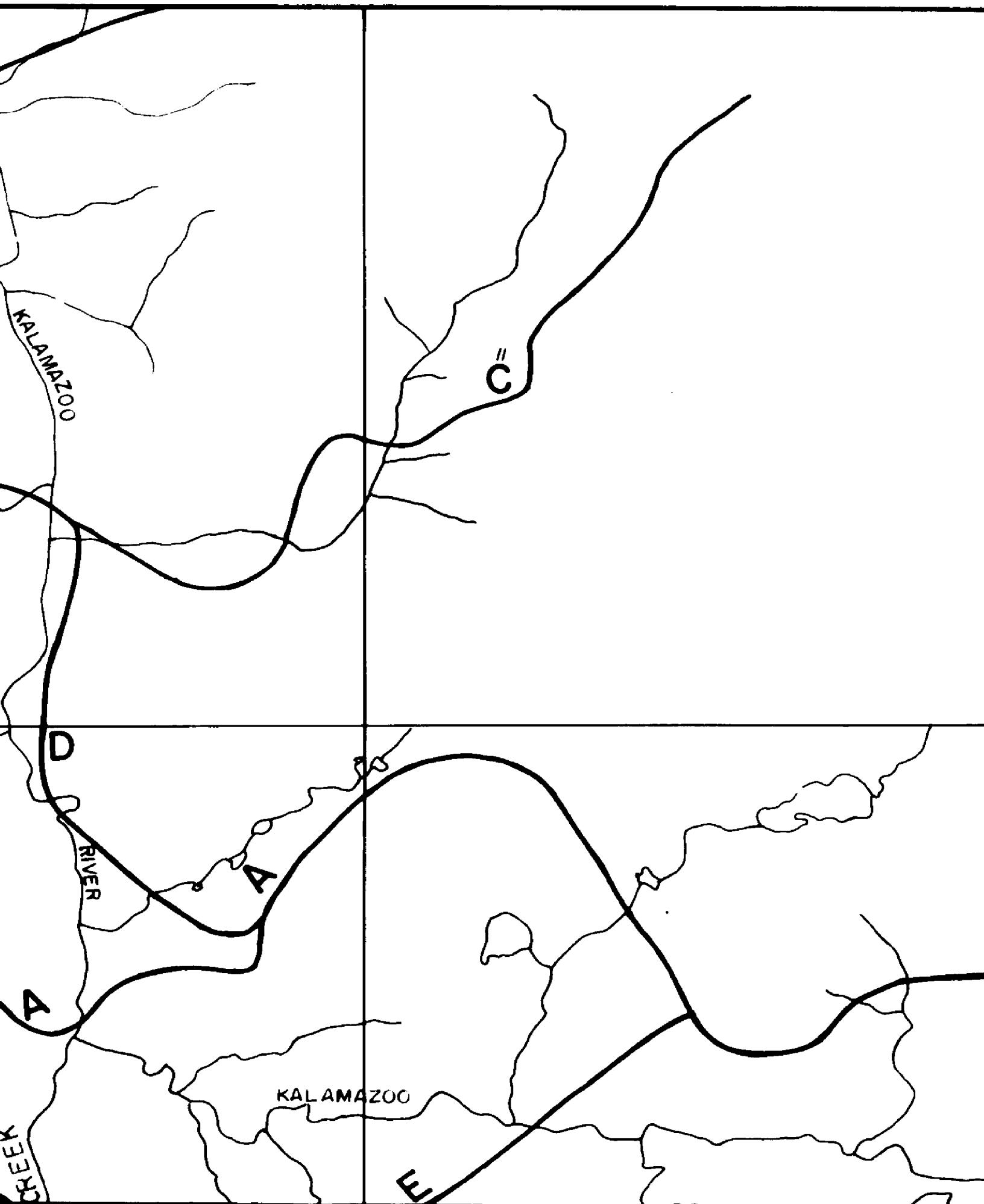
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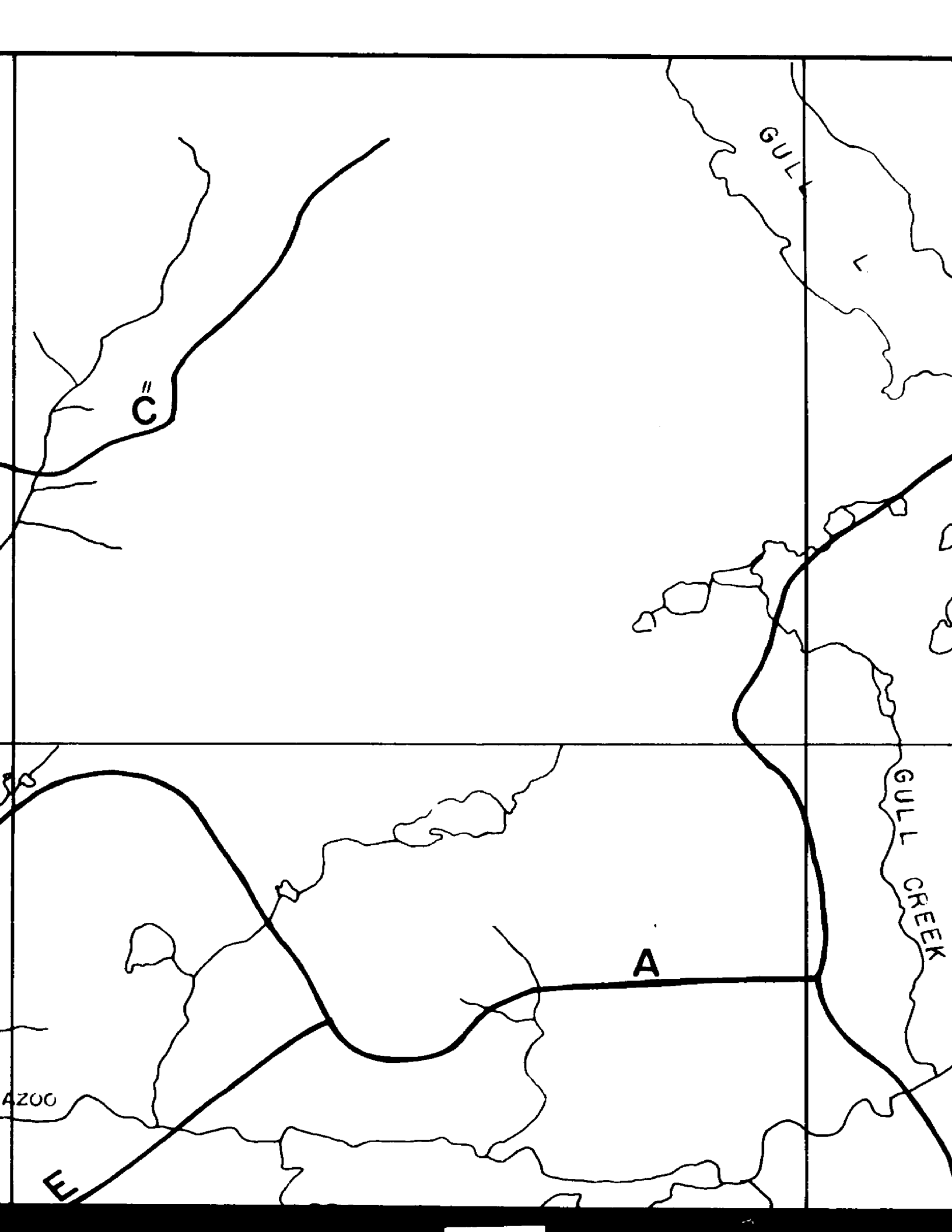


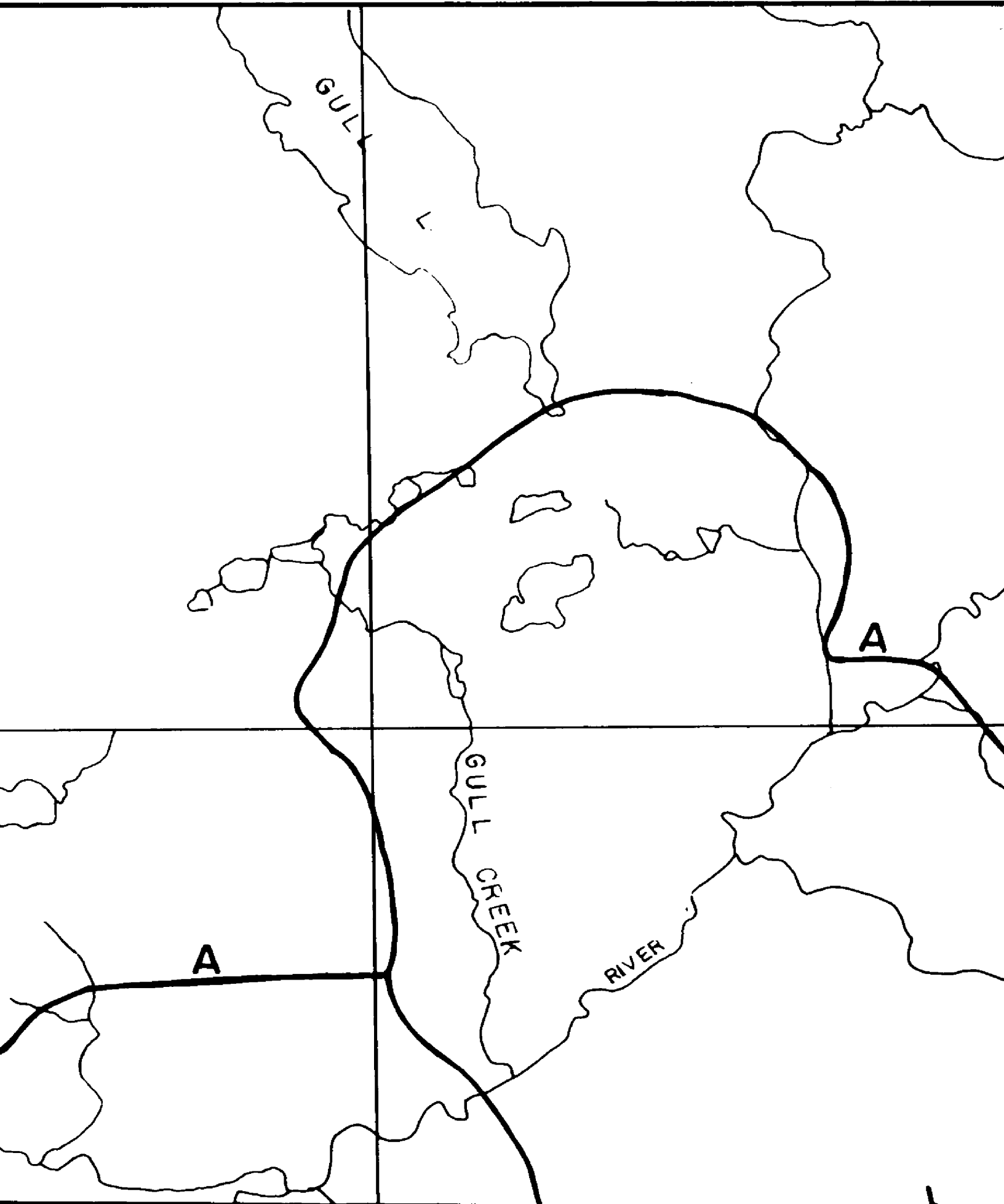


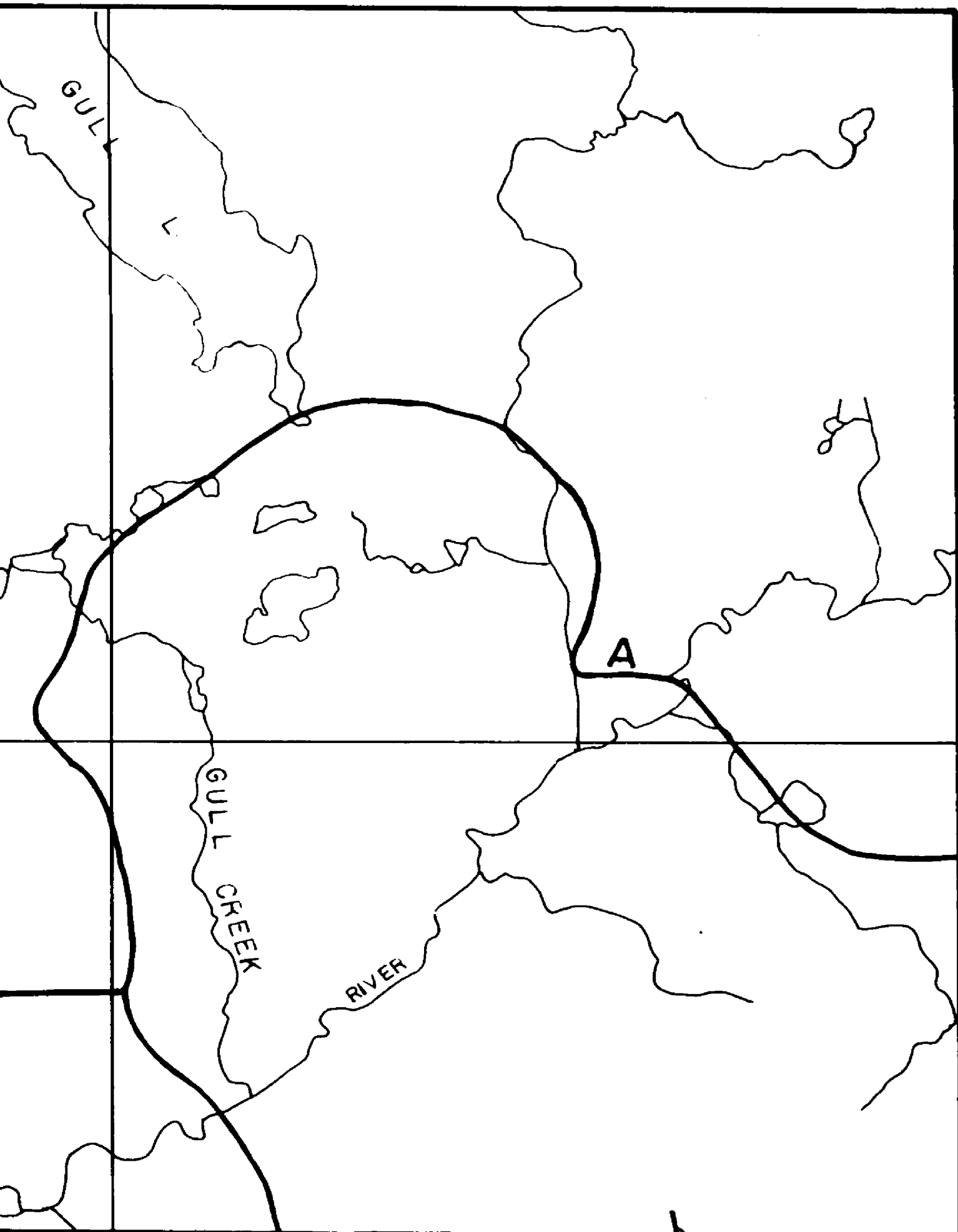


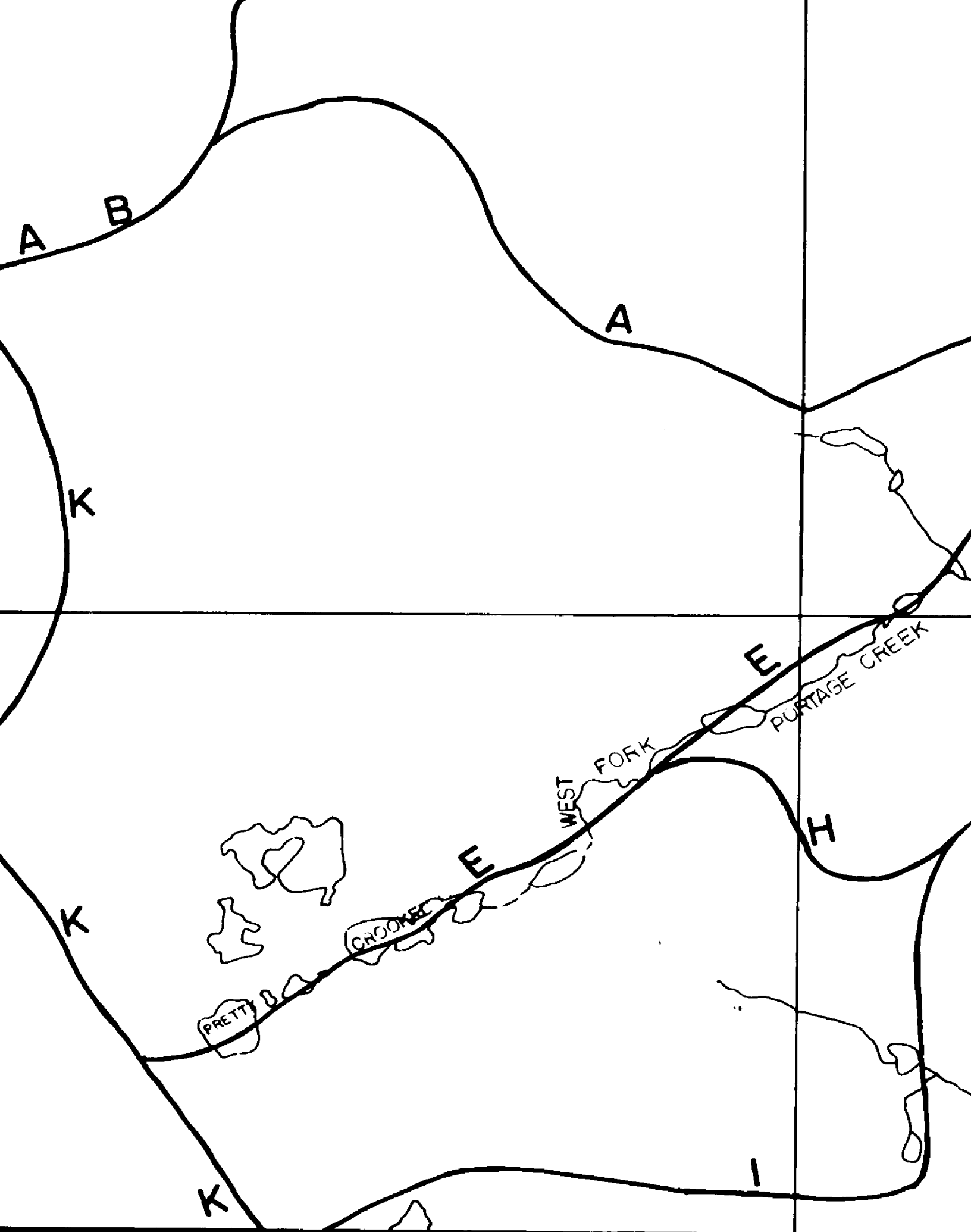


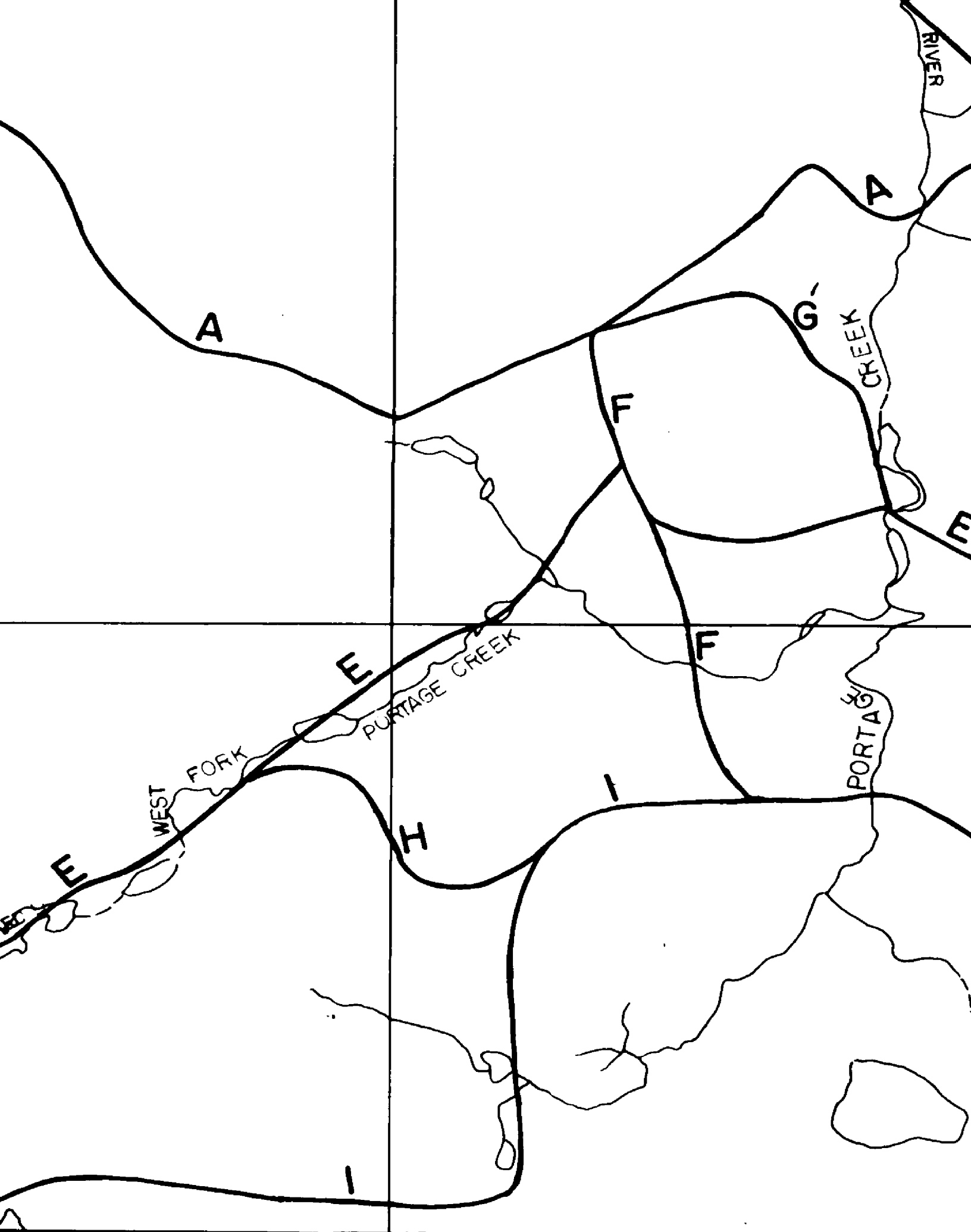


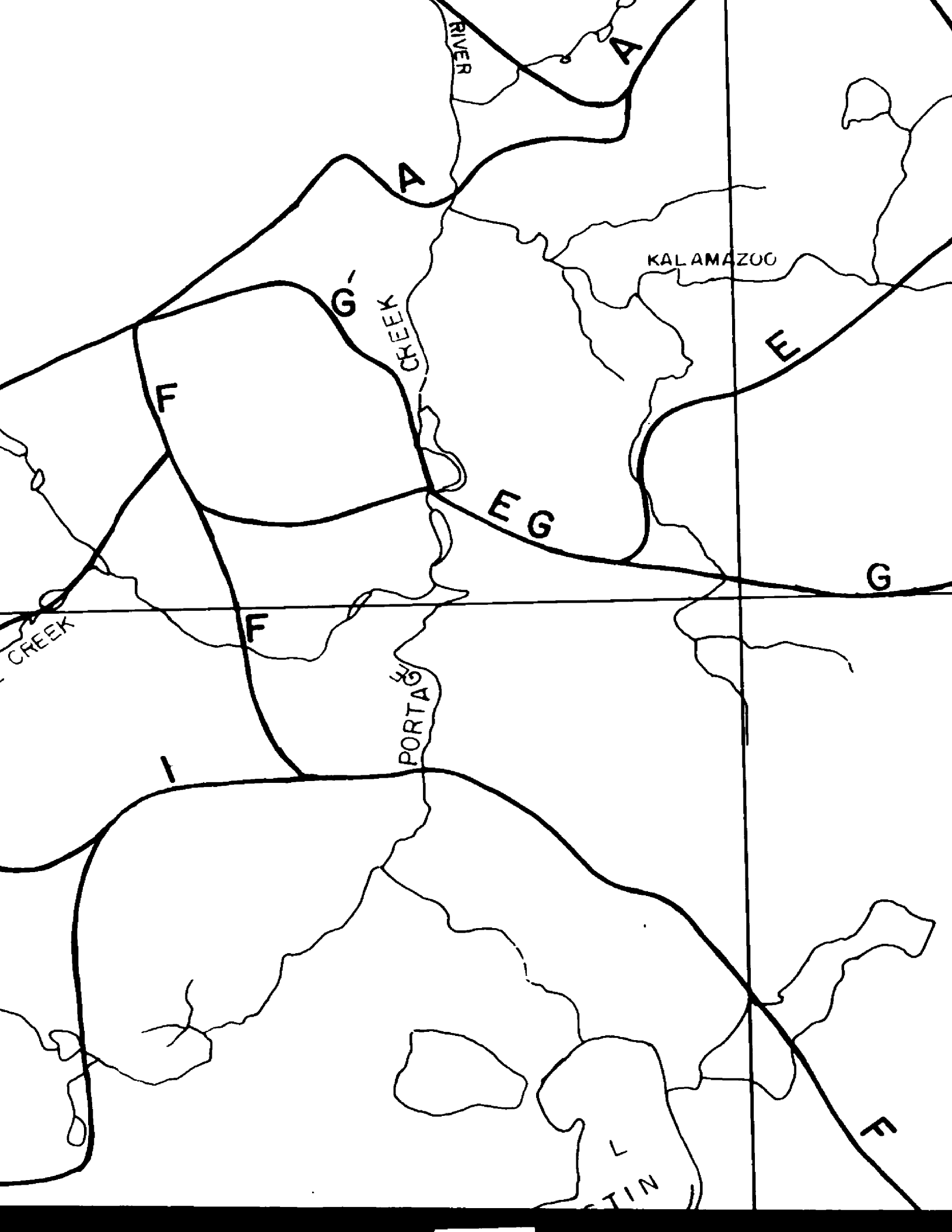


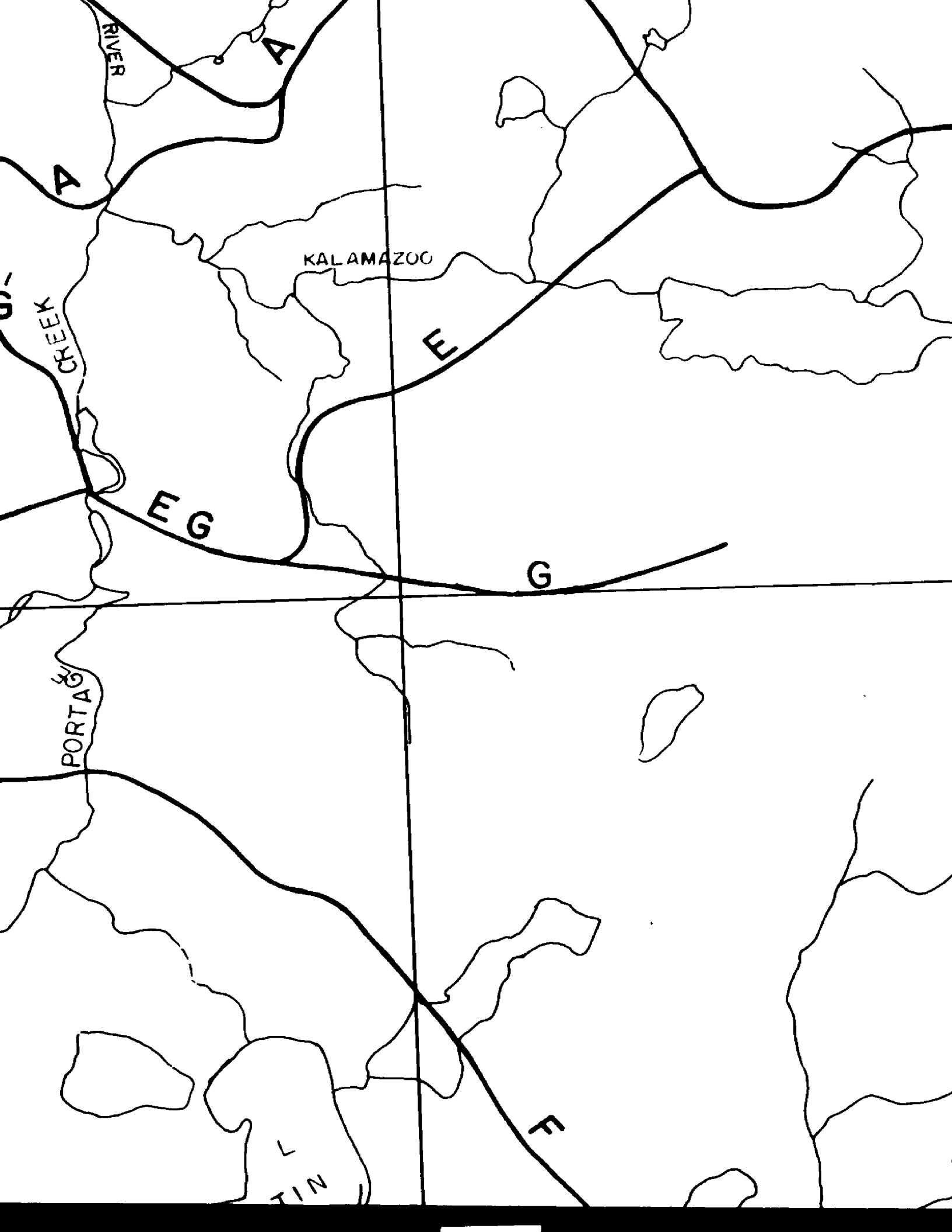




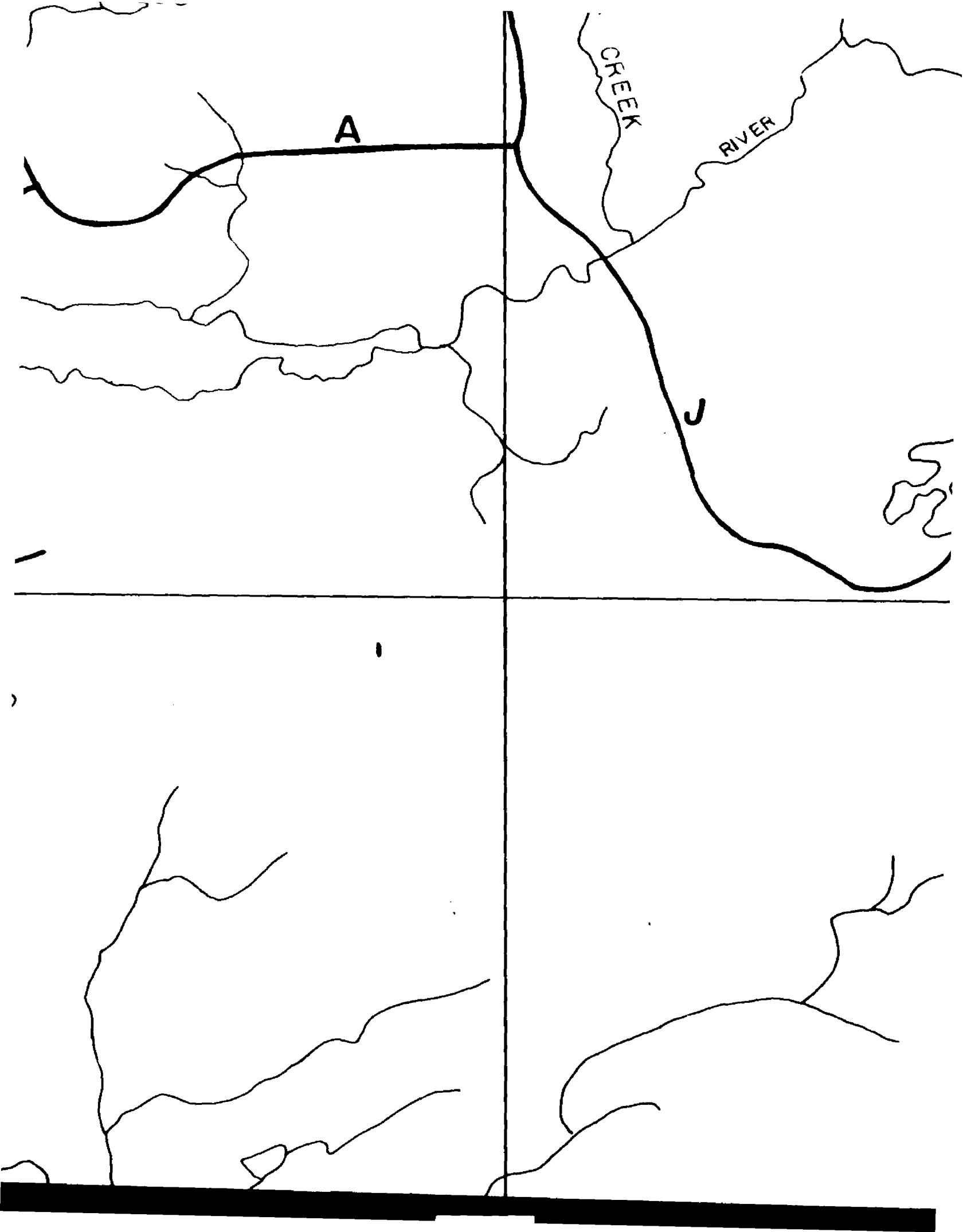


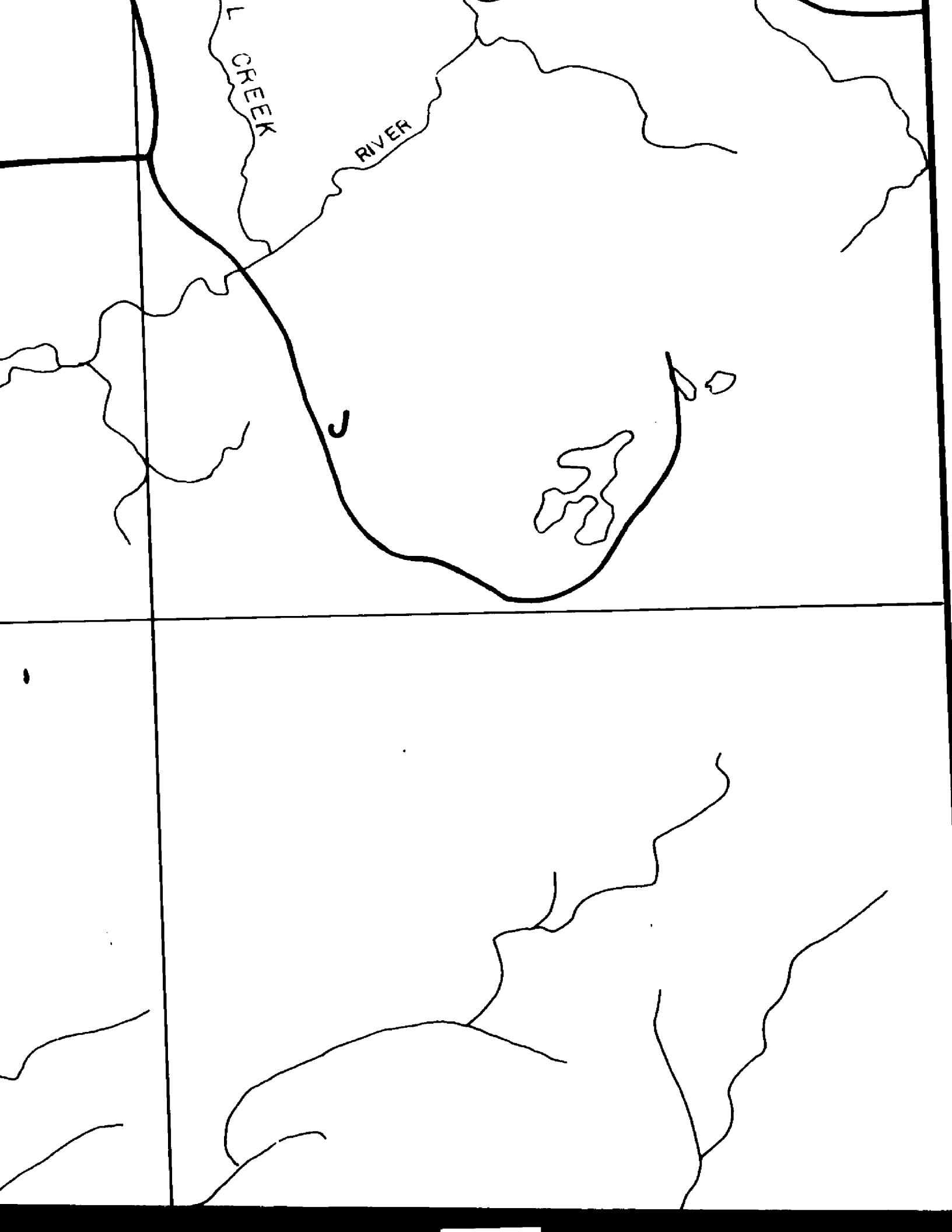


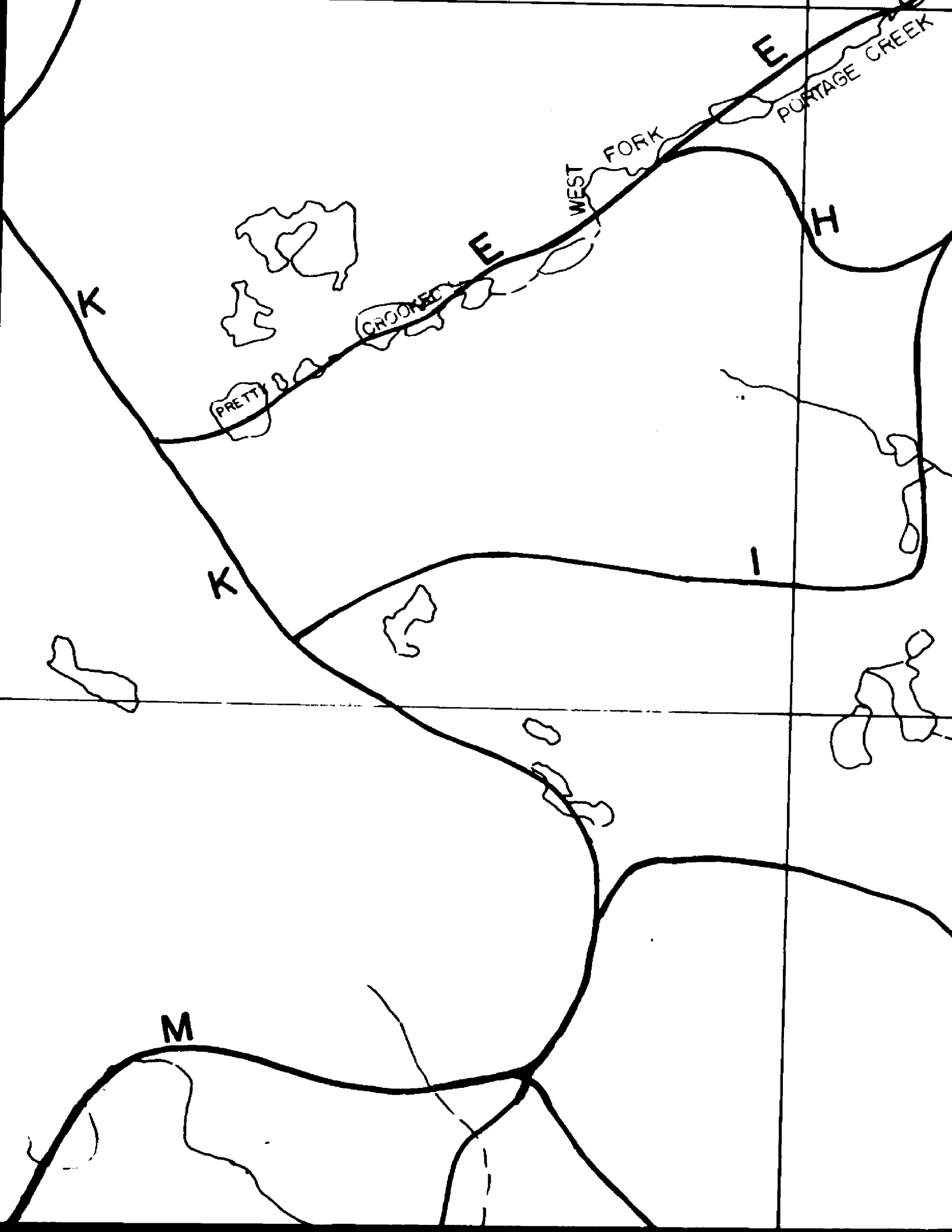


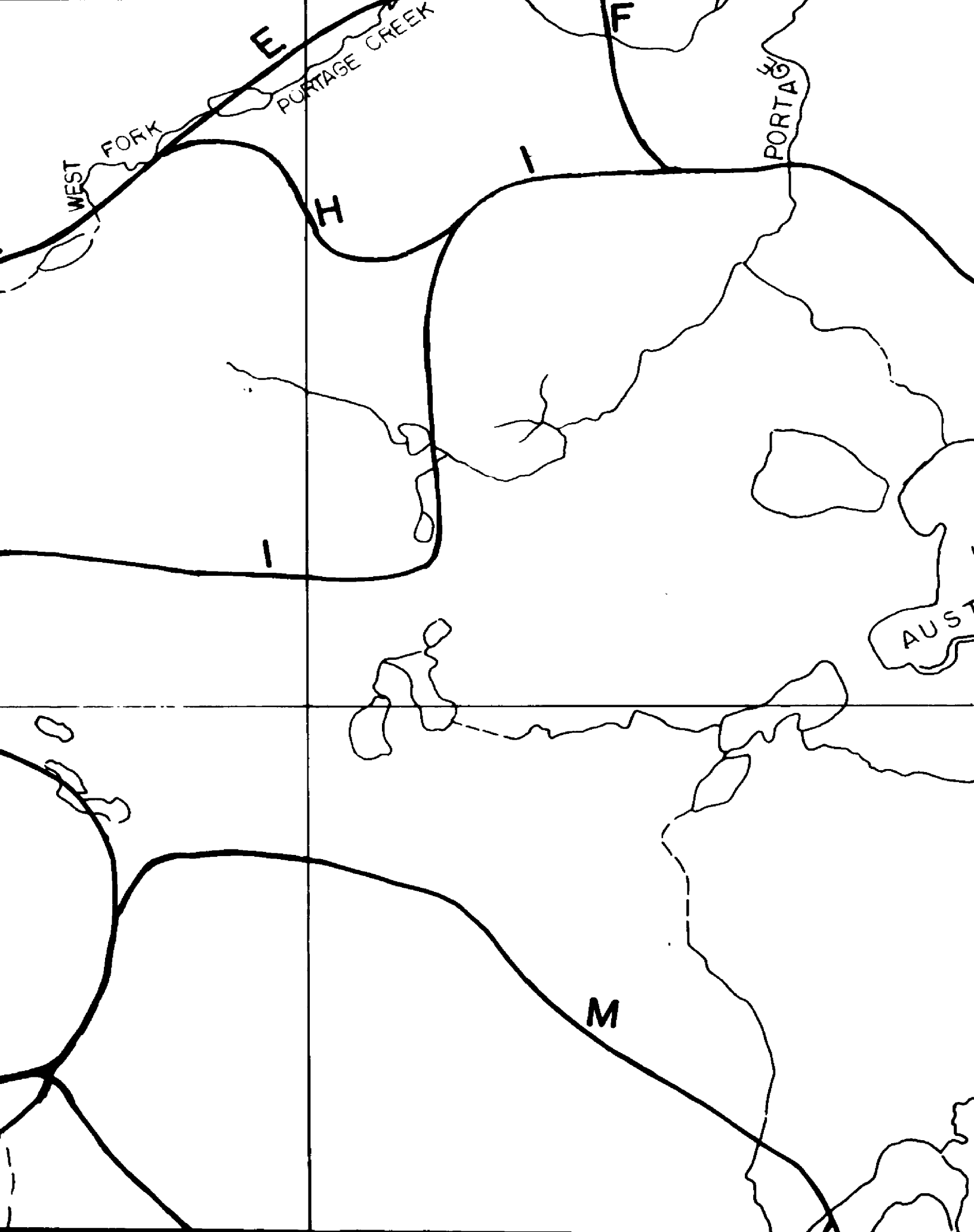




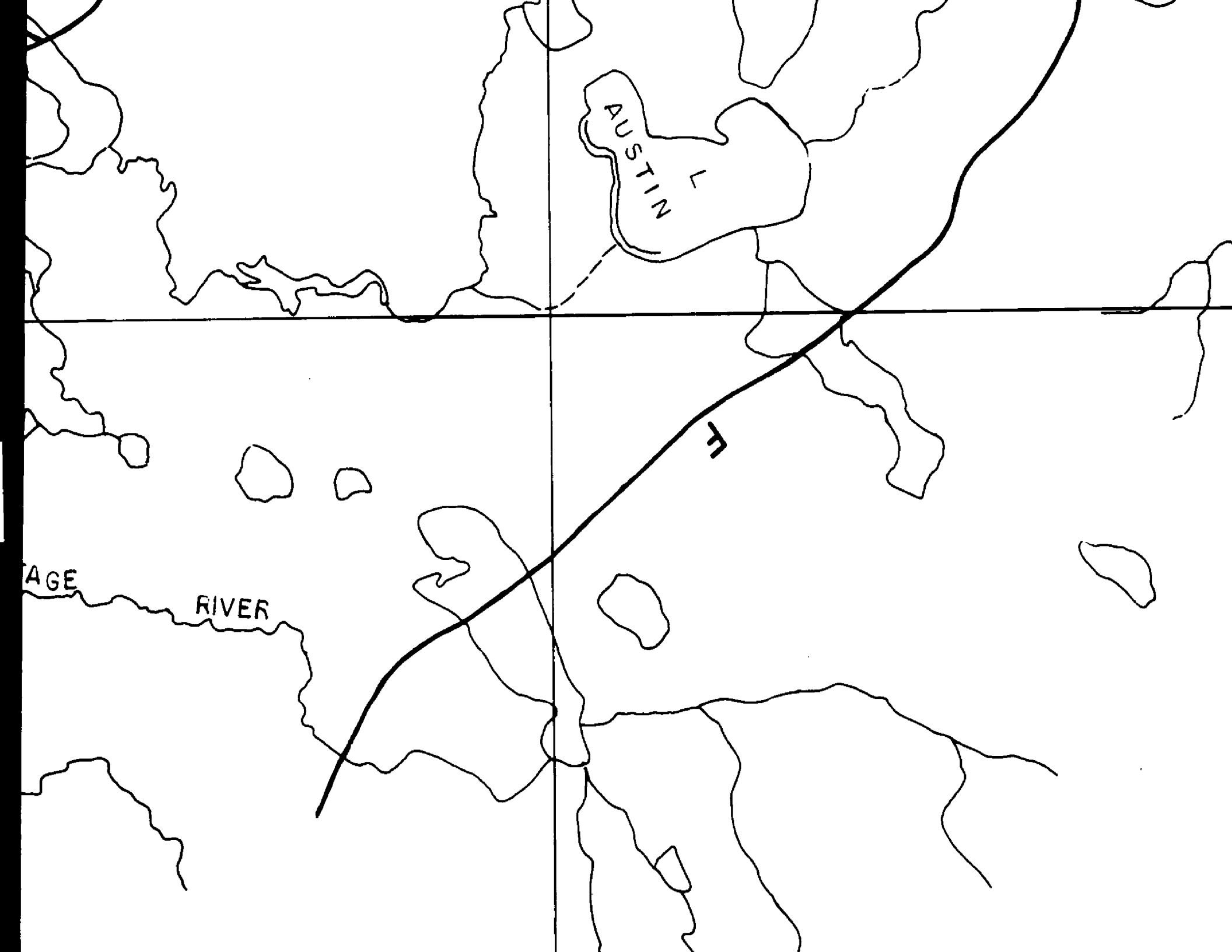


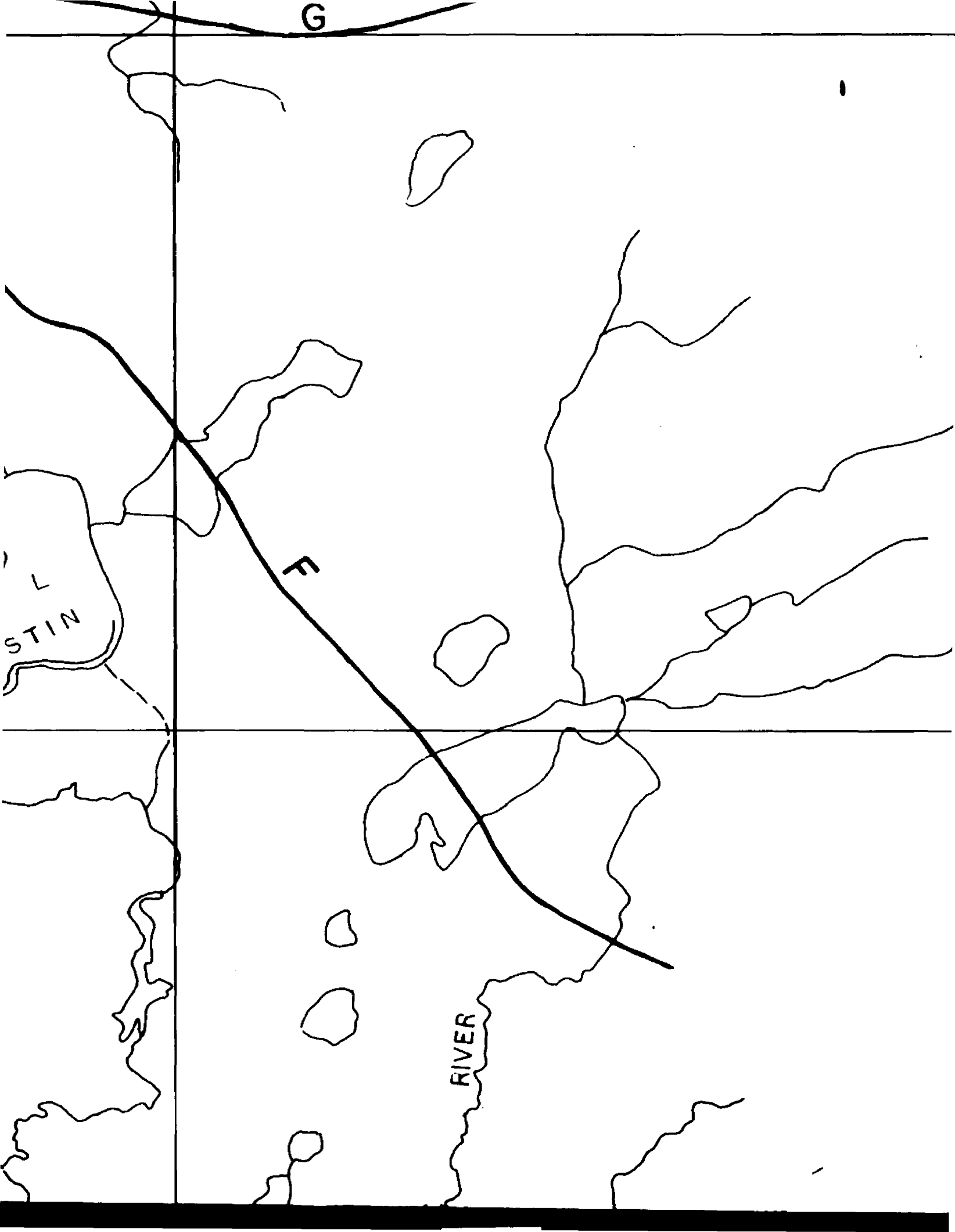










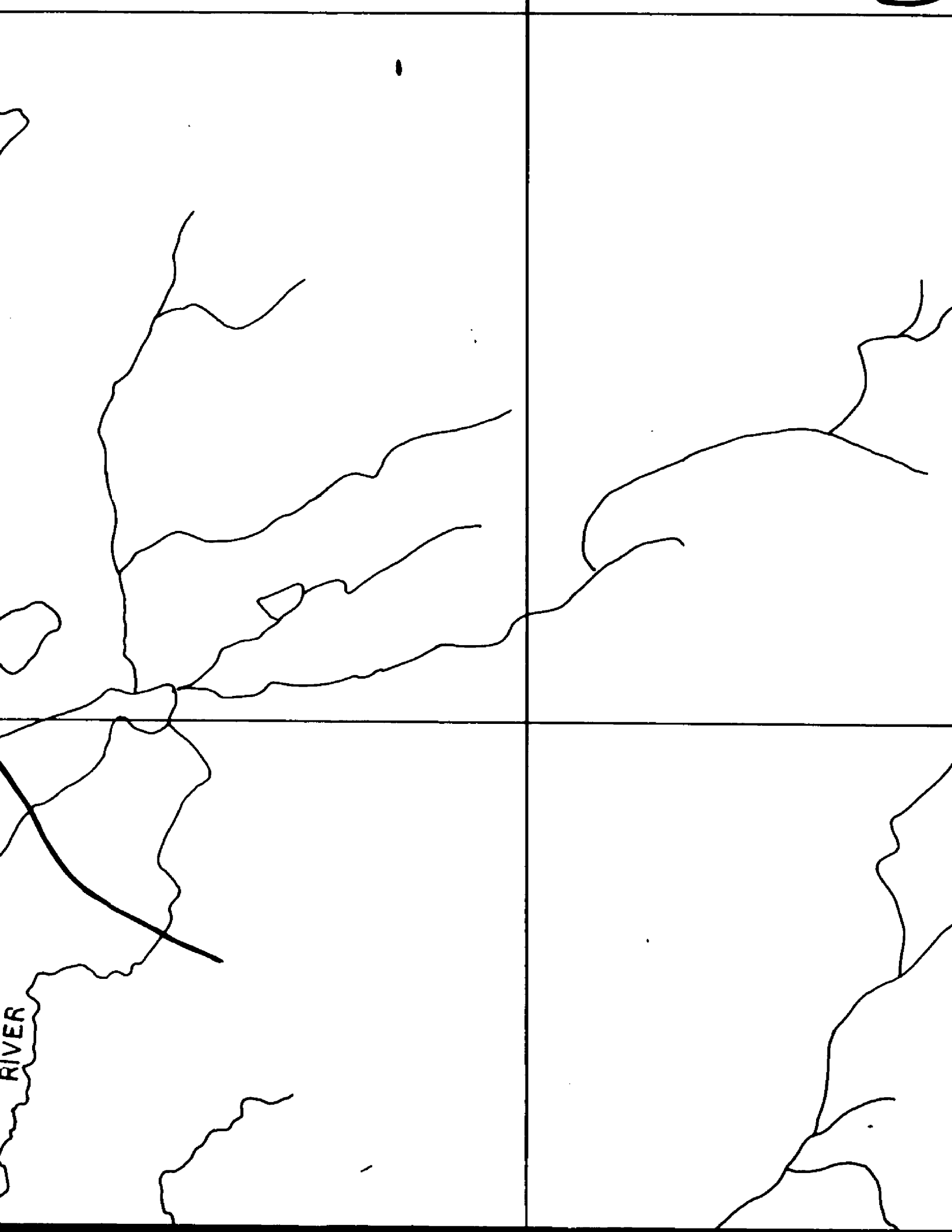


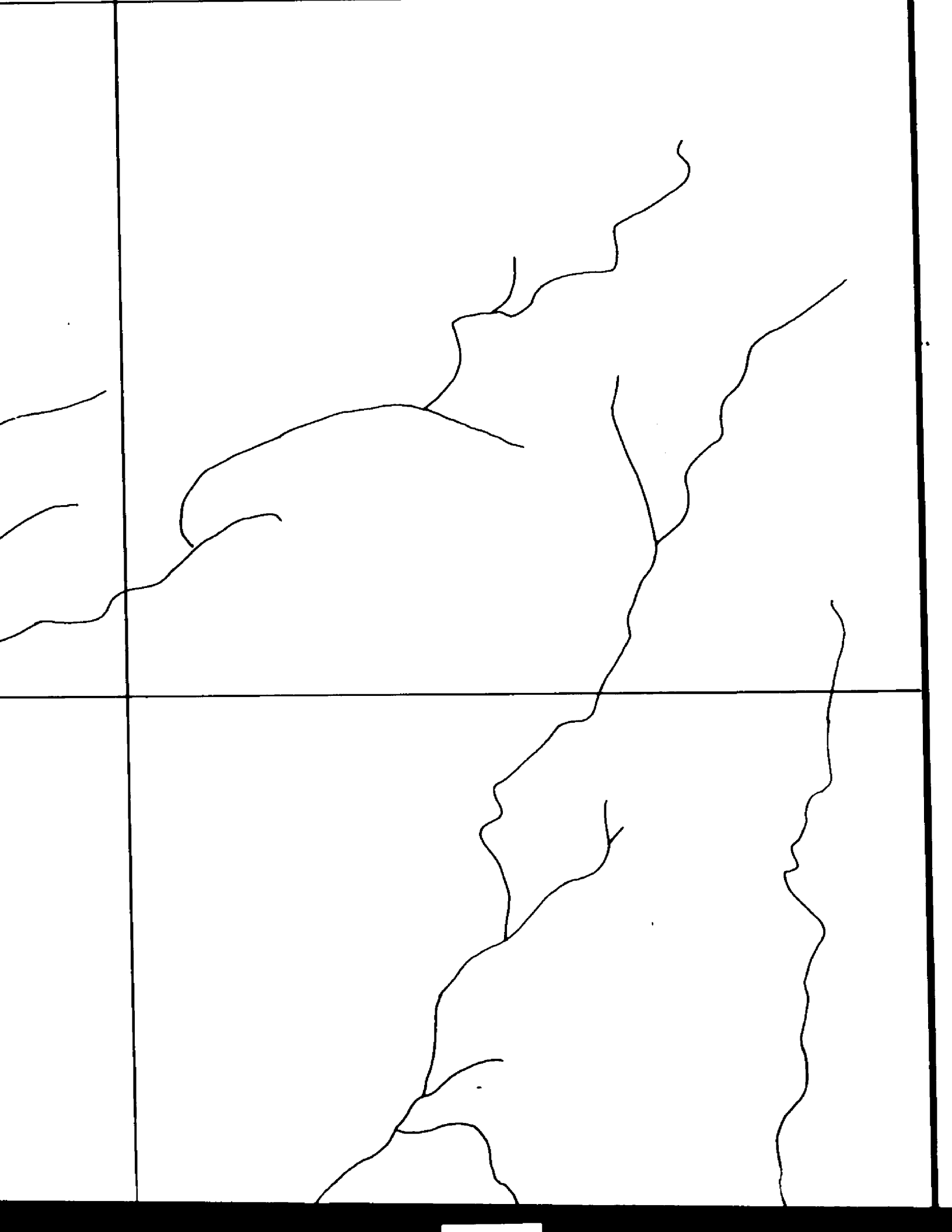
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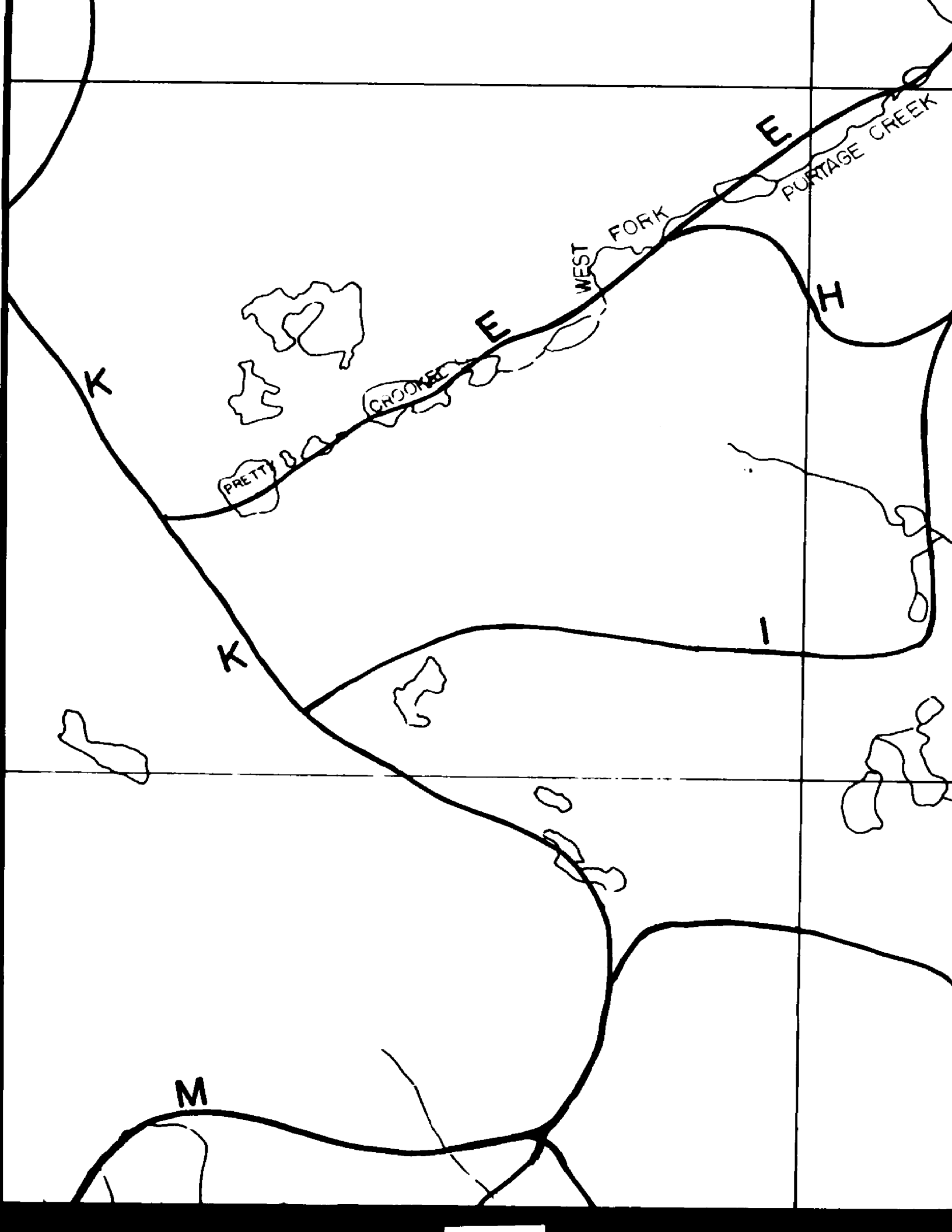
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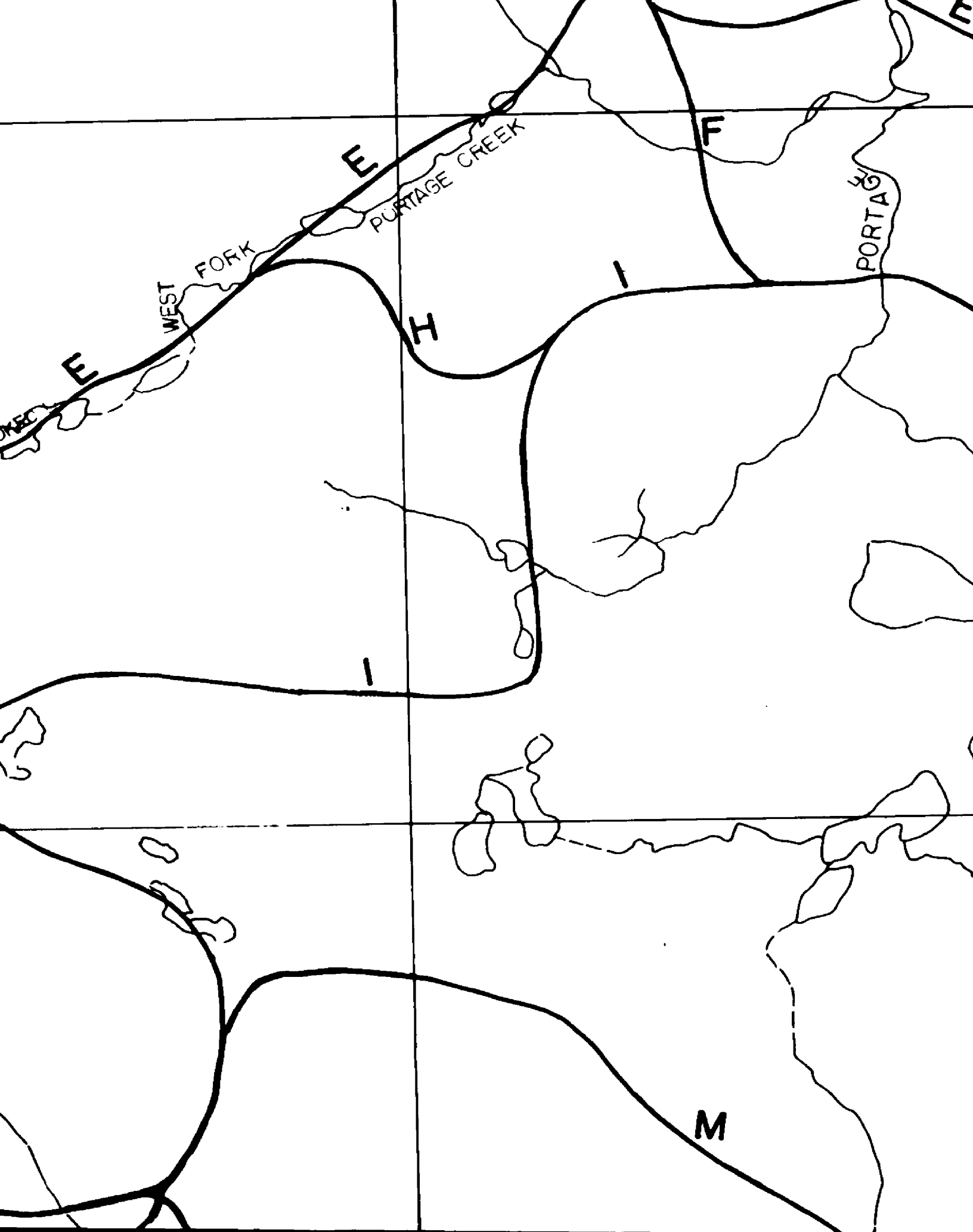
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STIN

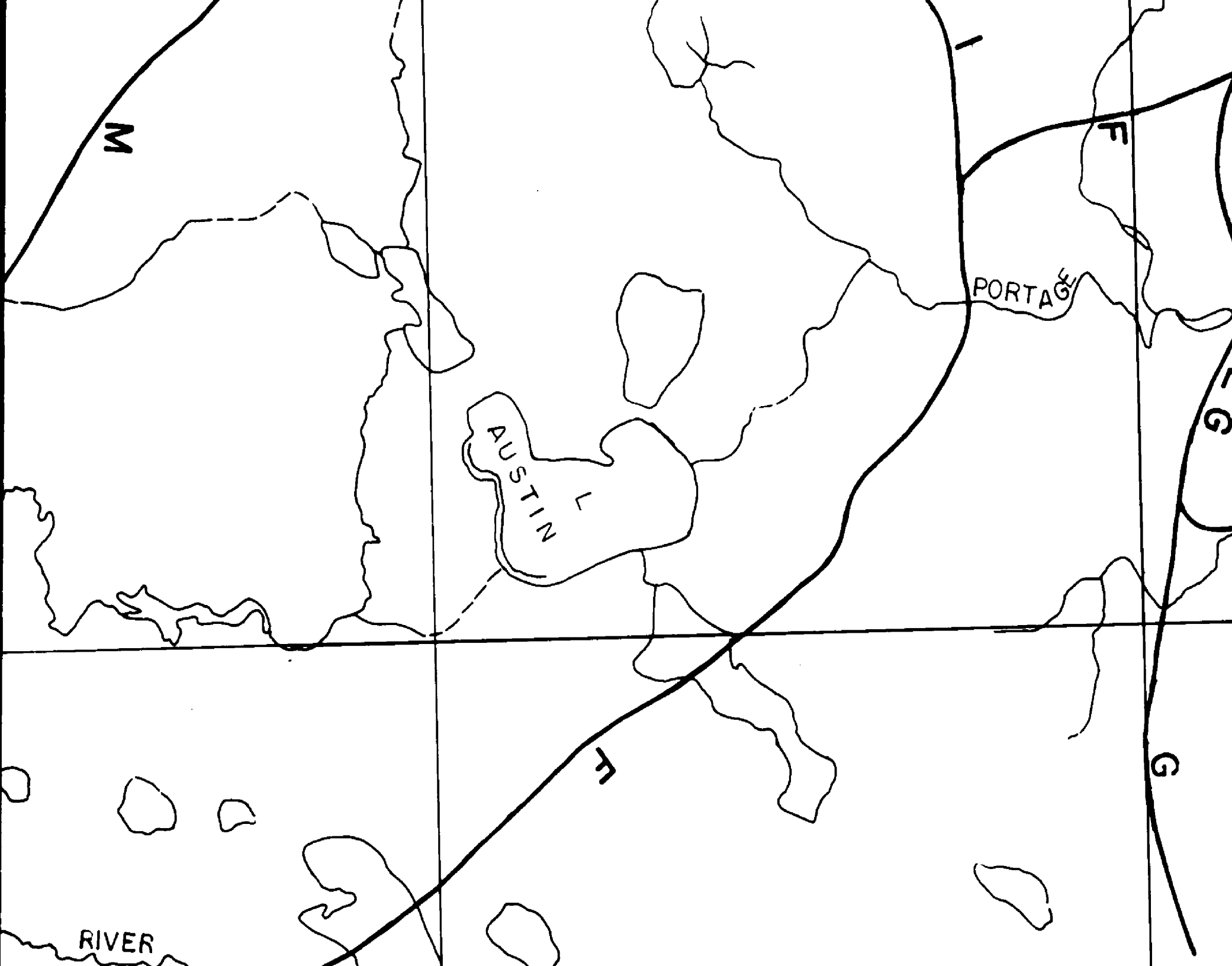
RIVER

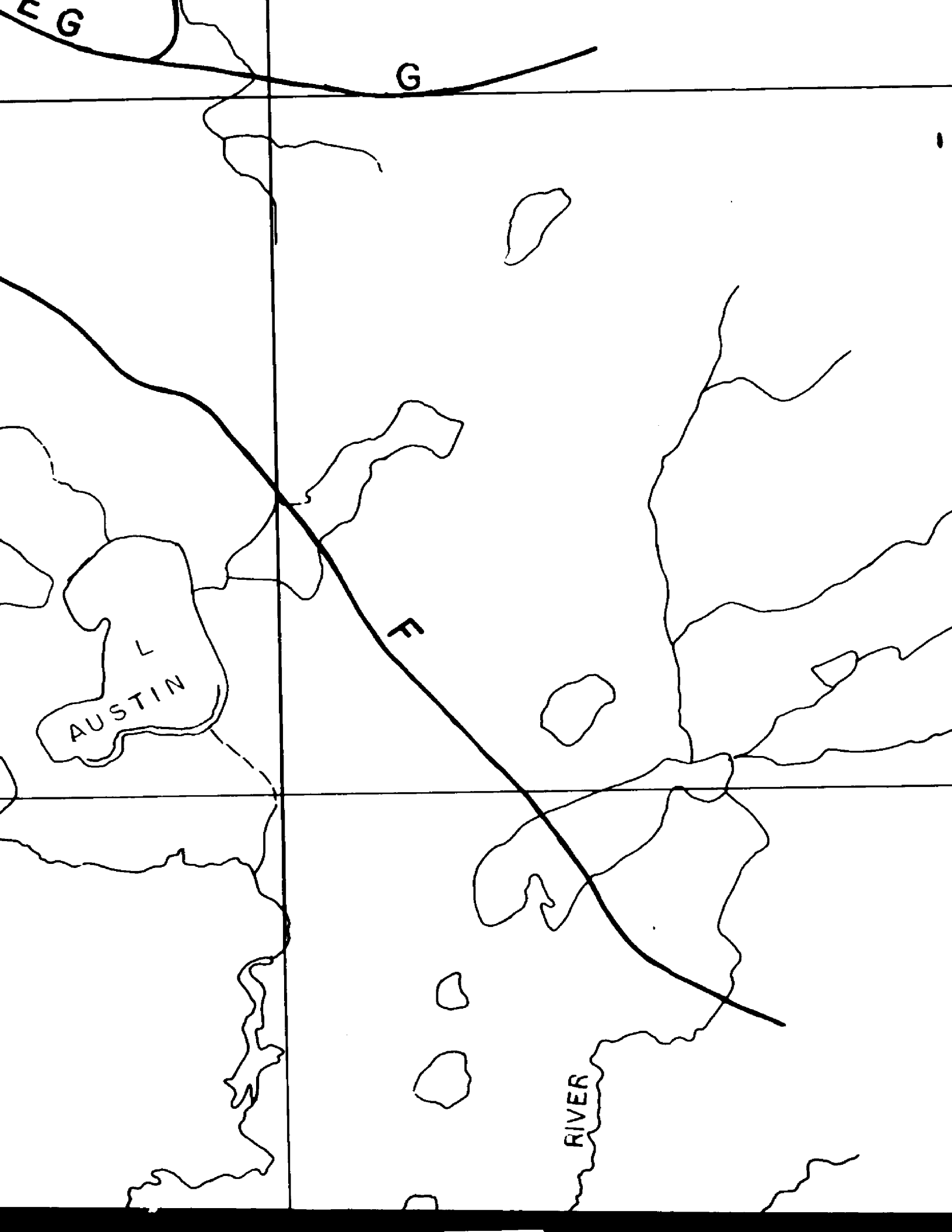




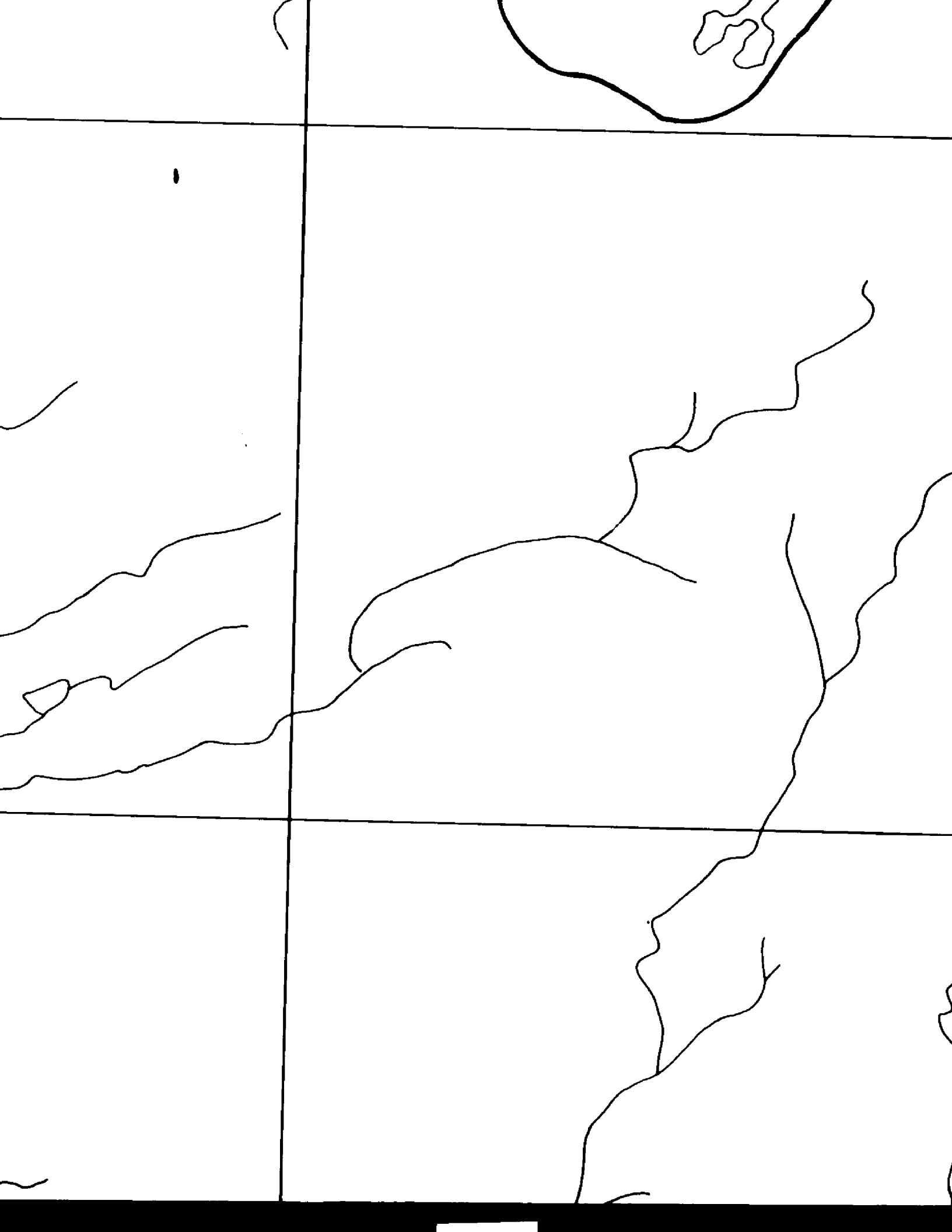


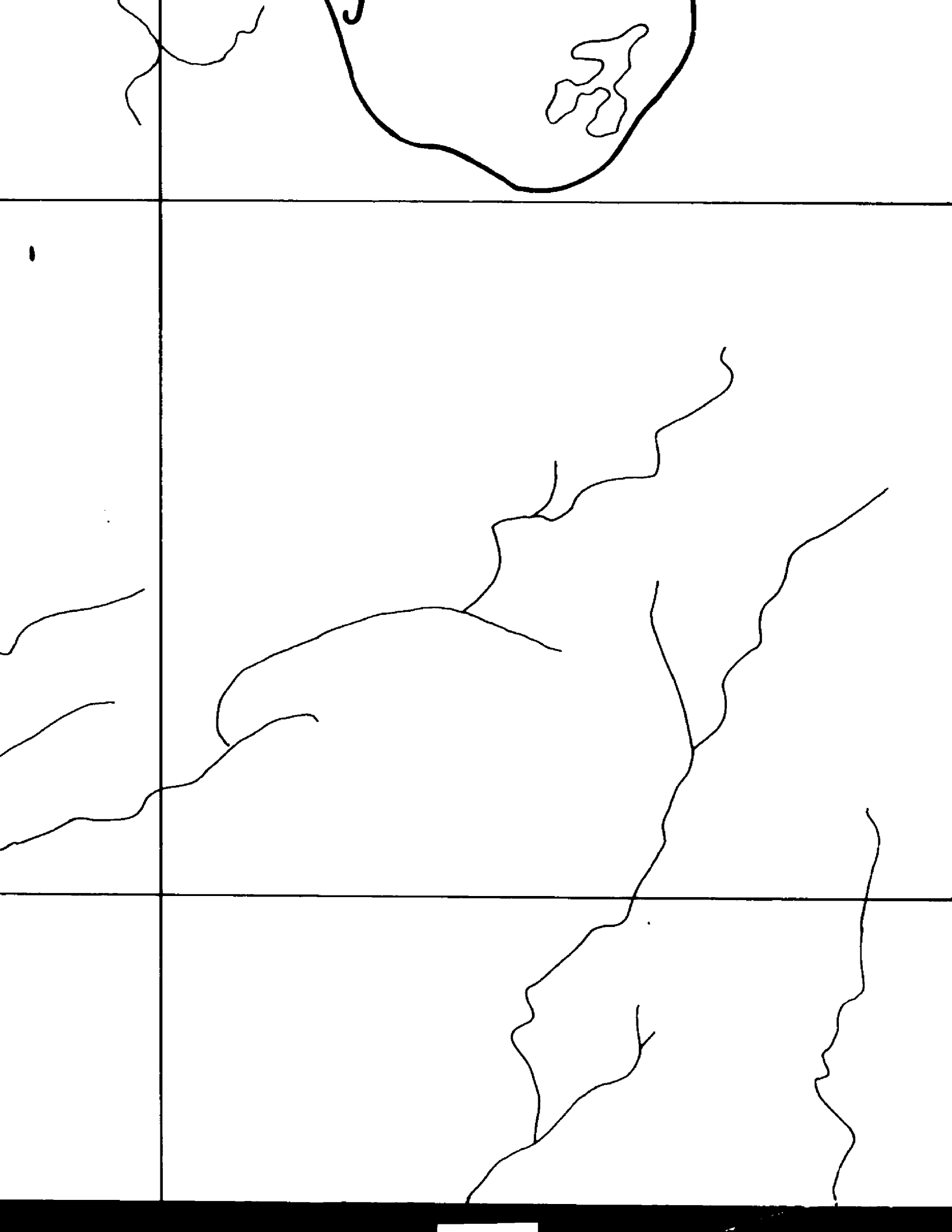












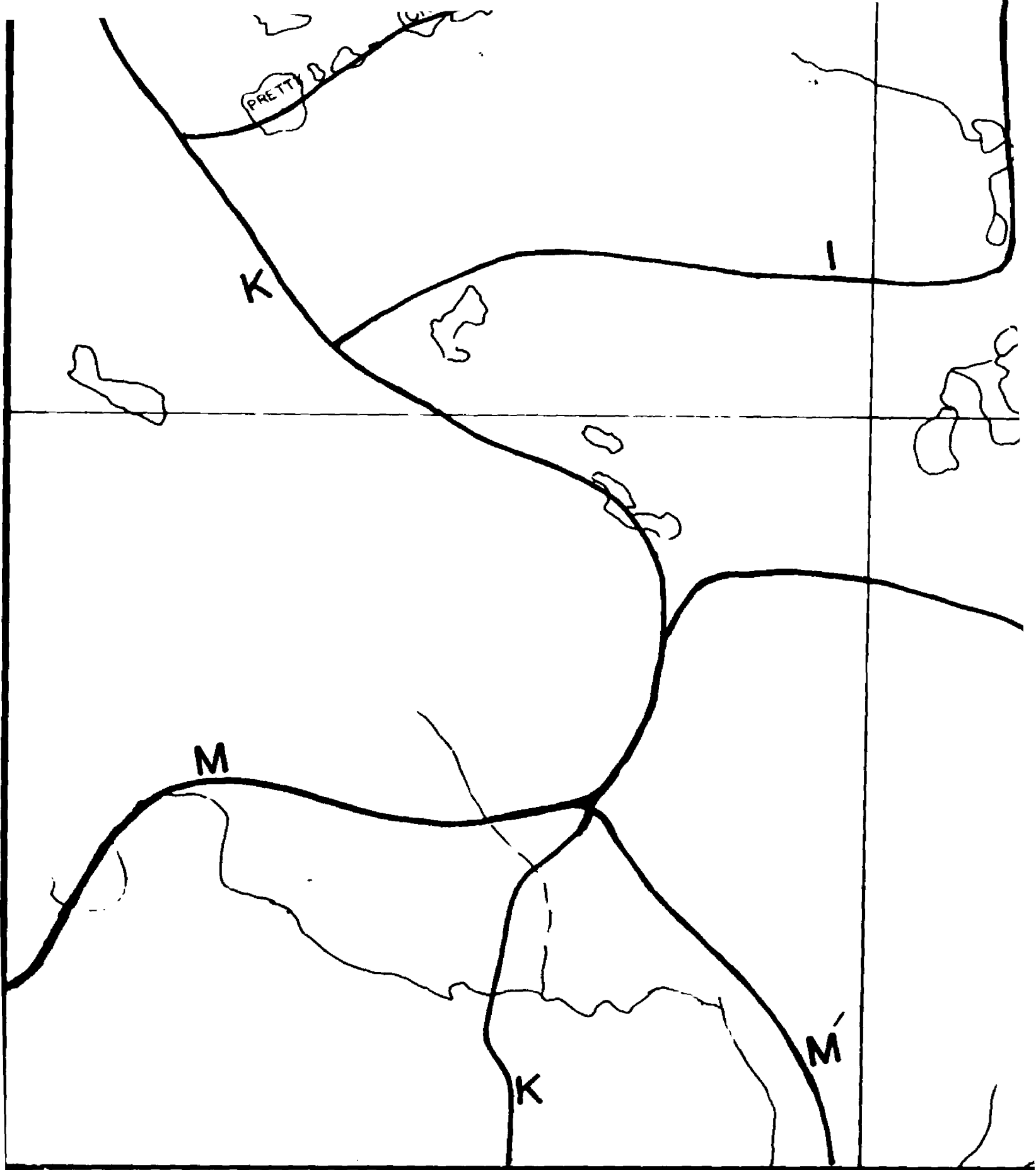
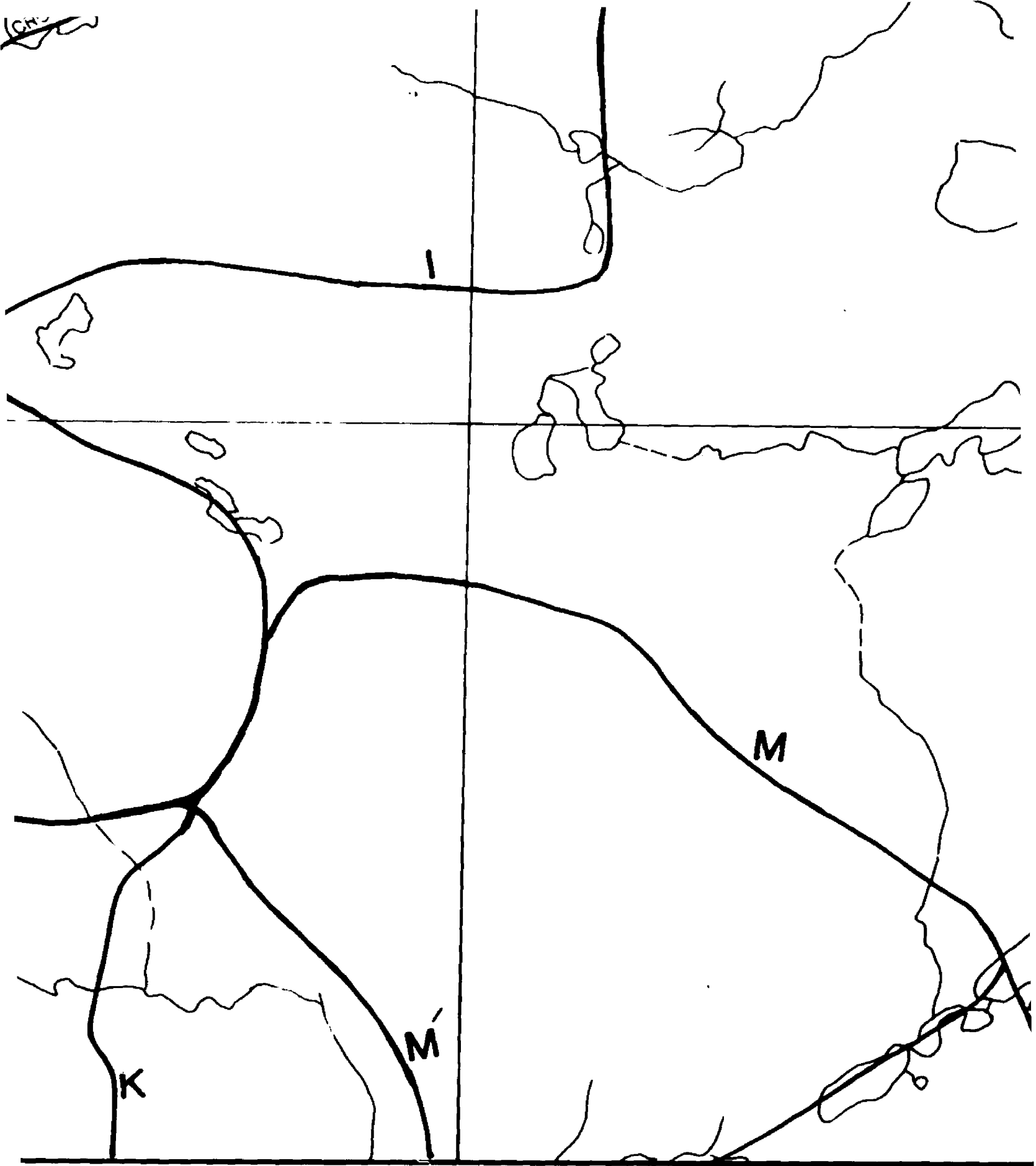
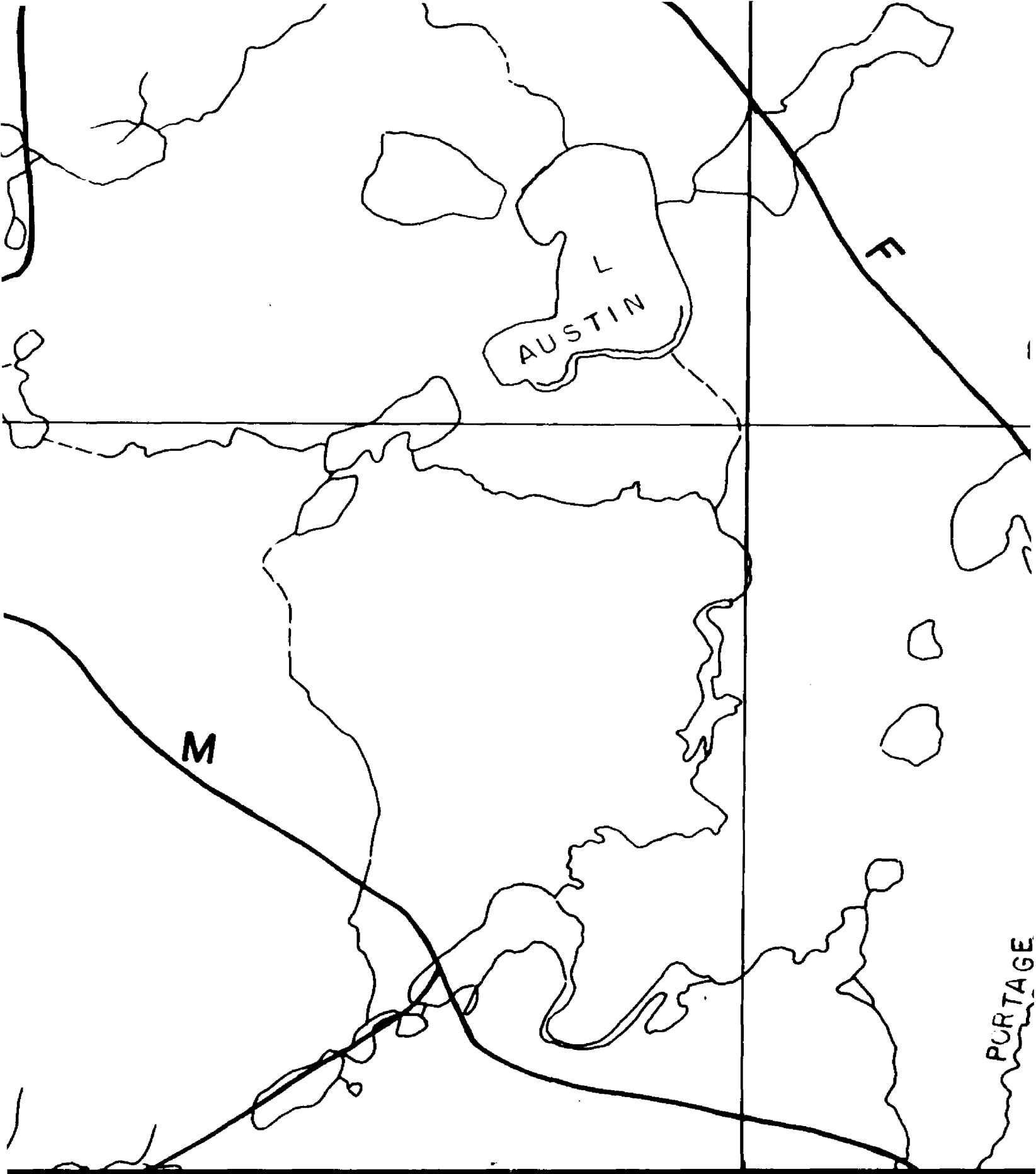


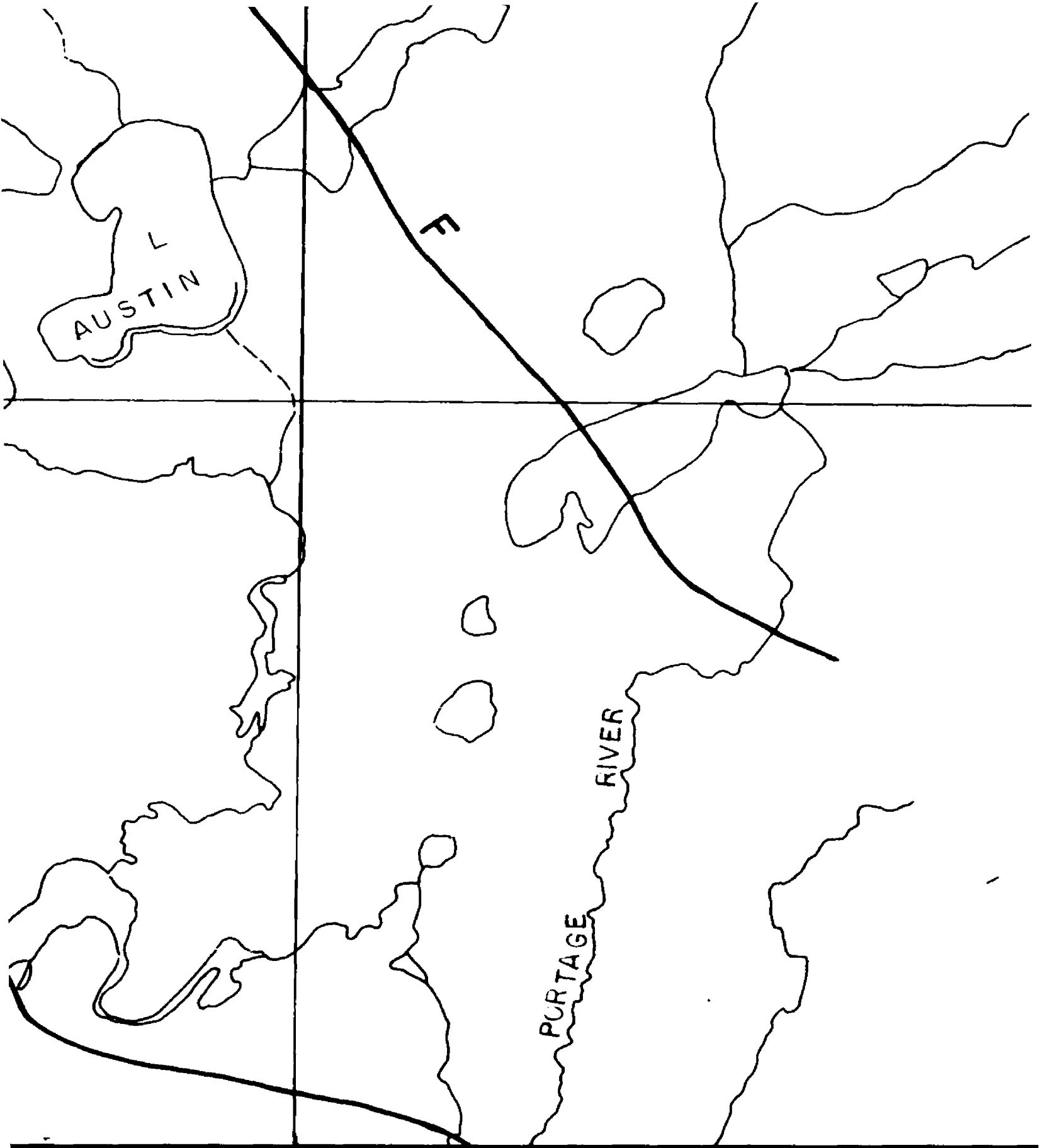
PLATE 9 SURFACE DRAINAGE AND BEDR



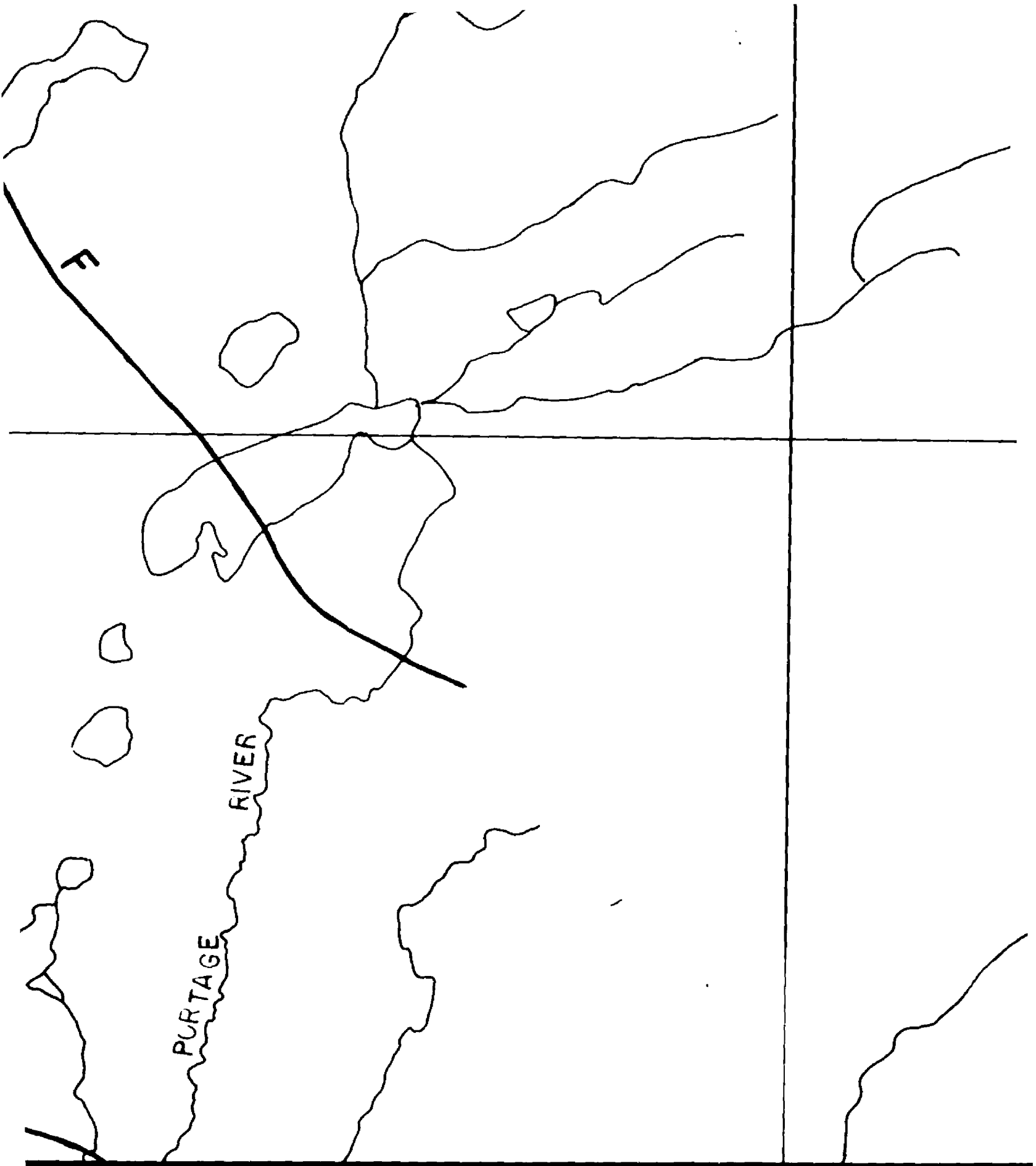
SURFACE DRAINAGE AND BEDROCK CHANNELS



ROCK CHANNELS IN KALAMAZOO CO

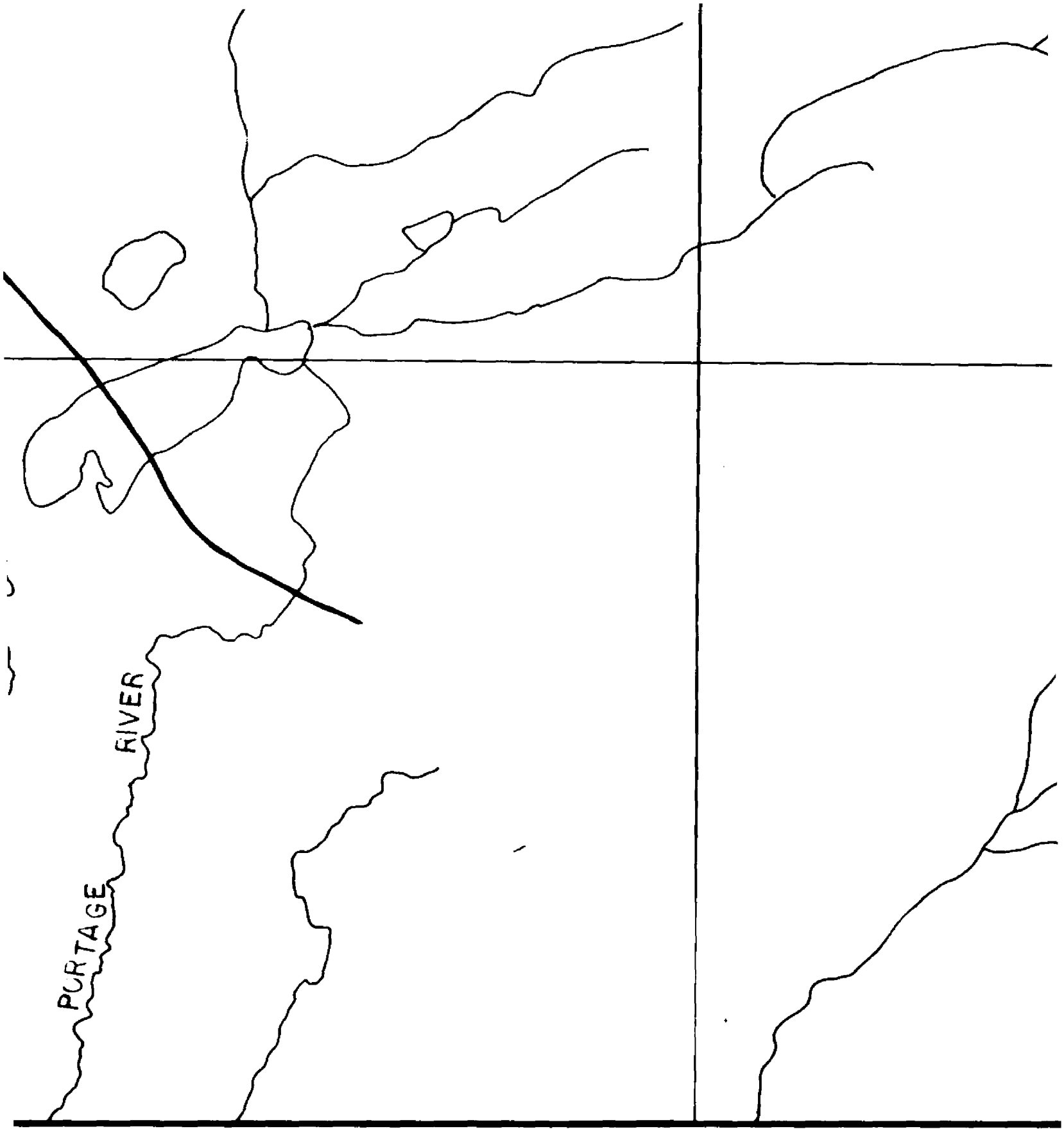


IN KALAMAZOO COUNTY



ZOO COUNTY

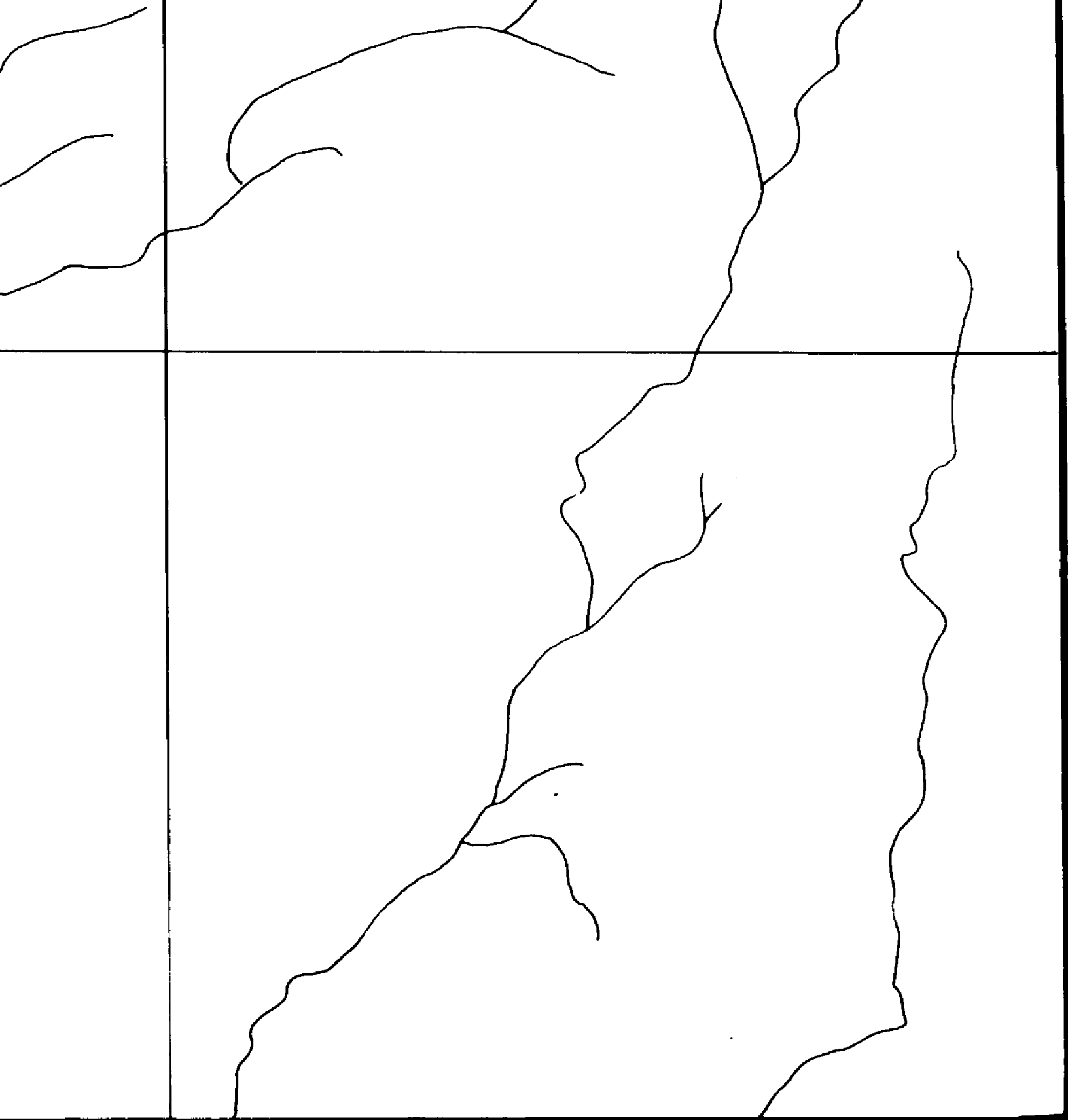
SCALE



COUNTY

SCALE 1

- BEDROCK CH
- SURFACE DRA



SCALE 1" = 1 MILE

— BEDROCK CHANNEL

— SURFACE DRAINAGE