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EXPRESSION OF A CROSS-STRIKE STRUCTURAL DISCONTINUITY IN PENNSYLVANIAN ROCKS OF THE EASTERN PLATEAU PROVINCE

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ABSTRACT

Major, cross-strike structural discontinuities appear to be large volumes of intensely fractured rock, and may be useful guides in exploration for fractured gas reservoirs. To determine whether the Petersburg lineament of the western Valley and Ridge province of West Virginia is expressed in the Pennsylvanian rocks of the eastermost Plateau province, LaCaze mapped about 60 square km (23 square mi) of late Paleozoic molasse atop Allegheny Front, in an area straddling the lineament's westward projection. Eight outcrops of Homewood sandstone strung across the projection contain longitudinal, transverse and an east-striking set of diagonal joints. Joint intensity (surface area per unit volume of rock) in the projection is about twice that outside. Structure contours show that a map-scale syncline is disrupted immediately west of the high-intensity zone. Thus the lineament is expressed in the Pennsylvanian rocks of the eastermost Plateau province as a zone of increased fracturing at least 1.3 km (0.81 mi) wide, with associated broader disruption of map-scale structure.

INTRODUCTION

Purpose

Cross-strike structural discontinuities (CSDs) are "map-scale structural lineaments or alignments, at high angles to regional strikes, and best recognized as disruptions in strike-parallel structural or geomorphic patterns" (Wheeler, Winslow, and others, 1979). CSDs are abundant in the central and southern Appalachians and in other overthrust belts. Wheeler, Winslow, and others summarize characteristics of many mapped CSDs, and much of the following discussion of CSDs is based on work cited by them.

Present evidence is that CSDs are several km (mi) wide and each may contain on the order of 1000 cubic km (240 cubic mi) of intensely fractured rock (Wheeler, 1978a and 1978c). The Devonian clastic sequence of the central and southern Appalachians contains gas in fractured reservoirs, and many workers are trying to improve exploration and stimulation methods applicable to such reservoirs (Shumaker and Overbey, 1976; Wheeler and others, 1976; Schott and others, 1977; Anonymous, 1978). CSDs and their associated fracture systems may provide a method for extending that exploration effort into the little tested eastern Plateau province of West Virginia and adjacent states, where the Devonian clastic sequence is detached.

One such CSD is the Petersburg lineament in the Valley and Ridge province of West Virginia (Figure 1; Sites, 1978 and 1979). This paper has two purposes: (1) To determine whether the Petersburg lineament is expressed in Pennsylvanian rocks of the easternmost Plateau province, atop the Allegheny Front, and (2) to test methods for mapping the Petersburg lineament and other CSDs westward, under the Pennsylvanian and Permian cover of the Plateau province.

Setting

In Grant and Hardy Counties, West Virginia, the Petersburg lineament treads about N75°E and is well exposed in the Silurian and Devonian rocks of the western Valley and Ridge province (Sites, 1978 and 1979; other work cited by Wheeler, Winslow, and others, 1979). Immediately west of the Wills Mountain anticline at the western edge of the Valley and Ridge province, the lineament is subtly present in Devonian and Mississippian rocks on Allegheny Front (Wilson and Wheeler, 1974). The westward projection of the lineament into the easternmost Plateau province passes through the Dolly Sods Wilderness Area of Tucker County, West Virginia (Figure 1). There, red, flaggy sandstones, siltstones, and shales of Late Mississippian age are overlain by coals, shales, siltstones, conglomerates, and thick, flaggy or cross-bedded sandstones of Pennsylvanian age. The exposed section is 1000 to 1500 feet thick (305 to 457 m), and sedimentary layers (as distinct from cross beds) have low dips on both limbs of the map-scale Stony River syncline that includes the map area (LaCaze, 1978; Reger, 1921).

Acknowledgments

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JOINTS

Systematic Joints

The topographic break of Allegheny Front exposes thick, cross-bedded, well-cemented, quartz sandstones and conglomerates of the uppermost Lower Pennsylvanian Homewood sandstone (LaCaze, 1978). There, the Homewood contains three sets of systematic joints: transverse, striking about N48°W; longitudinal, striking about N28°E; and diagonal, striking about N75°E. Eight large Homewood outcrops of relatively constant lithology and bed characteristics are scattered across the westward projection of the Petersburg lineament through Dolly Sods, and along the eastern border of the map area. In each outcrop, LaCaze measured spacing for those three sets: perpendicular separations of adjacent joints in the same set. The diagonal set was not found in the two outcrops southwest of the lineament's projection. Wheeler later found but did not measure that set in a smaller Homewood outcrop yet further southwest.

Wheeler attempted to estimate relative ages of the three sets, using criteria successfully applied to finer-grained rocks by Kulander and others (1977 and 1978), Wheeler and Holland (1978a and 1978b), Dixon (1979), and Wheeler and others (1979). Plumose and other delicate structures on joint faces (transient features of Kulander and others, 1977) can record the origin, propagation history, and end of a joint, but the Homewood exposures are too coarse-grained and joint surfaces too weathered to preserve such features recognizably. A young joint will usually abut against or hook into an older one in a T- or J-intersection, and such tendential features (Kulander and others, 1977) are abundantly preserved in the Homewood outcrops. However, evaluation of 105 tendential relations, mostly abuttings, in and near the outcrops that yielded spacing measurements gave no conclusive results. For each of the three possible pairings of joint sets, the tendential relationships are about equally divided on relative ages of the two sets involved. The most conclusive determination of relative ages was that transverse joints predate longitudinal joints, which was also found by Wheeler and Holland (1978a and 1978b) and Dixon (1979) elsewhere. However, that relative age has a significance value of only 0.227 by the binomial test. That is, there is one chance in four or five that the observed relative ages between longitudinal and transverse joints, or a relationship yet more conclusive, could have arisen by chance alone.

There are several possible reasons for the lack of clear-cut relative ages. (1) All three sets may have formed coevally. (2) Each set may have been filled and cemented shut, or its walls may have been pressed together with coarse grains interlocking, in stress-transmitting contact, before the next set formed. Neither of us saw any evidence of remaining joint fillings, but joint walls are intensely weathered, iron-stained, and eroded. (3) In some X-intersections where two joints appear to cross each other, one arm of the X is short and narrow. Also, some joints hook abruptly into other nearby and parallel joints, and in some such occurrences, the hook is much less weathered than the rest of the joints. Those observations are consistent with the possibility that physical and chemical weathering, acting long after jointing ceased, might cause a younger joint to propagate across an older one in some manner, changing a T-intersection into an X-intersection. At present, improving understanding of jointing and modification of joints by weathering seems more important than collecting more data.

Joint Intensity

Wheeler (1979) and Wheeler and Dixon (1979) define joint intensity (I) as the amount of joint surface area per unit volume of rock. Following Vialon and others (1976), they calculate the intensity of a single set as the inverse of the set's mean spacing. Then intensity of an exposure is the sum of the intensities of all sets in that exposure. Stearns (1968) and Rousell and Everitt (1978) independently developed an equivalent measure of intensity based on joint frequency (Price, 1966). Wheeler and Dixon (1979) argue that intensity is less distorted by a few extremely large or small spacing values if one replaces mean spacing by the trimean (Tukey, 1977). The resulting estimator of I is called I_T.

Values of I_T for the Homewood sandstone are in Figure 2. Intensities are higher in the westward projection of the lineament (outcrops 3 through 6). That occurs for all three sets, and all outcrops are on the topographic break of Allegheny Front, so topography and mass wasting are not responsible for the increased intensity.

Photolineaments are often found or assumed to overlie unusually fractured rock. Wheeler examined a false-color composite LANDSAT print (taken in October at 1:250,000), a positive LANDSAT print (at about 1:1,000,000) and color infrared images (taken in February, from about 65,000 feet elevation), and found no photolineaments passing through the high-intensity area. Thus the Petersburg lineament does appear in the Pennyslvanian rocks of the easternmost Plateau province as a zone of increased joint intensity.

The lineament narrows as it passes upsection, westward, or both from the Silurian and Devonian rocks of the western Valley and Ridge province to the Pennyslvanian rocks of the Plateau province. Outcrops 3 through 6 are more intensely jointed than are the other four, but only with a significance value of 0.09 (randomization test: Siegel, 1956). However, if outcrop 3 is regarded as lying northeast of the lineament, the significance value drops to 0.01. Thus the lineament at Dolly Sods includes only outcrops 4 through 6, and may be as narrow as 1.3 km (0.81 mi), rather than at least 2.7 km (1.7 mi) wide (Figure 2).

DISRUPTIONS OF SEDIMENTARY LAYERS

In Silurian, Devonian, and Mississippian rocks of the Valley and Ridge and eastern Plateau provinces, the Petersburg and other similar lineaments are expressed as disrupted patterns on strike-line maps and on contour maps of bed dip and bed strike (Trumbo, 1976; Sites, 1978; Wilson, 1979; other sources cited by Wheeler, Winslow, and others, 1979). We applied that approach to the Pennsylvanian and Upper Mississippian rocks of Dolly Sods.

Data

Many or most exposures are of cross-bedded sandstones. We measured or constructed orientations, not of cross-beds, but of the top or bottom contacts of cross-bedded depositional units (sedimentary layers: A. C. Donaldson, oral communication, April 1979). LaCaze measured strike and dip of layers directly, with a Brunton compass. Where several measurements on the same exposure were feasible, we use their median. LaCaze also constructed three-point solutions for mapped upper contacts of thick, resistant, continuous sandstones. Wheeler added layer orientations constructed from traces of layers on three faces of the same exposures (see discussion below). The four types of estimates of layer orientation were then smoothed by first weighting each estimate according to its uncertainty, and then taking medians of the weighted estimates falling within square cells 2000 feet (610 m) on a side (Figure 3). The number and uncertainty of orientation estimates in each cell were considered in interpreting maps of the smoothed data.

Structure Contours

Figure 4 shows structure contours on three horizons. Intersections of topographic contours with geologic contacts mapped by LaCaze (1978, Plate 1) on a 7 1/2 minute topographic base define contours atop the Upper Mississippian Princeton sandstone and the uppermost Lower Pennsylvanian Homewood sandstone, where those two members are exposed. Reger (1921) contoured the base of the uppermost Middle Pennsylvanian Upper Freeport coal. The contoured horizons span about 350 m (1150 ft) stratigraphically (LaCaze, 1978, Figure 11). All Three horizons show the trough of the Stony River syncline (Figure 4), and the upper two show structural relief of 500 to 700 feet (152 to 213 m). Dips calculated from Figure 4 range from about 10 degrees in the northwest part of the map area to a more representative three degrees along the area's eastern edge. For comparison, median layer dips for direct measurements, three-point solutions, and constructions from layer traces are five, one and eight degrees, respectively.

In the center of the map area, Figure 4 show a saddle in the trough at Princeton level, and anomalous bends in the trough line at that and Upper Freeport level. Indeed, Cardwell and others (1968) and LaCaze (1978, Plate 1) show two northeast-trending, en echelon synclines. LaCaze interprets them as separated by a northeast-trending anticline which he names the Breathed Mountain Anticline. The structure contours of Figure 4 are consistent with both existence and nonexistence of the anticline. In either case, map-scale structure is disrupted in the center of the map area, in an east-trending zone about three km (two mi) wide, and including outcrops three through six of the joint intensity work (Figures 2 and 3)

Structure contours atop deeper horizons are not detailed enough to determine the vertical extent of that disruption (Haught, 1968; Cardwell, 1971, 1973, and 1976). LaCaze (1978) suggests that the Breathed Mountain anticline has 75 m (246 ft) of closure and speculates that it may be formed over a detachment no deeper than the Upper Devonian.

Other Maps of Layer Orientations

We drew maps of strike lines, and contours on numerical values of strike, absolute dip, and angular deviation from a pi axis of N35E/02NE fitted by hand to all direct measurements of layer orientation. Those maps drawn by both of us independently are similar, and resemble computer-drawn maps of the same data. Thus our maps are both objective and reproducible, properties that should be demonstrated for hand-drawn contour maps (Dahlberg, 1975 and 1979).

On the strike-line map, Wheeler chose a disrupted zone 1.6 km (1.0 mi) wide measured in a north-south direction, and a broad synclinal nose 5.5 km (3.4 mi) wide. On the map of absolute dip he chose a high-dip zone 4.2 km (2.6 mi) wide, and on the map of angular deviations, a high-dispersion zone 2.6 km (1.6 mi) wide. All but the 1.6 km-wide disrupted zone also appear on longitudinal sections made by projecting cell values (Figure 3) onto the east edge of the map area. In the longitudinal sections, all three anomalous zones have widths of 3.6 km (2.2 mi) though they do not coincide. The resulting seven anomalous zones on maps or sections thus vary in width and location, but all are crudely coincident with the Petersburg lineament's westward projection and with the zone of high joint intensity.

However, the seven anomalous zones are subtle, so tests of statistical significance are necessary to demonstrate their validity. We test seven anomalies for significance. To insure that the probability of obtaining one or more spuriously significant results does not exceed the standard value of 0.05, we select a significance level of 0.05/7 = 0.007 (by the Bonferroni inequality: Miller, 1966; Wheeler and Holland, 1978b). The appropriate tests are the Siegel-Tukey and Kruskal-Wallis (Conover, 1971; Siegel, 1956).

The 5.5 km-wide synclinal nose on the strike-line map is clearly not a random pattern: the significance value is 0.0007. The 2.6 km-wide zone of high dispersions on the map of angular deviations approaches but does not achieve significance: the significance value is 0.0233. However, neither result adds much to the information already obtained from the structure contour map (Figure 4). None of the five other anomalies on the maps and longitudinal sections of layer orientations are remotely significant: significance values exceed 0.1.

In summary, for shallowly-dipping Pennsylvanian rocks of the eastern Plateau province, maps of layer orientations do not appear to provide information not more readily extracted from structure contour maps. Structure contour maps either already exist (Reger, 1921, and similar maps), or can be generated relatively fast using aerial photographs, maps of strip mines in known coals, and carefully designed field work to map tops of resistant sandstones and continuous coals. Even form lines, such as those of Shumaker (1974), may suffice to locate map-scale structural disruption characteristic of CSDs like the Petersburg lineament.

LAYER ORIENTATIONS IN CROSS-BEDDED ROCKS

As a by-product of this work, we found that a field technique in routine use in structural analysis of multiply-folded metamorphic rocks provides a fast, precise way to estimate orientations of irregular layers in the Pennsylvanian sandstones of the Plateau province. Large cross-beds and coarse grains often make location of a smooth, representative, directly measurable layer surface difficult, even in large exposures or when using an aluminum plate. Low dips make directly-measured strikes uncertain by 15 degrees or more (Woodcock, 1976). Averaging several independent direct measurements may solve the problem, but is often infeasible in small or weathered exposures.

However, our experience is that the eye can usually detect the traces of parallel sedimentary layers on at least two and usually three faces of an exposure. The traces need not be of the same layer, particularly if the three can be measured on faces at moderate to high angles to each other. By closing one eye to eliminate parallax, sight along each trace and measure its trend and plunge. The eye smooths irregularities in traces several m (yards) long.

Then fit a great circle to the three traces by constructing a beta axis (Figure 5; Ramsay, 1967, p. 12-14). That is, plot the traces in lower-hemisphere spherical projection. Great circles perpendicular to each trace define a spherical triangle. Construct the triangle's center of gravity as the intersection of the three great circles that connect each vertex with the bisector of the opposite side of the triangle. The great circle perpendicular to the center of gravity estimates the orientation of the layer or layers, and the mean of the angles between the center of gravity and the three side bisectors gives the precision of that estimate.

Wheeler estimated layer orientations for nine outcrops of Homewood sandstone along the east border of the map area. Precisions have a median of three degrees. That is about the minimum achievable using a Brunton compass and careful hand plotting and construction. Median precision of two or more direct measurements on each of 29 exposures is four degrees. Thus, for the rocks we studied, the beta axis method produces more precise results than does direct measurement. Because layers are irregular and the layer traces are visually averaged over large parts of an exposure, the beta axis method is also probably more accurate than direct measurement.

CONCLUSIONS

1. The Petersburg lineament extends west from the Valley and Ridge province, and appears in the Pennsylvanian rocks atop Allegheny Front as a zone of roughly doubled intensity of systematic joints at least 1.3 km (0.81 mi) wide.

2. In general, the lineament does not occur in the Pennsylvanian rocks of the easternmost Plateau province as a zone of disrupted sedimentary layers that can be efficiently mapped, and so is unlikely to do so further west in less deformed rocks. Thus it and other CSDs probably can best be extended west using joint intensity, structure contours, subsurface and geophysical data, and aerial and satellite images. The CSDs may have very narrow expressions in Pennsylvanian rocks, so close station spacing and careful planning are advisable.

3. Even in coarse-grained, weathered, cross-bedded Pennsylvanian sandstones, orientations of shallowly-dipping sedimentary layering can be estimated precisely and accurately if constructed from several traces. Even with dips of 10 degrees or less, precise and accurate strikes can be constructed.

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FIGURE CAPTIONS

Figure 1. Index map of eastern West Virginia. Dashed line is topographic break of Allegheny Front, with Valley and Ridge province to east and Plateau province to west. Circled dot is Petersburg, and heavy solid line through it is mapped extent of Petersburg lineament (lineament may be several times the length shown: Sites, 1978 and 1979). Black polygon atop Allegheny Front at west end of lineament is Dolly Sods map area (size and shape approximate).

Figure 2. Intensities of systematic joints across Petersburg lineament atop Allegheny Front. Shown is westward projection of lineament, from where it is mapped in more deformed and older rocks to the east (Figure 1). Based on data of LaCaze (1978). Outcrops 1 through 8 are also located in Figure 3.

Figure 3. Locations of stations (dots) and centers of cells (circles) in Dolly Sods map area (polygon). See text for explanation of cells. 1 through 8 are outcrops for which joint intensities of Figure 2 were calculated.

Figure 4. Structure contours in Dolly Sods map area. Contour interval is 100 feet (30 m). Contours are labeled in hundreds of feet. Dashed lines are trough lines of Stony River syncline, inferred from contours. Dotted lines are possible positions of parts of the hypothesized Breathed Mountain anticline, inferred from contours (see text). (4a) Eight-sided polygon in southwest encloses contours atop Princeton sandstone. Other contours are atop Homewood sandstone. Based on mapping by LaCaze (1978, Plate 1; see text). (4b) Contours atop Upper Freeport coal, traced from Reger (1921).

Figure 5. Constructing layer orientation from three traces (see text). Dots are traces of a layer on exposure faces. Solid curves are great circles perpendicular to the traces. Circled dot is center of gravity of the spherical triangle, constructed as the intersection of the dash-dot curves (great circles connecting triangle vertices to bisectors of opposite triangle sides). Dashed curve is estimated orientation of the layer. Precision is mean of the three values of θ, which are exaggerated here for clarity.

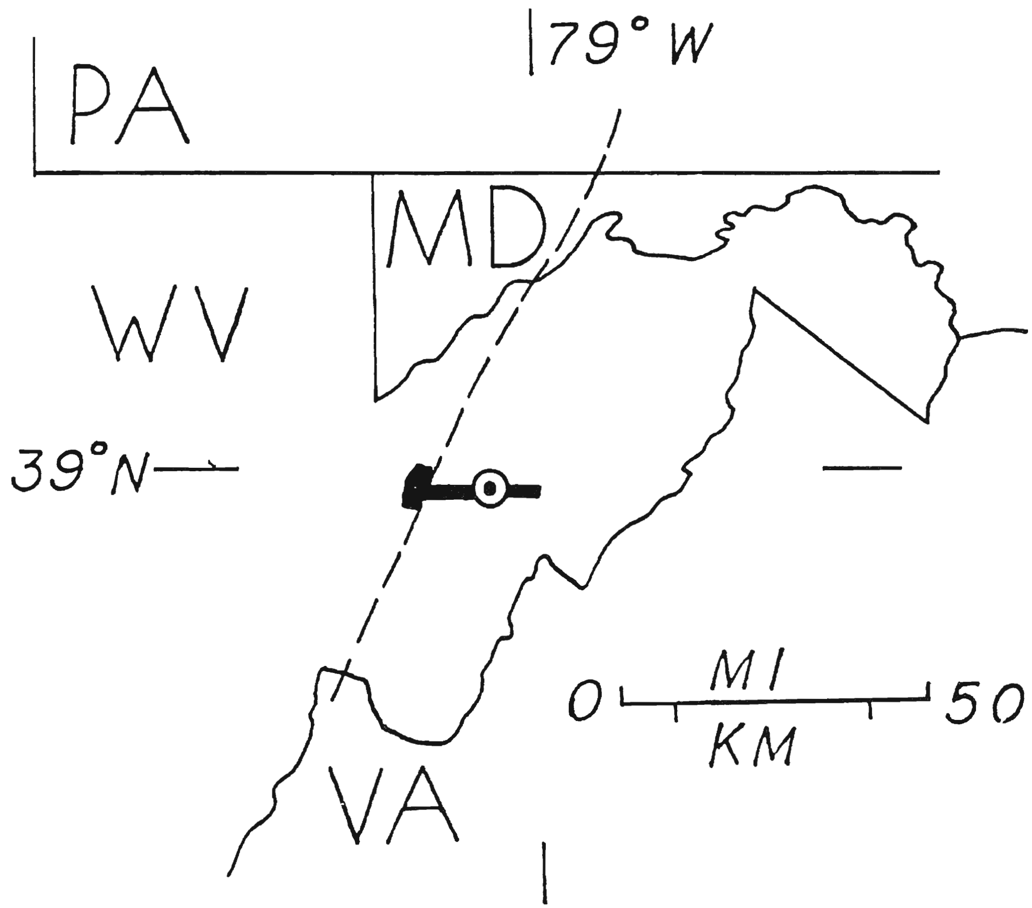

FIGURE 1

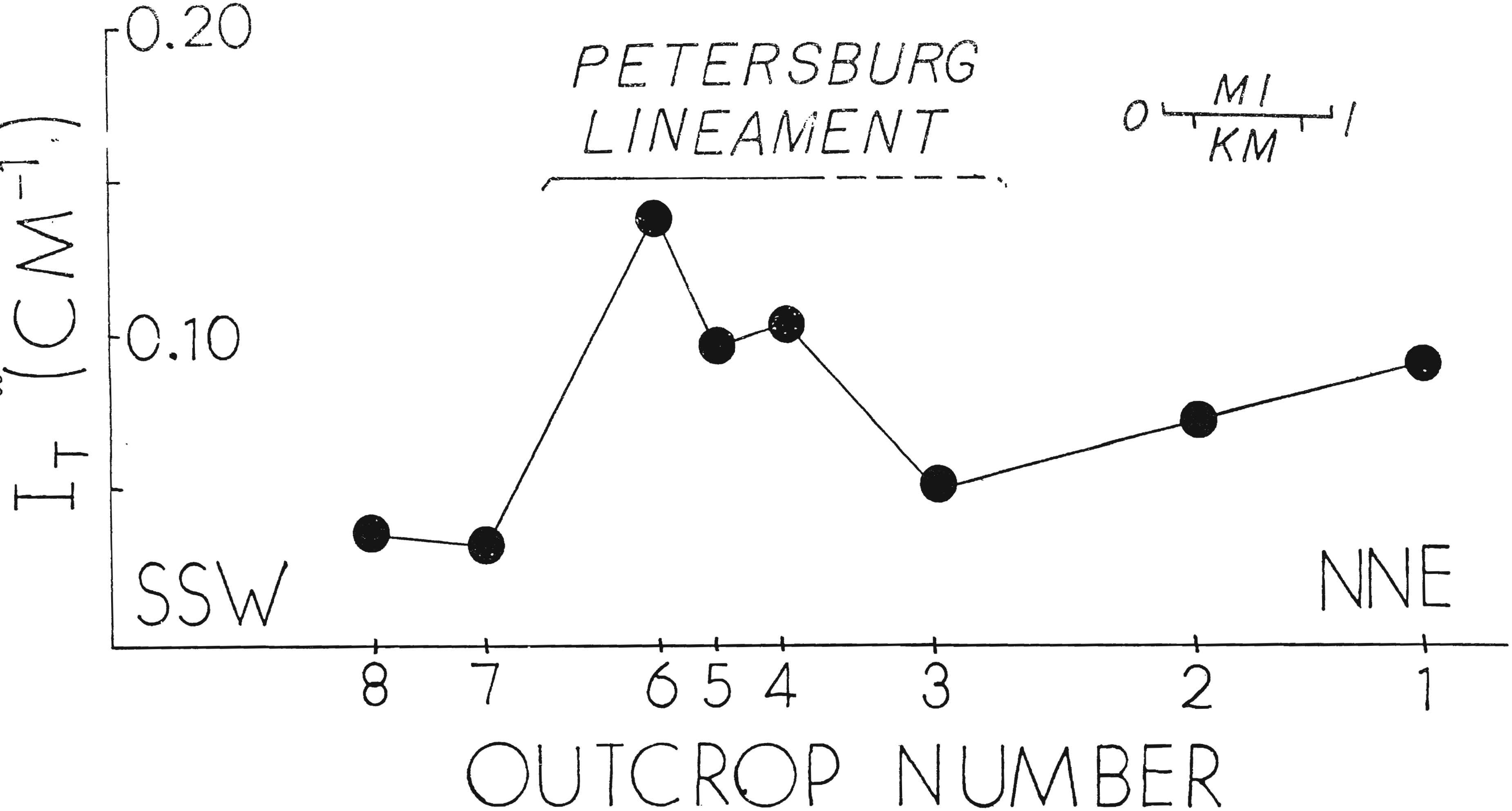
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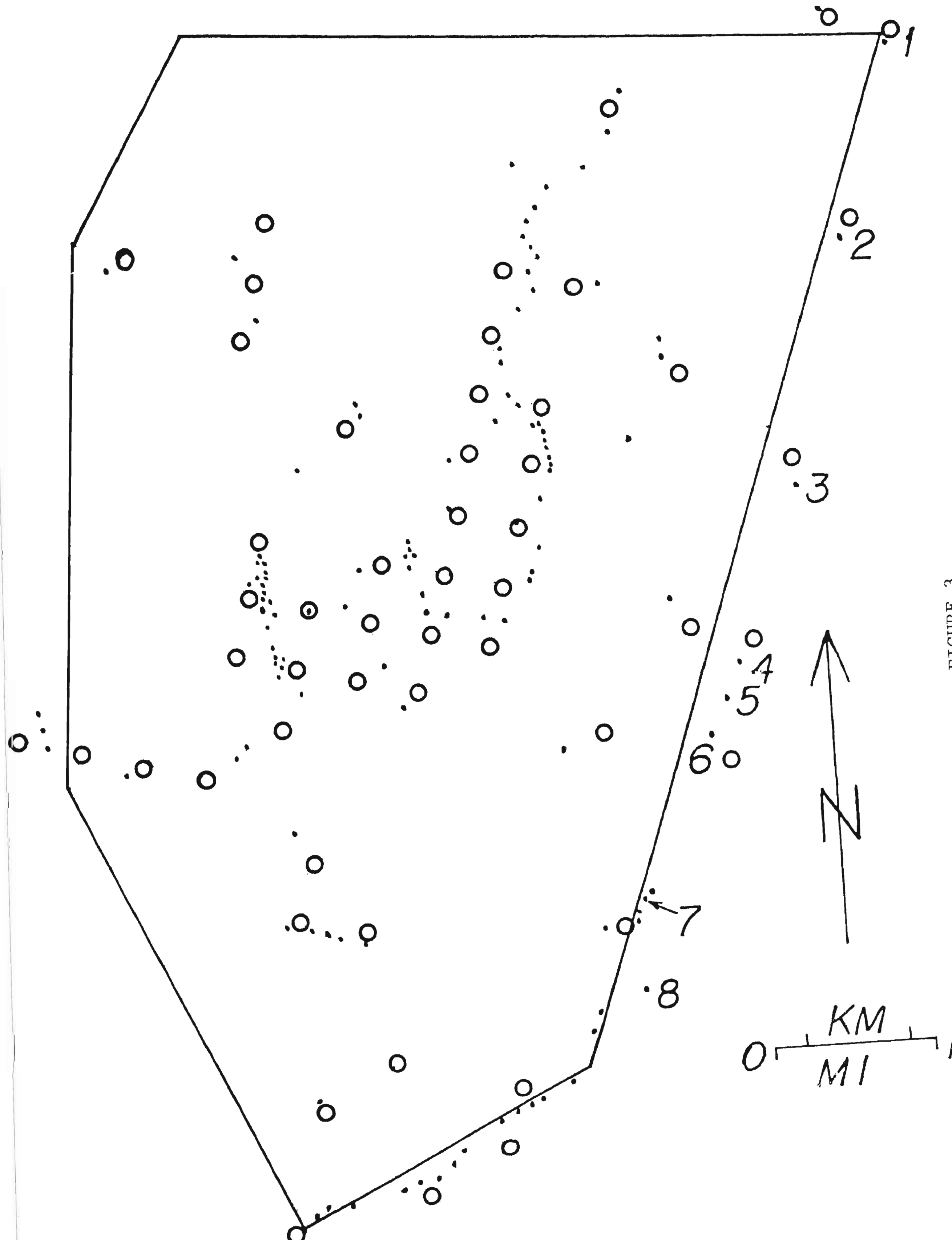
FIGURE 2



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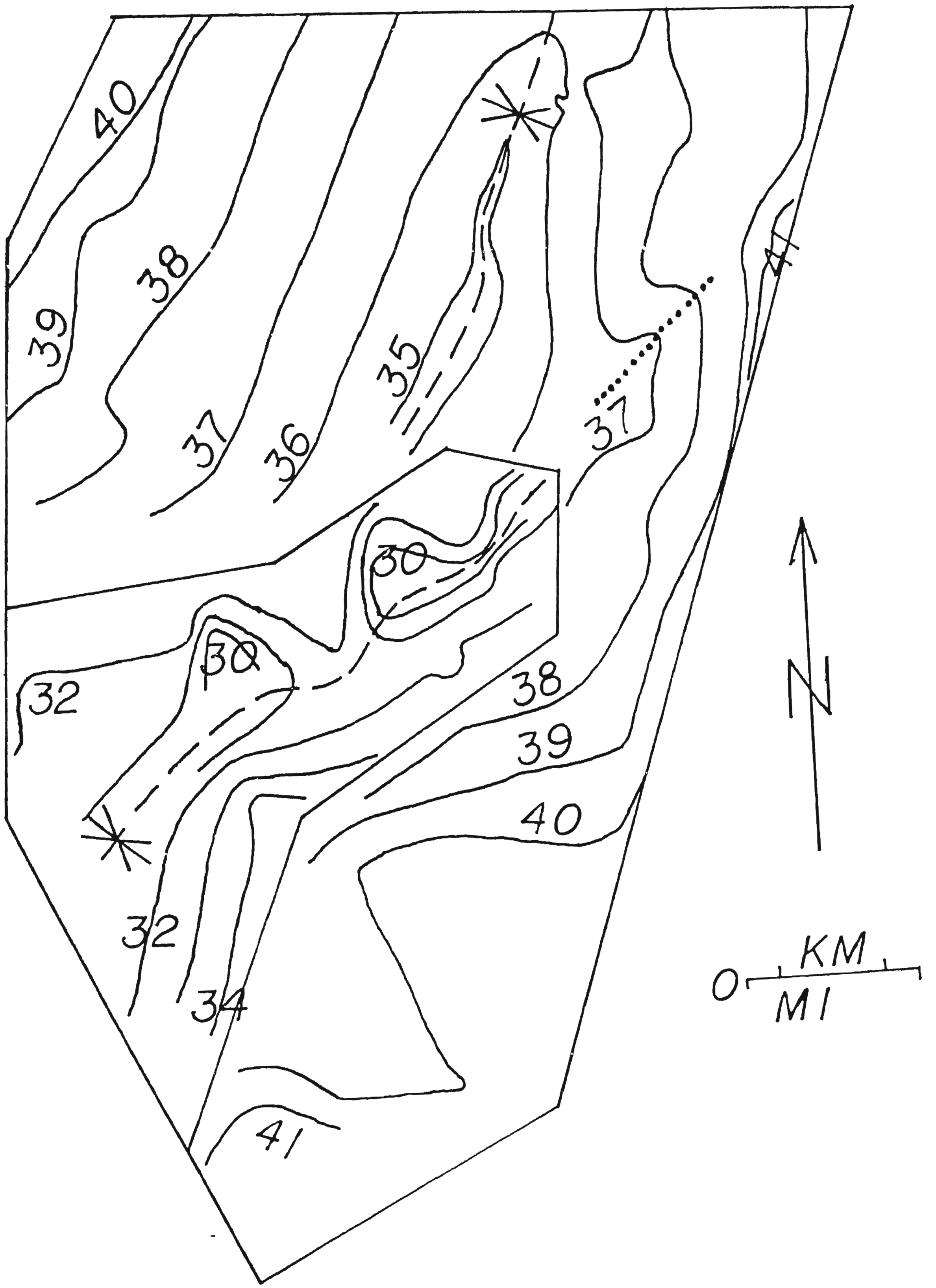

FIGURE 4

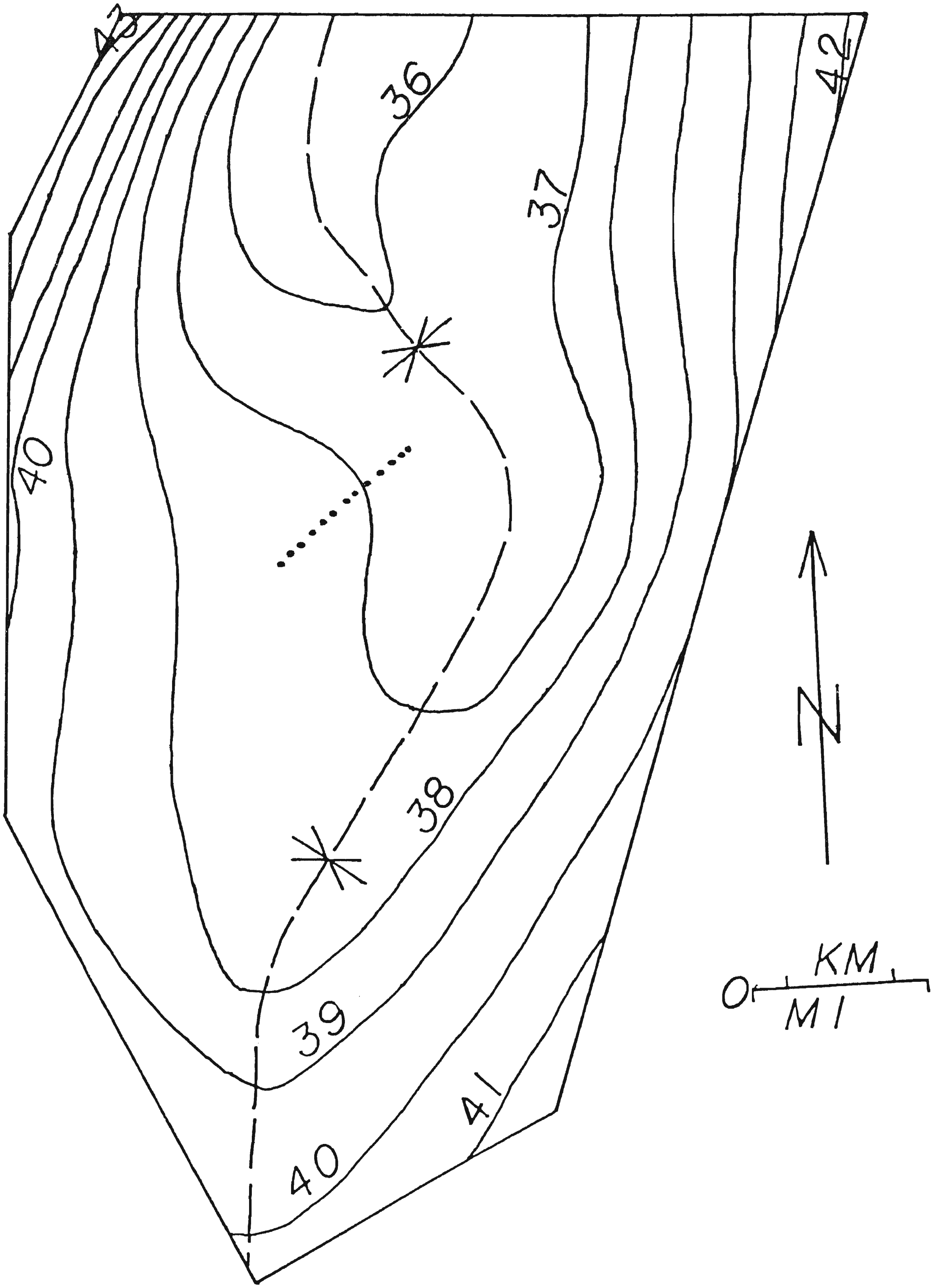

FIGURE 5

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