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Fractures in the Jacobsville Sandstone and the Precambrian "W" Rocks in Eastern Marquette County, Michigan

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FRACTURES IN THE JACOBSVILLE SANDSTONE AND THE PRECAMBRIAN "W" ROCKS IN EASTERN MARQUETTE COUNTY, MICHIGAN

by

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The major fracture systems in the Jacobsville sandstone likely originated by reverse faulting on the Keweenaw fault and by glacially produced thrusting. Fracture orientations, apertures, and spacings are uniform in the Jacobsville sandstone and Lighthouse Point member of the Mona Schist, and are variable in the Lower member of the Mona schist and Compeau Creek gneiss. Fracture sets in the Compeau Creek gneiss exist in domains separated by metadiabase dikes. The metadiabase dikes relieved the strain produced by the Penokean orogeny by fracturing. Fractures present in inclusions, quartz veins, metadiabase and diabase dikes can be used to temporally evaluate the strain history of the Compeau Creek gneiss.

Potential sources for useful groundwater wells will be found in areas of thrust faulted Jacobsville sandstone, fractured zones in the pillowed Lower member of the Mona schist, and linear sags in the topography of the Compeau Creek gneiss.

ACKNOWLEDGEMENTS

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Leonard Paul Belliveau

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INTRODUCTION

Statement of the problem

The search for adequate water supplies in areas dominated by crystalline or sedimentary rocks requires a delineation of the water chemistry and the physical properties of the fractures. Fractures in these rocks can provide a path for groundwater flow. An evaluation of the reservoir characteristics of these rocks requires a knowledge of: (a) the local and regional geologic history, (b) the types and structures of rocks, (c) the density and orientation of fractures, (d) the local hydrologic budget, and (e) the chemistry of the surface waters recharging the local aquifers. This paper presents the results of an analysis of fracture types in eastern Marquette County and the possible sources of crustal stress which might have produced those fractures.

Location and Access

Marquette County is located in the north-central part of Michigan's Upper Peninsula on the south shore of Lake Superior. It has a land area of 1,878 square miles (Figure 1). There are several railroad lines which connect the iron mines to the west with the docks at Lake Superior and the cities on the west side of Lake Michigan with the Marquette region. The main highway through the area is U.S. Route 41, which intersects several county and state roads and provides access to rural areas as well as the Marquette County Airport.

Access to the field area north of the city of Marquette, where outcrops of crystalline rock are numerous and where the Jacobsville sandstone is well exposed along the shoreline, was gained by the use of various unimproved roads which intersect Marquette County Road 550 (Figure 2).

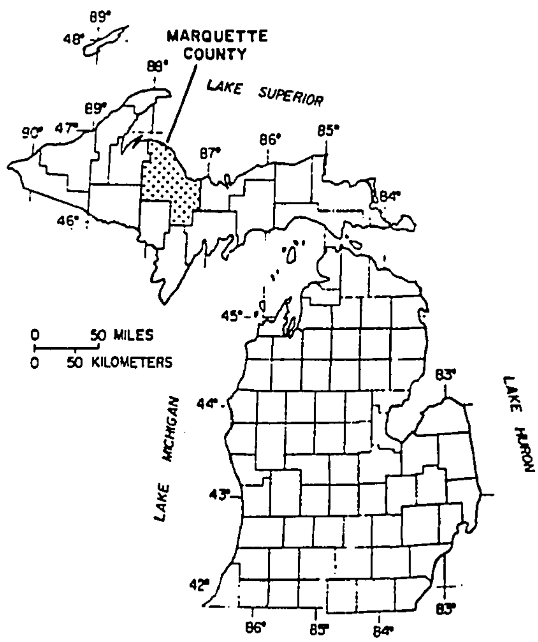

Figure 1. Location of Marquette County.

Population

The population of Marquette County was 70,887 in 1990. Of this total, 60,254 (85 %) live in and around the city of Marquette. The other 15 % live in the outlying rural areas. The greatest

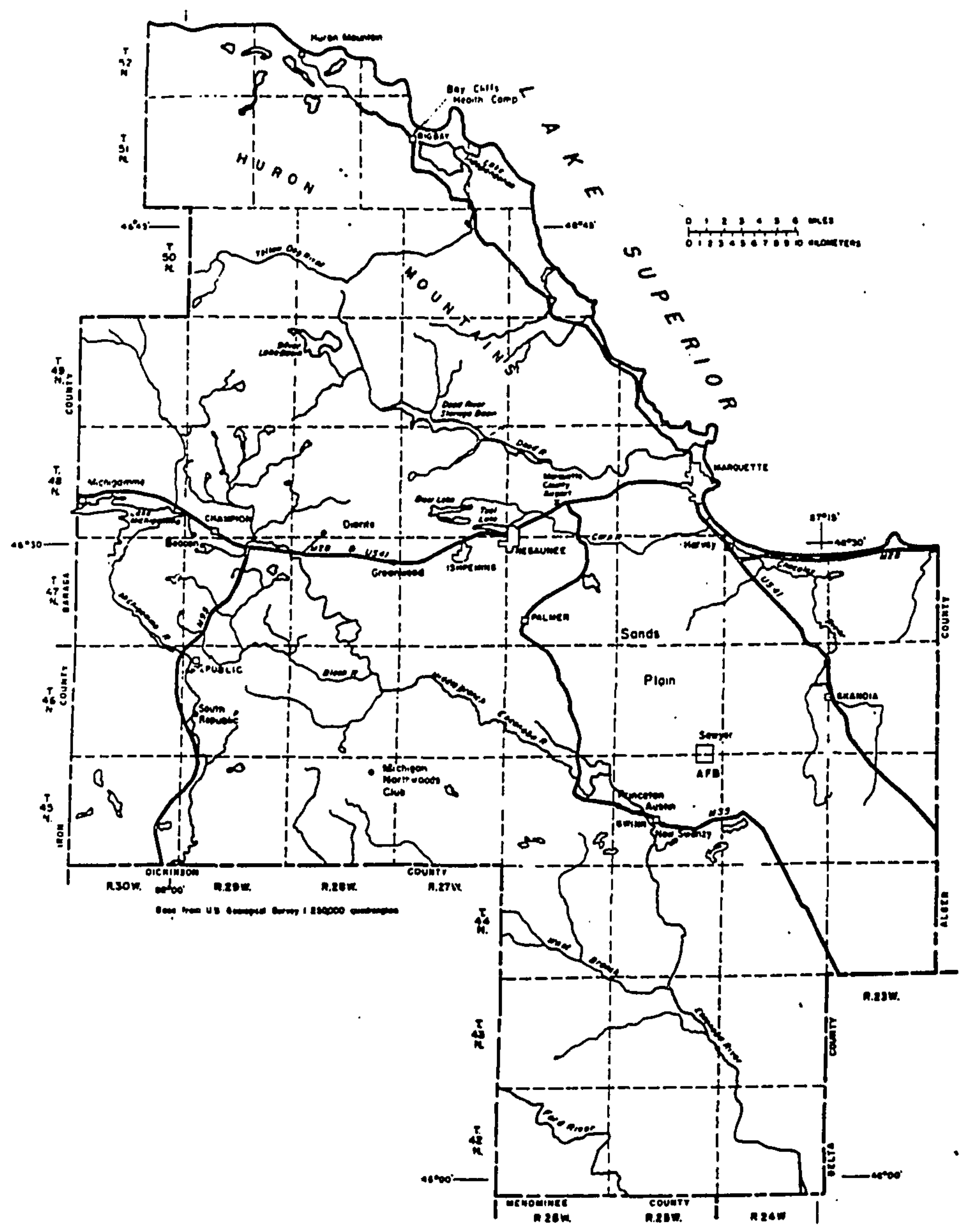

Figure 2. Physical and Cultural Features of Marquette County, Michigan (Doonan & VanAlstine, 1982).

Source: Doonan, C. J. & VanAlstine, J. L. (1982). Ground water and geology of Marquette County, Michigan. <u>U.S. Geological Survey Open-File Report 82-501</u>, p. 3.

concentration of people is at Sawyer Air Force Base and along U.S. Route 41. About 22,000 people live in the city of Marquette.

Climate

At the city of Marquette, the climate is influenced by the proximity of Lake Superior. Monthly average temperatures range from -9°C (15°F) in the winter to 21°C (70°F) in the summer. Normal precipitation is 81 centimeters (32 inches) annually and 3.3 to 8.6 centimeters (1.3 to 3.4 inches) monthly.

Water from precipitation is more than adequate for most needs. However, only about seven inches of this precipitation percolates to the groundwater reservoirs annually. The remainder is lost to evaporation, transpiration, and surface runoff (Twenter, 1981).

Pertinent Investigations

Of importance to this study are a report on the Cambrian sandstones of northern Michigan (Hamblin, 1958) and a report on the geology of the Marquette and Sands Quadrangles, Marquette County, Michigan (Gair & Thaden, 1968). Pertinent groundwater investigations have been performed by Grannemann (1979), Twenter (1981), and Doonan and VanAlstine (1982).

Method of Study

During the summer of 1986, approximately six weeks were spent measuring fracture orientations in the crystalline basement rocks. Fractures in the Compeau Creek gneiss were measured and plotted on a

Schmidt equal area projection for each area visited. The spacings, lengths, persistence of joint zones, apertures, and mineral fillings were measured to assess the rock's ability to act as an aquifer. To ascertain any age relations between the different fracture systems, fractures in inclusions, dikes, and quartz veins hosted by the Compeau Creek gneiss were also measured. Fractures observed in the Mona schist were then qualitatively compared with those measured in the Compeau Creek gneiss. Outcrops were located by the use of aerial photographs obtained from the Michigan Department of Natural Resources, and by published geologic maps in Gair and Thaden (1968). The recorded data were compared with data published in the references cited above.

During November of 1986, two weeks were spent measuring fracture orientations in the Jacobsville sandstone. The fracture systems were measured and plotted on a Schmidt equal area projection for each area visited, and assessed as above for their aquifer potential and possible origins. The recorded data were compared with data published in the above references.

ROCK TYPES AND GEOLOGIC HISTORY

The oldest rock type in eastern Marquette County is the Mona schist, an approximately 2.7 Ga "greenstone" consisting of two types of metamorphosed mafic volcanic rocks: a lower group in which pillow lavas are common and an upper group (known as the Lighthouse Point member) which is a layered amphibolite and schist. The Mona schist appears to have had a schistose structure before intrusion by the Compeau Creek gneiss, an approximately 2.5 Ga foliated granodiorite. Both of these rocks exhibit evidence of at least two periods of deformation and metamorphism prior to erosion and subsequent deposition of the middle Precambrian sediments.

The middle Precambrian sediments, collectively called the Marquette supergroup, consist of originally stratified sandstone, dolomite, shale, tuff, and ironstone, with a collective thickness of as much as eight kilometers (five miles). The lower units represent an approximately 2.1 Ga marine transgression, followed by sedimentation controlled by local graben formation. At approximately 1.9 Ga they were metamorphosed and deformed into a west trending synclinorium, perhaps along a structural axis established during early Precambrian time (Gair & Thaden, 1968).

A peridotite body crops out at Presque Isle Park. Its age is not known, but it is believed to be at least 1 Ga old (Figure 3). Gair and Thaden (1968) noted that the peridotite is probably middle to late Precambrian in age and that its emplacement occurred toward

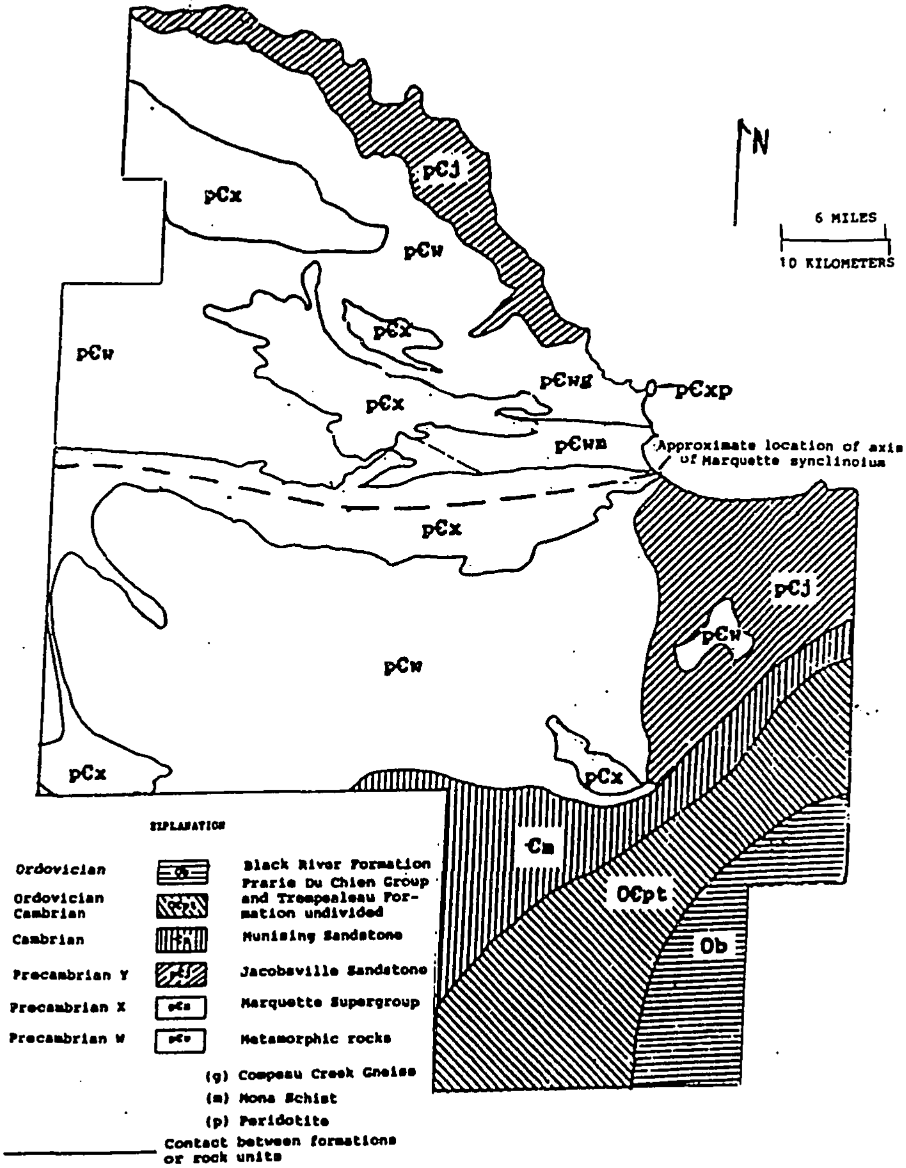

Figure 3. Distribution of Precambrian and Paleozoic Rocks. (Doonan & VanAlstine, 1982. Modified from: Martin, 1936; Boyum, 1964; and Case & Gair, 1965).

Source: Doonan, C. J. & VanAlstine, J. L. (1982). Ground water and geology of Marquette County, Michigan. U.S. Geological Survey Open-File Report 82-501, p. 7.

the end of the orogeny that folded the Marquette Supergroup.

Mafic dikes of two different ages have intruded the Compeau Creek gneiss and the Mona schist. The older set, composed of diabase now metamorphosed, appears to be truncated by the middle Precambrian sediments west of the field area and has been assigned a lower Precambrian age by Gair (1975). The younger set, composed of diabase, crosscuts the middle Precambrian sediments (Gair & Thaden, 1968) and the peridotite at Presque Isle (Kalliokoski, 1975). It has been suggested that these diabase dikes acted as feeders for the voluminous lavas of the Midcontinent Rift System, a major thermal-tectonic event that developed approximately 1.2 to 1.1 Ga ago (Wilband & Wasuwanich, 1980).

During an extended period of tectonic quiescence and cratonic stability, bedrock surfaces became weathered and covered by paleosols. As the axis of the Midcontinent Rift began to subside relative to its margins, vigorous fluvial systems developed which removed the surface paleosols and deposited these as alluvial fans. As erosion continued, fresh feldspars were removed from the highland basement rocks (south of Marquette) and deposited on top of the coarse grained alluvial fans (Kalliokoski, 1982). The maximum thickness of this fluvial sequence of feldspathic and quartzose sandstones, conglomerates, siltstones, and shales, known as the Jacobsville sandstone, is 3600 feet at the Keweenaw Peninsula and is about 600 feet thick north of Marquette at Big Bay. Based upon lithologic, structural, and paleomagnetic data, the Jacobsville sandstone is about 1.1 Ga old (Kalliokoski, 1982). Hamblin (1958) believes that the topography adjacent to the southeast shore of Lake Superior has been exhumed and is a near replica of the pre-Jacobsville topography, which had over 400 feet of relief (Figure 4).

The Jacobsville sandstone was unconformably overlain by Paleozoic sediments of the Michigan Basin, now eroded away north and west

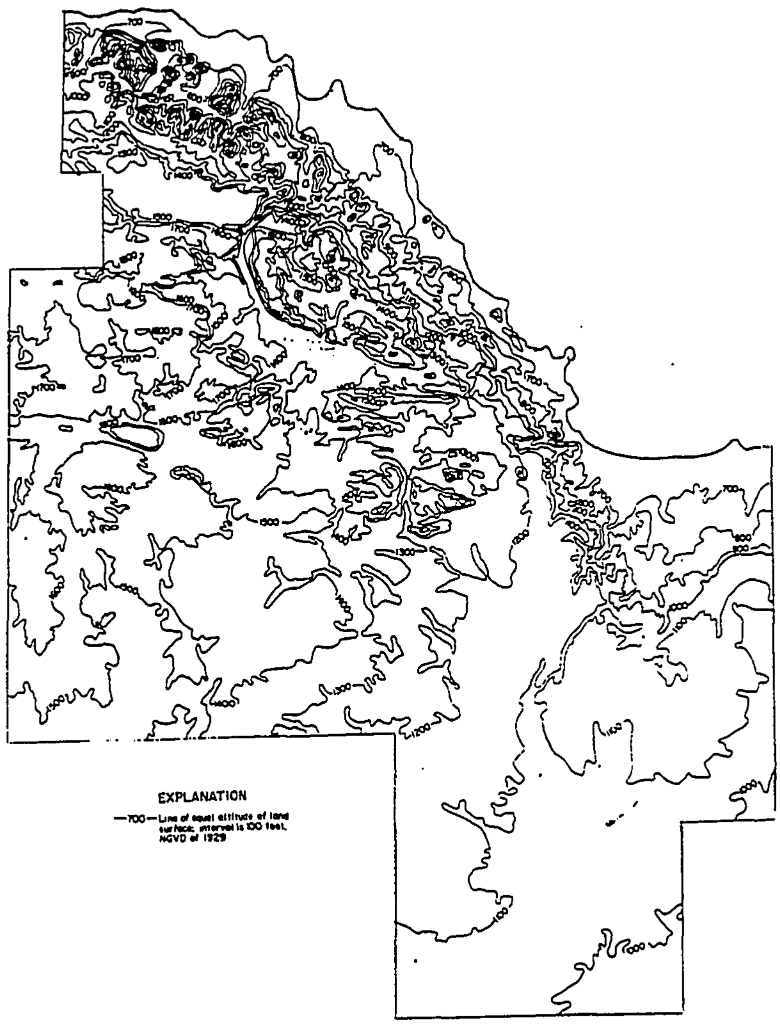

Figure 4. Topography of Marquette County.

Source: Doonan, C. J. & VanAlstine, J. L. (1982). Ground water and geology of Marquette County, Michigan. U.S. Geological Survey Open-File Report 82-501, p. 4.

of the city of Marquette but still present to the south, east and locally to the northwest (Figure 3).

The youngest sediments in the Marquette region are glacial moraine, outwash, and lakebed material (Figure 5).

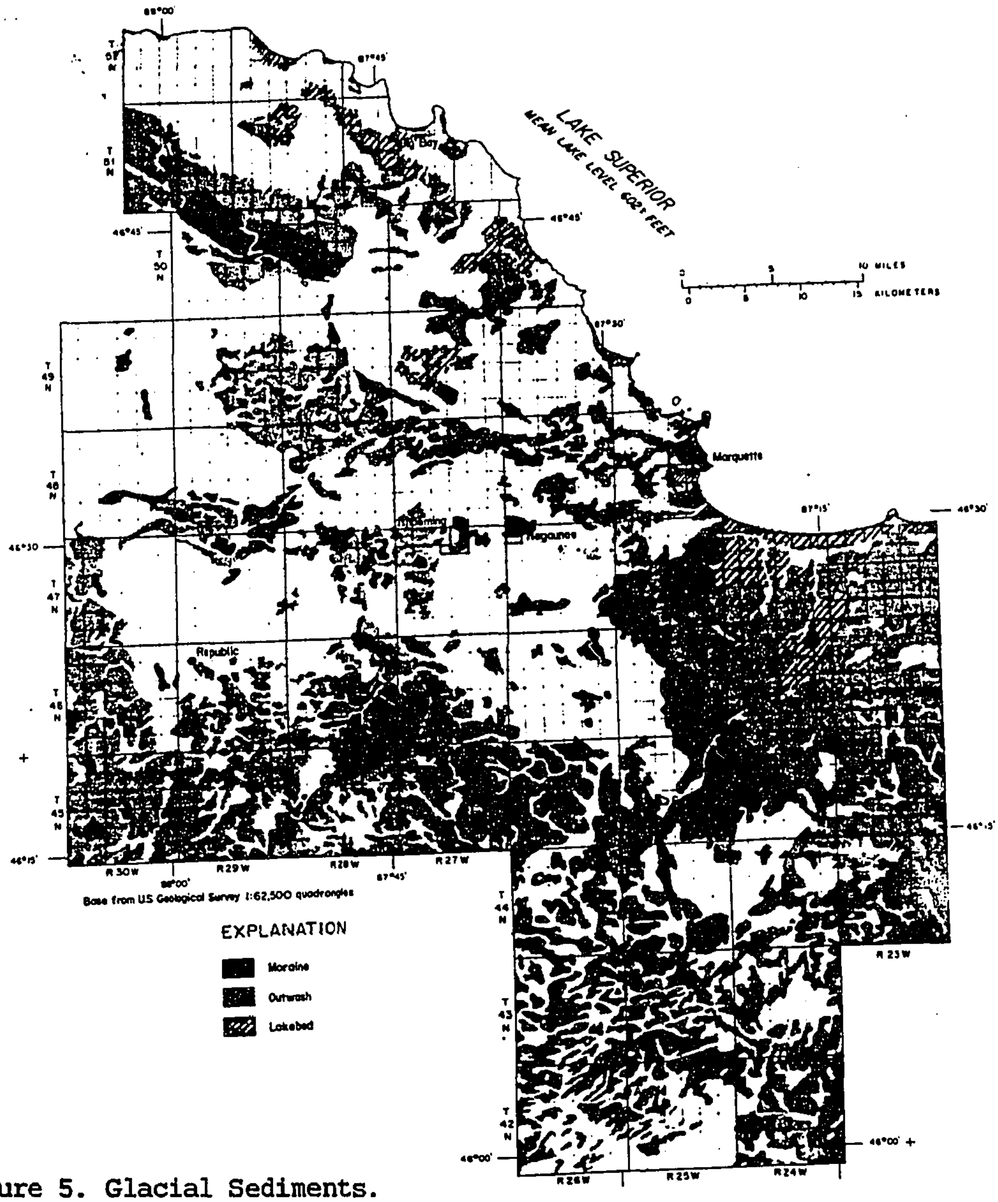

Figure 5. Glacial Sediments.

Source: Twenter, F. R. (1981). Geology and hydrology for environmental planning. U. S. Geological Survey Water Resources Investigation, (90) 80, p. 23.

STRESS HISTORY OF THE MARQUETTE REGION

Recent Stress

The modern maximum principal stress direction is oriented horizontally in a northeast-southwest to east-west direction (Engelder, 1982) (Figure 6). The region is currently undergoing isostatic uplift with the area to the northeast rising (Wold, Hutchinson & Johnson, 1982) (Figure 7). Clark (1982) noted the influence of flexure at the ice margins on the development of fractures in the sedimentary rocks of Ohio and Pennsylvania, and stated that fractures would tend to form radial and tangential to the margins of the ice in an area 50-175 kilometers south of the margin. He also noted that there have been approximately 20 glacial advances in the past 2 million years, which would cause oscillating flexure of the crust in the region. Furthermore, the Marquette area was once covered with Paleozoic sediments (based upon the limestone at Big and Little Limestone Mountains), the thickness of which is unknown; and the unloading caused by their removal must be incorporated into any discussion of the stresses incurred on all rock types.

Thrust faulting has occurred in the Jacobsville sandstone and the motion inferred from displaced fractures, imbricated strata, reduction spots and thrust generated fractures indicates a south to south-westward movement of the thrust blocks (see Figures 37, 38, & 39, pp. 59-61). One exception to the southward motion of thrusted

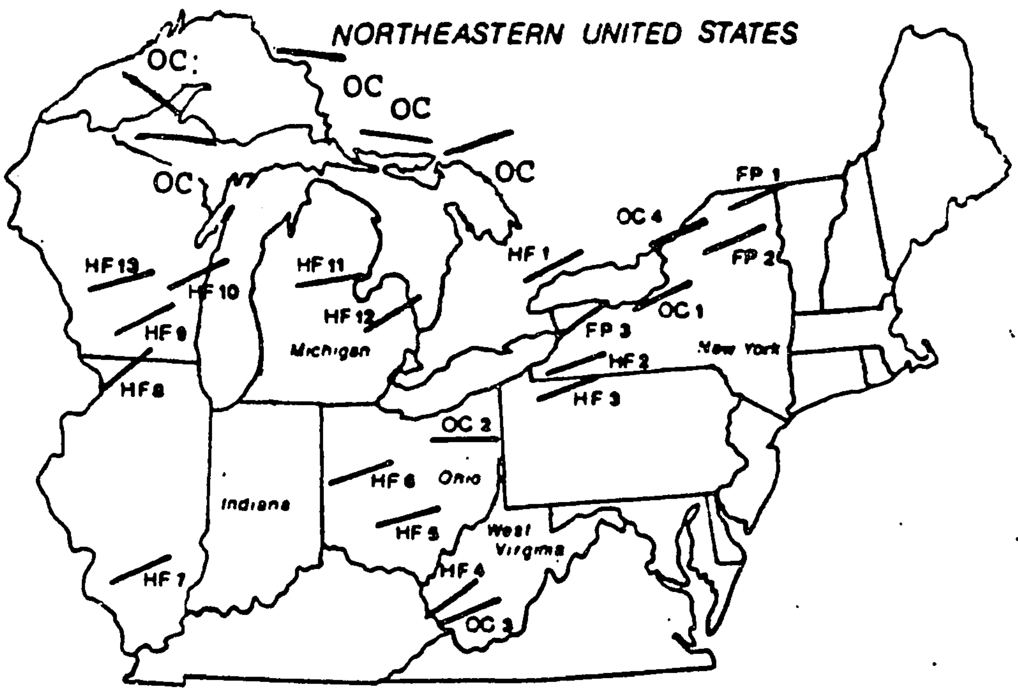

Figure 6. Strike of Maximum Horizontal Compressive Stress in the Northeastern United States and South-central Canada. The symbols are as follows: (FP) - fault plane solution: (HF) - hydraulic fracture; (OC) - overcoring.

Source: Engelder, T. (1982). Is there a genetic relationship between selected regional joints and contemporary stress within the lithosphere of North America? Tectonics, 1, p. 164. [Modified with data from Eisbacher, G. H., & Bielstein, H. U. (1971). Elastic strain recovery in Proterozoic rocks near Elliot Lake, Ontario. Journal of Geophysical Research, 76, p. 2017; Sbar, M. L., & Sykes, L. R. (1973). Contemporary compressive stress and seismicity in eastern North America: An example of intra-plate tectonics. Geological Society of America Bulletin, 84, p. 1879; and Haimson, B. C. (1978). Crustal stress in the Michigan Basin. Journal of Geophysical Research, 83, p. 5859.]
Used with permission of Mina Chung, publications division of the American Geophysical Union, and T. Engelder, 8-29-91.

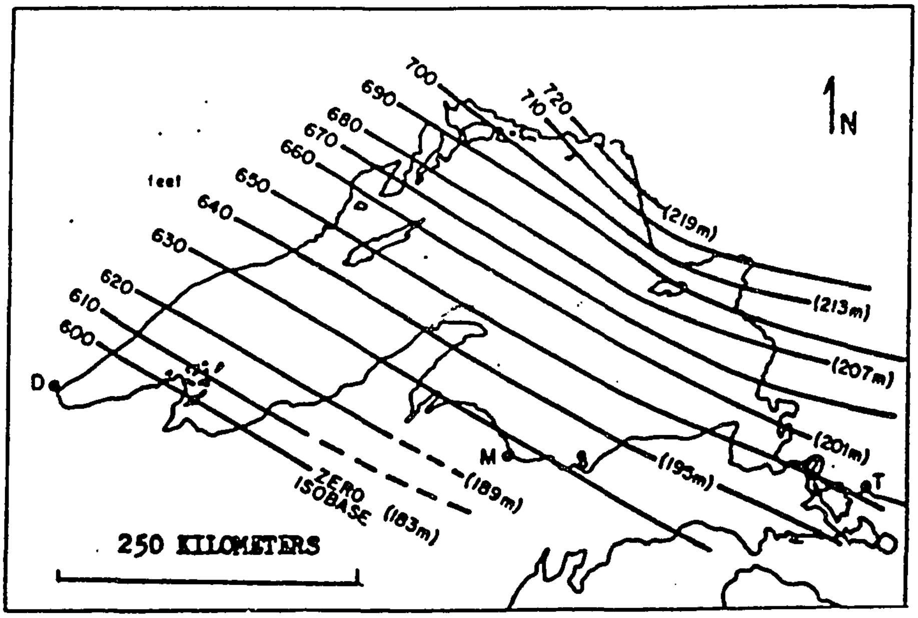

Figure 7. Elevation of Nipissing Isobases. Isobases are lines of equal uplift of Glacial Lake Nipissing's strandlines. South of the zero isobase the strandlines are horizontal. Levels of uplift derived from the tilted strandlines are variable, but it is estimated on the basis of these tilted strandlines that the northeast corner of Lake Superior is uplifting 45 centimeters per 100 years and Marquette is uplifting 11 centimeters per 100 years.

Source: Wold, R. J., Hutchinson, D. R., & Johnson, T. C. (1982). Topography and surficial structure of Lake Superior bedrock as based on seismic reflection profiles. Geological Society of America Memior, 156, p. 269. Used with permission of D. R. Hutchinson, 8-29-91.

Jacobsville Sandstone is at Presque Isle Point where a northerly striking fracture has been displaced to the west 7 centimeters (see Figure 36, p. 58). The presence of pulverized Jacobsville sandstone injected between rotated blocks of itself at Big Bay Point (see Figure 38, p. 60) (suggesting high pore water pressure), and the presence of natural shattering along a fault surface to the south along the shore at Buckroe (see Figure 37, p. 59), depict mechanically weak features which might not survive repeated glacial advances (see "Possible Fracture Origins" on p. 67).

The generation of fractures by the modern stress field, glacial flexing, unloading and possible thrusting, and unloading due to the removal of the Paleozoic sediments are conjectural.

Mesozoic and Paleozoic Stress

Hamblin (1958) noted that there are two sets of shear fractures which intersect at nearly right angles in the Jacobsville sandstone. Near Keweenaw Bay one set strikes N70°W and the other set strikes N10-30°E. Towards the east, this pattern rotates clockwise becoming N50°W and N40°E at Grand Island (see Figure 29, p. 50). Cannon et al. (1989) noted a possible continuation of the Keweenaw fault to a position east of Marquette, which was shown on two seismic profiles (Figure 8). The curving of the fault around the southern part of the Lake Superior basin might be responsible for the rotation of fracture trends which Hamblin (1958) discussed. Furthermore, it is known that the Keweenaw fault has been active since the Ordovician (Kalliokoski, 1982). Sims, Card, Morey, and Peterman (1980) noted that during the Cretaceous period, minor faulting occurred in Minnesota on the Great Lakes Tectonic Zone (GLTZ), which is located south of Marquette and trends east-west, and is the boundary between the greenstone and gneiss terranes (Table 1, Figure 9). Moreover, Watson (1980) noted that during the Cretaceous and Devonian periods, movement occurred on the Kapuskasing Feature (KF), which is located

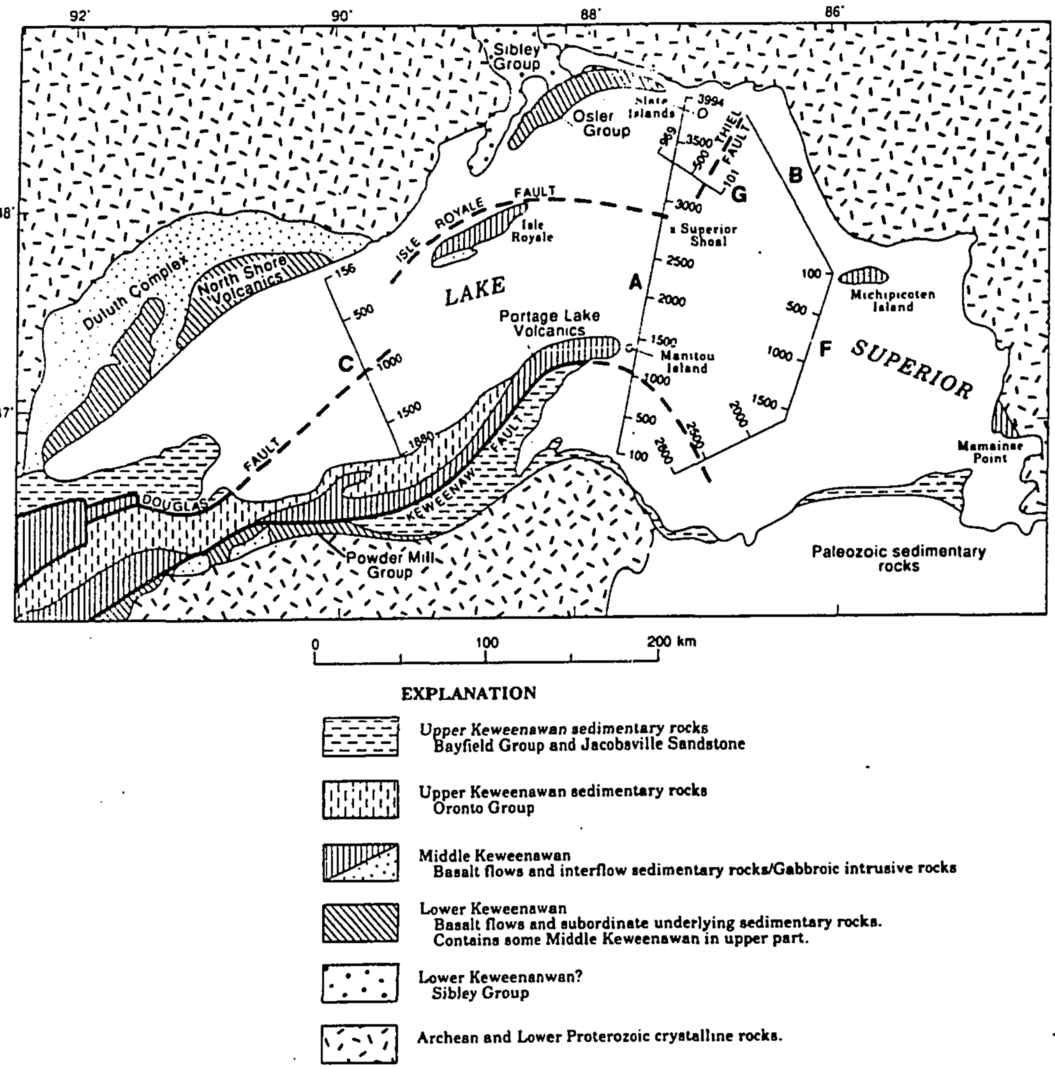

Figure 8. Generalized Geologic Map of the Lake Superior Region Showing the Possible Continuation of the Keweenaw Fault to a Position Northeast of Marquette. Location of seismic lines indicated by letters, and faults indicated by dashed lines. Note the Theil Fault, part of the Trans Superior Tectonic Zone (TSTZ), in the upper part of the figure.

Source: Cannon, W. F., Green, A. G., Hutchinson, D. R., Lee, M., Milkereit, B., Behrendt, J. C., Halls, H. C., Green, J. C., Dickas, A. B., Morey, G. B. Sutcliffe, R., & Spencer, C. (1989). The North American Midcontinent Rift beneath Lake Superior from GLIMPCE seismic reflection profiling. Tectonics, (2) 8, p. 308.
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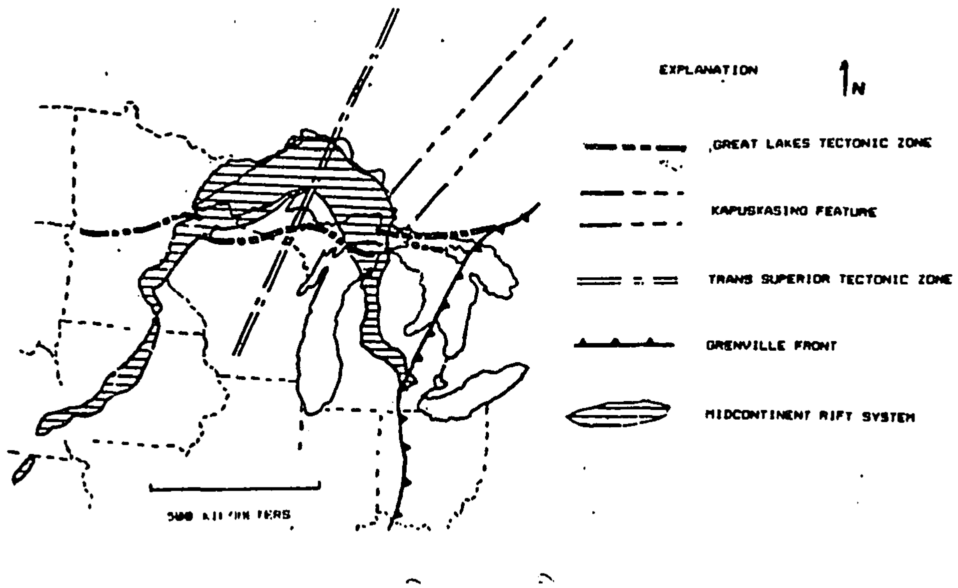


Figure 9. Regional Structural Features Within the Great Lakes Area.

Source: Modified from: Klasner, J. S., Cannon, W. F., & Van Schmus, W. R. (1982). The pre-Keweenawan tectonic history of southern Canadian Shield and its influence on formation of the Midcontinent Rift. Geological Society of America Memoir, 156, pp. 42 & 30; and Sims, P. K., Card, K. D., Morey, G. B., & Peterman, Z. E. (1980). The Great Lakes tectonic zone--A major crustal structure in central North America. Geological Society of America Bulletin, 91, p. 691.
Used with permission of J. S. Klasner, 8-29-91; and P. K. Sims, 9-2-91.

north of Lake Huron and is a northeasterly trending zone of major weakness in the crust (Table 1, Figure 9). Klasner, Cannon, and Van Schmus (1982) noted that the KF probably continues under the Michigan Basin (MB) and this movement might be the source of the Devonian folding that Holst and Foote (1981) described. During the Pennsylvanian period, either a diatreme was emplaced (Sage, 1978) or a meteorite impact occurred (Halls & Grieve, 1976) on the Trans Superior Tectonic Zone (TSTZ), which is located north of Marquette and is a N20 E trending zone of major weakness in the crust (Table 1, Figure 9).

Table 1

Regional Structural Features

Great Lakes Tectonic Zone (GLTZ)	Boundary between greenstone terrane and gneiss terrane. Initiated 2.7 billion years ago with local compression through 2.6 billion years, was extensional between 2.5 and 2.0 billion and was compressional between 1.9 and 1.85 billion years. Located south of Marquette, the GLTZ extends east-west from Minnesota to the Grenville Front in Ontario. The GLTZ is crossed by the Midcontinent Rift System east and west of Marquette, causing a 50 kilometer separation of the boundary to the south (see Figure 9). It includes the Penokean fold belt and has been the locus of minor tectonic activity in Mesozoic and Cenozoic time with minor earthquakes occurring along the zone in Minnesota in recent time (Sims et al., 1980).
Trans Superior Tectonic Zone (TSTZ)	Located west of Marquette it is a N20°E zone of faulting, alkalic intrusions and diatremes with repeated faulting and igneous activity from 2.0 billion (Ga) years to possibly 300 million years ago and extends from from Hudson Bay to central Wisconsin. West of the zone the sedimentary basins associated with Penokean deformation are much thicker. The TSTZ has been suggested to be a conjugate shear zone associated with the initiation of Keweenawan rifting (Weiblen, 1982) and possibly acted as an accommodation zone during rifting (Cannon et al., 1989).
Kapuskasing Feature (KF)	Located north of Lake Huron and trending northeastward the 150 kilometer wide zone has been a locus of intense faulting, carbonatite and alkalic intrusions from 2.5-1.05 billion years and is a major zone of weakness in the crust. The zone possibly extends beneath the Michigan Basin and might have been utilized for differential movement during rifting (Watson, 1980).
Grenville Front (GF)	Located east of Lake Huron it is a northeasterly trending 1.1 billion-year-old zone of deformation which separates terranes of contrasting style and metamorphic grade. The timing of deformation along the GF is coincident with the opening and filling of the Midcontinent Rift System, but the correlation between Keweenawan extension and Grenville compression remains undetermined (Cannon et al., 1989).

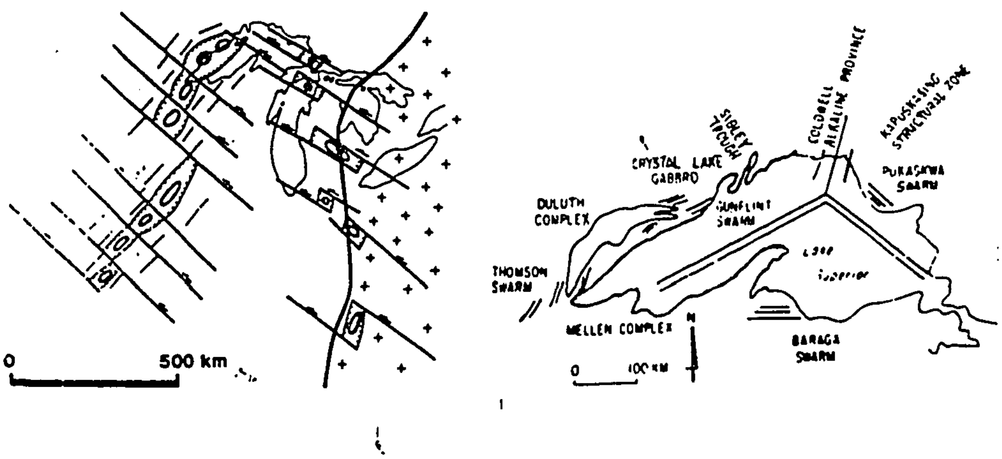
Table 1--continued

Midcontinent Rift System (MRS)	A 1.1 billion-year-old protoceanic rift system which extends northeastward from Kansas through Lake Superior and then arcs southeastward beneath the Michigan Basin. The MRS formed at high angles to the trend of the major structural features in the region and its location and orientation are related to the trends of older faults and dikes along zones of weaknesses in the crust. Crustal sagging, normal faulting, thinning of the crust to one-fourth its original thickness along the axis of the rift and up to 30 kilometers of volcanic and sedimentary rocks have all been documented with seismic profiling. Up to 5 kilometers of uplift of the central graben occurred along the normal faults which were reactivated as high angle reverse faults (Cannon et al., 1989).
Michigan Basin (MB)	Centered over the central part of the Lower Peninsula of Michigan, the MB is a roughly circular intracratonic sedimentary basin which contains over 4.5 kilometers of Cambrian to Upper Pennsylvanian and Jurassic sediments. They were deposited within mainly shallow marine environments and later continental environments in a slowly subsiding basin under varying climates and conditions of sedimentation.

Precambrian Stress

Midcontinent Rift System (MRS)

The initiation of the MRS has been suggested to be a result of passive rifting in response to northwest directed tectonism along the Grenville Front (GF), where the deformation has been dated to be the same age as the opening of the rift (Gordon & Hempton, 1986) [Figure 10(A)], or active rifting in responce to mantle generated plumes in a triple junction environment (Burke & Dewey, 1973) [Figure 10(B)]. Weiblen (1982) suggested that rifting possibly began by northwesterly striking left lateral wrench faulting, producing



A B

Figure 10. Suggested Mechanisms for Initiation of Midcontinent Rift System (MRS) in the Lake Superior Region. (A) Northwest Directed Tectonism on the Grenville Front (GF) Initiating the Development of the MRS as Pull-apart Basins). (B) Triple Junction Setting for the Initiation of the MRS.

Source: (A) Gordon, M. B., & Hempton, M. R. (1986). Collision induced rifting: The Grenville Orogeny and the Keweenawan Rift of North America. Tectonophysics, 127, p. 16; (B) Weiblen, P. W. (1982). Kewenawan intrusive igneous rocks. Geological Society of America Memoir, 156, p. 75.
Used with permission of M. R. Hempton 8-30-91, and P. W. Weiblen, 9-2-91.

Riedel fractures, which progressed to rifting and transform faulting within a fourteen-hundred kilometer wide shear zone.

Cannon et al. (1989) reproduced the results of seismic profiles recorded in Lake Superior and they correlated these results with results from rocks on land. They analyzed the structure of the MRS and summarized the rifting as a four step process: (1) a broad crustal sagging with the intrusion of the diabase dike swarms; (2) a rift valley stage with crustal extension and normal faulting; (3) a collapse of the thermal regime with a cessation of extension and the deposition of sediments; and (4) central graben uplift by reactivation of normal faults. Furthermore, they noted that the Theil fault (Figure 8), part of the TSTZ, possibly acted as an accommodation zone during the deposition of the volcanics and sediments, where the east side down-dropped early in the history of the basin, then was later uplifted.

The stress distributions during the four stages which Cannon et al. (1989) summarized, and also the stresses on the TSTZ, have significant implications for the generation of fractures in the Marquette region. However, the question of whether rifting was passive or active will influence the types of stress developed in the rocks on the periphery of the rift basin. If the rifting were passive, in response to northwest directed tectonism on the GF, the region would have been subjected to either strike-slip faulting with pull apart basins (Gordon & Hempton, 1986) [Figure 10(A)] or Riedel shears as proposed by Weiblen (1982). If the rifting were active, in response to mantle generated plutonism, [Figure 10(B)] the region would have been subjected to anomalously hot asthenosphere near the surface producing ductile behavior in the shallow crust. The induced seismic data (Cannon et al., 1989) shows listric faulting and ductile behavior of the crust with attendant necking and localized shearing of the Precambrian rocks down to 25 % of their original thickness. They propose that instead of plume related mantle upwelling, "a much broader 'super swell' was present in which hot asthenosphere underlay the entire rift and surrounding (Lake Superior) region" (p. 328).

Davidson (1982) noted that the Keweenawan diabase dike swarms were structurally controlled by the basement during their intrusion. He also described the paleocurrent directions in the pre-Keweenawan sedimentary units as having depositional transport away from what is now the present basin structure. This might indicate regional uplift prior to the onset of crustal subsidence with attendant sedimentation and subsequent volcanism.

Fractures generated prior to, during, and after the rifting event are summarized in the following paragraphs, but because the actual tectonics of rift initiation are unresolved, the discussion is largely speculative.

Northwesterly collision along the GF initiating strike-slip faults in front of the collision zone resulting in pull-apart basins would produce several types of fractures depending on the location of the faults and their closeness to Marquette, but extension fractures striking northeast and shear fractures striking west-northwest might be expected. Northwesterly wrench faulting as an initiation of rifting would produce a conjugate set of fractures striking approximately N55-60° W and N55-60° E. Doming of the crust prior to volcanism would tend to produce fractures which are tangential to the periphery and radial to the vertical axis of the dome, with the radial fractures possibly occurring orthogonal to each other: this might be the origin of the north-south and east-west, N45° E and N45° W orthogonal patterns (see "Results of The Investigation," p. 32).

Broad crustal sagging during volcanism would create tangential fractures, in this case the larger, east-west continuous ones utilized by the diabase dike swarms. Further thinning of the crust by extension would develop fractures parallel to the axes of extension, in this case approximately northeast, northwest and east-west.

In the rift valley stage, listric normal faulting might reorient previously formed fractures and cause differently oriented fractures to form within the faulted blocks. Movement on the Theil fault, initially east-side down and later east-side up, might develop two sets of differently oriented fractures. Although Marquette is along the periphery of the rift, its location within the area of rotation of the rift axis might have had an effect on the formation of fractures from stresses subjected to different segments of the rift (Figure 11).

Thermal collapse and the onset of sedimentation would cause subsidence of the central part of the rift. Erosion along the periphery would cause unloading of the gneissic rocks.

Reactivation of the bounding normal faults as reverse faults occurred after about 7 kilometers of sediment were deposited in the central part of the graben, causing fractures to form normal to the faults as tension fractures and at an angle to the faults as shear fractures. As noted below, this might be the source of the N10-30°E shear fractures in the Jacobsville sandstone and, further, this might also be a source of, or a reactivation of, the N10-20°E fractures in the gneiss.

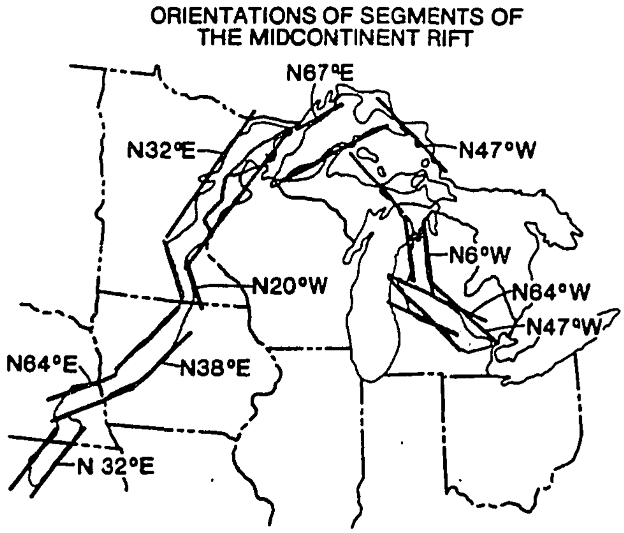


Figure 11. Orientations of Segments of the Midcontinent Rift System.

Source: Klasner, J. S., Cannon, W. F., & Van Schmus, W. R. (1982). The pre-keweenawan tectonic history of southern Canadian Shield and its influence on formation of the Midcontinent Rift. Geological Society of America Memoir, 156, p. 38.
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Post-Penokean Events

Prior to deposition of the Jacobsville, the region around Marquette had a topographic relief of over 125 meters. This relief included folded Marquette supergroup which itself was deposited directly on the Compeau Creek gneiss and the Mona schist. Kalliokoski (1975) discussed the paleosols which had developed on the rocks in the area (excluding the Mona schist and the Marquette Supergroup) and noted that there must have been a long erosion period before deposition of the Jacobsville sandstone. Therefore, prior to Jacobsville sedimentation, these igneous and metamorphic rocks had been exposed at the surface by erosion and/or tectonic activity, subjected to alternate loading and unloading by the deposition of sediments and then the subsequent erosion of them.

Sims et al. (1980) noted that, prior to the development of the MRS, there was right-lateral strike slip movement on the GLTZ in Canada which displaced 1.25 Ga diabase dikes. Because the GLTZ continues into the Upper Peninsula of Michigan, such movement might have set up some strain on the zone near Marquette, possibly generating fractures or storing residual elastic strain in the rocks.

Sims (1976) and Klasner et al. (1982) noted that, during the period following the Penokean orogeny, approximately 1.5-1.45 Ga, several anorogenic plutons were emplaced along the GLTZ from Canada through Northern Michigan and into Wisconsin. In Northern Michigan these plutons are represented as a series of metamorphic nodes with concentric metamorphic isograds near Republic, and as isolated small granitic bodies and pegmatite dikes. Silver et al. (1977) suggested that these plutons were emplaced during a tensional period. The development of fractures during this period would depend on the extent of tensional stresses produced and on the amount of doming which occurred during emplacement.

Penokean Orogeny

The next major fracture producing process was the Penokean Orogeny, an event which produced reverse faulting with south side up in the basement rocks near Marquette, multiphase folding of Proterozoic strata to the west and south, reactivation of faults and folds in the Archean gneisses and regional metamorphism (Sims et al., 1980;

Klasner et al., 1982). This event produced the fracture systems called cross, longitudinal and shear in this paper, the terms originating from Gair and Thaden (1968), and these are the well developed fractures in the Mona schist at Lighthouse Point (Figure 15, p. 34). Although Gair and Thaden (1968) refer to the similarly oriented fractures in the Compeau Creek gneiss with the same nomenclature, the fractures are not to be confused with those found in cooling plutons (i.e., cross and longitudinal) and, also, these fractures cannot be assumed to have been generated exclusively during that orogeny.

Pre-Penokean Events

The initiation of sedimentation in the Proterozoic basins, including the Marquette supergroup, was coincident with movement on both the GLTZ, dip-slip to the south producing thickening of the sediments to the south (Sims et al., 1980), and on the TSTZ, producing thickening of sediments to the west (Klasner et al., 1982) (Figure 9). As a result of this extension, diabase was intruded into the Marquette supergroup, but whether the swarms of diabase mentioned below were injected at this time remains unresolved.

The erosional period postdating the Kenoran orogeny and preceding the deposition of the Marquette supergroup has been suggested to be of glacial origin (Puffett, 1969). Glaciation would have loaded and flexed the bedrock as discussed above, but it also could have removed sheet-fractured gneissic blocks developed during the initial exposure of the gneiss. The paucity of sheet fractures in the gneiss is unusual in comparison to many other granitic-gneiss terranes elsewhere. The initial unroofing and exposure of the gneiss might induce thermal and unloading stresses; the net stress acting on the gneiss was the sum of the thermal stress and the stress due to removal of overburden. Thermal stresses are tensional as erosion occurs, but the magnitude of the stress depends on the initial heat flow (Haxby & Turcotte, 1976). The lack of sheet fractures was probably due to their removal during this erosional period and that the gneiss underwent thermal relaxation once brought to the surface and then reburied in a new thermal environment during subsequent sedimentation and metamorphism, inhibiting the development of future sheet fractures and resetting the residual strain in the gneiss (Tullis, 1977).

Post-Kenoran Events

Primary fractures which normally develop in cooling plutonic bodies do not exist in the Compeau Creek gneiss, probably due to at least two periods of deformation and metamorphism prior to the deposition of the Marquette supergroup (Gair & Thaden, 1968). These deformations are represented by three generations of folded aplite (tonalite), hornblende tonalite and amphibolite dikes, by tabular aplite dikes, quartz veins, epidote veins and shear zones of multiple ages (see Gair & Thaden, 1968, plate 3). Furthermore, there are at least two generations of quartz veins in the Compeau Creek gneiss, but no effort was made to determine their origins. Henceforth, discussions of orogenic processes (Table 2) not germane to

Table 2

Geologic History With Emphasis on Structural Processes

Quaternary Cenozoic	Current stress NE/SW, E/W (Engelder, 1982). GLTZ Locus of five earthquakes in the past 120 years (Sims et al., 1980). Tilting of Lake Superior NE up 23-45cm/100yrs (Wold et al., 1982). Glacial flexing of crust at margins (Clark, 1982).
Cretaceous Mesozoic	Minor faulting along GLTZ with south side down (Minn.) (Sims et al., 1980). Movement on KF (Watson, 1980).
Pennsylvanian	300my last activity on TSTZ (diatreme--Sage, 1978 or meteorite impact--Halls & Grieve, 1976).
Devonian	Folding in Michigan Basin NW/SE axes (Holst & Foote, 1981). Movement on KF (Watson, 1980).
Ordovician	Faulting of Jacobsville at Big and Little Limestone Mountains (Kalliokoski, 1982).
Cambrian Paleozoic	Michigan Basin sedimentation and subsidence (Fowler & Kuenzi, 1978).
	Jacobsville Sandstone sedimentation.
1100	Broad crustal subsidence. (Fowler & Kuenzi, 1978).
	Central graben uplifted 5km by reactivation of normal faults after Oronto group deposition (middle to late Keweenawan).
	Thermal collapse, cessation of extension, deposition of sediments of Oronto group.
	Crustal extension, normal faulting, rift valley development, crustal sagging with intrusion of diabase dike swarms (Cannon et al., 1989).
	Northwest directed tectonism on GF yielding strike-slip faulting and pull apart basins (Gordon & Hempton, 1986) or wrench faulting progressing to rifting and transform faulting, rifting possibly began as either a left-lateral wrench fault producing conjugate Riedel fractures at high angles to the shear direction (Weiblen, 1982).
1250	GLTZ - right-lateral strike-slip faulting (Sims et al., 1980).
1500-1450	Emplacement of anorogenic plutons along TSTZ in Canada and Wisconsin (Klasner et al., 1982).

Table 2--continued

1800-1500	Shearing in zones on TSTZ (Klasner et al., 1982).
1700-1650	Intrusion of diabasic gabbro dikes (Sims, 1976).
Precambrian Y	
1900-1850	GLTZ--Penokean orogenesis producing reverse dip-slip block faulting with south side up in basement rocks near Marquette, multiphase folding of Proterozoic strata, reactivation of Archean gneisses, and regional metamorphism (Sims et al., 1980; Klasner et al., 1982).
2000	Motion on TSTZ producing thickening of sedimentary basins to west (Klasner et al., 1982).
	GLTZ Dip-slip with downthrow to the south and thickening of sediments to south (Sims et al., 1980).
2200-1910	Intrusion of diabasic gabbro dikes (Sims, 1976; Klasner et al., 1982).
Precambrian X	
2600	Intrusion of diabasic gabbro dikes (Condie et al., 1988).
2700	Kenoran orogeny welding together greenstone and gneissic terranes (Sims, 1976).
Precambrian W	

fracture production will not be presented.

Fractures probably developed during the Kenoran orogeny, but their survival to the present as open, conductive features is in doubt. Of importance to this analysis is the extensional environment and erosional period which postdated the Kenoran orogeny: when metadiabase dikes were intruded and when the igneous and metamorphic rocks were brought to the surface by erosion. Gair and Thaden (1968) state that the metadiabase dikes are probably of at least two different ages and Condie et al. (1988) noted that there are at least five different swarms in Ontario and Quebec, ranging in age from 2.6 to 1.1 Ga. When the 2.6 Ga diabase (now metamorphosed) dikes were intruded, they tended to form conjugate sets with one set trending approximately north to northeast and the other set trending approximately east-west (Figure 12). The east-west metadiabase dikes tend to be much thicker and Gair and Thaden (1968) suggested that they acted as feeders for the thinner northeast dikes. The dikes tend to be near vertical. This orientation would imply compression in the east-northeast/west-southwest direction with extension in the north-northwest/south-southeast directions. These dikes are possibly related to major dike swarms throughout the region

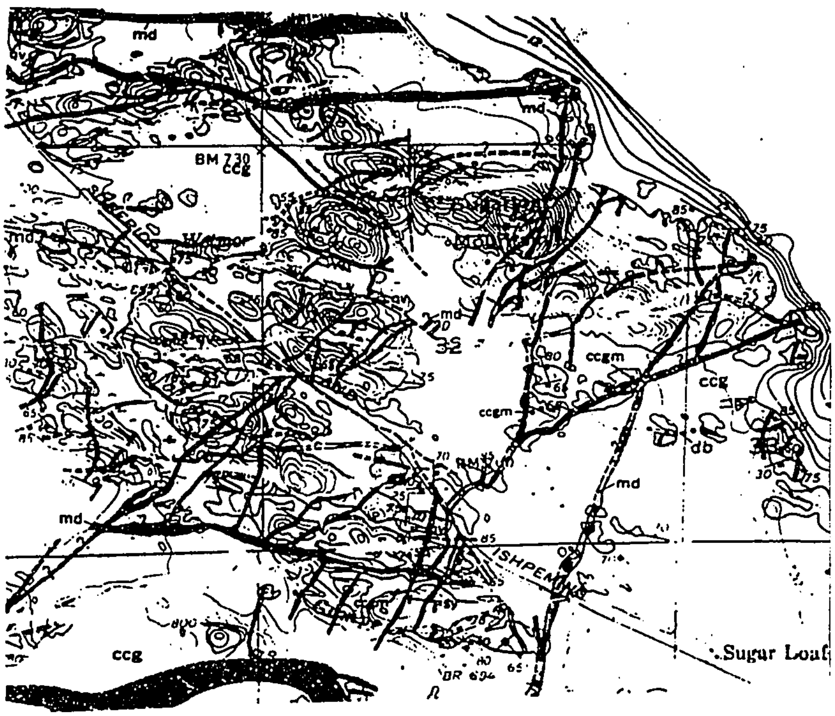

Figure 12. Trends of Metadiabase Dikes in the Compeau Creek Gneiss in the Northern Part of the Marquette Quadrangle. Note the angle of intersection of the conjugate dike systems (the unmetamorphosed diabase dikes have been removed from the original map for ease of presentation)

Source: Modified from Plate 1 of Gair, J. E., & Thaden, R. E. (1968). Bedrock geology of the Marquette and Sands Quadrangles, Marquette County, Michigan. <u>U. S. Geological Survey Professional Paper 397</u>.

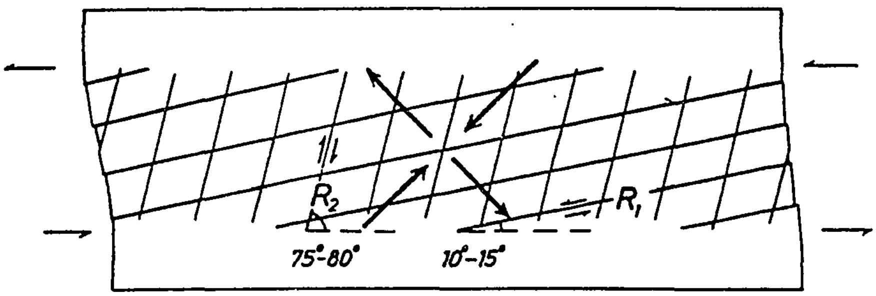

Figure 13. Conjugate Riedel Shears R1 and R2 Resulting From Secondary Fault Development in a Zone of Left-hand Shear. The heavy arrows show the principal axes of incremental strain developed as a result of simple shear in the zone.

Source: Ramsey, J. G. & Huber, M. I. (1987). The techniques of modern structural geology. Volume 2, folds and fractures. London: Academic Press, p. 530. Copyright 1987, Academic Press. Used with permission of Todd Rupp, Academic Press publications, 8-29-91.

Condie et al., 1988), and are unrelated to the Keweenawan dikes. There are unresolved questions regarding their timing of emplacement (Wilband, J.T, personal communication 1986). Upon relaxation of the forces which generated the dilation to accommodate these dike swarms, longitudinal fractures might have formed in a northwesterly trending direction. Alternately, the conjugate sets of dikes could have been intruded into Riedel shears within either a left-lateral, west-north-west/east-southeast or a right-lateral, north-northeast/south-southwest crustal-scale shear zone (Figure 13). Watson (1980) suggested that the northeast trending dikes might have been injected into fractures produced by a dextral transcurrent motion, but cited no orientation for the zone.

Throughout the preceding analysis, it was shown that the Marquette region has had a long history of variously oriented stress regimes of differing magnitudes and lengths of duration. Separating out the stress distribution over time has necessitated a summary of the regional structural features which might have played a role in generating fractures in the region. The tectonic processes involved in the evolution of each of the regional structural features remains unresolved. Inclusion of these features into any analysis of fractures in the region is due to their possible influence on fracture generation in light of the regional aspects of uniform crustal stress distribution, such as that which exists in the region today (Figure 6, p. 12).

Finally, for the Compeau Creek gneiss and the Mona schist, it is not known what influence each of the above listed processes had on the generation of fractures, nor is it known whether fractures formed during one process controlled the orientation of fractures during later events. Furthermore, for the Jacobsville sandstone, it is not known whether the thrust faulting was generated during the last major advance of the glacier, previous advances, the Marquette readvance (Farrand & Drexler, 1985) or if the thrusting occurred at an earlier time, such as the subsidence of the Lake Superior Basin or from movement on the postulated continuation of the Keweenaw fault. Moreover, it is not known whether the subsidence of the Michigan Basin, or the folding in the Devonian section within it, has had any influence on the generation of fractures in the Jacobsville sandstone.

RESULTS OF THE INVESTIGATION

Fracture distributions in the Mona schist, Compeau Creek gneiss and Jacobsville sandstone in eastern Marquette County are the end product of the application of stress fields with different magnitudes and orientations over time, which produced a system of several fracture sets. Fractures in these bodies of rock are analyzed for their tectonic significance and evaluated for their potential use as groundwater aquifers.

Joints in the Mona Schist

Gair and Thaden (1968) classified the fractures in the Lighthouse Point member of the Mona schist, an amphibole schist, as cross joints, longitudinal joints (Figure 14), and shear joints (Figure 15). They define cross joints as those which are perpendicular to the trend of layers, longitudinal joints as those which are parallel to the trend of layers, and shear joints as those which are oblique to the trend of layers.

The systematic fracture sets tend to be relatively planar, persist for moderate distances (tens of meters before interaction with other sets or lithologic change causes them to end), are generally smooth (plumose structures are rare), and have spacings which vary from several centimeters to a few meters. Fracture apertures are variable but appear to close with depth beneath the weathered surface of an outcrop. Based on the surface expression of leached

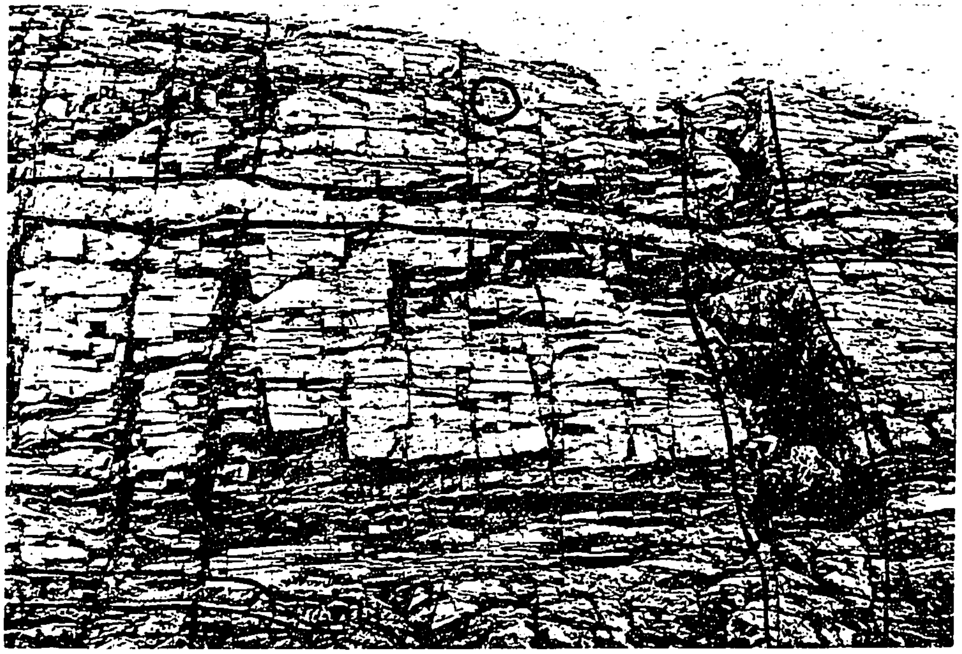

Figure 14. Systematic Cross and Longitudinal Joints in the Lighthouse Point Member of the Mona Schist at the Northeast End of Lighthouse Point. The hammer handle, at the upper center, is oriented north-south. The bedding in the amphibolite strikes east-west and dips 70° to the north. There are three dikes in the outcrop, a metadiabase dike oriented north-south (right side of photo), a diabase dike oriented east-west (upper center of photo, below hammer), and a small apophysis (off of a larger east-west diabase dike below the photo), which utilized fractures trending north-south and east-west, (lower left corner of photo). Note the abundant shear fractures in the metadiabase dike verses the lack of well developed shear fractures in the diabase dikes.

fracture walls and crosscutting relationships with dikes (Figure 14), fractures with the same or nearly the same orientation do not have the same age. For instance, in Figure 14 the two large fractures on the left side of the photo pass through the dike as hairline fractures; yet some of the smaller, similarly oriented, fractures nearby do not pass through the dike, but continue on the other side with the same orientation. Another example from Figure 14 is

Figure 15. Shear Fractures in the Lighthouse Point Member of the Mona Schist. The outcrop is located eight meters southwest of the outcrop in Figure 14. Note the horizontal sheeting (the hammer is vertical) and the approximately north-south shear fractures (looking due south).

the small diabase dike in the lower left corner of the photo, which is an apophysis off of a much larger dike below the edge of the photo. This dike utilized the north-south fractures as magma intruded mainly along the east-west fractures.

Stratigraphically below the Lighthouse Point member of the Mona schist is the Lower member: a massive, chlorite metabasalt which frequently contains pillow structures (Figure 16). Gair and Thaden (1968) describe the jointing in the massive meta-volcanic rock as "blocky" (p. 64), but whether they meant the obvious influence of pillow structure on joint orientation is not known. The fracture types tend to be less recognizable as cross, longitudinal, or shear. The average spacing of persistent, relatively planar, semi-rough

Figure 16. Fractures in the Pillowed Lower Member of the Mona Schist. South-east view of a roadcut on the south side of U.S. 41, 100 meters west of the intersection of U.S. 41 and Business Route U.S. 41. Note the blocky and irregular nature of the fractures and the lack of systematic sets as seen in Figures 14 and 15.

fractures appears to be up to a few meters. Their apertures are variable, but usually open up to five millimeters. Although much wider apertures are present, it is not known whether these were due to gravity sliding, frost wedging, or other processes. Interpillow fractures which utilized selvage material for propagation are common and thus are called selvage fractures (Figure 17). The spacing is governed by pillow spacing and the fractures tend to be curved, rough and short (but usually abundant enough to intersect other fractures). Short discontinuous fractures were observed within the

Figure 17. Selvage Fractures in the Pillowed Lower Member. View to the east at a quarry wall 800 meters west-north-west of the outcrop in Figure 16. The scale at the left is equal to one foot. Note the round shapes of the pillows, where fractures have tended to utilize the selvage material rather than the interior of the pillows.

pillows (intrapillow fractures) and appear to be a result of localized tensional forces set up within individual pillows during shear movements in the selvage material.

Joints in the Compeau Creek Gneiss

The 593 joints measured in the Compeau Creek gneiss north of the Marquette synclinorium were plotted as the percentage concentration of poles to joints on the lower hemisphere of a Schmidt equal-area projection [Figure 18(A)], and as a 5-degree moving average rose diagram of joint strikes [Figure 18(B)]. To facilitate a comparison of the variation of joint orientations measured at the selected outcrops, a 5-degree moving average rose diagram and a lower

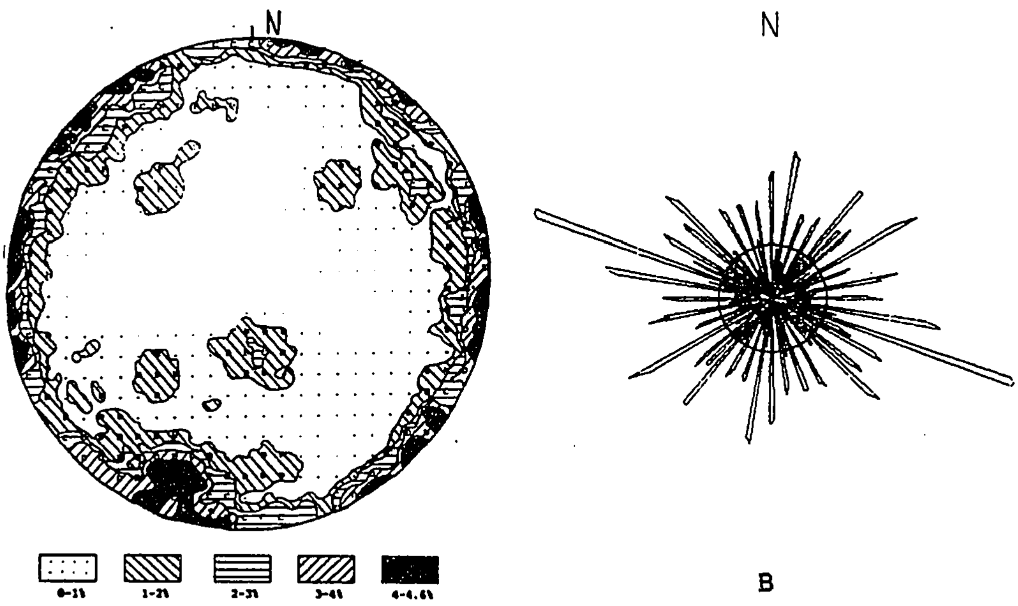

Figure 18. (A) Joint Diagram of Poles to 593 Joints in the Compeau Creek Gneiss North of Marquette Synclinorium. Lower hemisphere of Schmidt equal-area projection, with shaded areas depicting different percentage concentrations of poles per one percent area. (B) 5-Degree Moving Average Rose Diagram of Strikes of 593 Joints in the Compeau Creek Gneiss North of Marquette Synclinorium.

hemisphere Schmidt equal-area projection were produced for each selected outcrop in the Compeau Creek Gneiss north of the city of Marette (Plate 1). The variations in joint distributions from outcrop to outcrop could be due to proximity to fault zones and the influence of nearby dikes relieving stress by fracturing (compare Figures 19 & 20). For instance, the metadiabase dikes in the field area are oriented as if they were emplaced into a conjugate set of fractures (see Figure 12, p. 29). Their orientations and spacings relative to the fracture producing stresses might have caused unequal stress distributions within the blocks of gneiss enclosed by the intersecting dikes. As a result, variations in the fracture distributions at

Figure 19. Photograph Looking Southeast at Outcrop of Compeau Creek Gneiss at Freeman Landing. Hammer at middle right denotes scale. Note the joint sets and the abundance of quartz veins and aplite dikes.

individual outcrops would be expected. Therefore, the systematic fracture sets tend to exist in domains where an individual set will dominate over another set due to (a) fabric inhomogeneities (shear zones and small changes in the orientation of foliation), and (b) local stress deviations caused by inclusions (Figure 20), dikes (Figures 21 & 22) and quartz veins (Figure 23). Furthermore, many outcrops were observed with either no fractures, or a limited number of fractures, over areas of up to several square meters. Although

Figure 20. Fractures Preferentially Developed Within Inclusions in the Compeau Creek Gneiss. The outcrop is located 610 meters south of that in Figure 19, and contains inclusions which exhibit ductile behavior during emplacement. The fractures within the inclusions are oriented in an orthogonal pattern (northeast-southwest, northwest-southeast and north-south) and have been deuterically altered along their walls. Note the fracture refraction at the boundaries of the inclusions, the very thin fracture apertures, quartz veins and aplite dikes.

no attempt was made to quantitatively analyze variations in fracture spacing per linear foot of outcrop, there are great variations in fracture density within nearby outcrops (possibly due to fractured dikes separating them). Outcrops next to next to fault zones tend to be highly fractured. Outcrops farther from faults and dikes tend to be relatively less fractured. Finally, in all outcrops where

Figure 21. Photograph of a Diabase Dike Utilizing a N70° W Joint Zone in the Compeau Creek Gneiss. The outcrop is located on the shore east of Sugarloaf Mountain (NW 1/4 of SW 1/4 of NW 1/4 of sec. 33, T49N, R25W). The hammer handle is north-south and the head is toward the north. The dike is probably connected below the surface or was connected above the surface and has been eroded away. Note the pinching out of the dike within the joint zone, the chill border against the walls of the dike, the small columnar joints in the dike, and the curving, branching, and discontinuous joint sets in the host. There are small shear fractures in the dike but they are not visible in the photograph.

metadiabase and diabase dikes occur, the metadiabase dikes always exhibit greater fracture density.

The distance between fractures varies considerably, from several meters to several centimeters. Joint zones and bifurcations are very common (Figure 21), especially where fractures are planar and persist for many meters. The lengths of systematic fractures

Figure 22. Shear fractures in an East-west Striking Diabase Dike. The dike is located at the north-east end of Lighthouse Point and south-east of the outcrop in Figure 15. The joints along the left side of the photograph, parallel to the hammer handle, are part of a north-south striking columnar set. The joints striking north-west and north-east are shear fractures.

are generally less than ten meters, but several fractures were observed with lengths of over twenty meters.

The surface expressions of joint apertures exhibit considerable variation. In many outcrops the fractures appear as thin lines of no apparent aperture (Figure 23), whereas in others the apertures are larger, reaching widths of up to a few centimeters (Figure 19). The walls of many fractures are weathered, stained, and rough because of the preferential weathering of feldspars and mafic minerals. Plumose structures are absent. Many surfaces which appear

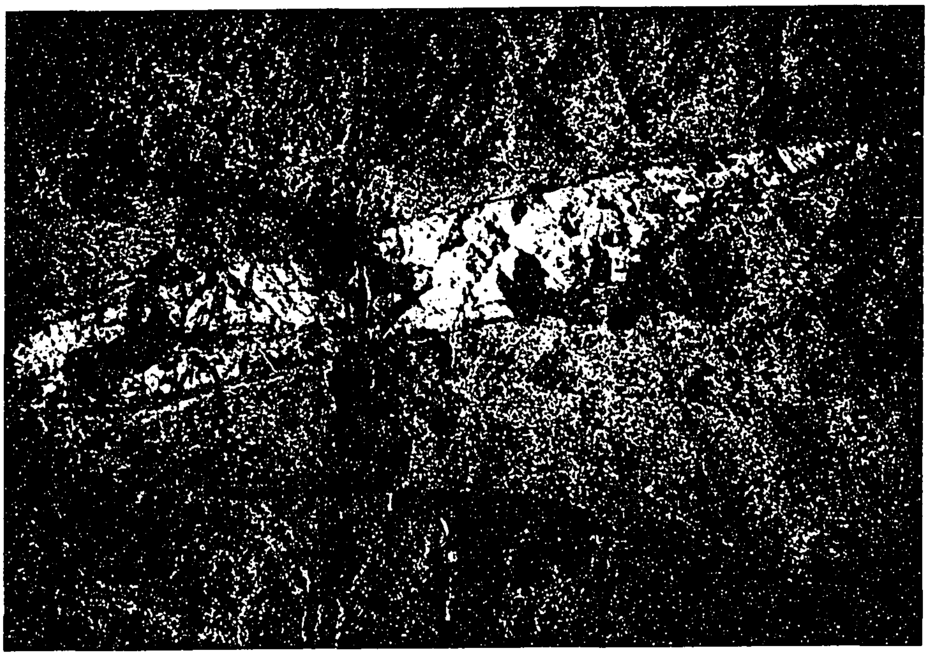

Figure 23. Joint Sets in a Lenticular Quartz Vein in the Compeau Creek Gneiss. The outcrop is located 230 meters southeast of the diabase dike in Figure 21. The hammer handle is oriented north-south, with the head toward north. Note the pinching out of the vein at the right, the joints in the quartz vein (only a few penetrate into the gneiss), the north-south joint, and the small east-west striking left-lateral ductile shear zone adjacent to the head of the hammer.

planar at a distance are undulatory upon closer examination. Apertures at the surface are most likely not representative of those at depth, except where glacial polish is highly developed above thin apertures.

Gair and Thaden (1968) noted that metadiabase and diabase dikes were controlled by pre-existing fractures during intrusion, and that joints of similar orientation are not necessarily the same age (Figure 21). They also noted the presence of quartz veins in the Compeau Creek gneiss, and recognized (on the basis of crosscutting relationships) that the metadiabase dikes are younger than the quartz veins. Although a detailed study of the spatial relationships of the quartz veins was not undertaken, fracture sets were discovered within quartz veins encountered at several outcrops (Figure 23). In outcrops spaced large distances apart, the quartz vein fractures have similar orientations.

Occasionally, systematic joint sets have superimposed upon them subsidiary sets which tend to occur in domains of limited area. An excellent example of a small fracture domain is shown in Figure 24. Five joint sets extend into the rock for several meters, while the orthogonal fracture pattern penetrates the surface only to a depth of about two centimeters.

The joint diagram prepared by Gair and Thaden (1968) [Figure 25(A)], represents the poles to 395 joint surfaces in the Compeau Creek gneiss north of the Marquette synclinorium plotted on the lower hemisphere of a Schmidt equal-area projection. The trends of idealized joint sets derived from the centers of 4-4.6 percent

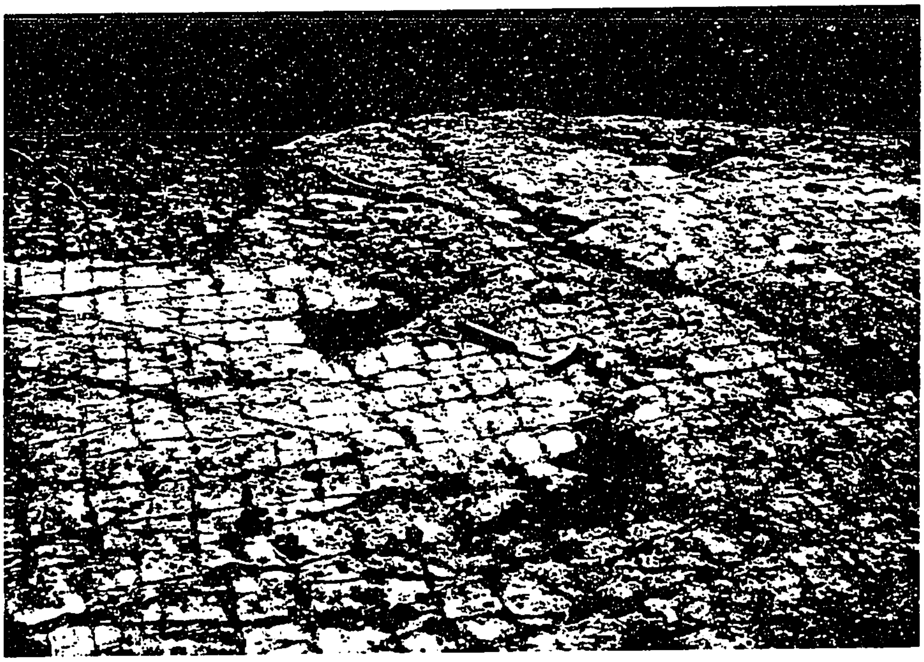

Figure 24. Photograph of Joints at the Top of the Center Knob of Hogback Mountain. The outcrop is located 360 meters south of sec. 25/36 boundary, 120 meters west of sec. 31/36 boundary, NE 1/4 of sec. 36, T49N, R26W. Hammer handle is parallel to north-south and the head is toward the north. Note the orthogonal joint pattern oriented northwest-southeast and northeast-southwest and the five other sets (N70° W, N-S, E-W, N20° W, and N30° E) which cross through the orthogonal set.

concentration are represented by broken lines in some of the arms of the rose diagram. The approximate dip of a joint set or idealized joints is shown only where the dip departs more than 10 degrees from the vertical.

Gair and Thaden (1968) noted that joint set A [Figure 25(A)] is probably cross joints and that joint set B is probably longitudinal joints, where both are related to the major deformation axis [Figure 25(B)] of the Marquette synclinorium, where joint patterns have

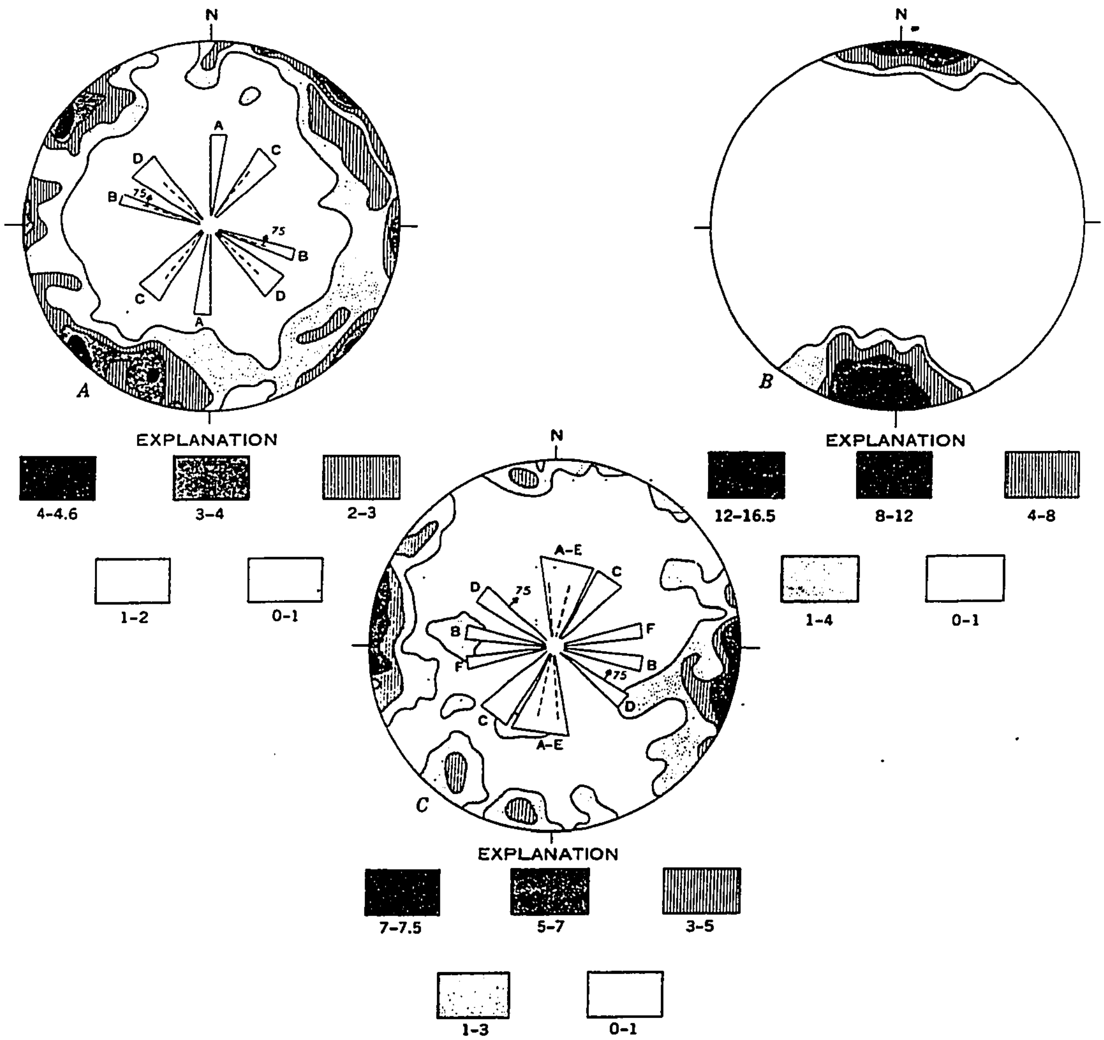

Figure 25. Poles to Joints and Rose Diagrams of Strikes of Joints in Eastern Marquette County. (A) 395 Poles to Joints in Compeau Creek Gneiss North of Marquette Synclinorium. (B) Cleavage Diagram of 219 Poles to Cleavage in Rocks of Animikie Age, Eastern Part of Marquette Synclinorium. (C) Joint Diagram of 105 Poles to Joints in Rocks of Animikie Age, Eastern Part of Marquette Synclinorium. Lower hemisphere of Schmidt equal-area projection, with shaded areas depicting different percentage concentrations of poles per one percent area. Superimposed rose diagrams derived from areas of (A) 3-4.6 and (C) 3-7 percent concentration, delineating the trends of major joint sets.

Source: Gair & Thaden (1969). Geology of the Marquette and Sands Quadrangles, Marquette County, Michigan. U. S. Geological Survey Professional Paper 397: A, Figure 30(A); B, Figure 29; and C, Figure 30(C).

strong similarities to those in the gneiss [Figure 25(C)]. The trends of idealized joint sets derived from the centers of 7-7.5 percent concentration are represented by broken lines in some of the arms of the rose diagram. The approximate dip of a joint set or idealized joints is shown only where the dip departs more than 10 degrees from the vertical.

Although there are similarities between the diagrams produced in this study [Figures 18(A) & (B)] and Gair and Thaden's (1968) diagram [Figure 25(A)], not all of their outcrops were visited. Moreover, many of the outcrops visited were covered with lichens and moss, concealing any joints which might have been measured by Gair and Thaden (1968).

Joints in the Jacobsville Sandstone

The spatial and physical properties of the fractures in the Jacobsville sandstone measured during this study were recorded and qualitatively analyzed for their aquifer potential and usefulness as indicators of past and present tectonic environments. All the fractures measured are plotted on a lower hemisphere Schmidt equal-area projection (Figure 26) and as a 5-degree moving average rose diagram (Figure 27). Fractures measured at outcrops accessible by foot between Presque Isle and Thoney's Point are plotted as 5-degree moving average rose diagrams for the individual outcrops visited (Figure 28). However, the lack of access to a boat hindered data collection between Big Bay and Thoney's Point, and thus, the data are not as complete as Hamblin's (1958) (Figure 29).

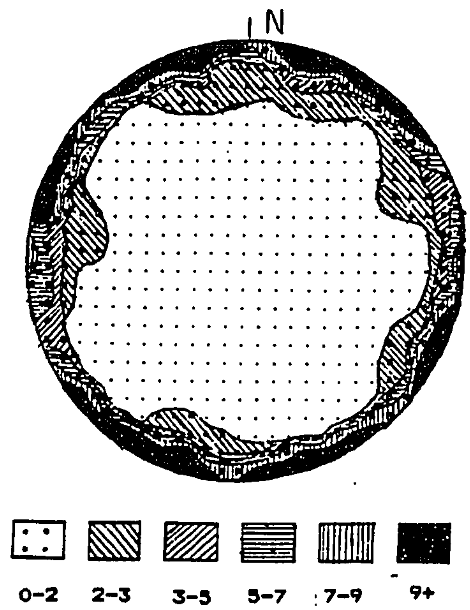

Figure 26. Lower Hemisphere Schmidt Equal-area Projection of 206 Poles to Joints in the Jacobsville Sandstone from Presque Isle to Thoney's Point. See Figure 28 for outcrop locations.

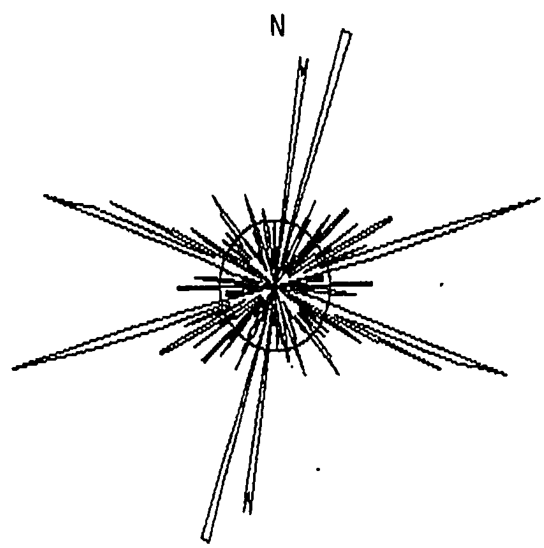

Figure 27. 5-degree Moving Average Rose Diagram of 206 Joints in Jacobsville Sandstone From Presque Isle to Thoney's Point. See Figure 28 for outcrop locations.

In the Jacobsville sandstone, there are bedding-perpendicular, bedding-parallel, shear, and thrust-generated fractures. Of all the fracture types the most persistent are the shear[1] fractures and their adjacent reduction zones. For instance, directly above the basal conglomerate of the Jacobsville (Figure 30, p. 51), one systematic joint zone along the shore north of Freeman Landing persists for over one hundred meters (Figure 31, p. 52). Shear fractures are usually quite planar, semi-smooth walled, near vertical, and occasionally are in sets with spacings measured in meters. Their apertures are usually less than two to five millimeters and are mostly open. However, at the south-east end of Presque Isle, the reduction zoned fracture (Figure 36, p. 58) is partially cemented with calcite.

Bedding-perpendicular fractures are generally discontinuous, short, slightly planar, near vertical (except within forset beds) and rough walled. Some bedding-perpendicular fractures exhibit plumose structures. The spacing depends on the grain size of the individual bed; where fine-grained shale and siltstone have the smallest spacings (centimeters), medium-grained sandstones have larger spacings (centimeters to tens of centimeters) and coarse-grained sandstones have the largest spacings (meters). Their apertures are generally less than five millimeters. Usually, bedding-perpendicular fractures are not developed in conglomerates.

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1. The term shear is used by Hamblin (1958) and is used here to signify the joints he refers to, not the process which produced the joints themselves.

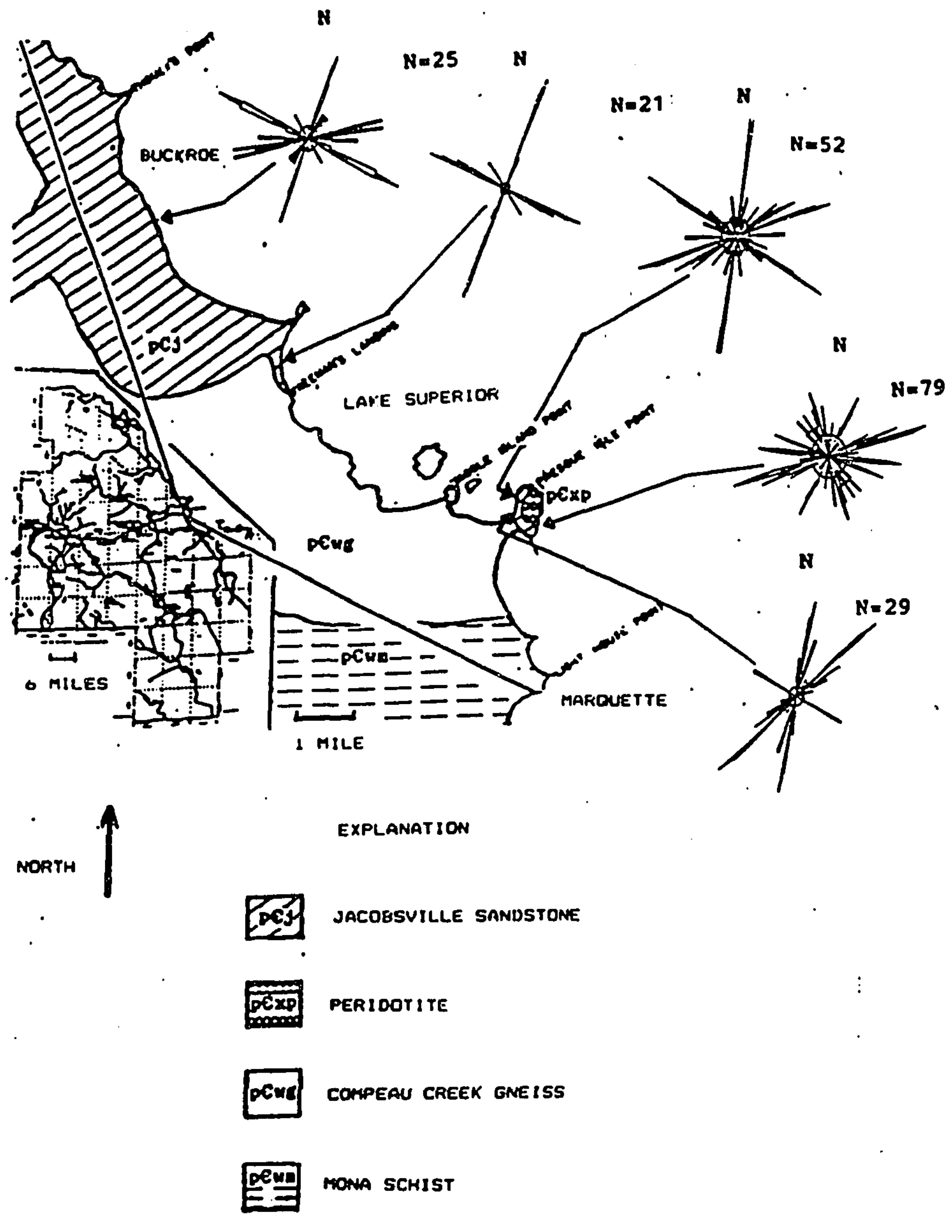

Figure 28. Rose Diagrams of Joints in Jacobsville Sandstone From Presque Isle to Thoney's Point. Arrows indicate location of outcrops (see inset map for location within county).

Bedding-parallel fractures are generally present at lithologic boundaries and especially where there is a change in grain size, such as graded bedding. They are semi-persistent, slightly planar, rough walled and can be closely spaced (i.e., along forset beds).

Thrust generated fractures are closely spaced, non-planar, non-persistent, rough walled and localized above a sliding surface. Their apertures are variable, but can be large where brecciation has occurred and/or small blocks have moved or rotated and particles have propped the fracture open.

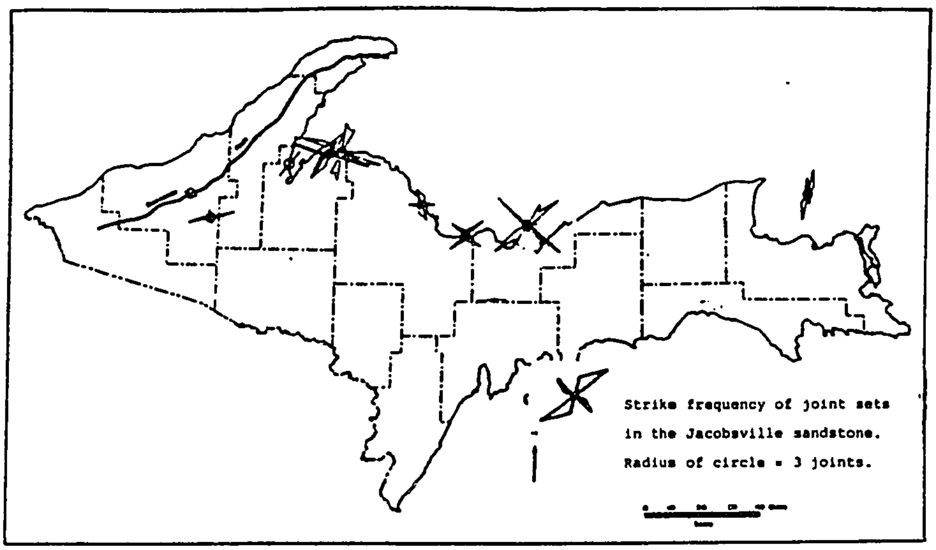

Figure 29. Strike Frequency of Joint Sets in the Jacobsville Sandstone.

Source: Hamblin, W. K. (1958). Cambrian sandstones of northern Michigan. Lansing: Michigan Geological Survey, Publication 51, p. 131.
Used with permission of Michigan Geological Survey, 8-29-91.

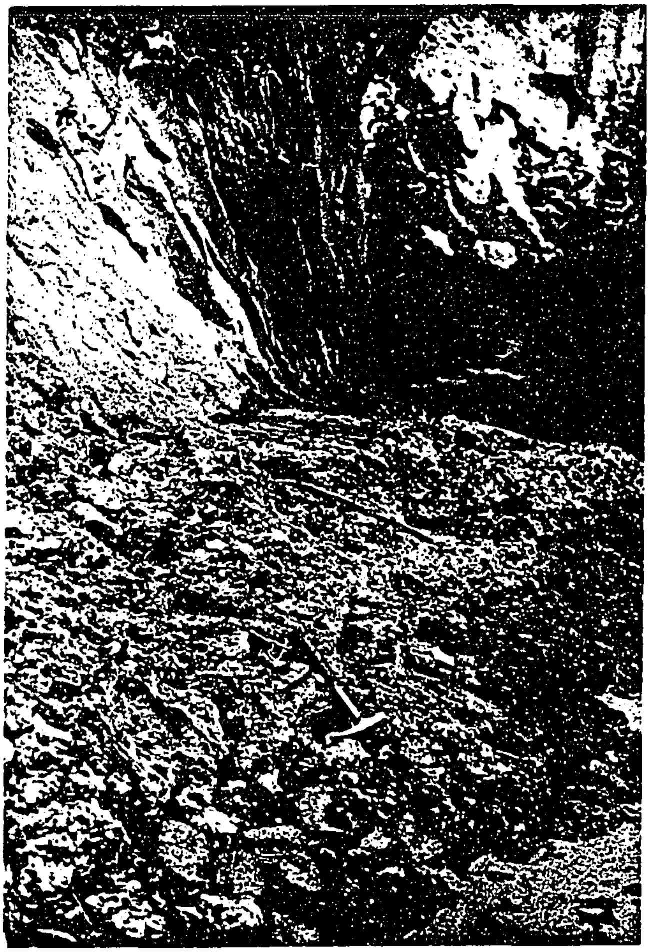

Figure 30. Photograph of the Conglomeratic Base of the Jacobsville Sandstone. The outcrop is located north of Freeman Landing (33 meters north of sec. 20/29 boundary, 80 meters west of sec. 20/19 boundary, SW 1/4 of sec. 20, T29N, R25W). Note the spalling of the vertical faces and the coarse grain size. The conglomerate is cemented with calcite and contains fractures with orientations controlled by the pebble- and cobble-sized particles in the fine-grained micaceous matrix.

There are similarities between Hamblin's (1958) data (Figure 29) and the data obtained in this study (Figures 26, 27, and 28). Hamblin (1958) noted that there are two sets of shear joints which

Figure 31. Photograph of Reduction Zoned Shear Fractures in the Jacobsville Sandstone. The outcrop is located north of Freeman Landing, 6 meters east of the outcrop in Figure 30, looking north parallel to the strike of the large shear fractures (N20°E). The height of the tree at the right is approximately 2 meters. Note reduction zones along fractures and within strata, bedding parallel fractures, wave cut notch and cave, and spalling of vertical faces into discontinuous sheets 2.5 to 7.5 centimeters thick, which are parallel to the current face and follow its curvature. The large fractures are part of a joint zone which can be traced northward along the shore for over one hundred meters.

intersect at nearly right angles in the Jacobsville sandstone. Hamblin (1958) defined the reduction zoned (having leached walls) fractures as the shear fractures. Near Keweenaw Bay, one set strikes N70°W and the other set strikes N10-30°E. To the east, this pattern rotates clockwise. At Grand Island, one set strikes N50°W and the other N40°E.

The data in Figures 26, 27, and 28 probably contain fractures possibly generated in the upper (hanging-wall) blocks of thrust faults during the advance of the glaciers (see Figures 36-39, pp. 58-61). It is not possible to determine if there are thrust faults below outcrop level. However, in those outcrops where thrust planes were observed, fractures were not measured above the fault plane. The purpose of not measuring thrust-generated fractures is to compare the fractures produced by tectonic processes (other than thrust faulting) with the data published by Hamblin (1958). Except for the outcrop at the southeast end of Presque Isle, where all the fractures at that outcrop are presented in the rose diagram (Figure 28, see also Figure 36, p. 58), all the other rose diagrams (Figure 28) are presented without fractures discernible as thrust fault generated. However, the fractures generated by thrust faulting were assessed for their aquifer potential.

In many exposures of the Jacobsville sandstone, the grain size and orientation of an individual stratum influence the degree of fracture development and the orientation of fractures. The fine-grained material tends to have a higher density of fractures. The fractures tend to be more planar in fine-grained material than in coarse-grained material. Also, the orientation of a propagating fracture could be changed by a change in grain size (Figure 32).

Figure 32. Photograph of a Stream Channel Conglomerate Overlying a Lens of Silty Sandstone in the Jacobsville. The outcrop is located at a shoreline cliff 60 meters north of Figure 31 and the view is to the southwest. The ruler at the center is six inches long and is oriented north-south. Note that the fractures are much more abundant in the silty sandstone than in the conglomerate, and the fractures in the conglomerate have broken around the grains. The fracture at upper left, which has broken both strata, ends approximately one foot into the conglomerate (the shadows in the photograph accentuate the actual apertures of the fractures)., and the border of the reduction zone is more diffuse in the conglomerate.

The orientation of the bedding could also influence the orientation of a propagating fracture, and in this case (Figure 33), the change in fracture dip in the contrasting grain sizes is only a few degrees. However, the fracture is oblique to bedding in the lower trata, whereas in the upper strata the fracture is perpendicular to bedding. Therefore, in this example a combination of factors

Figure 33. Photograph of a Set of Fractures Which Change Orientation Upon a Change in Grain Size and Orientation of Bedding. The fractures are beneath the thrust fault (see Figure 36) at the south-east end of Presque Isle. The hammer handle is oriented north-south and the head is toward the north. Note the lower fractures, N38 W, 61 SW, which change orientation to N60 W, 90 upon entering the coarse grained sandstone. The bedding in the lower fine- to medium-grained sandstone dips slightly away from the viewer, while the bedding in the upper coarse-grained sandstone dips slightly to the left.

probably influenced the propagation of these fractures, but the magnitude of each factor is unknown.

As noted by Hamblin (1958), there are two sets of fractures which intersect at nearly right angles in the Jacobsville sandstone.

Figure 34. Overhead Photograph of Intersecting Fractures at Quarry Pond. The outcrop is located 304 meters south of sec. 23/26 boundary and 304 meters east of sec. 27/26 boundary, sec. 26, T48N, R25W, displaying intersecting fractures which have an orientation similar to those described by Hamblin (1958). The hammer handle is north-south and the head is toward the north. Note the planar aspect of the fractures and their near right angle of intersection.

Two examples of this relationship are located at Quarry Pond, along the southern boundary of the city of Marquette (Figure 34), and at the south-east end of Big Bay Point (Figure 35). Although these two outcrops are approximately 24 miles apart, the fracture orientations are almost identical, N20°E and N70°W.

Hamblin (1958) noted that thrust faults exist in the Jacobsville sandstone. As a result of this investigation, several thrust

Figure 35. Photograph of Intersecting Fractures at the Southeast End of Big Bay Point. The outcrop is located 915 meters east of sec. 11/12 boundary and 183 meters north of sec. 13/12 boundary, sec. 12, T57N, R27W. At the upper left is a knapsack for scale. The view is parallel to the N70 W fracture at left center, and the fracture on which the knapsack is placed is oriented N20°E. Note the bedding-parallel fractures, the curving N70°W fracture surface at left center, the change in strike and dip of the fracture which passes through the reduction spots at center, and the spherical reduction spot at left. Proximity to the shoreline might have had an effect on the development of the subsidiary fractures at this outcrop.

faults were located which were not described by Hamblin (1958). For instance, a small bedding-plane thrust fault was discovered at the southeast end of Presque Isle (Figure 36). The source of the stress to produce this particular thrust is unknown. However, there is

Figure 36. Photograph of a Bedding Plane Thrust Fault at the Southeast End of Presque Isle. Note the 7 centimeter displacement of the vertical fracture and its symmetrical reduction zone. The view is to the north and the displacement along the thrust was to the west. The strike of the thrusted fracture in the hanging-wall changes about 3 degrees to the west from the fracture in the foot-wall.

evidence for glacially produced thrust faults in the Jacobsville. For example, a bedding plane thrust fault is present along the shore south of Buckroe which displays natural shattering in the hanging-wall block along the fault plane (Figure 37). Furthermore, examples of thrust faulted and brecciated Jacobsville are present at the northwestern end of Big Bay Point (Figures 38 & 39). The pulverized

Figure 37. Photograph of a Horizontal Thrust Fault in the Jacobsville Sandstone Along the Shore South of Buckroe. The outcrop is located on the sec. 11/2 boundary, T49W, R26E. The view is to the southwest and the 20 centimeter notebook at lower right center is the scale. The bottom edge of the notebook is placed on the fault surface. Note the radial fracture pattern above the notebook which is an example of natural shattering along a thrust plane. The direction of thrusting was to the left (south).

Jacobsville between the rotated blocks of Jacobsville strata is very friable (Figure 38), and the folded and imbricated light colored

Figure 38. Photograph of a Disturbed Zone in the Jacobsville Sandstone at the Northern End of Big Bay Point. The outcrop is located on the sec. 2/1 boundary, 550 meters north of sec. 12/1 boundary, T51N, R27W. At the center is a hammer for scale, which is resting on an isolated block of the Jacobsville sandstone that has been rotated out of the horizontal and surrounded by brecciated particles of the Jacobsville sandstone. Above the hammer is a zone of imbricated and folded layers of the Jacobsville sandstone, which appear as white layers (the white areas to the right of the hammer, the spotty areas at the left, and at the upper right are snow). At the top of the figure is a series of near horizontal layers which are highly brecciated and locally imbricated.

strata are composed of mechanically weak, reduction zoned Jacobsville sandstone.

Approximately 61 meters south-west of Figure 38 is another example of thrust fault generated brecciation in the Jacobsville

Figure 39. Photograph of Thrust Fault Generated Fractures in the Jacobsville Sandstone at Big Bay Point. The view is to the southeast and the outcrop is located 61 meters south-west of the outcrop in Figure 37. A hammer denoting scale is located at the right center. Note the highly fractured character of the outcrop, the lower and upper brecciated and imbricated layers and the small back thrust which passes through the reduction spot above the hammer. Approximately one foot beneath the hammer is the thrust surface upon which the fractured block at the center moved.

sandstone (Figure 39). The outcrop is highly fractured, bedding has been imbricated, and backthrusting has occurred through a reduction spot. Unfortunately, the outcrops located at Big Bay Point (Figures 38 & 39) are eroding rapidly, due to their location on a high wave energy beach, and it is unlikely that they appear the same today.

SUMMARY OF FRACTURE PROPERTIES AND POSSIBLE ORIGINS

Fracture Properties

The types of fractures found within each rock unit are summarized (Table 3), described according to their general physical features and properties within the individual rock units (Table 4), and categorized on the basis of their spatial and physical properties (Table 5). The categories are set up to produce an overall picture of the spatial arrangement and three-dimensional nature of the fracture sets, systematic and non-systematic, in the various rock types. The categories are averages of the observed properties, but the physical attributes at an outcrop surface cannot be predicted to continue and exhibit the same similarities at depth. The listing of other rock types within a particular category is due to the hosting of that other rock by the rock in the category.

Within the igneous rock types the apertures of fractures on the surface are probably not typical of the rock as a whole. Chemical weathering and frost wedging are currently acting to increase the apparent apertures on the surface, whereas glacial plucking and scour increased the apparent apertures in the past. For instance, in several samples of each rock type, the apertures were observed on the surface and then the sample was broken to observe the fracture a few centimeters into the rock. Usually, the aperture appeared to be smaller. However, in many instances the aperture appeared as a fine

Table 3

Summary of Fracture Types in Each Rock Type

Rock Type	Fractures
Jacobsville Sandstone	Shear, bedding-parallel, bedding-perpendicular, thrust generated fractures.
Compeau Creek Gneiss	Shear, longitudinal, cross (after Gair & Thaden, 1968) (see Dikes, Inclusions and Quartz veins).
Mona Schist	Shear, longitudinal, cross, selvage (interpillow), intrapillow (see Dikes).
Dikes	
Diabase	Columnar joints, shear.
Meta-diabase	Columnar joints, shear, propagation of other types through them, and by strain localization, preferential development within them.
Inclusions	Shear, propagation of other types through them, and by strain localization, preferential development within them.
Quartz Veins	Shear, propagation of other types through them, and by strain localization, preferential development within them.

line in the rock. Except for large clefts in the gneiss and schist (possibly faults) the apertures of the fractures were generally less than five millimeters at the surface and appeared to become thinner with depth.

Mineral filling of the fractures in the various rock types is quite variable. The Mona schist has mineralization which is discontinuous in both members, but the pillowed Lower member appears to have more unmineralized, open fractures. However, the fracture density is less in the Lower member.

The Compeau Creek gneiss has several types of mineralization

Table 4

Descriptive Features of Fractures

Rock Type	Fracture	Description
Jacobsville Sandstone	Exclusive of Shear	Preferential fabric control due to changes in the orientation of cross-bedding, grain size, and type of cement
	Shear	Commonly cut through clasts, have 5 to 40 centimeter wide leached zones into the fracture walls, generally are long, straight and near vertical and are relatively smooth.
	Bedding Perpendicular	Commonly found where there is a change in the cross-bed direction, grain size, and cement. Localized within individual strata, generally propagated around clasts and terminated either slightly within or against adjacent strata. When propagated into adjacent strata with differing strike and dip of cross-beds, trend is commonly changed.
	Thrust Generated	Pervasive fracturing along bedding planes where the upper masses have undergone differential movement produced by the southward movement of the glaciers. In some instances high pore water pressure has injected pulverized Jacobsville Sandstone in between rotated blocks of fractured Jacobsville Sandstone and in other cases natural shattering has occurred along the thrust surface.
Compeau Creek Gneiss	Cross, Longitudinal, and Shear	Termination of joints yields either an abrupt termination without any visible strain or en-echelon zones of microcraking leading into the next joint. Fabric control changes orientations of joints by a change in foliation trends and grain sizes in the gneiss by the presence of small scale shear zones, and by inclusions, aplite dikes, quartz veins, metadiabase and diabase dikes. Preferential joint development by strain localization within inclusions, aplite dikes, quartz veins, metadiabase and diabase dikes
Mona Schist Lighthouse Point Member	Cross, Longitudinal, and Shear	Well developed north-south joints at Lighthouse Point which are perpendicular to the to the trend of foliation.

Table 4--continued

Rock Type	Fracture	Description
Mona Schist	Cross	Well developed north-south joints at Lighthouse Point which are perpendicular to the trend of the foliation.
Lighthouse Point Member	Longitudinal	Well developed east-west joints at Lighthouse Point which are parallel to the trend of the foliation.
	Shear	Weakly developed joints which are oblique to the trend of the foliation.
Pillowed Lower Member	Cross	Weakly developed and undulating, controlled by selvages between pillows.
	Longitudinal	Weakly developed and undulating, controlled by selvages between pillows.
	Shear	Moderately developed and undulating, controlled by selvages between pillows.
	Selvage	Well developed interpillow fractures with some exhibiting shear.
	Intra-pillow	Variably developed fractures located within individual pillows but not continuous across selvage into adjacent pillows.

present within its fractures, indicating a complex history consisting of multiple quartz vein intrusions, epidote generation and intrusion, and the deposition of clay minerals during weathering.

The apertures of fractures in the Jacobsville sandstone appear to be wider than those in the igneous rocks, especially where the rock had been thrust faulted. In all types of systematic fractures, the apertures are about two to five millimeters at the surface, and do not appear to become thinner with depth into the outcrop. The apertures of thrust generated fractures generally are much wider, in

Table 5

Spatial and Physical Properties of Fractures

	Mona Schist		Compeau Creek Gneiss	Jacobsville Sandstone
	Lighthouse Point Mbr.	Pillowed Lower Mbr.		
Spacing	10cm - 3m	2cm - 3m	25cm - 5m	10cm - >10m
Length	5cm - 10m	2cm - 3m	5cm - 20m	2cm - >100m
Persistence of Sets	moderate	limited	moderate	limited to great
Planeness	straight	undulating	straight to curved	mostly straight
Roughness of Surface	smooth	rough	smooth to rough	smooth to rough
Weathering	<5mm leaching	variable	leached but variable	variable
Aperture	mostly closed	open but variable	closed but variable	mostly open, i.e., thrusts
Mineral Fill	quartz, calcite	quartz, calcite	quartz, epidote, clay	clay, some calcite
Typical Intersection Angles	orthogonal	variable due to pillows	many orthogonal sets, 45-60 are most common	shear orthogonal, thrust are variable

some instances reaching widths of greater than two centimeters.

The Jacobsville sandstone exhibits very limited mineralization in its fractures. Leaching of the fracture walls occurred locally. Calcite cement is present within a small section of the large reduction fracture present at Presque Isle Park (Figure 36, p. 58), but in all other cases fractures appear to contain only small amounts of clay minerals derived from weathering of the walls and/or from percolation from above.

Possible Fracture Origins

Fractures are enigmatic structures in bodies of rock which can develop at any time after the rock's formation. The presence of systematic sets of joints implies that systematically oriented stress must have either been applied to the rock body or was contained within the rock body. Many workers who have investigated the origin of joints and fractures agree with Price's (1966) opinion that joints develop upon uplift of rock, which releases the stored elastic stresses contained therein. Not only will the joint geometry depict the stress in the past, it can also depict the contemporary stress, as Engelder (1982) has shown for the northeast United States (see Figure 6, p. 12). The Marquette region has undoubtedly undergone more than one period of uplift, and is currently uplifting approximately 11 centimeters per 100 years (Farrand & Drexler, 1985) (see Figure 7, p. 13).

Developing a model or series of models for fracture reservoirs in different types of crystalline rocks requires a delineation of the fracture patterns to illuminate the subsurface geometry. Implicit in such a model is the assumption that the fractures at the surface are representative of the fractures at depth, which may or may not be a reasonable assumption. Furthermore, there are many assumptions which have to be made about the conditions which existed at the time of fracturing, especially in an area like Marquette, which has suffered multiple deformations. However, if bore-hole data exist concerning the conditions at depth, then the extension to depth of surface fractures might be possible.

Delineating the temporal relationships between individual fractures and the stresses which produced those fractures is a speculative process requiring knowledge of the various stress regimes existing in the area over time (Table 6), and evidence constraining fracture generating events (Table 7). The actual timing and tectonism of several of these events are still in question and the significance of them to fracture development is hypothetical.

There are differences in the mechanical behavior of the Mona schist versus the Compeau Creek gneiss due to the presence of lithologic changes in the Mona schist, the abundant dikes (metadiabase, diabase and aplite), inclusions and quartz veins in the Compeau Creek gneiss, and the degree of foliation development and its influence on fracture propagation. The fracture orientations present within rock units hosted by the Compeau Creek gneiss (Table 7) are listed without dip angles due to their general, near vertical attitude.

The temporal development of individual fractures might be constrained by rock units of known age, and although the actual age of the unit itself is not known, crosscutting relations bracket the time of origin. As noted above (see "Post-Kenoran Events," p. 26), the sequence of events between the Penokean orogeny and the Kenoran orogeny is still being debated. Although fractures were observed in several inclusions in the Compeau Creek gneiss, no attempt was made to analyze their spatial distribution. However, the fractures in the inclusions are post-consolidation features, based upon the

TABLE 6

Possible Origin of Fractures and Sources of Stress

Rock Unit	Sources of Stress
Jacobsville Sandstone All Fractures Except Thrust Generated	Current stress field in the midcontinent region is oriented northeast-southwest to east-west. Isostatic uplift of the northeast part of the Lake Superior basin basin and subsidence to the southwest. Glacial flexing of crust at ice margins. Glacial loading at peak of ice thickness. Uplift and erosion of Paleozoic sediments. Sediment loading developing intra- and/or interstratal stress due to differences in stratal thickness, grain size, cement and crossbed orientation. Movement on any of the regional structural features (GLTZ, TSTZ, KF). Possible continuation of Keweenaw fault, as shown on seismic profiles (Cannon et al., 1989), to a position east of Marquette and movement causing the development of the shear fractures and their clockwise rotation as noted by Hamblin (1958). Subsidence of the Michigan basin.
Thrust Generated	South and southwestward movement of the glaciers utilizing bedding plane weaknesses as glide planes, possibly during the Marquette readvance.
Compeau Creek Gneiss and Mona Schist	Includes all sources of stress listed above. Deposition of Jacobsville in actively subsiding basin preceded by compressional tectonics causing uplift on reactivated normal faults. Thermal collapse, extension ceased, erosion and deposition of pre-Jacobsville sediments causing sediment loading. Crustal extension, normal faulting, rift valley stage, TSTZ acting as accommodation zone along axis of rift with change of dip and thickening of volcanics to west due to fault movements. Crustal sagging with intrusion of diabase dike swarms around periphery of future Lake Superior basin, intrusion of alkalic and carbonatitic magma types within the TSTZ, KF. Northwest directed compression on GF possibly producing strike-slip faulting and fracture generation, but whether rifting was active (plume generated) or passsive (in response to Grenville tectonism) is undetermined. Right-lateral strike-slip movement on GLTZ.

TABLE 6--continued

Rock Unit	Sources of Stress
Compeau Creek gneiss and Mona schist	Anorogenic plutons emplaced along GLTZ in Canada and Wisconsin, movement on TSTZ producing northeast trending shear zones.
	Penokean orogenesis producing reverse dip-slip block faulting with south side up in basement rocks near Marquette, multiphase folding of Proterozoic strata, and regional metamorphism.
	Motion on TSTZ producing thickening of sedimentary basins to west and dip-slip motion with downthrow to the south on the GLTZ producing thickening of sediments to south.
	Kenoran orogeny welded together greenstone and gneissic terranes.

ductile deformation features exhibited by the inclusions, and are not remnant features from the country rock. Moreover, fractures in the inclusions might record strain in the gneiss, which subsequently could have acted as residual strain as exhibited by other rock bodies (Tullis, 1977), and allowed the propagation of the metadiabase dikes along zones of preferential weakness. There is a correlation between the orientation of the fractures in the inclusions and the orientation of the metadiabase dikes (see Figure 12, p. 29, & Table 7).

An analysis of the spatial distributions and orientations of the quartz veins was not performed during this study. However, many quartz veins were observed with the fracture orientations listed below (Table 7). The fractures represent stress on the gneiss which might, or might not, have fractured it. The orientation of the fractures indicates several regimes of stress, and a few can be correlated with tectonic events. For instance, the E-W and N50°E sets

Table 7

Fracture Sets Within Rock Units of Known Age as Potential Evidence to Possibly Constrain Temporal Fracture Development

Rock Unit	Significance	Fracture Sets
Diabase Dikes	Records syn- and post-rift deformation.	N45-55°W, N45-55°E, E-W columnar joints.
Metadiabase Dikes	Accommodated strain during Penokean Orogeny.	N20°E, N70°W, N80-85°E, N50°E, N20°W, N47-50°W, N80°W, N70°E, E-W.
Quartz Veins	Records strains in gneiss at early age and throughout history.	N48°W, N32°E, N70°W, N20°W, N50°E, N-S, E-W.
Inclusions	Records strains in gneiss at early age (deuteric alteration of fracture walls).	N10°E, N85°W, N45°E.

might be associated with the intrusion of the metadiabase dikes. Furthermore, the N-S, N70°W, N32°E and N48°W sets might be associated with the fractures called cross, longitudinal and shear in this paper, which were generated during the Penokean orogeny.

Gair and Thaden (1968) noted that during the Penokean orogeny the intensity of deformation north of the Marquette synclinorium was much less than that to the south. Some of the strain associated with the Penokean orogeny might have been relieved by the fracturing of the metadiabase dikes. Although an analysis of the spatial distribution of fractures in differently oriented dikes was not undertaken during this study, I believe that dike orientations relative to the maximum stress direction would have an influence on the spacings and orientations of fractures developed (Donath, 1961). Furthermore, the effect of the dikes relieving local stresses by fracturing, could have caused the non-homogeneous distribution of fracture sets (Plate 1) found in the Compeau Creek gneiss. Moreover, the fracture sets found in the dikes (Table 7) correlate with the fractures called cross, longitudinal, and shear in this study. However, there are sets of fractures in the dikes which correlate with those in the gneiss, and which do not correlate with the strain field of the Penokean orogeny. It is not known whether these sets of fractures were produced by movement on any of the regional structural features, such as the GLTZ (N20°W to N50°W) and TSTZ (N70°E), or were produced during the period preceding the rifting event, such as collision along the GF (N20°W and N70°E). The orientations of fractures produced during the rifting event would depend upon the mechanism(s) which initiated the event (still being debated); however, E-W fractures would correlate with the extension that occurred to accommodate the diabase dikes.

The fracture sets present in the diabase dikes (other than the columnar joints), at E-W, N45°E and N45°W orientations, might have been produced during the crustal extension period following initiation of the rift, or produced during the period following cessation of rifting when compression on former normal faults around the periphery of the rift developed during the closing stages of subsidence. Furthermore, the sets could be associated with the uplift and erosion of the Paleozoic sediments, the flexing of the crust during the 20 glacial advances, or the isostatic uplift which the area is currently undergoing. Whatever the cause of the NE-SW, NW-SE fractures (they are not the continuation of previously formed fractures through the dikes), they are evidence of an event, or set of events, which produced an orthogonal set of fractures to form in the Compeau Creek gneiss, such as those found at the top of Hogback Mountain (Figure 24, p. 44).

Of all the fracture sets in the Jacobsville sandstone (Tables 3 & 4), the most informative in terms of tectonics are the shear fractures that Hamblin (1958) described. He noted that the fracture orientations rotate clockwise from Keweenaw Bay to Grand Island. As noted above (see Mesozoic and Paleozoic Stress, p. 14), recent seismic lines in Lake Superior have found that the Keweenaw fault continues in a curving manner parallel to the shoreline to a point northeast of Marquette and possibly farther to the southeast (Figure 8, p. 15). The curving of fracture trends which Hamblin (1958) describes is likely due to the change in trend of the Keweenaw fault, and that his description of the joints as shear fractures was correct. The time of formation of the shear fractures is possibly constrained by the faulting of the Jacobsville Sandstone and the Paleozoics at Big and Little Limestone Mountain: where the youngest faulted rocks are Ordovician in age. However, movement along the Keweenaw fault might have occurred earlier, and thus Ordovician is possibly the youngest age of formation of the shear fractures. It is not known what influence the subsidence of the Michigan basin (MB), or any other movements (GLTZ, TSTZ, KF), had on the development of the shear fractures.

For the bedding-parallel and bedding-perpendicular fractures in the Jacobsville sandstone, the temporal relationships of fracture formation are not well constrained. For instance, sediment loading will cause intra- and interstratal stresses due to differences in stratal thickness, grain size, cement, and cross-bed orientation. Bedding-perpendicular fractures could have formed at any time after consolidation of the strata, during deposition of the Paleozoics, during the uplift associated with their erosion, during the glacial flexing of the crust by the 20 glacial advances, during the isostatic uplift which occurred after each glacial retreat, or during the current stress field of the area. Similarly, the same processes operated to form the bedding-perpendicular fractures, except the unloading processes would have had more of an influence on the development of the bedding-perpendicular fractures.

Some bedding-perpendicular fractures were observed which, in passing from one bed to another, change their orientation (Figure 33, p. 55). The change in orientation is probably a function of the competency contrast between the two beds, the grain size, and the change in the orientation of cross-beds. Some bedding-perpendicular fractures were observed which terminated upon entering a coarser bed (Figure 32, p. 54).

The thrust generated fractures observed during this study were probably formed during the most recent advance of the glacier. Although it is possible that thrust faulting in the Jacobsville might have occurred during the Ordovician or later activity on the Keweenaw fault, the mechanically weak condition of several outcrops of the Jacobsville would not survive 20 glacial advances. For instance, the outcrops at the northern end of Big Bay Point (Figures

38 & 39, pp. 60 & 61) contain imbricated layers of weathered Jacobsville sandstone which would be destroyed during a glacial advance (small thrust faults were observed within the friable, disrupted material). Moreover, the unconsolidated pulverized Jacobsville material injected between rotated blocks of Jacobsville strata is very friable and appears not to be a lodgement till, which tends to be much more indurated. Furthermore, the natural shattering fracture sets observed along the shore at Buckroe would probably be destroyed by a second glacial advance. Therefore, I believe that the thrust generated fractures were likely produced during the last glacial advance. Some fractures might have formed from a previous advance, but the weakness of the features observed represent a recent advance.

Finally, because fractures can be produced in the current stress field, fractures observed in the rocks with orientations from NE-SW to E-W must be taken into account as potential candidates resulting from current stress. Discontinuous hairline fractures with these orientations were observed in many of the rock types. For instance, the quartz veins (Figure 24, p. 44) have fractures which might have been produced by this process. Furthermore, in the Jacobsville sandstone many fractures were observed in clay concretions and discontinuous strata (Figure 32, p. 54) which might be candidates for fractures produced in the current stress field. Also, many of the metadiabase and diabase dikes contain E-W fractures (Figure 23, p. 42), although these fractures could have resulted from residual strain associated with the development of the foliation in the host rocks.

POSSIBLE GROUNDWATER YIELDS FROM BEDROCK FRACTURES

Rock fractures constitute important storage areas for water in the bedrock of Marquette County and their utilization for groundwater reservoirs will become increasingly necessary in the future as surface water resources become polluted or inadequate to satisfy the needs of the local populace.

In all the rock types investigated, contemporary stress and residual stress may have had an influence on the development of fractures, but the influence of these stresses on the in-situ fluid transport properties is not really known. However, several workers have shown that an increase in normal stress on a fracture surface will cause a great decrease in the aperture up to a limiting value (Brown & Scholz, 1986). In a fractured bedrock aquifer under a contemporary stress in the horizontal plane, where there are fractures oriented parallel to and perpendicular to the current stress direction, there will likely be anisotropic behavior of that aquifer. This anisotropy is caused by the closing of the fractures which are perpendicular to the contemporary stress direction and the opening of fractures which are parallel to the contemporary stress direction. Although this is an untested concept, it will have an application not only in groundwater studies, but also in the petroleum industry, in the disposal of fluid wastes by injection methods, and in the disposal of nuclear waste in deep holes where thermal gradients may set up anisotropic groundwater movements (Runchal &

Maini, 1980).

Finally, the distribution of the fracture systems observed in the various rock types supports the conclusions reached by others (Twenter, 1981; Doonan & VanAlstine, 1982) that, in the Compeau Creek gneiss, linear sags and near faults will be the most promising areas for well locations, due to the limited connectivity of the fracture systems in unfaulted domains. In the Mona schist, the pillowed Lower member has a variable density of fractures at the surface, variable apertures, and no mineral fillings, leading to possible zones of high permeability. The Lighthouse Point member has a high density of fractures in it, but the fractures appear to be healed and apertures are mostly closed. In the Jacobsville sandstone the shear and thrust generated fractures are probable zones of high permeability.

CONCLUSIONS

The fractures observed in the rocks investigated depict large variations in the stress regimes which have existed in the Marquette area and are a result of the complex geologic history the area has undergone. Ascribing individual fractures to specific events in the rocks' history is a speculative process, but several conclusions can be made: (a) the fractures called cross, longitudinal and shear in this paper were probably produced during the Penokean orogeny; (b) the fractures in dikes, quartz veins and inclusions can possibly be used to temporally identify periods of stress and fractures produced by those stresses; (c) the shear fractures present in the Jacobsville sandstone were probably produced by Late Precambrian or later (including Ordovician) movement on the Keweenaw fault; (d) and the thrust generated fractures in the Jacobsville sandstone were possibly produced during the Marquette readvance.

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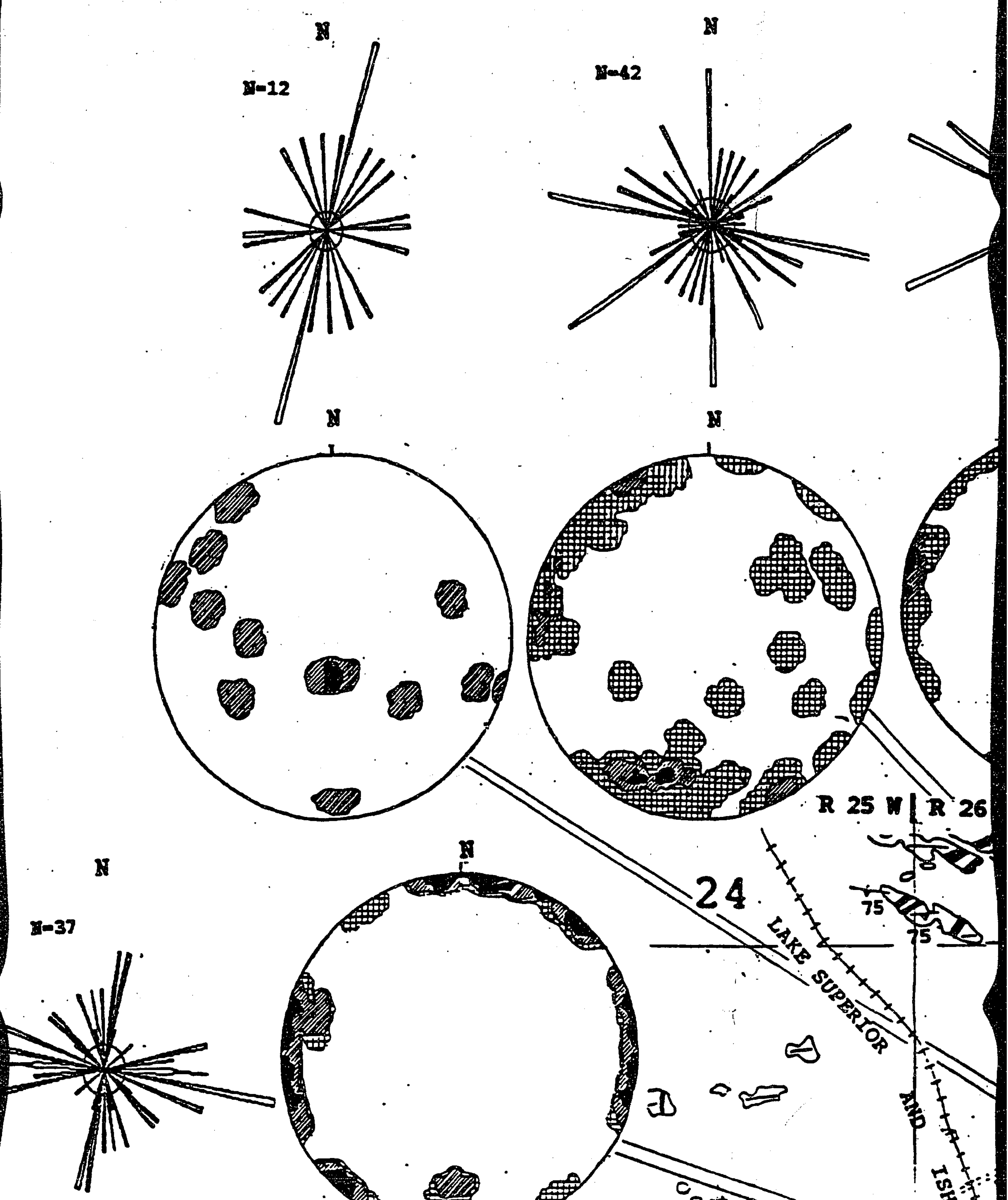
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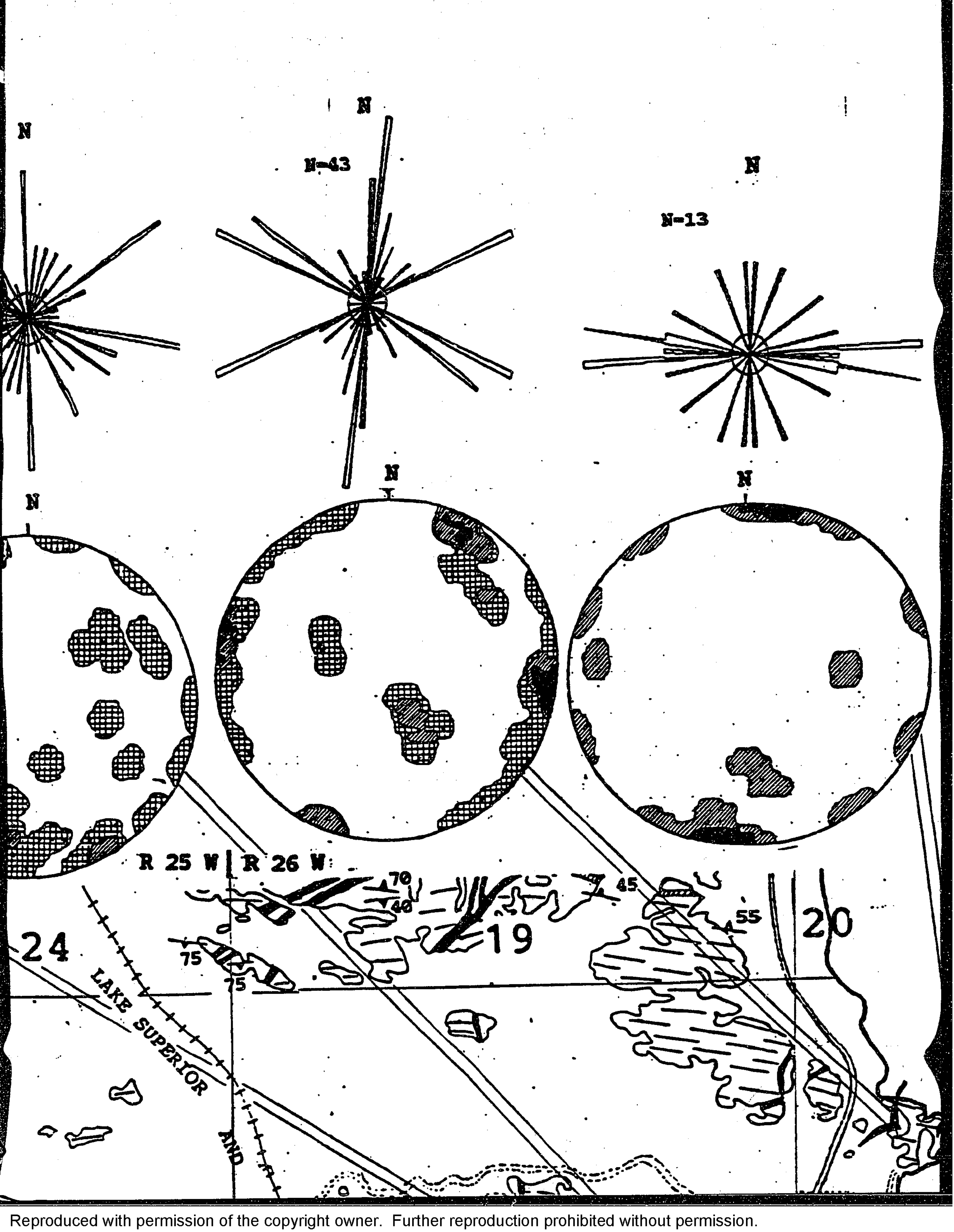

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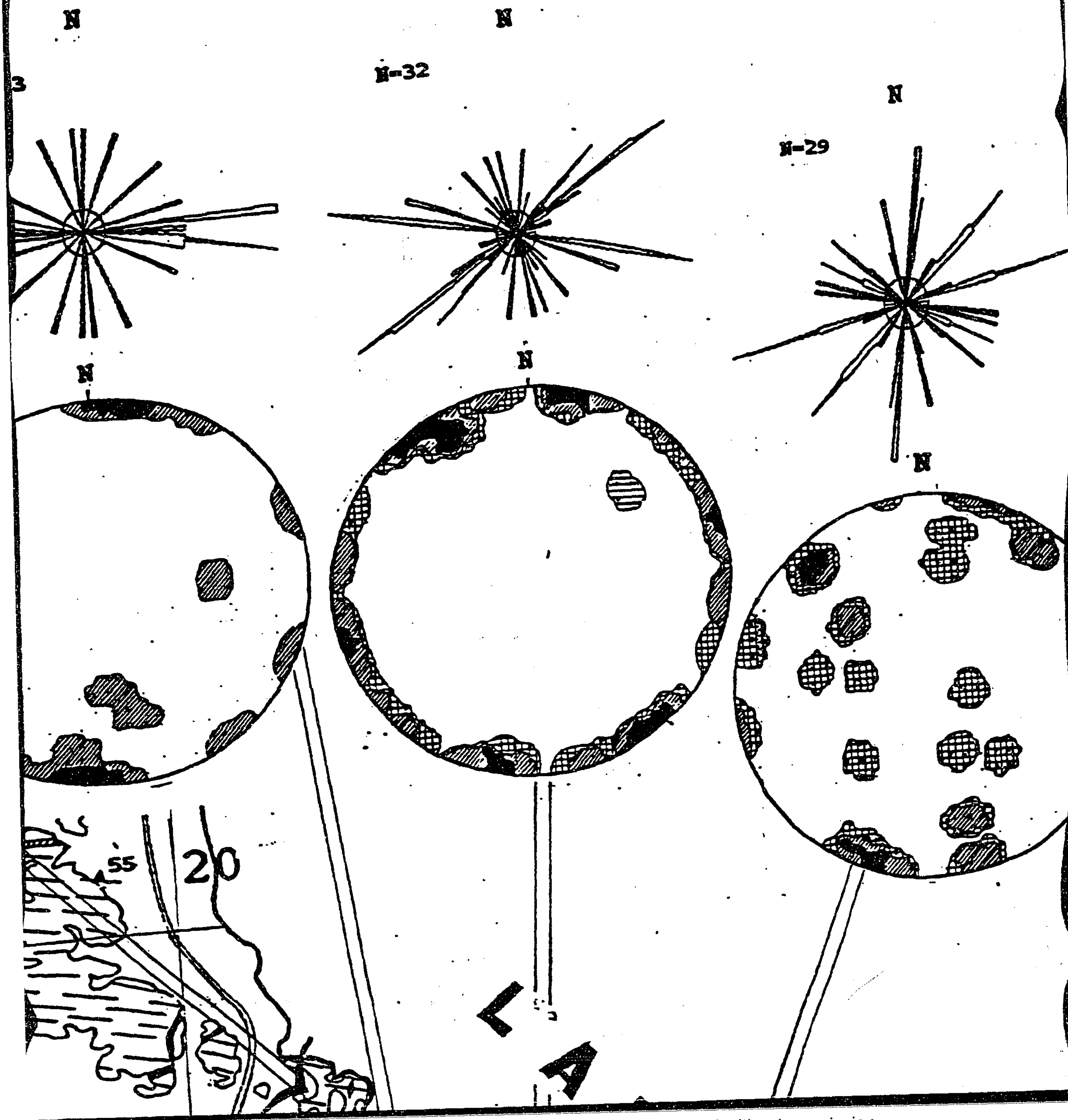
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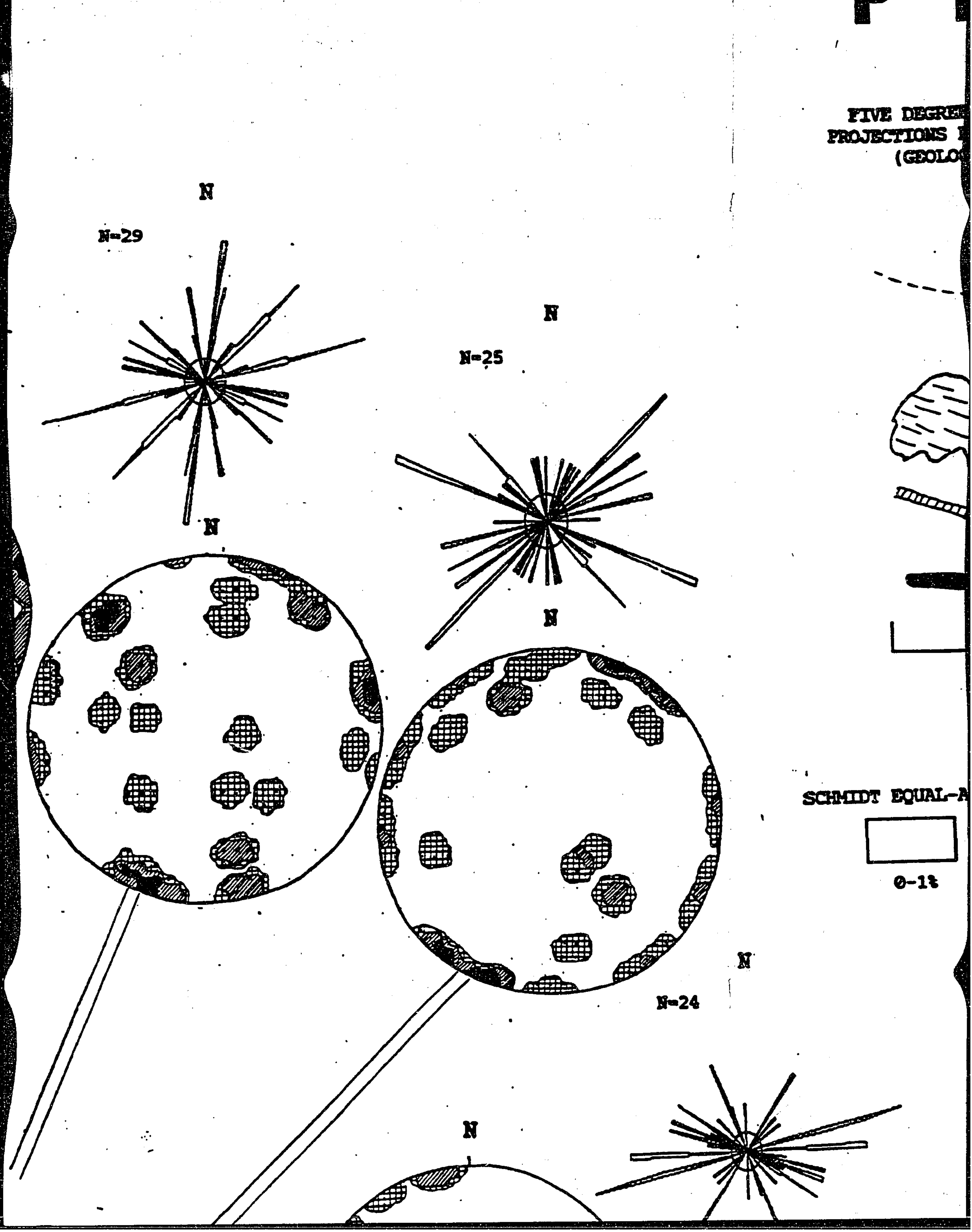
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PLATE 1

FIVE DEGREE MOVING AVERAGE ROSE DIAGRAMS AND SCHMIDT EQUAL-
PROJECTIONS FOR FRACTURE SETS MEASURED IN THE COMPEAU CREEK G
(GEOLOGY MODIFIED FROM GAIR & THADEN (1968), PLATE 1).

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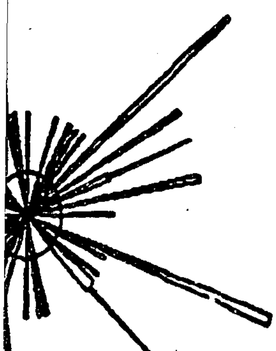

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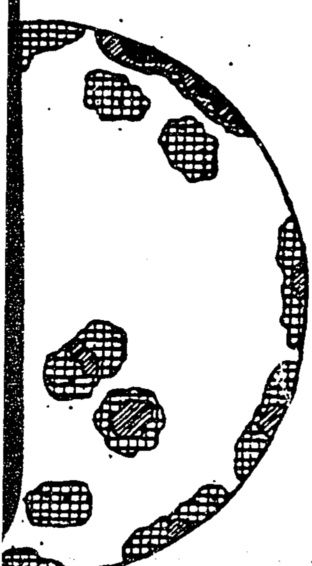

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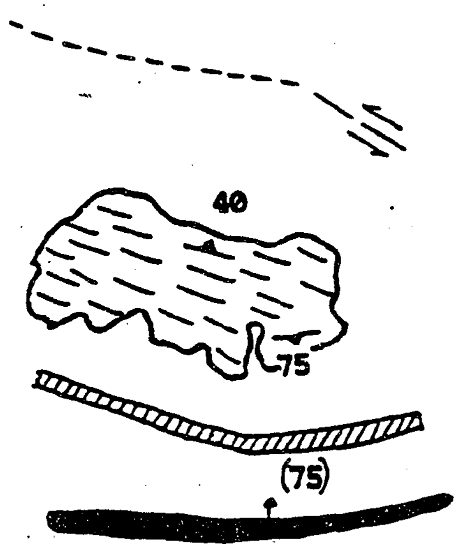
EXPLANATION



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OUTCROPS OF COMPEAU CREEK G
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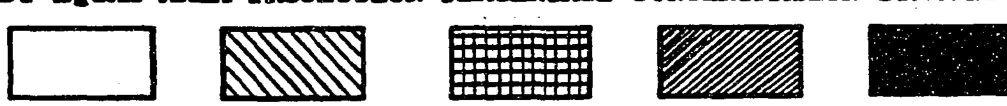

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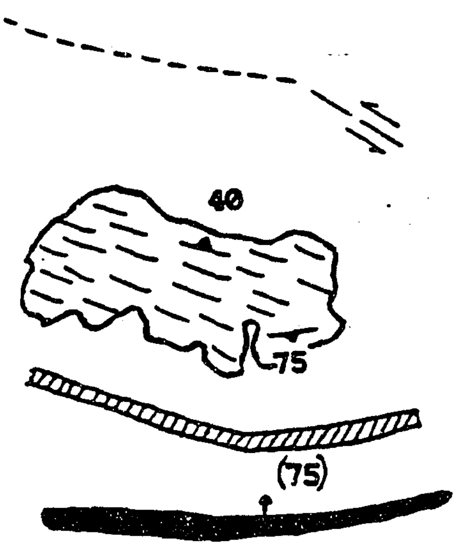
PLATE 1

FIVE DEGREE MOVING AVERAGE ROSE DIAGRAMS AND SCHMIDT EQUAL-AREA PROJECTIONS FOR FRACTURE SETS MEASURED IN THE COMPEAU CREEK GNEISS (GEOLOGY MODIFIED FROM GAIR & THADEN (1968), PLATE 1).

EXPLANATION



FAULTS. SHORT DASH = INFERRED, LONG DASH = EITHER OBSERVED OR KNOWN FROM OFFSET OF DIKES. INFERRED MOTION INDICATED BY ARROWS WHERE KNOWN.

OUTCROPS OF COMPEAU CREEK GNEISS SHOWING TRENDS OF FOLIATION. DIP SHOWN WHERE VALUES DEVIATE FROM VERTICAL TO 75 N OR TRENDS DEVIATE FROM N60-80 W.

DIABASE DIKES (MOSTLY VERTICAL).

METADIABASE DIKES. DIP SHOWN WHERE NON-VERTICAL.

1 MILE

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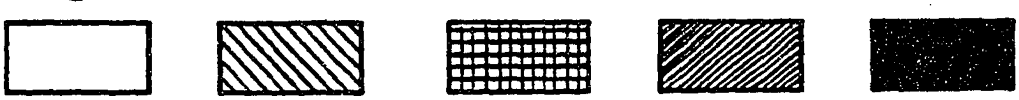
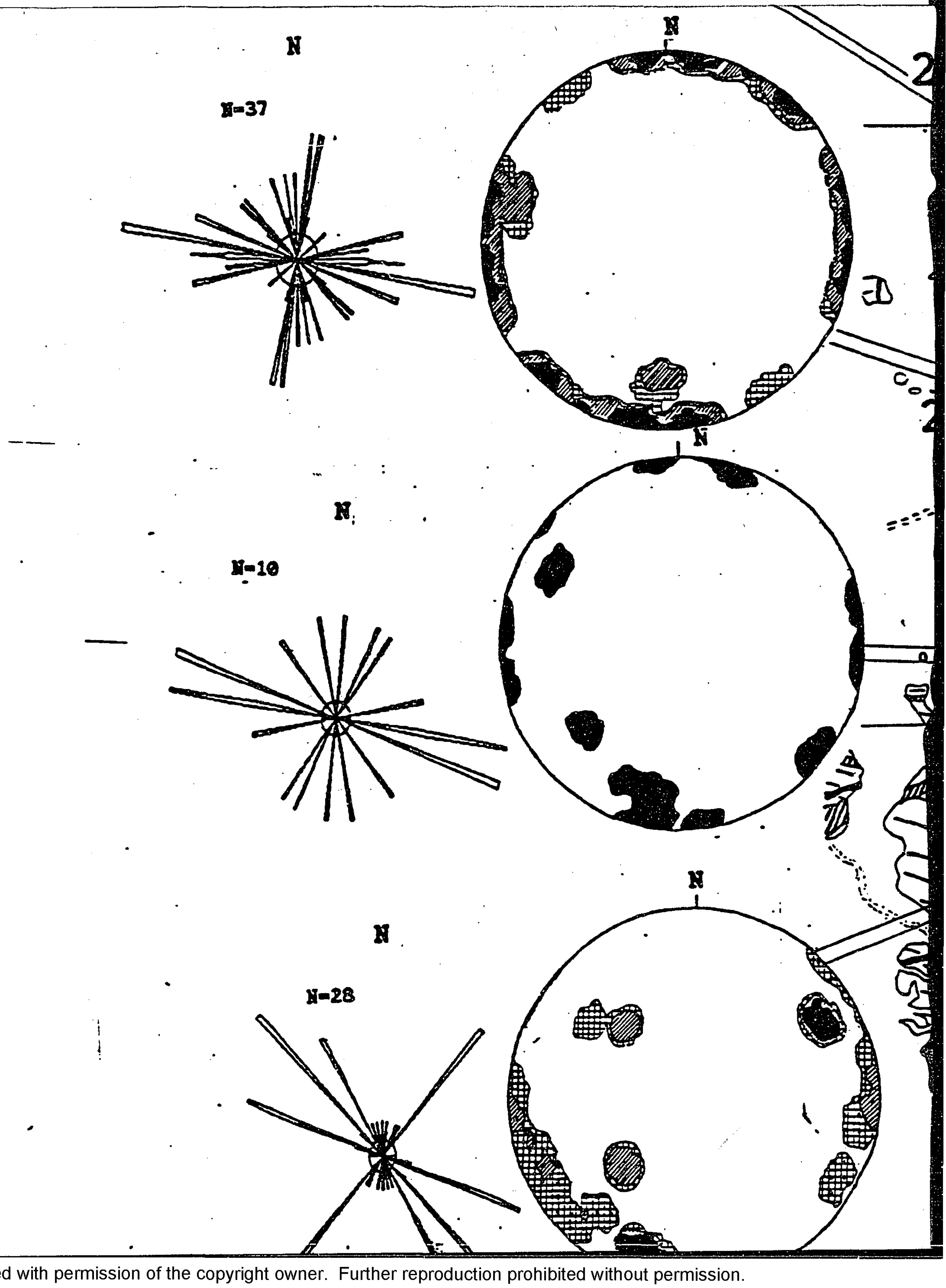
SCHMIDT EQUAL-AREA PROJECTION PERCENTAGE-CONCENTRATION SYMBOLS PER 1% AREA

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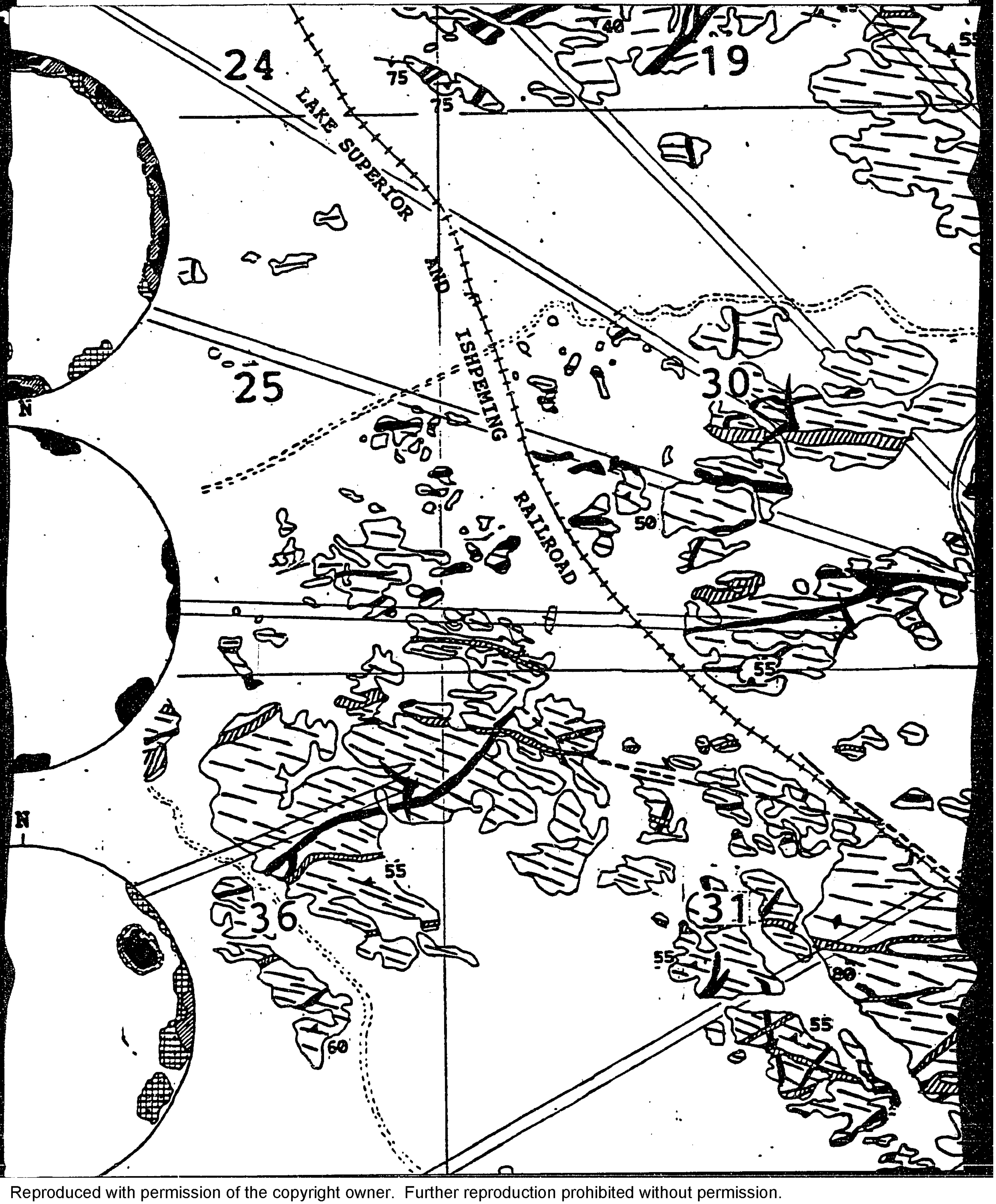
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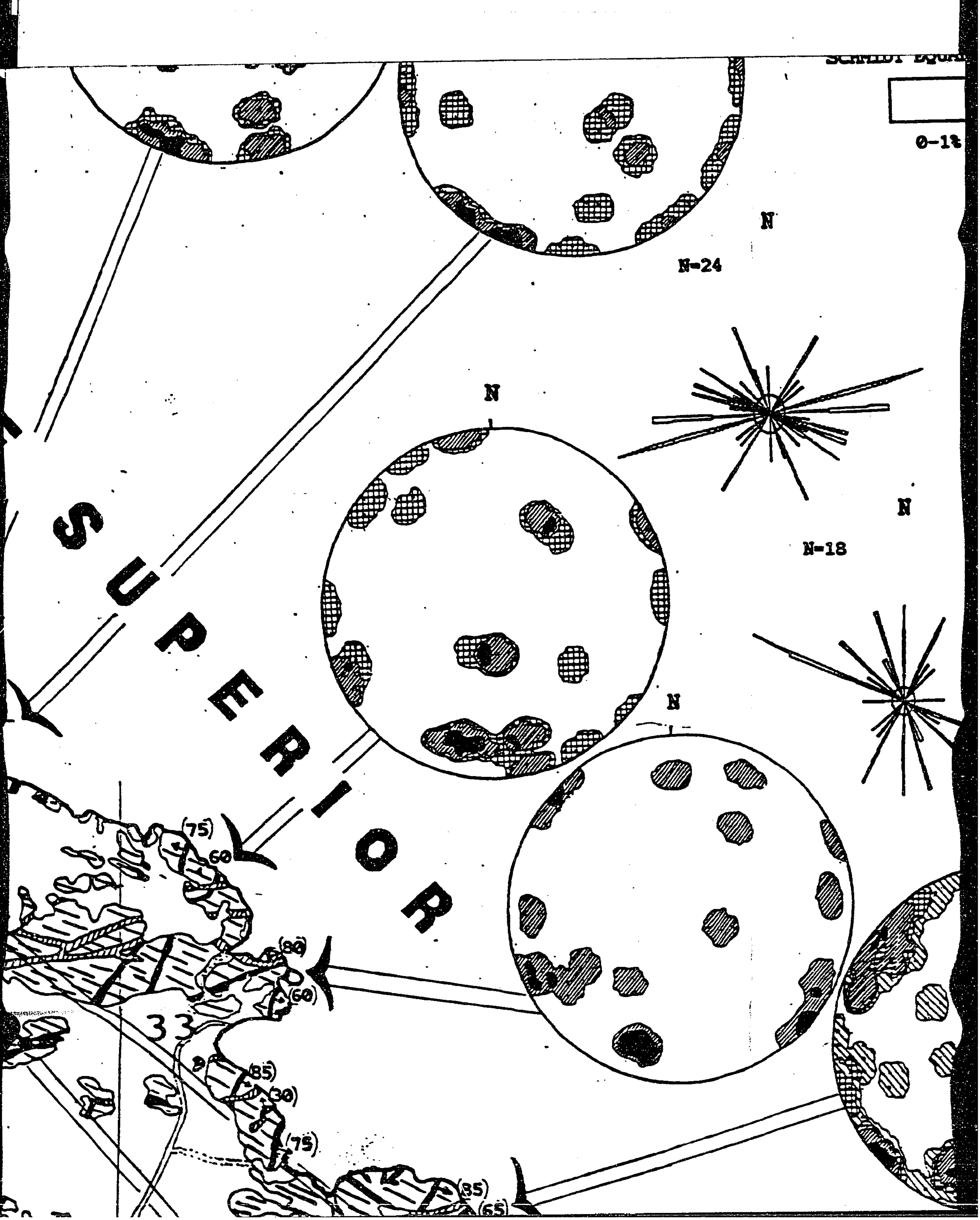

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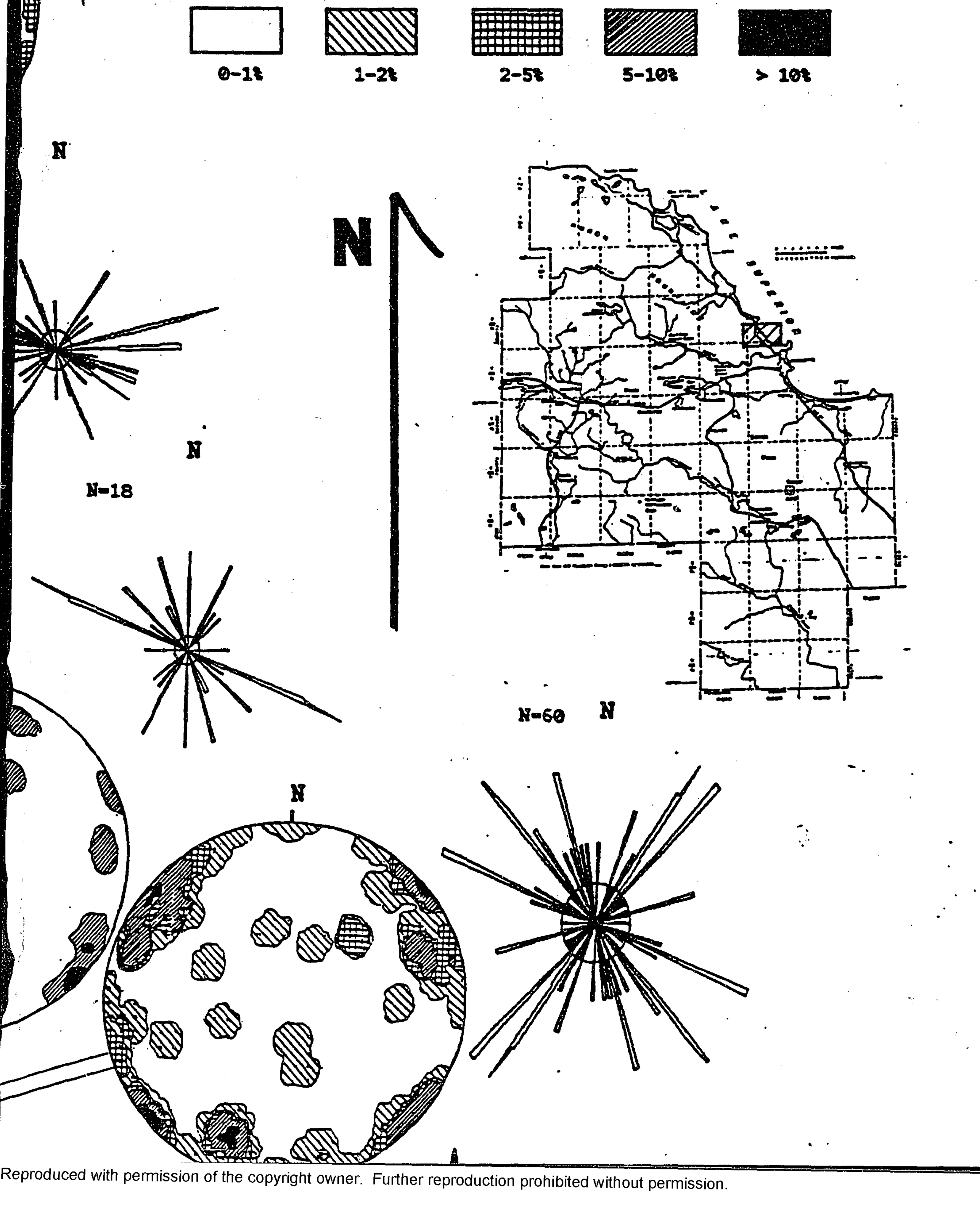

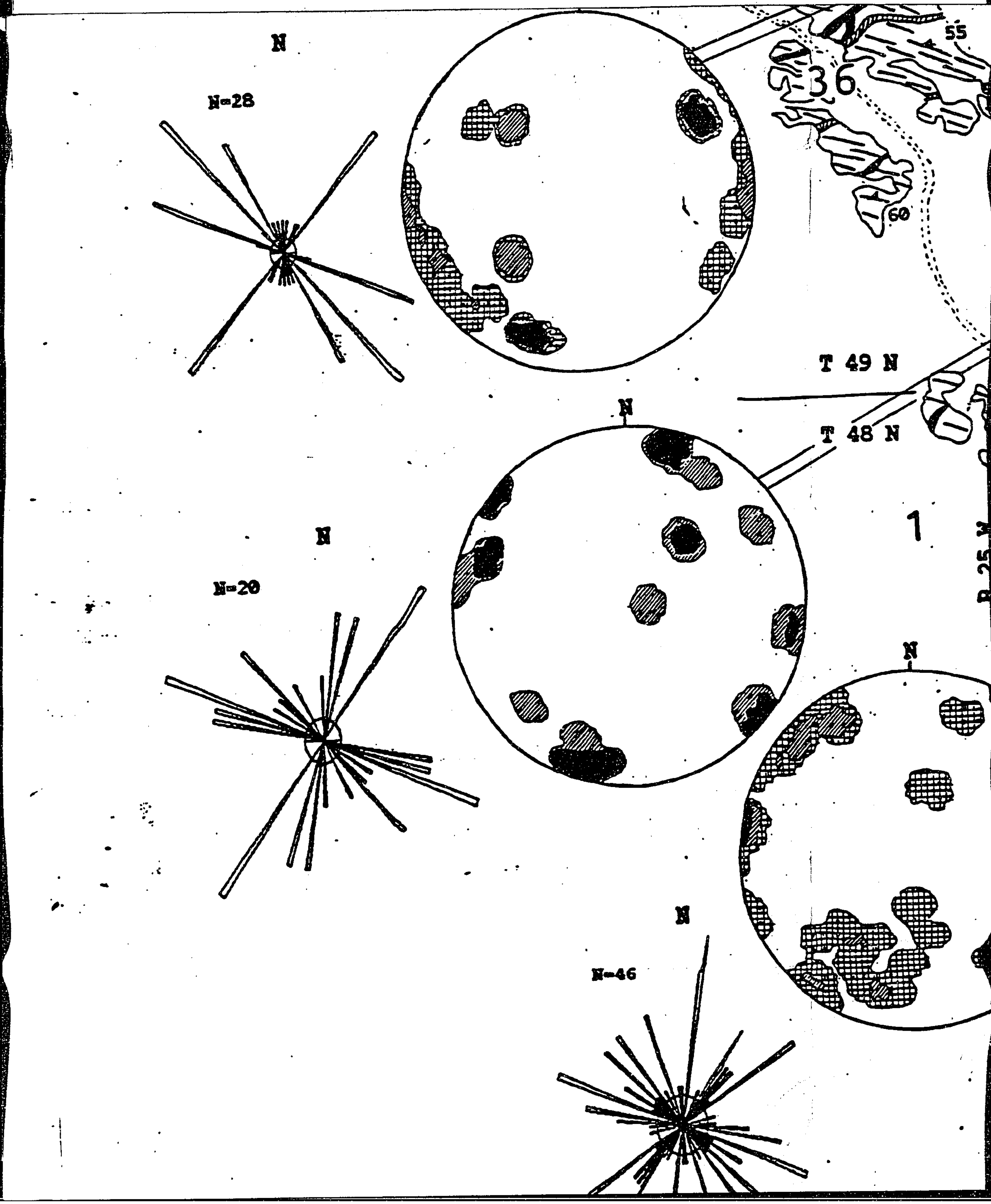
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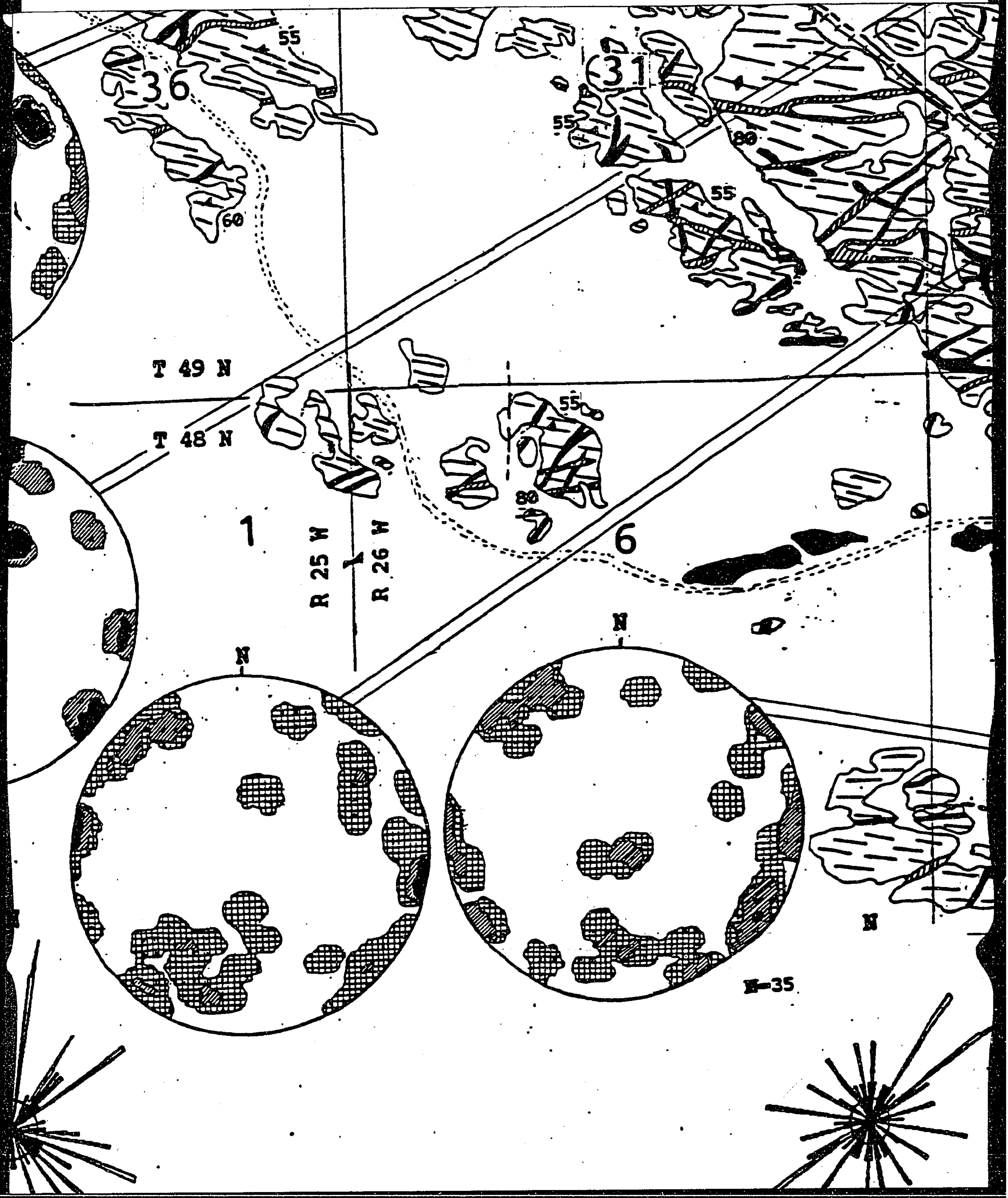
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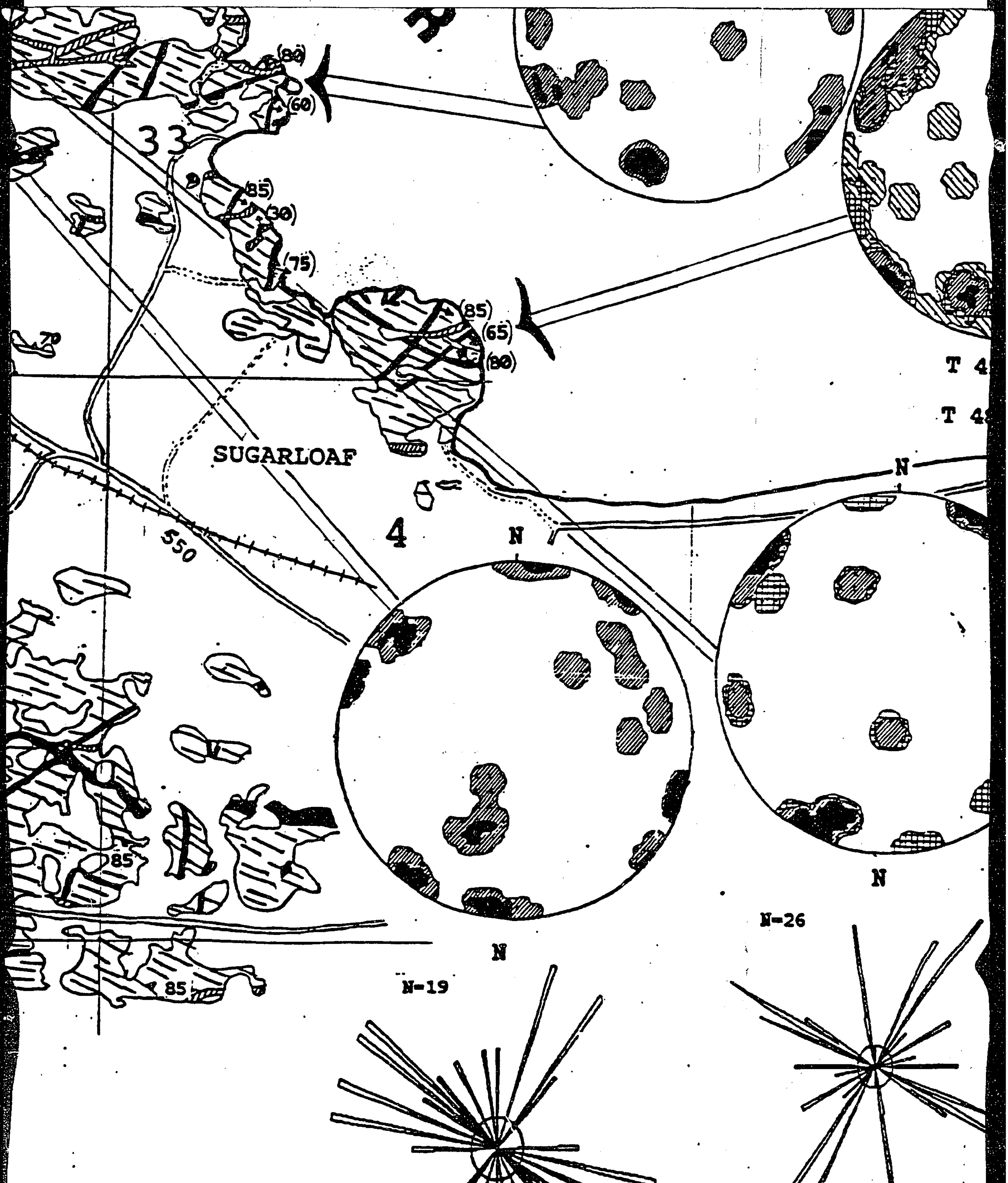
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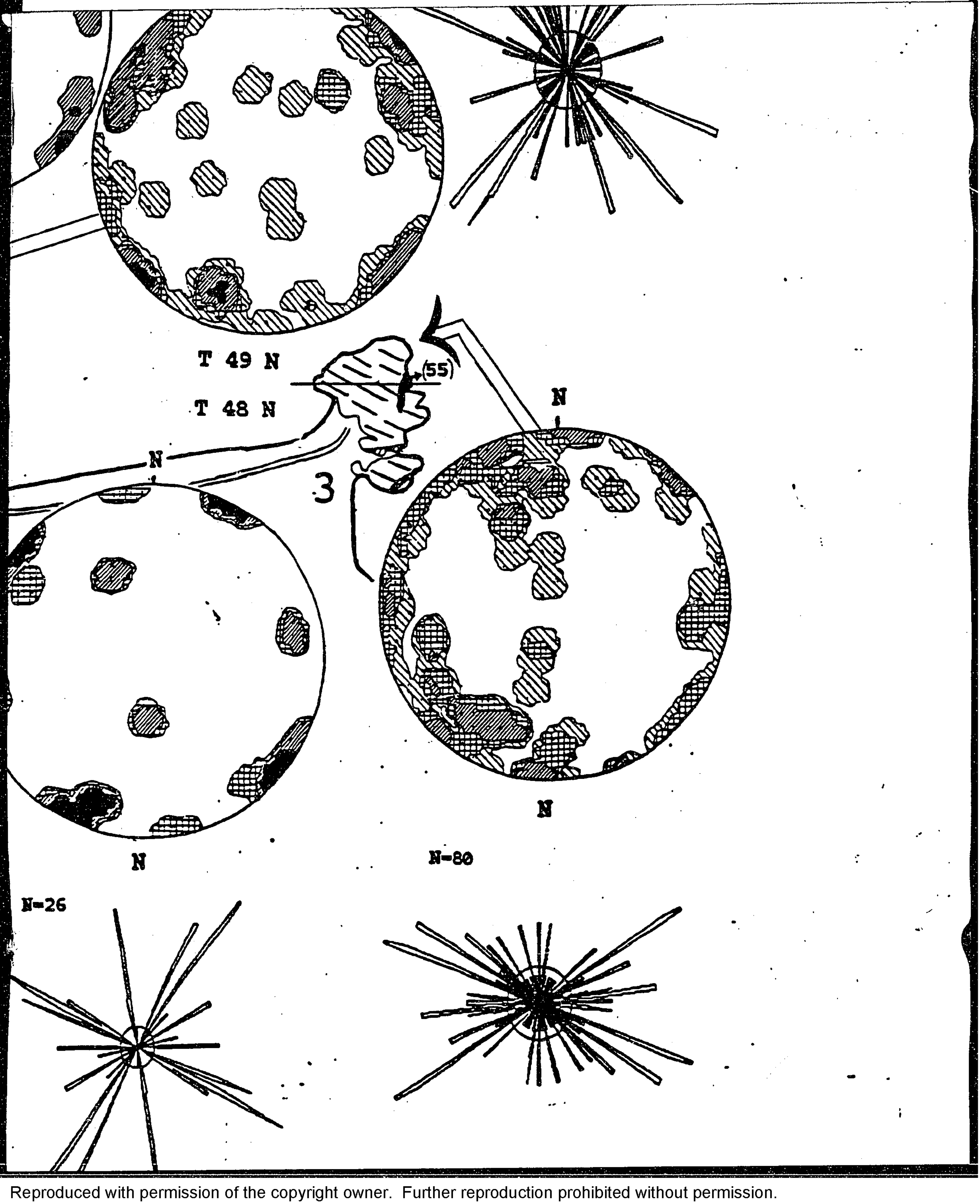

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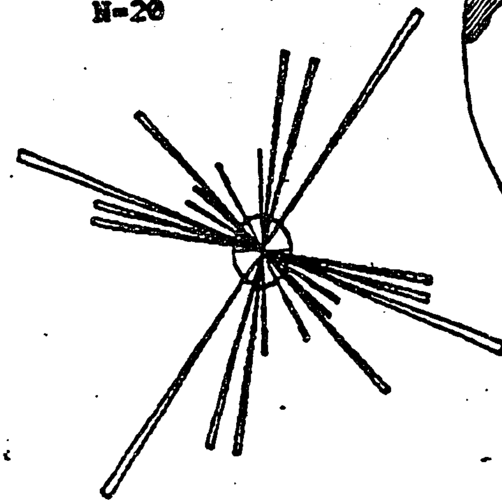
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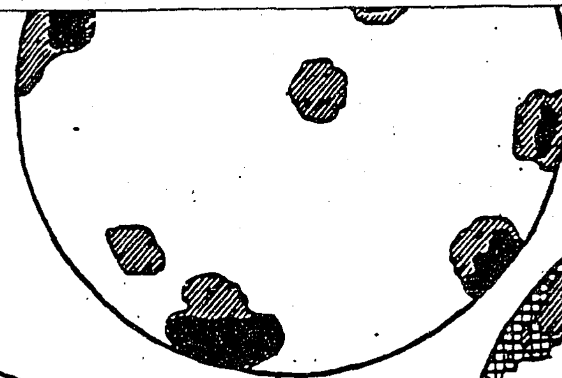

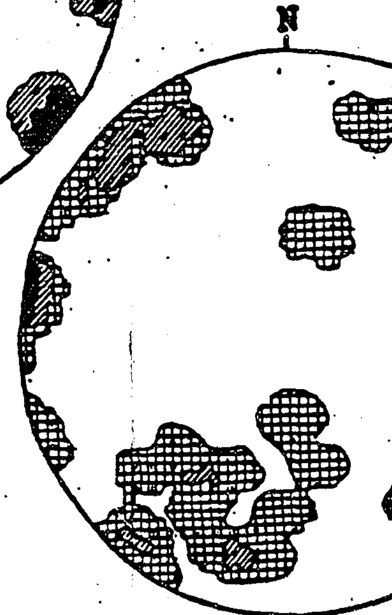
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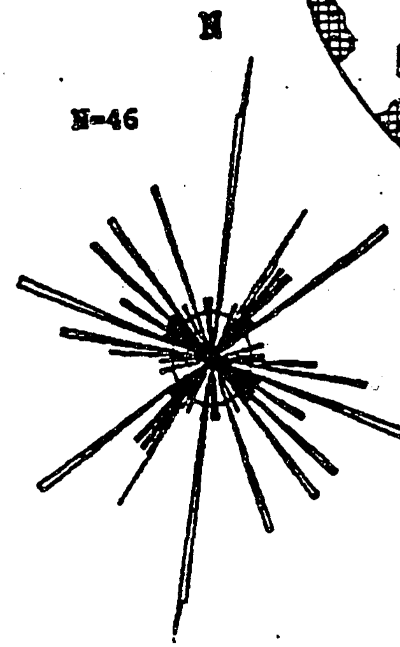
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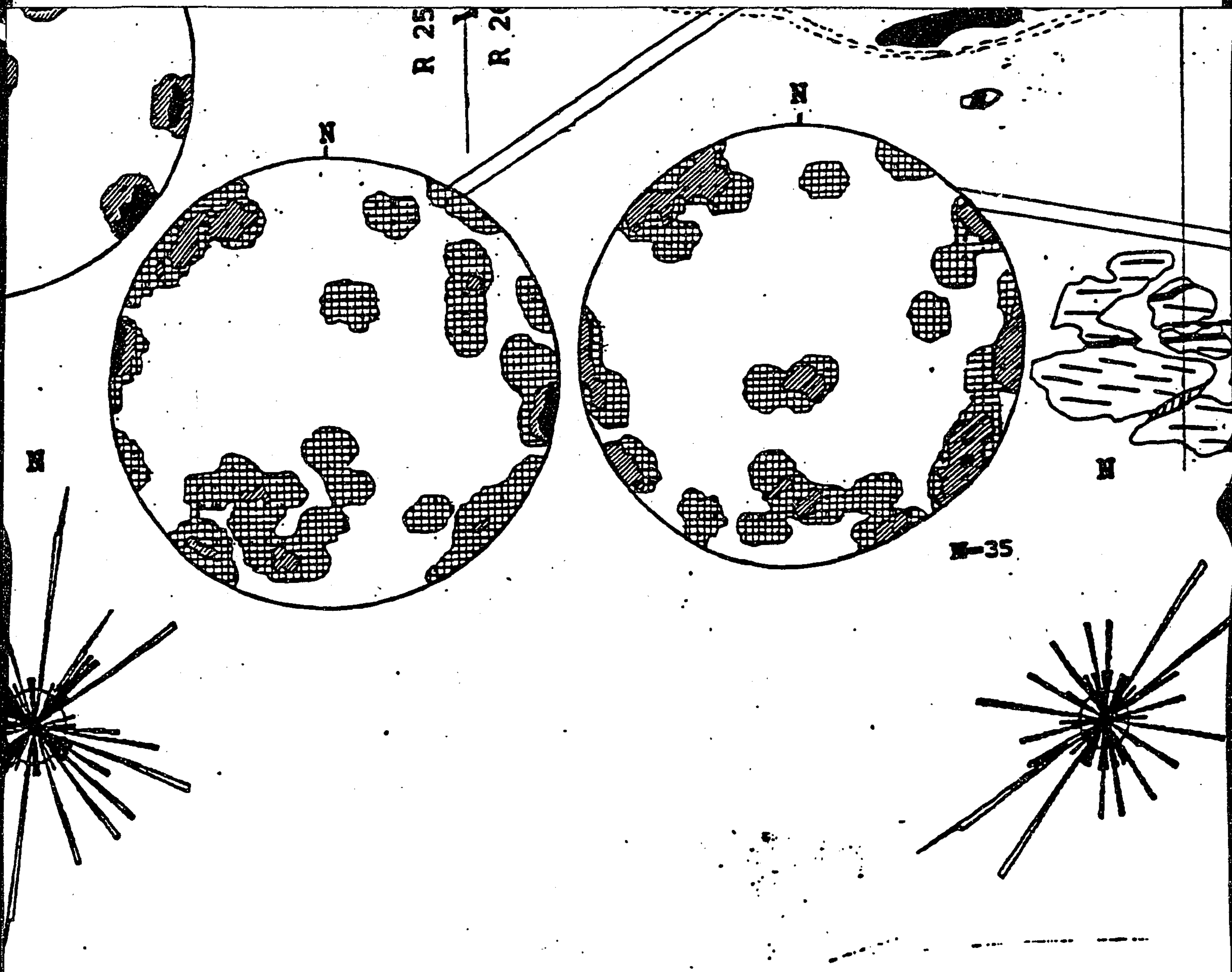
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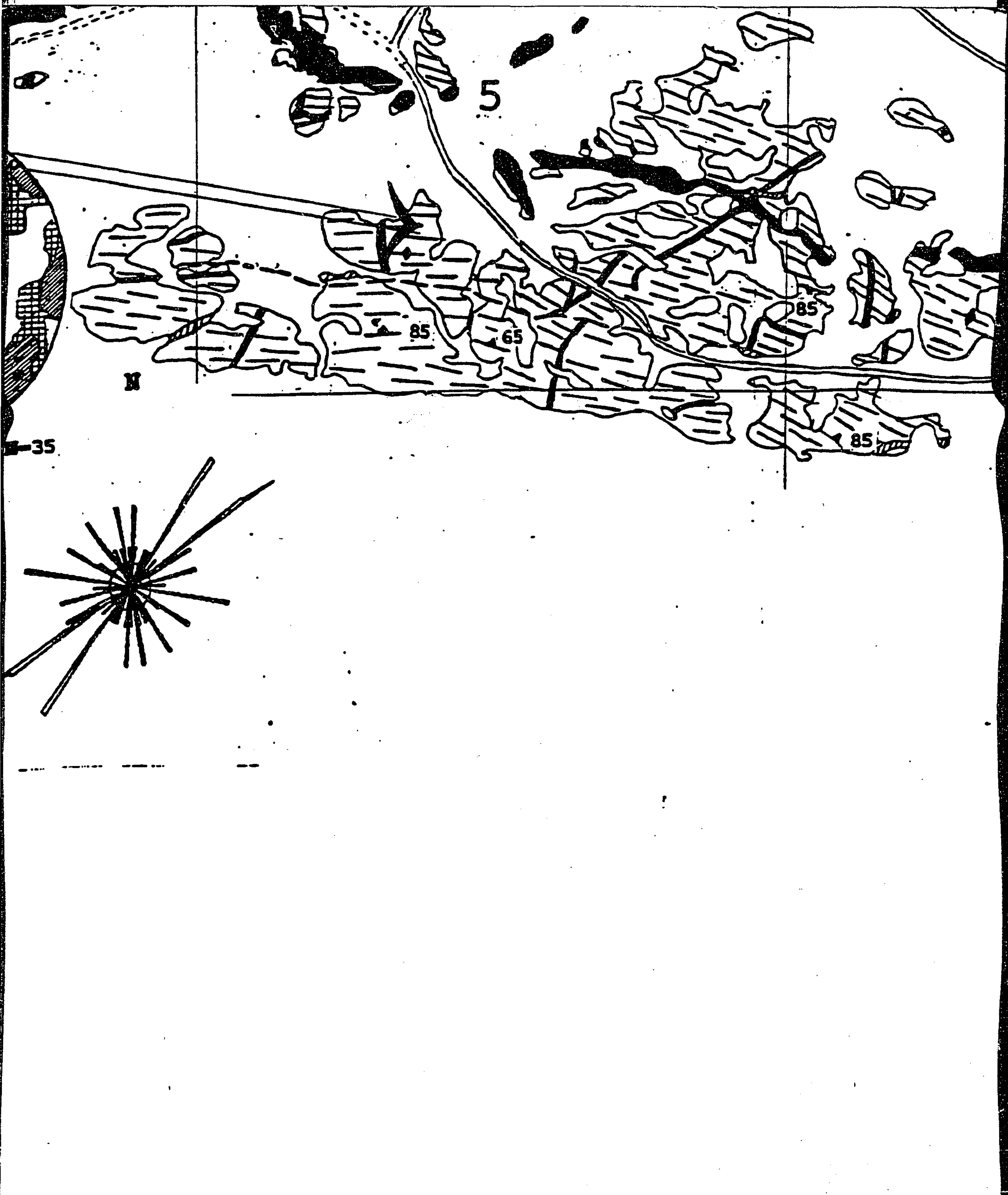
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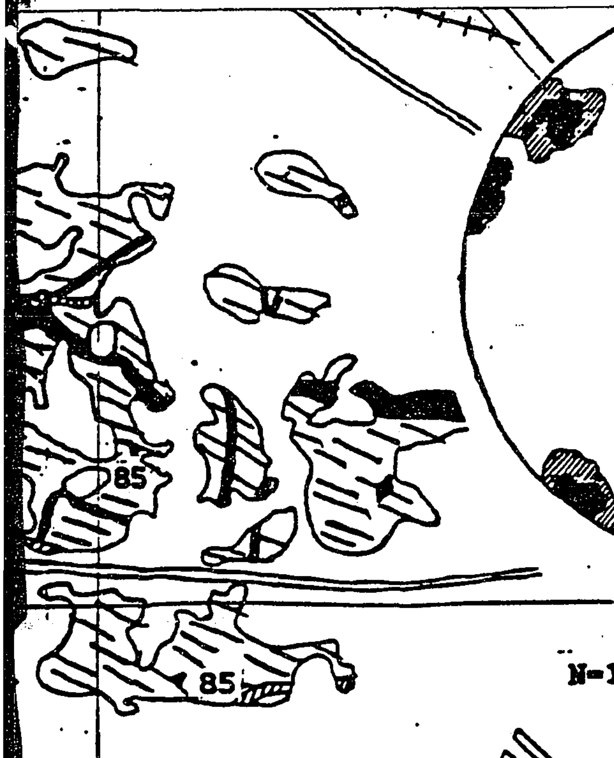

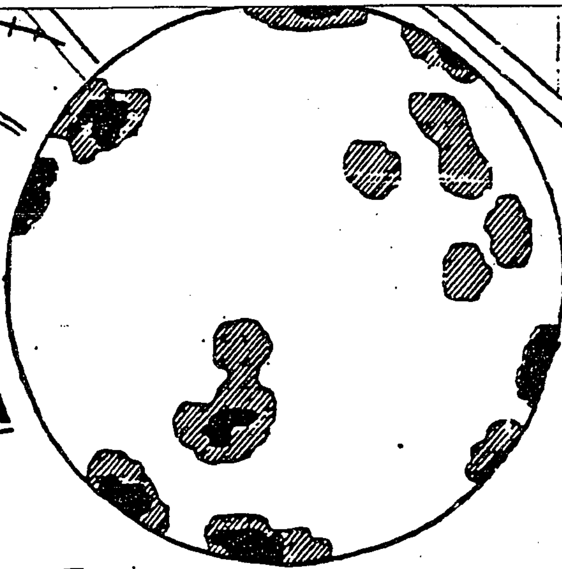

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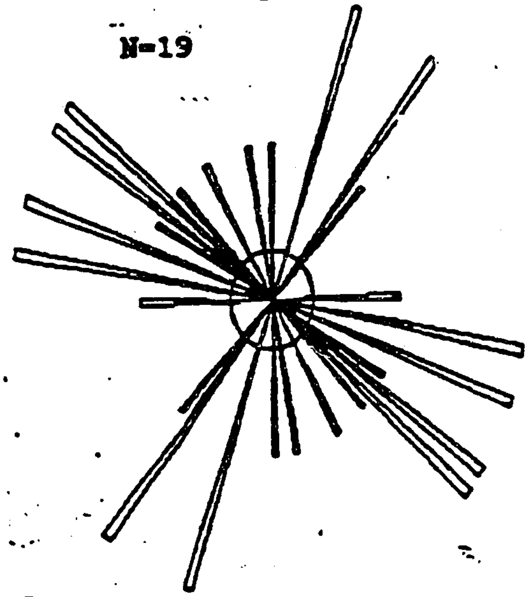

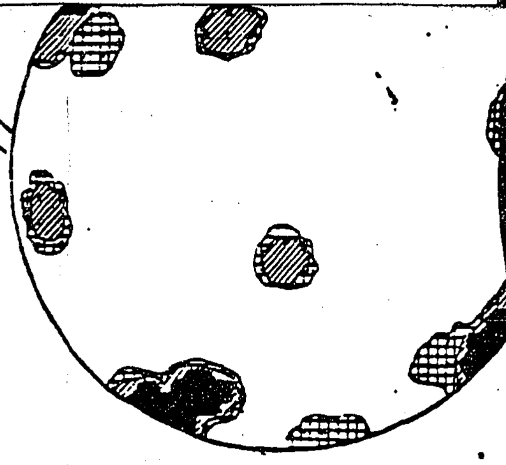

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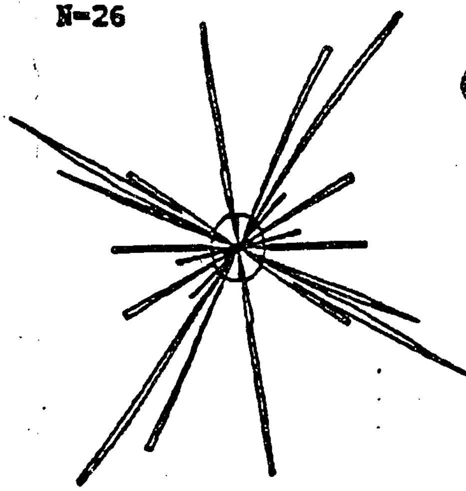

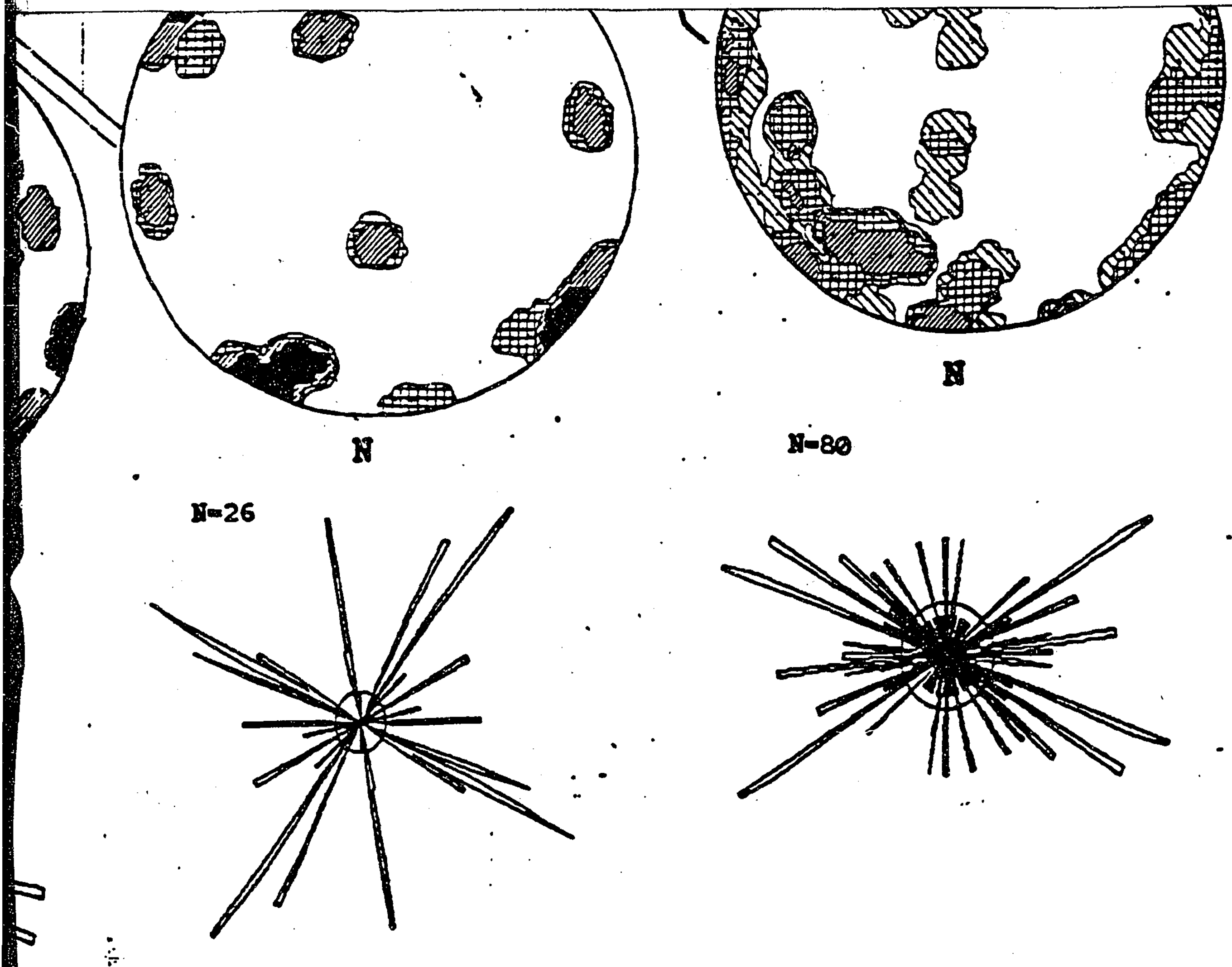
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