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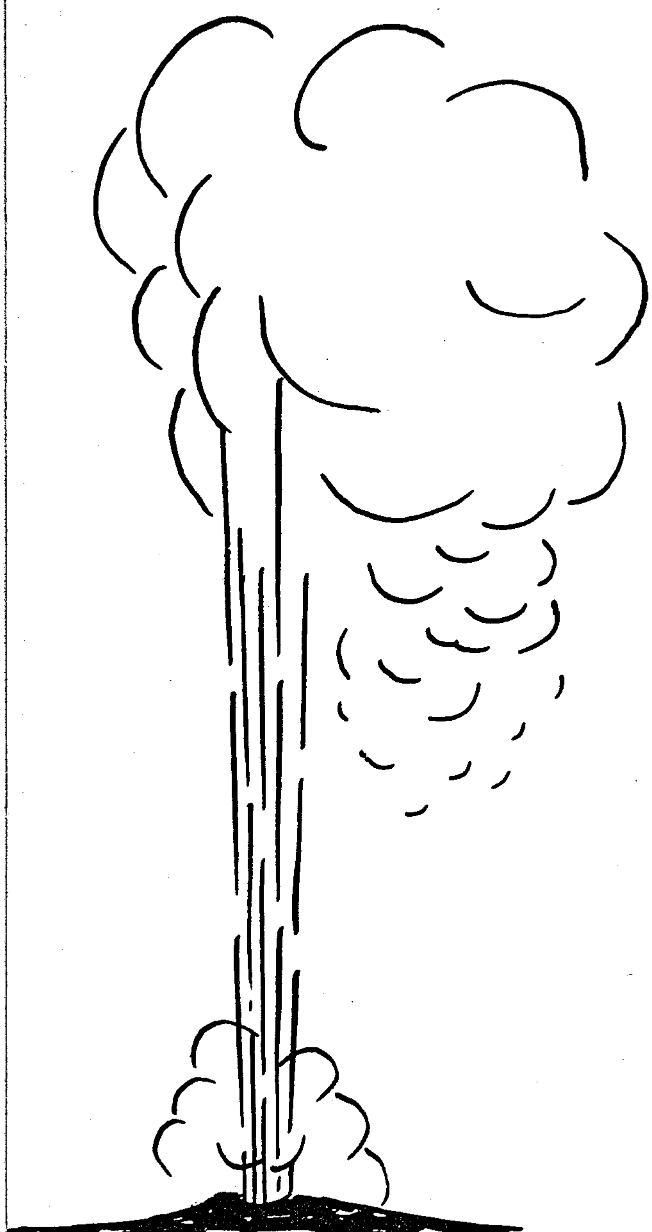

PRELIMINARY INVESTIGATION OF TWO AREAS IN NEW YORK STATE IN TERMS OF POSSIBLE POTENTIAL FOR HOT DRY ROCK GEOTHERMAL ENERGY

By
Yngvar W. Isachsen

September 27, 1978

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Yngvar W. Isachsen
Geological Survey - New York State
Museum, Albany, NY 12234

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ABSTRACT

Two areas in New York State were studied in terms of possible long range potential for geothermal energy: the Adirondack Mountains which are undergoing contemporary doming, and an anomalous circular feature centered on Panther Mountain in the Catskill Mountains.

The Adirondack Mountains constitute an anomalously large, domical uplift on the Appalachian foreland. The dome has a NNE-SSW axis about 190 km long, and an east-west dimension of about 140 km. It has a structural relief of at least 1600 m, and a local topographic relief of up to 1200 m. First order leveling in 1955, and again in 1973 along a north-south line at the eastern margin of the Adirondacks shows an uplift rate of 2.2 mm/yr at the latitude of the center of the dome and a subsidence rate of 2.8 mm/yr at the northern end of the line near the Canadian border. The net amount of arching along this releveled line is 9 cm $\pm$ 2 cm. In order to test the idea that this arching represented an "edge effect" of contemporary doming of the Adirondacks as a whole, I encouraged the National Geodetic Survey to relevel a 1931 north-south line between Utica and Fort Covington (near the Canadian border) which crosses the center of the dome. The releveling showed that the mountain mass is undergoing contemporary domical uplift at a rate which reaches 3.7 mm/yr near the center of the dome (compare with 1 mm/yr for the Swiss Alps). The rising area is one of recurring seismic activity. The domical configuration of the area undergoing uplift, combined with subsidence at the northeastern perimeter of the dome, argues for a geothermal rather than glacioisostatic origin.

A contemporary hot spot near the crust-mantle boundary is proposed as the mechanism of doming, based on analogy with uplifts of similar dimensions elsewhere in the world, some of which have associated Tertiary volcanics. The lack of thermal springs in the area, or high heat flow in drill holes up to 370 m deep, indicates that the front of the inferred thermal pulse must be at some depth greater than 1 km.

From isopach maps by Rickard (1969, 1973), it is clear that the present Adirondack dome did not come into existence until sometime after Late Devonian time. Strata younger than this are not present to provide further time stratigraphic refinement of this lower limit. However, the consequent radial drainage pattern in the Adirondacks suggests that the dome is a relatively young tectonic feature. Using arguments based on fixed hot spots in central Africa, and the movement of the North American plate, Kevin Burke (Appendix I) suggests that the uplift may be less than 4 m.y. old.

The other area of interest, the Panther Mountain circular feature in the Catskill Mountains, was studied using photogeology, gravity and magnetic profiling, gravity modeling, conventional field methods, and local shallow seismic refraction profiling. The presence of an 18 mgal negative gravity anomaly with steep gradients over the structure suggests that the feature is not a buried felsic plug (such as might produce a dry hot rock geothermal energy source beneath an insulating sedimentary cover), but rather a buried meteorite crater which was formed during deposition of the Upper Devonian continental clastics of the region. The gravity anomaly is consistent with an impact breccia lens about 8 km in diameter, which extends from a few hundred meters below the surface to about 4000 m depth. Such a breccia lens would cut several of the black shale sequences which serve as hydrocarbon source beds in the western part of the State. It is suggested that a brecciated lens of the above dimensions may provide a large reservoir for natural gas, analogous to the subsurface astroblemes inferred in the Williston Basin which are either producing fields or potential hydrocarbon reservoirs.

INTRODUCTION AND PURPOSE

The concept for these studies came about as a result of an invitation to participate in a "Near-Normal Geothermal Gradient Workshop" which was held in Washington March 10-11, 1975. The workshop was sponsored jointly by the Energy Research and Development Administration (ERDA) and the Los Alimos Scientific Laboratory of the University of California, in cooperation with the U.S. Geological Survey. Its purpose was to review current knowledge concerning geological environments which might be suitable for developing geothermal energy from dry hot rocks, with emphasis on the eastern United States. Proceedings of the workshop were published by the U.S. Energy Research and Development Administration (see References). A fair amount was known at that time about the potential for hot-dry-rock geothermal energy in the western United States (e.g. Brown, 1973), but relatively little information existed for the eastern part of the country.

The search for potential geothermal reservoirs in the eastern United States in predicated in part on the advancing technologies of deep basement drilling and heat extraction from dry hot rock (e.g. , the U.S. Department of Energy's contracted experiments being performed at the Los Alamos Scientific Laboratory). An important impetus to this search is the high population density along the east coast, and the numerous industrial centers which consume such vast amounts of "imported" energy. One goal of the national energy policy is that the northeastern United Stated, by the beginning of the next century, will be producing a greater percentage of the energy it consumes than at present.

With the exception of a relatively few warm springs, (Hobba and others, 1977) exploration for potential geothermal reservoirs in the "Eastern Heat Flow Province" of Potter (1975) requires the use of geological indicators far more subtle than the simple search for surface thermal anomalies or terranes of Quarternary volcanism like those occurring in many parts of the western United States. It might be fair to say that present geothermal exploration in the western states is analogous to the search for metallic mineral deposits half a century ago, when only areas with surface mineralization were explored. However, just as substantial hidden mineral deposits have subsequently been discovered through the use of indirect geological and geophysical methods, so hidden geothermal reservoirs probably exist which will require analogous imaginative and sophisticated approaches for discovery. This report discusses two areas in New York which were thought to fall into this latter category: the rising Adirondack Mountains Dome, and a circular feature in the Catskill Mountains which centers on Panther Mountain near Phoenicia. As will be explained later, the Panther Mountain structure is no longer considered a candidate for geothermal energy, but may constitute a natural gas reservoir.

Both the areas studied occur along the eastern edge of the Appalachian foreland. Based on extremely limited exploration to date, thermal reservoirs in foreland or platform areas are thought to have geothermal gradients limited to the world average of approximately 30^{o} C/km (McNitt, 1973, p. 34). There is a reasonable possibility, however, that the Adirondack Dome may be associated with an anomalous, potentially useful geothermal gradient. This will be discussed in the following section.

THE RISING ADIRONDACK DOME

Introduction

The Adirondack Mountains dome constitutes the southeasternmost extension of the Grenville Province, a billion year old metamorphic terrane which now forms cratonic basement. The Adirondack Dome is an elongate tectonic unit, with a north-northeast axis about 200 km in length and an east-west dimension of about 140 km (Fig. 1). Paleozoic rocks have been stripped from the upper part of the dome except where preserved in several north-northeast-trending graben in the southern, southeastern, and eastern Adirondacks (Fig. 1). The minimum amplitude of the dome, based on a "reconstruction" of the Proterozoic-Paleozoic unconformity using maximum present elevations, is 1600 m. Present elevations range from about 100 m to 1600 m above sea level. A striking feature of the dome is that it exhibits the highest elevations in the Canadian Shield south of the Torngat Mountains which are located nearly 1200 miles distant, at the northern tip of Labrador.

The boundaries of the dome are varied. To the northwest, the Precambrian core is connected to the rest of the Grenville Province of the Canadian Shield across a narrow arch called the Frontenac Axis, an uplift which is responsible for the "Thousand Islands" region of the St. Lawrence River. To the east, the dome is bounded by the down-faulted Champlain trough, beyond which lies the Middlebury synclinorium and the Green Mountain anticlinorium with its reactivated Precambrian core. The Adirondack Dome is much broken by block faulting along its eastern and southern flanks, and the Precambrian-Paleozoic contact is a fault along most of its length on the eastern border (Fisher and others, 1971).

At the "Near-Normal Geothermal Gradient Workshop", Isachsen (USERDA, 1975, pp. 113-147, 140-143) called attention to the surprising rate of contemporary vertical arching along the eastern border of the Adirondacks, as determined from first-order releveling of the National Geodetic Survey between Saratoga Springs (SS) and Rouses Point (RP) (Fig. 1). This showed an arching with a rate of uplift of 2.2 mm/yr at the center of the line, and a 2.8 mm/yr subsidence at the Canadian border, and led to the prediction that the arching was an "edge effect" of contemporary doming of the Adirondacks as a whole (Isachsen, 1975a). Possible geological implications of the predicted doming were enumerated by Isachsen (1975) as follows:

(1) The fact that the profile is one of arching rather than regional tilting, and that it shows subsidence at the northern end, indicates a tectonic rather than glacioisostatic origin.
(2) Lack of earthquake activity along the releveled line during the interval involved indicates that the arching was either aseismic or accompanied by undetected microearthquakes.

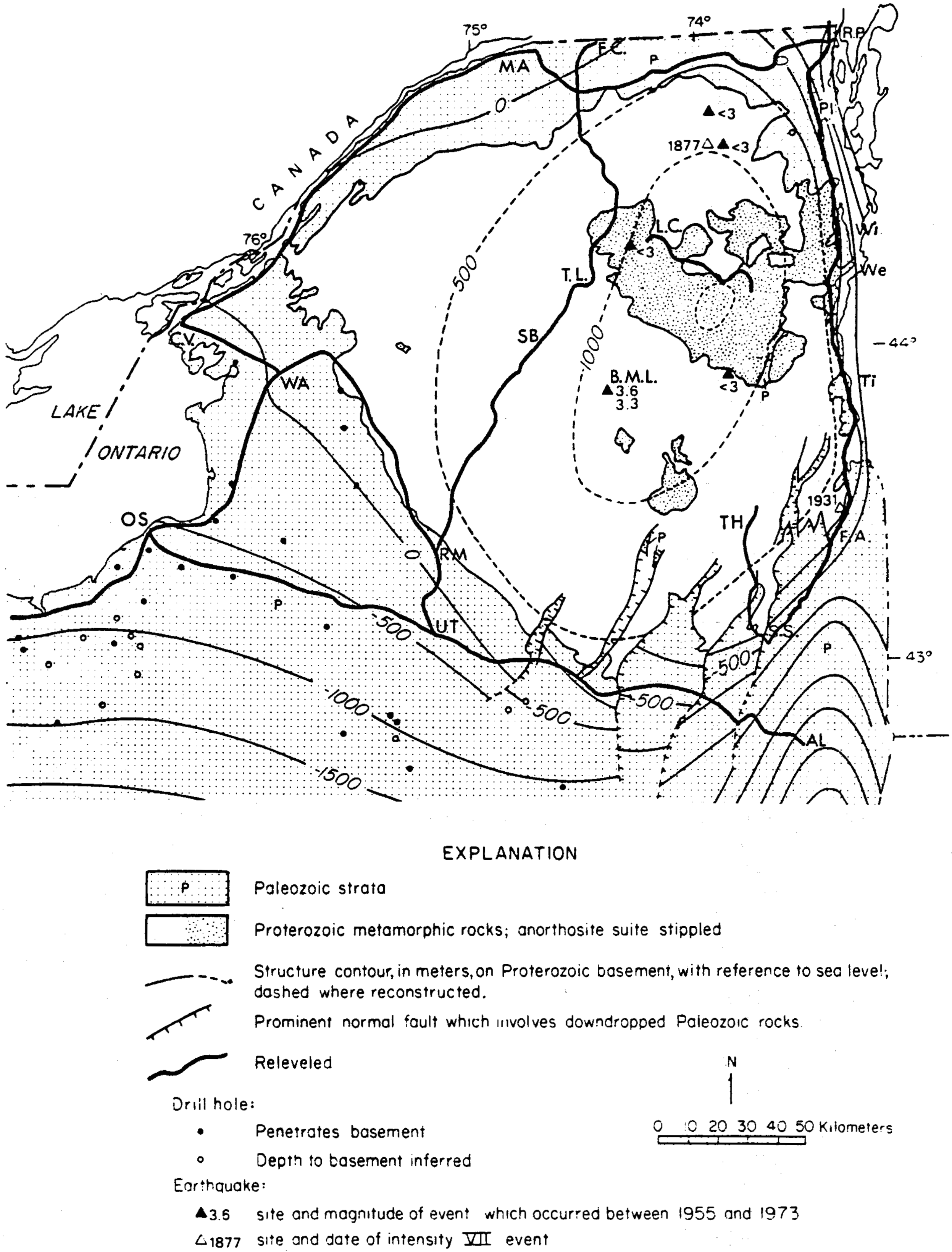

Figure 1. Map showing structural configuration of the Adirondack dome and locations of releveled lines in the area. Abbreviations refer to localities discussed in text. Earthquake data for 1955-1970 are from Government Sources, and for 1972-1973 from Lamont-Doherty Geological Observatory. Base map from Fisher and others, 1971.

(3) The arching would most readily be accounted for by either north-south compressive stress or vertical stress. This contrasts with the east-west compressive stress indicated by focal mechanisms for earthquakes which occurred in 1973 in the central Adirondacks at Blue Mountain Lake. (Sbar and others, 1972; Sbar and Sykes, 1973; Sykes and Sbar, 1973).

(4) If the arching along the eastern flank of the dome is indicative of contemporary preferential uplift of the Adirondacks as a whole, several important correlations become apparent, namely, the correspondence in strike (north-northeast) among 1) the axis of the Adirondack Dome, 2) Simmon's (1964) inferred mantle ridge, and 3) the prevalent fault-lineament set of the uplift. Also significant in this connection may be the recurrent earthquake activity, including swarms, at the geometric center of the dome (Blue Mountain Lake). Mogi (1967) has noted that swarm type earthquake activity chracterizes areas of high geothermal gradient and/or pervasive fracturing. Either or both of these conditions may apply in the Adirondacks, although surface thermal anomalies are not known in the area.

Method of Study

The present study of the rising Adirondack Dome as a possible future source of geothermal energy followed several lines of approach. The major one was to arrange with the National Geodetic Survey for the releveling of the first-order level line which runs south to north across the center of the dome from Utica (UT) to Fort Covington (FC) as shown on Figure 1. The purpose was to test the prediction that the contemporary arching along the eastern flank of the uplift was a manifestation of neotectonic doming of the Adirondacks as a whole. The releveling was done as a cooperative project, with $20,000 contributed from the present grant towards the total cost of $56,000.

A second goal of this study was to examine other releveling profiles for the Adirondack region to determine to what extent the contemporary uplift is confined to, and coincident with, the present dome.

To help explore the possible causes of doming, should it be verified by the trans-Adirondack releveling, profile, Kevin Burke was contracted as a consultant. Burke is a specialist in the geomorphological analysis of old hot spots (e.g., Burke and Dewey, 1973; Burke and Whiteman, 1973).

It was initially hoped that heat-flow measurements could be made in the lake-bottom muds of Blue Mountain Lake. This idea had to be abandoned, however, after repeated failure to borrow suitable probes for measuring thermal gradient and thermal conductivity of the muds.

Results

In using releveling data for geological purposes, a number of factors should be considered (e.g., Brown and others, 1976). Of particular importance from a geological standpoint is the question of stability of the monuments in which benchmarks are anchored. For example, from a statistical study of the various types of monuments used for mounting benchmarks, Karcs and others (1976) found that the reliability of movement measurements decreases with monument stability in the following order: rock-anchored, buildings, walls, bridges and culverts, concrete posts, bases, and platforms. It should therefore be emphasized that the contemporary movements interpreted from the releveling profiles in this study are based mainly on rock-anchored benchmarks.

Also of importance is the precision of measurements in geodetic leveling. Holdahl has made estimates of standard deviation from discrepancies between forward and backward levelings (Table 1).

Table 1 Estimates of standard deviation (α), from discrepancies between forward and backward levelings (S. Holdahl, oral communication).

Time Period	First Order, mm	Second Order, mm
Prior to 1900	2.5	5.0
1900-1916	2.0	4.0
1917-1955	1.5	3.0
1956 to present	1.0	2.0

A simple explanation of how to estimate the precision of geodetic leveling has been given by Holdahl (1976). An adequate formula for describing the precision, in millimeters, is $\alpha = D1/2$, where D is a number equal to the distance in kilometers between points along the leveled line and α is the standard deviation of leveling for 1 km (see Table 1). To compute a relative change in elevation between two points requires two levelings. The standard deviation of the computed vertical movement is then equal to the sum of the squares of the standard deviations from the two levelings.

Independent of the standard deviation is systematic error which accumulates at a constant rate that rarely exceeds 0.1 mm/km for short distances, and tends to become random for distance greater than 50 km (Holdahl, 1976). Since all useful releveled lines in the Adirondacks exceed this distance, these errors are considered random.

The locations of releveled lines in the Adirondack area are shown in Figure 1, and will be discussed below. The first-order releveling profile between Saratoga Springs and Rouses Point has been discussed in detail by Isachsen (1975). It is reproduced here (Fig. 2) for comparison with other releveling profiles in the area, which are discussed below.

The new movement profile between Utica and Fort Covington is shown in Figure 3. It is a first order line 280 km in length. The benchmark elevations for the earlier levelings (1931 and 1942) are represented by a horizontal base line. The changes in elevation between these dates and 1975, arbitrarily assuming no net vertical movement at the southern end of the line, are shown by the 1975 profile. Benchmarks which are anchored in bedrock are separately identified, in order to distinguish them from those mounted in less stable monuments.

The 1975 profile subscribes an arc which corresponds with the general topographic and tectonic cross-section of the dome (c.f. Figs. 1 and 3). The maximum uplift is 160 mm and occurs near the center of the dome at Sabattis. The uncertainty for this line is 30 mm. The 160 mm movement averaged over the 44 year interval represented amounts to an uplift rate of 3.7 mm/yr. This is a high value when compared, for example, with the 1 mm/yr rate of uplift for the central Alps of Switzerland over the past half century (Schaer and Jeanrichard, 1974).

The first order level line between Cape Vincent (CV) and Massena Point (MA) is 180 km long, and runs along the northwestern border of the dome (Fig. 1). It was leveled in 1941 and 1969 (Fig. 4). Of 49 stations along the line, 16 are in bedrock. Changes in elevation of benchmarks in bedrock range from -4 to 15, with all except 2 falling in the range -4 to 10. These changes are within the uncertainty (24 mm) of the measurements for this length line indicating that no measurable vertical movement occurred along it during the 28 year interval involved.

The first order level line from Cornwall (near Massena (MA)) to Rouses Point (RP) is 140 km long, and lies along the northern border of the dome. It was leveled in 1919 and 1973 (Fig. 5). None of the 18, twice-leveled benchmarks are anchored in bedrock. Changes in measured elevation range from -22 mm to 45 mm, with an uncertainty of 21 mm. If the line is generalized, it becomes arc-like, suggesting uplift along the central portion which reaches a maximum of 45 mm, between Chateaugay and Mooers. Averaging this uplift over a 54 year period, and noting the uncertainty, the uplift rate is of 0.5 - 1 mm/yr. The area of maximum uplift, corroborated by 5 adjacent benchmarks, coincides with the axis of the uplift (c.f. Figs. 1 and 5).

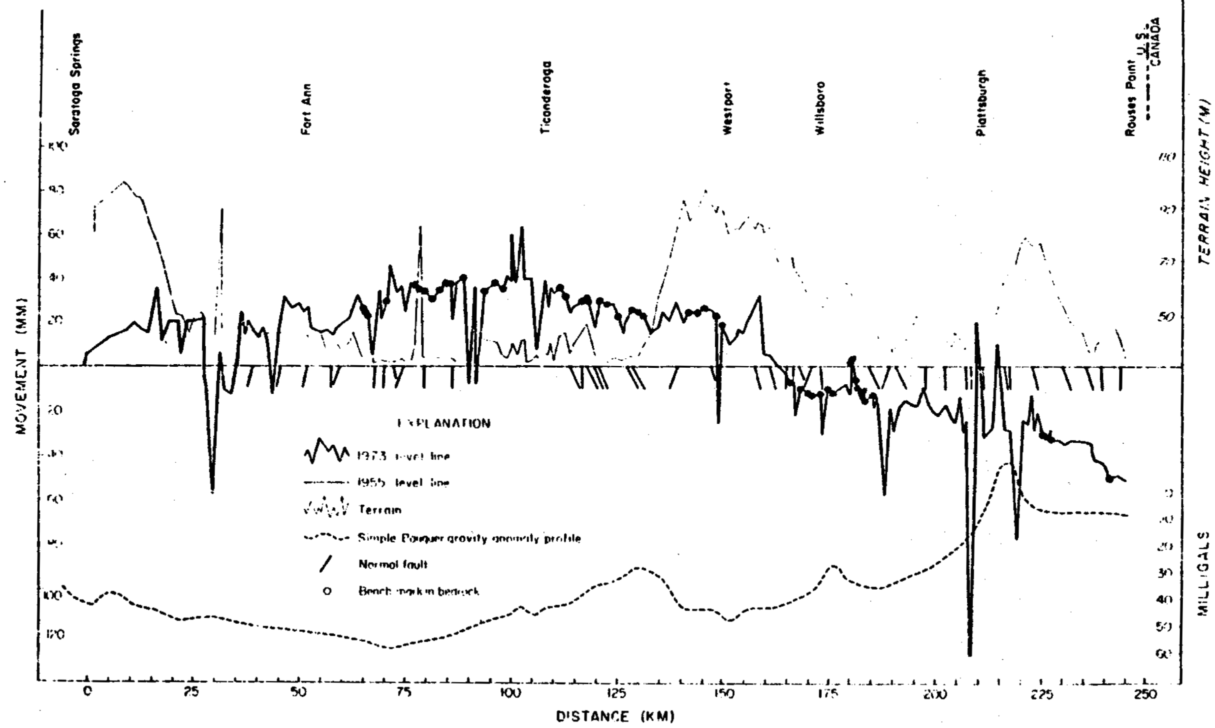

Figure 2. First-order geodetic leveling profile showing magnitude of arching along eastern flank of the Adirondack dome during the period 1955-1973. Leveling data from Vertical Network Branch of the National Geodetic Survey (NGS); gravity profile from Simmons and Diment (1972) and Diment et al. (1972a); fault data from Fisher et al. (1971). Reproduced from Isachsen (1975).

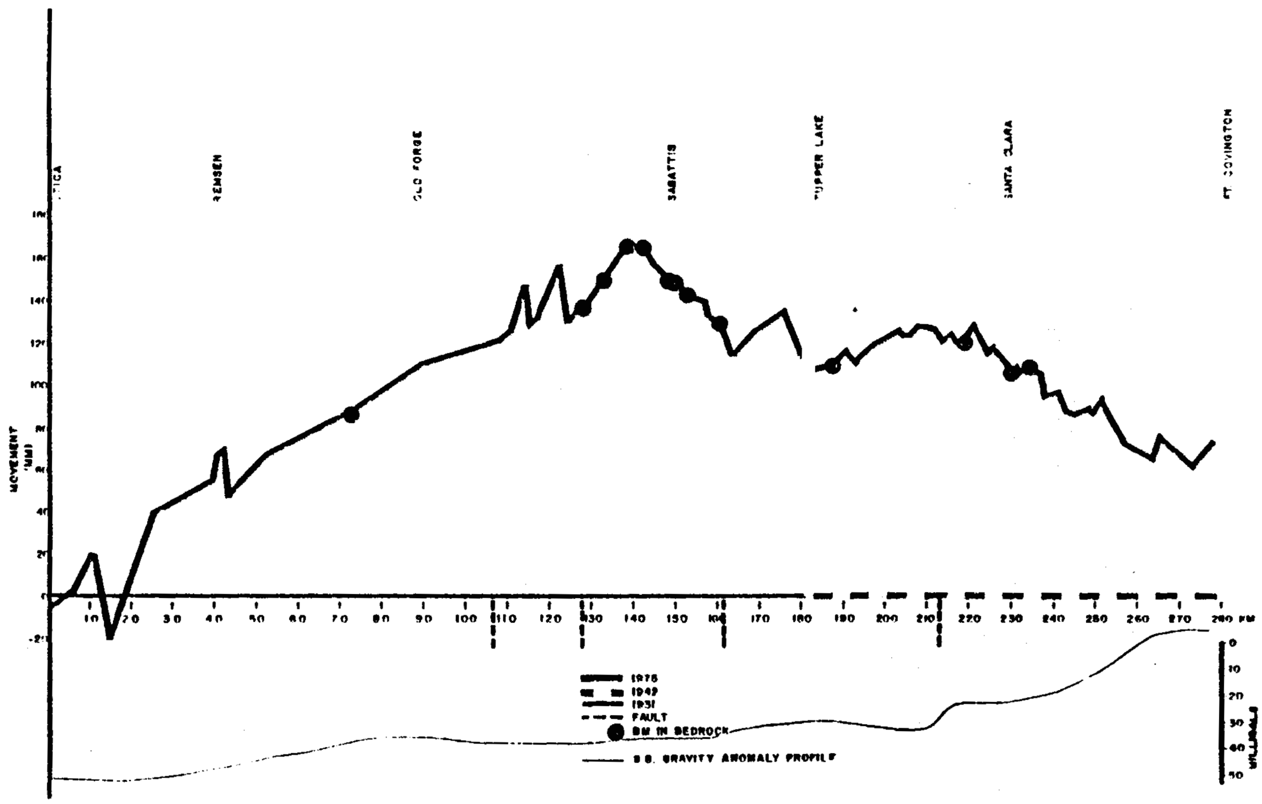

Figure 3. First-order releveling profile across the Adirondack dome between Utica and Fort Covington. Leveling data from Vertical Network Branch, National Geodetic Survey. From Isachsen, 1976.

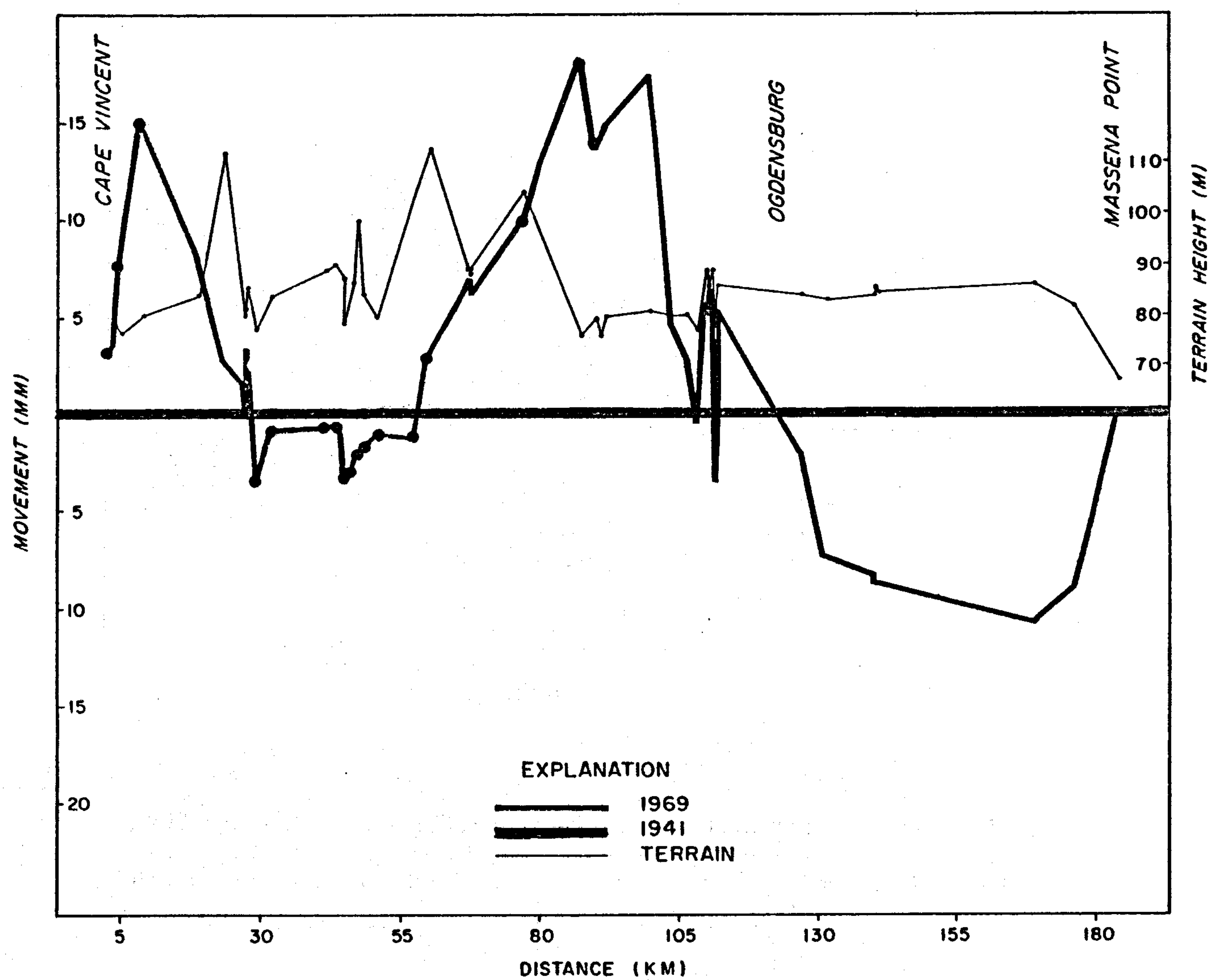

Figure 4. First-order releveling profile across the northwest flank of the Adirondack dome between Cape Vincent and Massena Point. Leveling data from Vertical Network Branch, National Geodetic Survey.

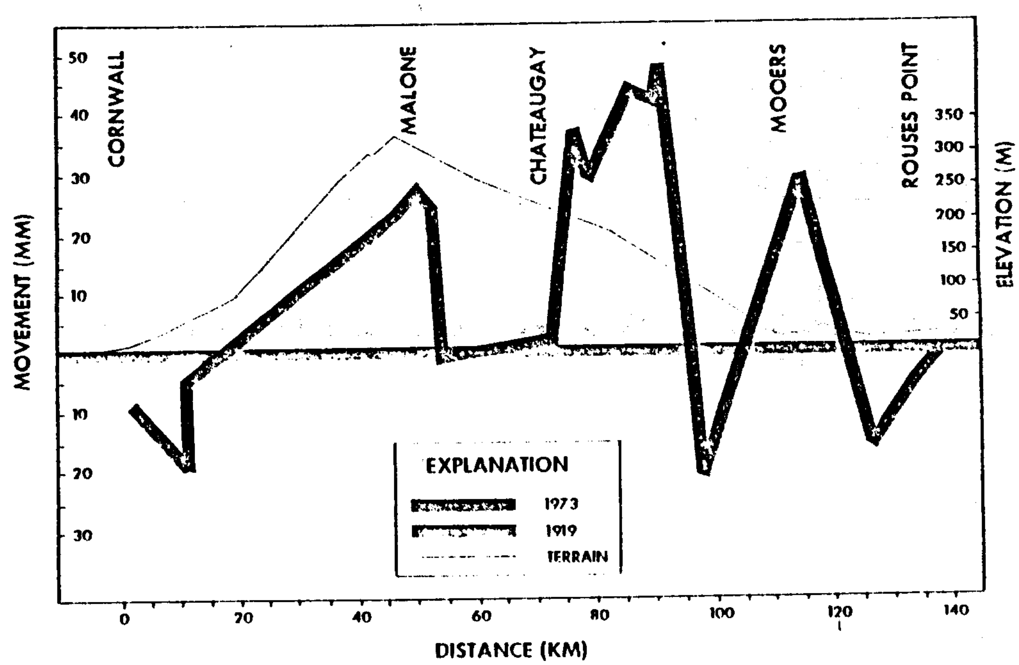

Figure 5. First-order releveling profile across the northern flank of the Adirondack dome between Cornwall (near Messena) and Rouses Point. Leveling data from Vertical Network Branch, National Geodetic Survey.

A second order releveled line extends eastward from Lake Clear Junction (LC) as shown in Figure 1. It was leveled in 1935 and 1955, over a length of 55 km (Fig. 6). Of 17 benchmarks which were releveled, none are in bedrock. Using Lake Clear Junction as an arbitrary reference point with no change in elevation, the 1955 profile rises steeply to 60 mm within the first 15 km, and climbs steadily to 90 mm at the eastern end of the line. The uncertainty along this second order line is 31 mm. The uplift rate along the line for the 20 year time interval involved is about 3 mm/yr, in agreement with that found nearby along the Utica-Fort Covington line.

Three of the first order releveled lines located on Figure 1 are of little value in this study because of 1) the low precision of the initial leveling which was done at the beginning of the century, 2) too few releveled benchmarks along the line, and 3) a lack of benchmarks in bedrock. They are however, described here for the sake of completeness: 1) Saratoga Springs (SS) to Thurman (TH), 42 km long, leveled in 1899 and 1955, with only 5 reoccupied benchmarks, none in bedrock; 2) Remsen (RM) to Watertown (WA), 120 km long, leveled in 1900 and 1933, with only 8 releveled benchmarks, none in bedrock; and 3) Tupper Lake (TL) to Fort Covington (FC), 110 km long, leveled in 1900 and 1942, with only 10 reoccupied benchmarks, none in bedrock.

A very short (10 km) second order level line exists in the Blue Mountain Lake (BML) area (Fig. 1) which was leveled in 1939 and again in 1942, only 3 years later. Only 5 stations were releveled, none in bedrock, and no systematic trend is shown in the profile.

The line from Utica to Troy was leveled in 1900 and 1931 but these data have not been seen.

Discussion

As shown in Figure 1, and discussed in the preceeding section, present releveling data are sufficient along the eastern, northern, northwestern and southeastern margins of the Adirondacks to confirm that little or no relative uplift has occurred around the perimeter of the dome with respect to the interior. Along the southwestern border of the uplift, however, releveling information is inadequate to draw any conclusions (i.e., the Remsen-Watertown levelings of 1900 and 1942 referred to above).

It should be re-emphasized that the releveling profiles referred to above show relative, not absolute movements. Absolute vertical movement (i.e., elevation changes with respect to sea level) can be determined only for the Saratoga Springs-Rouses Point profile. This was done by comparison with a releveling profile between the Tidal Station in New York City (the Battery) and Troy which is only 38 km southeast of Saratoga Springs (Isachsen, 1975). It shows that the profile between Saratoga Springs and Rouses Point is within 15 mm of being an absolute movement profile.

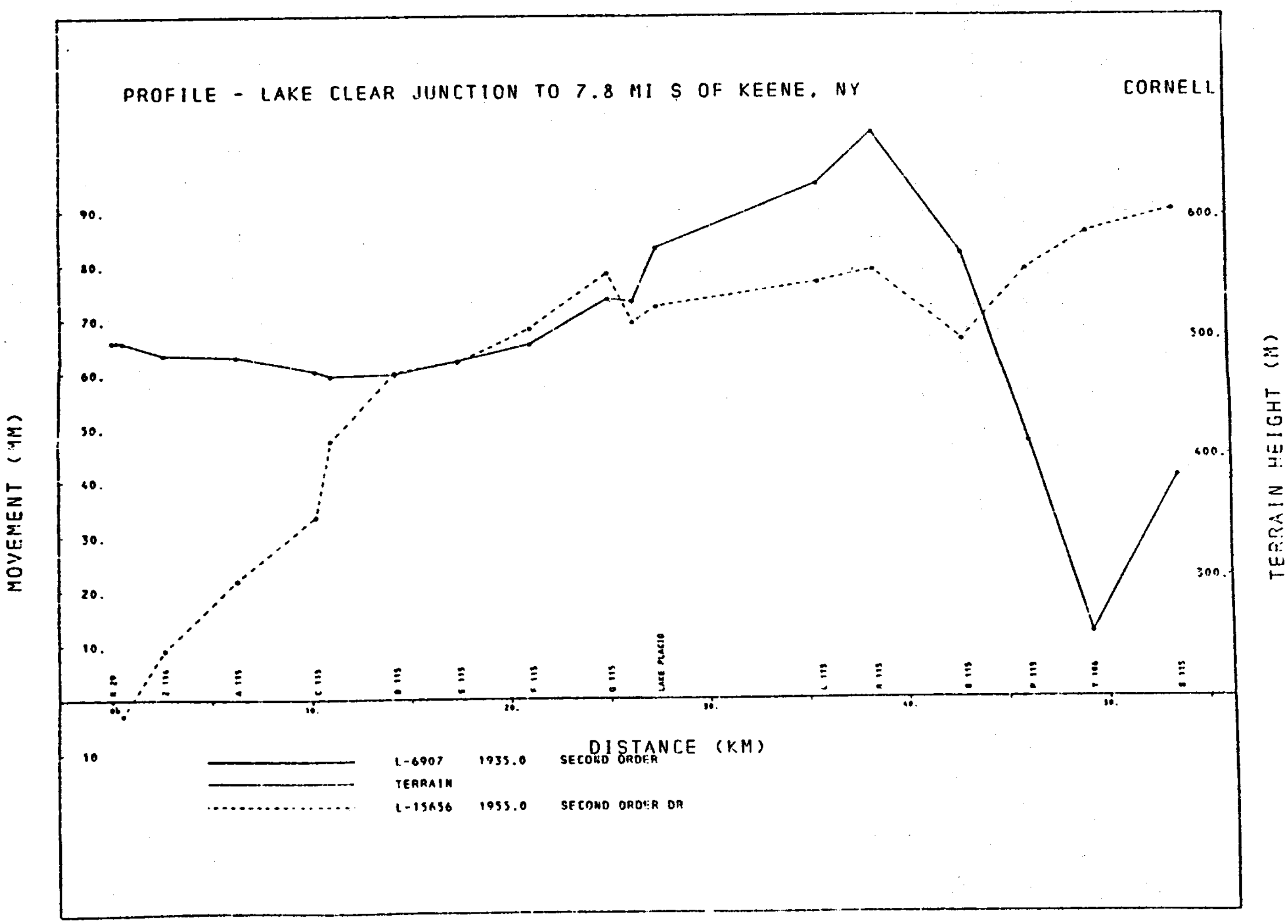

Figure 6. Second-order releveling profile in central Adirondacks, between Lake Clear Junction and a point 7.8 miles south of Keene.

Although contemporary vertical movement of a circular or elliptical area like the Adirondacks may be uncommon, it is not unique. An analogous area of vertical movement, but with opposite sign, occurs north of Quebec City, centering on Stoneham. The subsiding area is circular, and has the same diameter as the Adirondack Dome. The maximum rate of subsidence is 4 mm/yr (Frost and Lilly, 1966; Vanîcék and Hamilton, 1972), based on numerous relevelings made between 1919 and 1965. Dunbar and Garland (1975) interpret the subsidence as due to the decay of an enhanced proglacial prebulge. Because the St. Lawrence rift system (including the Champlain trough) lies between this area and the Adirondacks, an analysis of releveling data between these oppositely moving areas would be highly desirable.

Analogous areas of vertical movement are probably more common than can be determined from the limited compilations of neotectonic activity available at present. One published example is an elliptical area of uplift, almost identical in areal dimensions to the Adirondacks. It occurs on the Ukranian Shield north of Odessa which is located on the Black Sea (Mescherikov, 1973). A north-south profile drawn along the eastern edge of this uplift corresponds to the Saratoga Springs-Rouses Point profile in the Adirondacks, both in horizontal scale and rate of uplift. At the center of the uplift, however, the rate of movement is twice that at the center of the Adirondack Dome. This is an even more striking example of uplift not related to post-glacial rebound, because the area is more than 1000 km south of the limit of continental glaciation.

Age of Doming

The Paleozoic history of Adirondack vertical movement has been considerably illuminated by isopach maps derived from drill hole data (Rickard, 1969, 1973), and generalized in Figure 7. It can be seen from the maps that, although the present Adirondacks region was emergent during Cambrian to Early Ordovician time as part of a large landmass to the west and northwest, there is no evidence of a <u>domical</u> uplift of the region during this or later time for which a sedimentary record exists -- i.e., through the Early Devonian. Note that isopachs after the Early Ordovician trend towards the southern border of the present dome at a high angle, suggesting that they originally crossed it without defection. The same applies to Upper Devonian isopachs, based on work in preparation (Rickard, oral communication). Thus the constraints provided by subsurface map trends indicate that Adirondack doming began sometime after Late Devonian. Other data provide further constraints on the doming. One is topography. The present dome has a <u>topographic</u> relief which nearly equals its minimum <u>tectonic relief</u> of 1600 m (Fig. 1) indicating that the dome cannot have undergone a very lengthy period of erosion. Providing additional support for the youthfulness of the dome is the fact that the drainage pattern in the Adirondacks is still largely consequent (radial), as shown in Figure 8. The major exception to this generalization is the well-developed NNE drainage pattern in the central and

Figure 7. Isopach maps showing lack of relationship between Adirondack domical uplift and sedimentation during Paleozoic time. Maps generalized from Rickard, 1969, 1973).

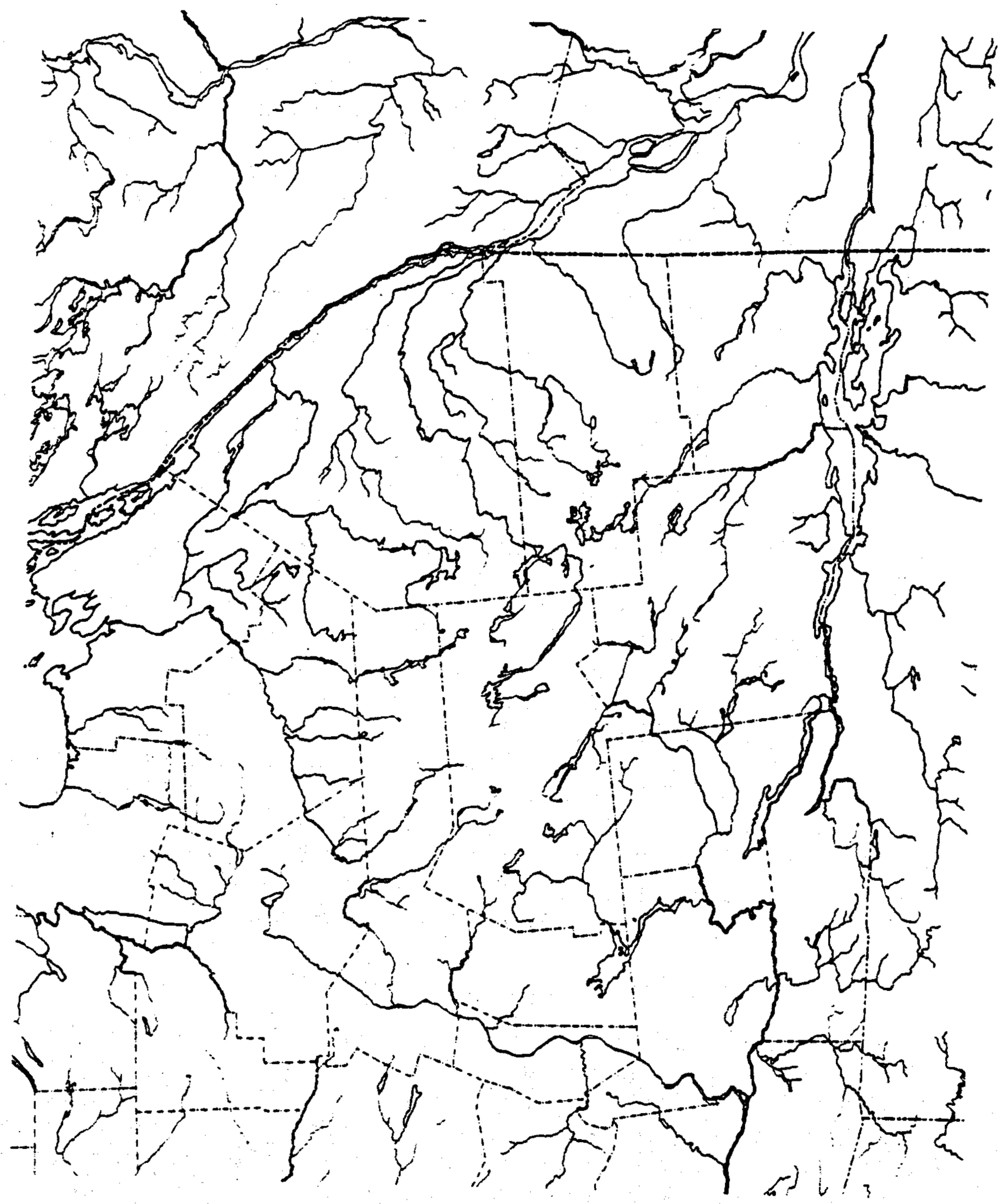

Figure 8. Map showing radial drainage pattern within the perimeter of the Adirondack dome.

eastern Adirondacks which is influenced by a particularly strong fault and lineament pattern (e.g., Isachsen, 1974; Appendix I). The dominant radial drainage, because it is still largely unadjusted to the variable lithologies it crosses (Fisher and others, 1971), was probably superimposed from Paleozoic strata which covered the region prior to doming and unroofing.

From arguments involving fixed hot spots in Africa and the movement of the North American plate, Burke (Appendix I) suggests that the Adirondack uplift may be less than 4 m.y. old.

The present rate of doming can be used in only a very speculative way to explore the possible recency of the doming, for several reasons. First, it is not known whether or not it presents a long-continued trend. Secondly, it is unknown whether the vertical movements have been undirectional and continuous, undirectional and episodic, or oscillatory. Nevertheless, it is interesting to note that if the present rate of doming were projected back in time, only 500,000 would have been required for the entire 1600 m uplift of the Adirondack Dome. This rate, however, is unrealistic even in terms of the most rapid erosion rates which have been estimated for eastern North America. Mathews (1975) computed the volume of sedimentary deposits in the western Atlantic Ocean and concluded that this required an average denudation of 2 km since the start of Cenozoic time. This amounts to 0.3 mm/yr. If this applies as an average value, a higher rate would be expected for an elevated region such as the Adirondacks. Using the above rate, however, a thickness of 1.2 km of Paleozoic rocks would have been stripped off the Adirondacks in 4 m.y.

Cause of Doming, and Potential for Geothermal Energy

Two independent lines of recent experimental work support the concept of a thermal plume as a cause of current Adirondack doming. Kukes and others (1977), using a 1,2 km diameter wire loop carrying 25 amperes RMS current in the central Adirondacks, found that a rapid increase in electrical conductivity occurs beneath the Adirondacks at a depth of about 20 - 25 km. The rise is from 10^{-4} to 10^{-2} (ohm meters)$^{-1}$. Kukes (oral communication) interpreted this to indicate a relatively high water content at these depths.

This proposal, however, is in serious conflict with the occurrence of dry, granulite-facies metamorphic rocks at the surface throughout the Adirondack Mountains. An alternate explanation is possible, namely, that the increased electrical conductivity is due to the formation of intergranular melts caused by rising isotherms related to Adirondack doming. Gough (1974) suggested that the high electrical conductivity of the low velocity zone (2x 10^{-3} Ω^{-1} cm^{-1} or 0.2 S/m) may be the result of partial melting. Recent confirmation of this effect has come from experimental work by Murase and others (1977, p. 418) who measured a sharp increase in electrical conductivity at the temperature at which peridotite begins to melt substantially (1170°C). It is suggested that the shallower region of high electrical conductivity beneath the Adirondack Dome is due to intergranular melting or introduction of less refractory quartzo-feldspathic material.

Additional detailed discussion of the cause of doming appears in Appendix I by Burke, and is only briefly summarized here. The Adirondack Dome fits into a class of anomalous circular to near-circular uplifts on the globe which have a relief of 1-2 km and a diameter of about 200 km, as noted by De Long and others (1975, and reproduced as Appendix II). Some of these uplifts have associated volcanics and are thus, demonstrably, old hot spots. Others, which lack volcanism but are otherwise identical, and may occur in the same region, are interpreted as old hot spots in which magma did not reach the surface. Inasmuch as the Adirondacks are undergoing contemporary domical uplift, thermal expansion at depth is implied, presumably due to a source of magma at some level in the crust; we infer that the rising Adirondack Dome is a contemporary hot spot which lacks surface magmatic activity. This immediately raises the question as to what heat flow data exist for the Adirondacks which may bear on this interpretation. In terms of heat flow, the Adirondacks lie in the "eastern Heat Flow Province" of Potter (1975), just north and west of the "Appalachian Lows", with values of about 1.2 HFU (Diment and others, 1972; Potter, 1975). The "Lows" form the northeast extension of the "Ohio-Pennsylvania Arc" region, which has an average heat flow of about 1.6 HFU.

Heat flow studies were made in the Adirondacks by Birch and others (1968), and give values of 1.2 HFU for granitic gneiss (charnockite) in the northern Adirondacks at Riverview, and 0.8 HFU for metanorthosite in the Marcy massif at Elizabethtown and Saranac Lake. The very low values in the anorthosite can be explained as due to the near-absence of radioactive minerals in the rock (e.g., Silver, 1968). In terms of geothermal energy potential of the region, these low values are discouraging if one assumes that they represent steady-state heat flow with respect to temperatures lower in the crust. There is, however, no valid reason for such an assumption. Indeed, the current high rate of uplift and the youthful drainage system argue for the contrary. Considering these factors, and low thermal conductivity of rocks, it is reasonable to suggest that surface heat flow values in the Adirondacks are paleo-indicators of a <u>predoming</u> thermal regime - i.e., the latest thermal pulse has not yet reached the upper kilometer or two.

Another point may be raised in this connection: is it possible that the 4 km thick slab of anorthosite (Simmons, 1964) in which the heat flow measurements were made, is serving as a thermal blanket? It has a relatively low thermal conductivity of 4.2×10^{-3} cal/cm sec °C, compared to $6.8\text{-}8.2 \times 10^{-3}$ cal/cm sec °C for other plutonic rocks (Clark, 1966).

In summary, the rising Adirondack Dome is interpreted as an active hot spot, and hence considered to have possible potential as a source of long-range, hot dry rock geothermal energy.

PANTHER MOUNTAIN CIRCULAR FEATURE

Introduction, Purpose and Methods of Study

A statewide study of Landsat 1 imagery led to the recognition of an anomalous circular valley, 10 km in diameter, which surrounds the Panther Mountain mass in the Catskill Mountains. The region is one of a flat-lying Upper Devonian continental clastics. Depth to Proterozoic basement is about 3 km. One of the several geological explanations which were entertained for this feature was the possibility that it was an indirect result of a buried felsic pluton, such as the Peekskill Pluton which occurs some 95 km to the southeast. Such a pluton, buried under a suitable insulating cover of sedimentary rocks, could have potential as a geothermal resource. This was one of the motives for selecting this feature for study.

The investigation of the Panther Mountain circular anomaly involved photogeology, gravity, magnetic, and scintillometer profiling, gravity modeling, structural mapping, and shallow seismic refraction profiling. Attempts to study the root zone of the circular feature by monitoring the attenuation of distant quarry blasts with portable seismographs failed for logistic reasons, despite repeated attempts. The other geophysical studies, however, provided more definitive constraints than could have been obtained from a successful seismic study.

Results and Discussion

Results of the Panther Mountain study have been published (Isachsen and others, 1977a, 1977b) and a copy of the latter reference is attached for reference (Appenxic III). The results of the scintillometer survey were not mentioned in these publications because they were not germaine to the conclusions reached. They are therefore included here. The gamma radiation was monitored during the structural field mapping, which included extensive traverses as shown in Figure 3 of Appendix III. No anomalous values were found over any areas traversed by either foot or car: all values feel within one or two times background.

The conclusions of the Panther Mountain study are summarized in the next section.

CONCLUSIONS

Considering the high density of population and the concentration of industry in eastern United States, and the wide range in temperature over which geothermal energy can be utilized (e.g., from 60° F for aquaculture to 250° - 300° F for central heating), the exploration for long range geothermal resources in the east appears desirable.

Two areas in New York State were studied for their possible long-range potential as sources of geothermal energy, the Adirondack uplift and an anomalous circular feature centered on Panther Mountain in the Catskill Mountains.

It is concluded that 1) the Adirondack uplift, an anomalous topographic and tectonic feature on the Appalachian foreland, is an actively rising intracontinental dome, 2) the dome is a youthful feature, perhaps as young as 4 m.y. old, 3) the most likely energy source responsible for this rise is a body of magma at depth (i.e., a thermal plume or hot spot). For this reason the area deserves further study in the future as a potential source of hot dry rock geothermal energy.

The Panther Mountain circular feature appears, from its morphology, associated gravitational and magnetic fields, structural geology, and local seismic refraction profiles, to be not a buried ("insulated") felsic pluton with potential for geothermal energy, but a buried meteorite crater of Late Devonian age. The steep gravity gradient and large mass-deficiency shown by the feature require that the low density source be located within 1 km of the surface. The mass deficiency is thought to represent a breccia lens some 8 km in diameter and up to 4 km in thickness. Inasmuch as a breccia lens of these dimensions would extend through the entire Paleozoic section, cutting several black shale horizons which serve as source beds for natural gas in the central and western part of the State, the structure may have potential as a natural gas reservoir. Subsurface astroblemes have been inferred in the Williston Basin, where they are either producing fields or potential hydrocarbon reservoirs (Sawatzky, 1975).

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APPENDIX I

PRELIMINARY INVESTIGATION OF TWO AREAS IN NEW YORK STATE IN TERMS OF POSSIBLE POTENTIAL FOR HOT DRY ROCK GEOTHERMAL ENERGY

Yngvar W. Isachsen
Geological Survey - New York State
Museum, Albany, New York 12234

with

an Appendix on "Adirondack
Topography: an interpretation"
by Kevin Burke, State University
of New York, Albany, New York 12222

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Washington, D.C.

Contents

Abstract

Most of the world's high topography can be related to plate margins. The Adirondacks, far from any active plate margin, most resemble a population of anomalously high areas termed hot-spots. Elevation of this group of objects appears linked to heat and the formation of magma at depth, and this process may also have helped to induce subsidence in the Adirondack area by triggering the basalt-eclogite transition beneath reactivated rifts in Lakes George and Champlain. Because the Adirondack possible hot spot uplift has left no track it may be less than 4my old. Analogy with African volcanic areas on hot spot uplifts suggests that a likely area for the present occurrence of subsurface magma is below the high peaks of the Adirondacks.

Introduction

Recognition of the plate-structure of the lithosphere within the last decade has revolutionized understanding of many geological phenomena. The close association between plate-margins and mountain-building processes throughout geological time is perhaps the most comprehensive revolutionary conception,but close associations between plate-margins and igneous activity,and plate-margins and topographic extremes are also striking.

It is the realization that plate-margins are commonly the sites of igneous activity and high topography that has permitted a new look at igneous and elevated areas away from active plate-margins. These areas are anomalous because nearly all high relief and igneous activity lies close to plate-margins. In terms of igneous activity non-plate-margin areas account for a very small amount, probably much less than one percent, of all igneous rocks. In terms of topography, although all areas more than 4 km above sea level are close to active plate-margins,there are large areas 2-3 km above sea level that are not plate-margin related.

DeLong and others (1975 and appendix 1) pointed out that although some areas of anomalous intra-continental relief roughly coincided in extent with old mountain belts, for example the Appalachians and Caledonides, others had no such association. A prominent set of anomalously high areas are the non-plate-margin volcanic regions best known from within the oceans and the African continent. Burke and Wilson (1972, 1976) suggested that these hot-spot volcanoes were particularly prominent in Africa because the African plate had been at rest, with respect to the underlying mantle, for about the last 25 million years (see also Burke, 1976a).

Burke and Whiteman (1973) in a review of African uplift, volcanism and rifting discussed the size of typical uplifts and concluded (Table 1) that elliptical areas averaging 80 km by 220 km were very common. Uplifts and clusters of uplifts on the African plate include several, especially in Southern Africa, that have no volcanic caps, and DeLong and others (1975) suggested that the presence or absence of volcanism on an uplift might be of less tectonic significance than the elevation itself.

The idea that high ground is structurally anomalous away from plate-margins is a simple one and it is worth considering why geologists have not, in modern times, devoted much consideration to the origin of this kind of topography. In areas where the anomalous topography is co-extensive with old mountains, as in the Appalachians, there has been a tendency to infer that the mountain belts are high because they have been up since they were originally formed but erosion rates are so great (e.g. Judson and Ritter, 1964) that mountains cannot stay elevated for more than a few million years unless dynamically supported. Holmes (1965, p. 514) discussed erosion rates and concluded that the activities of man had increased them very much so that the elevation of old mountain belts could have been preserved from their initial formation under the very slow rates of erosion that he thought pre-dated man's activities. Holmes' world picture, while internally quite consistent, placed strong emphasis on a long-persistent Pangea with an early Mesozoic continental rupture episode. Recognition of the great antiquity of plate-tectonic processes (Burke and others, 1976) implies a more dynamic earth history and is compatible with erosion rates today being similar to those of the past. The significance of the recognition of high erosion rates for the interpretation of topography is that it permits the inference made to areas on land that are high now because they are dynamically maintained. Plate interactions provide the dynamic maintenance of elevation at plate-margins. In other areas the source of the elevation is attributable to low density, perhaps hot or partly melted material beneath the lithosphere (called mantle diapirs, mantle plumes, melting spots and several other names by various workers).

Isolated non-plate-margin, or hot-spot volcanic areas on moving plates are known both from within oceans and on continents. In oceans a trail of extinct volcanoes commonly leads away from active hot-spots, but similar trails are poorly developed on land mainly because erosion destroys the old volcanoes.

The Adirondacks as Non-Plate-Margin Topography

Area: Although the Adirondacks lie close to the

Table 1. Physical characteristics of some African uplifts. The area and elevation of the Adirondack uplift are similar to those in the table (Table from Burke and Whitman, 1973).

Uplift	Width (km)	Length (km)		Uplift of basement (km)	Peak gravity value (mgals)	Type of volcanic activity
Adamawa	50	150		1	−100	minor alkali basaltic
Jos (Neogene)	100	300?		1	− 90*	alkali basaltic
Atakor (Ahaggar)	60	300?	}400	1	−120	alkali basaltic
Ajjer (Ahaggar)	50	100		1		alkali basaltic
Bamenda (Cameroun)	120	250	}500	1	−100	alkaline, mainly basalt
Cameroun Mt	120	250		1		alkaline, mainly basalt
Ngaoundere	50	150			−100	alkali basalt
Tibesti	100	300		1	− 70	alkali basalt to rhyolite
Jebel Marra	100	200		1		alkali basalt
Average Neogene Uplift	80	220		1	−100	alkali basaltic
Jos (Jurassic)	200	500?		1?		alkali, mainly acid subvolcanic

Appalachian mountains they represent a distinct topographic province separated from the Appalachians by the graben of Lakes George and Champlain. The area of the Adirondacks above the sea level contour on the top of the Grenville basement forms an ellipse about 200 km by 150 km (Isachsen, 1975) and the crest of the uplift lies at more than 1.5 km above sea level. These figures are comparable to those reported by Burke and Whiteman (1973 and Table 1) for typical active hot-spot uplifts on the African plate and it seems not unrealistic to consider whether the Adirondacks may be of comparable origin.

Adirondack Hot-Spot Track?

African hot-spot uplifts generally have no tracks and this is considered to result from the absence of relative motion between the African lithosphere and the immediately underlying part of the mantle during the time since the uplifts developed (Burke and Wilson, 1972). If the African plate is not moving with respect to underlying mantle then the North American plate, since it is moving with respect to Africa, must also be moving over the mantle. We can use this motion, which works out at about 40 mm/yr in a direction of about 300° to see whether a track extends away from the Adirondacks in the direction that would be produced by relative motion between the North American plate and a hot-spot. Such a track would not consist of high ground, which would have been rapidly eroded, but of an area in which basement is structurally elevated compared to its surroundings. Although the area to the west of the Adirondacks along the presumed track lies largely within the basement of the Canadian shield there is no indication of unusually deep exposure in the form, for example, of a belt of granulitic rocks along the track and this can be interpreted as implying that if the Adirondacks owe their elevation to hot-spot activity the activity has started too recently for a track to have developed. Since relative motion between the hot-spot and the North American plate would approximate 40 mm/yr and be capable of making a 40 km track length in 1 million years, the age of the Adirondack uplift (itself about 160 km across) would appear, if it is due to a hot-spot, to be less than 4 my.

Age of Uplift: Isachsen (1976) showed that present uplift rates in the Adirondacks indicated by relevelling, could produce all the doming of the area in less than 1 million years and this seems compatible with the extreme youth implied by the absence of a hot-spot track.

Although there have lately been suggestions that Pleistocene glaciations may have been a major force in eroding the shield areas of North America (e.g. White, 1972) the more traditional idea (e.g. Flint, 1971) that these glaciations have done little more than modify existing relief seems to be more strongly supported by the evidence (Sugden, 1976). Observations within the Adirondacks show that although evidence of glaciation in the form of till and fluvio-glacial sediment is ubiguitous, development of the characteristic land forms of glaciated terrains (e.g. u-shaped valleys, cirques and aretes) has occurred to only a very limited extent. The effects of glaciation on Adirondack erosion and relief are not extreme and the elevation we now see is a large part of the whole.

Radial Drainage Pattern: The radial drainage pattern of the Adirondacks has been illustrated in fig. 1 by emphasizing reaches of streams that exhibit parallelism. This procedure is frankly subjective and has been deliberately biased to reject stream lengths that are parallel to the prominent NNE joint and fault sets of the Adirondacks (Isachsen, 1974, fig. 6).

A regular radial pattern is well-defined on the Northern, Western and Southern flanks of the dome and a less well-defined pattern can be discerned along the eastern flank. In this eastern province Northeastern and Southeastern sections with radial drainage can be recognized, but the pattern is partly obscured by the local effects of the Lake George and Lake Champlain rifts. A circular area about 30 km in radius roughly centered on Blue Mountain Lake has no prominent radial drainage pattern and may for this reason lie near the center of the uplift. The mid-point of this area is displaced south-west some 30 km from the highest peaks and a possible explanation of the displacement is that the anorthositic rocks of the high peaks are unusually resistant to erosion.

The radial drainage pattern of the Adirondacks has long been recognized (   ) and is most readily explained as a development consequent on dome uplift. If, as seems probable (Rickard, 1975), the Adirondacks were overlain prior to doming by Cambrian and Ordovician sediments like those of neighboring areas then the drainage was superimposed on the complex structures of the Grenville rocks now at outcrop from consequent drainage off a structural dome formed of gently dipping Cambrian and Ordovician limestones, sandstones and shales.

Possible Lag in Surface Heat Flow Increase at a Hot-Sp[illegible]: Crough and Thompson (1976) have shown that an increase of heat flux below the lithosphere, such as is here suggested for the Adirondacks, produces immediate surface uplift and lithospheric thinning but that the associated increase in surface heat flow begins only 20 to 40 my later. This is valid for situations in which the heat is conducted through the lithosphere. Observation of volcanoes on the crests of uplifts (for example: in the Black Hills and at many places in Africa) indicates that heat is commonly transmitted rapidly to the surface by the intrusion and extrusion of magma so that although the Adirondacks are apparently a young uplift there is no need to wait tens of millions of years until an associated thermal pulse reaches the surface.

Compressional Earthquake Mechanisms: Strong evidence that the uplift of the Adirondacks is presently in progress comes from relevelling (Isachsen, 1975, 1976) and from the earthq uake activity that centers around Blue Mountain Lake (Sykes and Sbar, 1973). Composite first motion studies for the shallow earthquakes of the Blue Mountain Lake swarm yield a compressional mechanism trending roughly in the direction calculated for the motion of North America with respect to the underlying mantle using the Africa stationary hypothesis. Although this orientation of compressive stress is consistent with the expected response of the lithosphere to stresses applied to its base by moving mantle in the asthenosphere it is hard to understand a close association between the dome-shaped uplift of the Adirondacks and crustal compressive stress. The dome-shape and the evidence of uplift seem much more likely to be associated with shallow tensional stresses. Tensional stresses are likely to be dominant at shallow levels in the crust as a result of thermal contraction and uplift on a spherical earth (Haxby and Turcotte, 1976) and the occurrence at shallow depths (a few km) of compressional deviatoric stresses as indicated by earthquake mechanisms within plates is a widespread but as yet poorly understood phenomenon.

Lake Champlain and Lake George Rifts: A satisfactory theory of Adirondack topography must explain the adjacent rift troughs of Lakes George and Champlain that separate the Adirondacks from the Appalachians. The rift character of the Lake George and Champlain troughs is suggested by their topography with steep sides and rivers draining only short distances from the Adirondack and Appalachian mountains on either flank (figs. 1,2). No firm evidence of young faulting in the Lake George and Champlain troughs has yet been mapped but several phenomena are suggestive of its occurrence and the idea that this is fault-dominated terrain has long been in the literature (e.g. Quinn, 1933).

First the topography itself (as shown in fig. 2) seems hard to produce without faulting. The drop at the edge of the Lake Champlain trough is exceptionally abrupt, generally about 1000 ft. (∿300 m), and this seems likely to require a tectonic origin. Second the preservation of red-weathered fossil soils is concentrated at localities on the western side of the Lake George graben (Muller 19). These materials are readily erodable by ice and although comparable outcrops are known elsewhere in the Adirondacks they are generally along fault zones. The localized preservation near Lake George could well be the result of down-faulting in the graben. Third, Chase and Hunt (1972) in a seismic reflection survey of Lake Champlain revealed the existence of steeply inclined surfaces separating recent lake sediments from bed-rock. Their records are not clear enough to permit distinction between topographic bed-rock slopes against which sediments have been embanked, and recently faulted surfaces. There are, however, places on their published lines that could mark the crossing of Recent fault boundaries. Last, the proximity of the McGregor fault south of Lake George (fig. 3) to its scarp which lies less than 1 km to the west indicates that the scarp is a fault scarp that has retreated little through erosion, rather than a fault line scarp, and that the McGregor fault has been recently active. Other faults on the Adirondack eastern margin (for example: around Sacandaga reservoir (fig.4) appear similar.

Although none of these four lines of evidence is unequivocal, for example, it is possible to interpret the topography west of the McGregor fault as produced by recent erosion of a Paleozoic sequence embanked against the Adirondack crystalline rocks, together they add up to a strong indication of Recent rift-faulting in the Lake George and Champlain graben.

Why rift faulting? Isachsen (1975) has suggested that subsidence at the northern end of the Saratoga-Rouses Point relevelled line might be related to reactivation of the Mesozoic St. Lawrence rift of Kumaporeli and Saull (1966). A modification of this hypothesis is developed here.

The Mesozoic igneous and uplift event of the St. Lawrence valley does not appear to have been linked to significant rifting, having found its main expression in the emplacement of the igneous rocks of the Monteregian hills and in the erosion of sediment from those hills to form the Mississauga delta (Jansa and Wade, 1975) close to the present mouth of the St. Lawrence river. There was, however, an earlier rift episode in this area at the beginning of the Phanerozoic, and the Lake Champlain and Lake George graben are here suggested to be reactivitated structures on the sites of ancient rifts formed at that time.

The Ottawa-Bonnechere graben (Kay, 1942 and Fig.) has been shown to be a rift developed within North America at the time of inception of the Iapetus Ocean in the earliest Paleozoic (Burke and Dewey, 1973, Rankin, 1976). Closing of this ocean in arc and continental collisions has left the graben as a rift striking away from a fold belt, or an aulacogen. Shatsley long ago (1946) recognized the Ottawa-Bonnechere structure as an aulacogen. An outstanding question is are there signs of other rifts linked to the Ottawa-Bonnechere structure? Burke (1967b and fig. 6) has shown that the rift systems developed at the opening of the Atlantic ocean were generally made up of complexes of individual linked rifts and that several of these are commonly preserved within the continents on either side of the ocean after rupture. The occurrence of Cambrian continental shelf sediments in allocthonous units to the east (e.g. the Stockbridge marbles) indicates that the Ottawa-Bonnechere graben lay well within the North American continent at the time of continental rupture and the opening of Iapetus. Rickard's (1975) plots of Cambrian sediment thicknesses in the area south of the Ottawa-Bonnechere graben are suggestive of some sediment thickening roughly along the present trend of the Lake Champlain and Lake George graben and on this (admittedly slender) evidence it is suggested that a graben Cambrian complex, linked to and contemporary with the Ottawa-Bonnechere graben, underlay the present site of the two lakes (fig. 5).

Intra-continental rifts have been shown in many cases to contain axial dike systems of basaltic composition, and this is apparently a widespread, if not universal, association (Burke, in press and appendix 2). Where exposed, the igneous rocks occupying the axial dikes are everywhere, even when very ancient, of basaltic or gabbroic mineralogy. This observation is at first sight surprising since experimental work (Green and Ringwood, 1967) has shown that eclogitic mineral assemblages represent the stable form for rocks of basaltic chemistry over a wide range of temperatures and pressures. The generally accepted explanation of the scarcity of eclogite and the widespread preservation of basaltic and gabbroic rocks is that the rate of the change to the stable form is very slow even over geological time scales. Only very high temperatures will induce the transition to the eclogitic form.

The heating that has been here suggested to be responsible for the present elevation of the Adirondacks could be the cause of the simultaneous subsidence of the Lake Champlain-Lake George graben. If the graben overlie an ancient rift with a basaltic axial dike system, local heating could induce partial transition of the basalt of the dike to an eclogitic mineralogy, and since the eclogite is much denser (S.G. approximately 3.4 as opposed to approximately 2.95) local subsidence would result and reactivation of the old rift would ensue.

Conclusions and: Significance of the Topography as a Guide to Thermal Anomaly

The Adirondack uplift and the neighboring Lake George and Lake Champlain graben are interpretable as products of an underlying magmatic source comparable to the hot-spot volcanic areas of the African continent. The rift developments can be interpreted as the results of partial eclogitization of basaltic axial dikes in old rifts.

Comparison with the African hot-spot areas shows that there is a high (but not universal) association between the volcanism and the summit areas of the elevation. Fig (7) after Black and Girad (1970) illustrates the closeness of this association in the Ahaggar. Therefore the high peaks area is the most important prospect for a geothermal anomaly. This is the area where, by analogy with African examples, if a volcano does erupt in the Adirondacks in the next few million years eruption is most likely, and where, for the same reason, magma at depth is best sought today.

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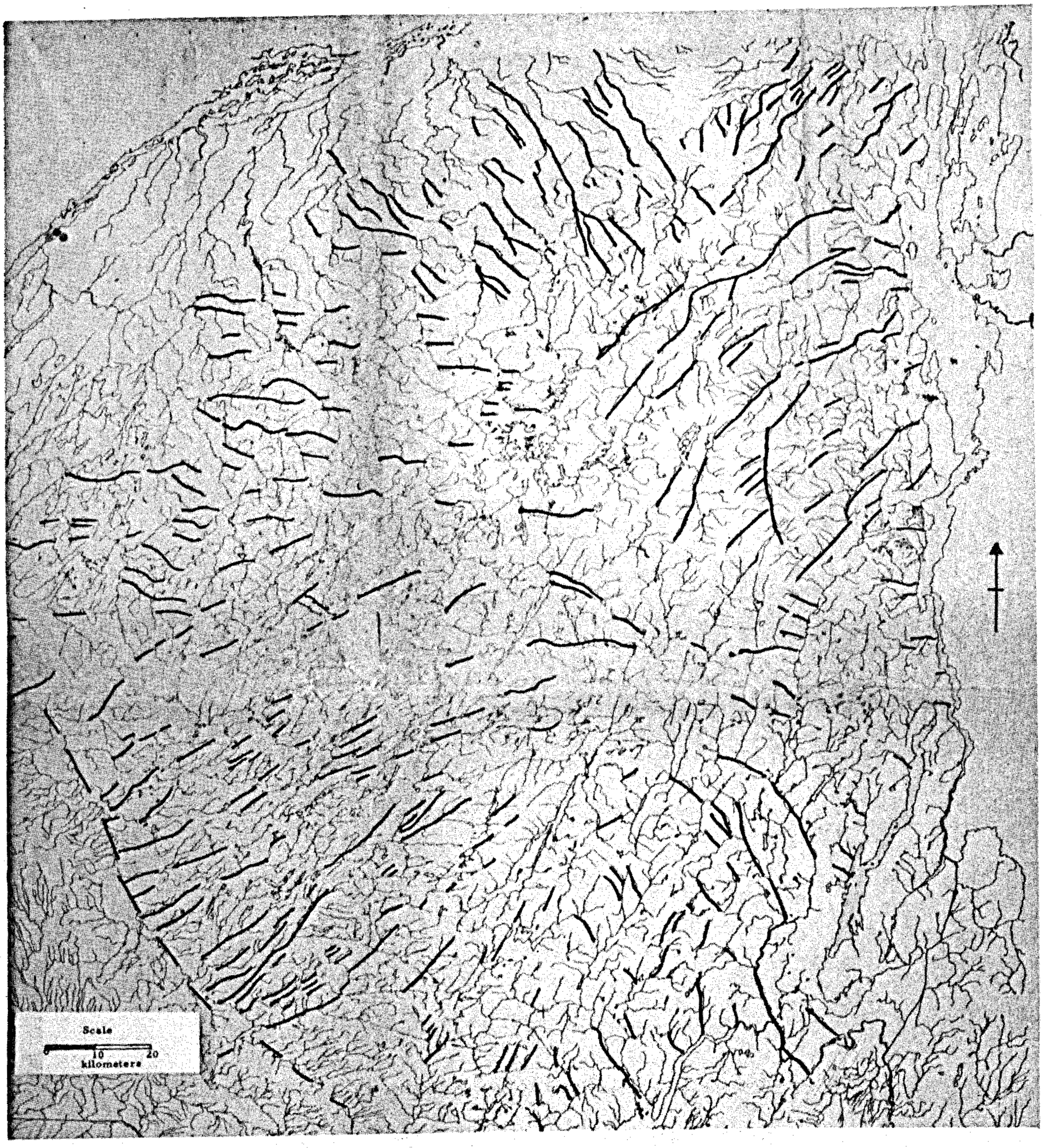


Fig. (1) ADIRONDACK RADIAL DRAINAGE. Selected reaches of streams have been marked with heavy lines to emphasize the radial consequent drainage pattern superimposed from a young dome of Paleozoic sediments that has very lately been eroded away. Stream courses influenced by the prominent NNE faults have been deliberately omitted from the marking process.

Fig. (2) LANDSAT I mosaic of the Adirondack Mountains region showing major features of relief and drainage.

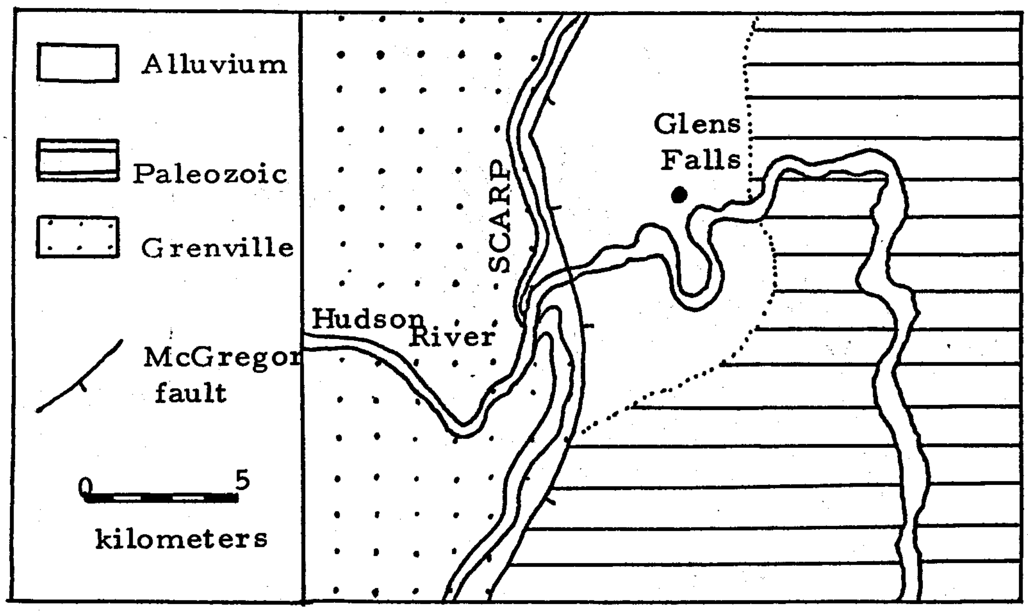


Figure (3) THE MCGREGOR FAULT SOUTH OF LAKE GEORGE MARKS THE WESTERN SIDE OF THE LAKE GEORGE GRABEN.The close proximity of the fault scarp(two contours indicated) to the mapped fault indicates that there has been little scarp retreat along the fault line and that the fault may have moved recently.Similar relations between faults and scarps are common in the area of the Lake George and Lake Champlain graben.

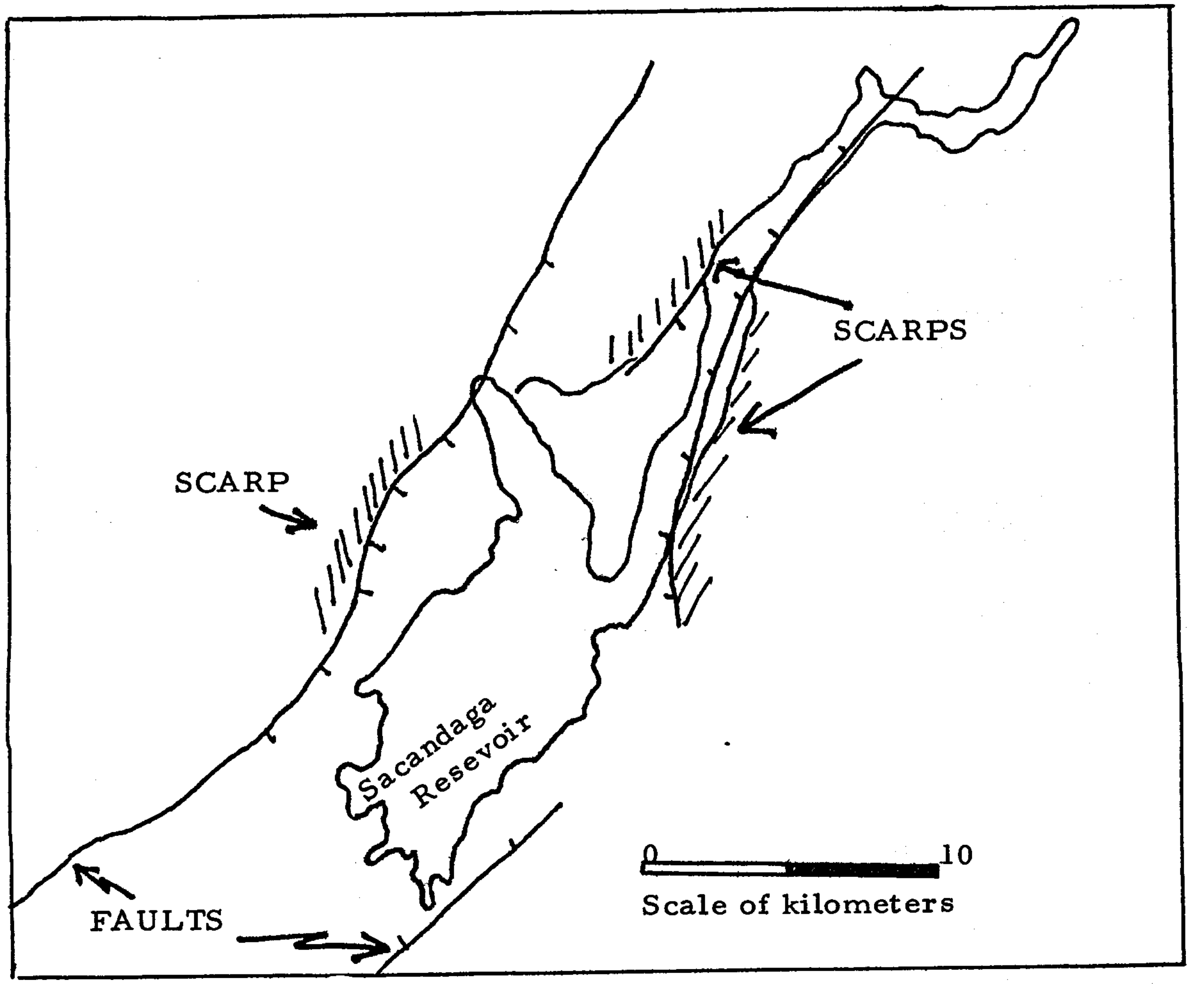


Fig.(4) Possible Recent faulting in the southern Adirondacks. Fault scarps around Sacandaga resevoir lie very close to the mapped traces of faults that downthrow Lower Paleozoic sediments among the Grenville rocks of the Adirondacks.

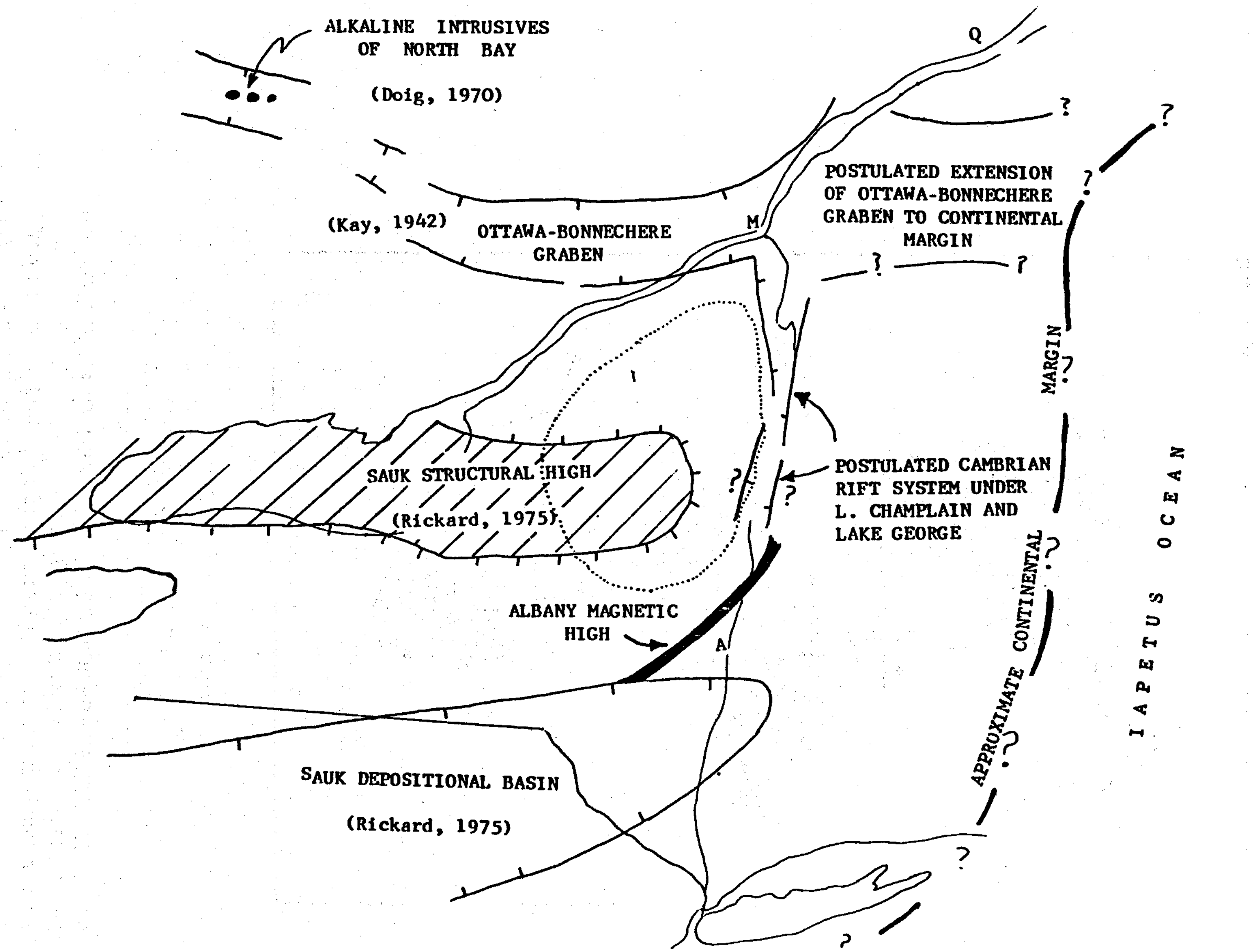


Fig. (5) CAMBRIAN STRUCTURAL FRAMEWORK OF THE ADIRONDACKS. The continental margin of Iapetus lay to the east of New York and may have changed from a north-south to an east-west trend in the area of Long Island. The Ottawa-Bonnechere graben was a failed rift marked by alkaline igneous activity and striking at a high angle to the continental margin. A structural high occupied roughly the area of Lake Ontario extending partly into the area of the Adirondacks. A parallel depositional trough lay south of this structural high. Cambrian rifts linked to the Ottawa-Bonnechere system are postulated to have occupied the sites of the present Lake Champlain and Lake George rifts. The Albany magnetic high may be related to a rift valley axial dike of the Cambrian rift system.

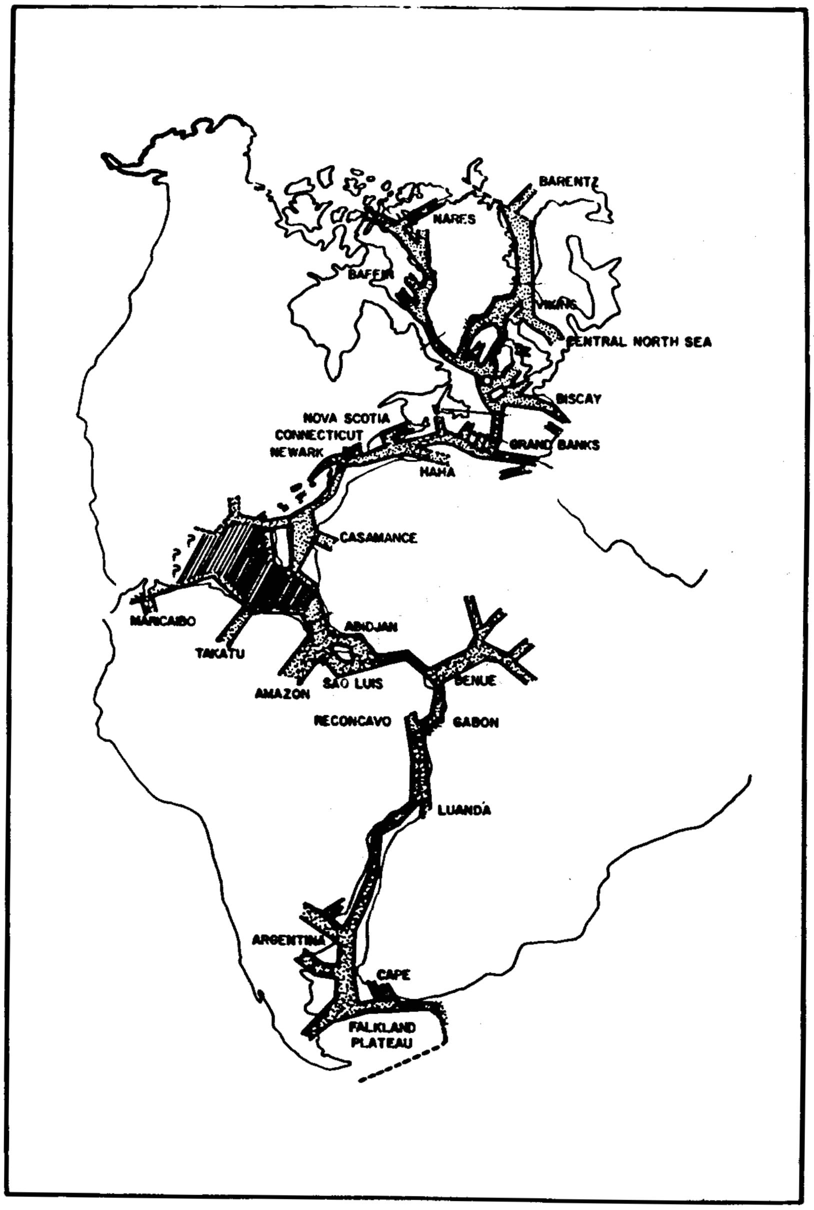


Fig. (6) RIFT VALLEYS ASSOCIATED WITH THE OPENING OF THE ATLANTIC (from Burke 1976b).
The complex rift pattern left within continents at continental rupture is illustrated by this diagram of rifts around the present Atlantic. A similar pattern is believed to have existed around the Iapetus Ocean part of which is preserved in New York.

the shield areas of North America (e.g. White, 1972) the more traditional idea (e.g. Flint, 1971) that these glaciations have done little more than modify existing relief seems to be more strongly supported by the evidence (Sugden, 1976). Observations within the Adirondacks show that although evidence of glaciation in the form of till and fluvio-glacial sediment is ubiguitous, development of the characteristic land forms of glaciated terrains (e.g. u-shaped valleys, cirques and aretes) has occurred to only a very limited extent. The effects of glaciation on Adirondack erosion and relief are not extreme and the elevation we now see is a large part of the whole.

Radial Drainage Pattern: The radial drainage pattern of the Adirondacks has been illustrated in fig. 1 by emphasizing reaches of streams that exhibit parallelism. This procedure is frankly subjective and has been deliberately biased to reject stream lengths that are parallel to the prominent NNE joint and fault sets of the Adirondacks (Isachsen, 1974, fig. 6).

A regular radial pattern is well-defined on the Northern, Western and Southern flanks of the dome and a less well-defined pattern can be discerned along the eastern flank. In this eastern province Northeastern and Southeastern sections with radial drainage can be recognized, but the pattern is partly obscured by the local effects of the Lake George and Lake Champlain rifts. A circular area about 30 km in radius roughly centered on Blue Mountain Lake has no prominent radial drainage pattern and may for this reason lie near the center of the uplift. The mid-point of this area is displaced south-west some 30 km from the highest peaks and a possible explanation of the displacement is that the anorthositic rocks of the high peaks are unusually resistant to erosion.

The radial drainage pattern of the Adirondacks has long been recognized ( ) and is most readily explained as a development consequent on dome uplift. If, as seems probable (Rickard, 1975), the Adirondacks were overlain prior to doming by Cambrian and Ordovician sediments like those of neighboring areas then the drainage was superimposed on the complex structures of the Grenville rocks now at outcrop from consequent drainage off a structural dome formed of gently dipping Cambrian and Ordovician limestones, sandstones and shales.

Possible Lag in Surface Heat Flow Increase at a Hot-Sp Crough and Thompson (1976) have shown that an increase of heat flux below the lithosphere, such as is here suggested for the Adirondacks, produces immediate surface uplift and lithospheric thinning but that the associated increase in surface heat flow begins only 20 to 40 my later. This is valid for situations in which the heat is conducted through the lithosphere. Observation of volcanoes on the crests of uplifts (for example: in the Black Hills and at many places in Africa) indicates that heat is commonly transmitted rapidly to the surface by the intrusion and extrusion of magma so that although the Adirondacks are apparently a young uplift there is no need to wait tens of millions of years until an associated thermal pulse reaches the surface.

Compressional Earthquake Mechanisms: Strong evidence that the uplift of the Adirondacks is presently in progress comes from relevelling (Isachsen, 1975, 1976) and from the earthq uake activity that centers around Blue Mountain Lake (Sykes and Sbar, 1973). Composite first motion studies for the shallow earthquakes of the Blue Mountain Lake swarm yield a compressional mechanism trending roughly in the direction calculated for the motion of North America with respect to the underlying mantle using the Africa stationary hypothesis. Although this orientation of compressive stress is consistent with the expected response of the lithosphere to stresses applied to its base by moving mantle in the asthenosphere it is hard to understand a close association between the dome-shaped uplift of the Adirondacks and crustal compressive stress. The dome-shape and the evidence of uplift seem much more likely to be associated with shallow tensional stresses. Tensional stresses are likely to be dominant at shallow levels in the crust as a result of thermal contraction and uplift on a spherical earth (Haxby and Turcotte, 1976) and the occurrence at shallow depths (a few km) of compressional deviatoric stresses as indicated by earthquake mechanisms within plates is a widespread but as yet poorly understood phenomenon.

Lake Champlain and Lake George Rifts: A satisfactory theory of Adirondack topography must explain the adjacent rift troughs of Lakes George and Champlain that separate the Adirondacks from the Appalachians. The rift character of the Lake George and Champlain troughs is suggested by their topography with steep sides and rivers draining only short distances from the Adirondack and Appalachian mountains on either flank (figs. 1,2). No firm evidence of young faulting in the Lake George and Champlain troughs has yet been mapped but several phenomena are suggestive of its occurrence and the idea that this is fault-dominated terrain has long been in the literature (e.g. Quinn, 1933).

First the topography itself (as shown in fig. 2) seems hard to produce without faulting. The drop at the edge of

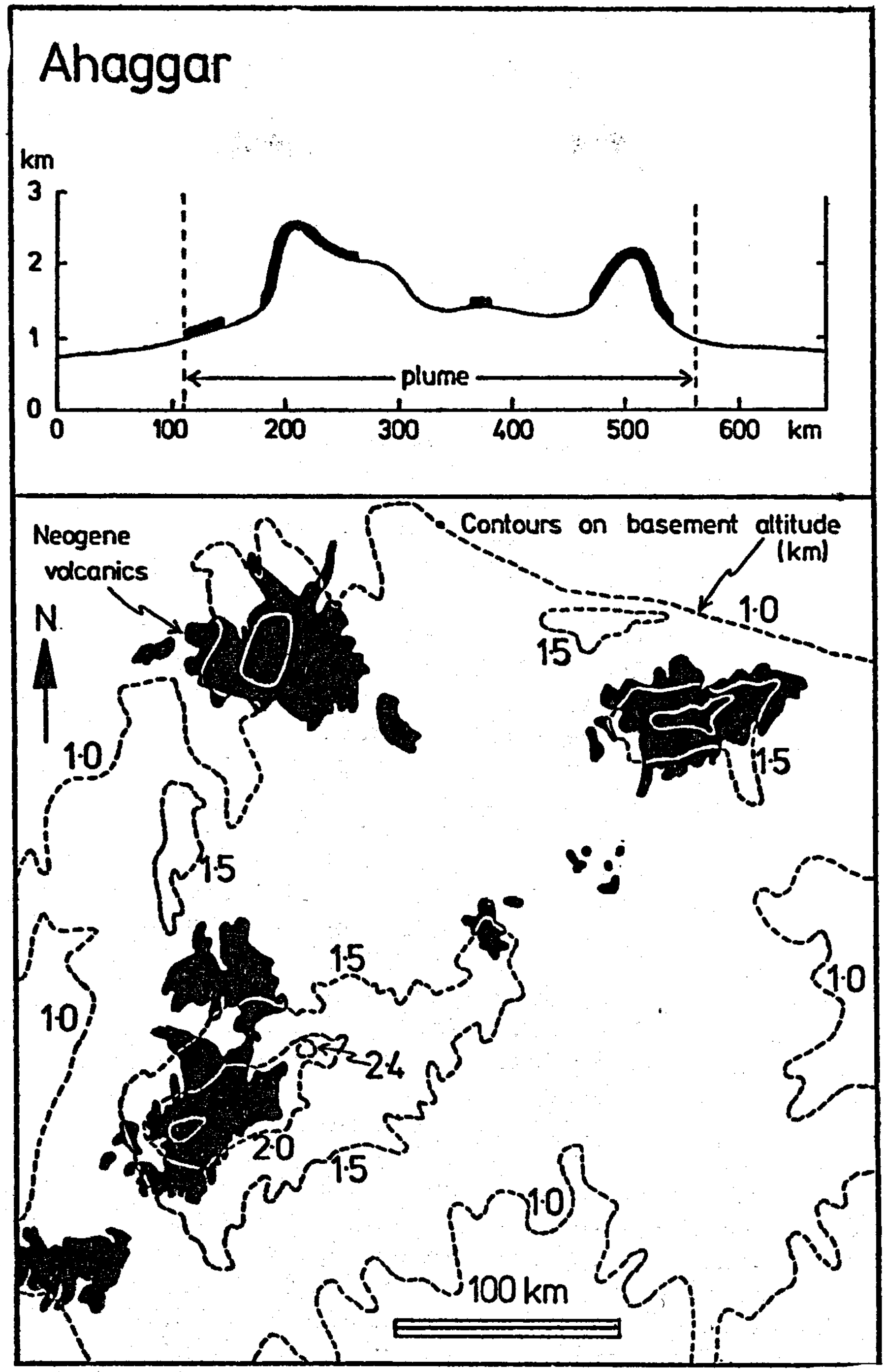


Fig. (7) THE AHAGGAR HOT SPOTS (Drawing by W.S.F. Kidd based on Black and Girod 1970).
This uplift in the central Sahara raises the crystalline basement nearly 2.5 km above the level of the Paleozoic contact. Basalt (black) is erupted from volcanoes on the crests of the three highest parts of the general uplift. If the Adirondacks overlie comparable hot spots the most likely site of magma is under the high peaks.

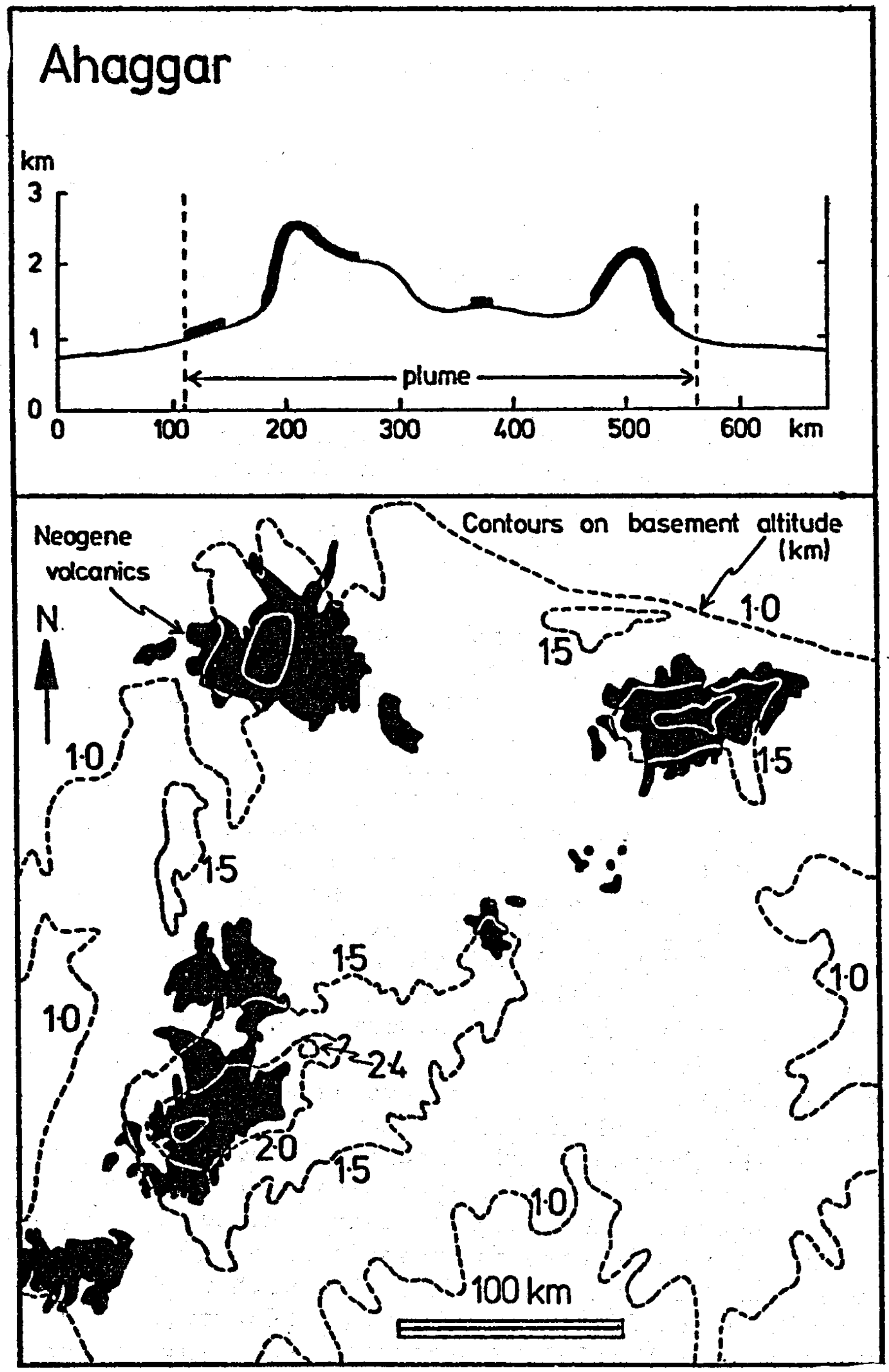
APPENDIX II

EOS, Trans. Amer. Geophysical Union 55:6:457, 1965

CATEGORIES OF ANOMALOUS TOPOGRAPHIC RELIEF WITHIN PLATES

S. E. DeLong
W. S. F. Kidd
K. Burke (all at: Dept. of Geological Sciences, State Univ. of New York at Albany, Albany, New York 12222)
Y. Isachsen (New York State Geological Survey, Albany, New York 12203)

Most major relief on earth is associated with active plate margins. Continental and insular slopes separating the two platform areas defining the maxima on the first derivative of the hypsographic curve are the main regions of relief away from active plate margins. Problematic areas of major relief away from plate and continental margins fall into three main categories: 1.Some old mountain belts (e.g. Urals, Appalachians, and Caledonides). These elevations (1-2 km ASL) are too high to be relicts of orogenic topography and a problem is why are they high now. 2a.Active intraplate volcanic areas (hot spots) in both continents and oceans, are always associated with circular to elliptical structural uplifts of 1-2 km about 200 km across (e.g. Hawaii, Tibesti). Old hot-spot sites persist as seamounts in oceans, but are eroded in continents. 2b.Uplifts indentical to those associated with hot spots, but with no vulcanism (e.g. Adirondacks, Agulhas Plateau, Putorana and several in Southern Africa. The presence or absence of volcanic rocks in these two categories is probably of minor significance. 3.Other areas with 1-2 km of uplift, of linear to near circular plan, usually of major extent (≈1-2000 km). SriLanka and the Nilgiri Hills are protoplate margin relief associated with 6 my old aborted convergence. The Bermuda Rise, E. Brazil, Tornegat Mtns, Baffin Island, and the Eastern Rockies are each unique in certain aspects and are therefore difficult to classify. Areas of high relief in central Asia and China are a mix of plate margin, collision, and hot spot types.



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APPENDIX III

THE PANTHER MOUNTAIN CIRCULAR STRUCTURE: A POSSIBLE BURIED METEORITE CRATER

Yngvar W. Isachsen, Stephen F. Wright, Frank A. Revetta, and Robert J. Dineen

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THE PANTHER MOUNTAIN CIRCULAR STRUCTURE: A POSSIBLE BURIED METEORITE CRATER

Yngvar W. Isachsen, Stephen F. Wright, Frank A. Revetta,[1]
and Robert J. Dineen

INTRODUCTION

We were led to a study of the Panther Mountain circular feature in the central Catskill Mountains, after discovering its striking appearance on satellite imagery. Our subsequent investigation to date does not permit us to explain the feature with any certainty, but it does enable us to narrow the range of possible explanations.

This article is a progress report which describes, in historical sequence, our investigations to date. Our work proceeded in the following, sometimes overlapping, stages: photogeology, gravity and magnetic measurements, conventional field study, and shallow seismic refraction profiling. A study of cuttings from a drill hole located inside the margin of the structure study is just beginning.

The structural geology of the region in which the feature occurs is not well known; the bedrock geology of the Phoenicia quadrangle, in which the Panther Mountain circular feature is located, has not been mapped in any detail. Chadwick (1936) shows a "preliminary map" of the Phoenicia and Kaaterskill quadrangles at very small scale (1:350,000), and the Geologic Map of New York by Fisher and others (1971) shows the geology only by projection. The formations shown on the State map, all continental clastic rocks of Upper Devonian age, are as follows: Walton Formation (shale, sandstone, conglomerate), which underlies the valley floor and most of Panther Mountain; the Slide Mountain Formation (sandstone, shale, conglomerate) which underlies the summit area, and the Honesdale Formation (sandstone, shale) which forms the summit itself. The colors of these rocks are red, green, and gray. The glacial geology of the region has been mapped and described by J.L. Rich (1934).

PHOTOGEOLOGY

The physiographic and drainage features of the Catskill Mountain region are remarkably well displayed on Landsat imagery (Fig. 1). The regional morphology reflects major geologic and tectonic provinces, as well as providing insights into the history of brittle deformation in the region (Isachsen 1973, 1974; Isachsen and others 1974).

The Allegany Plateau, with the Catskill Mountains forming its eastern projection, comprises all but the eastern portion of Figure 1. For the most part, the Plateau is marked by dendritic drainage, with major consequent streams flowing southwestward down the gentle (1^{o}-2^{o}) regional dip of Devonian continental and marine strata.

[1]State University College at Potsdam; other authors from Geological Survey New York State Museum.

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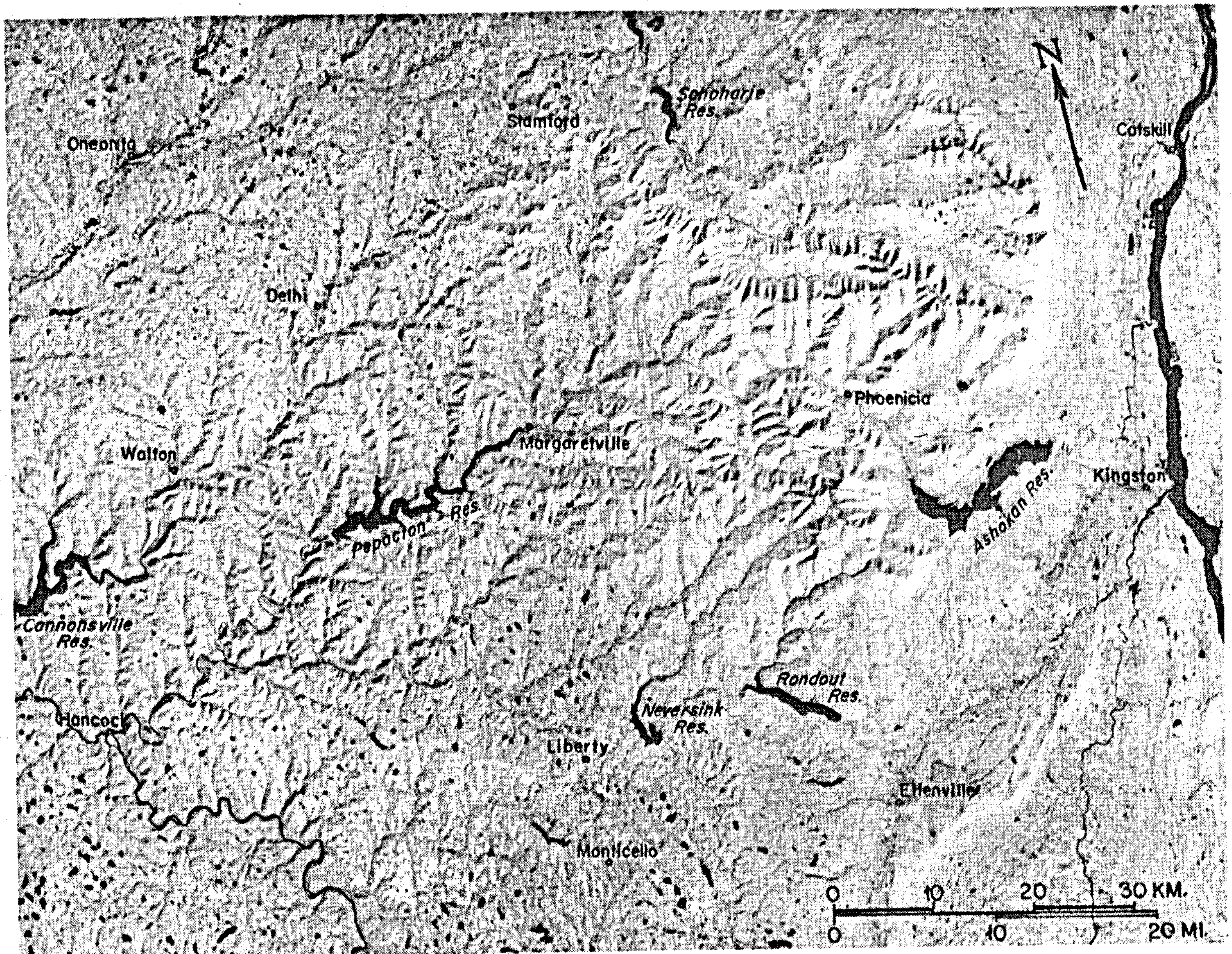

Figure 1. Landsat 1 (ERTS) infrared image of Catskill Mountain region (portion of Image No. 1079-15124-7). Note how the circular form of Esopus Creek near Phoenicia contrasts with the general dendritic pattern of the region.

Esopus Creek, however, which drains into the Ashokan Reservoir, departs markedly from this dendritic pattern (Fig. 1, 2). Together with its uppermost tributary, Woodland Creek (Fig. 3), it forms an anomalous circular drainage feature 10 km in diameter. This drainage encircles Panther Mountain (el. 858 m, 2680 ft.), and is herein referred to as the Panther Mountain circular structure. Surrounding this structure is a series of interrupted arcuate ridges which together form an enclosing circular rampart of about twice the diameter of the Panther Mountain structure, and offset to the north. This circular alignment of ridges is open to the east. It can be discerned on Figure 1, but the ridge crest is better defined on a good drainage map (e.g. Isachsen, in press) where it shows up as a divide of gross circular dimensions. This outer circular feature has not been studied and will not be referred to further. Other arcuate features may be seen in the imagery, but these are much less striking, and may be fortuitous.

Another set of morphological features deserve mention, namely, the set of closely spaced NNE linear features which cross the prominent EW ridges of the Catskills at right angles. These may be zones of closely spaced joints produced as a result of reactivated basement faults (Isachsen and others, 1974). Be that as it may, we wish to point out for later reference that they occur both north and south of the Panther Mountain structure but, with one possible exception, do not pass through it.

The morphological details of the Panther Mountain structure can be seen in Figure 2, which is a high-altitude (U2) infrared photograph. For geographic orientation, see the topographic map at the same scale on the facing page (Fig. 3). At this scale, many irregularities can be seen in the circular rim valley, the most noteable being the right-angle bend of Woodland Valley in its upper reaches. Close examination of the photograph shows that much of the rim valley is actually made up of such north-south and east-west segments. Similarly, Figure 1 shows numerous examples in the general region of north-south and east-west tributary valleys which feed the major southwest-flowing streams. The north-south set appears to be longer (up to 15 km) and thus more prominent; their trends actually range from north-south to north-northeast. We will refer to these linear features later.

PREVIOUS RECOGNITION OF THE PANTHER MOUNTAIN STRUCTURE

Sometime after our photogeological "discovery" of the Panther Mountain feature, L.V. Rickard called our attention to an entertaining article by Chadwick (1950), written for the layman, in which he referred to the Panther Mountain mass as "a great rosette," and interpreted it as a "low dome." Chadwick referred to this "dome" in four unpublished consulting reports written in 1943, 1944, 1948 and 1951. We were unable to evaluate this documentation for his interpretation because maps were missing from each of the reports available to us. Another unpublished consulting report on the Panther Mountain feature, written by Ralph Digman in 1948, also lacked a reference map which incorporated both Chadwick's and Digman's strike-dip data. Digman was less certain of the validity of strike-dip measurements in the continental Catskill facies but concluded that "The domical structure for the area of the Panther Mountain massif is considered a strong possibility."

Figure 2. High altitude (U-2) infrared photograph of the Panther Mountain circular feature. Note the lack of lateral continuity of the continental clastic rocks which make up this region. For geographic orientation, see topographic map at same scale on opposite page. Ignore darkroom blemishes near center of photograph.

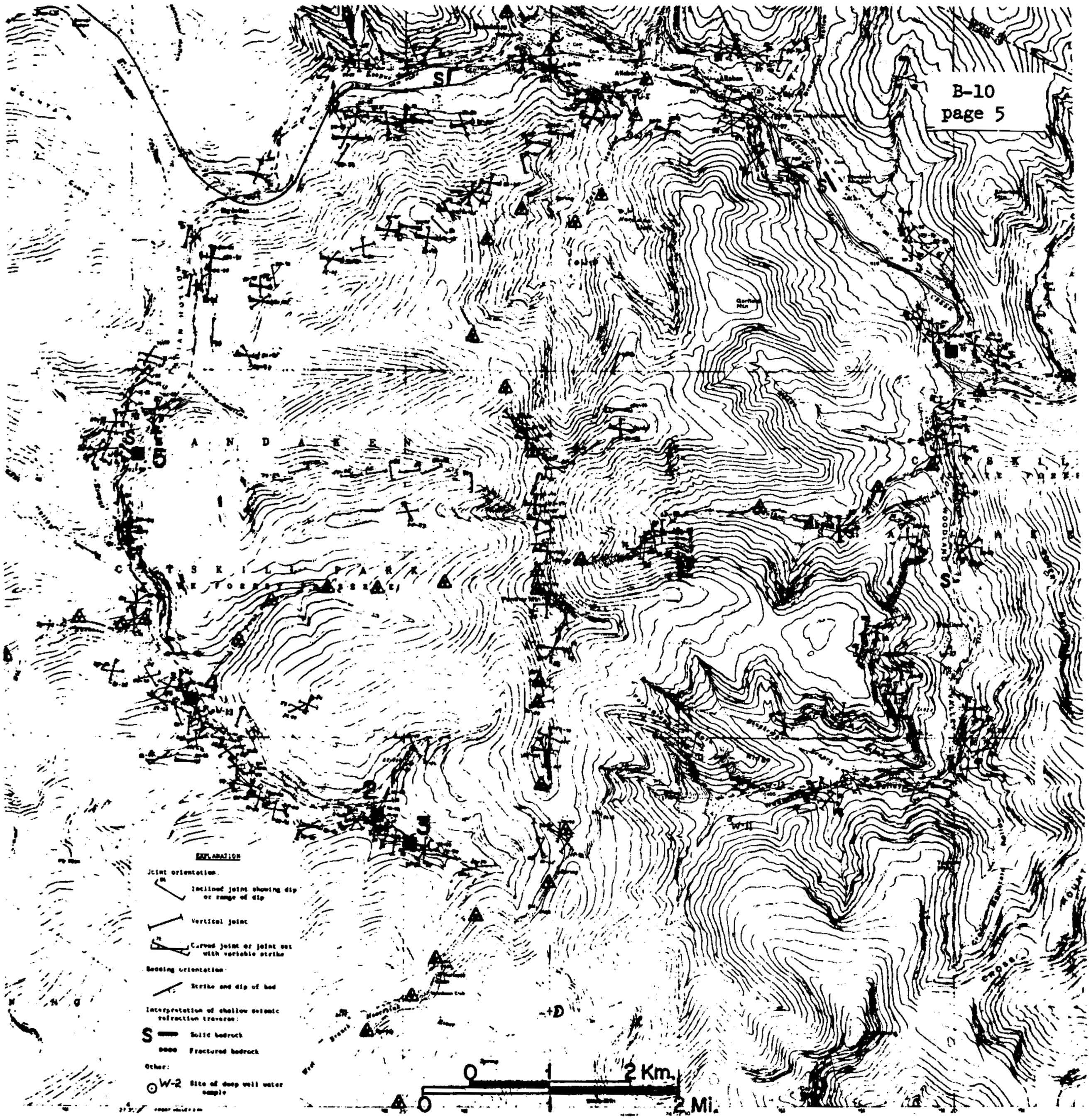

Figure 3. Reduced copy of joint work map of the Panther Mountain structure (7 1/2 minute topographic base from Shandaken and Phoenicia quadrangles). Triangles show locations of NS and EW gravity and magnetic stations, and squares with numbers indicate field trip stops. Sites of seismic refraction profiles are, in clockwise direction, Bedell Street, Golf Course Road, St. Vincent De Sales Cemetery, and Woodland Creek floodplain.

Several years after the submission of these consulting reports the Herdman well was drilled in Fox Hollow, near the northern edge of the Panther Mountain mass, to test for gas. The hole penetrated the Paleozoic section down to the Shawangunk Conglomerate in which it bottomed at 6400 feet. Selected cuttings from this well will be studied during the next phase of our investigation.

GRAVITY AND MAGNETIC STUDIES

Introduction

The above observations were made before any field visits to the area. Our first thoughts were that field study would show the structure to be either a very low-amplitude dome or basin. This led to the question: If it is a dome or basin, what might be the underlying cause? We decided that the best approach to this question would be to run two perpendicular gravity and magnetic surveys across the circular feature, and to extend them about one diameter beyond. A prior examination of the simple Bouguer gravity anomaly map at 1:250,000 of the region by Diment and others (1973) showed only that the circular feature was located on an elongate gravity gradient sloping 1 milligal/km to the southeast, without any associated perturbations.

Measurements

Gravity and magnetic measurements were made across the Panther Mountain circular feature at some 70 stations with a station spacing of approximately 1 km. Each traverse was about 30 km long, sufficient to extend across the 10 km diameter of the Panther Mountain mass and 6-10 km beyond in each direction. Figure 3 shows station locations within the area of the map.

The gravity measurements were made using a Worden Gravity Meter. For the measurements, a base station was established at Phoenicia which is tied to the U.S. Geological Survey network. Two readings were taken at each station to minimize errors due to drift and misreading the meter. Meter drift between readings was assumed to be linear, and corrected readings were determined from a drift curve plotted at the end of each day's work. Station elevations were determined by altimeter which was corrected for changes in temperature and barometric pressure. Four corrections were applied to the gravity measurements: free air, latitude, Bouguer, and terrain (32 stations).

The magnetic survey was made using an M50 magnetometer made by Varian Analytical Instrument Division.

Observations

Results of the gravity and magnetic surveys are summarized in Figure 4, with topographic profiles added for purposes of location and comparison.

It may be noted at the outset that the magnetic profile does not show any clearly anomalous characteristics over the Panther Mountain massif, nor over the rim valley. This indicates that if the Panther Mountain circular anomaly is controlled by some buried feature, that feature has

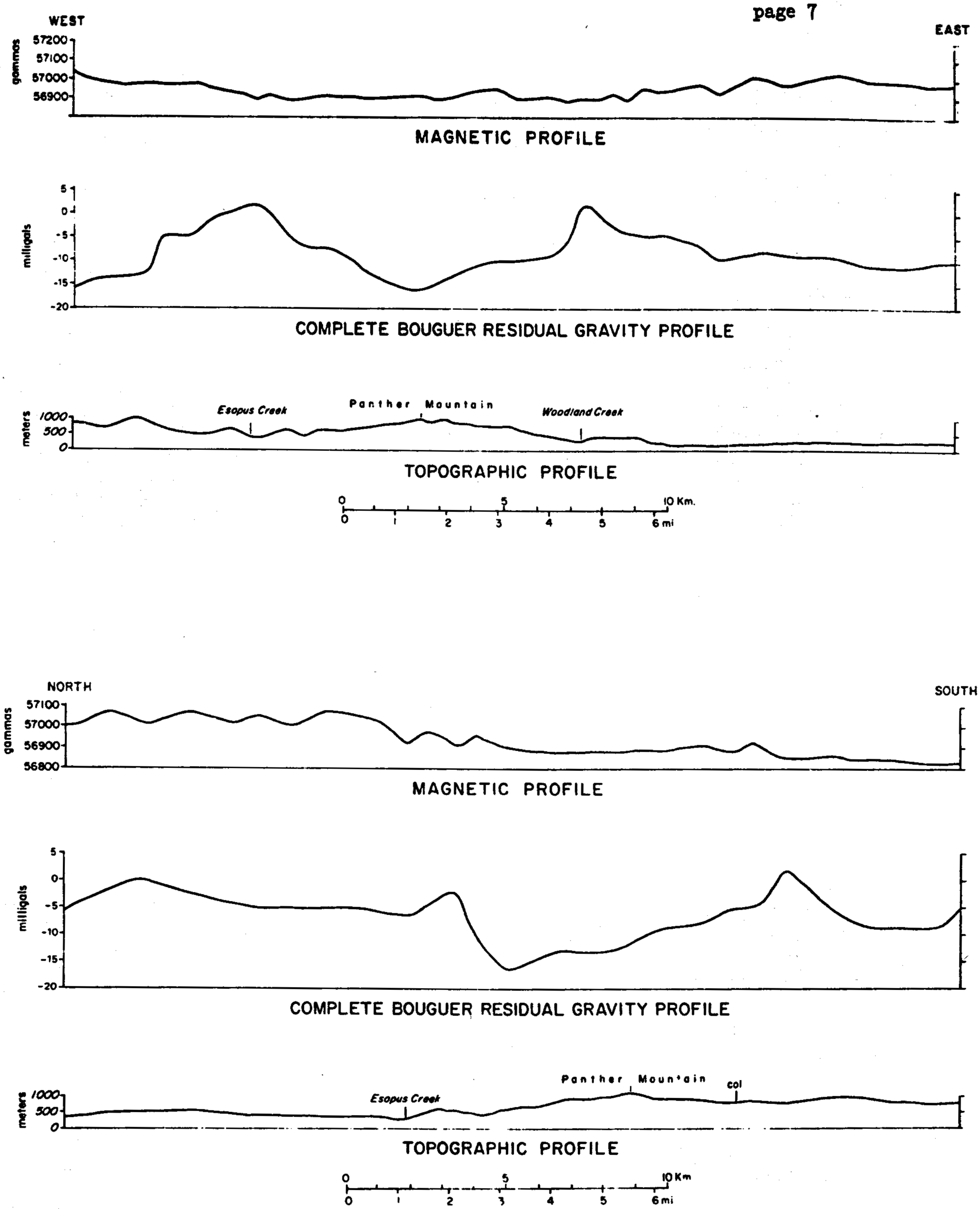

Figure 4. West-east and north-south topographic, gravity, and magnetic profiles across the Panther Mountain circular structure. Locations of geophysical stations are shown in Figure 3. See text for discussion.

essentially the same magnetic susceptibility as the surrounding area. We will refer again to this point later in the text.

The gravity profiles are more exciting in that they show a pronounced (18 mgal) negative anomaly over the feature. However, there are differences in the shapes of the west-east and north-south gravity anomalies, so they will be discussed separately.

The west-east profile shows a highly symmetrical negative gravity anomaly. It has a very steep gradient on the east and a moderately steep one on the west. These lead to an interior "bench" and then to a deeper depression in the center. The gravity relief from the rims to the bench is 12 mgal, and the total relief is 18 mgal. The remainder of the profile outside the Panther Mountain area is not particularly anomalous except near its western end where a steep gradient with 7 mgal relief occurs. This may be due to measurements which were not terrain-corrected.

The north-south profile is a pronounced, asymmetrical gravity low with a long, steep gradient on the north side and a relief of 18 mgal. A relatively small (9 mgal) low occurs north of the main anomaly but the remainder of the gravity profile is relatively featureless. It is important to note that the diameter of the gravity depression is the same as that of Panther Mountain, although the depression is shifted slightly south with respect to the Panther Mountain mass. In the topographic profile, this mass is bounded by Esopus Creek to the north and a col to the south. The rims of the gravity depressions on both sections are bounded by small peaks. The significance of these is still uncertain.

Interpretations

It appears clear from the gravity data (pending additional gravity traverses across the feature) that a high-magnitude gravity low coincides closely with the Panther Mountain circular feature. In addition, whatever the underlying "source," it has the same magnetic susceptibility as the surrounding rock, and hence must have about the same ferromagnesian mineral content.

There are several ways to explain the gravity anomaly. All call for a drastically less-dense mass underlying Panther Mountain, and the occurrence of this mass at a shallow level (1 km), in order to account for the steep gravity gradients. The first possibility, an intrusive salt diapir, might fulfill these requirements inasmuch as the specific gravity of salt is 2.16 vs an estimated value of about 2.7 for the Paleozoic section. However, the eastern edge of the Salina salt basin is known from drill hole information to be some 70 km west of the Panther Mountain area (Rickard 1969).

Two other categories of explanation were considered: 1) intrusion of foreign rocks of relatively low density, such as granite or rhyolite, into the Paleozoic section, and 2) severe brecciation of existing rocks, due to hypervelocity impact into the Paleozoic stratigraphic section and underlying basement rocks which would reduce their density. These two

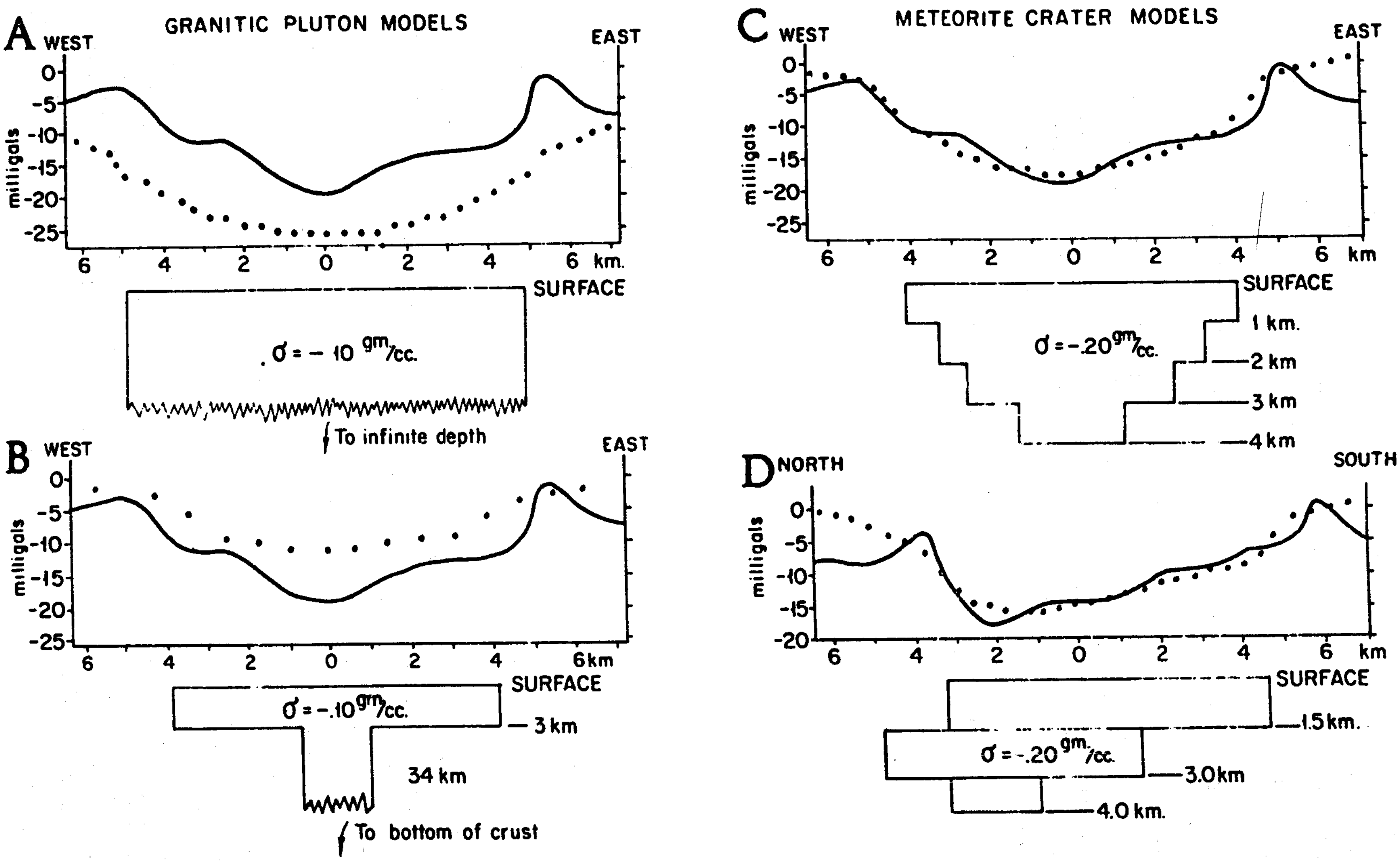

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Figure 5. Gravity models that were tested for compatibility with measured values across the Panther Mountain circular structure. The modeled granitic plutons were chosen to simulate a stock (upper left) and an intrusive sheet and feeder pipe (lower left). Models of a near-surface breccia lens such as would be associated with a buried astrobleme are shown for both the west-east and north-south profiles. Solid lines show measured values, and dotted lines the computed gravitational attraction of the model tested.

were modeled in many configurations, and four of the better fits are shown in Figure 5. Profiles A and B show two of numerous shapes and dimensions of granitic plutons that were modeled. A density contrast of 0.10 gm/cc was used, based on an average value for granite (2.65 gm/cc) vs an estimated value of 2.75 gm/cc for the Paleozoic section and underlying Proterozoic rocks. Density figures were taken from Clark (1966). The poor correspondence between measured and calculated gravity values is obvious. The 0.1 gm/cc density contrast thought representative of a felsic pluton is not great enough to produce the steep gradients in the measured gravity profile, even when the intrusive is modeled as a cylinder of 10 km diameter, placed close to the surface.

For the model of in situ brecciation we chose a buried meteorite crater, or astrobleme, with its associated breccia lens, and modeled it as a series of cylinders of decreasing diameter stacked to represent the shape of a breccia lens. We chose an empirical density contrast, using the 0.2 gm/cc value found in drilled breccias of Canadian astroblemes (e.g. Innes, 1961). The resulting fit between measured and calculated values shown in Figure 5C is very good. Analogous modeling of the asymmetrical north-south profile produced a rather good fit using the arrangement of cylinders shown in Figure 5D.

Thus the best computational models of the gravity of the Panther Mountain circular structure permit the interpretation that it is caused by an asymmetrical lens of brecciated rock such as might have been produced by the impact of a meteorite entering the area from the south, with a low angle of trajectory.

Although the above interpretation fits the gravity data, perhaps nothing short of a drill hole near the center of the structure or a seismic profile across it would adequately test the idea - unless study of the Herdman well cuttings shows clear evidence of shock metamorphism.

We will return to a consideration of the buried-astrobleme model after describing and analyzing our field structural and seismic refraction studies.

STRUCTURAL GEOLOGY

A fundamental question we had hoped to resolve by field study was whether the Panther Mountain structure is slightly domical, basinal, or unwarped. That question remains unanswered due to the fluvial depositional fabric of the sedimentary rocks in the region. They consist largely of alternating continental sandstones and pebble conglomerates characterized by large-scale cross-stratification and erosional scour marks at the base of units. Overbank deposits of red silty shale make up the remainder of the section, but these units are generally obscured except at the base of some sandstone cliffs. When exposed, they are commonly scoured and channeled by the overlying sandstone units. Sub-horizontal bedding surfaces are very rare due to pervasive cross-bedding of sandstones and scouring of shale units. The few surfaces we were able to measure gave inconsistent results concerning possible flexing of the structure. We were probably measuring scoured surfaces of shale. Thus, we were unable to support or refute the previously mentioned conclusions of Chadwick that the Panther Mountain structure is a low dome.

Field studies, nevertheless, did provide a considerable amount of data relating to brittle deformation - specifically jointing. Some 500 individual joints or joint sets were measured at a total of 236 stations in an effort to determine whether the joints located within the circular valley differ in any way from those located away from the valley. Features examined included orientation, spacing, degree of curvature, surface irregularity, and host lithology. Two main features which characterize the majority of joints seen in individual outcrops are: 1) general lack, with some notable exceptions, of any single, dominant, through-going set against which other joints abut, thus making the systematic versus non-systematic classification inapplicable, and 2) the comparative rarity of planar as opposed to curved joint surfaces. Such curvatures occur in both the horizontal and vertical dimension. Even joints of the same set in a single outcrop or nearby outcrops differ markedly in their expression.

Where extensive joint faces are exposed, such as in the many old flagstone ("bluestone") quarries of the region, the degree of planarity can be seen to vary considerably over distances of a meter to a few meters. The character of these surfaces ranges from planar to broad, regular, cylindrical rolls through irregular, non-cylindrical curves, to local bumps and depressions. From such giant exposures one gains the impression that all, or nearly all, joints in the area are probably curved, and that "planar joints" are really only planar segments along larger, hidden, irregular surfaces.

Surprisingly, we could find no visible relationship between the curvature of joint surfaces and either the attitude of cross-lamination or the coarseness of grain size in host sandstones and conglomerates. Similarly, rare, extremely planar joints (or segments of curved joints?) cut through highly cross-bedded rocks without deflection. We speculate that the joint-surface irregularities may be related to variations in cementation, but have not studied this question; the local control of joint curvature remains an enigma.

The considerable variation in strike and dip of joints in the region made the recording of strike-dip data more complicated than usual. Joint surfaces which curved in the horizontal plan were recorded as having a range in strike, the limits of which were usually at either end of the exposure. Dips were similarly recorded as a range of values. As always in joint studies, difficult decisions had to be made where outcrops were small, as to which surfaces should be classified as joints and which as irregular fractures.

The recorded data on joint orientations were plotted on a joint work map, which is reproduced as Figure 3. The joint azimuths, without regard for dips, were plotted on rose diagrams. Strikes were lumped into 10^{o} sectors to show azimuth frequency. Curved joints were given proportional representation in each sector covered by its range in strike. Thus,

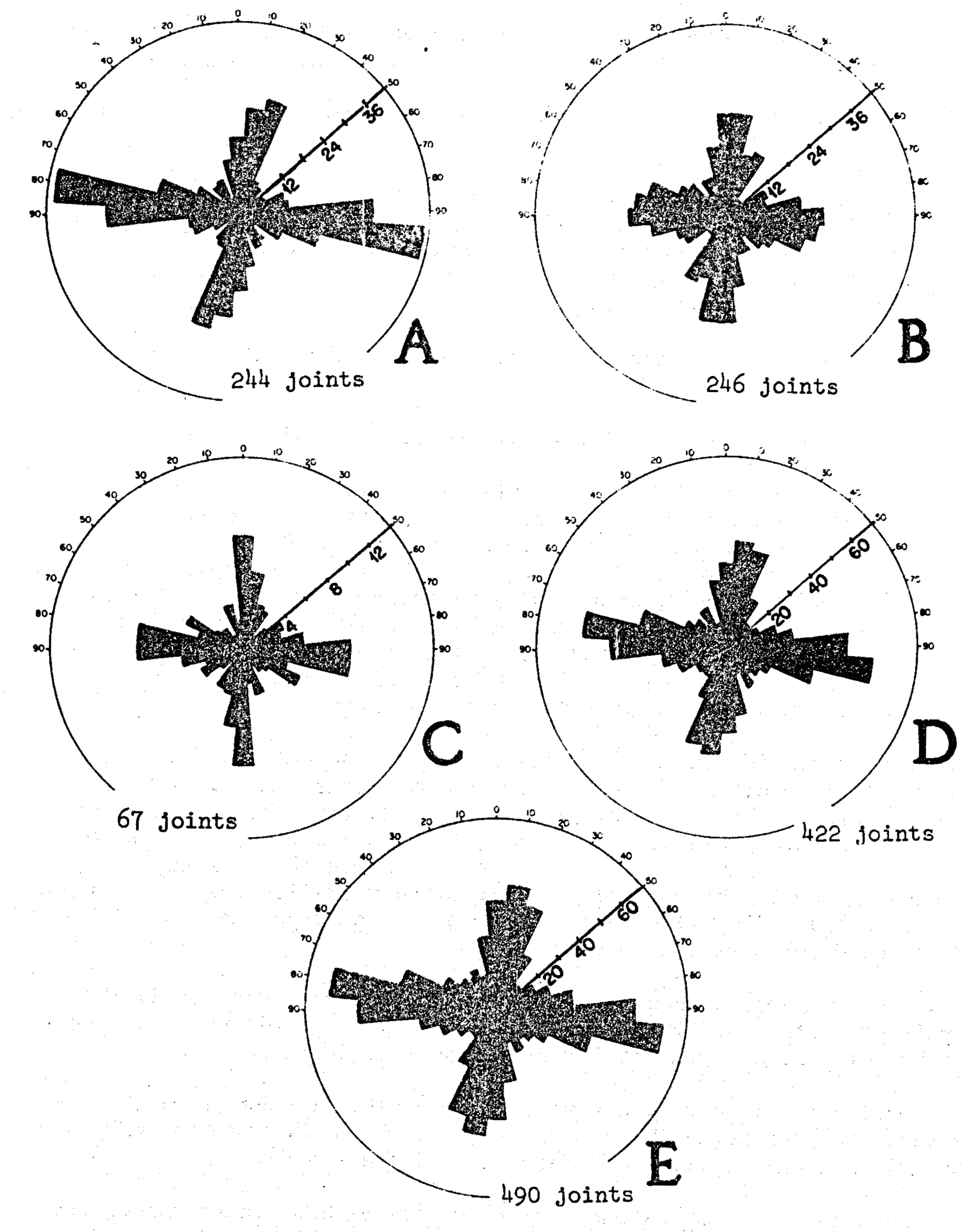

Figure 6. Joint frequency diagrams for: (A) joints of variable strike range (5^{o}-30^{o}), (B) joints of constant strike (range<5^{o}), (C) joints occurring in the center of the rim valley, (D) joints occurring at all localities other than the center of the rim valley, (E) total of all joints measured. Note scale differences. See text for discussion.

for example, a curved joint with a strike range of N10-30W was tabulated as 1/2 joint in the N10-20W sector and 1/2 joint in the N20-30W sector.

The joint measurements were plotted in five categories as shown in Figure 6:

A. Joints of variable strike ("curved joints"): range 5°
B. Joints of constant strike ("planar joints"): range 5°
C. Joints located in or near high-density joint zones
D. Joints located away from high-density joint zones
E. Total of all joints measured.

A comparison of rose diagrams 6A and 6B shows the following relationships:

1. The number of joints with constant strike equals those with variable strike.
2. The population of "curved joints" shows stronger maxima and less scatter than that of "planar joints." (Recall that these terms refer only to strike, not dip).
3. The "planar joints" form an orthogonal system, or "pairset" (Gay 1973), trending essentially NS and EW. The curved joints form a pairset trending NNE and WNW. Considering the great variabilities in curvature of individual joints described earlier, this apparent shift 10° clockwise may not be real, despite the clean appearance of the diagrams.

Rose diagrams 6C and 6D were constructed to compare the frequency distribution of joints in the center of the anomalous rim valley with those elsewhere in the area. Diagram 6C suggests that the rim joints are localized in a strong, equally developed, NS-EW pairset which shows very little dispersion. However, it must be acknowledged that the number of measurements made in the rim valley is relatively small. This is because exposures in the valley floor are restricted to the upper reaches of Esopus and Woodland Creeks (Fig. 3).

The non-rim joints shown in diagram 6D constitute essentially the same pairset, although with less sharp maxima, more prominent development of the EW set, and an apparent 10° clockwise rotation.

Comparing all five rose diagrams of Figure 6, it seems safe to conclude that one prominent pairset, ranging from N to NNE and W to WNW, characterizes the main-brittle deformation of the region.

These joint sets correspond extremely well with orientations of the numerous, earlier-mentioned, linear stream courses within the Panther Mountain structure, as well as with the short N-S and E-W segments of the Esopus valley and the larger rectangular corner of Woodland Valley (Figures 2 and 3). Thus it is clear that the major joint sets control much of the topography of the area. This is not to overlook the modifications produced by Pleistocene glaciation, of which an especially prominent example is the cirque at the head of Panther Kill.

It seems likely that the N to NNE and W to WNW linear tributary valleys in the greater Catskill region referred to earlier (Fig. 1) are also controlled in some way by the same orthogonal joint system. This has been discussed at greater length elsewhere (Isachsen and others, 1974).

It is now pertinent to ask if the circular rim valley is controlled by joint orientations. If so, it is not obvious in the frequency distribution of rim joints (diagram 6C). Observation of the joint work map (Fig. 3), however, does show jointing parallel to the stream course in nearly all exposures found in the rim valley or valley walls. However, the limited amount of outcrop in the center of the rim valley makes it difficult to determine whether joint orientation alone might control the circular valley. This is especially true in view of the N-S and E-W segmented nature of the valley in many places.

It is noteworthy that these segments are extremely short as compared to similar joint-controlled drainage within the structure and elsewhere in the region. This suggested that some factor other than joint orientation was responsible for the circular valley development, and that, quite likely, the cause was an increase in joint density due to an intensification of jointing along directions of the regional pairset.

Our field measurements of joint spacing confirmed this prediction. Aside from the center of the rim valley, joint spacing throughout the area consistently falls in the range 1.5-10 m, and commonly exceeds 2 m. This includes valley floors as well as slopes and summits. An example of this regional spacing is shown in Figure 7A, where joints are about 3 m apart in the massive sandstone unit above the excavated shale.

The opportunity to examine joint frequency in the center of the rim valley is, unfortunately, restricted to the heads of Esopus and Woodland Creeks where gradients are relatively high. Elsewhere in the valley the bedrock floor lies beneath a floodplain ranging in width from tens to hundreds of meters (Figures 2 and 3). Where outcrops are found, the spacing between joints is commonly 1 m or less, and, over short distances, as low as 2-5 cm. Figure 7B is a view of Stop 3 located in the upper reaches of Esopus Creek. The joints shown strike about N5E, and the spacing ranges from 5 to 50 cm. Note that these closely spaced joints or joint zones do not continue into the overlying beds. This is typical. These joint zones are restricted to the center of the rim valley but are localized within it both vertically (as shown here) and horizontally.

Figures 7C and 7D are photographs taken at Stop 4 of a joint zone in which a nearly orthogonal system is developed. The general spacing is 20-30 cm, with local zones having joints spaced only 2-4 cm apart. Dips of the joints range from 52°W to 60°E, suggesting that many could be classified as conjugate joints. Here, again, the joint zone can be see in the field to be limited in both horizontal and vertical extent.

For the sake of completeness, it should be added that bedding plane separations or "bedding plane joints" are common. However, they are interpreted as a response to erosional unloading, and were not recorded.

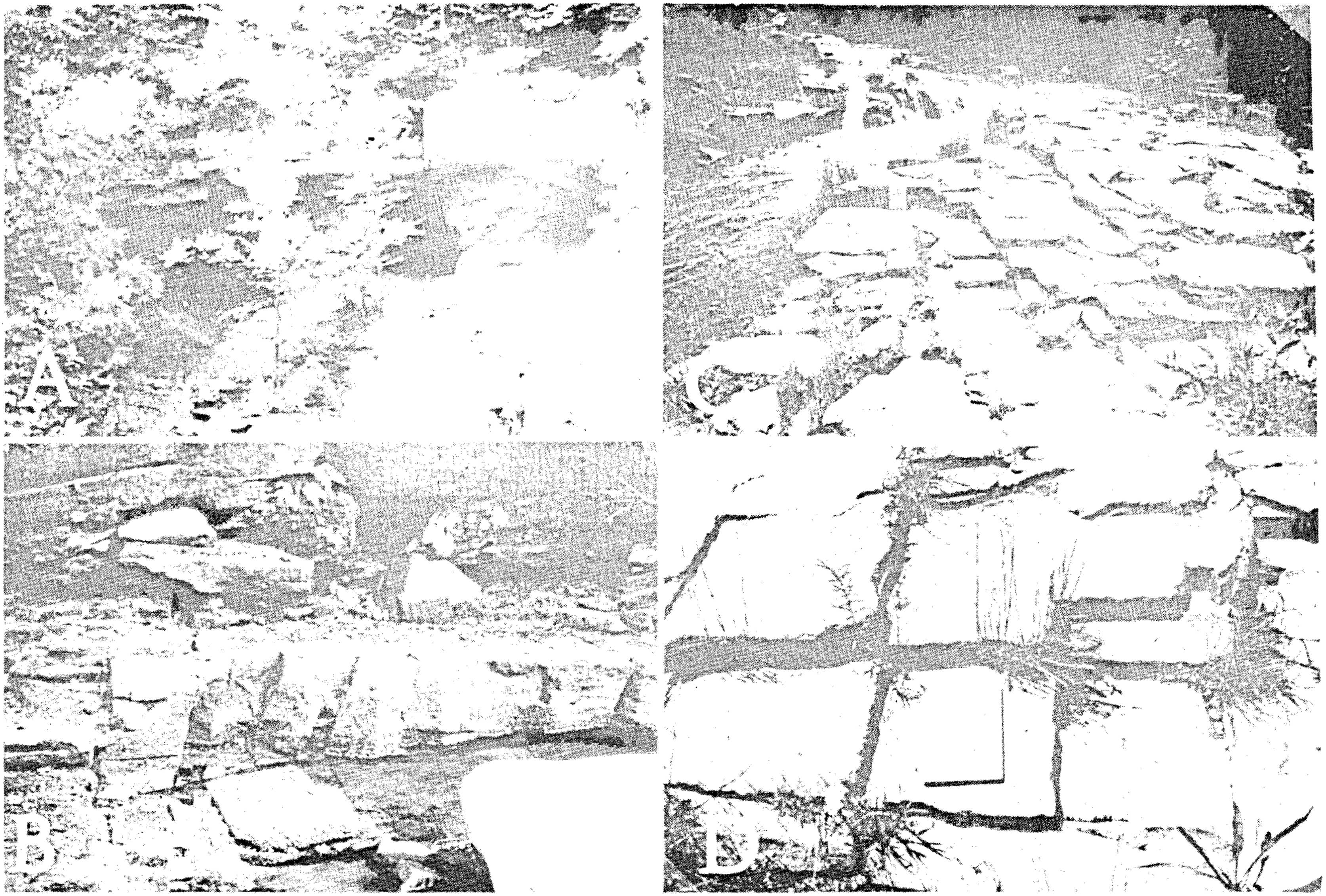

Figure 7. Photographs of joint exposures at: A, "Indian Cave Quarry" (at Roadlog mileage 7.8) showing joints with average regional spacing of 3 m; B, Stop 3 in center of rim valley, looking SSW at joint set with .4-.5 m spacing; C and D, Stop 4 in center of rim valley, looking SSE at pairset with .3-.4 m spacing.

SEISMIC REFRACTION STUDY

As is well known to field geologists, attempts to ascertain the relationship of valley development to bedrock structure are commonly thwarted by alluvial sediments which obscure bedrock at critical localities. Esopus Creek provides another fine example of this dilemma, as can be seen by the restriction of bedrock exposures to small portion of the valley rim (Fig. 3).

To obtain bedrock structural data beneath the extensive, alluvial-filled parts of the valley, we ran several shallow seismic refraction profiles across it. The goal was to search for a low-velocity zone in bedrock which would delimit a possible zone of intense jointing or other fracturing.

The seismic refraction data were gathered with a Huntec FS-3 single-channel seismograph, using a hammer-and-plate sound source. The hammer was a standard twelve-pound sledge, impacting on a ten-pound steel plate measuring 12 inches on a side and 1 1/2 inches in thickness. See Huntec, Ltd. (1970) for a description of the instrument and accessories.

The geophone position was held stationary and readings were taken of hammer blows spaced at ten-foot intervals. Traverses were reversed in order to eliminate the effect of interface slopes and inhomogeneous seismic layers.

The seismic refraction profiles were interpreted using the time-intercept and critical-distance methods, as described by Ewing (1960) and Mooney (1973). A Texas Instruments SR-56 programmable calculator was used to calculate the thickness, station offset, and true velocities of the seismic layers. The time-intercept method gave more consistent results than the critical-distance method in this area.

Four profiles were made across portions of the rim-valley flood plain. Their locations are shown in Figure 3. The sites were selected on the basis of ease of access, flat terrane, and avoidance of power line interference.

The seismic velocities of bedrock in two of the profiles (St. Vincent De Sales Cemetery and the floodplain of Woodland Valley) were found to be between 13,000 fps and 14,900 fps, values which fall in the normal range for sandstone and shale. These lines, therefore, define segments of the rim valley which are not abnormally fractured, and thus place spatial constraints on where a rim fracture zone might be.

The Bedell Street profile (Figure 8), on the other hand, shows an abrupt decrease in bedrock velocity from a normal sandstone-shale value of 14,500 fps on the east to 11,000 fps on the west. This low bedrock velocity is compatible with a zone of sandstone and/or shale having an abnormally high fracture density. Unfortunately this line is too short to show the full width of the low-velocity zone, but the zone appears to be at least 18 m (60 ft.) wide.

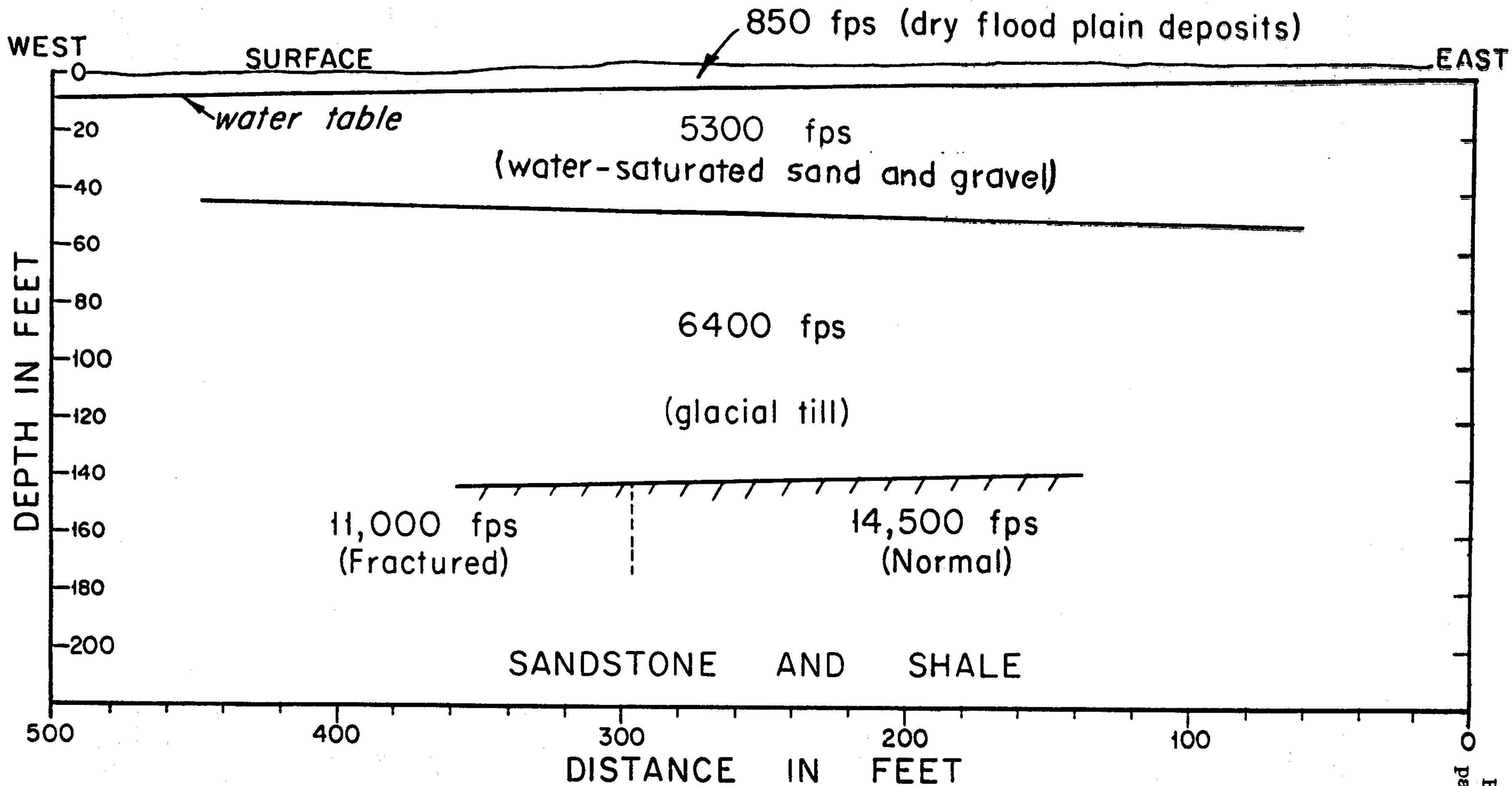

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Figure 8. Seismic refraction profile along Bedell Street on the western rim of the Panther Mountain circular structure. Inferred lithologies for the four velocity layers are shown in brackets. The low velocity in bedrock is interpreted as due to closely spaced joints (joint zone) or other abnormal fracturing.

The profile along Golf Course Road yielded somewhat ambiguous results due to a "phantom" third-layer velocity in the data; analysis of the data using the critical-distance method yielded normal bedrock velocities. The time-intercept method, however, gave low values suggestive of abnormal-fracture density. The latter results are favored because the time-intercept method in this area produced the more consistent results.

"PUTTING IT ALL TOGETHER"

The interpretations given in each of the foregoing sections are here incorporated into a model which might satisfactorily explain the anomalous Panther Mountain circular feature. We believe that the model accommodates the observed morphology, the gravitational and magnetic fields associated with the feature, and the structural geology and seismic refraction profiles derived from our field work.

Figure 9 is a scaled cross-section of the hypothetical buried meteorite crater deemed most probable from the gravity modeling previously mentioned. The stratigraphic section down to the base of the Silurian is derived from the Herdman well located in the northern portion of the Panther Mountain mass. The remainder of the Paleozoic section is based on projection from deep well data to the west (Rickard 1973). The shape and dimensions of the modeled breccia lens were based on a combination of our gravity data and information from Canadian crater studies (e.g. Innes 1961). The partially eroded crater and rim are shown infilled with Devonian continental deposits. Subsequent differential compaction of these sediments produces a zone of high tensional stress directly over the rim of the crater, as indicated by arrows. We visualize this as having two structural effects on the overlying sedimentary rocks: 1) extension occurs via slight openings along pre-existing joints in the thicker sandstone units of the section, and 2) in the thinner beds, an intensification of jointing occurs parallel to the regional joint sets, and perhaps to some degree, along new directions. These effects, together, would produce a zone of erosional weakness congruent with the buried crater rim. This is one possible explanation of the anomalous, circular rim valley.

To date, no evidence exists for repetition of units, or other major stratigraphic disruption, in either lithologic or electrical logs of the Herdman well (L.V. Rickard, oral communication). Whether or not rock units within the section have been tilted is not known because no dip meter survey was made in the hole. The lack of a magnetic low over the structure is not surprising, because although brecciation would disrupt the paleomagnetic alignment of ferromagnesian minerals, such minerals are either absent, or present in very minute amounts, in the Paleozoic section.

The time of meteorite impact according to the above model would be Upper Devonian. The steep gravity gradient and large mass-deficiency beneath the structure require that the low-density source be located within 1 km of the present surface, thus further refining the stratigraphic control on time of impact. In addition, the model dictates that the crater itself must have been relatively young, with still well-developed crater rims, when entombed beneath Devonian sediments. It may thus be a remarkably well-preserved fossil crater.

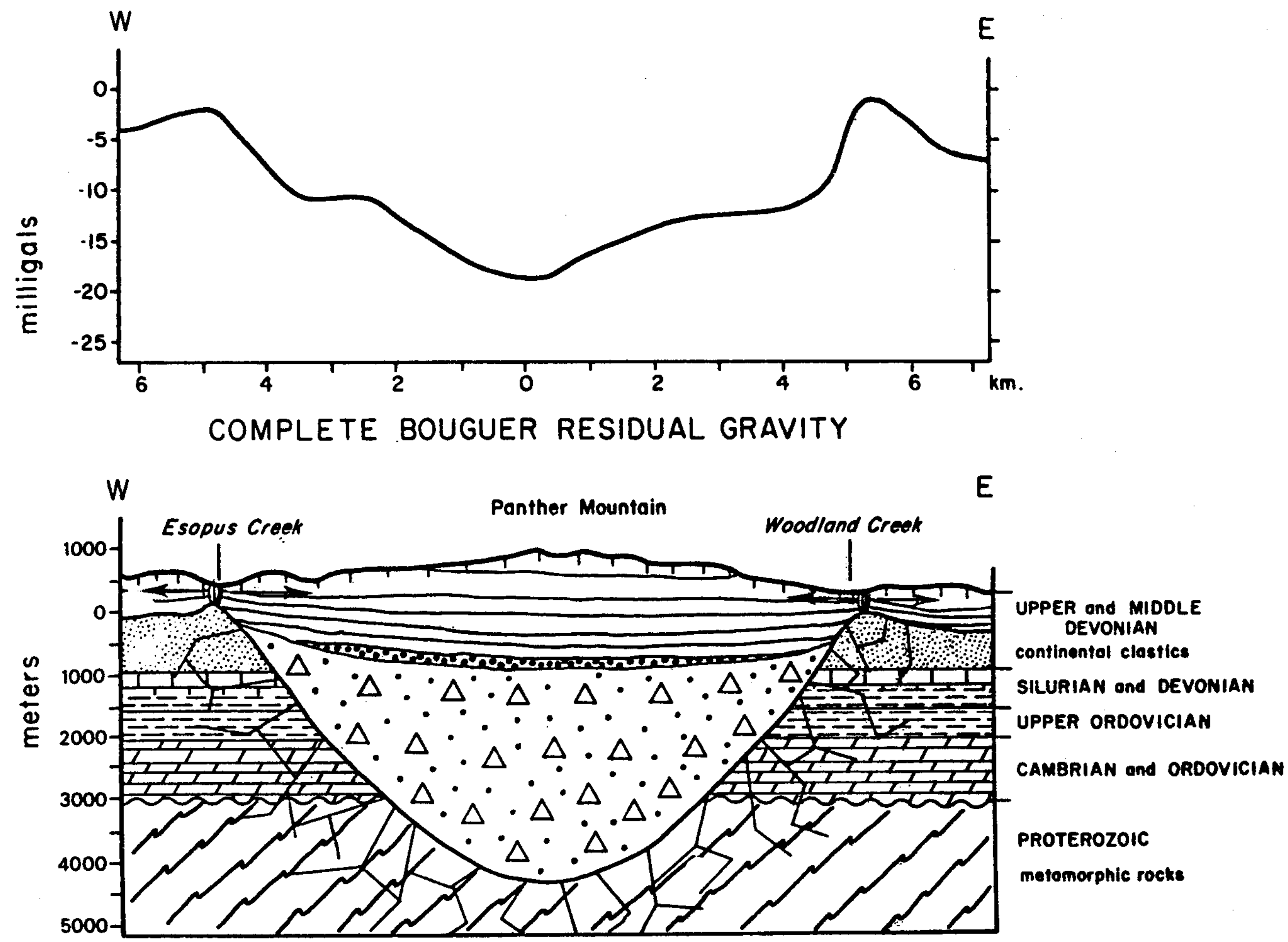

Figure 9. West-east gravity profile and scale drawing of possible buried astrobleme showing eroded crater infilled with Devonian sediments and underlying breccia lens. Draping of sediments over former crater rim exerts abnormal tensional stresses in the overlying rocks resulting in an increased joint density. Vertical and horizontal scales are equal.

As to possible associated flexing, we anticipate that, if it exists, it may exist as downwarping over the crater depression caused by differential compaction, rather than as doming. We would also predict that differential compaction might lead to the formation of a low-amplitude rim anticline located over the present rim valley.

In the section on photogeology, we noted the numerous NNE linear valleys which cross the prominent EW mountain ranges north of Panther Mountain. We referred to the suggestion by Isachsen and others (1974) that they might be zones where joints were intensified due to reactivated dip slip movement on pre-existing basement faults. Without reiterating the reasons for this interpretation, we wish to note here that these linear valleys, with one possible exception, do not pass through the Panther Mountain structure. This is consistent with the interpretation of a large breccia lens underlying Panther Mountain because such a lens would probably re-orient and/or absorb any such upward-propagated stresses.

ECONOMIC IMPLICATIONS

At the outset of this study, we thought that the Panther Mountain circular anomaly might be a domical surface expression of an underlying felsic pluton, similar to the Upper Devonian Peekskill granite body located 80 km to the southeast.

Such a pluton would produce sufficient heat through radioactive decay of uranium, thorium, and potassium to exist as a vast reservoir of thermal energy if the overlying rocks possessed sufficient insulating qualities to raise locally the geothermal gradient. If the resulting thermal gradient were sufficiently elevated, the area would have potential as a source of dry hot-rock geothermal energy. As shown by our modeling experiments (Fig. 5), however, a felsic pluton does not have a sufficiently low density to account for the enormity of the negative gravity anomaly.

Another possible energy source can be considered, however, with respect to the astrobleme model. The large brecciated lens associated with the astrobleme would provide a large reservoir for gas, and black shale source beds exist in the stratigraphic section. Subsurface astroblemes have been inferred in the Williston Basin, where they are either producing fields or potential hydrocarbon reservoirs (Swatsky 1975).

Only a limited quantity of gas was found in the Herdman well which is located at the northern edge of the 10 km structure, but this single well, located as it is near the rim of the structure, may not provide an adequate test for gas reserves beneath the Panther Mountain mass.

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ROAD LOG

BIG INDIAN TO PHOENICIA

Mileage	Difference	
0.0	0.0	Big Indian is located between Kingston and Oneonta on N.Y. Rte. 28. Mileage starts at intersection of Rte. 28 and County Road 47 leading to Oliverea. Start trip by heading east on Rte. 28.
2.2	2.2	Golf Course Road. Edge of Gulf Course Road between Rte. 28 and creek was the site of shallow seismic traverse (Fig. 3). The seismic refraction data closest to the creek suggests a possible fracture zone in underlying bedrock. See text.
2.9	0.7	Large road cut and small quarry on south side of road at first R.R. crossing on Rte. 28 since Big Indian. Many examples of joints typical of the Panther Mountain area can be seen.
2.95	.05	Bridge on Rte. 28 crosses Esopus Creek just east of above outcrop.
3.15	.2	Junction Rte. 28 and Rte. 42 at Shandaken, crossing point for N-S gravity and magnetic traverse. Traverse continued north along Rte. 42, and south via Fox Hollow and trail across the Panther Mountain structure and to the south (Fig. 3).
5.55	2.4	St. Vincent De Sales Cemetery. Gravel pit behind cemetery is site of another shallow-seismic refraction survey. This seismic line essentially paralleled the valley. Interpretation showed bedrock to be unfractured.
7.4	1.85	STOP 1. Access to field trip stop is via a small, steep gravel road seen on the left as the highway takes a sharp left curve around a protruding kame. This rough access road switches back several times and passes a currently open gravel pit before reaching a large abandoned quarry. Total walking distance is slightly over one-fourth mile. This stop is included to display a series of well-developed joint faces in a large, fresh, man-made outcrop. These joints can be seen to be widely spaced, generally pervasive through this thick sandstone bed, and roughly planar in nature. Note the large amount of small-scale irregularities

		on even the largest and best developed joint faces. This is one of the many flagstone ("bluestone") quarries of the Catskill region which were operated in the early part of this century before being superseded by Portland Cement. It was quarries such as this which provided the old "sidewalks of New York."
7.8	0.4	"Indian Cave Quarry." Visible high on the slope through opening in trees on north side of road just opposite the junction of Rte. 28 and the Woodland Valley Road (see photo, Fig. 7A). The quarry was named locally for the cave-like nature of the holes created by the removal of red silty shale from beneath the overlying sandstone. We were not able to ascertain why the shale was mined, but its removal has allowed some shifting of the overlying sandstone blocks along joint planes. This allows easy observation of typical regional joint spacing (here about 3 m) in an outcrop near to, but not directly in, the rim valley.
8.4	0.6	Intersection Rte. 28 and Rte. 214. Turn left to enter Phoenicia. Rte. 28 continues to Kingston. At this point return to Big Indian for second leg of field trip along Big Indian Hollow.
16.8	8.4	Big Indian.

SECOND LEG OF FIELD TRIP - BIG INDIAN HOLLOW

0.0	0.0	Big Indian. Second part of field trip starts here. Turn south from Rte. 28 onto small road (County #47) and proceed south up Big Indian Hollow towards Oliverea.
2.85	2.85	Oliverea Shell Station and general store.
2.95	0.1	Small road to right crossing bridge over the Esopus Creek and heading up McKenley Hollow. The stream channel and broad alluvial floodplain are visible to the right. Downstream from this point, the stream meanders and braids across the valley. Nowhere in this area or further downstream is bedrock exposed in the stream channel.
3.75	0.8	Slide Mountain Inn. Located where small road branches west up the Bushkill Creek valley. The stream valley here is still deeply filled with alluvial sediments. Outcrop is limited to the very edge of the valley, where hillsides meet

the valley floor. This intersection is also a station point on the E-W gravity and magnetic traverse of the Panther Mountain structure. Gravity stations are often located at road intersections or other well defined and surveyed locations to minimize error when correcting the gravity data.

The Slide Mountain Inn is typical of many Catskill summer resorts in the area, a number of which have catered to the summer tourist for over one hundred years. Access to the area was formerly via the railroad line from Kingston to Oneonta which was abandoned early in 1977. Passengers left the train at Phoenicia or Big Indian and were met by carriages from the particular resorts at which they planned to stay.

6.3 2.55 STOP 2. Stop at large pull-off on right side of road, often used by the county to store road stone and gravel. Walk .05 mile to small hollow where road crosses tributary of the Esopus Creek. Just beyond the stream, take a small unmarked trail to the right which leads immediately to the tributary.

In this lovely little glen the small feeder stream plunges down to Esopus Creek via a series of cataracts and spill pool. The jointing here is typical of jointing observed at most localities on or near the Panther Mountain structure even though this outcrop is located within 50 m of the Esopus Creek rim valley (which at this point is bottomed in alluvial gravels). Many joint surfaces can be seen, with strikes ranging between N63W and N78-83E. Note the lack of any dominant joint set traceable throughout the outcrop. Most joints are non-through-going, generally abutting other joint surfaces in either horizontal or vertical directions or both. Note also the characteristic lack of any consistent relationship between cross-bedding and the curvature of joint surfaces. The stream has greatly modified joint surfaces in its channel. Note also that this steep-walled stream channel has undergone a considerable amount of erosional unloading without any increase in joint density or other observable brittle deformation in the channel. Similar observations have also been made in the larger non-rim valleys of the area. In short, erosional unloading of valley floors has not, in itself, been found to cause an increase in joint density.

Proceed to Stop 3.

6.8 .50 STOP 3. Look for an old brown house close to the left side of the road, and park where possible along the road margin. Exactly opposite this house, bushwack directly down to the stream (about 50 m) and the outcrop shown in Figure 7B should be visible on the opposite (SSW) stream bank. Here, two sets of very closely spaced joints can be seen at stream level, one striking N2-9E and dipping 63°-80°W and the other striking N30-34E and dipping 45°-56°SE. Joints in these sets are spaced from 50 cm apart to as little as 2 cm apart in a narrow (50 cm wide) zone in the outcrop. This outcrop of closely spaced jointing is very restricted in space. The jointing is not present in the thicker overlying sandstone nor in outcrops immediately up or down stream. Although joint spacing of about 1 m characterizes exposures present in the center of the rim valley, this outcrop and several others further downstream are the only ones observed in the entire Panther Mountain area which display this extremely dense jointing. Although outcrop control is limited, high-density fracturing appears to be the structural control on the arcuate pattern of Big Indian Hollow.

6.9 .3 TURN AROUND HERE. Bus or car turnaround. Small remnant of logging road on right just beyond culvert. Turn around and go back down the valley towards Big Indian.

9.5 2.6 STOP 4. A small field opens to the left. Walk down farm path which runs along the far edge of this field until the stream is reached, at about 200 m. The outcrop itself is a broad, flat exposure located on the opposite stream bank. In some seasons it may be necessary to wade the stream, although a less detailed view can be had from the opposite bank.

Two closely spaced, planar, nearly orthogonal joint sets are exposed here (Fig. 7C, D). The N60-70E set is systematic (generally through-going) in a strike direction and trends perpendicular to the stream course. Dips are mainly 68°-80°NW, but several are seen to dip 78°-80°SE. The N10-30W set is non-systematic. It trends parallel to the stream course and displays a range of dips suggestive of conjugate pairs. These dips generally have values of 60°-67°NE and 52°-76°SW though some are vertical. Joint spacing in both sets is consistently 30-50 cm and locally as little as 2 cm. Although we have found a general inverse relationship between bedding thickness and joint spacing, nowhere, regardless of bed thickness, have we seen such a display of closely spaced joints over this large an area.

This joint zone is limited in both horizontal and vertical extent. In the beds upstream, joint spacing increases to 1 m just above the waterfall. Similarly, joint spacing is 1 m or greater in the outcrop 20 m downstream and also in a large, thick-bedded outcrop located in woods 15 m southwest of the main exposure. At low water, joints in the N60-70E set can be seen to be only variably continuous into the underlying beds. This is another example where high-density joint zones seem to be restricted to certain beds in limited lateral positions along the rim. The significant fact is their restriction to the rim and, thus, their apparent control on stream development.

At the downstream end of this outcrop, jointing is extremely intensified in a narrow zone 40-50 cm wide, where the spacing is only 3-6 cm. This occurs within the N70-60E set. Note the resulting differential erosion between this zone and the remaining outcrop. Perhaps this illustrates, in microcosm, the way in which closely spaced joints control the circular rim valley that defines the Panther Mountain mass.

Continue driving down valley to Stop 5.

9.7	0.2	Green Bridge crosses the stream flowing in Little Peck Hollow.
11.05	1.35	Oliverea Bridge - on road to left over Esopus Creek.
11.65	0.6	<u>STOP 5; BEDELL STREET</u>. Small path crosses perpendicularly nearly the entire width of the valley. At this location and several others like it where the Esopus Valley is deeply filled with alluvial deposits, the shallow seismic refraction technique was used to search for zones of abnormal bedrock velocity. This is the site of our most definitive traverse. The near-level field provided

an ideal test site where few corrections were needed, and the ease of access to the entire valley width was excellent. Interpretation of this traverse has identified a bedrock zone of low seismic velocity, which we interpret to be a continuation of the abnormally dense jointing mapped upstream (Fig. 8). The seismic refraction method will be demonstrated here.

END OF TRIP.

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