THE PANTHER MOUNTAIN CIRCULAR STRUCTURE: A POSSIBLE BURIED METEORITE CRATER

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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.

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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.

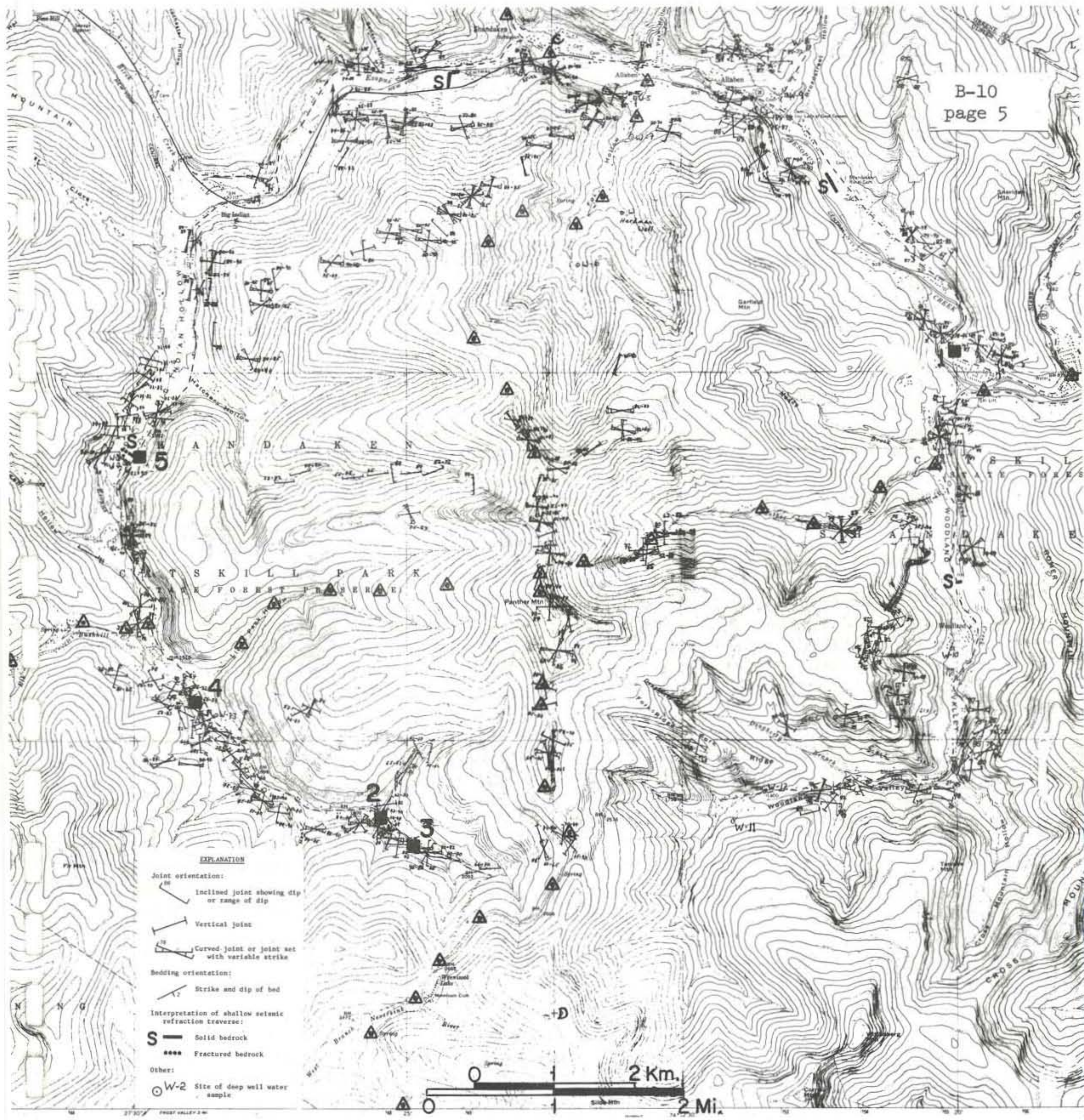

Figure 3. Reduced copy of joint work map of the Panther Mountain structure (7 1/2 minute topographic base from Shandaken and Phoenicia quadrangles). Triangles show locations of NS and EW gravity and magnetic stations, and squares with numbers indicate field trip stops. Sites of seismic refraction profiles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

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

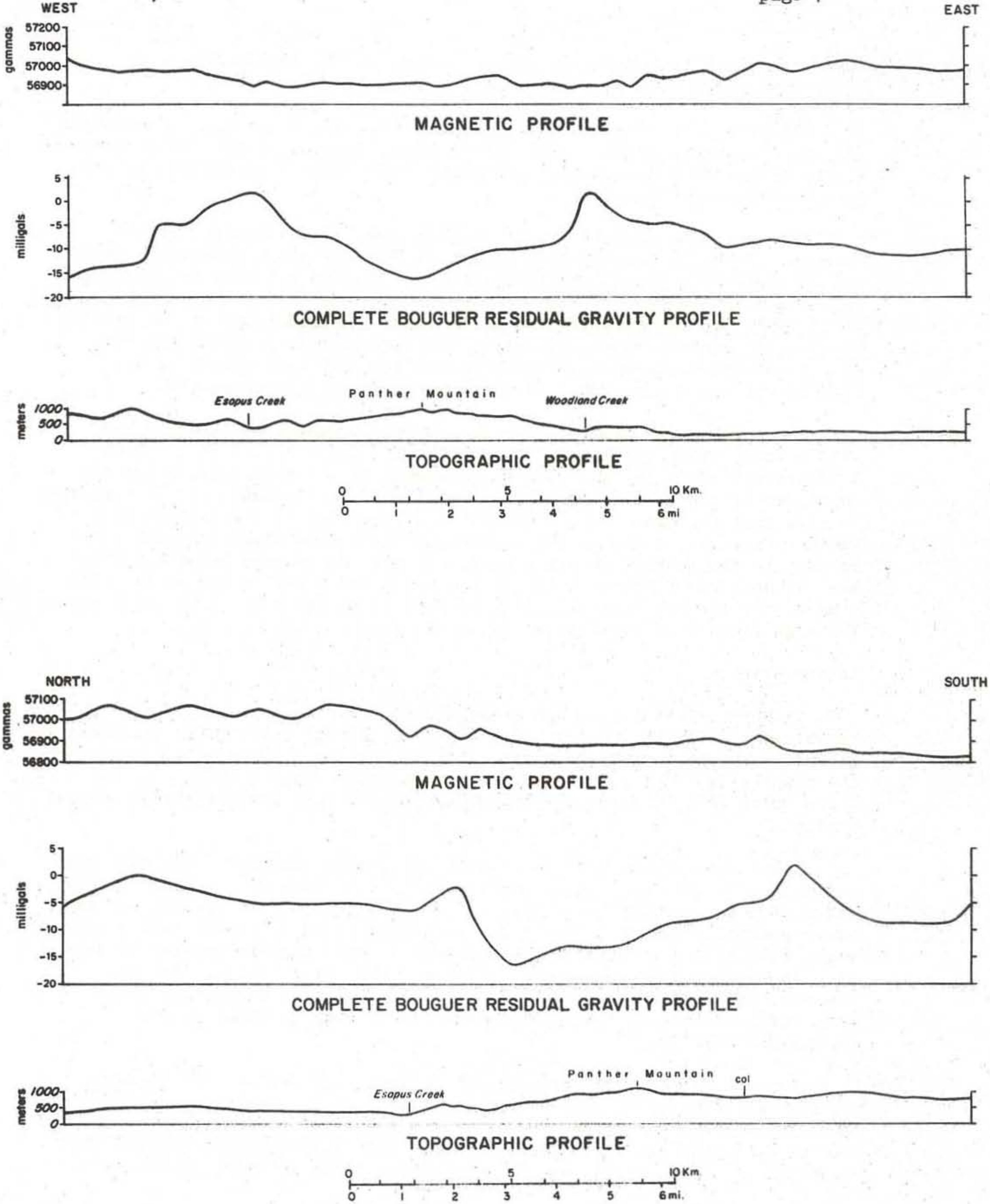

Figure 4. West-east and north-south topographic, gravity, and magnetic profiles across the Panther Mountain circular structure. Locations of geophysical stations are shown in Figure 3. See text for discussion.

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

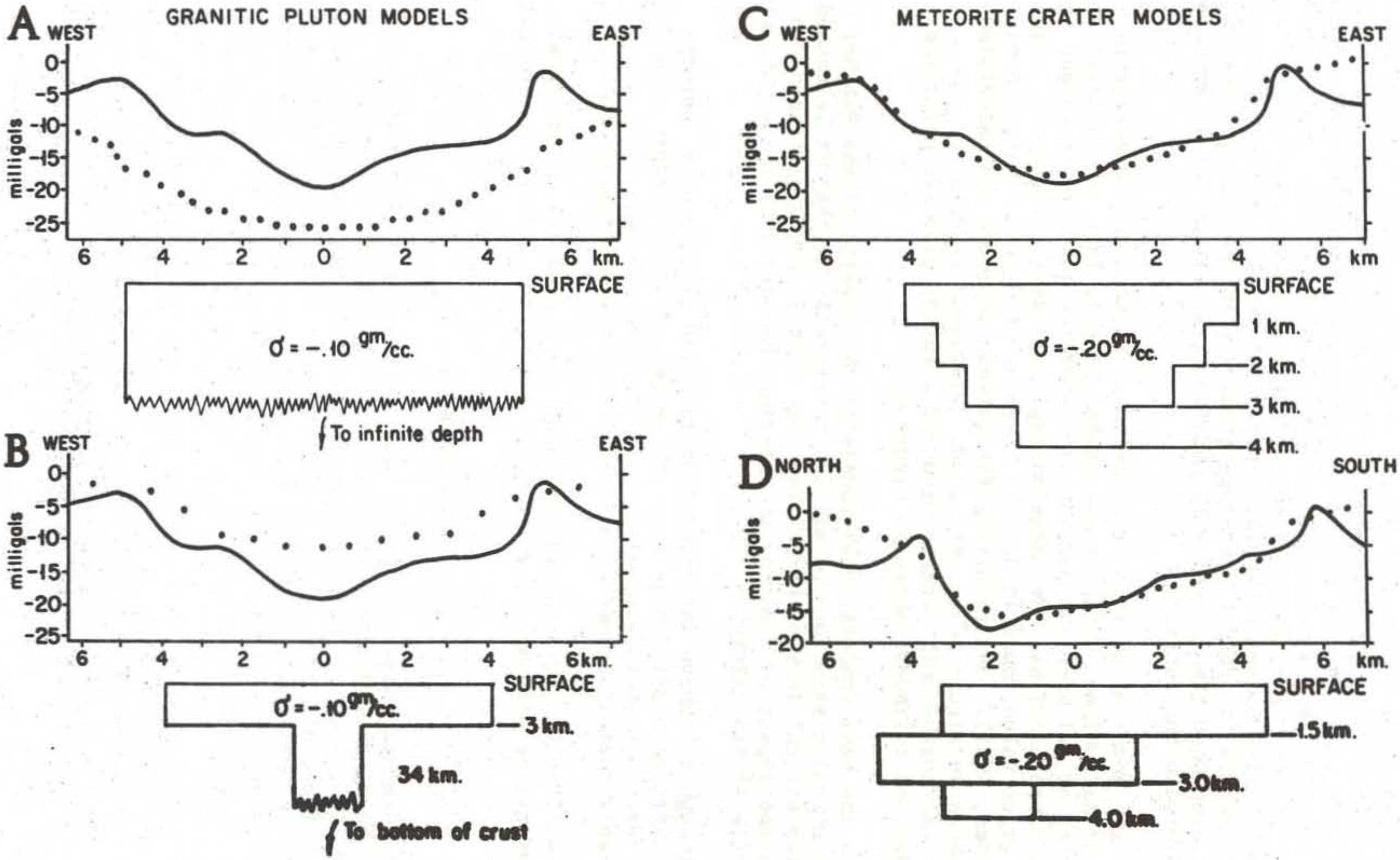

Figure 5. Gravity models that were tested for compatibility with measured values across the Panther Mountain circular structure. The modeled granitic plutons were chosen to simulate a stock (upper left) and an intrusive sheet and feeder pipe (lower left). Models of a near-surface breccia lens such as 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,

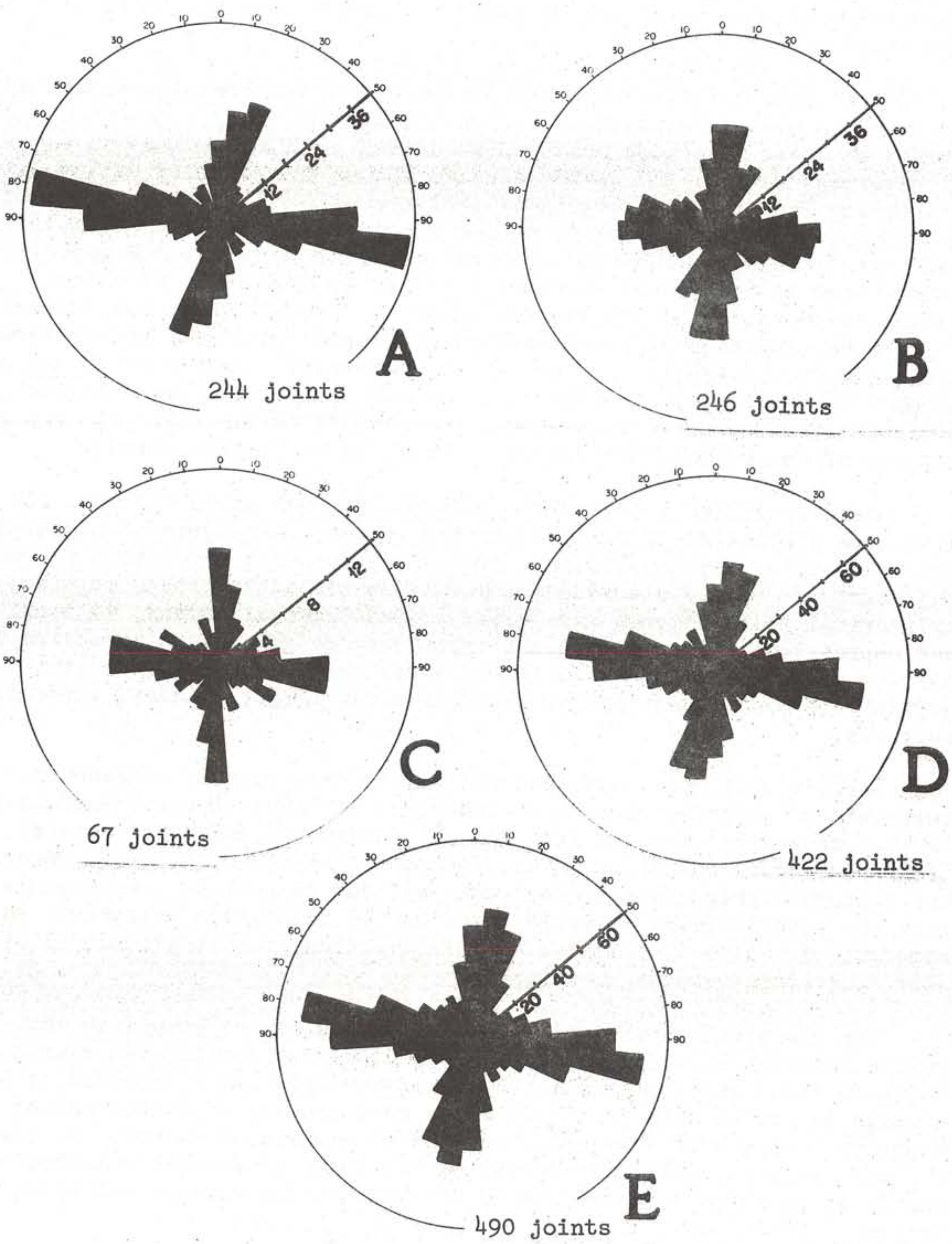

Figure 6. Joint frequency diagrams for: (A) joints of variable strike range (5°-30°), (B) joints of constant strike (range$<5^{\circ}$), (C) joints occurring in the center of the rim valley, (D) joints occurring at all localities other than the center of the rim valley, (E) total of all joints measured. 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^{o}
B. Joints of constant strike ("planar joints"): range 5^{o}
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^{o} 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^{o} 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 <u>orientation</u> was responsible for the circular valley development, and that, <u>quite likely</u>, the cause was an increase in joint <u>density</u> due to an intensification of jointing along directions of the regional pairset.

Our field measurements of joint spacing confirmed this prediction. Aside from the <u>center</u> 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^{o}W to 60^{o}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.

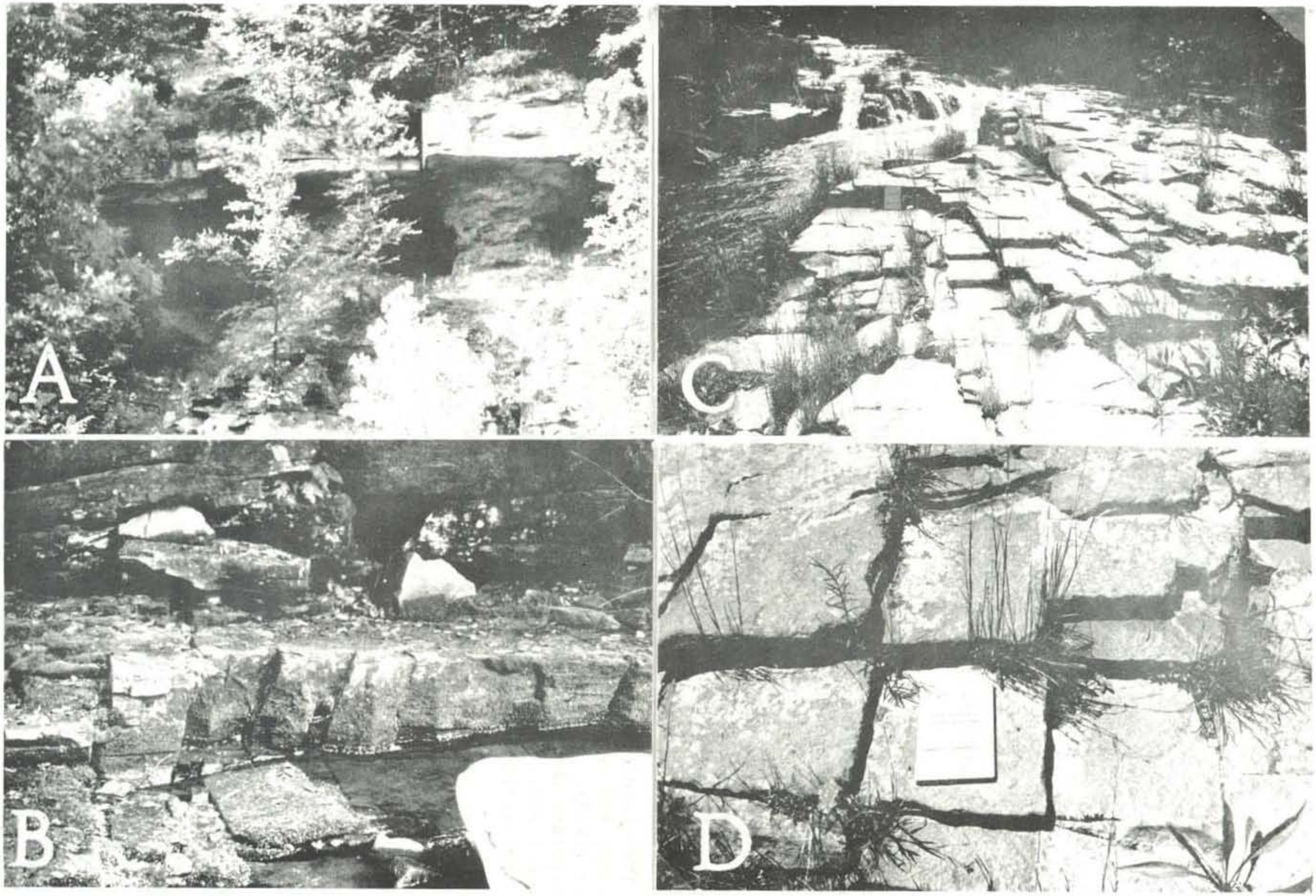

Figure 7. Photographs of joint exposures at: A, "Indian Cave Quarry" (at Roadlog mileage 7.8) showing joints with average regional spacing of 3 m; B, Stop 3 in center of rim valley, looking SSW at joint set with .4-.5 m spacing; C and D, Stop 4 in center of rim valley, looking SSE at pairset with .3-.4 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 <u>not</u> 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.

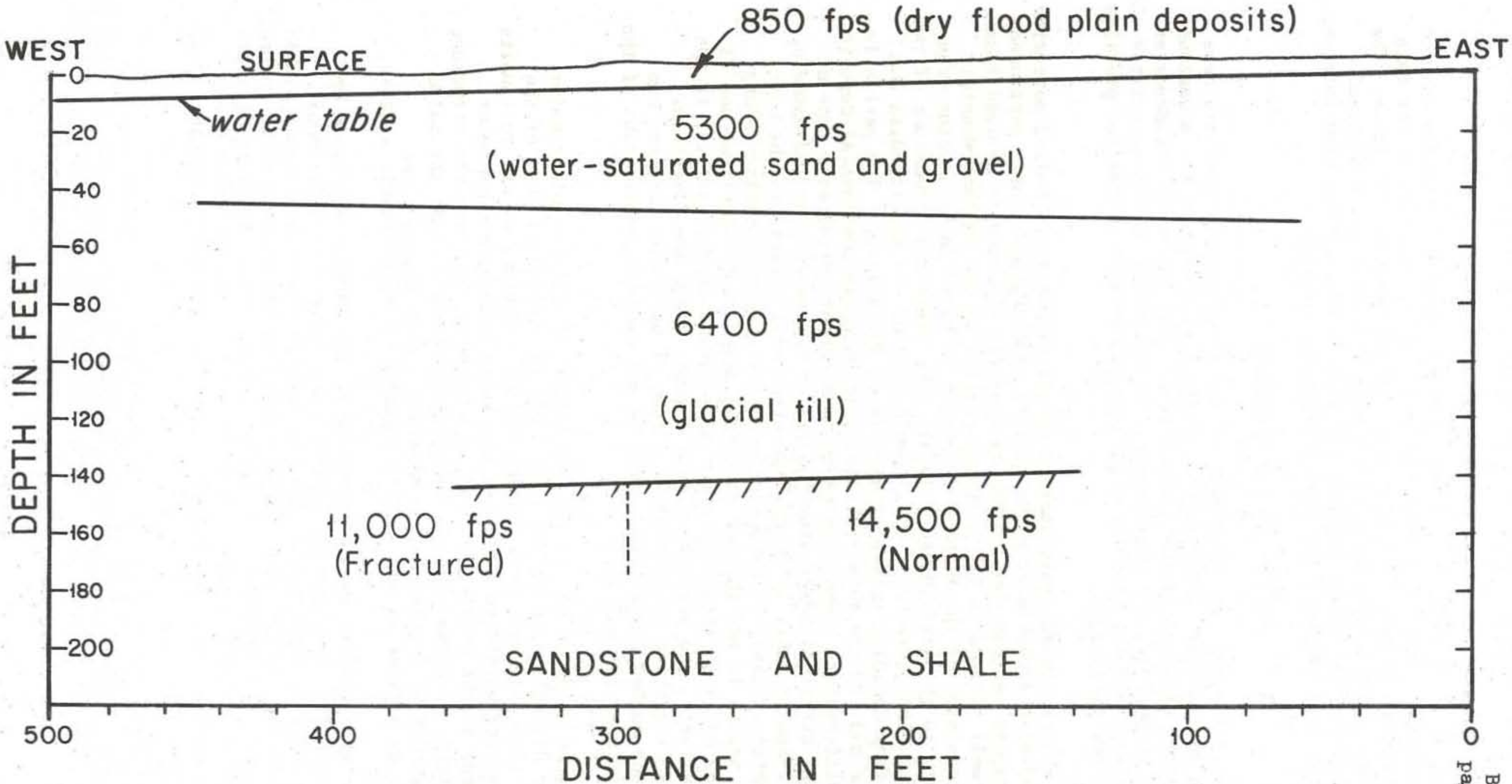

Figure 8. Seismic refraction profile along Bedell Street on the western rim of the Panther Mountain circular structure. Inferred lithologies for the four velocity layers are shown in brackets. The low velocity in bedrock is interpreted as due to closely spaced joints (joint zone) or other abnormal fracturing.

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.

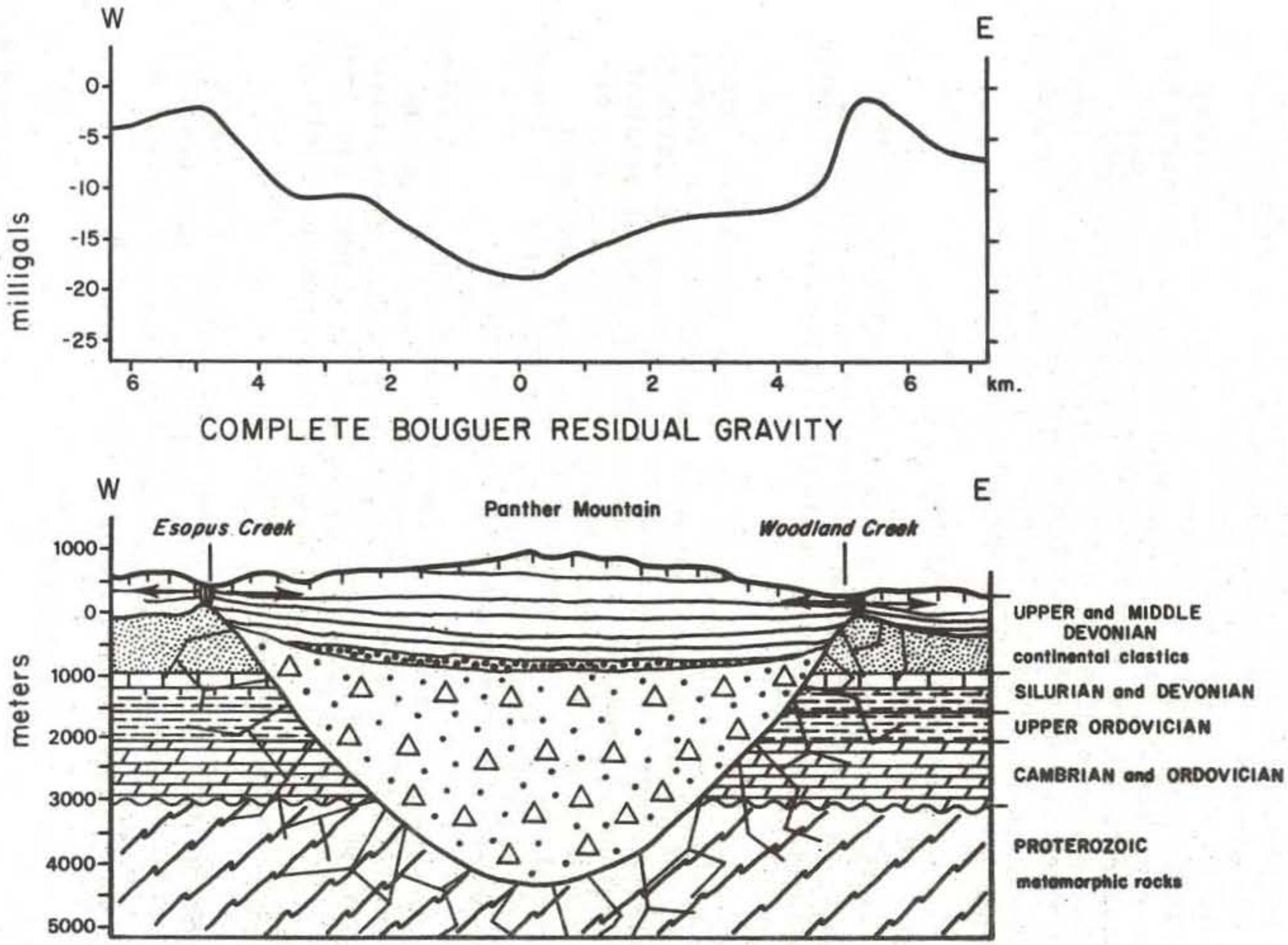

Figure 9. West-east gravity profile and scale drawing of possible buried astrobleme showing eroded crater infilled with Devonian sediments and underlying breccia lens. Draping of sediments over former crater rim exerts abnormal tensional stresses in the overlying rocks resulting in an increased joint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

Chadwick, G.H., 1950, Mountains young and old: The National Science Assn. of the Catskills, Leaflet No. 2, 14 pp.

____________, 1936, The name "Catskill" in geology: N.Y.S. Mus. Bull. 307, 116 pp.

Clark, S.P., ed., 1966, Handbook of physical constants: Geol. Soc. Amer. Mem. 97, 587 pp.

Diment, W.H., Revetta, F.A., Porter, C.O., and Simmons, G., 1973, Simple Bouguer gravity anomaly map of east-central New York (1:250,000): N.Y.S. Mus. and Sci. Service Map and Chart Series No. 17B.

Ewing, J.I., 1960, Geophysical exploration: Part 1, Elementary theory of seismic refraction and reflection measurements: The Sea, Vol. 3, p. 3-19.

Fisher, D.W., Isachsen, Y.W., and Rickard, L.V., 1971, Geologic Map of New York, and generalized tectonic-metamorphic map of New York State: N.Y.S. Mus. and Sci. Service Map and Chart Series No. 15.

Gay, S. Parker, 1973, Pervasive orthogonal fracturing in earth's continental crest: Amer. Stereo Map Co., Salt Lake City, Utah, 124 pp.

Huntec Ltd., 1970, FS-3 portable facsimile seismograph operator's manual: Huntec Ltd., Toronto, Canada.

Innes, M.J.S., 1961, The use of gravity methods to study the underground structure and impact energy of meteorite craters: Jour. Geophys. Research, v. 66, p. 2225-2239.

Isachsen, Y.W., 1973, Spectral geological content of ERTS-1 imagery over a variety of geological terranes in New York State: in Anson, A., ed., Symposium on management and utilization of remote sensing data, Sioux Falls Amer. Soc. Photogrammetry, 677 pp.

____________, 1974, ERTS-1 imagery, a tool in regional geological studies and teaching: Empire State Geogram, v. 10, p. 5-11, N.Y.S. Educ. Dept., Albany, N.Y.

____________, Fakundiny, R.H., and Forster, S.W., 1974, Assessment of ERTS-1 imagery as a tool for regional geological analysis in New York State: U.S. Technical Information Service, E74-10809, 181 pp.

Mooney, H.M., 1973, Handbook of engineering geophysics: Bison Instruments, Minneapolis, Minnesota.

Rich, J.L., 1934, Glacial geology of the Catskill Mountains: N.Y.S. Mus. Bull. 299, 180 pp.

Rickard, L.V., 1969, Stratigraphy of the Upper Silurian Salina Group, New York, Pennsylvania, Ohio, Ontario: N.Y.S. Mus. and Sci. Service Map and Chart Series No. 12.

___________, 1973, Stratigraphy and structure of the subsurface Cambrian and Ordovician carbonates of New York: N.Y.S. Mus. and Sci. Service Map and Chart Series No. 18.

Swatzky, H.B., 1975, Astroblemes in Williston Basin: Amer. Assoc. Petroleum Geologists Bull, v. 59, p. 694-712.

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^{o}-67^{o}NE and 52^{o}-76^{o}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	STOP 5; BEDELL STREET. 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.