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ABSTRACT

A geological and geophysical site survey has been made of the area around the National Radio Astronomy Observatory (NRAO) to determine whether there are at present local tectonic movements that could introduce significant errors to Very Long Baseline Interferometry (VLBI) geodetic measurements. Since the 38th parallel lineament and several other fracture zones have been shown by various authors to pass through the Green Bank area, this poses potential problems for VLBI measurements. The site survey consisted of a literature search, photogeologic mapping with Landsat and Skylab photographs, a field reconnaissance, and installation of a seismometer at the NRAO. It was found that, although the 38th parallel lineament does not reach this far east, several other major transverse lineaments do pass through the Green Bank area. However, there was no evidence of offset along any of them, and they do not appear to be faults. Furthermore, the seismometer detected no natural seismicity within 15 km of the NRAO in nearly two years' operation. It is concluded that local tectonic movement will not contribute significantly to VLBI errors. It is recommended that similar site surveys be made of all locations used for VLBI or laser ranging.

INTRODUCTION

The technique of measuring, at two unconnected radio telescopes, differential delays on the same celestial radio source permits an extremely precise measurement of the distance between the two telescopes regardless of their separation. This technique, known as very long baseline interferometry (VLBI), has already measured transcontinental baselines to an accuracy of 10 cm in 3900 km using telescopes located in Massachusetts and California (Robertson et al., 1979). Improved precisions of 3 to 5 cm are expected in the near future (Coates et al., 1975).

One of the more intriguing geophysical experiments possible with this system is directly detecting continental drift by measuring motions between the various plates constituting the surface of the Earth. However, while the most significant crustal motions occur along the plate boundaries, there is no guarantee that intra-plate areas, well away from plate margins, are always tectonically rigid. Thus, for inter-plate measurements to be truly indicative of continental drift, local motions unconnected with drift must be negligible or measurable.

Obviously the amount of local motion varies according to location. For VLBI stations located in areas of active faults, such as Goldstone and Owens Valley, California, and Fairbanks, Alaska, continual monitoring will be required. In more stable areas such as Haystack, Massachusetts, or Green Bank, West Virginia, local motion should either be very small or non-existent. This paper describes the work undertaken to verify the above assumption in regard to the National Radio Astronomy Observatory (NRAO) at Green Bank, West Virginia.

Although West Virginia is considered an aseismic area, a few earthquakes in the state have had sufficient energy to be felt locally or detected on networks of widely separated seismographs, mostly located in neighboring states (Bollinger, 1969). The most recent was a magnitude 4.6 shock located some 150 km from NRAO but not felt at the site which occurred at Elgood, West Virginia on November 20, 1969 (Bollinger and Hopper, 1970). None of these events were sufficiently close to Green Bank to suggest permanent deformation at the site. Of more obvious concern is the occurrence, near the NRAO site, of several large lineaments. These poorly understood features, occurring throughout the Appalachian Mountains, have alignments that often approach right angles to the structural trend of the mountains. They are not evident on the ground but are clearly discernible in aerial photographs and especially satellite pictures.

In November 1976 a survey of the Green Bank area was undertaken to verify the expected stability of the site and to look for evidence of movement along the lineaments. This information was of importance due to the close proximity to the Kentucky River Fault Zone and the 38th parallel lineament (Heyl, 1972). At the same time, with aid and cooperation of the National Radio Astronomy Observatory personnel, a short-period vertical seismometer was installed on the site to search for local micro-earthquakes which would be indicative of high frequency ground motions and small scale faulting.

REGIONAL GEOLOGY

The National Radio Astronomy Observatory is geologically in a transition zone, possibly in more than one sense. NRAO is roughly 10 km northwest of the Allegheny Front (Figs. 1, 2) which marks the boundary between the Ridge and Valley province on the east and the Appalachian Plateau (locally the Allegheny Plateau) on the west. In addition, the Green Bank area marks an apparent transition along strike, from relatively open folds to the northeast in Maryland and Pennsylvania to the thrust faulting and much tighter folds to the southwest. Physiographically, both these transitions are quite real. However, Gwinn (1964) has given strong evidence that along strike transition is primarily the result of depth of erosion, and there is little difference structurally.

Rocks of the Green Bank area are practically all Paleozoic, ranging from Ordovician to Pennsylvanian. Pennsylvanian units cap the higher parts of the Plateau; Silurian and Devonian units make up most of the valleys and ridges, with Ordovician units exposed only in the cores of larger anticlines. A number of Eocene igneous dikes occur nearby in Highland County, Virginia. The local stratigraphic section is well described in the legend accompanying the Geologic Map of West Virginia (Cardwell, Erwin and Woodward, 1968). The units with which this survey was primarily concerned are described below.

The Silurian Tuscarora sandstone, about 100 meters of sandstone and orthoquartzite, is the principle ridge-former in this part of the Appalachians. Lantz Mountain is largely Tuscarora sandstone. The

Devonian System near Green Bank includes, among other units, the Brallier Formation (a marine shale with some siltstone), the Chemung Group (chiefly marine sandstone and shale), and the Hampshire Formation (non-marine sandstones and siltstones, easily recognized by their red-brown color). The Mississippian System in this area includes the Pocono Formation (sandy or silty shale), Macrady Formation (shales and sandstones), the Greenbrier Group (chiefly marine limestones), and the Mauch Chunk Group (varicolored sandstones and shales), totaling about 700 meters.

A detailed discussion of regional structure would not be appropriate here. However, the main characteristics of the Green Bank area can be briefly summarized. If Lantz Mountain (northwest limb of the Wills Mountain anticline) is considered the boundary of the Appalachian Plateau the area can be described as one of transition from very tight folds and thrust faults in the east to more open folds in the west. The Appalachian Plateau is structurally a broad synclinorium (Spencer, 1969). As mentioned previously, the Green Bank area is also a zone of transition along strike (see Fig. 1), in which the folding appears to become much tighter to the southwest compared with the relatively open folds of the Appalachian chain northeastward in Pennsylvania. (These relationships are also shown well on the maps by H.P. Woodward accompanying the Geologic Map of West Virginia (Cardwell et al., 1968).) Gwinn (1964) has shown that subsurface thrust faulting is prominent to the northeast in the Pennsylvania part of the Ridge and Valley province. This is contrary to the formerly popular view that the tectonic style changed from one of dominant thrusting to folding along strike toward the northeast from West Virginia. Gwinn also showed that the open folds west of the Allegheny Front, such as the Elkins Valley anticline (Fig. 3), are probably the expression of subsurface thrusts rather than basement uplifts. His view that the Appalachian folds and faults in this area are primarily "thin-skinned," i.e., not involving basement, is now generally accepted (e.g., Cardwell et al., 1968).

The transverse structures are of particular interest for the motion survey. The Green Bank area, located at about 38^{o}30' latitude, is on the eastward segment of the proposed "38th parallel lineament" described by Heyl (1972). The lineament trends N80^{o}E to N85^{o}E in the Green Bank area. According to Heyl's map, this structure appears to extend from the front of the Rocky Mountains to Virginia, localizing a wide variety of tectonic and petrologic features. Heyl interpreted the lineament as a zone of right-lateral wrench faults in the mid-continent region, and as similar faults, fold terminations, and fold axis bends and sags in Virginia and West Virginia (Hinze et al., 1977). He concluded that the lineament had experience movement as recently as middle Mesozoic time in eastern West Virginia.

Other transverse structures in the Green Bank area include a number of cross-strike fractures mapped by Gwinn (1964), and interpreted by him as zones along which local thrust faults change stratigraphic horizons. One of these, on Gwinn's map, passes through the

Green Bank area in a N70^{o}W direction, terminating the Elkins Valley anticline. There is some indication on the Landsat picture of a lineament matching Gwinn's map (Fig. 2). It should be mentioned that farther southwest along strike there are many prominent cross-strike faults (tear faults) bounding overthrusts; if Gwinn's interpretation of subsurface thrusting in the Green Bank area and to the north is correct, one would expect corresponding tear faults there also.

The age of the transverse faults is difficult to determine, other than that they are younger than the youngest rocks they cut, i.e, post-middle Paleozoic in the Green Bank area. York and Oliver (1976) have compiled a list of faults with movement as young as Pleistocene in eastern North America, although none are in the Green Bank area. There is of course a wide belt of shallow, minor seismicity throughout the Appalachians, some of which, in Pennsylvania, is associated with transverse fractures. Collectively, this evidence pointed to the possibility that some of the lineaments in the Green Bank area could be active.

FIELD INVESTIGATIONS

After the above literature survey, the next step was a search of available Landsat imagery to pick out the most useful pictures, which proved to be low-sun-angle winter coverage. A single-frame synoptic lineament map was prepared (Figure 3). Next, all visible lineaments within 30 miles of Green Bank were plotted on 1:500,000 Band 5 (Red) or 7 (near infrared) enlargements, and their locations transferred to USGS 1:250,000 and 1:24,000 topographic maps. NASA RB-57 aircraft and Skylab S-190B photographs were then checked to examine the details of these lineaments. In nearly all cases, they proved to be zones, generally from several hundred meters to over a kilometer wide, of various features such as stream valleys, gaps, and ridge ends, aligned and spaced closely enough to constitute a single line on the Landsat picture.

The field reconnaissance was intended to (1) verify the existence of structures corresponding to the transverse fracture zones, (2) investigate their nature, and (3) find out whether there has been appreciable offset along any of them. Emphasis was put on horizontal offset since precise horizontal measurements are a primary objective of the VLBI experiments; however, when distinctive marker horizons were exposed, evidence of vertical offset was also sought.

Field work concentrated on locating intersections of ridges with lineaments both east and west of Green Bank, so as to completely bracket the NRAO site. Lantz Mountain, a vertically-dipping or overturned ridge of Tuscarora sandstone, offered the best opportunities for this. Five lineament-ridge intersections along Lantz Mountain were checked. Three were related to northeast-trending lineaments: (Figure 4, 1) at Mick Run (near Cherry Grove), (Figure 4, 2) near Snowy Mountain, (Figure 4, 3) near the divide on the headwaters of Straight Fork (Fig. 4). At the first two sites (Fig. 4, numbers 1 and 2), sharp erosional notches occur at the places where the lineaments cross the ridge; however, there is no measurable lateral offset present (Fig. 5).

At the third site (Fig. 4, number 3), there is no such gap and no outcrops were found. This site was of particular interest, since this lineament appears to be one of the longest in the area on the Landsat picture (Fig. 2). In addition, its trend, N80°E, is close to that of the 38th parallel lineament in this area (Heyl, 1972), although the photolineament is mapped a few kilometers to the north. For this reason, the exposures of the continuation of the photolineament where it crosses U.S. 250 (Fig. 6) were studied to see if there was any evidence for a structure with this trend. No such evidence was found; there were no faults, folds, or joints with a N80°W trend. The existence of a fracture zone corresponding to this lineament thus seems open to question; it has at any rate no apparent expression in outcrop.

The remaining two Lantz Mountain sites (Fig. 4, numbers 4 and 5), are both related to northwest-trending lineaments. Both were erosional gaps, and neither showed any lateral offset of the Tuscarora sandstone ridge.

The prominent northwest-trending lineament passing just north of the NRAO site (Fig. 3) was studied in more detail, since it is one of the longer lineaments and, more importantly, corresponds to one of the transverse tear faults shown by Gwinn (1964, Fig. 16) with a N70°W trend. The photolineament trends N60°W, but this difference is not significant since Gwinn's map was based on broad stratigraphic features such as fold terminations. It was found that, near the intersection of the photolineament with Lantz Mountain, several outcrops in Tuscarora sandstone had prominent steeply-dipping or vertical joint sets trending between N60°W and N70°W. This would appear to support Gwinn's interpretation, although it should be pointed out that northwest-trending joints appear common in the Green Bank-Monterey area. The lineament was also investigated west of Green Bank, where it localizes a gap through Little Mountain near the Greenbrier River. A series of sandstones, belonging to the Chemung Group, dips about 45°NW, and exhibited no lateral offset across the gap.

Another lineament, possible representative of several, is visible just east of the NRAO (Figs. 2,3), where North Fork (a tributary of the Greenbrier River) turns sharply to the northeast. This stream has clearly come under some sort of structural control in cutting headward, but there was no indication on the state geologic map (Cardwell et al., 1969) of any structure that might be responsible. Accordingly, a brief reconnaissance was carried out near the head of North Fork and along U.S. 250, which cuts across any possible lineament. As shown on Fig. 6, strata of the Hampshire Formation appear disordered along North Fork, with a wide range of attitudes showing no consistent pattern. (Every effort was made to take measurements on true outcrops, rather than float.) Structure readings made for five kilometers along U.S. 250, however, are easily interpreted, and it is clear that the road crosses a syncline whose axis coincides with North Fork. This is the

Stony River Syncline, although the state geologic map (Cardwell et al., 1968) does not indicate its continuation this far south. The nature of the structural control of drainage is not clear. The apparently random scatter of dip directions suggest that simple axial plane jointing is not an adequate explanation. No direct evidence of faulting was found, nor was there any vertical offset of distinctive sandstone units. At this time, we can only conclude that a fracture zone of some sort, localized by the axis of the Stony River Syncline, has controlled the course of the North Fork. Further investigation showed that a similar lineament (Fig. 4), locally expressed by Knapp Creek, is the result of erosion along an anticlinal axis; axial plane jointing appears to be responsible.

During the field survey a short period vertical seismometer operating at a magnification of about 30,000 at 1 Hz was established on the grounds of the NRAO (National Earthquake Information Service (NEIS), identification code GBV). The sensor is at a depth of about 2 m in the Quaternary alluvium which overlies the Devonian Brallier shale. Observations have been made since November 15, 1976 and to date no seismic activity within a 20 km radius of the observatory has been detected. It is difficult to detect very weak local activity during week days due to the frequency of blasting at the various surface and deep mines in the Appalachian region. The absence of discernible earthquake activity during the night hours and on week ends does support a quiescent interpretation.

DISCUSSION

Although our results indicate that the Green Bank site is probably stable at the few (3-5) cm level, there are several problems which remain. As Sbar and Sykes (1973) point out, eastern North America is a region of high horizontal compressive stress. Since Brown and Oliver (1976) have also shown that vertical movements of a few (2-3) mm/yr are common, it may be that a more precise analysis would confirm the potential for measurable deformation implied by Sbar and Sykes (1973).

In view of the relative infrequency of earthquakes in the east in general, two years' observations are not sufficient to confirm a lack of local seismicity. Although it is clear that the Green Bank area is inactive by California standards, it is not yet established that this area is less active than the surrounding active areas. With some ten or so regional events per year, the statistics are not yet large enough to give a meaningful assessment. Accordingly, we expect to continue seismic monitoring for some time.

We can only speculate on the origin of the lineaments in the area. However, it seems clear that at least some of the lineaments are expressions of joint zones, reflecting regional stress. These may also be entirely "fossil" features, the stress region that caused them having long since changed. The most prominent N80^{o}E lineament, parallel to and just north of the supposed 38th parallel lineament, appears to have no effect on exposed rocks, and may be illusionary. No evidence of major transverse faulting was found in the vicinity of the NRAO.

It should be stressed that the investigation reported here is only preliminary. Further work is desirable along some of the N80^{o}E lineaments that may be related to the 38th parallel lineament. A problem not resolved by this study is that of minor oscillatory movements with a period of a month or so along lineaments, which might contribute to the VLBI error budget even though they would not result in geologically detectable offsets.

We have detected no convincing evidence of local movement on the scale of a few cm in the Green Bank area. We thus conclude that Green Bank motions will not contribute to the VLBI error budget. This conclusion probably does not follow in the cases of the Goldstone and Owens Valley sites. In active areas such as these, similar studies, modeled on this work, are essential to the interpretation of any observed baseline changes.

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FIGURE CAPTIONS

Figure 1: Sketch map of the regional setting of the NRAO at Green Bank, West Virginia. Note the location of Green Bank between Lantz Mt. and the Greenbrier River. North is up.

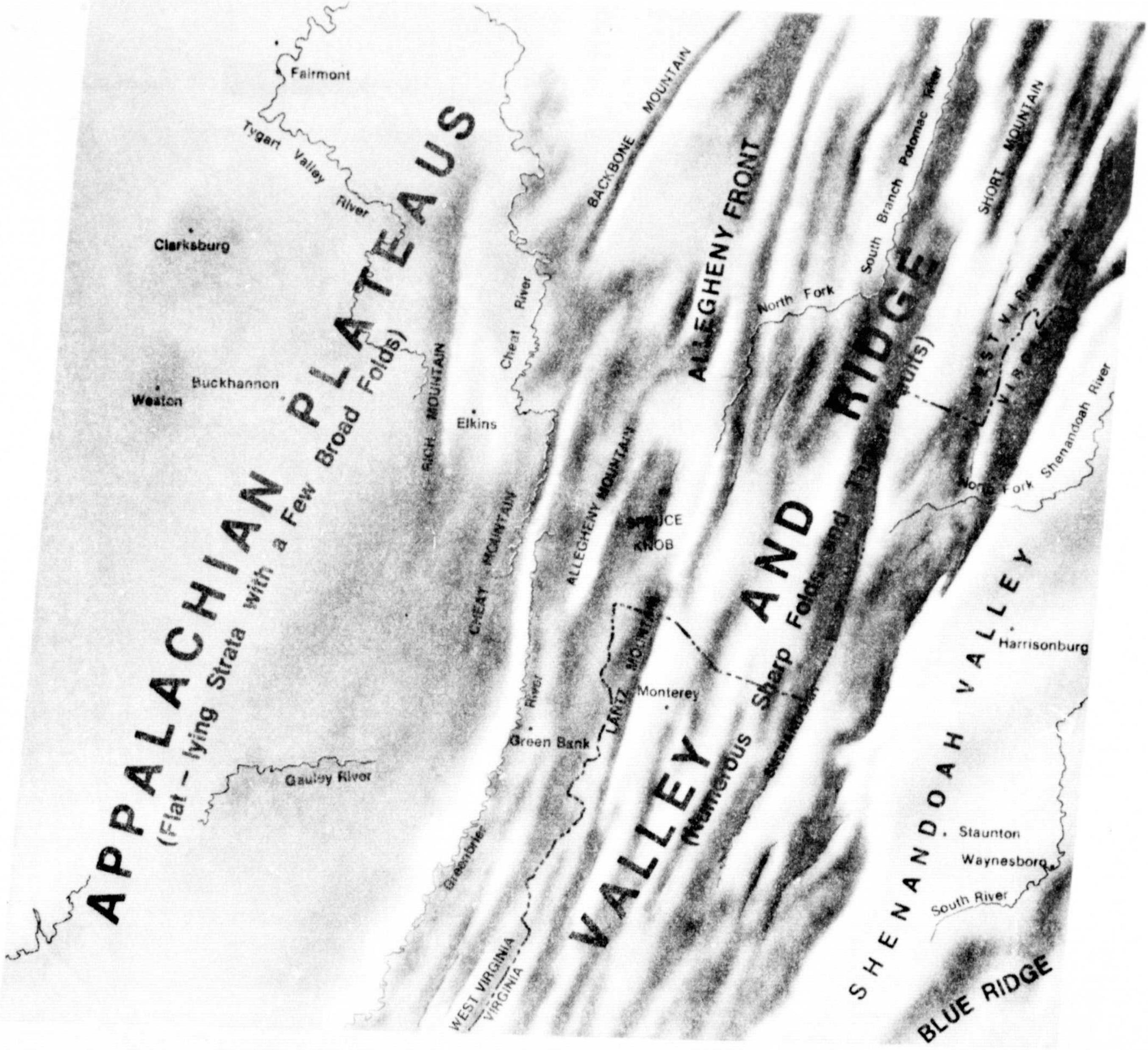
Figure 2: Landsat view, Band 7 (near IR) of NRAO site and adjacent area. See Fig. 3 for landmarks and structure. Landsat 1 image 1172-15310, January 11, 1973. G marks the location of Green Bank. North is up.

Figure 3: Lineament map drawn from Fig. 2. Note the dark square marking the location of the NRAO at Green Bank.

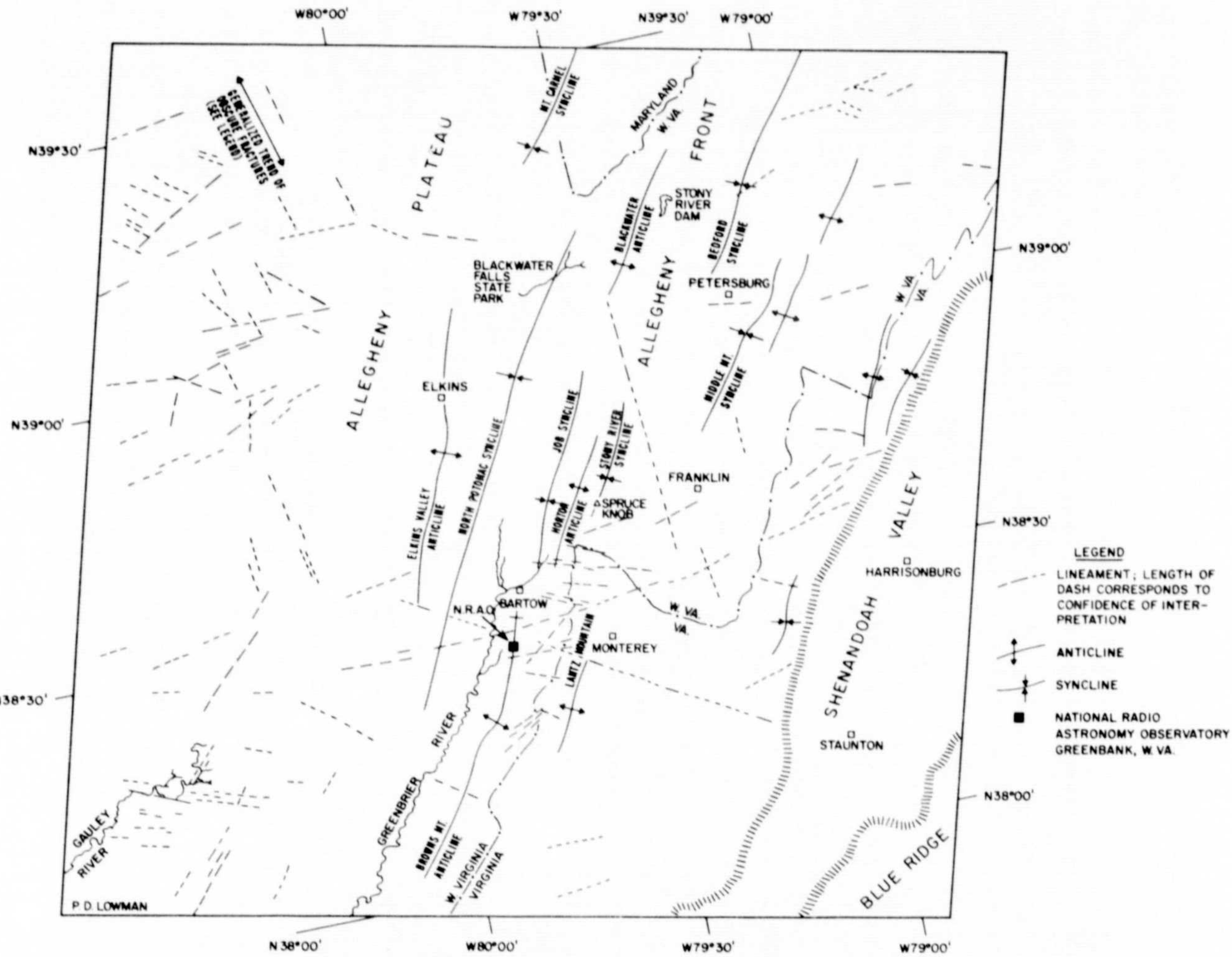
Figure 4: USGS 1:250,000 topographic map, Charlottesville, VA sheet, showing major transverse photolineaments investigated. numbers refer to locations described in text.

Figure 5: View to south along Tuscarora sandstone ridge near Cherry Grove, W. Va., on Lantz Mt. Picture taken from north side of erosional gap corresponding to lineaments; note the lack of horizontal offset.

Figure 6: Structure map of lineament along North Fork. Note structural disorder in vicinity of lineament.


Fairmont
Tygart Valley River
Clarksburg
Buckhannon
Weston
APPALACHIAN PLATEAUS
(Flat – lying Strata with a Few Broad Folds)
RICH MOUNTAIN
Elkins
Cheat River
BACKBONE MOUNTAIN
ALLEGHENY FRONT
North Fork
South Branch Potomac River
SHORT MOUNTAIN
ALLEGHENY MOUNTAIN
KNOB
CHEAT MOUNTAIN
LANTZ MOUNTAIN
Monterey
Green Bank
Gauley River
Greenbrier River
WEST VIRGINIA
VIRGINIA
VALLEY AND RIDGE
North Fork Shenandoah River
Harrisonburg
SHENANDOAH VALLEY
Staunton
Waynesboro
South River
BLUE RIDGE


W080-30
W080-00
W079-30
W079-00
W081-00
W080-30
W080-00
N038-00
W079-30
19FEB76 C N38-52/W079-54 N N38-50/W079-48 MSS 7 D SUN EL27 AZ134 190-8210-N-1-N-D-1L NASA ERTS E-5306-14534-7 01



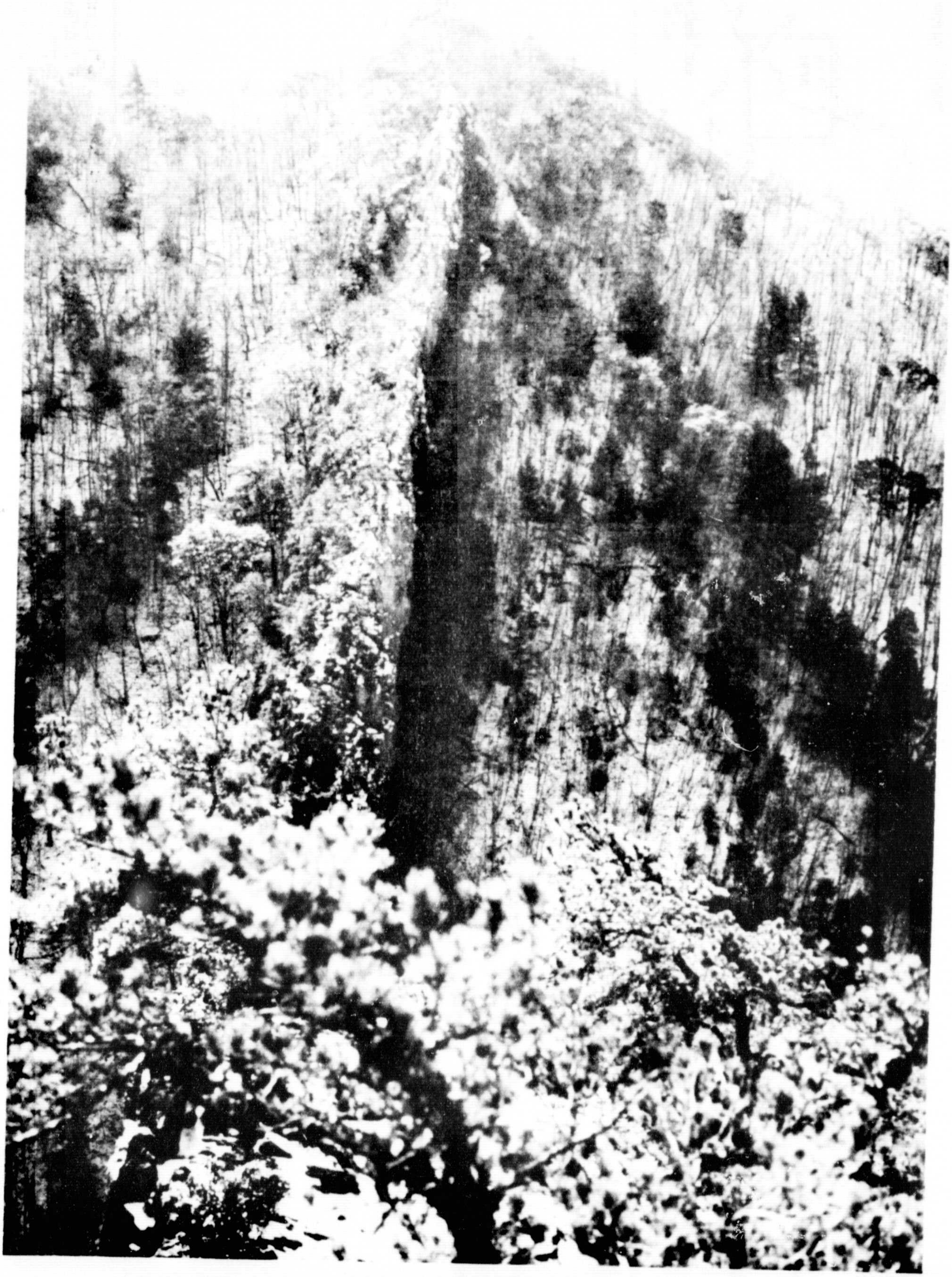
LINEAMENT MAP

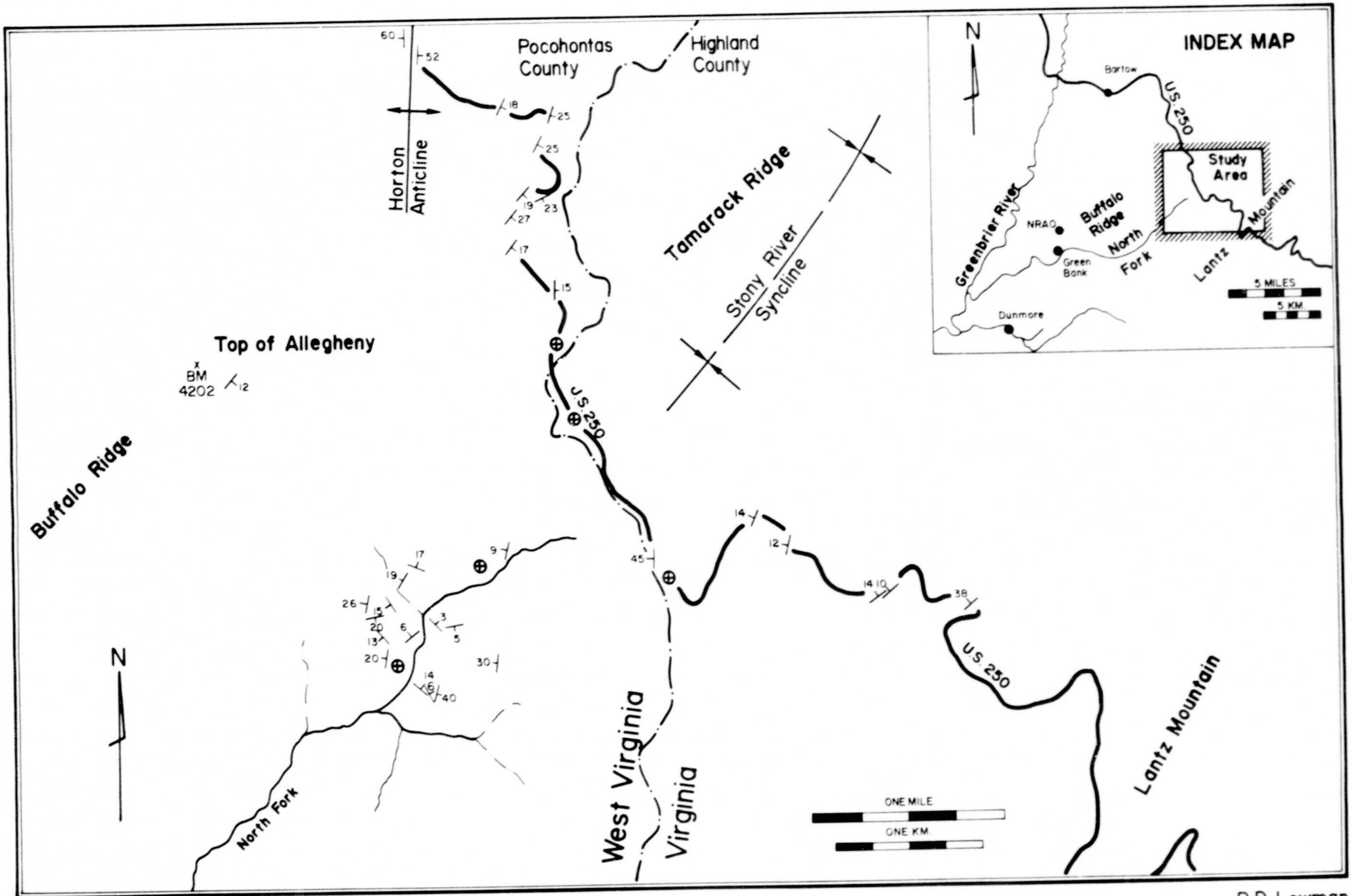
BASED ON LANDSAT IMAGE 1172-15310, 11 JAN. 73

PAUL D. LOWMAN

GODDARD SPACE FLIGHT CENTER


CHARLOTTESVILLE
APPALACHIAN
MOUNTAINS





STRUCTURE SKETCH MAP

North Fork Lineament

Topography from U.S.G.S. 7 1/2' Map

Hightown, Va.- W.Va.

P.D. Lowman

R.J. Allenby

1977