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POSSIBLE EVIDENCE FOR CONTEMPORARY DOMING OF THE ADIRONDACK MOUNTAINS, NEW YORK, AND SUGGESTED IMPLICATIONS FOR REGIONAL TECTONICS AND SEISMICITY*

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ABSTRACT

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The Adirondack Mountain massif is a dissected elongate dome having a north-northeast axis about 190 km long, and an east—west dimension of about 140 km. The dome exposes a core of Proterozoic metamorphic rocks from which the Paleozoic cover rocks have been eroded, except in several north-northeast-trending graben. The minimum amplitude of the dome, based on a 'reconstruction' of the Proterozoic—Paleozoic unconformity is 1600 m.

The Adirondack dome is an anomalous feature of the eastern edge of the North American craton. It differs from other uplifts in the Interior Lowlands of the craton not only in terms of the greater combined amplitude and area of its uplift, but in the present high elevation of its Mountains (up to 1600 m) which are unequalled on the craton except along the Rocky Mountain front and in the Torngat Mountains of northernmost Labrador.

This prompted an interest in the possibility that the Adirondack dome has undergone neotectonic regeneration and may be undergoing domical uplift at the present time. Accordingly, leveling records were consulted at the National Geodetic Survey data base in Rockville, Maryland, and used to construct leveling profiles. The most informative of these extends north—south along the block-faulted eastern flank of the Adirondack dome, extending from Saratoga Springs to Rouses Point, a distance of 245 km. A comparison of the level lines for 1955 and 1973 demonstrates that arching has occurred. An uplift of 40 mm along the central portion of the line, and a corresponding subsidence of 50 mm at the northern end, has produced a net increase in the amplitude of arching of 90 mm in the 18-year interval. This differential uplift, particularly with subsidence at the northern end, argues for a tectonic rather than glacio-isostatic mechanism. Pending releveling across the center of the Adirondack dome, it is tempting to extrapolate the

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releveling profile and suggest that the Adirondacks as a whole may be undergoing contemporary doming at a rate far in excess of denudation. This inference leads to a consideration of other tectonic features which may be related in both the short and long term to such a postulated doming. One is the periodic occurrence of anomalous earthquake swarms located very near the geometric center of the Adirondack dome at Blue Mountain Lake, although horizontal rather than vertical compressive stresses have been shown to be dominant by Sbar and Sykes in 1973. Another, is the predominance of faults and topographic lineaments in the Adirondacks which parallel the long axis of the dome and are so remarkably well displayed in the infrared bands of ERTS-1 imagery.

INTRODUCTION AND TECTONIC SETTING

The releveling data discussed in this paper are such as to suggest the operation of tectonic rather than normal glacio-isostatic mechanisms. Accordingly it is necessary to provide, at the outset, a geological-tectonic frame of reference for the region.

The Adirondack Mountains are located along the eastern margin of the North American platform (see King, 1969). The constitute the southeasternmost extension of the Grenville Province of the Canadian Shield, and represent a deeply eroded, billion year old orogenic belt which now forms cratonic basement.

The Adirondack Mountain massif is a dissected elongate dome cored by Proterozoic metamorphic rocks and flanked by strata of Late Cambrian through Middle Ordovician age which dip outward at angles of from 1 to 5° (Fig. 1). Paleozoic rocks have been entirely stripped from the upper part of the dome except where preserved in several north-northeast trending graben in the southern, southeastern and eastern parts of the structure. The dome has a north-northeast axis about 200 km long, and an east—west dimension of about 140 km. Topographic elevations range from about 100 m to 1600 m above mean sea level, with local relief up to 1200 m.

An attempt was made to 'reconstruct' the configuration of the dome by grossly generalizing present topography in such a manner as to 'fill in' all eroded depressions. The results are shown by dashed contour lines in Fig. 1, and indicate the minimum convexity of the Proterozoic—Paleozoic unconformity which defines the dome. The reconstructed configuration shows a minimum amplitude of domical uplift of 1600 m and suggests that the dome is an elliptical upwarp with an axis trending about N17° E.

In combined areal dimensions and amplitude of uplift, the Adirondack dome is an anomalous feature on the central craton of North America (see Tectonic Map of North America by King, 1969, and the Basement Map of the United States by Bayley and Muehlberger, 1968). In addition, the high elevation of its mountains is unequalled on the craton except along the Rocky Mountain front and in the Torngat Mountains of Labrador.

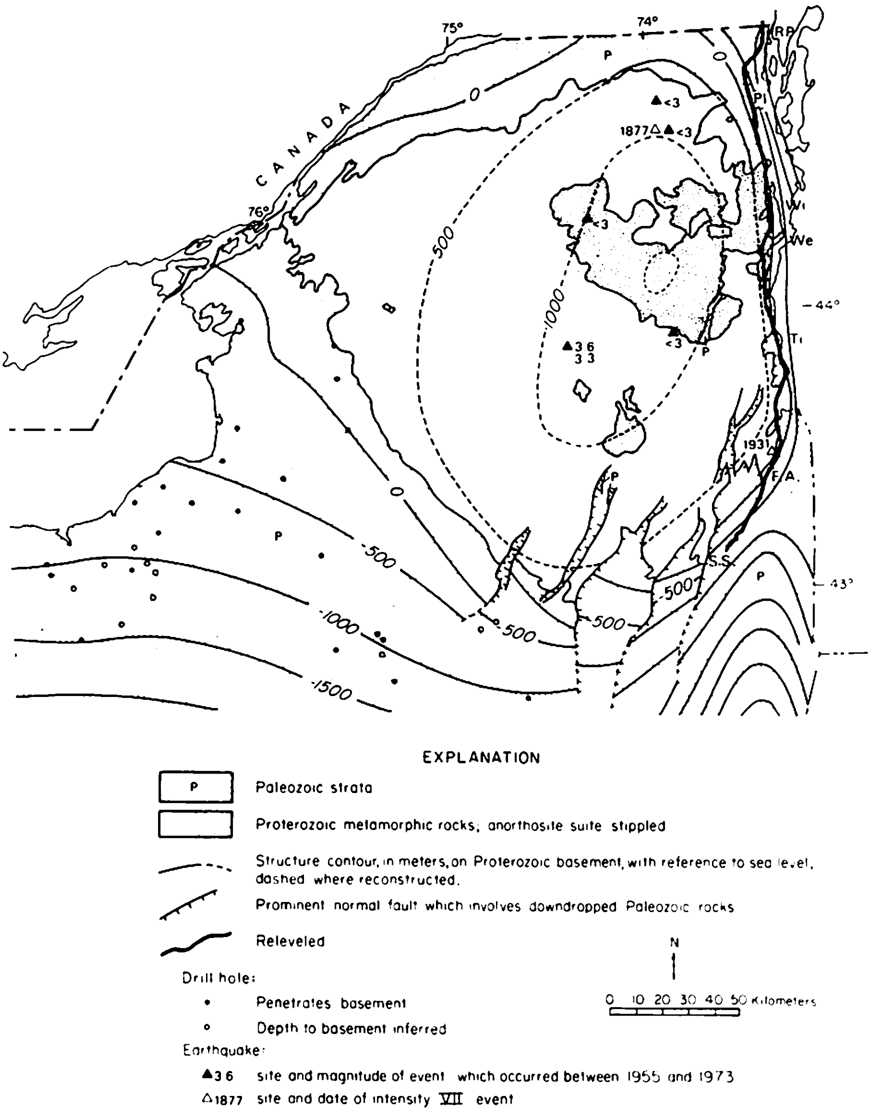

Fig. 1. Map showing structural configuration of the Adirondack dome and locations of major graben and Adirondack border faults. Also shown are the Saratoga Springs (S.S.) to Rouses Point (R.P.) releveled line, and, by abbreviations, the locations of Plattsburgh, Willsboro, Westport, Ticonderoga, and Fort Ann. Earthquake data for 1955—1970 are from U.S. Government Sources, and for 1972—1973 from Lamont-Doherty Geological Observatory data (P.W. Pomeroy, personal communication).

LEVELING PROFILE, SARATOGA SPRINGS—ROUSES POINT, NEW YORK

These and other considerations prompted an interest in the possibility that the Adirondack dome has undergone neotectonic regeneration and may

Fig. 2. ERTS-1 infrared mosaic of the Adirondack Mountain region showing the pronounced development of north-northeast and east-northeast topographic lineaments in the eastern and northern Adirondacks. The arcuate east—west trend of valleys and ridges in the southern Adirondacks is the result of variations in bedrock composition. The Saratoga Springs—Rouses Point releveled line is shown along the eastern flank of the dome, with localities along the line being the same as shown in Fig. 1. Note north arrow. ERTS-1 images used are 1079-15115, 1079-15122, 1080-15174, and 1080-15180. Blue Mountain Lake (discussed in text) is the oval-shaped lake near the geographic center of the Adirondacks.

be undergoing domical uplift at the present time. Accordingly, unadjusted first-order leveling data for the Adirondack region were abstracted from the data base of the Vertical Network Branch of the National Geodetic Survey (NGS) in Rockville, Maryland, and used to construct releveling profiles (see Holdahl and Morrison, 1974). The most informative of these profiles extends north—south along the eastern flank of the Adirondack dome between Saratoga Springs and Rouses Point, a distance of 245 km (Figs. 1 and 2). The level line follows the railroad bed of Amtrack. The relief along the line is slight (Fig. 1) eliminating any need for refraction corrections. Leveling was done along this line at various times from 1916 to 1973.

Fairbridge and Newman (1968) used the relevelings through 1955 to construct a vertical movement-rate profile and a regional isobase map. An attempt was made in the present study to evaluate the 1973 data in terms of that for 1916, 1919 and 1921 as well as that for 1955. The use of a composite profile that would include the older levelings was abandoned, however, due to numerous inconsistencies and discrepancies in the data. Accordingly, only the 1955 and 1973 levelings were used in the present study. The density of releveled stations is very favorable for this time interval, an average of one per 2.5 km: of the total, 23% are in bedrock according to NGS records (Fig. 3).

In constructing the profile, Saratoga Springs was selected as a starting point and *arbitrarily* assigned zero elevation change (Fig. 3). It is desirable to attempt to convert the relative vertical movement shown in Fig. 3 to 'absolute' movement by comparing it with observed movement at the Tidal Station in New York City (Battery). Continuous tide gage records there from 1893 show a rise of sea level with respect to land of 2.87 mm/year (Hicks and Crosby, 1974). From this can be subtracted the value of 1.2 mm/year, which is a common estimate of the rate of glacio-eustatic rise in sea level (Fairbridge and Newman, 1968, p. 297), to obtain an actual velocity of subsidence at New York City of 1.67 mm/year. (This differs little from the rate of —1.83 mm/year adopted by Balazs, 1974.) Using this figure, the crustal subsidence of New York City during the 18-year period represented by Fig. 3 was 30 mm. The movement at Saratoga Springs may be closely correlated with that at New York City by examination of the available leveling profile for New York City to Troy, inasmuch as Saratoga Springs is only 38 km northwest of Troy. Examination of the New York City—Troy profile for the period 1934—1955 (S.R. Holdahl, unpublished) shows a *relative* subsidence of 18 mm for New York City with respect to Troy. However, for the 21-year period involved, the 'absolute' subsidence of New York City would have been 21 years × 1.67 mm/year, or 35 mm. The difference of 17 mm, therefore, indicates a small downward movement at Troy between 1934 and 1955. If this rate of subsidence is extrapolated to the 1955—1973 time interval, the 1973-line of Fig. 3 should be moved downward by (—17 mm/21 yrs.) × 18 yrs. = —15 mm. This amount is about equal to the uncertainty (29 mm) of the movement at Troy as computed from the 1934- and 1955-level

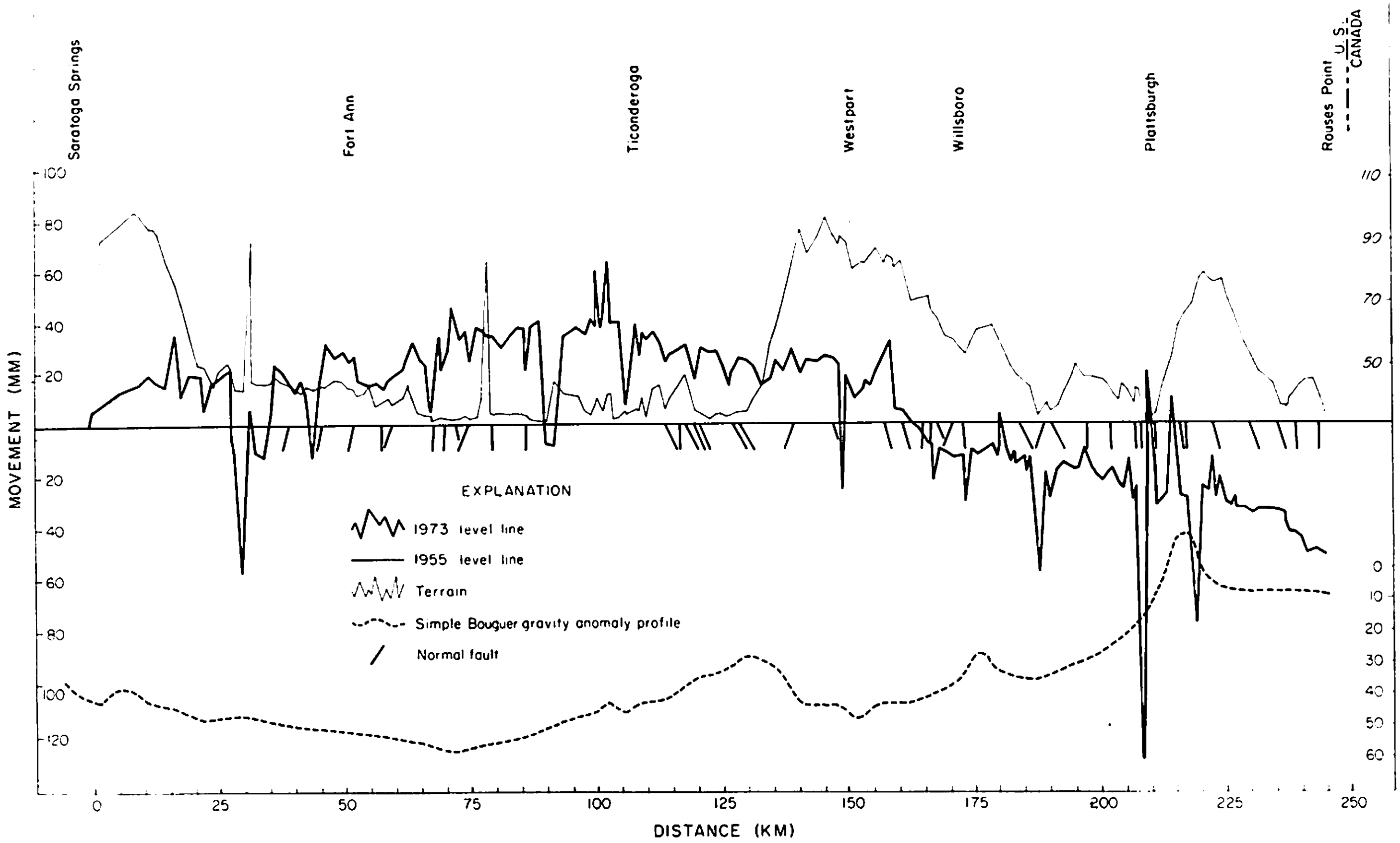

Fig. 3. Geodetic leveling profile showing magnitude of arching along eastern flank of the Adirondack dome during the period 1955–1973. Leveling data from vertical Network Branch of the National Geodetic Survey (NGS); gravity profile from Simmons and Diment (1972) and Diment et al. (1972a); fault data from Fisher et al. (1971).

lines. If this extrapolation is realistic, the profile in Fig. 3 is within 15 mm of being an absolute movement profile.

An examination of the profile in Fig. 3 (ignoring for a moment the several anomalous "spikes") suggests that broad arching has occurred between Saratoga Springs and Rouses Point, with the possibility of a more abrupt offset being located midway between Westport and Willsboro. The magnitude of the vertical displacement is +40 mm around Ticonderoga (which is located approximately opposite the center of the Adirondack dome), and −50 mm at Rouses Point. This corresponds to a rate of 2.2—2.8 mm/year. The standard deviation of the 1955 first-order leveling is approximately equal to 1.0 mm (distance in km)$^{1/2}$, and that for the 1973 leveling 0.7 mm (distance in km)$^{1/2}$, as estimated by NGS (S.R. Holdahl, oral communication). The standard deviation of the computed elevation change along this 245 km line is equal to 19 mm. The total arching along the line is thus 9 cm ± 2 cm.

The points corresponding to the anomalous spikes have not been checked in the field. A reading of the bench mark descriptions made available by NGS permits elimination of three. As to the remainder, it may be noteworthy that most are 'down-spikes' such as could be caused by vibration and compaction along a railroad bed if bench marks were affixed to any monument subject to movement.

INTERPRETATION OF RELEVELING PROFILE BETWEEN SARATOGA SPRINGS AND ROUSES POINT

Magnitude of vertical crustal movement

The vertical movements represented in Fig. 3 are interpreted as real. The maximum velocity indicated, about 2.8 mm/year, is near the maximum range (3—5 mm/year) for platform and shield areas of the eastern United States (Mescherikov, 1968, p. 224). It is more than twice the 1 mm/year rate of uplift of the Swiss Alps during the 52-year period, 1918—1970 (Schaer and Jeanrichard, 1974, p. 105). Such comparisons must be interpreted with caution, however, because the vertical movements in question are not known to be unidirectional rather than oscillatory during the interval involved.

The wavelength of the arching and corresponding depression along the Saratoga Springs—Rouses Point profile exceeds 250 km, inasmuch as the northern end of the line does not show an upturn. Taking Saratoga Springs as the southern hinge of the upward movement, and the midpoint between Westport and Willsboro as the northern hinge, and assuming this to be a half wavelength distance, the wavelength of the uplift and corresponding depression to the north would be about 300 km. This is relatively short compared with that of contemporary uplifts and depressions on the Russian Platform, which are on the order of 800 km (Mescherikov, 1968, p. 225). The value given by Mescherikov for the Japanese Islands is about 200 km, but that applies to an orogenic belt as opposed to the cratonic Adirondack region.

Origin and mechanism of the vertical movement

Vertical movement in glaciated regions is quite naturally first evaluated in terms of possible postglacial rebound. Such isostatic recovery is generally manifested as regional tilting, with the magnitude of rebound increasing toward the center of former ice sheets — in this case toward north (e.g. Moore, 1948). The present profile, however, shows just the reverse of this: subsidence beginning near Willsboro and increasing northward. This suggests that, although isostatic recovery may be incomplete in the central part of the region occupied by the Laurentian ice cap in northern Canada (Walcott, 1970, 1972; Andrews, 1974) it has been superceded in the Adirondack region by tectonic arching.

Normal faults located along the releveled line have been added to Fig. 3. They typify the block-faulted eastern Adirondacks (Fig. 2, and Fisher et al., 1971). In Fig. 1 are shown epicenters and magnitudes of all recorded seismic events which occurred in the eastern Adirondacks during the 1955—1973 interval between levelings. (Also shown are the sites of the two older Intensity VII events which have occurred in the region.) The distribution of the 1955—1973 earthquakes shows that although there are abundant sites for fault reactivation, there is no seismic evidence of fault activity. It thus appears that the vertical movement was manifested either aseismically or as unrecorded microearthquake activity.

It should be noted that small-scale postglacial faulting of glacially striated surfaces is common along a north—south belt on the east side of the Hudson—Champlain Valley (Oliver et al., 1970). The movement tends to be on northeasterly-trending cleavage planes, with the south or east side upthrown. I know of no similar examples of postglacial faulting in the Adirondacks.

A simple Bouguer gravity anomaly profile along the level line is shown in Fig. 3. The sharp positive anomaly at Plattsburgh is probably caused by a shallow intrusion of mafic or ultramafic rocks analogous to the Monteregian Hills plutons in southern Quebec (Diment, 1968, p. 399). The Plattsburgh anomaly shows no relationship to the movement profile. Elsewhere along the section, the gravity profile shows a general inverse correlation with the leveling data. The shape of the gravity profile, however, does not of itself indicate whether or not isostatic imbalance exists. Simmons (1964) has shown that the isostatic anomaly over the central part of the Adirondacks is approximately zero, and the surrounding area is negative (to about —35 or —40 milligals). He concludes that the region is in gross isostatic equilibrium, and attributes the broad anomaly to a north-trending ridge with 2°-dips developed in the crust—mantle boundary. The depth to this boundary has been determined by an unreversed seismic refraction profile to be 36 km (Katz, 1955). It may be noteworthy in a regional context that the north-northeast axis of this isostatic anomaly coincides with that of the reconstructed Adirondack dome.

The possibility of contemporary doming of the Adirondacks

Pending releveling across the center of the Adirondacks, it is tempting to consider the possibility that the arching occurring along its eastern flank is a manifestation of contemporary uplift of the dome as a whole, and to consider some geophysical and geological correlatives and possible implications.

(1) A strong negative simple Bouguer gravity anomaly characterizes the main (Marcy) anorthosite massif except for the fairly large extension to the east which reaches the leveling profile in the Westport—Willsboro area (see Fig. 1). Heat-flow measurements in the Marcy massif yield anomalously low values (Birch et al., 1968, p. 477; Diment et al., 1972b, p. 555). However, the low heat flow corresponds directly with the relatively low radioactive heat generation of the pluton, and *may* have no significance beyond that.

(2) Very near the geographic center of the Adirondack dome, at Blue Mountain Lake (Fig. 2), is an area which has produced shallow earthquake swarm activity during the summers of 1971 and 1973 (Sbar et al., 1972; Sbar and Sykes, 1973; Sykes and Sbar, 1973). The strongest 1971 quakes were of magnitude 3.6 and 3.4. Two composite thrust planes were initially proposed, one striking N12W and dipping 25°E for earthquakes shallower than 2 km, and another striking N31E and dipping 59°E for events at 2—3.5 km depth. In a later paper (Aggarwal et al., 1973) the mechanism is given as a single tabular zone that dips gently eastward to a depth of about 2 km, then steepens for depths from 2 to 3.5 km. The fracture experiments of Mogi (1967) suggest that the reason for swarm-type activity, in contrast to discrete shocks such as typify epicenters elsewhere in the craton (P.W. Pomeroy, oral communication), may be the pervasive fracturing within the dome (Fig. 2).

The fact that the Blue Mountain earthquake epicenter is situated at the center of the dome may be significant if the entire dome is undergoing contemporary uplift. However, the above authors invoke an east—west principal compressive stress to account for the earthquake activity, whereas doming would imply a major vertical stress, and the observed arching either a vertical stress or a north—south compressional stress. The determination of contemporary stresses at Blue Mountain Lake is now under investigation by Lamont-Doherty Geological Observatory and the New York State Geological Survey using a seven-unit seismic network. In addition, in-situ overcoring methods are being employed elsewhere in the region (Sykes et al., 1974).

(3) The diffuse Boston—Ottawa seismic zone of Sbar and Sykes (1973) passes northwesterly across the Adirondack region, with the maximum concentration of historical and recent seismic activity occurring in a northwesterly swath across the northern third of the Adirondacks.

(4) The eastern and northern Adirondacks are marked by a pronounced development of normal faults and topographic lineaments trending north-northeast in the eastern Adirondacks and fanning gradually to an east-northeast direction in the northern Adirondacks (Fig. 3). The majority trend north-northeast, parallel to the axis of the Adirondacks dome (compare Figs.

1 and 3) and it is this set which accounts for most of the major graben. A high percentage of the lineaments are either known or suspected high-angle faults (Isachsen, 1973, 1974).

(5) An analogous roughly circular area of contemporary subsidence is located about 500 km north-northeast of Ticonderoga near the City of Quebec (Frost and Lilly, 1966; Vaníček and Hamilton, 1972). Its definition is based on numerous relevelings in the region between 1919 and 1965. It is a region of low relief, but has areal dimensions comparable to those of the Adirondacks. The maximum subsidence, 4 mm/year, is centered on Stoneham. This occurrence strengthens the interpretation that the entire Adirondacks may be undergoing domal uplift. However, an alternative interpretation of the arching deserves consideration: the subsidence at the northern end of the Saratoga Springs—Rouses Point profile may be indicative of reactivation of the Mesozoic St. Lawrence rift system of Kumarapeli and Saull (1966). In their paper they envision the Adirondacks as a major horst. An analysis of releveling data between the Adirondacks and the Stoneham subsidence area is highly desirable.

History of Adirondack doming

The Paleozoic history of Adirondack vertical movement has been considerably illuminated by subsurface map information extracted from drillhole data by Rickard (1969, 1973). For the Lower Paleozoic, isopach trends indicate that the Adirondack region was receiving sedimentation from Cambrian through Early Ordovician time, then mildly uplifted in the western part at the end of Early Ordovician time, and shortly resubmerged to receive Middle Ordovician sediments (Rickard, 1973). Isopachs in the Silurian (Rickard, 1969) head toward the southern border of the present Adirondack dome with northerly trends, suggesting that they originally crossed the region. The same applies to isopach trends throughout the Devonian (L.V. Rickard, oral communication, 1975). In summary, sedimentary trends of Paleozoic rocks peripheral to the present Adirondacks provide strong evidence that the doming occurred in post-Paleozoic time. The absence of strata younger than Late Devonian around the Adirondacks precludes a similar analysis of Carboniferous, Mesozoic, or Cenozoic movement history of the region.

The glacioisostatic uplift that followed deglaciation in northern New York amounted to about 175 m (Andrews, 1970, p. 705). The initial rebound was extremely rapid, amounting to about 95% recovery within 6000 years after deglaciation (by extrapolation from uplift curves for the Arctic by Andrews, 1968, p. 45).

The present rate of arching of 2.5 mm/year is unrealistically high for a long-continued trend. Uplift to produce the entire relief of the Adirondack dome at the present rate of uplift would have required only about 1 m.y. This suggests that the rapidity of contemporary uplift must be part of a discontinuous, or even oscillatory process.

CONCLUSIONS

(1) A new north—south releveling profile in northern New York State indicates that a crustal arching of 9 ± 2 cm has occurred over a distance of 245 km along the eastern flank of the Adirondack dome during the 18-year period 1955—1973. The absolute velocity of this vertical movement is from 2.2 mm/year to 2.8 mm/year.

(2) The fact that the profile is one of arching rather than regional tilting, and that it demonstrates subsidence at the northern end, suggests a tectonic rather than glacioisostatic origin.

(3) Lack of earthquake activity along the releveled line during the interval involved indicates that the arching was the result of either aseismic deformation or undetected microearthquakes.

(4) 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 determined from 1971 and 1973 earthquakes in the central Adirondacks at Blue Mountain Lake. A continuation of in-situ stress measurements in the area is highly desirable.

(5) The arching along the eastern flank of the dome may be indicative of contemporary preferential uplift of the Adirondack dome as a whole. If this is the case, several important correlations become apparent, namely, the correspondence in strike (north-northeast) between the axis of the Adirondack dome, Simmons' (1964) inferred mantle ridge, and the prevalent fault-lineament set. Also significant in this connection may be the earthquake swarms at the center of the dome, at Blue Mountain Lake. These correlations suggest cause and effect relationships that deserve further investigation. Particularly desirable would be releveling along the 1931 first-order level line between Utica and Malone, which passes across the Adirondack dome and has numerous bench marks located in bedrock.

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