MESOZOIC FAULTS AND THEIR ENVIRONMENTAL SIGNIFICANCE

IN WESTERN VERMONT

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ABSTRACT

A 50 km long system of north-trending, remarkably linear faults of small to moderate displacement cut the folded Paleozoic carbonates of the Champlain synclinorium, and cuts the eastern edge of the Hinesburg thrust near St. George and Colchester Pond. Associated minor faults, slickensides and right-lateral offset of stratigraphic units indicate down-to-the-east displacement of 500 m.

The St. George fault, the longest fault in the system, extends through kaolin mines and goethite-manganite deposits several km south of East Monkton, offsets major folds in an apparent sense by as much as 1 km in the eastern part of the Hinesburg synclinorium, and cuts the western edge of the Hinesburg thrust near St. George and Colchester Pond. Associated minor faults, slickensides and right-lateral offset of stratigraphic units indicate down-to-the-east displacement of 500 m.

Four km north of Monkton Ridge, the St. George fault branches to the southwest forming the west-dipping Monkton fault which was originally interpreted by Cady (1945) as a low-angle thrust. Stratigraphic offset, fracture fabrics, and dip slickensides on the exposed fault surface indicate 850 m displacement. Numerous small cross faults of normal and poise strike-slip movement of less than 100 m cut the north-trending system and probably inhibited subsequent movement.

This regional system of high-angle faults developed during early Mesozoic extension since they cut compressional structures of western Vermont and are transected in several places by lamprophyre dikes of presumed Early Cretaceous age. Post-dike fracture systems are well documented in the Burlington area but definitive evidence for younger faulting has not been recognized yet. The fault system is important in controlling mineral deposits and groundwater resources. The potential for earthquakes on the high-angle system appears low because the inferred resolved shear stress is small and it is locked by discontinuous cross faults. Seismic potential on the Champlain thrust beneath the Green Mountains could well be a far more significant hazard if the east-west compressive stress characteristic of eastern New York extends into Vermont.

INTRODUCTION

Low- and high-angle faults have long been recognized as an important structure in the Champlain basin (Doll and others, 1961; Isachsen and McKendree, 1977; Fig. 1). The Champlain and Hinesburg thrusts and those of the Taconic allochthons are important regional low-angle thrusts. Regionally, extensive high-angle faults are well known west of the Champlain thrust where they strike northeasterly and generally are downthrown to the east forming a step-like sequence from the core of the Adirondacks to the shores of Lake Champlain. In fact, they may be present in the bedrock beneath Lake Champlain as they are to the south in Lake George (Hunt, 1979, personal commun.).

In the last 10 years, seismicity in the northeastern United States has attracted considerable attention due to current and proposed construction of nuclear power plants, dams, and underground structures for storage or disposal of waste material (Fletcher and others, 1978). The extensive network of sensitive instruments in New York and New England that has been active during this time can now detect and locate earthquakes of magnitude 4 or less. These data combined with older information indicate considerable seismic activity in the northeast, particularly in the St. Lawrence lowlands, the Adirondacks of northern New York and the Boston area of Massachusetts. Sykes and Sbar (1973) have suggested that these areas are part of a northwest-trending belt of earthquakes extending from Boston to Ottawa, Canada (Boston-Ottawa Seismic Zone). This belt passes directly through the Hinesburg synclinorium where approximately 25 percent of Vermont’s population resides. Despite subdued seismic earthquake activity in west-central New Hampshire and Vermont (Fletcher and others, 1978), it is appropriate to examine the earthquake hazard of western Vermont in light of a recent discovery of a regionally extensive, high-angle fault system along the trace of the Hinesburg thrust in west-central Vermont (Figs. 1 and 2).

This north-trending system is here designated the St. George-Indian Brook-Monkton fault system (GIM). It has been mapped from Milton southward to Bristol for over a distance of 50 km. It is remarkably straight throughout much of its extent but
it is offset by small cross faults in the latitude of the Monkton culmination. Dip-slip movement varies from 100 m for the Indian Brook fault to 500 m for the St. George fault to 850 m for the Monkton fault. The short, east-west faults which offset the GIM system are normal faults with 50 to 70 m displacement.

Although mapping has been confined to the Hinesburg synclinorium, there is evidence that it may be part of a larger system that extends just west of the Green Mountains to the Massachusetts state line (Fig. 1). South of Rutland, Vermont, a 6 km-long normal fault borders the eastern side of a ridge of Precambrian rocks in the Cambrian and Ordovician rocks of the Vermont valley (Doll and others, 1961). Its age is largely unknown. A similar fault of unknown extent cuts a lamprophyre dike dated at 105 m.y. in West Rutland (Zen, 1972, p. 2583). Both faults are downthrown to the east. Eleven km south of Bennington, Vermont, a 10 km-long, west-dipping normal fault extends southward into Massachusetts...
George-Monkton fault system enters the main region of Quartzite (Figs. 2 and 4). Here the St. of Monkton Ridge near Cedar Lake (Figs. 2 and 4) Ridge, the Monkton fault branches southwestward from Five hundred meters of this total displacement is wide. Exposed dip-slip slickensides on the minor faults of the St. George-Monkton fault system suggest a similar structural control for the Bennington region as well as the other reported deposits in Brandy Brook west of Monkton. Bennington uncovered a number of north-trending normal faults all with displacement less than 50 m. Two kaolin deposits occur just to the northeast. This fault zone lines up nicely with the Reservoir Brook fault. The association of kaolin deposits and iron-manganese deposits with the St. George-Monkton fault system suggest a similar structural control for the Bennington region to the south as a horst cored by Cheshire Quartzite south and east of Monkton Ridge are fault controlled. Some of these contain kaolin. The evidence is best displayed where the rocks are quartzitic - it is most cryptic where the rocks are marble and shale.

The first area is located at the hinge of a major north-trending anticline about 1.6 km south of the town of Hinesburg (Figs. 2 and 3). Here a large swamp occupies the hinge region of the anticline. It is continuous with a major valley that extends northward to the fault-controlled valley of Bennington north of Monkton. Recent excavation along the Route 7 bypass north of Bennington uncovered a number of north-trending normal faults all with displacement less than 50 m. Two kaolin deposits occur just to the northeast. This fault zone lines up nicely with the Reservoir Brook fault. The association of kaolin deposits and iron-manganese deposits with the St. George-Monkton fault system suggest a similar structural control for the Bennington region to the south as a horst cored by Cheshire Quartzite south and east of Monkton Ridge are fault controlled. Some of these contain kaolin. The evidence is best displayed where the rocks are quartzitic - it is most cryptic where the rocks are marble and shale.

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The folds are large enough to control the outcrop pattern of the thrust zone and produce a major south-plunging anticline at Brigham Hill and a major syncline at Colchester Pond. This is basically the interpretation suggested by Stone and Dennis (1964, pl. 1). Detailed mapping by Rosencrantz (1975) and Agnew (1977) in this area has shown that the thrust surface and the bedding and regional cleavage in both plates do not change dip systematically from Brigham Hill to the west edge of the Hinesburg thrust as required by the syncline interpretation (Fig. 5).

The key area is just north of Colchester Pond where the western edge of the Hinesburg upper plate is remarkably straight. If this were the western limb of a major syncline, the bedding or older layering should be vertical. Instead, it dips at very gentle angles to the west. Rosencrantz (1975) suggested that the western margin of the Hinesburg thrust has been cut by the northern extension of the St. George fault. Upthrown movement on the western block has partly removed the upper plate resulting in 2 km of left-lateral strike separation on the map (Fig. 5).
Quartzite are abundant in outcrops near the fault. Quartzite (Gilman facies) and the underlying North-trending high-angle fractures in the Cheshire Bascom Formation. They do not offset the St. George fault, because they are of middle to late Paleozoic age, however, cannot be ruled out in western New England (Geiser, 1980).

What, then, are the age constraints on the GIM fault system? Clearly, it is younger than the Hinesburg thrust and the major folds of the Hinesburg synclinorium (Fig. 2). The apparent strike-slip offset southward into the Middlebury synclinorium and the Taconic allochthon where they are considered Middle Devonian (Acadian orogeny) in age (Zen, 1972, p. 2556; Crosby, 1963, p. 128; Voight, 1972), although a Middle-Late Ordovician (Taconic orogeny) age is not completely ruled out to the north (Stanley, 1972, Fig. 17). Late movement of the Champlain thrust folded the penetrative slaty cleavage in the lower plate and gently flexed the western edge of the upper plate. Although radiometric age control is lacking, these events probably represent a late event in the Acadian orogeny. The Alleghanian stage of the Alleghanian orogeny and the Alleghanian phase of the Appalachian orogeny is considered Middle Triassic in age, however, cannot be ruled out in western New England (Geiser, 1980).

The lamprophyre and trachyte dikes could provide the chronological key for better establishing the age of faulting in the region. Dated dikes are Late Jurassic-Early Cretaceous in age (125-160 m.y.; McHone, 1976, Fig. 5; Zaartzman and others, 1967). The age spectrum of the lamprophyre and trachyte dikes in western Vermont and Ascutney in eastern Vermont cover the same age range. Unfortunately, the highly fractured character of the fault zones and the lack of continuity of the fault slickensides hampers the application of these dikes to the GIM fault system. One lamprophyre dike does cut a minor normal fault associated with the St. George fault near the hinge of the anticline north of Monkton Ridge (point A, Fig. 3). Another well-exposed dike cuts north-trending normal faults of minor displacement at Winooski Falls, Winooski, Vermont (point B, Fig. 7). These faults are considered coeval with the St. George system because they cut compressional fracture fabric correlated with the Champlain thrust. Faulted dikes are reported from several localities in western Vermont (Zen, 1972, p. 2554; McHone, 1978, Table 2). Thus, the GIM fault system and its possible extension to the north appears to have been developed before the intrusion of the dikes. I suggest a Late Triassic or Early Jurassic age because other major grabens were developing in the Appalachians and the North Atlantic at this time (Deboer, 1967; Burke, 1976). An older middle to late Paleozoic age for the system, however, cannot be ruled out.

**ENVIRONMENTAL SIGNIFICANCE**

The Mesozoic high-angle faults are important in terms of mineral deposits and groundwater resources. They may also form a potential earthquake hazard. Although the available information is far from complete, important conclusions can be suggested for each of these three.
Figure 6. Geological map of the St. George area showing the Hinesburg thrust, short east-west faults to the west, and fracture zones to the east truncated by the St. George fault. Map modified east-west faults to the west, and fracture zones to from unpublished work of M. Black and M. Bergeron for Field Geology, University of Vermont, 1975.

Most of the kaolin deposits in western Vermont are found in surficial material underlying glacial drift (Burt, 1927). They commonly overlie the Cheshire Quartzite and occur very close to the steep western front of the Green Mountains where faults are abundant. Many of the low grade iron-manganese deposits in western Vermont are associated with or occur near kaolin deposits. At Brandon, lignite is also present (Burt, 1927, p. 80). Similar deposits are reported through the central and southern Appalachians (for example, Foose, 1945; King, 1950; and King and Ferguson, 1960). They are commonly thought to originate as residual products from the normal weathering of iron- and manganese-bearing carbonate rocks (King, 1950, p. 68, to cite only one example) or of feldspar-bearing rocks, in the case of kaolin. The residual material was deposited in topographic depressions. It is suggested that differential weathering of fractured rock may control the depressions in western Vermont.

The iron-manganese deposits at East Monkton certainly fit this interpretation because the ore is deposited as a cement in brecciated quartzite along the St. George fault. Burt (1927, p. 79-80) suggests a late Mesozoic to early Cenozoic age, perhaps Miocene, for these deposits based on the fossils in the lignite at Brandon. This age would
Figure 7. Geologic map of the Salmon Hole along the Winooski River, Burlington Vermont (Fig. 2), showing fractures, faults and en echelon fracture arrays. Based on field work and analyses by P. Winner and G. Smith, University of Vermont, 1979. Point B locates site where north-trending lamprophyre dike cuts north-trending normal fault.

also apply to the surficial kaolin deposits associated with the iron and manganese.

The kaolin deposit at East Monkton, however, is quite different from the other kaolin deposits in Vermont in that it occurs in fractures and distinct layers within the Cheshire Quartzite rather than a surficial deposit on bedrock. According to Ogden (1969, Fig. 5), the deposit is at least 35 m deep and consists largely of kaolinitic quartzite interlayered with massive quartzite. The kaolin has replaced silica cement in porous quartzite. Fresh, authigenetic feldspar is common in voids between fractured quartz grains. Partly kaolinitized feldspar is absent. Feldspathic quartzites are not reported from the Cheshire Quartzite in western Vermont, thus precluding formation of the deposit by deep weathering of indigenous material by groundwater solutions. Thus, irrespective of the origin of the kaolin, it does appear that many of the kaolin, iron manganese deposits of western Vermont are controlled by faults. Those to the south of the Hinesburg synclinorium may or may not be part of the GIM system although their trend seems to suggest they are.

Perhaps one of the more important practical aspects of the high-angle faults is their
relationship to the bedrock groundwater resources in western Vermont. The clastic rocks are devoid of inherent intergranular porosity because they are thoroughly recrystallized. Instead, the porosity and permeability are controlled by postmetamorphic fractures. Fracture density and extent (horizontal-vertical) are a function of rock type, strain intensity and relationship to such major structures as faults and folds. Whereas fold-related fractures have been documented elsewhere (Stearns, 1969; Marcotte, 1975), these are absent in the clastic rocks. Fracture studies in western Vermont have shown this relationship (Sarkisian, 1970; Marcotte, 1975). Instead, the fractures cut across the major folds of the Hinesburg synclinorium and presumably show the same relationship to the major folds to the south and north. Many of the fracture fabrics increase towards major faults and infer stress configuration compatible with known displacement on the faults. Fractures in shale are limited in extent and are tight due to the weak nature of the rock. In dolostone, they are commonly healed, whereas they are more open and extensive in marble due to ground water solution. Although fractures are less abundant in quartzite, they are far more continuous both horizontally and vertically. Furthermore, they appear to be tightly controlled by the present-day elastic strain compared to carbonates and shale. The fracture characteristics in quartzite and marble, therefore, are important in providing significant porosity and permeability in the bedrock aquifers of western Vermont. Because fractures are more abundant near faults, particularly where they intersect each other, the geometry of the high-angle faults where they cross marble and quartzite takes on added importance. Areas underlain by the Cheshire Quartzite and cut by the high-angle faults are topographically high and thus form potentially important recharge areas. The Monkton area is a good example of the three-dimensional geometry of the thick marbles (Shelburne Marble) and quartzites (Cheshire and Monkton) will also provide a valuable basis for evaluating bedrock reservoir potential.

Considerable attention has recently been paid to seismicity in the northeastern part of the United States (Sbar and Sykes, 1973; Fletcher and others, 1979). Shallow earthquakes of magnitude 4 or less are abundant (Sbar and others, 1972). Here the fault-plane solutions suggest that $\sigma_3$ plunges S 78 W at 5 degrees for shallow quakes (2 km or less) and S 61 E at 30 degrees for deeper events (2-3.5 km) (Sbar and others, 1972). Figure 6 is a schematic representation of this quantity is not available for Vermont to the author's knowledge. Oliver and others (1970, Fig. 1) report numerous small post-glacial faults in the Paleozoic shale and slate along the east side of the Hudson and Champlain valleys northeasterly into Quebec. Nearby all of these faults parallel the dominant cleavage (essentially north or northeasterly strike) with the east or east-northeast side upthrown. This indicates that the westerly orientation of $\sigma_3$ may persist into at least western Vermont.

In contrast, strain relief in situ stress measurements from Proctor (dolostone) and Barre (granite), Vermont, indicate a north-trending direction (N 14 W-N 4 W) almost 90 degrees to the orientations to the west. According to Sbar and others (1972), this same general orientation persists to the east and south into Pennsylvania. Therefore, western Vermont appears to be on the threshold of a major change in the orientation of $\sigma_3$, assuming that the rock mass is in an equilibrium state of stress. Interestingly enough, both orientations are reflected in the fracture fabrics, minor faults and deformation lamellae in quartz and dolomite from west-central Vermont. Many of these features appear to have developed in Paleozoic and Mesozoic time (Stanley, 1974; Sarkisian, 1970; Marcotte, 1975, for example). At Shelburne Access area near Burlington, Vermont, $\sigma_3$ has switched from east-west to north-south, although the former was an orientation of long duration and is thought to be associated with Acadian movement on the Champlain thrust (Stanley, 1974). The second configuration is also interpreted as Acadian, although a younger date certainly cannot be ruled out. Better chronological control is found, however, directly north at Winoski Falls where four stress configurations have been worked out primarily on en echelon fracture arrays, non-trending normal faults, and a north-trending lamprophyre dike (Fig. 7). A west-trending $\sigma_3$ position and northwest-trending $\sigma_1$ position (vertical in both cases) are older than the normal faults (vertical). A direction indicated by the dike of presumed Early Cretaceous age (point B, Fig. 7). Northeast-trending fractures and coeval en echelon arrays of both left- and right-handed patterns in the dike and indicate a subhorizontal configuration trending northeast and essentially parallel to the orientation for shallow earthquakes from the 1971 Blue Mountain Lake earthquake swarm (Sbar and others, 1972).
Figure 8. Lower hemisphere, equal-area projection of the St. George fault and associated cross faults in the Monkton area (Fig. 5). Asterisks (*) locate $\sigma_1$ positions for the Blue Mountain quakes for 1971 and 1972. In situ stress measurements are labeled ISS. Stippled area labeled "St. George fault" shows range of dips (80E - 90). Stippled area labeled "Normal fault", "reverse fault" are optimum $\sigma_1$, positions assuming a coefficient of friction of 30 degrees according to the Coulomb-Mohr fracture criterion. For pure dip-slip motion, the position is marked by short line with arrow. Other $\sigma_1$, positions within the stippled area result in oblique motion. The $\sigma_1$ position for pure strike-slip motion on the St. George fault is indicated by western arc near the circumference of the net. Resolved shear stress on the fault decreases to zero when $\sigma_1$ falls on the short line labeled "pole to fault". Arcs are restricted by looking cross faults that inhibit oblique slip with a major strike-slip component. Plane of the projection is horizontal with N marking north.

With this information as a background, I will attempt to evaluate the potential for seismic activity of the St. George fault, the Monkton fault and the Champlain thrust. The Hinesburg thrust is not considered because it is folded and offset by subsequent faults, although all the evidence has not been considered in this paper. The cross faults are also not considered hazards since they are discontinuous and have only been displaced by less than 100 m. They are, however, important in retarding strike-slip movement.

If the in situ stress measurements for Proctor and Barre do represent the regional stress in western Vermont, then the seismic hazard of these three faults is very low since the inferred $\sigma_1$ direction would essentially parallel their strike (Figs. 8 and 9). The east-west $\sigma_1$ direction based on a variety of data from northeastern New York requires careful consideration. In Figures 8 and 9, I have plotted the St. George fault, the Monkton fault, the cross faults of the Monkton Ridge area, and the inferred stress positions from the Blue Mountain earthquake swarms of 1971 and 1972 (Sbar and others, 1972). I have selected this solution because it is probably the most representative measurement of the current regional stress system. Two fault plane solutions were given for the Blue Mountain swarm, one for shallow quakes (less than 2 km) and one for deeper quakes (2-3.5 km). Although both positions are plotted in Figures 8 and 9, Sbar and others (1972, p. 1314) believe the shallower $\sigma_1$ position probably represents the regional system.

If we compare the relationship of the shallow $\sigma_1$ position to all three faults, it is obvious from Figure 10 that the resolved shear stress is largest for the Champlain thrust, and smallest for the St. George fault. The lack of recognizable activity on the Champlain thrust may mean a reorientation of the $\sigma_1$ direction to a position where the resolved shear stress is greatly reduced, i.e., the north-south direction indicated by the in situ stress measurements. Alternatively, the thick section of shale below the thrust could very well dissipate the differential stress for east-west stress systems by distributed shear throughout the section. Earthquakes, however, should still develop to the east where the thrust cuts through the carbonate rocks and quartzite and finally into the crystalline rocks of the Precambrian (Fig. 10).

The St. George and Monkton faults appear to constitute low potential hazards since the resolved shear stress is moderate to low. The inferred deep $\sigma_1$ position of Sbar and others (1972) would produce right-lateral motion on both faults with a reverse component for the Monkton fault (Figs. 8 and 9). The cross faults in the Monkton Ridge area obviously prevent this type of movement, particularly in the case of the Monkton fault. Interestingly enough, many of the markers are offset in a right-lateral sense by the St. George fault, although the actual movement is thought to be dip-slip. If the inferred deep $\sigma_1$ position of Sbar and others (1972) represents the stress system in western Vermont, then left-lateral movement would occur on both faults with a definite reverse component for the St. George fault.

What happens to the St. George and Monkton faults at depth? In Figure 10, the faults are shown as planar surfaces. The data by Monrad (1976) on
Figure 10. Cross section through west-central Vermont simplified from section B-B' (Doll and others, 1961) showing the earthquake potential of the Champlain thrust, Hinesburg thrust, Monkton fault, and St. George fault. Arrows on either side of the St. George-Monkton coeval fold fabrics in the Monkton horst and the adjacent blocks clearly shows that the faults must be curved at depth. If they curve away from the horst as shown by the dashed lines in Figure 10, the St. George fault would become more parallel to the Champlain thrust at depth. Therefore, the resolved shear stress would become larger for both the shallow and deep positions projected into the line of section. Solid lines represent planar surfaces and dashed lines represent curved surfaces for the St. George and Monkton faults at depth.

In summary, then, it appears that the Champlain thrust forms the most likely seismic hazard in western Vermont if preexisting faults are only considered. Along this surface, earthquakes are more likely to form beneath the Green Mountains than the Champlain Valley (Fig. 10). The GIM fault system may form a lock on the Champlain thrust surface if its form is anything like that shown in Figure 10. The significance of the lock in preventing westward upper-plate movement, however, may not be important since the down-to-the-east movement is only estimated at 500 m and, thus, trivial on a regional scale. The Monkton fault is a low seismic hazard because it is relatively short and the resolved shear stress appears to be small. The St. George fault may be more of a hazard because it extends for a minimum strike-distance of 50 km and may flatten toward the Green Mountains at depth. Both the St. George and Monkton faults are locked by cross faults in the Monkton culmination.

Thus, the lack of seismic activity in western Vermont appears to be due to a combination of factors: the lack of continuity of fault surfaces (Hinesburg thrust, cross faults) and low resolved shear stress on the GIM fault system. The thick shale section on the lower plate of the Champlain thrust may absorb elastic strain, thus minimizing seismicity. Alternatively, all of western Vermont could be decoupled on a still lower ductile surface as suggested by Dimant (1980).

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