# 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 plate into horsts and grabens. Similar structures are probably expressed in bedrock beneath Lake Champlain.

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.

East of Colchester Pond, the Indian Brook fault is also downthrown to the east and may well extend 30 km southward through Essex Junction to Lake Iroquois.

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 possible 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.)

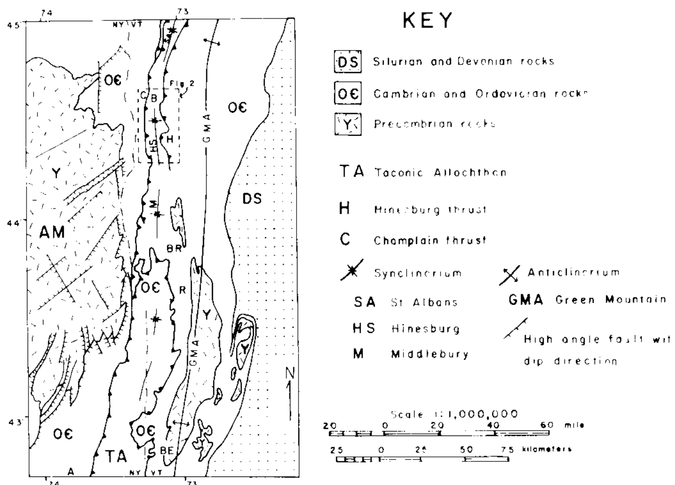


Figure 1. Simplified geological map of Vermont and eastern New York showing the distribution of the major areas of Precambrian (Y) rocks, Cambrian and Ordovician (OЄ) rocks and Silurian and Devonian (DS). Also shown are major high-angle faults of the eastern Adirondack massif (AM), the Champlain thrust, the Hinesburg thrust and the Taconic allochthons. Figure 2, the Hinesburg synclinorium, is located by dashed rectangle. Burlington B, Brandon Br, Rutland R, Bennington Be, and Albany A are shown.

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

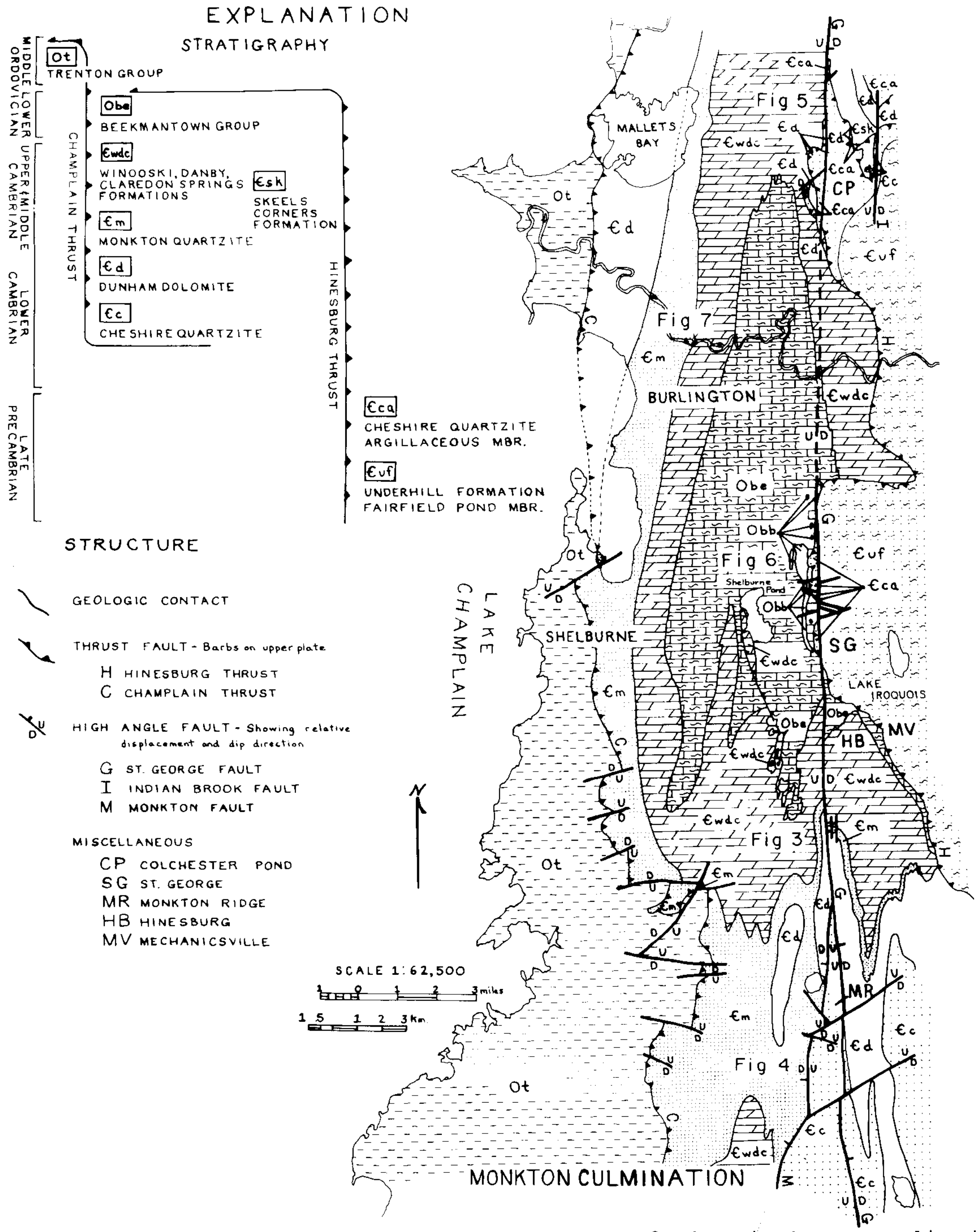


Figure 2. Generalized geologic map (1:62,500 ) of the Hinesburg synclinorium, west-central Vermont showing the St. George (G)-Indian Brook (I)-Monkton (M) fault system with associated cross faults in the Monkton Ridge area (MR). Champlain thrust (C) places Dunham Dolomite (€d) and Monkton Quartzite (€m) on shales of the Trenton Group (Ot) along Lake Champlain. Hinesburg thrust (H) to the east places argillaceous Cheshire Quartzite (€ca) and Underhill Formation (€uf) on carbonate rocks and quartzites of the Cheshire through Beekmantown interval. Obb are calcereous phyllite of the Brownell Mountain Member of the Bascom Formation in the Beekmantown Group. Details of the GIM system are shown in Figures 3-6.

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

(Fig. 1). This fault, called the Reservoir Brook fault by MacFayden (1956, p. 48) is very similar to those of the St. George-Monkton system in that the adjacent rocks are brecciated and highly polished. Slickensided surfaces are numerous, and high-angle fracture fabrics are common. Displacement on this fault is estimated to be 750-900 m in the dip direction. Harwood and Zietz (1974, p. 182), however, estimate displacement in the order of 1900 m based on offset estimates of regional magnetic anomalies in the area. The kaolin deposits of the Bennington region are oriented along an elongate belt that overlies or is adjacent to the Cheshire Formation (Burt, 1927, Fig. 9). The two southern deposits coincide with the Reservoir Brook fault. Burt (1927, p. 66-67) shows that other deposits are present near the "Green Mountain Front Fault". 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 as well as the other reported deposits in Brandon, Vermont. It appears, therefore, that the St. George-Monkton fault system is part of a larger system of normal faults that extends throughout the length of western Vermont.

The first part of this paper describes the structural geology of the GIM system in 4 recently mapped areas and the second part addresses the environmental significance of the system, with specific reference to mineral and water resources and the potential for seismic activity on this and other major faults in western Vermont.

STRUCTURAL GEOLOGY OF THE GIM FAULT SYSTEM

The evidence for the St. George-Indian Brook-Monkton fault system falls into three major catagories; stratigraphic (offsets and abrupt "pinch-outs"), structural (offset folds, fracture fabrics, breccia zones and exposed fault surfaces), and geomorphic (valleys, swamps and notches not controlled by a change in rock type). 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 at St. George to the north (Fig. 2). Excellent exposures of the Monkton Quartzite in the hills on either side of the swamp indicate a cumulative strike-slip separation of 1450 m of which 1100 is attributed to displacement on the master fault (Fig. 3). Parallel minor faults offset the eastern limb and indicate that the St. George fault zone is at least 500 m wide. Exposed dip-slip slickensides on the minor faults plunge 80 degrees due east. Assuming an inclination of 80 degrees due east for the major fault, a calculated net slip of 690 m is obtained. Five hundred meters of this total displacement is assigned to the master fault.

The second area is located south of the first zone near Monkton (Fig. 2). Four km north of Monkton Ridge, the Monkton fault branches southwestward from the St. George fault, isolating Monkton Ridge and the area to the south as a horst cored by Cheshire Quartzite (Figs. 2 and 4). Here the St. George-Monkton fault system enters the main region of the Monkton culmination where resistant quartzites of the Monkton and Cheshire formations are prevalent. The Monkton fault was first recognized by Keith (1932) as a thrust because of its irregular trace and the fact that the Dunham Dolomite "pinches out" between the stratigraphically older Cheshire Quartzite and the younger Monkton Quartzite just west of Monkton Ridge near Cedar Lake (Figs. 2 and 4).

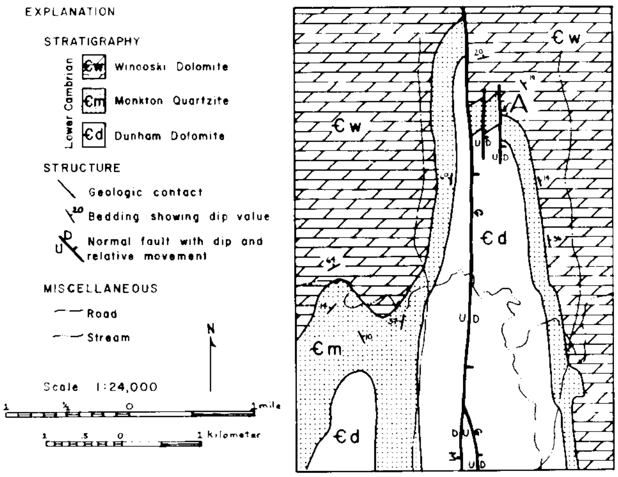


Figure 3. Geologic map of the Monkton anticline just north of Monkton Ridge (Fig. 1) showing the St. George fault (G) and the Monkton fault (M). Locality A is a lamprophyre dike cutting across high-angle fault. Based on unpublished work by P. Moreau, M. Crane and R. Stanley, 1974.

Cady (1945, p. 574) estimated the stratigraphic throw in the order of 760 m. Detailed mapping has shown that the fault actually dips 60-70 degrees westward and is offset by several short cross faults, thus explaining its apparent irregular trace. Actual exposures of the fault surface in three places display polished slip surfaces with slickensides in the dip direction. Steep fracture fabrics compatible with the normal fault geometry are abundant near the Monkton fault, but decrease away from it. Total dip-slip movement is calculated at 850 m, assuming the faults dip west at 65 degrees and the stratigraphic throw cited by Cady of 760 m is correct.

Stratigraphic separation on the St. George fault is missing south of Monkton Ridge but its position is determined by actual exposures of the fault zone and breccia deposits, some of which are mineralized by goethite and manganite. A pronounced valley in the quartzite also follows the trace of the fault. Furthermore, the kaolin deposits south of Monkton Ridge occur along this fault zone and appear to be specifically localized by the intersection of small cross faults with the St. George fault. These intersections formed vertical channels of highly fractured rocks that trapped residual alumina in the Cheshire Quartzite and formed commercial kaolin in this area.

It is likely that the St. George and Monkton faults curve at depth because the folds that have been mapped in the Cheshire Quartzite of the central horst trend slightly east and plunge steeper than the minor and mapped folds of the same age in the adjacent downthrown blocks (Monrad, 1976).

At least four major cross faults offset the Monkton fault and the St. George fault although the exact geometry of these offsets is not defined by closely-spaced outcrops (Fig. 4). Cross faults offset mappable folds in the Cheshire Quartzites, and are otherwise marked by fracture zones, fault breccias, and actual slip surfaces with slickensides. Most of the notches in the ridges underlain by the Cheshire Quartzite south and east of Monkton Ridge are fault controlled. Some of these contain kaolin.

The third area is located in the northern part of the GIM fault system east of Mallets Bay near Colchester Pond (Figs. 2 and 5). Here south-plunging minor folds gently deform the penetrative, regional cleavage. It would appear from the map (Fig. 5) that

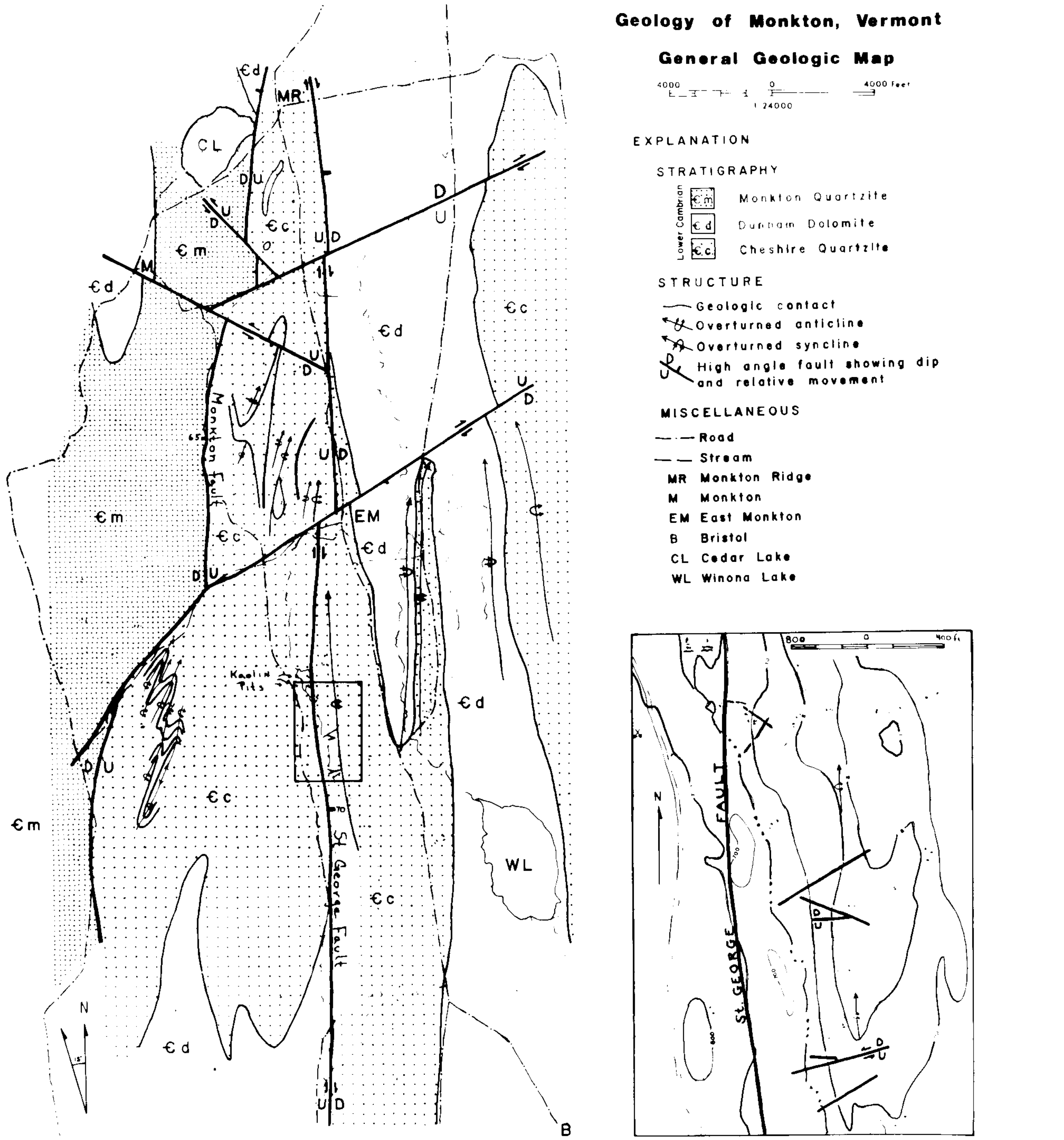


Figure 4. Geologic map of Monkton, Vermont, showing the St. George and Monkton faults. Black phyllite is folded tightly in the horst of Cheshire Quartzite. Geology by Black (1975) and Monrad (1976). Inset map shows the St. George fault and east-west faults and fracture zones near the kaolin pits.

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).

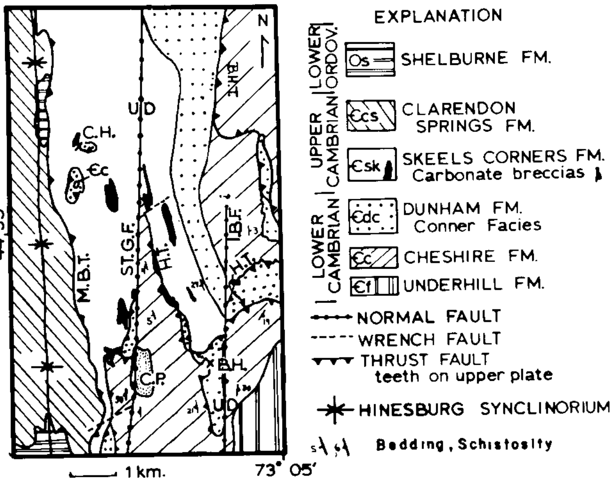


Figure 5. Generalized geologic map of the Colchester Pond area, modified from the Geologic Map of Vermont (Doll and others, 1961), by Rosencrantz (1975) and Agnew (1977) showing the location of the Muddy Brook thrust (M.B.T.), St. George fault (St.G.F.), Hinesburg thrust (H.T.), Indian Brook fault (I.B.F.) and Bald Hill thrust (B.H.T.), Colchester Pond (C.P.), Brigham Hill (B.H.), Cobble Hill klippe (C.H.) are also shown.

This interpretation is supported by a pronounced valley which passes through Colchester Pond. North-trending high-angle fractures in the Cheshire Quartzite are abundant in outcrops near the fault trace.

Approximately 2 km east of the St. George fault, just east of Brigham Hill, (Fig. 5), the Hinesburg thrust is again offset 200 m in an apparent left-lateral sense by the Indian Brook fault (Agnew, 1977). This fault is based on the abrupt change in the elevation of the Hinesburg thrust that occurs along the line marked "IBF" in Figure 5. West of this line, the Hinesburg thrust steps up 30-35 m exposing carbonate rocks and shale of the lower plate. Minor folds, which deform the regional schistosity and are coeval with flexing of the Hinesburg thrust to the east of the Indian Brook fault, are open and are not abundant in the vicinity of Brigham Hill as they should be if the map pattern of the Hinesburg thrust were due soley to late folding. Thus, the south-plunging anticline is also ruled out here.

The St. George fault and the Indian Brook fault, therefore, form two down-to-the-east step faults that offset the map pattern of the Hinesburg thrust in a left-lateral sense. The Indian Brook fault has not been traced southward, but Lake Iroquois may be controlled by it.

South of the Winooski River, the trace of the Hinesburg thrust swings westward forming a prominent "flap" on the eastern limb of the Hinesburg synclinorium. The St. George fault occupies a minor valley that extends from Williston southward through St. George to Monkton Ridge (Fig. 2). In the vicinity or St. George, the fourth area, the fault is marked by the sharp contact between the Cheshire Quartzite (Gilman facies) and the underlying Underhill Formation (Fig. 6). This contact is normally a very gradational boundary marked by a progressive increase in quartz in pelitic rocks, beds of quartzite and the simultaneous decrease in pelite as the section becomes younger. In this area, the Cheshire forms isolated blocks that terminate abruptly against the Underhill along the St. George fault. Throughout this area, small east-west vertical faults offset the Hinesburg thrust and a syncline in the Brownell Mountain Phyllite of the Bascom Formation. They do not offset the St. George fault, and therefore, must be older. In the Underhill Formation, they are represented by fracture zones (Fig. 6). Displacement on the cross faults is dip-slip because the apparent strike-slip offset varies according to the dip of the offset feature.

## SUMMARY AND AGE OF THE GIM FAULT SYSTEM

Based on the above discussion, the GIM fault system is a remarkably continuous structure of small to moderate displacement. This fact probably explains why it has not been recognized earlier by workers in western Vermont. Although the evidence for its existence was taken from the Hinesburg synclinorium, the information cited in the Introduction indicates the GIM fault system may extend southward to Massachusetts. Furthermore, it may be a landward expression of the north-trending faults that appear to control the major topographic features beneath Lake Champlain (Hunt, 1979, personal commun.). Together, these faults may represent east-west expansion during the early stages of the opening of the present-day North Atlantic as suggested by Burke (1976).

What, then, are the age constraints on the GIM system? Clearly, it is younger than the Hinesburg thrust and the major folds of the Hinesburg synclinorium (Fig. 2). These major folds extend southward into the Middlebury synclinorium and the Taconic allochthon where they are considered Middle Devonian (Acadian orogeny) in age (Zen, 1972, p. 2578; 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. Alleghenyan deformation of late Paleozoic 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, 1978, Fig. 5; Zaartman and others, 1967). The alkaline stocks of Charlotte and Cuttingsville 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 dikes across fault zones 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, Winnoski, 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. 2584; McHone, 1978, Table 2). Thus, the GIM fault system and its possible extensions appear to have 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.

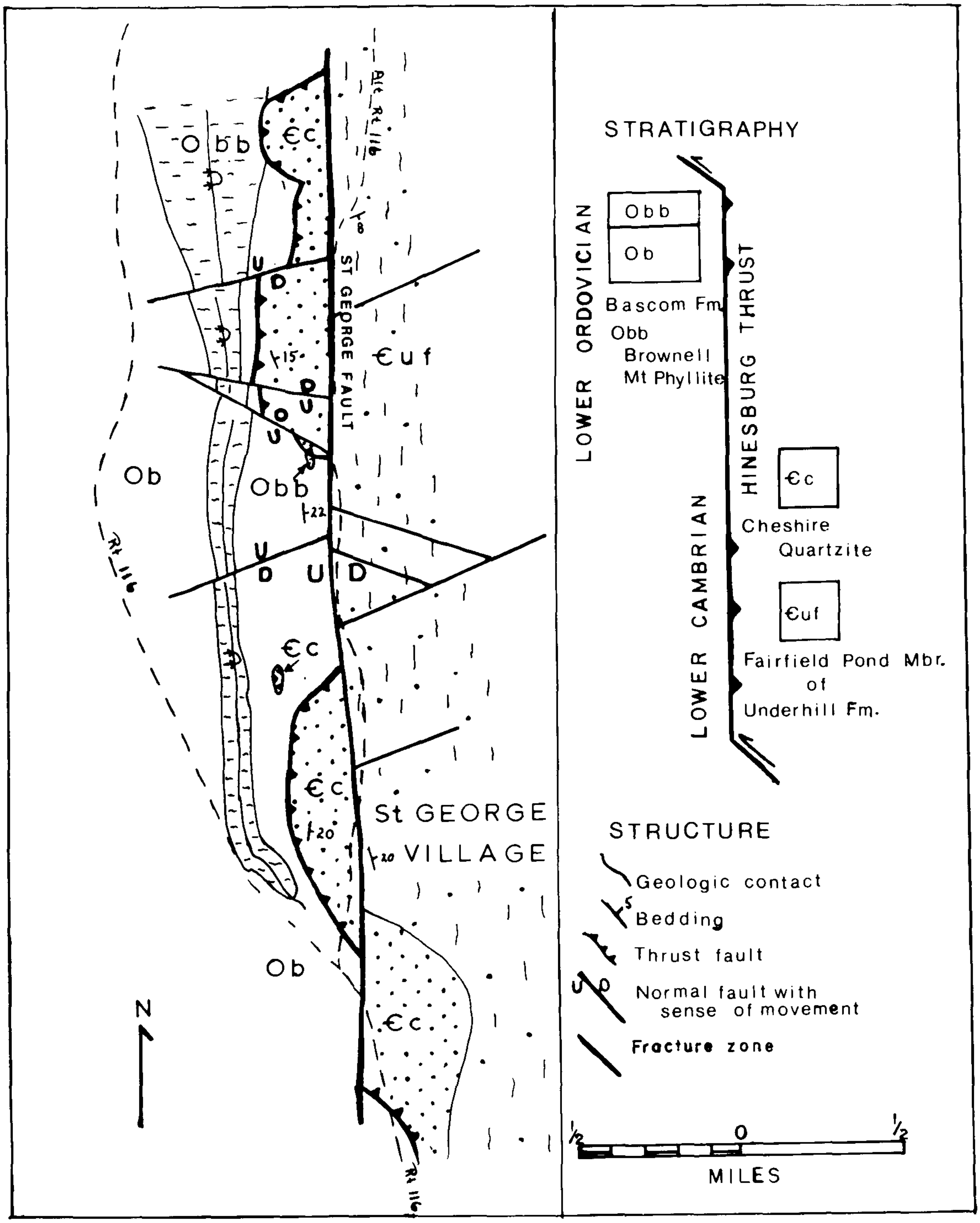


Figure 6. Geological map of the St. George area showing the Hinesburg thrust, short east-west faults to the west, and fracture zones to the east truncated by the St. George fault. Cross faults and fracture zones are vertical. St. George fault is assumed to dip east. Map modified from unpublished work 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

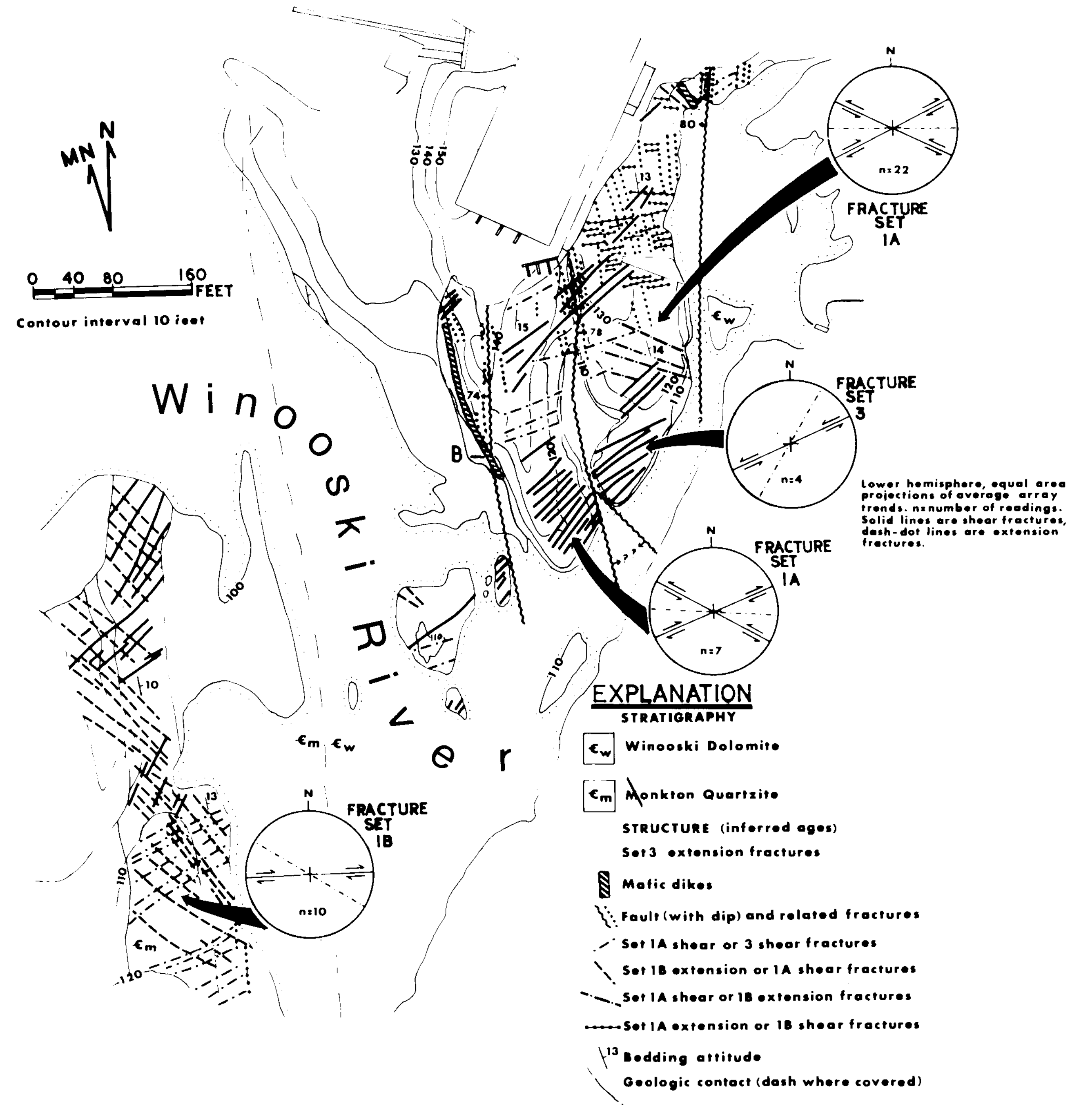


Figure 7. Geologic map of the Salmon Hole along the Winooski River, Burlington Vermont (Fig. 2), showing fractures, faults and en echelon fracture arrays. Based on field work and analyses by P. Winner and G. Smith, University of Vermont, 1979. Point B locates site where north-trending lamprophyre dike 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 kaolinized 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 throughly 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, 1968; Friedman and Stearns, 1971), none of the 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. Fracture density is more abundant in shale and dolostone and less abundant in marble and quartz. 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 open possibly due to larger stored elastic strain compared to carbonates and shale. The fracture characteristics in quartzite and marble, therefore, are important in providing significant porosity and permeability for bedrock aquifers in western Vermont. Because fractures are more abundant near faults, particularly where they intersect each other, the geology 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. Knowledge 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, 1978, for example). Western Vermont is a part of a suggested northwest-trending belt of seismic activity from Boston to Ottawa. The activity, however, in Vermont is sparce compared to the Adirondacks where earthquakes of magnitude 4 or less are abundant (Sbar and others, 1972). The question here, then, is whether or not the fault system described in this paper constitutes a potential hazard in light of the seismic activity to our east and west. Despite its relative inactivity, this hazard cannot be disregarded. The length and remarkable planarity of the St. George-Indian Brook-Monkton system makes it an ideal candidate for reactivation. Furthermore, the Champlain and Hinesburg thrusts should be considered, although seismic displacement on the Hinesburg thrust may be unlikely because it is folded by Acadian deformation and offset by the high-angle faults described here. Displacement by stable sliding as represented by minor quakes would be expected if the differential stress were of sufficient value, and the direction of $\sigma_1$ oriented in such a position to generate sufficient finite shear stress along the fault surface. No such displacement has been reported in the historical past in western Vermont. The geology of the north-trending fault system is offset by a number of cross faults. These may well lock the north-south system allowing the deviatoric stress to build up until the strength of the locks is exceeded or until the frictional resistance is reduced by abnormal pore pressure. Thus, the lack of seismicity in Vermont may be deceptive.

The degree to which the faults of western Vermont are a hazard not only depends upon their geometry, but also the orientation of the present-day direction and magnitude of maximum compression, $\sigma_1$. If, for example, this direction is oriented at an angle to the north-trending faults, then a finite shear stress would exist. The severity of the resulting quake then depends upon the frictional resistance to movement. Thus, the degree to which the cross faults offset the planarity of the north-trending system becomes increasingly important since they effectively prevent strike slip movement. This aspect of the problem can be evaluated by straightforward geological mapping of the fault system. The other parameter, the orientation of the principal axis of compression, can be determined by in situ stress analysis, hydrofracture, or analysis of seismic first motion studies. The latter two are far more reliable in evaluating the present day regional stress in rocks, compared to in situ stress analysis which is complicated by retention of residual stress.

Sbar and Sykes (1973, Fig. 5) show that the direction of maximum compression trends east-northeast in a nearly horizontal position for a considerable part of the northeastern United States, stretching from eastern New York through Illinois. This information is based on hydrofracture, pop-up features, and seismic-first-motion studies. One of the most complete analyses comes from an earthquake swarm in 1971 at Blue Mountain Lake directly west in the Adirondacks (Sbar and others, 1972). Here the fault-plane solutions suggest that $\sigma_1$ 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, Figs. 9 and 10). Information 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 extending along the east side of the Hudson and Champlain valleys northeasterly into Quebec. Nearly all of these faults parallel the dominant cleavage (essentially north or northeasterly strike) with the east or southeast side upthrown. This indicates that the westerly orientation of $\sigma_1$ 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 Sykes (1973, Fig. 5) 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 $\sigma_1$, assuming that all the data reflects the present-day 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, although 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, $\sigma_1$ 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 Winooski Falls where four stress configurations have been worked out primarily on en echelon fracture arrays, north-trending normal faults, and a north-trending lamprophyre dike (Fig. 7). A west-trending $\sigma_1$ position and northwest-trending $\sigma_1$ position ($\sigma_2$ vertical in both cases) are older than the normal faults (vertical $\sigma_1$ direction) which are in turn cut 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 cut the dike and indicate a subhorizontal $\sigma_1$ configuration trending northeasterly and essentially parallel to the orientation for shallow earthquakes from the 1971 Blue Mountain Lake earthquake swarm (Sbar and others, 1972).

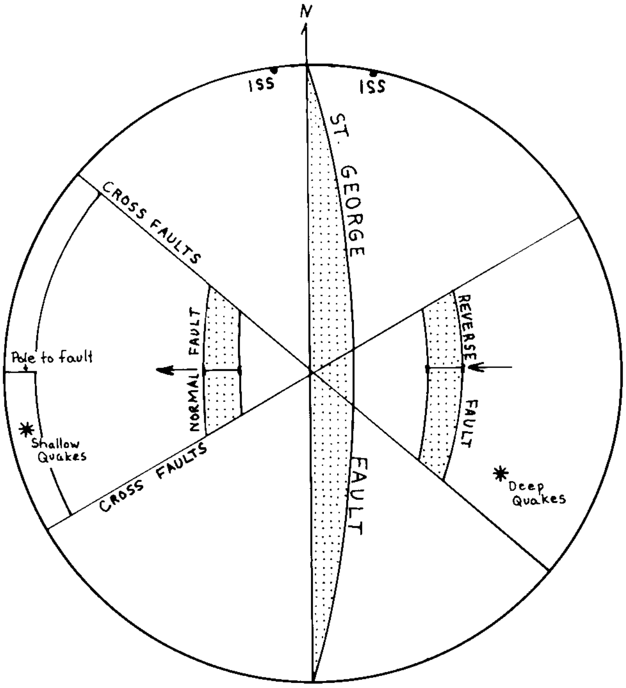


Figure 8. Lower hemisphere, equal-area projection of the St. George fault and associated cross faults in the Monkton area (Fig. 5). Asterisks (*) locate $\sigma_1$ positions for the Blue Mountain quakes for 1971 and 1972. In situ stress measurements are labeled ISS. Stippled area labeled "St. George 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 locking cross faults that inhibit oblique slip with a major strike-slip component. Plane of the projection is horizontal with N marking north.

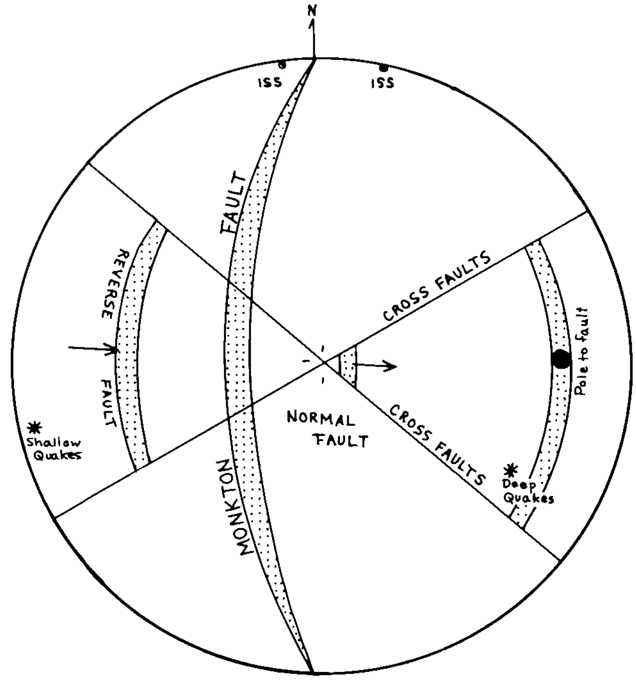


Figure 9. Lower hemisphere equal area projection of the Monkton fault and associated cross faults in the Monkton area (Fig. 5). Stippled area labeled "Monkton fault" shows range of dips (65 - 70W). Refer to Figure 8 for all other features on net.

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 shallow $\sigma_1$ 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

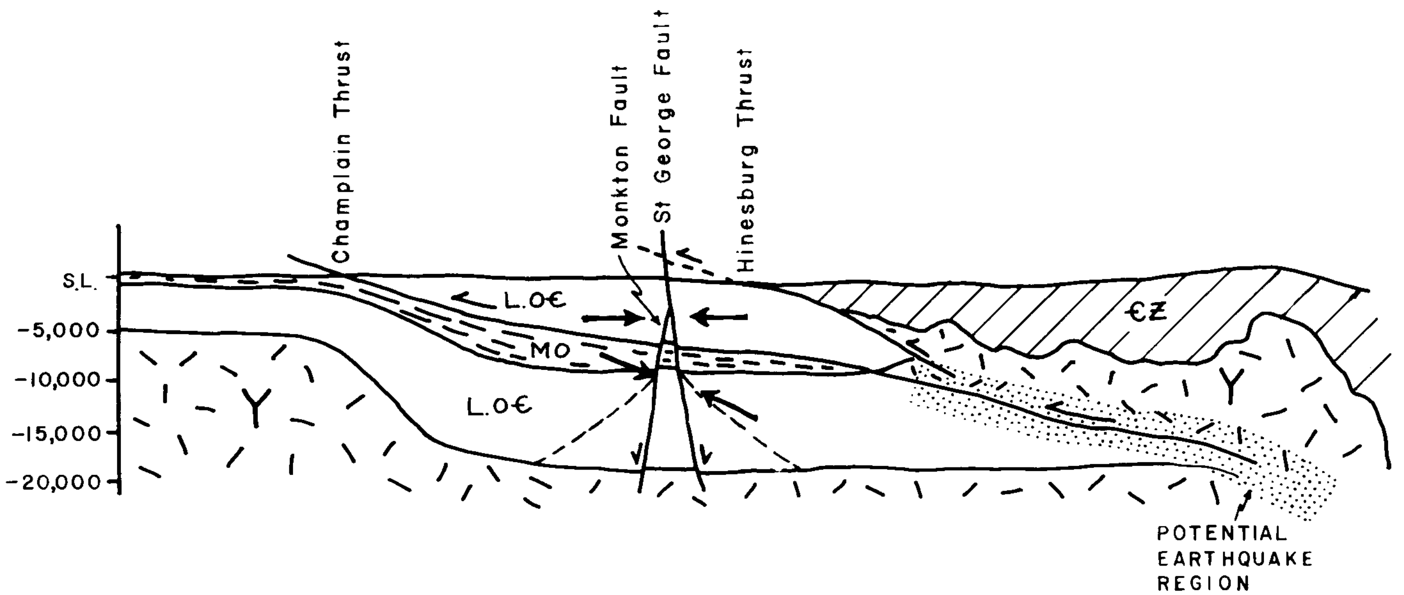


Figure 10. Cross section through west-central Vermont simplified from section B-B' (Doll and others, 1961) showing the earthquake potential of the Champlain thrust, Hinesburg thrust, Monkton fault, and St. George fault. Arrows on either side of the St. George-Monkton fault are based on the Blue Mountain data for 1971 and 1972 and represent the inferred shallow and deep $\sigma_1$ 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.

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 $\sigma_1$ positions of Sbar and others (1972). The critical relation, however, is the $\sigma_1$ orientation at the level where the high-angle faults begin to flatten out.

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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REFERENCES CITED

Agnew, P.C., 1977, Reinterpretation of the Hinesburg thrust in northwestern Vermont [M.S. thesis]: Burlington, Vermont, University of Vermont, 82 p.

Black, Martin, 1975, The St. George fault, Monkton Ridge, Vermont [Senior honors thesis]: Burlington, Vermont, University of Vermont, 32 p.

Burke, K.C.A., 1976, Development of grabens associated with the initial ruptures of the Atlantic Ocean: Tectonophysics, v. 36, p. 93-112.

Burt, F.A., 1927, The origin of the Bennington Kaolins: Vermont State Geologist, 16th Report, p. 65-84.

Cady, W.M., 1945, Stratigraphy and structure of west-central Vermont: Geological Society of America Bulletin, v. 56, p. 515-558.

Crosby, G.W., 1963, Structural evolution of the Middlebury synclinorium, west-central Vermont [Ph.D. thesis]: New York, Columbia University, 136 p.

DeBoer, J., 1967, Paleomagnetic-tectonic study of Mesozoic dike swarms in the Appalachians: Journal of Geophysical Research, v. 72, p. 2237-2250.

Diment, W.H., 1980, Significance of the Aseismic Regions of the Eastern United States: Geological Society of America Abstracts with Programs, v. 12, p. 30-31.

Doll, C.G., Cady, W.M., Thompson, J.B., Jr., and Billings, M.P., Compilers and editors, 1961, Centennial geologic map of Vermont: Vermont Geological Survey, scale 1:250,000.

Fletcher, J.B., Sbar, M.L.and Sykes, L.R., 1978, Seismic trends and travel-time residues in eastern North America and their tectonic implications: Geological Society of America Bulletin, v. 89, p. 1656-1676.

Foose, R.M., 1945, Iron-manganese ore deposits at White Rocks, Cumberland County, Pennsylvania: Pennsylvania Geological Survey, Bulletin M 26, Fourth series, 34 p.

Friedman, M., and Stearns, D.W., 1971, Relations between stresses inferred from calcite twin lamellae and macrofractures, Teton anticline, Montana: Geological Society of America Bulletin, v. 82, p. 3151-3162.

Geiser, P.A., 1980, Cleavage in Lower and Middle Ordovician rocks of the Hudson and Delaware River Valleys: Its implications for Appalachian tectonics: Geological Society of America Abstracts with Programs, v. 12, p. 37.

Harwood, D.S., and Zeitz, Isidore, 1974, Configuration of Precambrian rocks in southeastern New York and adjacent New England from aeromagnetic data: Geological Society of America Bulletin, v. 85, p. 181-188.

Isaachsen, Y.W., and McKendree, W.G., 1977, Preliminary brittle structure map of New York: New York State Museum Map and Chart series No. 31A.

Keith, Arthur, 1935, Stratigraphy and structure of northwestern Vermont: Washington Academy of Sciences Journal, v. 22, p. 357-379, 393-406.

King, P.B., 1950, Geology of the Elkton area, Virginia: United States Geological Survey, Professional Paper 230, 82 p.

King, P.B., and Ferguson, H.W., 1960, Geology of northernmost Tennessee: United States Geological Survey, Professional Paper 311, 136 p.

MacFayden, J.A., Jr., 1956, The geology of the Bennington area, Vermont: Vermont Geological Survey Bulletin 7, 72 p.

Marcotte, R.A., 1975, A paleostress analysis of a major fold in the southern part of the Hinesburg synclinorium [M.S. thesis]: Burlington, Vermont, University of Vermont, 96 p.

McHone, J.G., 1978, Distribution, orientation and ages of mafic dikes in central New England: Geological Society of America Bulletin, v. 89, p. 1645-1655.

Monrad, G.A., 1976, Cross fault geology and fault block rotation in Monkton Ridge, Vermont [Senior honors thesis]: Burlington, Vermont, University of Vermont, 39 p.

Moreau, Peter, 1975, Structure of the southern Hinesburg synclinorium near Hinesburg, Vermont [Senior honors thesis]: Burlington, Vermont, University of Vermont.

Ogden, D.G., 1969, Geology and origin of the kaolin at East Monkton, Vermont: Vermont Geological Survey, Economic Geology no. 3, 40 p.

Rogers, John, 1970, The tectonics of the Appalachians: Wiley Interscience, New York, 271 p.

Rosencrantz, E., 1975, The geology of the Colchester Pond area (NE), Milton quadrangle, Vermont [Senior honors thesis]: Burlington, Vermont, University of Vermont.

Sarkisian, A.C., 1970, A petrofabric analysis of the Monkton quartzite of west-central Vermont [M.S. thesis]: Burlington, Vermont, University of Vermont, 120 p.

Sbar, M.C., Armbruster, John, and Aggarawal, Y,P., 1972, The Adirondack, New York, Earthquake swarm of 1971 and tectonic implications: Seismological Society of America Bulletin, v. 62, p. 1303-1317.

Sbar, M.C., and Sykes, L.M., 1973, Contemporary compressive stress and seismicity in eastern North America: An example of intraplate tectonics: Geological Society of America Bulletin, v. 84, p. 1861-1882.

Stanley, R.S., and Sarkisian A.C., 1972, Analysis and chronology of structures along the Champlain thrust west of the Hinesburg synclinorium: New England Intercollegiate Geological Conference Guide Book, 1972, p. 117-149.

Stanley, R.S., 1974, Environment of deformation, Monkton Quartzite, Shelburne Bay, Western Vermont: Geological Society of America Bulletin, v. 85, p. 233-246.

Stearns, D.W., 1968, Certain aspects of fracture in naturally deformed rocks: in Reiker, R.E., ed., Rock mechanics seminar: Bedford, Mass., Air Force Cambridge Research Laboratories, p. 97-118.

Stone, S.W., and Dennis, J.G., 1964, The geology of the Milton quadrangle, Vermont: Vermont Geological Survey Bulletin 26, 79 p.

Thompson, J.B., and Schumaker, R.C., 1967, Bedrock geology of the Pawlet quadrangle, Vermont: Vermont Geological Survey Bulletin 30, 98 p.

Voight, Barry, 1972, Excursions at the north end of the Taconic allochthon and the Middlebury synclinorium, west-central Vermont, with emphasis on the structure of the Sudbury nappe and associated parautochthonous elements: New England Intercollegiate Geological Conference Guidebook, 1972, p. 49-96.

Zaartman, R.E., Brock, M.R., Heyl, A.V., and others, 1967, K-Ar and Rb-Sr ages of some alkalic intrusive rocks from central and eastern United States: American Journal of Science, v. 265, p. 848-870.

Zen, E-an, 1972, Some revisions in the interpretation of the Taconic Allochthon in West-central Vermont: Geological Society of America Bulletin, v. 83, p. 2573-2588.