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CONTENTS

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FORWARD

The Vermont Geological Society was founded in 1974 for the purpose of "1) advancing the science and profession of geology and its related branches by encouraging education, research and service through the holding of meetings, maintaining communications, and providing a common union of its members; 2) contributing to the public education of the geology of Vermont and promoting the proper use and protection of its natural resources; and 3) advancing the professional conduct of those engaged in the collection, interpretation and use of geologic data". To these ends in its 8 year history, the society has promoted a variety of activities. Four yearly meetings have become established: an all-day fall field trip, presentation of professional papers in the winter and student research papers in the spring, and a fall teacher's workshop and field trip. The Society publishes a quarterly newsletter, The Green Mountain Geologist, containing announcements of these meetings and also short articles.

This second issue of Vermont Geology contains papers from two symposia, "The Taconic orogeny - new thoughts on an old problem" and "Applied geology in Vermont", presented at our fourth annual winter meeting in February 1981 at University of Vermont. Future issues of Vermont Geology will be based upon papers presented at our winter meetings, the latest of which, held at Montpelier, Vermont in February 1982, featured papers about Vermont's ground water and surficial geology. Other manuscripts for Vermont Geology are also solicited. All manuscripts submitted for publication in Vermont Geology will be evaluated by the following criteria established by the Executive Committee of the Society in July 1981:

1. The major context of the paper must relate to an accepted earth science discipline, and must involve Vermont geology but not necessarily restricted to Vermont geographical borders.
2. The paper must present some element of new information gathered either through research or observation and experience, or must be a compilation of information from a variety of sources presented in a creative fashion using new analytical and interpretive procedures.
3. Papers must be written in a clear, concise and well-organized style, and must show literary integrity and honesty through proper credit-giving and referencing techniques.

Papers submitted to Vermont Geology will be reviewed by at least two outside professionals.

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ROCK MECHANICS AND STRUCTURAL GEOLOGIC CONSIDERATIONS IN SITING CRUSHED STONE QUARRIES

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ABSTRACT

The purpose of this paper is to describe the rock mechanics and structural geologic methods that have been recently applied to the location and development of crushed stone quarries. The methods involve the combination of geotechnical information with the normal cost-effective requirements of the construction aggregate industry for the purpose of producing useful crushed stone products at minimum volume-unit costs. The development and refinement of these various methods has taken place during studies in connection with four such quarries developed in Vermont during the last four years. These quarries are referred to in the text, and are used in the illustrations as examples of the application of the methods.

The relationship between the modulus of elasticity and the uniaxial compressive strength of various rock types is expressed in the paper as their Modulus Ratio, since it is believed that this relationship best describes the intact strength properties desirable for sources of crushed stone. Plots of Modulus Ratio are included, and their use in quarry site reconnaisance is described. The Talobre (1967) method of stereographic (pole diagram) analysis is described in relation to its usefulness in the design of quarry layouts. The paper demonstrates the procedure by which the optimum working design for a quarry can be calculated so as to insure maximum fragmentation efficiency.

INTRODUCTION

The purpose of this paper is to review the structural geologic and rock mechanics considerations that have been more recently applied to the location and development of crushed stone quarries. The paper describes techniques that have been largely refined during the studies connected with four such quarries located in Vermont. It is believed that these techniques help to provide for the production of high-quality crushed stone aggregates at minimum volume-unit costs.

Figure 1 shows the locations of four crushed stone quarries in the State of Vermont where these techniques have been effectively applied. These quarries will be referred to in several of the diagrams later in this paper. Quarry No. 1 is located in Barnet, Vermont in the quartzite of the Siluro-Devonian Gile Mountain Formation (Hall, 1959, p. 28). Quarry No. 2 is located in Shaftsbury, Vermont in the siliceous dolomitic limestone of the Cambrian Monkton and Winooski formations (MacFayden, 1956, p. 23). Both of these quarries have been closed and fully reclaimed. Quarry No. 3 is a permanent development in New Haven, Vermont in the slightly siliceous, dolomitic limestone of the Beldens Member of the Ordovician Chipman Formation (Coney, and others, 1972, p. 2), and Quarry No. 4, which is also a permanent development, is located in Waterford, Vermont in the meta-quartzite and meta-diabase of the Ordovician Albee Formation (Eric and Denis, 1958, p. 16). The techniques described in this paper were used during the location and development phases of these quarries, and while the techniques are certainly not uniquely applicable to Vermont quarries, these Vermont sites do provide actual case histories which demonstrate the utility of the methods.

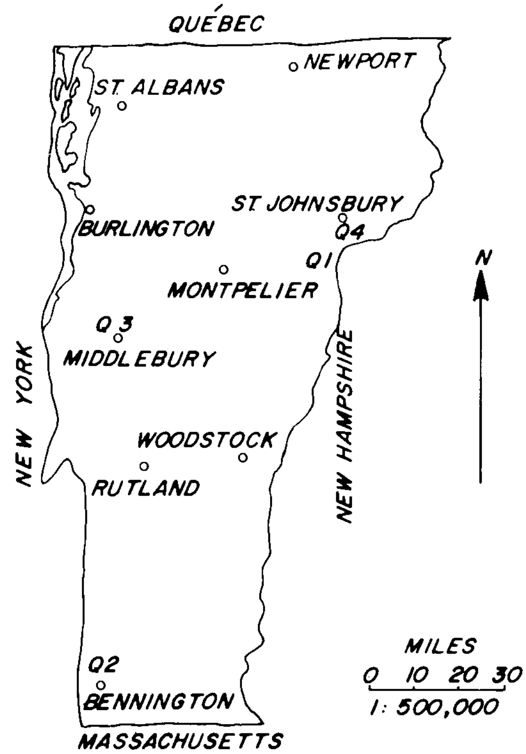

Figure 1. Selected quarry sites in Vermont. Quarry sites: Barnet, Q1; Shaftsbury, Q2; Middlebury, Q3; Waterford, Q4.

ROCK MECHANICS CONSIDERATIONS

Various properties are used to describe the strength of rocks, and thereby their suitability as sources of crushed stone. Any good text on structural geology or rock mechanics will contain a more complete listing than is provided here (e.g. Billings, 1972, p. 9-34; Obert, 1973, sections 6-20 to 6-52; and Jaeger, 1972, p. 27-188). However, for the purposes of this paper, only those general and specific properties which have been shown to be most directly related to the mechanical breakage characteristics of rock will be used.

The first of the general properties is that group of specific quantitative mechanical properties which collectively represent a rock's intact strength. Obert has defined "intact" rock as "pieces or possibly bodies of relatively uniform rock of a single petrological type that do not contain gross mechanical defects of a geologic origin, such as faults, joints or micro-fractures" (Obert, 1973, section 6.2.1; see also Jaeger, 1972, p. 8 and Hendron, 1972, p. 21-51). The strength of a piece of "intact" rock is described on the basis of the intact specimen's response to specific, controlled laboratory tests, such as those measuring unconfined compressive strength, angle of internal friction, shear strength and elastic moduli.

The second of these general properties is that group of qualitative properties which represent the in situ strength of a rock mass. Once again, Obert has provided a simple definition. In situ rock is a "mass of rock of sufficient size to contain a representative sample of the gross mechanical defects" typical of the rock mass in question regardless of the rock type present or the individual intact strength properties (Obert, 1973, section 6.2.1; see also Hendron, 1972, p. 21-51). The in situ strength of a rock mass is based upon the distribution and character of these gross mechanical defects, which are referred to as "discontinuities" (see Deere, 1972, p.2; Jaeger, 1972, p. 8; and Goodman, 1976, p. 40). The detailed description of the character of various types of discontinuities will be discussed later in this paper. For now, a description of three of the more important specific mechanical properties of intact rock is given below.

Three specific mechanical properties of intact rock, which collectively contribute to its intact strength, are modulus of elasticity, uniaxial compressive strength, and angle of internal friction. These properties are all described (quantified) on the basis of the ratio of stress to strain within intact samples as measured during laterally confined and unconfined axial loading tests.

Rock is considered to be elastic if the amount of strain measured in the test sample is proportional to the amount of stress being applied and if all of the measured strain is recovered following the removal of the stress. Most rock types will exhibit elastic behavior only up to some individually-specified stress, above which point the application of additional stress results in non-recoverable strain or permanent deformation. This condition is referred to as inelastic behavior, and it continues as stress is increased until the limiting stress value for the sample is attained, at which point failure of the sample occurs. This limiting stress value is known as the uniaxial compressive strength.

A stress-strain diagram is usually prepared from the data obtained in a loading test such as that described above (see Billings, 1972, p. 22). The "curve" which results from the construction of such a diagram shows the progressive reaction of the test specimen to the controlled application of stress during the test. The slope of the curve at any specified stress, that is the ratio of stress to resulting strain, is known as the modulus of elasticity for the test specimen at that particular stress. Generally speaking, the stress-strain curves for various rock types will show some variation in slope, leading to corresponding variations in the calculated modulus of elasticity. Obviously, the selection of a specific stress level at which to calculate the modulus is critical, as will be shown in the next section of this paper.

The angle of internal friction is determined through the use of a confined, triaxial loading test. The sample is axially loaded to failure, which usually occurs as a fracture plane that lies at an angle to the sample's axis. A Mohr diagram (normal stress vs. shear stress) is constructed for the results (see Billings, 1972, p. 162), and the angle of internal friction is read directly from the tangent Mohr envelope (see Billings, 1972, p. 163 and Hendron, 1972, p. 21-51).

The specific properties of in situ rock that will be used in this paper are those that describe the character of the discontinuities in the in situ rock mass. Goodman (1976, p. 40) has described a single discontinuity as "including two mating surfaces and a space or filling". He includes such geologic features as joints, bedding surfaces, banding and mineral segregations, contacts, cleavage, schistosity, foliation, sheared zones and faults in his list of features that when present create a discontinuous rock mass.

The properties of discontinuities that are important are orientation, distribution, extent and planarity (Goodman, 1976, p.40-47; and Jaeger, 1972, p.27-32). These descriptive properties are all measured either in the field on outcrops or in diamond core samples if they are available. The tabulation and analysis of the results of these measurements is usually carried out using one or more of the methods for stereographic projection, as will be illustrated later.

Obviously, the suitablilty of a mapped rock unit for use as a crushed stone quarry site involves a combination of favorable intact and in situ properties. The specific intact properties of elasticity and uniaxial compressive strength will determine the rock's crushing and drilling characteristics, along with its level of compliance with the prevailing durability or abrasion specifications. The specific in situ properties of the discontinuities, on the other hand, will determine the blasting and fragmentation characteristics of the rock mass, along with the orientation of the quarry workings. In terms of intact properties, the optimum rock type for a crushed stone quarry would be one which was sufficiently elastic to resist low to moderate stress levels, such as would be directly applied to the rock fragments in the subbase foundation of an Interstate Highway, while at the same time being sufficiently inelastic so that only slightly higher stresses would need to be applied through drilling, blasting and crushing to exceed the rock's limiting stress level (uniaxial compressive strength) and to effect breakage. In terms of in situ properties, the optimum rock mass would be one with a dense and evenly distributed array of closely-spaced discontinuities oriented nearly normal to each other. This would lead to a "blocky" in situ rock mass that would require a relatively low level of impact-induced stress (drilling, blasting, and crushing) in order to effect breakage of the mass. Obviously, these optimum conditions are rarely, if ever, encountered, but careful study of the intact and in situ properties of a rock and its mass can lead in most cases to an adequate approximation.

During the preliminary phases of a quarry siting study, it is helpful to be able to eliminate from consideration those sites where the existing rock is of inferior quality. This can be done by referring to the literature on rock mechanics, where one will find numerous schemes for classifying rock types according to their intact strength properties (e.g. Jaeger, 1972, p. 35-80; Goodman, 1976, p. 30-49; and Deere, 1972, p. 2-20). Experimentally derived data obtained from unconfined axial loading tests have been summarized in a series of seven plots published by Deere (1972, p. 4-12). Figures 2, 3, and 4 are composite diagrams taken from these plots, which further summarize the information for the purpose of this paper. These plots have been found to represent one of the more useful classification schemes, because they are based upon the critical mechanical relationships of intact rock. Referring to the figures, it will be noted that the strength of each rock type is expressed as its "modulus ratio". This ratio is calculated by determining the ratio between the test results for the rock's uniaxial compressive strength and the test results for its modulus of elasticity (Young's Modulus). In the original plots, the modulus of elasticity was calculated at 50 percent of the limiting stress for each rock type, and the envelopes contained 75 percent of the data points obtained from the calculations (see Deere, 1972, p. 5-11). These preconditions have been retained in the preparation of these summary plots, which are based strictly upon the previously reported data. The estimated locations of the modulus ratios for the rock types in each of the four Vermont quarries are also shown on the plots. These are qualitative estimates based upon the mechanical requirements of the crushing operations undertaken at each site. Complete tests such as those described earlier would be necessary to precisely define these locations on the plots.

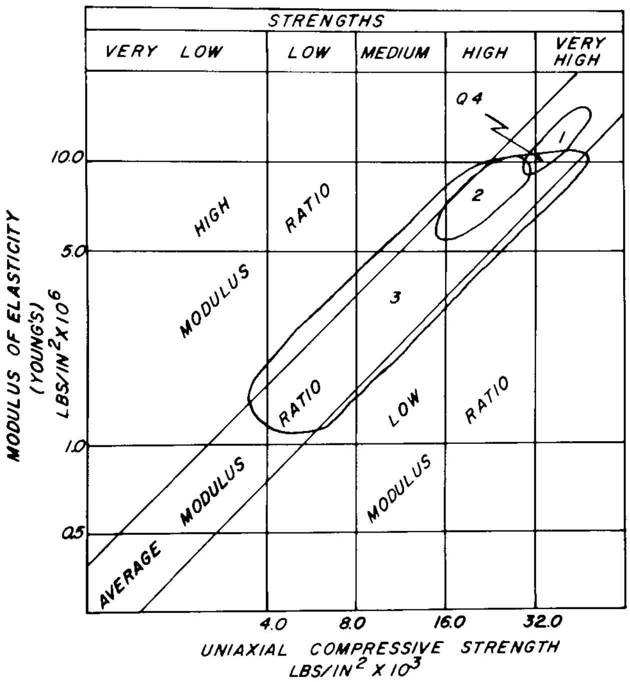

Figure 2. Summary plot of modulus ratio for igneous rocks. Unless otherwise indicated, all data from Deere, 1972. Envelope designations: 1 - diabase; 2 - granitics; 3 - basalt and miscellaneous flow rocks.

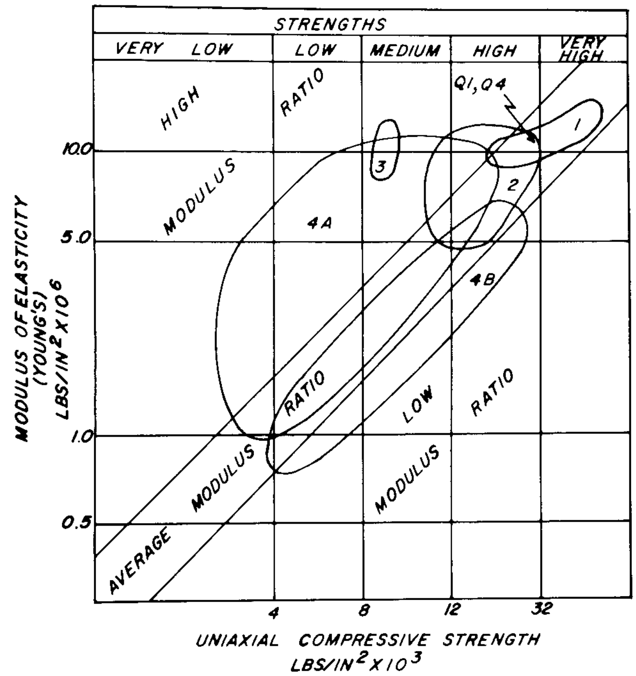

Figure 4. Summary plot of modulus ratio for metamorphic rocks. Unless otherwise indicated, all data from Deere, 1972. Envelope designations: 1 - quartzite; 2 - gneiss; 3 - marble; 4A - schist, foliation parallel; 4B - schist, foliation normal.

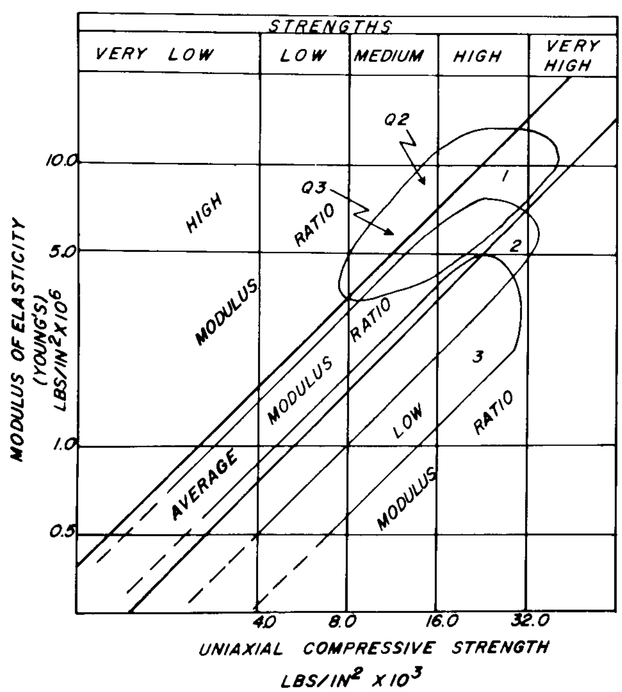

Figure 3. Summary plot of modulus ratio for sedimentary and low-grade metasedimentary rocks. Unless otherwise indicated, all data from Deere, 1972. Envelope designations: 1 - dolomite and limestone; 2 - sandstone; 3 - shale.

Nevertheless, these estimated locations do point out that it is possible, through careful macroscopic geologic study, to locate and exploit rock which falls into the desirable strength designations and to approximate, as closely as possible, the optimum conditions for crushing stone that were mentioned earlier.

As can be seen in the figures, the modulus ratio for the various rock types fall into representative envelopes across the strength designations. Using the plots for selecting rock types suitable for crushed stone quarrying, however, requires caution and careful study of the rock type in question, unless, of course, facilities are available for the proper types of loading and mechanical property tests. This caution is necessary, because the rocks with large envelopes, and, therefore, with widely ranging intact strength characteristics, need to be carefully studied to determine in what portion of the appropriate envelope their designation will lie. This is especially important if foliated rocks are under consideration, because intact strength properties can vary widely from the foliation-normal to the foliation-parallel loading direction (see Figure 4). The study of such variable rocks usually requires that the actual mechanical tests be conducted so as to accurately locate the rock type's position on the applicable plot.

STRUCTURAL GEOLOGICAL CONSIDERATIONS

The foregoing information is used to locate geologic units that may provide rock with adequate intact strength properties to meet the requirements for optimum efficiency in quarrying, along with those for the prevailing durability and abrasion specifications. However, structural geologic or in situ information is required in order to properly locate the proposed quarry within the mapped unit and to insure an efficient quarrying operation. The optimum site within a rock unit for an efficient quarry will be one which will provide sufficient space and elevation for adequate production development, while at the same time provide for adequate screening of the operation, both during its activity and following its reclamation.

Once a potential site has been identified, a detailed structural geologic map must be prepared for the specific area on the site where the quarry is to be located. During the preparation of this map, special attention must be paid to the determination of the orientation of all discontinuities in the rock mass. The plane table (or better yet, transit and tape) survey should extend to outcrops lying as far as 500 feet from the proposed quarry site to insure the establishment of a fully representative data base. Once the field work is complete, all observations should be plotted on a map base at a fairly detailed scale, for example, one inch to 50 feet, and all strike and dip data should be analyzed stereographically.

A diamond core drilling program is always advisable in spite of the detailed structural mapping. A typical drilling program will involve a minimum of two holes, drilled at strategic points based upon the foregoing surface structure observations and extending to a depth of at least 10 feet below the anticipated quarry floor elevation. Data to be collected from the core samples includes petrography, drilling rates, density variations, thickness and attitude of structural discontinuities, and the presence of any stratigraphic or structural marker horizons that may be useful in plotting the position of the workings in the rock mass as excavations proceed. In addition to the bedrock verification that can be obtained from the cores, the resulting core holes also provide an excellent opportunity to obtain a considerable amount of information about the subsurface ground water conditions under the site and in the area of the proposed workings, thus allowing for the design of adequate drainage expedients and reclamation plans.

Following completion of the field work and the preparation of the structure map, stereograms must be prepared and analyzed. Many methods of stereographic analysis have been evaluated for their utility in this specific type of quarry application, and none has emerged as more useful that a technique developed by Talobre (1967; see also Goodman, 1972, p. 88-90). This technique allows for the determination of the direction within the rock mass in which the maximum in situ compressive strength (or resistance) will be developed upon the application of a stress. The method is based upon the in situ properties of the observed structural discontinuities in the rock mass.

Referring to Figure 5, the method can be described as follows. First, the poles to the planes of all observed discontinuity surfaces are plotted on a polar equal-area stereonet. If there is a large number of poles plotted, the resulting stereogram should be contoured and an average pole should be selected to represent the poles from each discrete set of poles (see Billings, 1971, p. 102; and Goodman, 1976, p. 58 for details of pole selection procedures). This was done in the preparation of Figure 5, where a large number of observations was available for plotting.

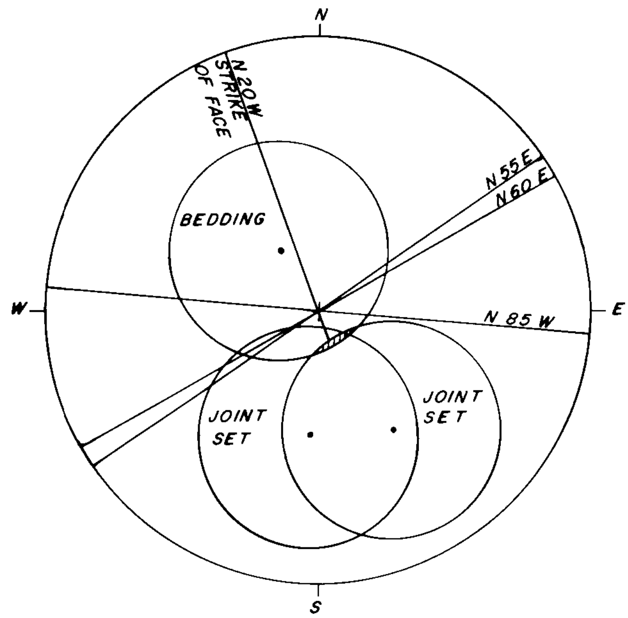

Figure 5. Polar equal area stereonet (pole diagram) with constructions to determine quarry orientation. Quarry No. 2, Shaftsbury, Vermont. Lower hemisphere projection. Total points plotted prior to average pole selection shown equal 412.

The next step is to construct small circles around the average pole of each discrete set of structural discontinuities, as shown on Figure 5. The radii of these small circles, as measured on the stereonet, is equal to the value of the intact angle of internal friction (Ø) for the rock type under study. A Ø value of 35° was used in the construction shown in Figure 5 (as estimated for the dolomitic limestone in Shaftsbury, Vermont). At this point, "one can try to find a position which makes an angle with each pole of less than the angle of friction. Such a direction will be in the area common to the small circles of radius Ø about each pole..." (Goodman, 1976, p. 89). The center of the hachured area common to the circles in Figure 5 represents the pole to the plane in which the maximum compressive strength or resistance can be mobilized within the rock mass. In the case of the distribution shown in Figure 5, the plane is oriented N 70° E 20° NW. The direction in the horizontal plane would simply be N 70° E.

This orientation or direction represents the attitude within the rock mass in which maximum compressive strength will be available, were one looking for a strong rock-founded base for a large structure, such as a dam or bridge. It also represents the direction in which the rock mass will offer the greatest resistance to breakage or in situ disaggregation of its mass. Consequently, a blasting face (working face) in a quarry oriented parallel to this plane or vertically parallel to this direction will not exhibit optimum efficiency in producing broken rock, because blasting impact forces will be dissipated along the adjacent and nearly parallel in situ discontinuities before they can be coupled in sufficient strength directly to the intact rock to overcome its maximum compressive and elastic limits. On the other hand, a blasting face oriented vertically perpendicular to this plane or direction, while meeting with the same degree of intact resistance, will exhibit optimum efficiency, because the blasting forces will not be dissipated as rapidly along the now nearly perpendicular in situ discontinuities. This allows for the coupling of the blasting impact forces directly to the intact portions of the rock mass at maximum magnitude immediately upon detonation and prior to any significant in situ dissipation. When dissipation does finally occur, it further assists in the breakage process by providing for secondary and tertiary impacts as the rock fragments begin to displace along the discontinuities and collide with one another within the mass of broken rock.

Using the information to be obtained from an analysis such as that just described provides for a rationale that establishes the centerline orientation for the quarry workings. Working faces are oriented, then, perpendicular to this centerline. If one is working on a site where folding or faulting rapidly change the attitudes of the planar discontinuities in the rock mass, this kind of stereographic analysis may have to be undertaken a number of times during the progress of the quarry excavations to insure proper orientation of the workings for maximum blasting efficiency at all times.

CONCLUSION

The various concepts and techniques described in this paper have been used to provide a quarry operator in Vermont with specification-quality crushed stone products at lower volume-unit cost. Prior to the application of these techniques, more experiential and intuitive methods had been applied with considerable historic success. Consequently, one might question the additional time and expense of these studies for quarry development. The need for this type of approach lies in the nature of today's competitive economy, with its high interest rates and deteriorating markets for large volumes of crushed stone products (e.g. the completion of the Interstate Highway System and reduced Federal construction programs). The application of techniques such as these that are rapidly emerging from the study of rock mechanics can help to refine the methods already being applied, and can provide an operator or his mining geologists with tools to anticipate and compensate for the natural variations that occur in rock masses while holding costs to a minimum.

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EVOLUTION AND STRUCTURAL SIGNIFICANCE OF MASTER SHEAR ZONES WITHIN THE PARAUTOCHTHONOUS FLYSCH OF EASTERN NEW YORK

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ABSTRACT

Progressive deformation of the synorogenic medial Ordovician flysch of eastern New York during emplacement of the Taconic Allochthon led to the eventual development of through-going master thrust faults or shear zones. The location of these structures is marked in the field by laterally persistent belts of melange and juxtaposed faunally-dissimilar flysch terranes. Structures observed in shear zone lithologies include narrow horizons of fault breccia, small, disrupted asymmetric folds and striated phacoidal cleavage. The best exposed shear zone runs approximately north-south at least 15 km along the present Hudson River Valley in the vicinity of Schuylerville, New York. Here the associated melange includes blocks of pillow basalt (Stark's Knob), thick-bedded chert and "anomalous" Early Ordovician shale and argillite. The master shears produce a large-scale imbricate structure in the flysch similar to that found along the western margin of the Taconic Allochthon. They may merge at depth along a surface of decollement above the underlying Cambro-Ordovician carbonate shelf sequence. Previous tectonic models which invoked down-slope gravity emplacement of massive sections of "Austin Glen" graywacke to produce outliers or klippen structures in otherwise autochthonous flysch are not supported by structural and lithostratigraphic field evidence. This evidence is believed consistent with deposition and deformation in a trench-accretionary prism setting during the attemped subduction of the Atlantic-type margin of North America.

INTRODUCTION

The greater part of the lowlands of the Hudson River Valley is underlain by a sequence of interbedded graywackes, siltstones and shales variously referred to as the Hudson River Group (Mather, 1843), Normanskill and Snake Hill Shales (Ruedemann, 1914; Rickard and Fisher, 1973; Fisher, 1977) or simply Normanskill Formation (Berry, 1962, and others). These units belong to the synorogenic flysch terrane of the western Appalachians (Enos, 1969), interpreted to have been deposited and subsequently deformed in a trench-accretionary prism setting in association with an east-dipping subduction zone in medial Ordovician times (Chapple, 1973; Rowley and Kidd, 1981). In New York, the flysch is bounded on the east by allochthonous units of the Taconic Mountains, and to the west by block-faulted Grenville basement with overlying Cambro-Ordovician shelf sequence (Adirondack massif), by unconformably overlying Silurian and Devonian carbonates (Helderberg escarpment) or by fine-grained distal equivalents of the flysch itself (Utica and Canajoharie shales).

A general structural analysis of the Hudson flysch has been initiated by Bosworth (1980a) in the vicinity of Schuylerville, New York, and by Vollmer (1980, 1981) in the Capital District south of Albany, New York (field areas are located in Figure 1). The preliminary results of these studies have been reported elsewhere (Bosworth and Vollmer, 1981). The purpose of the present paper is to present a re-evaluation of the biostratigraphic and lithostratigraphic data available for this part of the flysch, and to suggest a possible evolutionary scheme for the development of fault structures in the parautochthonous zone of the Taconic orogenic belt.

STRUCTURAL AND LITHOLOGIC FIELD OBSERVATIONS

It has not proven possible to define a workable lithostratigraphy for the Ordovician shales and wackes of the Hudson River lowlands (Ruedemann, 1914; Bosworth, 1980a). Lacking recognizable marker horizons, folds larger than individual outcrops are difficult to trace out accurately, and fossil control has only been useful in recognizing the grossest structural features. The small-scale structures employed in the present analysis are slaty and phacoidal cleavage, small faults with slickenside striations, and mesoscopic folds. Representative structural measurements and lithologic observations of a portion of the field area are presented in Figure 2.

Cleavage

Two foliation morphologies are observed in the lowland flysch terrane: (1) a form appearing as flat surfaces in hand specimen, the familiar "slaty cleavage", and (2) an irregular, anastomosing fabric referred to as "phacoidal cleavage" (Vollmer, 1980; Bosworth, 1980a). These microstructures have been interpreted to correspond respectively to strain regimes dominated by (1) bulk flattening and (2) high shear strains (Bosworth and Vollmer, 1981). The orientation and local distribution of these fabrics provide important insight into the large-scale structure of the flysch.

The foliations first appear in the shaly lithologies of the flysch 10 to 15 km west of the present Taconic Allochthon boundary. Slaty cleavage here strikes northeast-southwest and dips 35° to 45° east. Bedding is generally gently dipping, with cleavage equally well-developed on the limbs and hinge regions of the local megascopic folds. Slaty cleavage is approximately axial planar to infrequently observed mesoscopic folds. Phacoidal cleavage is found in an average orientation similar to that of the slaty cleavage in these same units, but its areal distribution appears to be confined to narrow belts or zones between uncleaved rocks or rocks with weak slaty cleavage (well documented to the south in Albany County, New York, by Vollmer [1981]). These phacoidally cleaved zones are typically only tens of meters in width.

Strength of the foliations intensifies from these western units toward the allochthon boundary. The shaly lithologies most proximal to the allochthon are true slates, and associated siltstones and wackes, uncleaved to the west, also show a strong tectonic planar fabric. The frequency of occurrence of phacoidally cleaved rocks follows a similar

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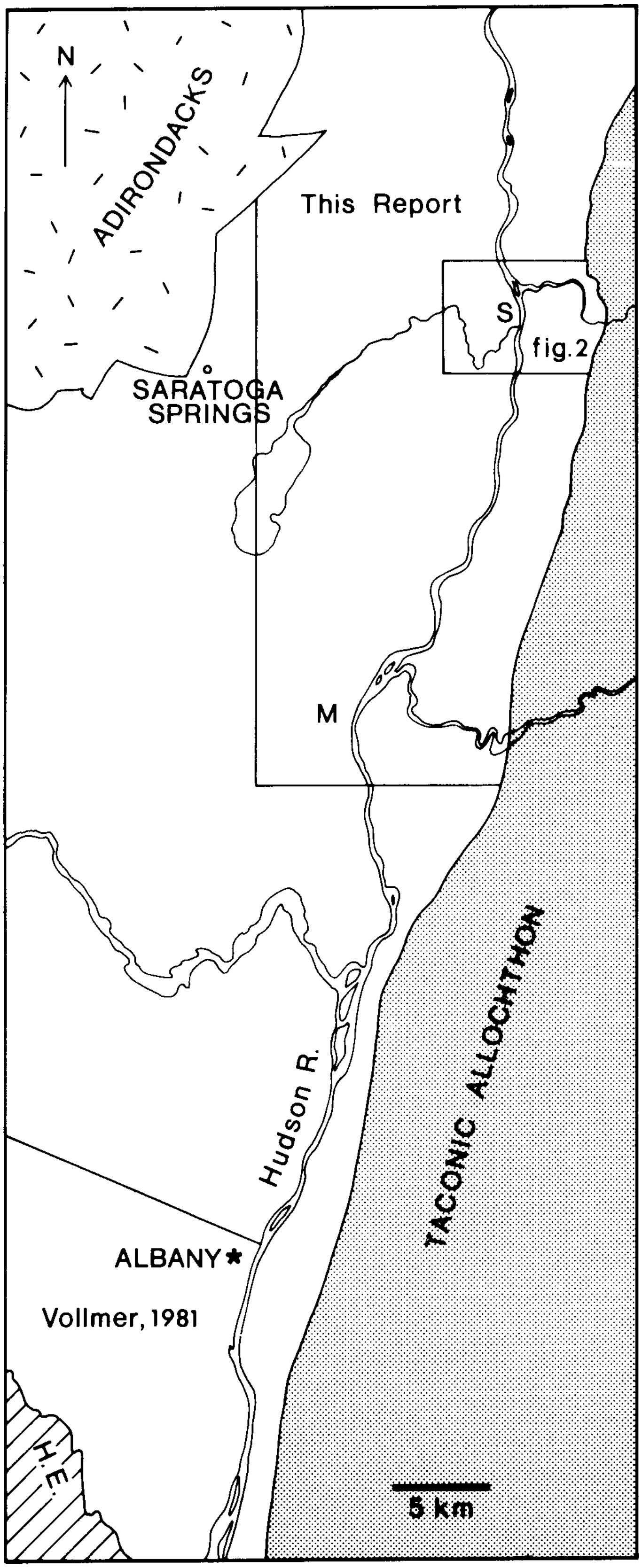


west-to-east increase, as does the upper limit of the width of the phacoidally cleaved zones. Accompanying this increase in strength of the foliations is a progressive steepening of both the slaty and phacoidal cleavages (Figure 2). Close to the allochthon the foliations are nearly vertical in places. It is important to note also that the slaty cleavage observed in the units of the allochthon itself dips only at moderate (40°to 60°) angles to the east (Platt, 1960) and does not generally parallel the strike of the cleavage in the flysch (Bosworth, 1980a).

Folds

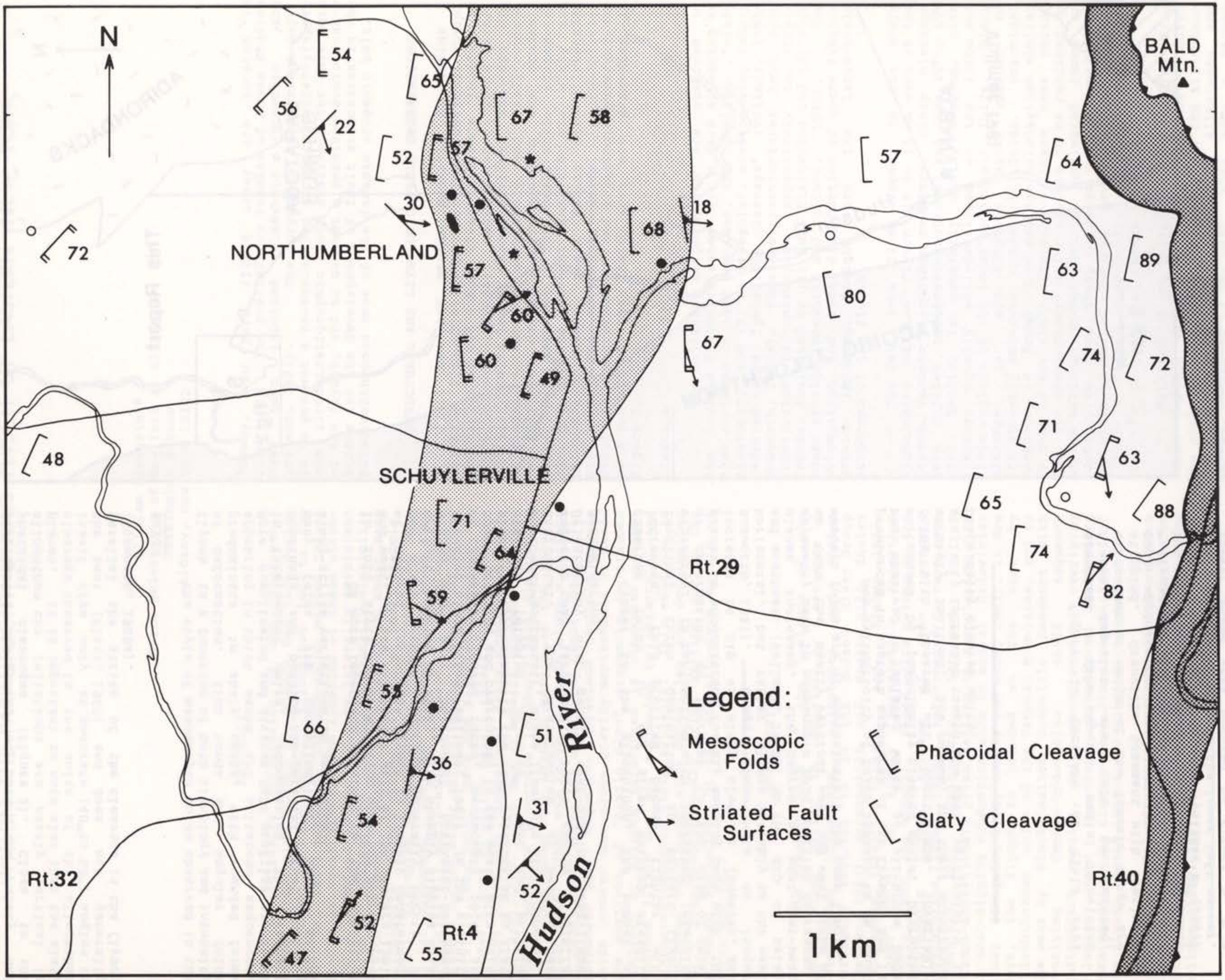
The style of mesoscopic folds observed in the flysch is a function of both lithology and intensity of deformation. Kink bands and angular folds predominate in shaly units, with rounded forms appearing in thick wacke and siltstone sequences. More complicated and diverse fold profiles are found in interbedded units, accompanied by frequent boudinage and bedding-sub-parallel thrust faulting. Many folds are noncylindrical, with marked along-strike variations in amplitude.

Of more immediate interest is the variation in fold style and orientation observed between east and west. A few kilometers west of the western limit of cleaved rocks the flysch is largely undeformed, but where present, folding generally occurs as upright buckles or kinks, with steeply dipping axial planes and near horizontal northeast-southwest trending hinge lines (Vollmer, 1981). In the vicinity of the weakly cleaved rocks, mesoscopic folds are open to tight and overturned to the west, with axial planes in approximately the same orientation as slaty cleavage (dipping 30°to 40° east and striking northeast-southwest). Hinge lines are still generally horizontal. The distribution of bedding here suggests that large-scale folds occupy a similar orientation, with gently east-dipping "long-limbs" predominating.

Closer to the allochthon, the number of observed folds in any given outcrop steadily increases. Fold profiles become tighter with isoclinal forms dominating in eastern flysch exposures. In conjunction with increased intensity of deformation an increase in the dips of axial planes is encountered, roughly keeping pace with the increase in dip of slaty cleavage (however, see Bosworth, 1981). Hinge lines are no longer horizontal, but rather plunge variably to the east and southeast (Vollmer, 1980). As the dip of axial planes increases, the degree of east-over-west asymmetry seen in mesoscopic fold profiles decreases, so that the nearly vertical east and west limbs of eastern folds are of approximately the same length.

Non-cylindricity of folds appears to be most pronounced in eastern exposures of the flysch, and is best observed in isolated wacke or siltstone beds surrounded by phacoidally cleaved shale. Disrupted folds with "sheared off" short-limbs, invariably strongly inclined, are common, and their occurrence similarly increases toward the east, particularly in phacoidally cleaved units.

Figure 1. Location of field area discussed in this report. Medial Ordovician flysch deposits are left unornamented, allochthonous units of the Taconic Range are stippled. Grenville basement with overlying Cambro-Ordovician shelf carbonates are labeled "Adirondacks" and Siluro-Devonian carbonates of the Helderberg Escarpment (H.E.) are diagonally ruled. Eastern portion of Vollmer's (1981) field area is located in the lower left corner. Insert shows area covered by Figure 2. S = Schuylerville, M = Mechanicville. Regional geology from Fisher, and others, 1970.


N
BALD
Mtn.
NORTHUMBERLAND
SCHUYLERVILLE
Rt.29
Rt.32
Rt.4
Rt.40
Hudson
River
Legend:
Mesoscopic Folds
Phacoidal Cleavage
Striated Fault Surfaces
Slaty Cleavage
1 km

Faults

A variety of small-scale fault and fault-like structures are present in the Hudson flysch, including (1) bedding parallel striated and polished surfaces, (2) discrete discontinuities oblique to bedding, (3) mineralized slickenside surfaces oblique and parallel to bedding, (4) narrow zones of brecciated rock fragments in a shaly or quartz-calcite "vein" filling matrix, and (5) narrow shaly zones bearing an intense foliation oblique to the local slaty cleavage. On a somewhat larger scale, zones of phacoidally cleaved shale surrounded by uncleaved rock or rock with slaty cleavage are believed to represent broader, more complex, shear zones (Vollmer, 1980).

In the slightly deformed western region of flysch, faults appear simply as polished or mineralized surfaces parallel to the gently east dipping long-limbs of folds. Grooves and finer striations plunging down dip on the fault surfaces are common. Bedding-parallel faults are similarly found in more eastern units where bedding generally dips steeply east, but the dominant fault surfaces are here again low-angle surfaces dipping shallowly to the east (10° to 30°), which now cut obliquely across bedding. In the east the discrete thrust surfaces are associated with narrow zones of fault gouge and breccia, and occasionally broaden to shear zones with steeply east-dipping foliations. The best exposed fault rocks are found at the basal thrust of the Taconic Allochthon. In places they include slivers of shelf carbonate (Bald Mountain carbonates; Ruedemann, 1914) which are frequently brecciated and occasionally mylonitized (Bosworth, 1980a, 1980b). In others, where Taconic slates and arenites abut directly against units of the flysch, the fault breccias consist of angular fragments of chert, wacke and broken quartz-calcite veins and are similar to the fault rocks found within the flysch proper.

The progressive increase in width and structural complexity of low-angle fault-like structures culminating in the east with the basal Taconic fault zone is accompanied by an increased frequency of occurrence and width of zones of phacoidal cleavage (Vollmer, 1980; Bosworth and Vollmer, 1981). Observations critical to the interpretation of these structures are (1) their general restriction to north-south striking "zones" or linear belts of rock, (2) the highly deformed nature of the included rock, with frequent boudined wacke and siltstone beds and disrupted folds, commonly surrounded by terranes of similar lithologies with more continuous, folded (but undisrupted) beds, (3) the presence in these zones of phacoidal cleavage, dipping steeply east with down-dip striations, in rocks "normally" diplaying slaty cleavage, and (4) the frequent occurrence of heavily mineralized and striated fault surfaces within the zones. It should be noted that Vollmer (1980,1981; Bosworth and Vollmer, 1981) has found a 20 meter wide zone of phacoidally cleaved, highly deformed rock in an otherwise only mildly deformed section of the flysch in Albany County, New York. Phacoidal cleavage, or at least its local development, is therefore not restricted solely to the most highly deformed (in a large-scale sense) flysch terranes.

Relative sense of movement on the fault-structures of the flysch is suggested to be east-over-west by consistent shearing-off of the overturned short-limbs (west limbs of antiforms) of folds. More conclusive although less frequently observed are the fault zone foliations that strike northeast-southwest and dip more steeply to the east ($>45^{\circ}$) than do the fault bounding surfaces ($<30^{\circ}$). The standard interpretation of such fabric would be that of an east-over-west sense of shear (Ramsay, 1980, for example).

Figure 2. Representative structural data from a portion of the field area. Numbers with each symbol give dip of structural element, arrows indicate orientation of fold hinge lines on axial planes and striations on fault surfaces. Fault rocks at the basal Taconic thrust (Bald Mountain terrane carbonates) are indicated with heavy stipple. Major belt of melange along the Hudson River is shown with light stipple. Elliptical black body at Northumberland is Stark's Knob (pillow basalts). Biostratigraphic data from Ruedemann (1914) is portrayed as follows: asterisk = Schagticoke shale (early Ordovician, Graptolite Zone 1 of Berry, 1960) locality; solid circle = Normanskill shale (medial Ordovician, Graptolite Zone 12) locality; open circle = Snake Hill shale (medial Ordovician, Graptolite Zone 13) locality.

Melange

Flysch lithologies have been subdivided into a number of informal lithofacies units (Bosworth and Vollmer, 1981) in the absense of a properly defined lithostratigraphy. The units recognized are (1) black shale or slate, with only minor sandy or silty laminations, (2) interbedded shale, siltsone and wacke, with less common conglomerate, (3) melange with no demonstrable exotic blocks ("exotic" indicating lithologies not found undisrupted in the flysch terrane), and (4) melange with exotic blocks. Of particular significance in the analysis of structures in the flysch is the manner of occurrence and distribution of melange in the sequence. The term "Taconic melange" as used here includes the Forbes Hill Conglomerates (Zen, 1961) and is roughly synonomous with the "block-in-shale" unit of Berry (1962), the "wild flysch-like" conglomerate of Bird (1963) and the "Poughkeepsie melange of Fisher (1977). It typically consists of lensoid-shaped blocks and clasts or disrupted fold "hooks" surrounded by a phacoidally cleaved, fine-grained matrix. Blocks present and not considered exotic include graywacke, fine-grained arenites, siltstones, argillite, slate and chert. At least some of these can be shown to be locally derived, as blocks at some localities can be seen to pass into disrupted beds and finally undisturbed strata along strike.

The most spetacular occurrence of melange with exotic blocks is found just west of the Hudson River at Northumberland (Figure 2). In 1901, Woodworth discovered a volcanic "plug" here, which he referred to as "Stark's Knob". Woodworth (1901) and Ruedemann (1914) have described the field relations seen at the Knob in considerable detail. The volcanics occur in the form of pillow basalts, dissected by numerous carbonate-filled extension fractures and cavities. The overall structure of the plug is sheet-like (100 plus meters long by roughly 25 meters in thickness), lying in the plane of the foliation in the surrounding slates. In exposures along strike are found numerous fist-sized clasts of chert and arenite in a phacoidally cleaved shaly matrix, and it appears that these units are part of an extensive belt of melange which continues south at least as far as the southwest corner of the Schuylerville 7 1/2′ Quadrangle.

The most western exposures of melange are associated with the moderately folded units of flysch lying about 10 km west of the Taconic Allochthon (Bosworth and Vollmer, 1981; see also discussion of units at "Snake Hill" in Berry, 1963). From here east to the major belt of melange running north-south along the Hudson River, the melange appears to be confined to narrow zones tens of meters thick. East of the Hudson, melange exposures define a number of disrupted zones, some of which measure several hundred meters across. A broad area of melange is generally found immediately adjacent to the allochthon, where it is closely associated with units more likely to be described as "fault rocks" of the basal Taconic thrust.

BIOSTRATIGRAPHY

Ruedemann (1914) recognized three principal units in the flysch terrane of Saratoga and Washington Counties (present field area). These were, from youngest to oldest: (1) Canajoharie Shale (black shale), (2) Snake Hill Shale (dark shale, some wacke and conglomerate), and (3) Normanskill Shale (dark shale alternating with many wacke and chert beds). As discussed by Berry (1962, 1963), a great deal of confusion existed in Ruedemann's biostratigraphic versus rock-stratigraphic definition and usage of these terms. Ruedemann, however, was quite explicit (1914, p. 94) in stating that the Snake Hill and Normanskill (which make up the bulk of the deformed part of the flysch) could only be consistently and reliably distinguished on basis of their enclosed faunas; hence, the unsatisfactory nature of these terms for detailed lithologic and structural mapping.

Although this stratigraphic terminology has not been employed in the present work, the areal distribution of ages in the flysch as dated by graptolite faunal assemblages (Ruedemann, 1914; Fisher, and others, 1970) has proven critical in assessing the regional structure of this terrane. Berry (1962) found that the Austin Glen member (his usage) of the Normanskill Formation, or the flysch proper, was deposited from late Champlainian through early Mohawkian times, corresponding to his (1960) Climacograptus bicornis ("Zone 12") and Orthograptus truncatus ("Zone 13") graptolite zones. Rowley and Kidd (1981, and references therein) have synthesized regional evidence which indicates that the basal flysch deposits become younger in an east-to-west traverse across the Taconic orogenic belt. They suggest that flysch deposition on untransported continental rise sediments in the east (what is now the "Taconic Sequence" of rocks) began just following Zone 12 (Diplograptus multidens zone of Riva, 1974) and not until the end of Zone 13 (Orthograptus ruedemanni zone of Riva) on the subsiding continental shelf in the vicinity of the present field area (the standard "New York Sequence" of rocks).

The present distribution of flysch ages (plotted in Figure 2) is considerably complicated by the folding and thrusting described in previous sections (clearly recognized by Ruedemann, 1914), but areal biostratigraphic analysis still suggests several important points. Shales bearing Zone 13 graptolites (Snake Hill of Ruedemann; Canajoharie of Fisher, and others, 1970) are found between the Taconic Allochthon and the west bank of the Hudson River, and then again a few kilometers further west of the Hudson. Separating these two belts of Mohawkian units is a strip of older, Zone 12 aged flysch (Normanskill of Ruedemann; Mt. Merino of Fisher, and others, 1970) running north-south just west of the Hudson. This older flysch pinches out north of Schuylerville, but continues south some 25 km to the vicinity of Mechanicville, New York (Ruedemann, 1930). Similar belts or wedges of older flysch are also found along strike to the north and south of the Schuylerville area (Ruedemann, 1914, 1930; Fisher and others, 1970.)

A second fact recognized only through the use of biostratigraphic data is the presence of two exposures of early Ordovician shale ("Schaghticoke Shale") discovered by Ruedemann (1914) in the area of Stark's Knob (Figure 2). Berry (1962) confirmed the age of these shales as early Canadian, belonging to his Anisograptus ("Zone 1") graptolite zone (Berry, 1960). The geologic features found in close association at Schuylerville therefore include: (1) pillow basalt (Stark's Knob) and anomalously old shale, (2) a biostratigraphic boundary between Mohawkian and pre-Mohawkian aged flysch terranes, and (3) an extensive belt of melange (Figure 2).

STRUCTURAL INTERPRETATIONS

Bosworth and Vollmer (1981) have presented a model for the progressive development of structures in the flysch of eastern New York. This model assumes that the observed west-to-east (least-to-most deformed) sequence of structures represents also the chronologic sequence of structures developed through time at any one locality. Folding initiated as upright buckles or kinks, with no field-recognizable axial planar foliation (Figure 3a). Hinge lines were approximately horizontal, trending north-south to northeast-southwest. Low-angle thrust faults and zones of phacoidal cleavage with disrupted bedding occasionally cut through sections of this weakly deformed flysch. As deformation continued, fold profiles became overturned to the west (direction of tectonic transport) and a weak axial planar slaty cleavage appeared (Figure 3b). Low-angle faults were now abundant, commonly on mineralized and striated, east-dipping bedding planes. Hinge lines of folds varied from sub-horizontal to moderately inclined orientations. Shearing off of short-limbs of folds and boudinage of less ductile beds led to the development of melange units containing blocks of wacke, chert and argillite in a phacoidally cleaved shaly matrix. In the most deformed sections of the flysch (Figure 3c), fold axial planes and strong slaty cleavage have rotated back to steeply east-dipping or near vertical positions. Hinge lines now have variable plunges, remaining sub-horizontal or moderately inclined in areas of good slaty cleavage, but invariably steeply plunging in phacoidally cleaved melange units. This melange is found in numerous local zones and occasionally in continuous belts, as at Schuylerville and along the basal thrust of the Taconic Allochthon.

The initiation and evolution of low-angle fault structures plays an important role in this model. Ruedemann (1914, p. 104) believed that displacement was restricted to a few centimeters for each of the discrete fault surfaces so commonly observed in the flysch, but that their cumulative effect could have resulted in over-thrusting on the scale of many kilometers. He also suggested (p. 105-107) that major boundary faults separated the western edge of the Normanskill Shales from adjacent Snake Hill Shale, and similarly further west Snake Hill from Canajoharie Shales. The structurally highest, most eastern fault was believed by Ruedemann to be the youngest.

Fault structures in the flysch probably do begin as discrete surfaces of limited slip, confined initially to bedding or fissility parallel movements. As the number of folds and their amplitudes increase, cross-cutting faults will eventually be a requirement for continuation of the thrusting mode of deformation. Some of these faults then evolve to narrow shear zones, with fault gouge and breccia and distinctive shear-zone foliations. With progressive rotation of the flysch sequence during imbrication, some of the "steepened" faults will become inactive, with displacement accomplished in the most highly deformed sections of the flysch along flat-lying master faults, perhaps near the underlying contact with Cambro-Ordovician shelf rocks. As the shelf rocks themselves were block-faulted before deposition of the flysch (Zen, 1967), the actual "top" of the carbonate sequence probably does not present an ideal surface for decollement, and may have resulted in detachment of large blocks of carbonate as fault slivers along some of the major thrusts, as at the base of the Taconic Allochthon.

Several fundamental questions remain as to how these "master faults" evolve. Merging of narrow shear zones is undoubtedly a contributing factor. However, a further complication is apparent. As noted above, Vollmer (1980) has found a twenty meter wide zone of phacoidally cleaved shale and disrupted folds in a relatively undeformed western area of the flysch. No constraints on the relative displacement across this zone are known (Vollmer, personal communication). This suggests that shear zones of considerable width can evolve very early in the deformational history of the flysch. The location of these structures may determine the eventual position of master shear zones, across which faunal dissimilaries are most likely to be encountered.

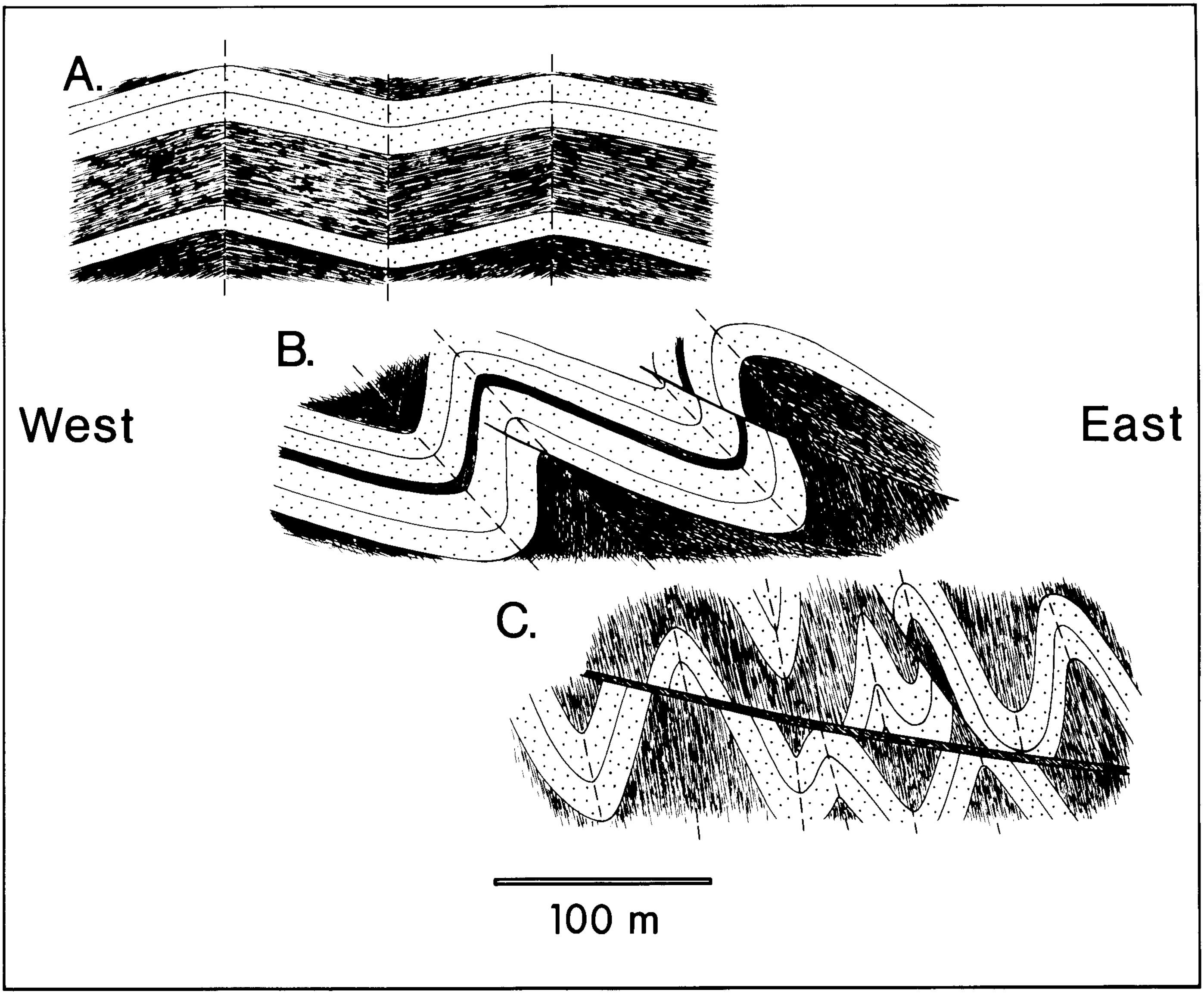


Figure 3. Proposed structural evolution for the Taconic flysch. The sequence from A to C has been observed in crossing the flysch from west to east, and this is interpreted to represent to a large extent the evolution of structures through time at any one particular locality. Scale is approximate. Folding initiates as upright buckles or kinks (A) in response to horizontal compression. Low-angle fault structures with east-over-west sense of shear develop, and folds become progressively overturned to the west (B). Weak tectonic foliations now become visible in the shalier units of the flysch. In later stages stages of deformation (C), thrusting is accomplished along a few master shear zones or through-going faults (illustrated) and deformation within the intervening material approaches that of bulk horizontal shortening, rotating structures (slaty cleavage, fold axial planes) back towards the vertical. Evolution of structures within disrupted melange units (shear zones) is much more complex.

DISCUSSION

A geologic cross-section from Bald Mountain to Stark's Knob is presented in Figure 4. Many details including small-scale faulting and folding and the more localized occurrences of melange have been omitted for clarity. The structure of the Hudson River master shear zone has been greatly schematized. Flysch units to the west of the Stark's Knob melange are of Mohawkian (Zone 13) age, those within (excluding blocks of Schaghticoke Shale) and immediately east are of pre-Mohawkian (Zone 12) age, and those nearest the Taconic Allochthon are again Mohawkian aged.

The large-scale imbricate structure observed in the western Giddings Brook Slice of the Taconic Allochthon (Rowley, and others, 1979) has been interpreted as well for the parautochthonous flysch terrane of the Hudson lowlands. Structural observations suggest that the fold-thrust mode of deformation apparent in the allochthonous units continues in the flysch, without a break in structural style at the allochthon boundary (Ruedemann, 1914; Bosworth 1980b). Figure 4 in many respects resembles the cross-section proposed by Ruedemann (1914) for the Schuylerville area. The structural and tectonic setting for deformation of the flysch has been interpreted to be that of a trench-accretionary prism environment during attempted subduction of the North American plate in late medial Ordovician (Caradocian or Mohawkian) times (Rowley and Kidd, 1981; Bosworth and Vollmer, 1981).

An alternate interpretation for the tectonic evolution of the flysch has been presented by Rickard and Fisher (1973) based on a more extensive analysis of the biostratigraphic data breifly described above. Rickard and Fisher disputed Berry's (1962) claim that some of the "Normanskill Formation" was Zone 13 in age, claiming that these arenites and shales of the flysch belonged properly in either the Snake Hill/Canajoharie Formation or the purportedly shallow water Schenectady Formation. They envisioned the true Normanskill beds as representing an earlier phase of flysch deposition, gravity slid to their present location during uplift of "Appalachia" in the late medial Ordovician. Ruedemann's Normanskill outcrops therefore represent "klippen" surrounded by the younger Snake Hill.

Regardless of the names used to describe the units mapped by Ruedemann in the flysch, his faunal lists and localities do suggest a two-fold division in the vicinity of Schuylerville which is amenable to Rickard and Fisher's model. The biostratigraphic data is, however, also compatible with the imbricate structure advocated by Bosworth and Vollmer, and this interpretation is further supported by observed structural relationships and through comparison with other orogenic belts and along strike segments of the Northern Appalachians.

ACKNOWLEDGMENTS

The author would like especially to thank F. W. Vollmer for numerous invaluable discussions of the structure of the flysch of the Hudson Valley, and for his continued collaboration on a variety of problems encountered in overthrust structural settings. S. Chisick first introduced the author to the geology of the Schuylerville area, and has continually provided alternate, stimulating interpretations for its tectonic history. W. D Means, W. S. F. Kidd, D. B. Rowley, G. W. Putman and H. X. Willems accompanied the author in the field on numerous occasions and contributed much insight to the analysis of the local and regional geology. Funding was provided through a NSF Graduate Fellowship and a Penrose Grant from the Geological Society of America. A field vehicle was furnished by the State University of New York at Albany, and assistance with the preparation of this manuscript by the staff of Colgate University. D. W. Fisher, R. Stanley, Kidd, Rowley and Vollmer critically reviewed an earlier version of this paper and offered important suggestions for its improvement.

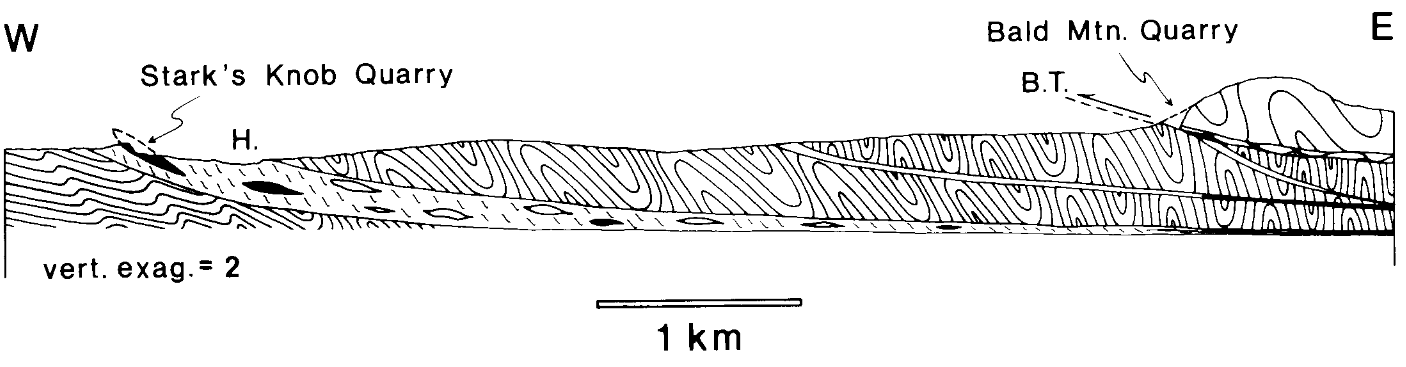


Figure 4. Schematic cross-section from Stark's Knob to Bald Mountain. B.T. = Basal thrust of the Taconic Allochthon; H. = Hudson River. Final movement of the Allochthon is believed to post-date some imbrication of the flysch; hence the basal thrust is shown cutting across a shear zone in the flysch. Biostratigraphy corresponds with Figure 2, that is west of Stark's Knob = Snake Hill shale; Stark's Knob melange = in part, Normanskill shale, with blocks of Schaticoke shale; east of the melange = Normanskill shale followed by Snake Hill shale.

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ROAD SALT EFFECTS ON GROUND WATER

IN THE WILLISTON AND ST. GEORGE AREA, VERMONT

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ABSTRACT

Local zones of shallow ground water in the study area, primarily downslope from and within 60 meters of salted roads, are clearly contaminated by road salt. Levels of sodium and chloride ions in shallow ground water in these zones are roughly one order of magnitude higher than background levels of 5 to 10 ppm. Bedrock ground water appears to be unaffected by road salt, perhaps due to soil adsorption of salt ions, dilution in the large bedrock ground water body, and the location of salted roads away from sensitive recharge areas.

INTRODUCTION

The purpose of this study was to determine the extent to which application of de-icing salt on some specific roads in Williston and St. George has contaminated the ground water. Since the time period available for data-gathering in this study was relatively short, the study was designed to look at ground water contamination at approximately the same point in time for a variety of geologic, hydrogeologic, and salt application rate conditions. Data were gathered in July and August of 1978.

The study area, shown in Figure 1, is comprised of the adjacent watersheds of Muddy Brook and Allen Brook, in west-central Chittenden County of northwestern Vermont. The watersheds, encompassing approximately 90 square kilometers, are located in the towns of Shelburne, South Burlington, St. George, Williston, and Richmond.

PREVIOUS WORKS

The impact of highway de-icing chemicals on the environment has been an area of concern for the last two decades, as total tonnage of salt applied to highways has increased and as awareness of environmental and public health factors has grown. Comprehensive summaries and extensive literature surveys prepared in the early 1970's (Hanes and others, 1970; Field and others, 1974; Terry, 1974) identified several major areas of environmental concern, including damage to roadside vegetation, contamination of surface and ground water supplies, disruption of aquatic systems, and alteration of soil characteristics.

Contamination of ground and surface waters by application of salt on roads has been documented in several New England localities (Arthur D. Little Inc., 1972; Commonwealth of Massachusetts, 1965; Coogan, 1971; Frank, 1972; Hall, 1975; Handman, 1976; Huling and Hollocher, 1972; O'Brien and Majewski, 1975; Hutchinson, 1966, 1967, 1968, 1969, 1970; Pollock and Toler, 1973; Toler, 1972; U.S. Geological Survey, 1976)

In Vermont, several studies have identified contaminated soils, surface waters, and ground waters due to road salt (Hanes and others, 1976; Kunkle, 1972; Moody and Associates, 1974; Sweetser, 1977; Vermont Agency of Environmental Conservation, 1975; Vermont Agency of Transportation, 1971a, 1971b, 1976; Witherell, 1977).

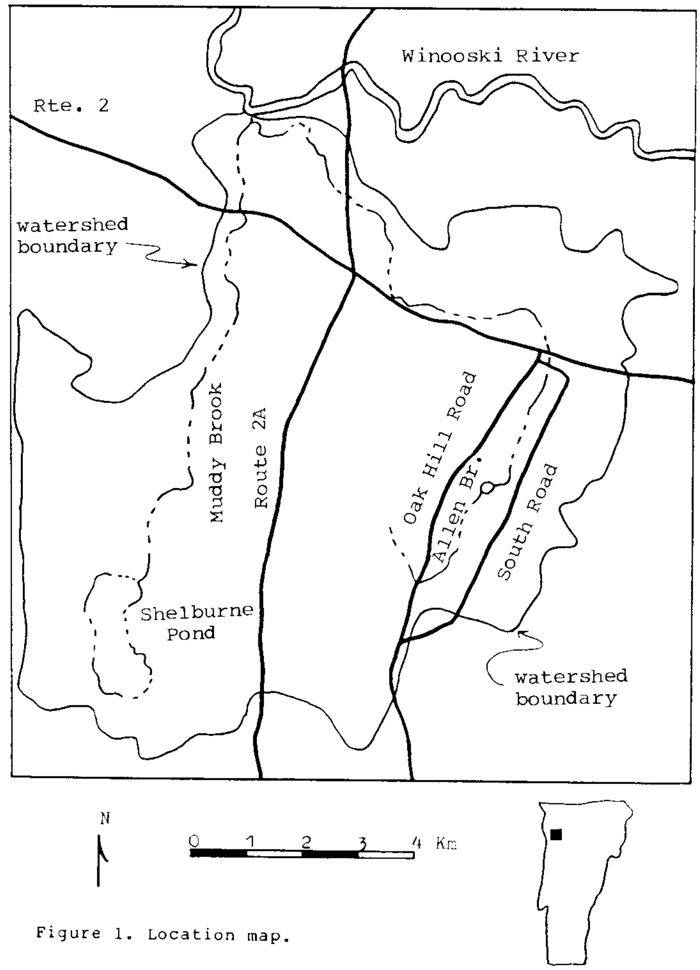

Figure 1. Location map.

The health hazards of drinking water high in sodium and chloride have been summarized by Hanes and others (1970), Field and others (1974), Brenner and Moshman (1976), Murray and Ernst (1976), Witherell (1977) and others. Health officials generally agree that chloride levels up to as high as 1000 ppm are not a serious health problem, but that the taste of drinking water becomes unpleasant when chloride levels exceed about 250 ppm (Vermont Department of Health secondary standard). The Vermont Department of Health (primary standard) recommends that people using drinking water with sodium levels greater than 20 ppm consult their physicians.

METHODS

The determination of the degree of road salt contamination in the groundwater was done by chemical analysis of samples of well water. Water samples from 96 wells from a variety of locations throughout the study area were analyzed for sodium and chloride concentrations and for electrical conductance. Contributions of these parameters from many sources, both natural and man-made, can cause their concentrations to be higher than background levels in ground water. However, when interpreted carefully in conjunction with detailed field information, the levels of these parameters can give an accurate indication of the degree of contamination by road salt.

The electrical conductance of a sample is a measure of the degree to which the water contains dissolved ions. It is a non-specific indicator; ions from any source will cause increased electrical conductance. Ions in ground water can be derived from natural sources such as dissolved soil particles, organic material, or carbonate rocks (especially prevalent in the watersheds studied). Man-made sources could include road salt, septic systems, manure piles, and refuse piles.

Because of the wide variety of potential sources for increased electrical conductance, and particularly because of the presence of carbonate rocks at many locations in the watersheds, background levels of electrical conductance would be expected to vary considerably throughout the study area. It is therefore difficult to determine whether a particular analysis of ground water shows elevated levels of electrical conductance, and to determine its source. Electrical conductance values are reported in this study for general information, but little significance can be ascribed to their absolute values.

Natural sources of sodium and chloride ions in ground water are few in Vermont, as indicated by the low background levels described in the literature. Man-made sources include septic systems, manure piles, refuse piles, road salt, and so on. Careful attention in this study was paid to distance, slope, and hydraulic relationships between sampling sites and non-road sources of these ions. Distance measurements were made by pacing; slope was visually estimated. Approximately ten wells in the chosen sampling area were not included in the data file because of the possibility of contamination from other sources.

Well samples were taken in late July of 1978, during a period of little precipitation. Samples were taken from the cold water tap at the kitchen sink, unless the home used a water softener, in which cases the samples were taken before the softener. At the home, a measurement of the electrical conductance of each sample was made, using a portable specific conductance-temperature-salinity meter, which could be adjusted for water temperature and which gave results in units of micro-mhos. A four-millimeter sample was then taken in a plastic vial, for analysis for sodium and chloride by the Vermont Department of Health. Analysis for sodium was done by flame emission; for chloride by an automatic colorimetric procedure using mercuric thiocyanate and ferric nitrate. Results were reported in parts per million (ppm).

At each well sampled, the following information was gathered:

- present owner, and original owner, if known
- date of well, and driller (if bedrock well)
- well type (drilled or dug)
- well depth, yield, and static level
- depth of casing
- height of casing above ground surface
- degree of seal from surface water
- distance and slope from roadways
- distance and slope from septic systems, leach fields, barnyards, and other sources of ions
- owner's remarks on quality, seasonal change, taste
- bedrock or soil type

Most of the wells were sampled once. Duplicate samples were taken on twelve wells, to check the reliability of the data, and to provide information on wells whose first analyses appeared anomalous. Duplicate analyses of wells were generally within 10 percent of each other, indicating adequate reliability for a study of this scope.

RESULTS

Background levels

In order to make a valid determination of the degree of ground water contamination by road salt in the watersheds, the range of background levels of sodium and chloride ions and electrical conductance was obtained. Dug wells and bedrock wells located away from any man-made source of ions were sampled and analyzed.

In the study area, analyses of ground water in surficial deposits uncontaminated by man indicate that background levels of sodium and chloride ions are less than 10 ppm, in general agreement with literature values (Hutchinson, 1969,1970; Hall, 1975; Moody and Associates, 1974; Witherell, 1977). Sodium levels in 22 dug wells in surficial deposits with no obvious sources of man-made contaminants ranged from 1 to 37 ppm, with a median value of 4 ppm. Chloride levels in 21 wells ranged from 0 to 75 ppm, with a median value of 8 ppm. The median electrical conductance for the 22 wells was 340 micro-mhos, ranging from 130 to 750 micro-mhos.

Although a much smaller number of bedrock wells was sampled in this study, analyses indicate that background levels in bedrock ground water are similar. Twelve bedrock wells away from heavily salted roads had median values for electrical conductance of 393 micro-mhos, for sodium of 10 ppm, and for chloride of 6 ppm.

Four surface water samples were taken from three ponds and a brook isolated from man-made sources of sodium and chloride. The mean value (mean rather than median value is reported here due to the small sample population) for electrical conductance was 485 micro-mhos, for sodium was 6 ppm, and for chloride was 7 ppm.

Dug Wells

Of the 96 wells sampled, 69 were dug wells in surficial deposits. These wells are 0.6 to 1.2 meters in diameter, are lined with stone, brick, concrete, metal, or occasionally wood, and have a median depth of about 4 meters. They are located in all types of soils ranging from coarse sands and gravels to clayey lake bottom sediments or tills, and they penetrate the water table.

All dug wells. When considered as a whole, the 69 dug wells show median values of sodium and chloride ion concentrations higher than background levels, indicating that surficial ground water in general is reflecting the effects of development in the watersheds (see Figure 2):

Ion Levels: All Dug Wells

	median electrical conductance (micro-mhos)	median sodium conc. (ppm)	median chloride conc. (ppm)
All dug wells (69 wells)	481	16	30
Background (22 dug wells)	340	4	8

Dug wells, grouped by application rate. To evaluate the road salt contamination hypothesis, the data were analyzed by breaking them into groups of similar salt application rates, as determined by the Vermont Agency of Transportation (for Route 2A) and by road commissioners in Shelburne, South Burlington, and Williston. Twenty-two wells were sampled along roads receiving moderate amounts of salt (Oak Hill Road and the paved portion of South Road in Williston; 12 to 23 tons per mile per year), and 35 wells were sampled along a highly salted road (Route 2A; 34 tons per mile per year). See Figure 1 for the location of these roads. Electrical conductance, sodium, and chloride levels were notably higher along salted roads (as indicated in Figure 3):

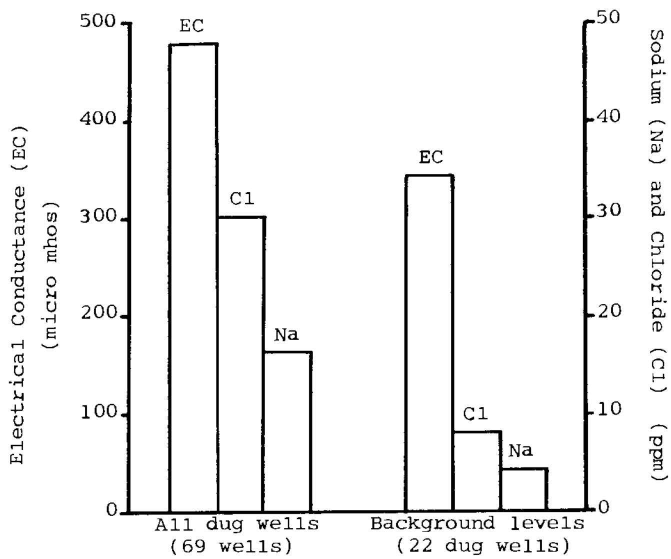

Figure 2. Ion levels: All dug wells.

Ion Levels: Dug Wells Grouped by Application Rate

	median electrical conductance (micro-mhos)	median sodium conc. (ppm)	median chloride conc. (ppm)
highly salted (36 dug wells)	649	60	146
moderately salted (13 dug wells)	375	28	30
background (22 dug wells)	340	4	8

Dug wells along a heavily salted road, grouped by slope from road to well. As discussed in the literature, salt ions, especially chloride, are mobile in ground water, and will tend to travel downslope with water. If contamination of ground water in surficial deposits is due to road salt, a distinct difference in degree of contamination should be observed depending on whether the sample location is upslope or downslope of a salted road.

Of the 33 dug wells near the highly salted road (Route 2A) for which slope information was recorded, 11 are upslope from the road, and 22 are downslope. The 11 upslope wells, even though most of them are within a few hundred feet of a salted roadway, exhibited chloride and sodium ion concentrations similar to background levels. Wells downslope from the roadway, however, have ion levels approximately one order of magnitude greater than background levels (as indicated in Figure 4):

Ion Levels: Dug Wells Near a Heavily Salted Road Grouped by Slope from Road

	median electrical conductance (micro-mhos)	median sodium conc. (ppm)	median chloride conc. (ppm)
downslope (22 dug wells)	1098	104	245
upslope (11 dug wells)	468	6	4
background (22 dug wells)	340	4	8

Dug wells downslope from a highly salted road, evaluated for distance from the road. The literature shows that surficial ground water contamination by road salt is most concentrated near a salted road, and tends to decrease as distance downslope from the road increases. This general pattern is seen in the study area, where contamination beyond about 60 meters from the roadway is noticeably less than closer to the roadway, and beyond about 200 meters little ground water contamination is observed. Figures 5 and 6 plot sodium and chloride levels against distance from the roadway, and show this trend. Several wells exhibit relatively low ion levels in spite of their close proximity to the roadway (circled on Figures 5 and 6). Each of these wells was reported by the owner to supply inordinately large amounts of water continuously throughout the year, indicating that the road salt in the soils and ground water in these particular locations may be flushed or diluted by the unusually heavy ground water flows.

The pattern of ion levels versus distance downslope from salted roadways shown on Figures 5 and 6 appears to represent curvilinear relationships. When both parameters in Figures 5 and 6 are transformed to the logs (base 10) of the parameters (excluding the four anomalous wells described earlier and circled on Figures 5 and 6), linear relationships are observed. Figures 7 and 8 plot ion levels versus distance from roadway on log-log scales, and show the logarithmic association between sodium and chloride ion levels in surficial ground water and distance downslope from salted roadways. This association shows that sodium and chloride ion levels in surficial ground water fall off very quickly as the distance downslope from the salted road increases. Wells more than 60 meters from a salted road are much more likely to be uncontaminated by road salt (sodium less than 20 ppm) than wells within 60 meters.

Conclusions: Shallow Ground Water

Based on these data, it appears that a definite and highly predictable zone of salt-contaminated shallow ground water is located downslope from salted roads in the study area, for distances of less than 100 meters from the roads. Within this zone of contamination, the levels of sodium and chloride generally exceed background levels by one order of magnitude, and in some cases exceed recommended drinking water quality standards. Beyond a few hundred meters from salted roads, contamination was not detected.

Bedrock Wells

To investigate the effects of road salt on bedrock ground water, samples from 24 bedrock wells were analyzed. Of the 24 wells analyzed, 3 were near unsalted roads, 9 were near secondary roads receiving moderate amounts of salt, and 12 were near Route 2A, receiving higher amounts of salt. The values obtained are not significantly different from the background levels cited in the literature or reported in this study (see Figure 9):

Ion Levels: Bedrock Wells

	median electrical conductance (micro-mhos)	median sodium conc. (ppm)	median chloride conc. (ppm)
bedrock wells (24 wells)	400	9	7

Two wells show elevated levels of sodium (60 and 28 ppm, respectively) and are of concern because of possible health problems. The two wells are both within 100 feet of a highly salted road, are downslope from the road, and do not have other sources of these ions obviously nearby. Both well heads are in small surface depressions, and are located close enough to the road or driveway to receive salt-laden snow thrown by snowplows. No nearby bedrock outcrops close to salted roads were observed, and the estimated recharge areas for these wells do not indicate any unusual contamination conditions. It therefore appears that the contamination in these two specific wells is most likely due to road salt application in the near vicinity of the well heads themselves.

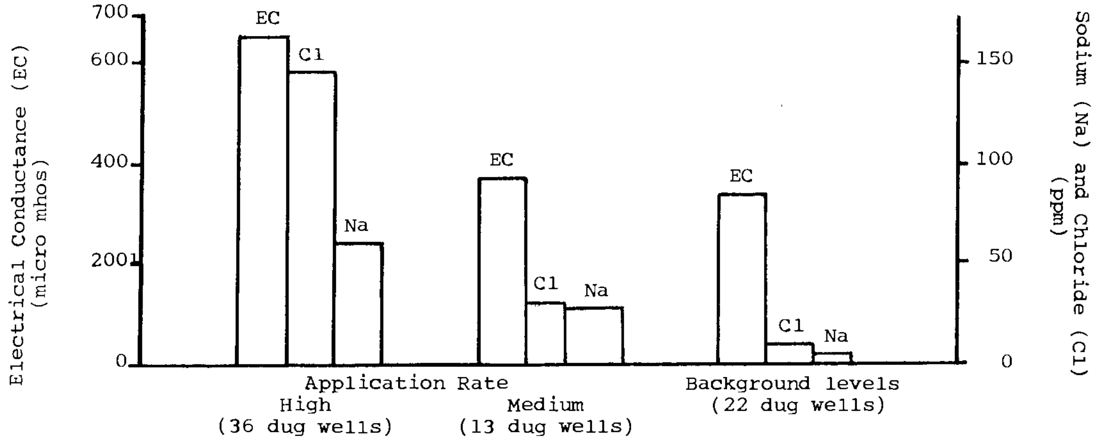

Figure 3. Ion levels: Dug wells grouped by salt application rate.

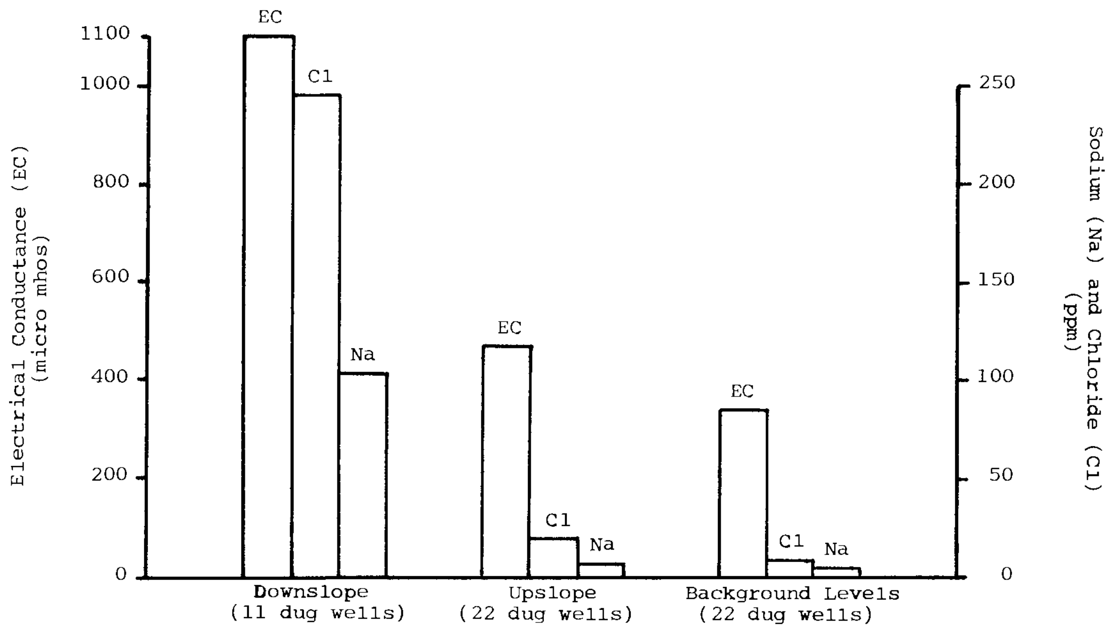

Figure 4. Ion levels: Dug wells near a heavily salted road, grouped by slope from road.

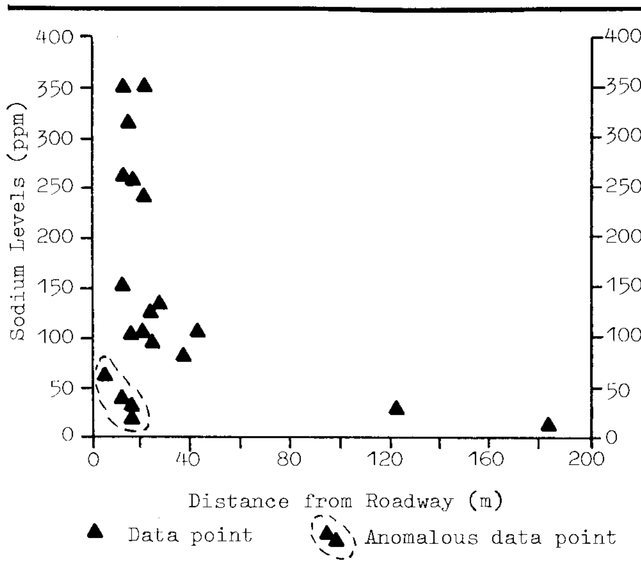

Figure 5. Sodium levels versus distance: Dug wells downslope from a heavily salted roadway.

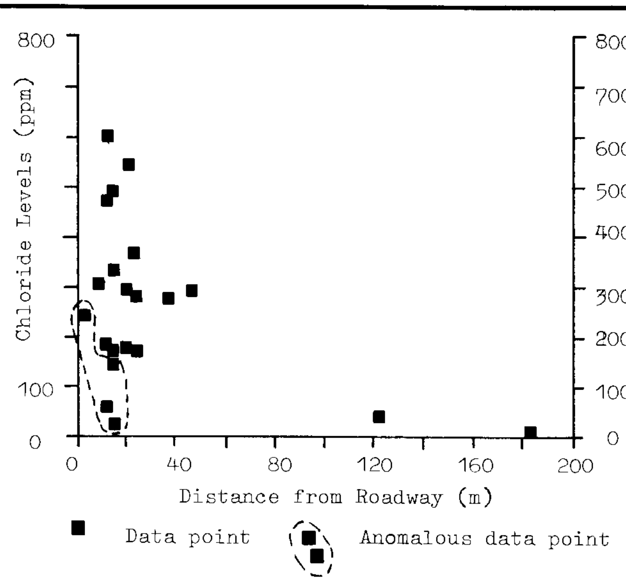

Figure 6. Chloride levels versus distance: Dug wells downslope from a heavily salted roadway.

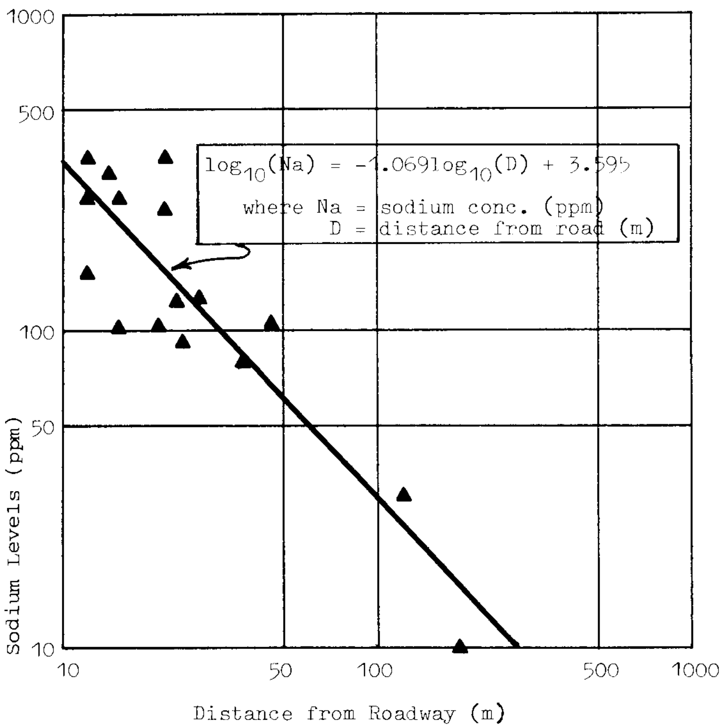

Figure 7. Log-log plot of sodium levels versus distance: Dug wells downslope from a heavily salted roadway.

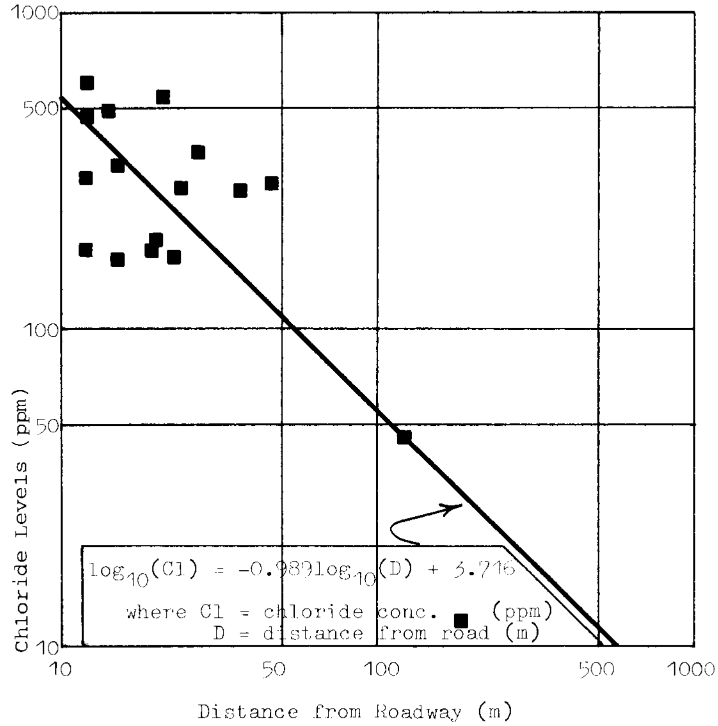

Figure 8. Log-log plot of chloride levels versus distance: Dug wells downslope from a heavily salted roadway.

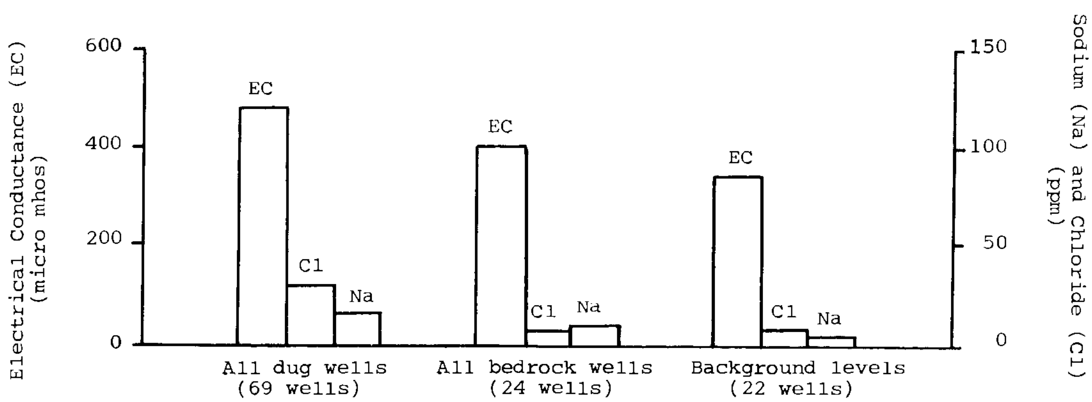

Figure 9. Ion levels: Dug wells, bedrock wells and background levels.

Conclusions: Bedrock Ground Water

Based on these limited data, bedrock ground water in the study area appears to be generally unaffected to date by the application of road salt. Small localized zones of contamination exist, and appear to be due to bedrock wells with casings in surface depressions that can receive salt-laden plow-thrown snow or direct surface runoff from the road.

Existing Water Quality Information

In years past, some residents in the study area have requested water quality analyses of their drinking water by the Vermont Department of Health. In every case (approximately 70 analyses), Health Department results are similar in value to results reported in this study. This suggests that sodium and chloride levels in ground water do not fluctuate wildly, but tend to show some uniformity over time.

ACKNOWLEDGEMENTS

The author extends thanks to the residents of the study for the helpful information offered about their wells, and for their patience in allowing water samples to be taken from their homes. Ken Stone and the laboratory personnel of the Vermont Department of Health provided chemical analyses of water samples, without which this study could not have been completed. Advice, well data , and literature from David Butterfield and Jim Ashley of the Vermont Department of Water Resources and from Richard Willey of the U. S. Geologic Survey are appreciated. Information on road salt application rates was generously offered by the Vermont Agency of Transportation and the road commissioners in the towns of Shelburne, St. George, and Williston. John Howe, previous science advisor to the state legislature, was helpful in developing the statistical material. Equipment loaned from the Department of Geology at the University off Vermont is appreciated. Helpful review of this text was offered by Winslow Ladue, David Cable, Jim Ashley, and Fred Larsen.

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THE TACONIC OROGENY OF RODGERS, SEEN FROM VERMONT A DECADE LATER

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ABSTRACT

Rodgers (1971) showed that the Taconic orogeny consisted of three phases in the interval from just before late Medial Ordovician to about the end of the Ordovician. His synthesis of classical field geology can be fleshed out by applying new kinds of understanding that involve plate tectonics, environments of deposition, and the absolute time scale. Contemporary plate tectonic relationships of Indonesia suggest that the Taconic orogeny was the series of events affecting a continental margin that collided with a volcanic arc. Environments of deposition of the sedimentary rocks, and rates of sedimentary and tectonic processes in terms of an absolute geologic time scale, refine our understanding of crustal subsidence and uplift during the orogeny.

Thus, the pattern of trailing-edge subsidence of the continental margin continued into the Medial Ordovician; by the time of Chazy sedimentation, subsidence had almost ceased and the sedimentary record became one of sea-level carbonates with a very slow accumulation rate. The Taconic orogeny began with the Tinmouth phase, late in the early Medial Ordovician time, as an unconformity in the carbonate sequence. The Vermontian phase occurred in late Medial Ordovician time, with emplacement of the Taconic allochthon on the former shelf. This accompanied accelerated tectonic subsidence as the continental margin began to enter the subduction zone. The Hudson Valley phase occurred in Late Ordovician, as an angular unconformity. Evidently, collision with the arc caused some folding and thrusting, and isostatic uplift provided a source area for the Upper Ordovician terrigenous wedge named the "Queenston delta."

INTRODUCTION

In his 1970 presidential address to the Geological Society of America, John Rodgers (1971) drew attention to three distinct kinds of record of the "Taconic orogeny", each occurring at a different time:

a. Hudson Valley phase: the angular unconformity with sedimentary rocks as old as Early Silurian beveling folded mid-Ordovician sedimentary rocks;
b. Vermontian phase: the emplacement of the Taconic allochthon in late Medial Ordovician time;
c. Tinmouth phase: the early Medial Ordovician unconformity in the carbonate sequence.

A decade has passed since his analysis. With a focus on Vermont geology, the present article looks at the kind of data he has raised for scrutiny, but with the addition of geologic approaches that have matured in the past decade or two. Plate tectonics is probably the most important, because it provides a model that suggests an array of geographic settings through time. A commonly accepted model (Chapple, 1973; Rowley and Kidd, 1981) is that the Taconic orogeny is the result of proto-North America colliding with a volcanic arc. Hamilton (1979) maps and documents a modern example of this -- the northern margin of the Australian platform has been colliding with the Indonesian volcanic arc (Baldwin and Butler, 1982). In the vicinity of Timor, the platform is entering the subduction zone (Carter and others, 1976; Rowley, 1980), whereas New Guinea records the results of collision with the volcanic arc 10 m.y.a. (million years ago).

A second advance is the increased precision in interpreting the environment of deposition of sediments. Sedimentary and metasedimentary rocks are no longer merely sandstones or schists, but rather are considered as records of water depth and of source areas. Thus, Rodgers (1968) argued that the carbonate conglomerates of northwest Vermont marked the east edge of the continental shelf and upper continental slope. More recently, Rogers (1976) showed that the Monkton Quartzite (Lower Cambrian) of west-central Vermont thins east from more than 300 m on Snake Mountain, which is northwest of Middlebury, to the pinchout shown near Hinesburg (Doll and others, 1961). This supports the long-accepted inference that a continental source area lay to the west. Also, she showed that subaerial red silty quartzite of the Monkton changes eastward into gray surf-zone quartzites. Now, Rowley (1979) has suggested that the terrigenous sheets of Cheshire, Monkton, and Danby spread east across the shelf at times when sea level was lower and the shoreline had regressed east to the edge of the shelf. Baldwin (1982) has correlated intervals of terrigenous sand turbidites in the deep-water Taconic sequence with the Monkton and Danby of the shelf.

A third tool that has developed in the past decade or two is the fairly detailed calibration of the geologic time scale in terms of absolute years. This new absolute time scale, even with its imprecisions, permits us to calculate rates of geologic processes. More particularly, we can calculate rates of sediment accumulation and use these to determine the approximate rates of tectonic subsidence associated with a continent-arc collision.

Figure 1*summarizes the data used in the present report. The absolute time scale comes from Churkin and others (1977); Bluck and others (1980) support that geochronology. This absolute calibration is the framework into which I have set information presented by Fisher (1977). The figure shows Berry's and Riva's graptolite zones, which are cited in many reports on Taconic geology. It shows stratigraphic units, which are assigned according to the correlation chart of Fisher (1977) but modified slightly by other reports. For example, Bergstrom (1976) found Whiterockian conodonts in the Bridport Formation, extending its age up into the early Medial Ordovician. Rowley and Kidd (1981) carry the Poultney Slate up through the Whiterockian.

* See back cover.

PRE-TACONIC SUBSIDENCE

Rates of sediment accumulation before the Tinmouth phase are a response to tectonically controlled subsidence. Baldwin (1980) showed that from Early Cambrian through Early Ordovician time, sediments of the ancient shelf accumulated at a rate of 15 or 20 m/m.y. (metres per million years). The space for these sediments was provided in part by isostatic loading, but 30 percent of the thickness must have been provided by tectonic subsidence, as indicated by the formulae for shallow-water sediments:

$$T_s = S_l + S_t$$

$$T_s \times D_s = S_l \times D_m$$

$$S_l = \frac{D_s}{D_m} T_s = 0.7\ T_s$$

where: T_s = total thickness of sediments

D_s = density of sediments (2.3 gm/cm)

S_l = subsidence due to isostatic loading

D_m = density of mantle (3.3 gm/cm)

S_t = subsidence due to tectonic causes

The subsidence rates of the Cambrian to Medial Ordovician platform sequence can be explained by the combination of a cooling margin and the isostatic loading of sediments. The curve of Parsons and Sclater (1977, Fig. 13) can presumably be applied to behavior of a continental margin, and this curve shows subsidence of about 5 m/m.y. at a time of 150 m.y. after rifting. Before Medial Ordovician, the crust was subsiding 5 or 7 m/m.y. due to tectonic causes.

By the early Medial Ordovician, subsidence slowed nearly to a halt. For perhaps 19 m.y. from the start of Whiterockian time to the start of Turinian time, the sediment accumulation rate averaged a scant 5 m/m.y. This would fit the curve of Parsons and Sclater at a time of about 200 m.y. after rifting, where the subsidence is scarcely 2 m/m.y. As would be expected, the sediments of this interval were deposited essentially at sea level. Fisher (1968) and Pitcher (1964) described coral and bryozoan reefs of Isle la Motte and vicinity, and Baldwin (1980) noted the surf zone lime-sands exposed in the parade ground of Fort Crown Point. Accumulation of such sediments is permitted only to the degree that the crust subsides or sea level rises.

DEEP-WATER SEDIMENTS

While carbonate sediments, along with some sheets of quartz sand, were being deposited on the ancient continental shelf, muds were accumulating in deep water. The West Castleton, Hatch Hill, and Poultney formations, which are black and dark gray argillites with associated interbeds, are Early Cambrian to Early Ordovician in age. The argillite for this interval of about 80 m.y. is about 330 m thick and so accumulated at about 4 m/m.y. (Baldwin, 1982). The very slow rate suggests tectonic quiessence with no prominent nearby terrigenous source area. Interbeds in some of the dark argillites consist of carbonate and quartzose grains and clasts, and so these must have come from an ancient continental shelf, mostly as turbidites (Baldwin, 1982).

Beneath that sequence is the Nassau Formation (St. Catherine Formation of Doll and others, 1961; Bull Formation in Zen, 1961) of Hadrynian and Early Cambrian age. These green and purple argillites are about 500 m thick (Zen, 1961), and if they too accumulated at 4 m/m.y., the Nassau Formation would represent an interval of about 125 m.y., from 670 to 545 m.y.a.

TINMOUTH PHASE

Rodgers drew attention to the "Tinmouth disturbance" of Thompson (Shumaker and Thompson, 1967); near Danby, Vermont, the mid-Ordovician Ira Formation rests across tilted and block-faulted beds down to and including Precambrian basement rocks. The Ira is Barneveldian (Fig. 1) and certainly no older than Turinian. Similarly, Zen (1964) mapped the Ira as overlapping its Whipple Marble member, which in turn lies across a series of Cambrian formations at West Rutland. These glimpses of the regional unconformity of approximate Montyan age place the gap in record as being older than the Whipple, which is earliest Barneveldian or possibly Turinian, and younger than the Bridport, which may be as young as Whiterockian, as noted above.

In a contrary view of age of the faulting, Rowley and Kidd (1981, p. 213) argue against deep erosion before the Turinian, because off-shelf deep water sediments of this age do not contain the coarse detritus that would result.

The deep-water sedimentation similarly reflects a change in tectonism. The Normanskill Group is a flysch that is younger, perhaps just younger, than the Poultney Slate. It occupied perhaps 7 to 10 m.y. of Montyan into Turinian time, about the time span of Riva's _Nemagraptus gracilis_ zone, and the early part of the _Diplograptus multidens_ zone (Fig. 1). Bird and Dewey (1975) estimated the thickness at more than 1500 m. If so, argillite plus interbeds accumulated at about 150 or 200 m/m.y.

The Normanskill includes the Austin Glen Graywacke of the Albany area, which is named the Pawlet Graywacke in Vermont (Zen, 1961). The Pawlet contains sand-sized grains of volcanic rock (Kenyon, 1977), and Rowley (personal communication, 1981) reports that the Austin Glen also has volcanic grains. The Normanskill's proximal turbidites, high accumulation rate, poor sorting, and volcanic grains are consistent with ocean-floor sedimentation near a volcanic arc, east of the east-moving proto-North American plate.

VERMONTIAN PHASE

Rodgers' second unconformity is associated with emplacement of Hadrynian, Cambrian and Ordovician deep-water sediments onto carbonate shelf sediments of the same age. This occurred during the first part of Berry's graptolite zone XIII, in early Barneveldian time, as shown in Figure 1. The Livingstone slide of Normanskill was emplaced during _Corynoides americanus_ time, and the Giddings Brook slice (the first of the Taconic slices) was emplaced just afterwards, in _Orthograptus ruedemanni_ time (Rickard and Fisher, 1973; Fisher, 1979).

Accumulation rates of the post-Chazy continental shelf sediments help explain the emplacement. According to Baldwin (1980), the Orwell and Glens Falls limestones at Crown Point indicate that the water was deepening from shallow photic zone to deeper conditions in or below the photic zone. It is significant that rates for the Orwell and Glens Falls limestones increased to perhaps 30 m/m.y. (Baldwin, 1980). Evidently, the deepening water and the increase in rate of sediment accumulation were due to more rapid crustal subsidence. Indeed, immediately after deposition of the Glens Falls, the shelf subsided enough to be buried under 1450 m of Iberville and Stony Point shale, in a time that may have lasted only 6 m.y. (Fig. 1). Baldwin (1980) gave a figure of 200 m/m.y., for these late Medial Ordovician shales, and he calculates a figure of about 350 m/m.y. (Baldwin, 1982) for the argillites in the Martinsburg Formation, from data reported by McBride (1962). To determine rates of crustal subsidence for west-central Vermont, the 1450 m should be recalculated to its thickness before final compaction, and the increase in water depth should be added. Comparable rates occur with the Cloridorme Formation of Enos (1969), which is late Turinian and Barneveldian in age. Enos estimated the total thickness at perhaps as much as 7700 m, of which 4500 m is argillite. This was deposited in about 7 m.y. The argillite accumulated at a rate of perhaps 650 m/m.y., and the formation must have accumulated at more than 1100 m/m.y. It is not clear how much of the 7700 m merely filled in the deep water existing at the start of Cloridorme deposition, and how much space was provided by crustal subsidence during deposition of the Cloridorme.

Plate tectonics gives meaning to these rates, and to some other features of the sedimentation. The most common plate model for the Taconic orogeny is that of a plate moving eastward into a subduction zone, with the proto-North Atlantic continent finally colliding with the arc (Chapple, 1973; Rowley and Kidd, 1981). Remnants of the Ordovician arc are believed to be represented by the Ammonoosuc Volcanics along the Connecticut River and by the gneiss domes just to the east (for example, Rowley and Kidd, 1981).

A modern example shows that the rates of crustal subsidence are not abnormal. In the Timor trench DSDP Site 262 (Veevers and others, 1974), encountered lower Pliocene shallow-water calcarenite at 2,700 m below sea level. This indicates that the leading (north) edge of the Australian continent has subsided at a rate of some 600 m/m.y. as it has entered the subduction zone, which lies just north of Timor (Carter and others, 1976).

With the continental margin subsiding rapidly, it should not be difficult to emplace the deep-water sediments. In the recent past, writers (for example, Zen, 1961, 1967, 1972; Bird and Dewey, 1970, 1975) followed the idea that at least the western (Giddings Brook) slice of the Taconics was emplaced by gravity sliding from an uplifted part of continental crust. Contemporary plate tectonic settings suggest a different model. Coney (1973) showed that the Australian continent has driven north into the subduction zone and he concluded that most or all fold-thrust belts on leading edges of continents are formed by the continent underthrusting the ocean-floor and continental margin sedimentary prism. In brief, the crust of proto-North America probably tilted down just before it collided with the volcanic arc, thrusting itself beneath the Taconic allochthon, which was what Rowley and Kidd (1981) interpret as a "preassembled thrust stack."

Following the emplacement of the allochthon, with associated deformation, there was uplift and erosion. This is marked by an angular unconformity that can be traced south along the Appalachian Mountain system. In places the overlying strata are as old as Late Ordovician, though at Becraft Mountain and Mt. Ida near Albany they are lowermost Devonian (Rodgers, 1971). For comparison, southern New Guinea has a fold-thrust belt involving Paleozoic basement rocks, and in the last 10 m.y. New Guinea has been rising (Hamilton, 1979). This example suggests that folding and thrusting occurred during the Taconic orogeny, possibly including the folding of Taconic slices (Schumaker and Thompson, 1967), and movement on the Champlain thrust; deformation was followed by isostatic uplift.

This last phase of the Taconic orogeny is represented by sediments of a prograding terrigenous wedge. Evidently, the Martinsburg Formation filled the basin on the collapsed margin of the continent. Then, as the terrigenous sediments prograded westward they changed upward into shallow water and subaerial sediments of the Schenectady Formation (Rickard and Fisher, 1973) and the Upper Ordovician "Queenston delta."

The coarser sediments of this wedge tend to be mature quartz sands, and this poses the question of how collision with an arc could generate a quartz-rich source area. The quartz sands must have come from an earlier continental source and somehow must have been incorporated in the Late Ordovician source area. Dickinson and Valloni (1980) demonstrate that modern quartz-rich ocean-floor sands come from a continental source, by way of some particular "dispersal path". Moore (1979) notes that Nias Island, south of Sumatra, exposes former continental slope deposits that are 55 to 76% quartz. He suggests that the quartz sands came from continental rocks of Sumatra. Similarly, Velbel (1980) described middle Eocene sandstones with more than 80% quartz, on Barbados; these too must have come from a continental source. The process of continent-arc collision must make these continent-derived quartzose materials available for transport back toward the continent; moderate reworking should make the sands mature.

CONCLUSION

Rodgers (1971) defined the Taconic orogeny with a quote from Poole (1967), "...the orogenic events which affected the Appalachian Geosyncline and bordering the St. Lawrence Platform during Ordovician time." Now, the Taconic orogeny can be best understood as the events that occurred as the east-moving proto-North American plate "felt" the presence of the arc, began to be subducted eastward, and then collided with the arc and rose isostatically. This summary is drawn from work of Rowley and Kidd (1981), Bird and Dewey (1970, 1975), Chapple (1973), and many others.

At first, when the leading edge of the continent was still far from the arc, the continental margin continued to subside as a result of cooling, according to the model posed by parsons and Sclater (1977). Ocean-floor sedimentation in the fore-arc belt would reflect volcanism, and the process of underthrusting by subduction would begin to stack the sediments along with some ultramafic fragments from the ocean crust.

Just after deposition of the Chazy, the Taconic orogeny began; this was the Tinmouth phase. Perhaps the leading edge of the continent was about to reach the trench and so it began to buckle.

The thick shale sequences of the late Medial Ordovician indicate that subsidence had now accelerated. This collapse of the shelf not only made room for deposition of the shale, but also permitted obduction of the Taconic allochthon as the continental margin was forced part way beneath the thrust-faulted stack of ocean-floor sediments. This was the Vermontian phase.

Collision with the arc stopped the subduction and caused folding and thrusting along the continental margin. This Hudson Valley phase was accompanied by uplift because the "Queenston delta" is a Late Ordovician terrigenous wedge that indicates a newly rising source area. Evidently, once the North American plate ceased moving and stresses began to be released on some other plate boundary, the leading edge of the continent could rise isostatically, as New Guinea has been doing since mid-Miocene time.

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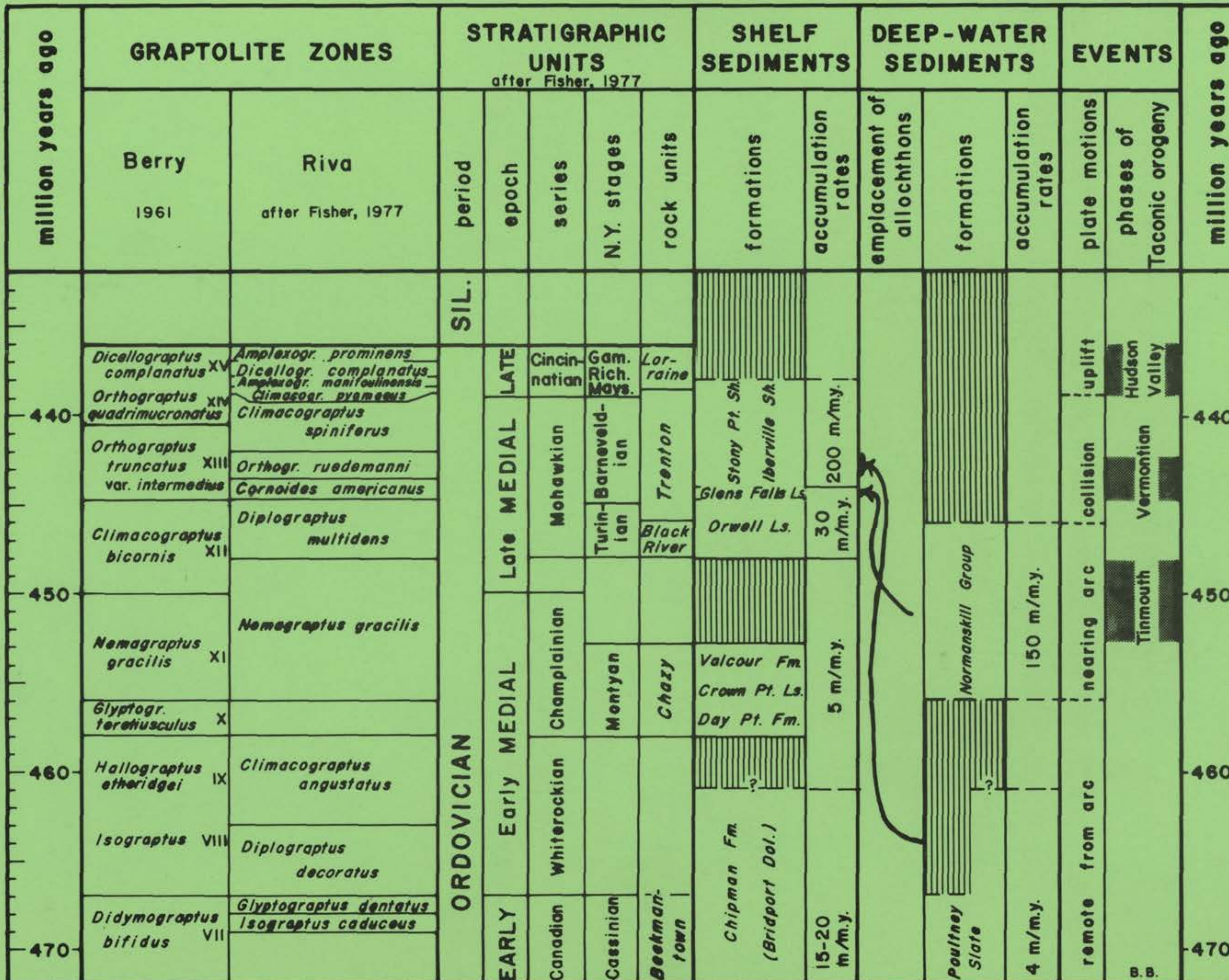

Baldwin, Figure 1 (see Page 20)

TYPE SECTIONS OF FORMATIONS IN VERMONT

Middlebury College
Brewster Baldwin
April 1982

This listing of references for type sections of formation in Vermont was compiled for COSUNA in 1981. In the listing, the first reference is the original naming, and the second reference is the most significant description. The formations are those used for:

Column 2 (western Vermont)
Column 6 (northwest Vermont)
Column 10 (central Vermont)

Formations in other parts of Vermont are represented in COSUNA sections for bordering states; they will be added at a later date.

Formations

Barnard volcanic member of Moretown Formation
(10) Richardson, 1927; Ern, 1963
Bascom Formation
(2) Cady, 1945; Cady, 1945
Brandon Lignite
(2) Hitchcock and others, 1861; Tiffney and Barghoorn, 1976
Cheshire Quartzite
(2) Emerson, 1917; Osberg, 1952
(6) Emerson, 1917; Stone and Dennis, 1964
Chipman Formation
(2) Kay and Cady, 1947; Cady and Zen, 1960
Clarendon Springs Dolomite
(2) Keith, 1932; Cady, 1945
Cram Hill member of Moretown Formation
(10) Currier and Jahns, 1941; Doll, 1951
Cutting Dolomite
(2) Cady, 1945, Cady, 1945
Danby Formation
Keith, 1932; Cady, 1945
Dunham Dolomite
(2) Clark, 1934; Cady, 1945
(6) Clark, 1934; Stone and Dennis, 1964
Gile Mountain Formation
(10) Doll, 1944; Goodwin, 1963
Glens Falls Limestone
(2) Ruedemann, 1912; Welby, 1961
Gorge Formation
(6) Raymond, 1925; Shaw, 1958
Hazens Notch Formation
(10) Cady and others, 1963; Chidester and others, 1978

Highgate Formation
(6) Keith, 1923; Shaw, 1958
Hoosac Formation
(10) Emerson, 1917; = Granville Formation of Osberg, 1952
Hortonville Slate
(2) Keith, 1932; Cady, 1945
Hungerford Slate
(6) Schuchert, 1937; Shaw, 1958
Middlebury Limestone
(2) Cady, 1945; Cady, 1945
Mill River Conglomerate
(6) Howell, 1929; Shaw, 1958
Monkton Quartzite
(2) Keith, 1923; Cady, 1945
Moretown Formation
(10) Cady, 1956; Cady, 1956
Morses Line Slate
(6) Shaw, 1951; Shaw, 1958
Mt. Holly Complex
(2, 10) Whittle, 1894; Brace, 1953
Northfield Slate
(10) Currier and Jahns, 1941; Cady, 1956
Orwell Limestone
(2) Cady, 1945; Welby, 1961
Ottauquechee Formation
(10) Perry, 1929; Brace, 1953
Parker Slate
(6) Keith, 1932; Shaw, 1958
Pinnacle Formation
(2) Clark, 1934; = Mendon series of Osberg, 1952
(6) Clark, 1934; Booth, 1950
Pinney Hollow Formation
(10) Perry, 1929; Brace, 1953
Plymouth member of Hoosac Formation
(10) Doll and others, 1961; Chang and Thompson, 1965
Rockledge Conglomerate
(6) Schuchert, 1937; Stone and Dennis, 1964
Rugg Brook Dolomite
(6) Schuchert, 1933; Shaw, 1958
Saxe Brook Dolomite
(6) Howell, 1939; Shaw, 1958
St. Albans Slate
(6) Howell, 1926; Shaw, 1958
Shaw Mountain Formation
(10) Currier and Jahns, 1941; Cady, 1956
Shelburne Marble
(2) Keith, 1923; Zen, 1964
Skeels Corners Slate
(6) Howell, 1939; Shaw, 1958
Standing Pond Amphibolite
(10) Doll, 1944; Goodwin, 1963
Stowe Formation
(10) Osberg, 1952; Cady, 1956

Tibbit Hill volcanic member of Pinnacle Formation
(6) Clark, 1936; Booth, 1950
Tyson Formation
(10) Doll and others, 1961; Chang and Thompson, 1965
Umbrella Hill Formation
(10) Albee, 1957; Badger, 1979
Underhill Formation
(6) Christman and Secor, 1961; Stone and Dennis, 1964
(10) Christman and Secor, 1961; Christman and Secor, 1961
Waits River Formation
(10) Currier and Jahns, 1941; Goodwin, 1963
Winooski Dolomite
(2) Hitchcock and others, 1861; Cady, 1945

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