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SEDIMENTATION RATES OF THE TACONIC SEQUENCE AND THE MARTINSBURG FORMATION

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ABSTRACT. By calibrating thickness of deep-water argillites in terms of absolute geologic time, it is possible to estimate frequency of turbidite events. The calibration can be tested by comparing the age of quartz-sand interbeds in the deep-water sequence with that of quartz-sand sheets of the adjacent shelf sequence.

This approach has been applied to part of the Taconic sequence, deposited in about 80 m.y., of Early Cambrian to Early Ordovician time. Strata were studied in glacially polished vertical beds near Fair Haven, Vt. Four sections expose 188 m of the 420-m sequence. Argillite thickness totals no more than 330 m of this, indicating an accumulation rate of merely 4 m/m.y. Graded interbeds of dolostone and quartz sandstone are common in part of the sequence, where they are as frequent as 10 to 40 events per meter of argillite. This indicates a turbidite event every 25,000 to 6000 yrs.

These data are for sedimentation in the tectonically quiet setting of a trailing edge. They contrast with the argillite accumulation rate of about 330 m/m.y. and turbidite events every 200 yrs, calculated for the Martinsburg Formation from data by McBride (1962); the Martinsburg was deposited during the Taconic orogeny.

INTRODUCTION

Beginning with Kulp (1961) and Harland, Smith, and Wilcock (1964), calibration of the geologic time scale in terms of absolute time has become increasingly precise. This new tool has been widely applied to *history* — the use of radiometric dates to place igneous and metamorphic events within the geologic time scale.

Yet in science, *the most obvious role for absolute time is to determine rate.* This article illustrates the use of estimated absolute ages to calculate sedimentation rates of a section in the Taconic sequence of Vermont. These rates are in turn used to analyze the stratigraphic and tectonic implications of this section and that of the Martinsburg Formation of the central Appalachians.

There has been some study of sediment accumulation rates in the Cenozoic (for example, Worsley and Davies, 1979), because the absolute time scale here is well established. There is reluctance, however, to use the absolute time scale to estimate rates in older tectonic settings, especially in the Paleozoic. Shanmugam and Walker (1980), for instance, used modern sediment accumulation rates in their analysis of mid-Ordovician rocks.

Reluctance to use estimates of absolute age for the Paleozoic is understandable, because a 3 percent error is a discrepancy of 10 or 15 m.y. Yet, the many absolute age determinations throughout the Phanerozoic time scale place constraints on how much error there can be in estimating the absolute age of any particular time-rock boundary. Also, imprecision in estimating absolute age is in part a systematic error that would change both ends of an interval in the same direction, so that the span of the interval would remain about the same. In brief, it is not likely that a stratigraphically dated interval of some 50 m.y. can be more than 10 m.y. in error, even for Paleozoic rocks, and this would cause no more than a 20 percent error in calculation of a rate. This is acceptable as a first approximation where rates for two different situations differ by one or two orders of magnitude.

Churkin, Carter, and Johnson (1977) took this attitude in calculating the accumulation rate of 4 m/m.y. for some "relatively pure" Ordovician shales in Nevada. They then used thickness of the graptolite zones in these shales as a direct measure of time span for each zone and so were able to present a precise absolute time scale for part of the Ordovician and Silurian. Bluck and others (1980) support their age assignments.

McBride (1962, p. 70) anticipated this use of sedimentation rates:

> "Assuming that pelagic sedimentation took place at a constant rate, the time interval between successive turbidity currents is represented by the thickness of shale between adjacent turbidite units."

A caveat is that deep-water muds evidently accumulate at variable rates, when considered in detail. Published studies of deep-water muds show that some are hemipelagic, but most are deposits of turbidity currents (Enos, 1969; Hesse, 1975; Maldonado and Stanley, 1977). Shanmugam (1980) has demonstrated cyclic patterns in deposition of mid-Ordovician muds. On the other hand, the net accumulation rate for deep-water muds, in meters per million years, may be fairly constant for a given tectonic setting, whatever the process(es) of sedimentation. Until and unless we find otherwise, it is useful to assume this constancy and see where it leads us.

Here, I calculate the sediment accumulation rate for a deep-water argillite and use this as a tool in stratigraphic and tectonic analysis. The study concerns a series of Cambro-Ordovician sediments of the Taconic allochthon in western Vermont. No reasonable error in the thickness or absolute age of the sedimentary sequence will affect the rates by more than 50 percent. The study includes a comparison with rates for the Martinsburg Formation; it goes further than McBride was able to do because it uses absolute time data that were not available two decades ago. The comparison shows a large contrast between rates for the Taconic sequence and those for the Martinsburg Formation, and this can be related to their respective tectonic settings.

Present work.—The field area lies along Poultney River just west and northwest of Fair Haven, Vt.; the river here flows north along the east, vertical limb of a simple and open syncline that verges west (fig. 1). Glacial processes developed smooth surfaces on the rocks, and glacial deposits have preserved the rocks from weathering. Poultney River has cut 30 m through the surficial deposits, exposing fresh glacially polished outcrops within 10 m of river level. Though the rocks have some sec-

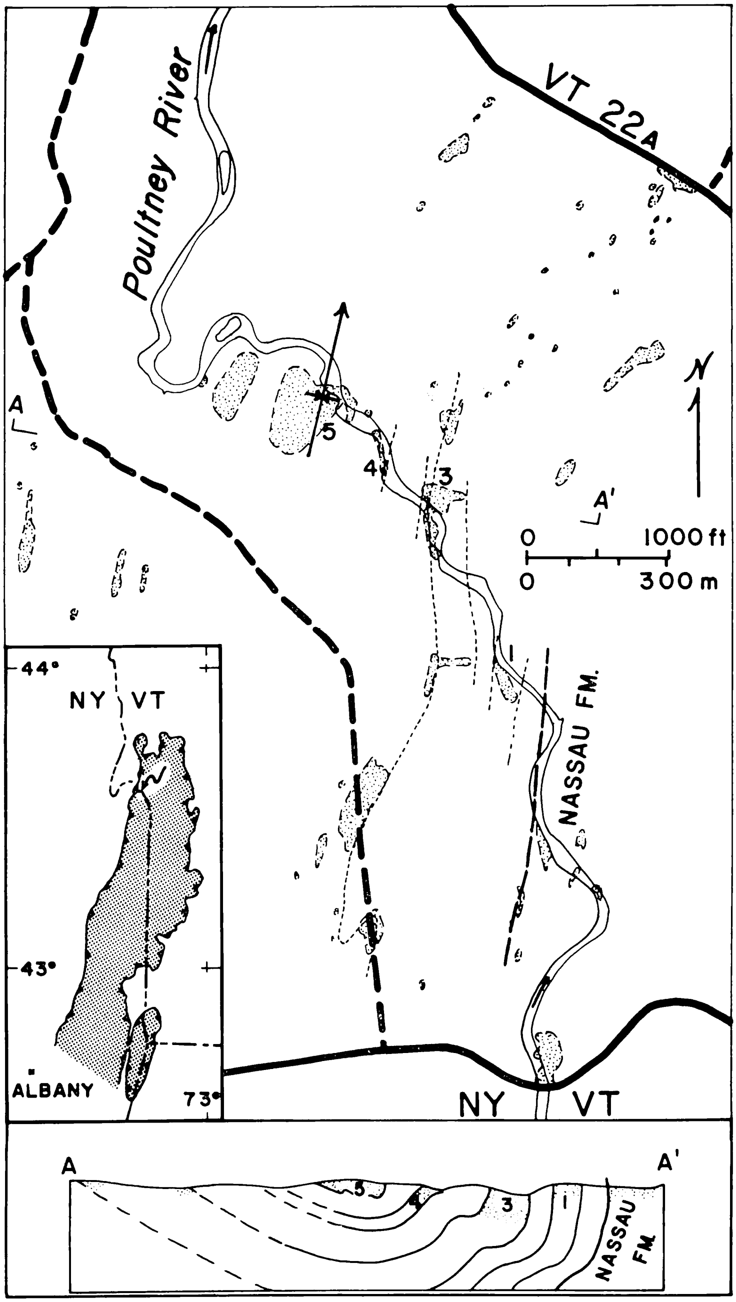

Fig. 1. Map showing outcrops (stipple) along Poultney River. Inset map shows Taconic allochthon (dark stipple) and field area (arrow). A-A′ is structure section. Numbers (1, 3, 4, 5) are measured sections.

ondary cleavage, there has been little metamorphic recrystallization, and primary sedimentary structures are well displayed. These structures indicate there has been no reversal of dips (and so no repetition of beds) in the syncline studied here.

Field study along Poultney River, northwest of Fair Haven, Vt., was conducted in the summers of 1967, 1968, and 1969. Grain size and bedding features of the stratigraphic sections were recorded graphically at 1 cm per 1.2 m. Mapping and structural studies provided the basis for determining thickness of covered intervals that separate the measured sections. In the laboratory, 40 thin sections were examined, 10 samples were analyzed for heavy minerals, and 16 samples were analyzed with HCl for percent insoluble residue. A preliminary report has been presented (Baldwin, 1977).

Past work.—The area of the present study is part of that mapped by Zen (1961) and Theokritoff (1964). Zen (1961) showed the rocks here to be part of the Giddings Brook slice of the Taconic allochthon. He (1967, 1972) recognized that the Taconic sequence is thinner than the carbonate sequence of the same age in western Vermont, indicating a slower rate of accumulation. Bird and Dewey (1970, 1975) and Keith and Friedman (1977) interpreted the origin as continental slope and rise sediments.

DESCRIPTION OF STRATA

The stratigraphic interval of concern in this study is the sequence of dark argillites and associated interbeds that lie on green to maroon slates of the Nassau Formation. The interbeds (so-named to emphasize the spasmodic and event-like nature of deposition) are dolostone, sandstone, and some chert breccia and limestone. The sequence of dark argillites continues to the highest beds exposed in this reach of Poultney River.

The entire sequence measures 420 m in thickness. Four exposed sections (fig. 1, secs. 1, 3, 4, and 5) measure 188 m, and the intervening four covered areas represent about 230 m. Outcrops away from the river give some control on the nature of beds in the covered areas along the river (fig. 1). The section numbers are field designations; section 2 is in a location away from the river sequence.

The 420-m sequence is the stratigraphic interval of the West Castleton Formation, the Hatch Hill Formation, and most of the Poultney Slate. This represents an age range from Early Cambrian to about the end of the Early Ordovician. My thickness is about that reported by Zen (1961, fig. 2), who treated the interval as the West Castleton Formation and part of the Mount Hamilton Group.

The argillites are black to dark gray. Some argillites weather a light silvery gray, and there are a few red-weathering laminae of black argillite. The color banding is parallel to bedding. Associated with some of the dark argillites are lenses of white-weathering chert and black silicified argillite; green oxidation stains on these silicified beds indicate weathering of sulfides.

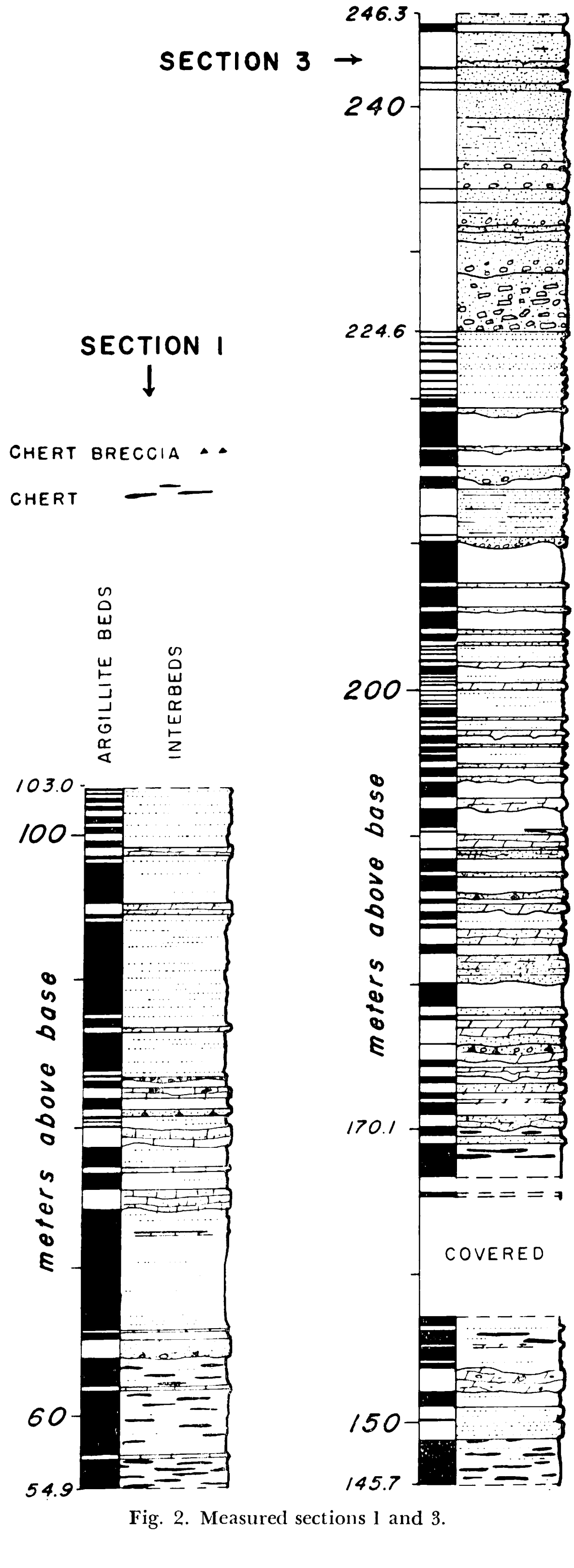

Fig. 2. Measured sections 1 and 3.

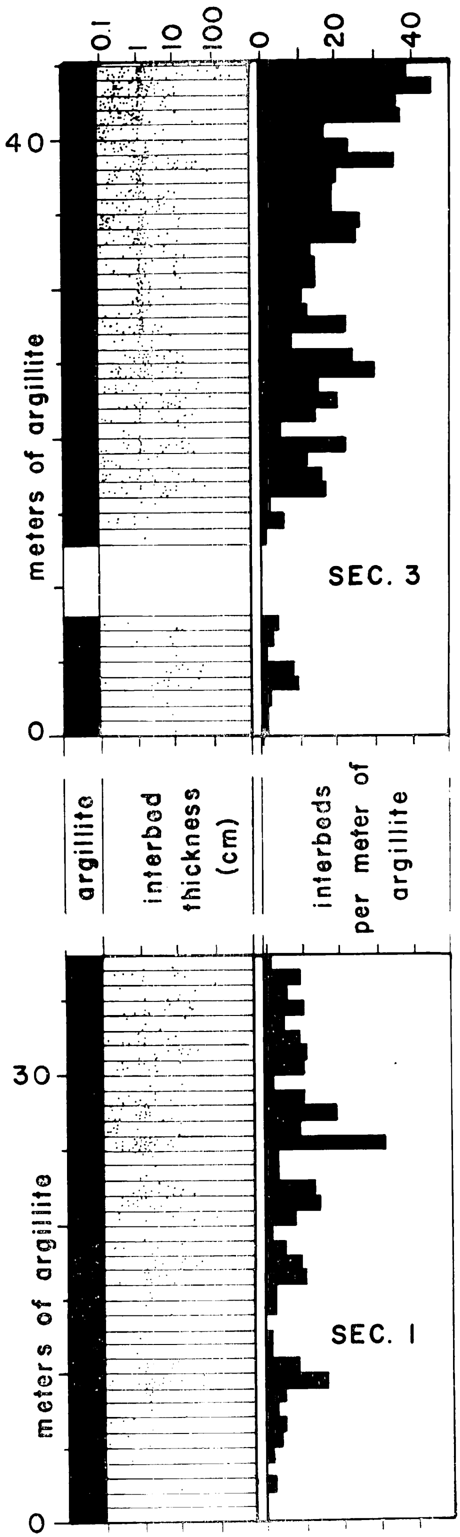

Fig. 3. Frequency of interbeds per meter of argillite in sections 1 and 3.

Interbeds are abundant in sections 1 and 3 (fig. 2). Their thicknesses range from laminae that are scarcely visible to one bed that is 4 m thick. Figure 3 shows thickness of interbeds in sections 1 and 3; the common thickness is between 1 and 10 cm. Internal structures are typical of those in the Bouma sequence. The thicker interbeds have a lowermost unit that is graded (Bouma A), overlain by parallel lamination (Bouma B), and some cross-lamination (Bouma C). Thinner interbeds, especially the quartz siltstones and fine sandstones, have parallel lamination at the base (Bouma B) and small-scale cross-lamination at the top (Bouma C). Convolute bedding is seen in only two interbeds. Typically, the interbeds have a sharp base and a somewhat transitional top. Small linear marks are seen on some of the poorly exposed soles of interbeds.

Interbeds maintain a constant thickness along as much as 60 m of exposure. For example, in section 3 two interbeds, each 20 cm thick, merge northward in 35 m to a single interbed 55 cm thick, and this continues 25 m to the north end of the outcrop, with a thickness of 40 cm.

In one interbed, three-dimensional exposure of cross-lamination of the Bouma C unit shows current motion in the direction straight up, out of the ground. If the beds are unfolded around a cylindrical axis, which trends about N 10° E (fig. 1), what is now directly up would trend S 80° E. Unfolding of the beds would thus indicate eastward (rather than westward) motion of the currents.

Some interbeds in section 3 exhibit shallow channels, which cut as much as 20 cm into the underlying argillite. For six channels, margins of the channels are exposed with enough relief on the glacially smoothed outcrop to determine the attitude of the margin. Nine readings on these margins average 20 degrees from vertical; only three of them are more than 25 degrees from vertical. Therefore, the channel margins would have trended between N 80° E and S 60° E, if emplacement of the allochthon involved no rotation.

The carbonate and quartzose materials that constitute the interbeds must have come from a continental shelf. Chert breccia in a quartz-sand matrix is present in both section 1 and section 3. In the interbeds, most of the carbonate is dolomite, occurring either as dolostone beds or as dolostone grains and dolomite cement in quartz sandstone beds. In section 3, there is a progression upsection from dolomite to quartz. The lower interbeds are dolostone, dolostone conglomerate, and dolostone with some quartz sand in the basal parts. Higher interbeds are thin quartz sandstone with dolomite cement, quartzite, and a series of thick quartz sandstones with dolomite cement. Clasts of sediments are found in the basal part of several of the thick sandstones, and in the thickest of these (225-229 m in fig. 2) clasts of laminated quartz siltstone, quartzite, and dolostone constitute a third of the rock. The clasts measure as much as 20 cm long, and a few clasts are bent. No limestones occur in section 3, but there are some in section 1 (for example, Zen, 1961, pl. 2, fig. 3).

The mature nature of the terrigenous grains in the quartzose interbeds indicates a source area of continental terrane. Although there is some feldspar, the grains are mostly quartz, and grains coarser than fine sand are rounded. Heavy minerals are rounded zircons with some tourmalines and occasional grains of rutile.

It is generally agreed that the Taconic sequence was deposited in deep water, probably on the slope or rise of the North America continental margin (Bird and Dewey, 1970; Keith and Friedman, 1977; Rodgers, 1971). Evidence in the outcrops along Poultney River gives more detailed definition of depositional environments (Baldwin, 1971, p. 298). The lower 24 m of section 3 (fig. 2, 146-170 m) is almost devoid of interbeds, and it is likely that the cherts and black argillites and siliceous argillites were deposited in reducing conditions of an ocean floor. Up-section, interbeds are common, and the argillite color is somewhat less dark, suggesting that the emplacement of the interbeds was accompanied by introduction of some oxygen. Primary structures of the interbeds indicate that most are distal turbidites. The 4-m bed of conglomerate in section 3 (225-229 m), noted above, was probably emplaced by debris flow in a submarine canyon, because all but the uppermost 20 cm is structureless and choked with clasts derived from beds typical of a continental shelf. The beds in section 3 suggest that a submarine fan had come into existence and migrated laterally into this locality for a brief time. Turbidity currents carried dolomite particles and then quartz sand to build the fan. The source is interpreted as the carbonate and quartzose sediments that had been deposited on the stable continental shelf to the west.

ARGILLITE ACCUMULATION RATE

The preceding discussion distinguishes between argillite and interbeds. The interbeds were deposited almost instantaneously, after transport down the continental slope by gravity flow, mostly as turbidity currents. Thus, the thickness of such an interbed has no meaning in terms of time; an interbed whose thickness is measured as a few centimeters in one place may be only a few millimeters in another and a meter or two thick in a third place, this being a function of the lobate shape of an individual turbidite.

As noted earlier, the argillites were deposited in two ways. One was by settling of hemipelagic sediment, at a slow and presumably constant rate. The other was by turbidity currents, presumably occurring spasmodically — quickly, but with some time interval between one and the next lamina. The present study cannot identify the ratio of hemipelagic to turbiditic argillite, but this distinction is not important in considering the net rate of accumulation over a period of millions of years. Furthermore, absence of shales in the continental shelf sequence suggests that the muds of the Taconic sequence came from the water mass of the open ocean. This hemipelagic mud would have settled on the ocean floor and continental slope. The latter muds could then move as turbidity currents to be resedimented on the ocean floor. Such a model would indicate that the net rate of accumulation would be governed by the rate of supply of hemipelagic mud in the water mass of the open ocean, rather than being governed by a direct terrigenous source and by the particular depositional processes. In support of this model, it will be shown that the accumulation rate was so slow as to be negligible in terms of source areas. Also, it will be shown that intervals of quartz-sand interbeds in the Taconic sequence can be correlated with quartz-sand sheets of the shelf sequence, by assuming that the argillite rate was constant.

Figure 3 shows the position of each interbed in sections 1 and 3, in the cumulative argillite sequence, and also the thickness of each interbed. Note that section 1 is only 38 m of argillite plus 10 m of interbeds and section 3 is only 45 m of argillite plus 55 m of interbeds.

The 420-m sequence is estimated to have 330 m of argillite (fig. 4), the remainder being interbeds. The 330 m represents 420 m minus the thickness of interbeds measured in sections 1 and 3 and minus 10 percent of the thickness of the covered intervals. Of course, if the covered intervals have no interbeds, the argillite would be nearly 360 m thick. Absolute ages can be assigned to the bottom and top of that sequence, according to the absolute time scale of Churkin, Carter, and Johnson (1977). The boundary between the Nassau and West Castleton formations is of late Early Cambrian age (Fisher, 1977), or about 545 m.y.a. This age is assigned to the base of the 54-m covered interval below section 1 (fig. 4). The top of the Poultney Slate is about the end of the Arenig (end of the Early Ordovician) or about 467 m.y.a. This age is assigned to the youngest beds in section 5 (fig. 4). In other words, the 330 m of argillite accumulated in about 80 m.y., a rate of 4 m/m.y. At this rate, the 500 m of Nassau Formation (Zen, 1961) would represent an interval of 125 m.y., and deposition would have begun about 670 m.y.a.

The calculated rate is not sensitive to imprecision in assigning ages to the bottom and top of the sequence nor to error in determining thickness of the covered interval below section 1. If the base were 555 m.y.a. and the top 467 m.y.a., the interval would be 90 m.y. long, for a rate of 3.7 m/m.y. Conversely, if the top is as old as 490 m.y., the interval would be only 55 m.y., giving a rate of 6 m/m.y. An argillite thickness of 360 m would give a rate of 4.5 m/m.y., and a thinner value (due to minor folding, or due to overestimating the thickness of the covered interval below sec. 1) would give a rate somewhat less than 4 m/m.y. Whether the rate is 3, 4, or even 10 m/m.y. the rate is low.

For Ordovician shales in Nevada, Churkin, Carter, and Johnson (1977) calculated a sediment accumulation rate of 4 m/m.y. To compare this with modern rates, it is useful to recalculate as if the sediments had 70 percent porosity (30 percent solidity; Baldwin, 1971). Thus, 4 m/m.y. of argillite would equal 13 m/m.y. of mud.

The low rate is fairly constant, according to an independent test. As noted above, the quartz-sand interbeds of sections 1 and 3 must have come from the shelf, and so their timing must coincide with timing of quartz-sand sheets of the shelf sequence. Rowley (1979 and personal commun.) concludes that the quartz-sand sheets spread east across the shelf, and the sand was resedimented in deep water at those times when the shoreline had regressed nearly to the edge of the shelf. Yet the shelf sequence (Cady, 1945) includes only three sheets of quartz sand that could extend east to the shelf margin. The oldest is the Cheshire Quartzite of Early Cambrian age, and its off-shelf equivalent is considered to be the Mudd Pond quartzite of the Nassau Formation (Zen, 1967; Fisher, 1977). The next two are the Monkton Quartzite of late Early Cambrian age (Shaw, 1958) and the Danby Formation (Potsdam Formation) of Medial and Late Cambrian age.

Quartz-sand interbeds in section 1 are probably the off-shelf equivalent of the Monkton. The Monkton is typically red in color and subaerial in origin along the west side of the Middlebury synclinorium, but it tongues eastward into subtidal dolostone with gray quartzite interbeds (Rogers, 1976). According to figure 4, the quartz sands of section 1 have an age of 530 m.y.a., in the Medial Cambrian. This is perhaps 15 m.y. younger than what is generally accepted for the Monkton. One explanation of the discrepancy might be that the argillite accumulation rate was greater for beds in and beneath section 1. This is not likely because those argillites that are exposed are not visibly laminated, and

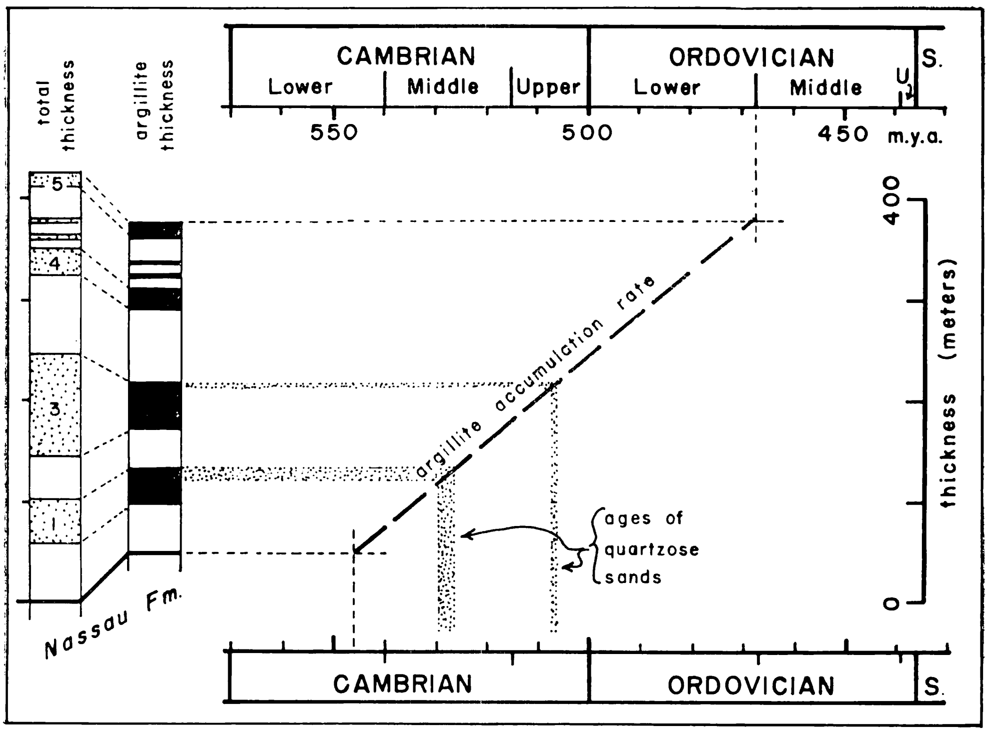

Fig. 4. Argillite accumulation rate.

the cherty layers suggest slow deposition of argillaceous sediment. Alternatively, the discrepancy would almost disappear if section 1 rests directly on the Nassau Formation — that is, if the 54-m covered interval that is mapped east of and beneath section 1 does not exist.

The quartz-sand interbeds in the upper part of section 3 would be the off-shelf equivalent of the Danby Formation. Their age would be about 510 m.y.a., and this Late Cambrian age is in keeping with what is generally accepted for the age of the Danby.

In brief, the quartz-sand interbeds in the deep-water sequence are here used to test or calibrate the graph (fig. 4) of the argillite accumulation rate. The results indicate that, as a first approximation, the argillite accumulation rate can be considered to have been constant, at about 4 m/m.y.

Parenthetically, the above discussion suggests a way of applying absolute time to a continental shelf sequence. Where the accumulation rate of the shale is established and where the shale sequence is punctuated by somewhat unique interbeds known to have come from the shelf, the absolute age of the interbeds can be projected to their source beds on the shelf. For example, the Monkton has a poor fossil record, and its age might indeed extend up into the Medial Cambrian.

The argillite accumulation rate of 4 m/m.y. is helpful in another way, because it indicates that the upper part of section 3, with its thick sandstone beds, must be the Hatch Hill Formation. The interval is, as noted in figure 4, Late Cambrian in age. Theokritoff named the Hatch Hill for thick quartz sandstones and black shale; fossils date it as Late Cambrian in age (Theokritoff, 1959, 1964). Curiously, he mapped these beds of section 3 as Poultney B instead of Hatch Hill.

Another stratigraphic implication arises. Correlation charts (for example, Zen, 1967; Keith and Friedman, 1977) typically equate the Hatch Hill with two Upper Cambrian formations — the Clarendon Springs Dolomite and the Danby Formation. Similarly, Fisher (1977) equates it with the Theresa Formation and Potsdam Sandstone. Sedimentologically, deep-water quartz sandstones of the Hatch Hill should not be correlative with a dolostone of the continental shelf.

FREQUENCY OF TURBIDITE EVENTS

Figure 3 shows the position (and thickness) of each interbed in sections 1 and 3. The bar graphs show number of interbeds per meter of argillite. With an argillite accumulation rate of 4 m/m.y., each meter of argillite represents 250,000 yrs; 10 interbeds per meter of argillite is a recurrence interval of 25,000 yrs. Thus, sections 1 and 3 record that a turbidite event occurred every 6000 to 25,000 yrs, on the average.

The 4 m/m.y. for the Taconic sequence is a rate very different from that of the Martinsburg Formation, as reported by McBride (1962). Parenthetically, McBride (1962, p. 70) had used a shale rate of 0.9 inches per 1000 yrs (23 m/m.y.), taken from a published rate calculated for flysch sedimentation in the Carpathian Mountains of Europe; his shale rate and turbidite recurrence interval therefore need recalculation using absolute ages for the Ordovician. McBride (1962) reported a maximum thickness of argillite as about 2150 m, after discounting the thickness of interbeds. The Martinsburg, of Barneveld age (late Medial Ordovician; Fisher, 1977), was deposited in only 6 or 7 m.y., according to the absolute time scale used here, and so the argillite accumulation rate was about 330 m/m.y. — two orders of magnitude greater than the rate for argillites in the Taconic sequence.

McBride (1962) found that three-fourths of the shale beds (between underlying and overlying turbidite interbeds) are less than 0.4 inches (10 mm) thick, and that 98 percent of them are less than 3 inches (76 mm) thick. At an argillite accumulation rate of 330 m/m.y., or 0.33 mm/yr., this gives a recurrence interval of 30 yrs for three-fourths of the interbeds and no more than 230 yrs for 98 percent of them.

The strong contrast in rates of the Martinsburg and the Taconic sequence is consistent with what we know about their respective tectonic settings. For the Taconic sequence, the average argillite accumulation rate is scarcely 4 m/m.y. This is 4 microns a year, or a film only a few clay-size particles thick every December 31. The rate is so slow that one need not be concerned with the sources of the mud; it is not necessary to discuss ways that the mud could have bypassed or crossed the carbonate shelf. Rather, the mud probably was transported as hemipelagic sediment that either settled directly to the ocean floor or was first sedimented on the continental slope and then resedimented by turbidity currents on the ocean floor. This slow rate of argillite accumulation and the infrequent turbidite events suggest tectonic stability, up through the Early Ordovician. Indeed, common opinion is that the Taconic sequence was deposited at the east base of the ancient North America continental slope, in the tectonically stable setting of a trailing edge (for example, Bird and Dewey, 1970).

In contrast, argillites of the Martinsburg Formation accumulated at 330 m/m.y. on a rapidly subsiding continental shelf. Similarly, the Stony Point and Iberville shales of western Vermont accumulated at about 200 m/m.y. (Baldwin, 1980). For a modern analog, drilling at DSDP Site 262 (Veevers and others, 1974) encountered a lower Pliocene shallow-water calcarenite at 2700 m below sealevel, indicating that the north edge of the Australian continent has subsided at a rate of some 600 m/m.y. as it entered the trench just north of Timor. Evidently, a sediment accumulation rate of several hundred m/m.y. is compatible with collapse of a continental margin that is approaching a trench.

It is a common opinion that in the later part of the Ordovician, the ancient North American continent was approaching the associated volcanic arc (Bird and Dewey, 1970; Chapple, 1973; Zerrahn, 1978). The arc and its accretionary prism formed an outer wall that, for the first time, created a trough controlling sedimentation along the continental margin. Probably sediments from this trough were re-suspended to move westward against the margin. Some of the muds probably moved as a nepheloid layer to be deposited as a hemipelagic sediment, in a process summarized by Shanmugam and Walker (1978). The interbeds and perhaps much of the argillite in the Martinsburg Formation, and in the Stony Point and Iberville formations of Vermont, were deposited from turbidity currents (McBride, 1962; Hawley, 1957) that evidently turned in the trough to move parallel to the ancient continental margin.

CONCLUSIONS

1. Cambrian through Early Ordovician argillites in the Taconic sequence accumulated at about 4 m/m.y.
2. Turbiditic interbeds were deposited only as frequently as every 6000 to 25,000 yrs.
3. By assuming a constant accumulation rate of the argillite, some sets of interbeds can be correlated with quartz-sand sheets of the nearby continental shelf.
4. McBride's data (1962) for the Martinsburg Formation indicate an argillite accumulation rate of about 330 m/m.y., and interbed frequency every 230 yrs or less.
5. Accumulation rates as slow as 5 m/m.y. are found in stable tectonic settings, whereas rates more than 200 m/m.y. are found in tectonically active settings.

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