Geological Evolution of Vermont

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Geol0201: Bedrock Geology of Vermont

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1. Abstract

This paper presents the geologic evolution of Vermont, U.S.A, from 565 Ma-390 Ma for *"Geol0201: Bedrock Geology of Vermont"*. Sedimentary, metamorphic and igneous rocks formed at different period and environments were visited in six field trips around Vermont between September 21st, 2017 and Nov. 2nd, 2017. Descriptions of rocks presented in six geologic belts of Vermont give evidence to their environments of formation, which explain the tectonic evolution in the "tectonic summary" section. The paper also pay attention to how geochemistry provides evidence of tectonic environment, and the role of Taconian Orogeny (470-460 Ma) and Acadian Orogeny (410-370) in reshaping the Vermont bedrock history. The appendices include complete field reports for the six field trips.

Keywords: *Vermont, bedrock geology, Taconian Orogeny, Acadian Orogeny, tectonic environment*

2. Introduction

This paper is the final research report for *"Geol0201: Bedrock Geology of Vermont"*. In the course, places around Vermont, U.S.A., were visited in six field trips, when exposed rocks were observed, measured, and interpreted to understand the changing depositional environment of different rock formations and the tectonic history through time (Fig. 1). Additional lectures, indoor labs, and field trips on rock types, tectonics, understanding the geologic map of Vermont, and using geologic tools support the field trips.

Data are mainly collected from the field. On September 21, 2017, formations exposed at the Crown Point State Historic Site, New York, were observed. On September 28th, 2017, the Monkton Quartzite exposed at the Redstone Quarry in the Champlain Valley was measured and interpreted. On October 5th, 2017, rocks of the Taconic Belt were observed at the Poultney River, Route 22A, Abandoned Quarry, and West Castleton Syncline in the Fair Haven Area. On October 19th, 2017, several formations of the Green Mountain and Rowe-Hawley belts in Central Vermont were visited. On October 26th, 2017, the Proterozoic basement, and rocks of the Pinnacle Formation, Fairfield Formation, and Cheshire Quartzite were seen along the New Haven River. On November 2nd, 2017, a local outcrop of the Plymouth Granite near Plymouth was walked through.

Other scholarly sources were also used as additional materials. *Bedrock geologic map of Vermont* (Ratcliffe et al.; 2011) is a main source of reference used for rock members not observed. Graphs from other sources, like the composite stratigraphic column of the Snake Mountain by Janeann Rogers, a lithofacies description with geological cross-section of French Farm, and generalized hypothetical sequence produced during over-all fan progradation were also used for data and interpretation.

3. Data

3.1 Proterozoic Basement

The Mount Holley Complex is the Proterozoic Basement formed 1.3GA in Middle Mesoproterozoic period (Fig. 2). The Y^{3A}mb, Y^{3A}ma, Y^{2}mig members are exposed at the Brandon Gap on Route 73, and the Y^{2}lg of the Lincoln Mountain Massif is exposed at the Crash Bridge in the Green Mountain Belt. It is mainly light-grey to tan coarse-grained gneiss that has been greatly deformed. The Brandon Gap outcrop exposes eye-shaped potassium-felspar augens and gneissosity and the Crash Bridge outcrop exposes foliation and cleavage in two directions. Its high grade of metamorphism and deformation is due to its old age and exposure to environmental and tectonic change.

3.2 Champlain Valley Belt

The Champlain Valley Belt consists of 10 formations formed in Cambrian and Ordovician period (Figs. 1, 2). Rocks of the six formations formed in Cambrian (Cheshire Quartzite, Dunham Dolostone, Monkton Quartzite, Winnoski Dolostone, Danby Formation, and Clearendon Springs Formation) are mostly dolostone or quartzite in nature, while the rocks of the four formations formed in the Ordovician (Middlebury Limestone, Orwell Limestone, Glens Falls Limestone, Hortonville Formation) are limestone or shale.

Rocks of the Champlain Valley Province were generally deposited in a shallow marine environment. The deposition environment altered between a carbonate system in which limestone and dolostone were formed, and a carbonate system in which quartzite was formed. The shale of the Hortonville Formation also suggests a deeper marine depositional environment in the Upper Ordovician period.

3.2.1 Cheshire Quartzite at the Rocky Dale

The Cheshire Quartzite exposed at the Rocky Dale was formed in the Lower Cambrian Period (Fig. 2). It is massive tan-gray quartzite interbedded with thin (mm-scale – 1cm) beds of fine-grained and well-sorted red mudstone. The rock is not very deformed and still has a well-preserved sedimentary structure. Beds of mudstone also indicates that the Cheshire Quartzite was deposited in a tidal flat environment.

3.2.2 Monkton Quartzite at the Redstone Quarry, the Snake Mountain and the French Farm

The Monkton Quartzite is discontinuous and was formed in the Middle Cambrian Period (Fig. 2). Rocks of the Monkton Quartzite exposed at the Redstone Quarry, the Snake Mountain, and the French Farm are deposited in different source areas of a siliciclastic system.

Gray medium- to coarse-grained quartzose exposed at the Snake Mountain was deposited in a fluvial (alluvial fan) environment. Trough cross-bedding, medium- to coarse-grained sand, and its lack of features associated with a tidal flat or beach suggest its high energy depositional environment and fluvial nature.

Tan coarse-grained dolomitic sandstone, fine- to medium-grained sandstone, dark red mudstone, and red well- and moderate-sorted, medium- to coarse-grained feldspathic sandstone interbedded with white sandstone exposed at the Green Mountain and the Redstone Quarry were deposited in a tidal flat environment. Mudstone and mudcracks in some beds, for example, are typical tidal flat features, and the abundance of crossbedding also suggest that these mature rocks were deposited in a high energy environment.

Massive white or grey coarse-grained and well-sorted quartzose sandstone exposed at the Redstone Quarry and the French Farm was deposited in a beach environment. Planar crossbeds can be seen, and ripple marks suggest the movement of wave.

Massive grey fine to sandy dolostone are also exposed at the Redstone Quarry and the French Farm. Since dolostone is a carbonate rock, it was formed in a carbonate barrier.

3.2.3 Formations exposed at Crown Point

The formations exposed at Crown Point, New York are related to the Middlebury Limestone, Orwell Limestone, and Glens Falls Limestone in Vermont formed in the Middle Ordovician (Fig. 2). Rocks of these formations are generally fine-grained well-sorted limestone formed in a carbonate-dominated shallow marine environment.

Dark-grey 2-10-cm beds of limestone are interbedded with thinner, tan and yellowish dolostone and crossbedding can be seen in rocks of the Crown Point Formation. The average ratio of limestone-dolostone is around 85%-15%. Only a few tiny (mm-scale) maclurites and girvanellas can be seen. With evidence indicating both high and low energy, it was deposited in a barrier reef at the transition from a subtidal zone to a shallow shelf zone.

Rocks of the Valcour Formation have thinner beds (mm-scale), and bigger fossils in cm-scale of worm borrows, brachiopods, and maclurites can also be seen. Crossbedding and tidal channel in some beds also suggest a high energy tidal-flat depositional environment.

Rocks of the Orwell Limestone are thickly-bedded to massive, and contain abundant large (up to 50cm) fossils such as Forestephylum, brachiopods(orchids), malchurites, nautoloid, Pelmatozoan stems, and beds of chert. The abundance of large shallow-water organisms and fine-grained carbonate rocks of the Orwell Limestone suggest a lagoon depositional environment.

The Glens Falls Limestone is thinly-bedded (2-10cm) and very fine-grained. Only a few small fossils of gastropod, prasopora, sowerbyella, nautoloid, and bryozoans can be seen in rocks of the Glens Falls Limestone at Crown Point. These facts suggest that rocks of the Glen Falls Limestone were deposited in a very low-energy deep shelf environment.

3.3 The Taconic Belt

The Taconic Belt consists of the Bull Formation, the Brown Pond Formation, the West Castleton Formation, the Hatch Hill Formation, the Poultney Formation, the Indian River Formation, the Mt. Merino Formation, and the Pawlet/Austen Glen Formation formed in Cambrian and Ordovician period from 540Ma to 450Ma (Figs. 1, 2). Rocks of these formations are mainly slate.

These formations were deposited in a deep-marine prograding submarine fan environment. The older lower fan produces mostly fine-grained rocks, while the younger upper fan produces thick beds of coarse-grained beds with cobble-size breccias (Walter, 1984). This prograted submarine fan sequence explains why the rocks get coarser and coarser as we go upsection.

A thrust fault exists at the Fair Haven Area. The Taconic Formation is a klippe after the older Taconic Sequence thrust on top of the younger Champlain Valley Belt. It has since been deformed.

3.3.1 Bull Formation and Browns Pond Formation

The Bull Formation was formed in the Lower Cambrian period (Fig. 1). Rock of the Bull Formation is mostly fine-grained red, purple, or green slate. The color difference is caused by different oxidation condition and existence of distinct mineral. While the purple and red slates contain hematite, and were formed with high oxidation when iron was combined with +3-state iron, the green slate contains chlorite, and was formed when iron was combined with +2-state iron.

The Browns Pond Formation is not continuous (Fig. 1). The slate of Browns Pond Formation is black in color, because it is not oxidized at all.

3.3.2 West Castleton Formation and Hatch Hill Formation

The West Castleton Formation and the Hatch Hill Formation were formed in Middle to Upper Cambrian, and can sometimes be undifferentiated form each other (Fig. 1; Ratcliffe et al., 2011). Beds of fine-grained slate is interbedded with coarse-grained quartz-rich or medium- to coarse-grained tan dolomitic sandstone for the West Castleton Formation, and pebble-or cobble-sized brecciated sandstone for the Hatch Hill Formation. Some graded beds and flame structures can be seen in some beds. The formations are very deformed. The West Castleton Syncline, for example, indicates a compressional force accompanying orogenic mountain building movement.

3.4 Green Mountain Belt

The Green Mountain Belt consists of the Camels Hump Group of the Hoosac Formation, Tyson Formation, Pinney Hollow Formation, Pinnacle Formation, Hazens Hotch Formation, and the Underhill Formation formed 565-540 Ma (Figs. 1, 2). The Proterozoic Basement is in contact with the Camels Hump Group with an unconformity.

The metamorphosed rocks of the Camels Hump Group have sedimentary or igneous protolithes. Based on greenstone chemistry, the Pinnacle Formation and Underhill Formation were formed in rift environment, while the Hazens Notch Formation and Pinney Hollow Formation were formed in a spreading boundary (Pearce and Cann, 1973).

3.4.1 Pinnacle Formation

The Pinnacle Formation consists primarily schistose wacke and meta-conglomerate with quartz veins and schistosity formed in the Cambrian and Neoproterozoic period (Fig. 2). The contact between the Pinnacle Formation and the Proterozoic basement is an unconformity that represents 700Ma. The abundance of sedimentary structures like cobbles and boulders suggests that the protolith is coarse-grained, poorly-sorted sedimentary rock formed in a fluvial high-energy depositional environment. The Pinnacle Formation also contains a volcanic member of dark-green amphibolitic, calcareous, and feldspathic greenstone whose protolith is basalt.

3.4.2 Pinney Hollow Formation

Rocks of the Pinney Hollow Formation at Route 100 is chlorite-quartz-actinolite-plagioclase-pyrite greenstone formed in Cambrian and Neoproterozoic period (Fig. 1). The outcrop is strongly deformed and folded that some distinct bands of quartz can be seen (Fig. 2). The protolith of a greenstone is basalt, which can also suggest that the Pinney Hollow Formation was formed in an ocean floor environment.

3.5 Rowe-Hawley Belt

The Rowe-Hawley Belt consists of the Stowe Formation, the Ottaquechee Formation, the Moretown Formation, the Cram Hill Formation, and the North River Igneous Suite formed 500/520-465 Ma (Figs. 1, 2). Rocks of the formations are either greenstone, phyllite and schist or igneous rock. Based on greenstone chemistry, the Stowe Formation was formed in an ocean spreading boundary (Pearce and Cann, 1973). Ignoues rocks of the North River Igneous Suite are not intrusive but similarly folded like other formations. The Negative Nb anomaly of the North River Igneous Suite also indicates a subduction zone (Karabinos et al., 1998).

3.5.1 Stowe Formation and Ottaquechee Formation

Rocks of Stowe Formation are dark-green, non-foliated and massive chlorite-rich greenstone formed in Cambrian and Neoproterozoic period (Fig. 2). The roadcut on Rt100 has undergone bending and folding with two faces of deformation. The protolith of the Stowe Formation is basalt, which suggests that the Pinney Hollow Formation was formed in an ocean floor environment.

Rocks of the Ottauquechee Formation visited at the Verde Antique Quarry are green, non-foliated greenschists formed in Cambrian. Lineation and slickensides can be seen. The abundance of serpentine indicates a peridotite protolith, which may be formed in mantle and also suggest an ocean floor environment.

3.5.2 Moretown Formation

Rocks of the Moretown Formation was formed in Lower Ordovician and Cambrian period (Fig. 1). The outcrop visited at Putnamville contains fine-grained and foliated chlorite-plagioclase-quartz-muscovite phyllite and granofels (Fig. 2). Dikes of younger green non-foliated medium-grained Ordovician igneous diabase and brown to orange Mesozoic mafic igneous rock are intruding into the phyllite and crosscutting each other.

The protolith of rocks of the Moretown Formation is fine-grained sedimentary rock. Sediments deposited on continental margins or accretionary prism of a subduction zone may account to the sedimentary protolithes of the Moretown Formation.

3.6 Connecticut Valley Belt

The Connecticut Valley Belt is contacted with the Rowe-Hawley Belt with the Richardson Memorial Contact (RMC), an unconformity that separates pre-Silurian rocks from younger rocks of the Connecticut Valley Belt (Fig. 1). The belt consists of sedimentary rocks of the Shaw Mountain Formation, the Northfield Formation, the Waits River Formation and the Gile Mountain Formation, and igneous rocks of the Standing Pond Volcanics, an intrusive class in the Waits River Formation, and the Devonian Granites (Dg) of the New Hampshire Plutonic Suite formed 390-370 Ma (Fig. 2).

3.6.1 Plymouth Granite

The Plymouth Granite, a Devonian Granite, is plutonic, equigranular, and coarse- to moderately-grained igneous felsic boulders with baked contact and local dikes that intrude into the surrounding country rock. The outcrop visited is S-type granite, although I-type granite can also be seen at other locations. The S-type granite was formed through continental collision, while I-type granite at other locations also suggests the existence of a subduction zone.

3.7 Branson Hill Belt

The Branson Hill Belt consists of the Albee Formation, the Ammonoosuc Volcanics, the Oliverian Plutonic Suite, the Patridge Formation, the Clough Formation, the Fitch Formation, and the Littletone Formation formed in 460-390 Ma (Fig. 1). Though sedimentary rocks are present, the Branson Hill Belt is dominated by igneous rocks, especially basalt, andesite and rhyolite, which suggests a Calc-alkaline trend (Hollocher et al., 2002). The Calc-alkaline trend and its negative Nb anomaly indicates that rocks of the belt was formed in volcanic arcs in a subduction zone.

3.8 Taconian Orogeny and Acadian Orogeny

Two orogenies happened in the geologic evolution of Vermont. The first one is the Taconian Orogeny in 470-460 Ma. The Taconian Orogeny happened to the west of the Richardson Memorial Contact, when the development of the Champlain Valley Thrust brought the older Taconic Belt rocks on top of the Champlain Valley Belt. The second one is the Acadian Orogeny happened in 410-370 Ma. The orogeny happened throughout Vermont, but is most dominant to the East of the Richardson Memorial Contact. The Acadian Orogeny formed the Devonian Granite in the Connecticut Valley Belt with a subduction zone and continental collision.

4. Tectonic Summary

Figures 3-10 shows the tectonic evolution from 565 Ma to 390 Ma. It can be divided into two sections, 565 Ma-465 Ma, and 450Ma-390Ma. The Taconian Orogeny and the Acadian Orogeny marked the end of these two periods.

The tectonic evolution in 565 Ma–465Ma showed a Wilson Cycle. At 565 Ma (Fig. 3), a continental rift was initiated when the continental crust was extended and thinned up as the mantle upwelled. As the continental crust moved away from rising magma, it started to fell down due to the lack of support, and created a rift valley, where rocks of the Camel's Hump Group were formed. As the rift valley deepened and filled with water at 530 Ma (Fig. 4), the magma created oceanic crust and its expansion created Middle-ocean ridges at divergence boundary, when rocks of the Taconic Belt were deposited in a deep marine environment while those of the Champlain Valley Belt in a shallow marine environment at a passive margin. As the rocks of the Champlain Valley Belt and Taconic Belt continued their deposition at 490 Ma, a subduction zone emerged, creating accretionary wedge and a volcanic arc in the Rowe Hawley Belt. Finally, at 465 Ma (Fig. 6), the continental crust collided together after the oceanic crust was completely subducted in the Taconian Orogeny.

After the Taconian Orogeny, subduction zone was formed between the Ganderia and the Branson Hill Belt, where basalt, andesite, and rhyolite were formed at the volcanic arc at 450Ma (Fig. 7). At 420 Ma (Fig. 8), slab roll-back of the Ganderia under the Branson Hill Belt and the Ganderia caused back-arc extension, creating the Connecticut Valley Belt. As the Back-Arc Extension created the Connecticut Valley Belt Trough, the Acadian Orogeny started as the Ganderia collided into the Branson Hill Belt at 400 Ma (Fig. 9).

The Acadian Orogeny continued at 390 Ma, when S-type and I-type Devonian Granite were formed at the Connecticut Valley Belt because of continental collision and subduction zone respectively.

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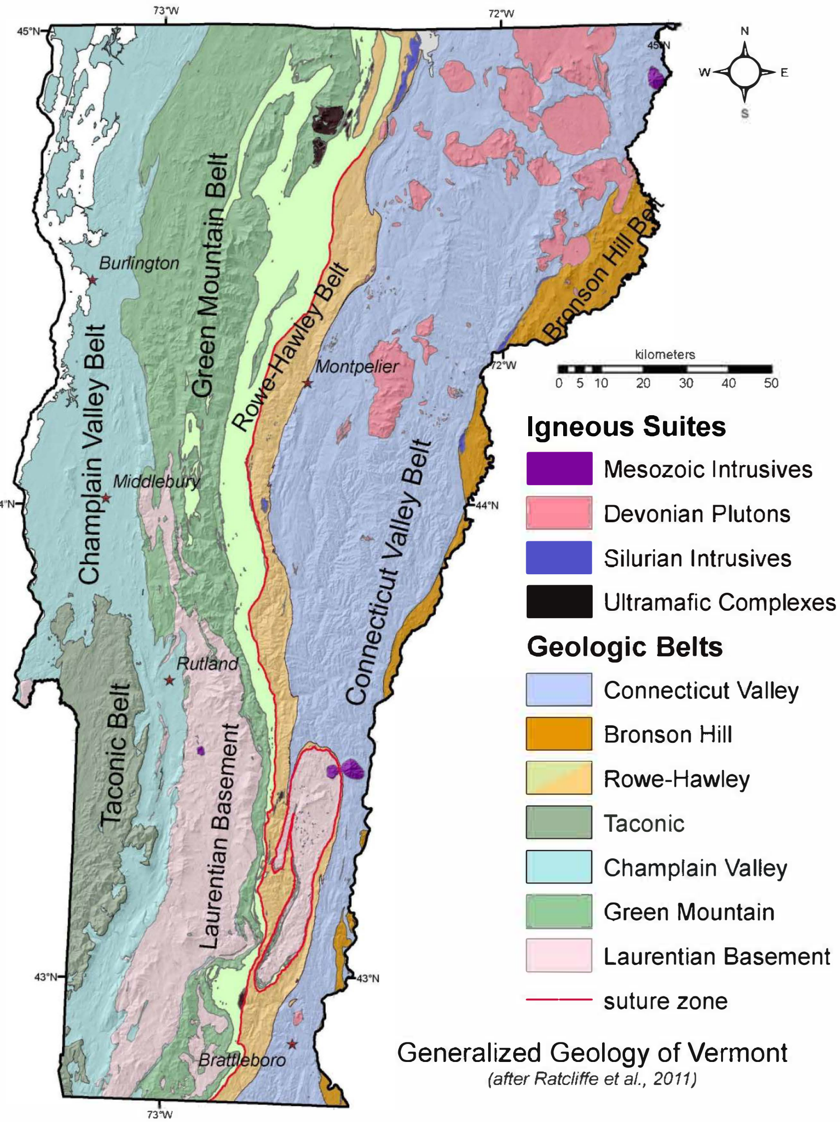
Fig. 1 Geologic Map of Vermont



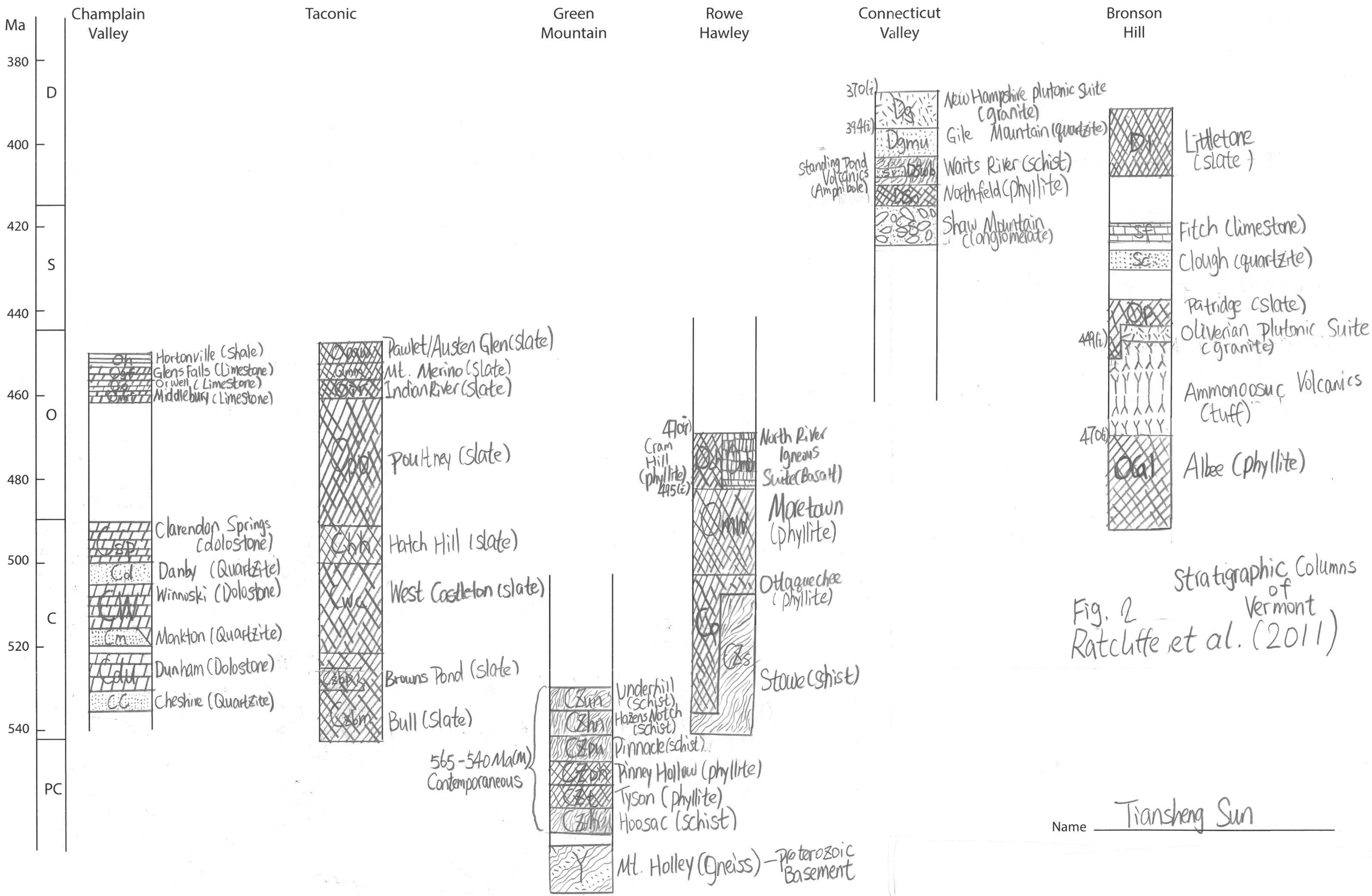


Fig. 2 Stratigraphic Columns of Vermont
Ratcliffe et al. (2011)

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Fig. 3
Tectonic at 565Ma

565 Ma

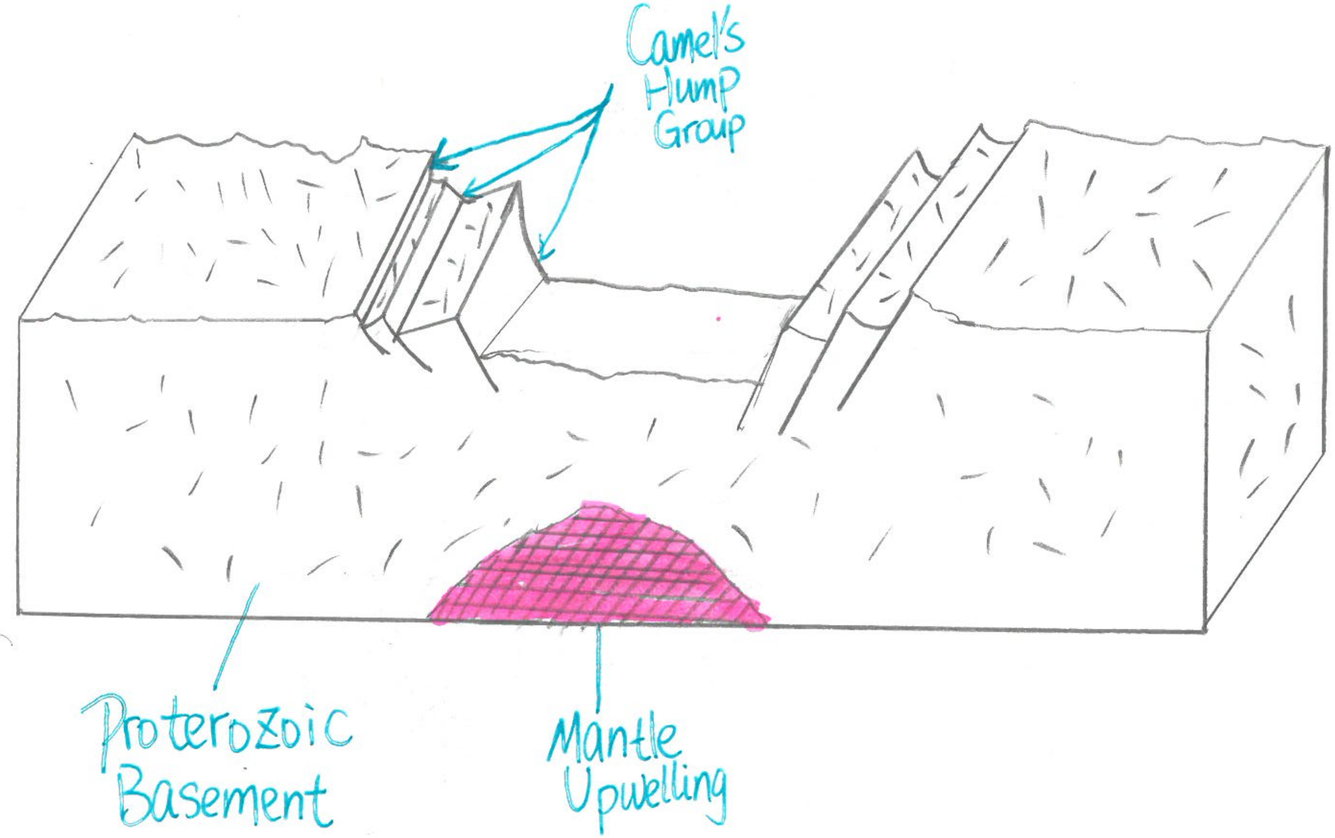


Fig. 4
Tectonic at 530 Ma

530 Ma

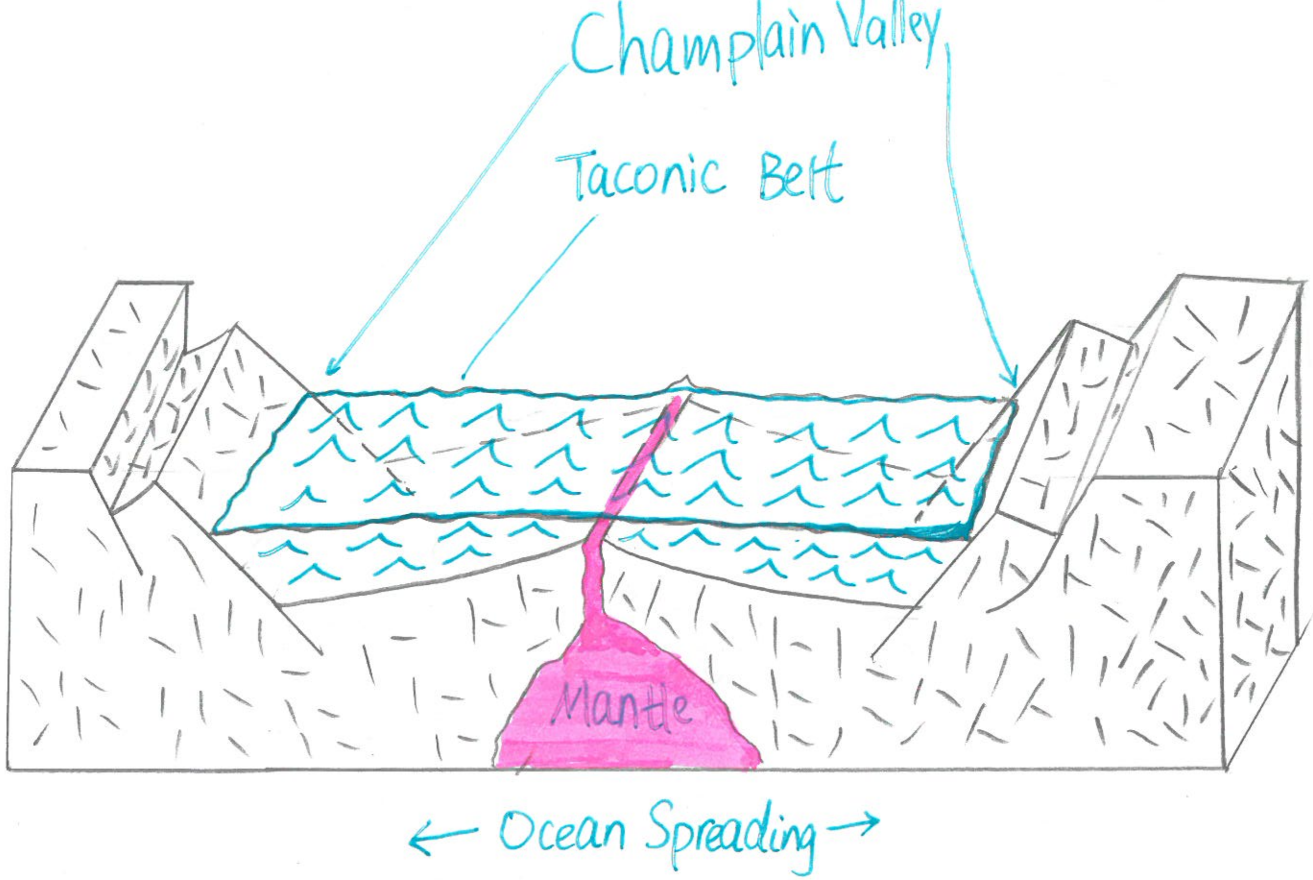


Fig. 5
Tectonic at 490Ma

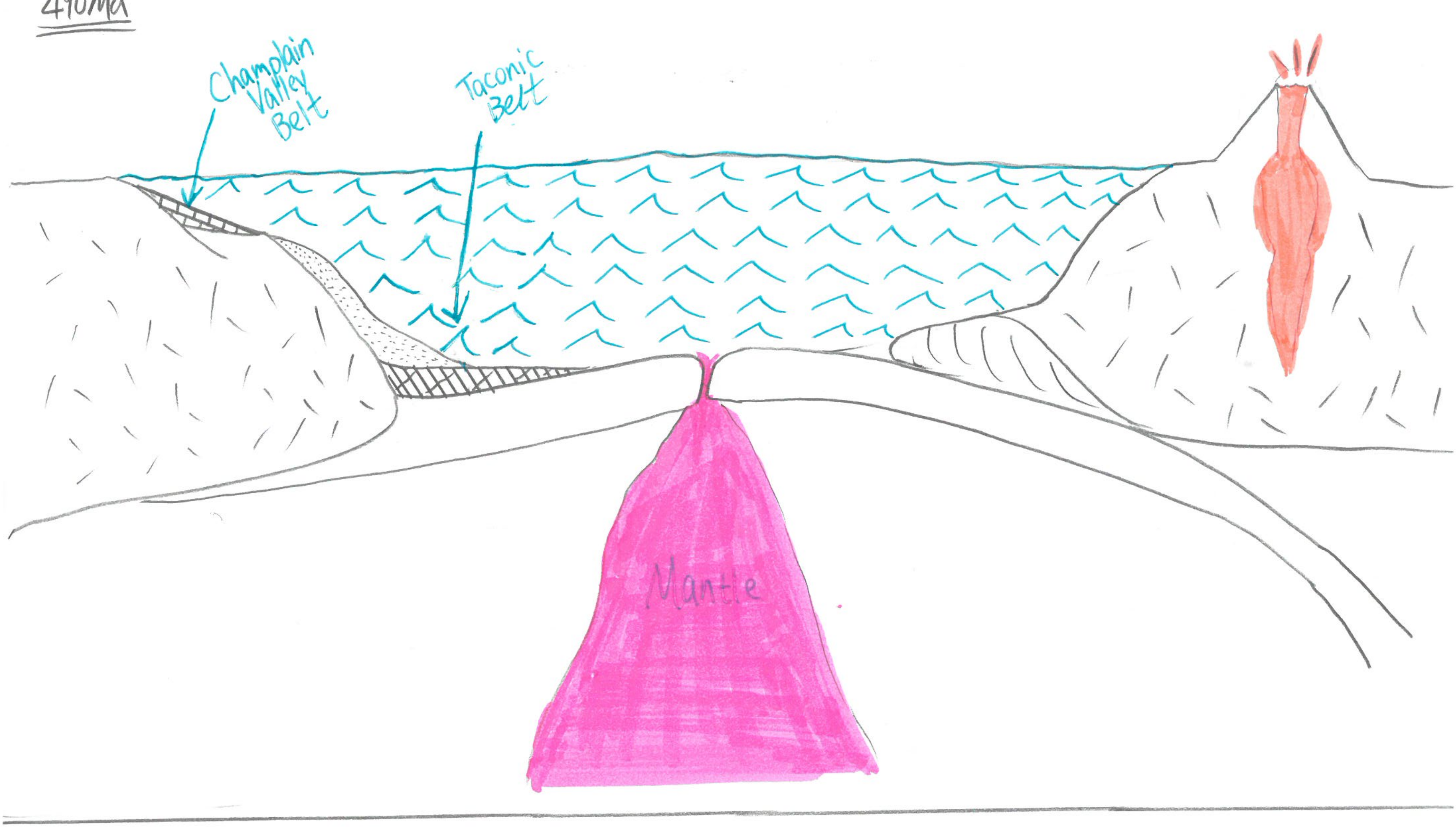


Fig. 6

Tectonic at 465Ma

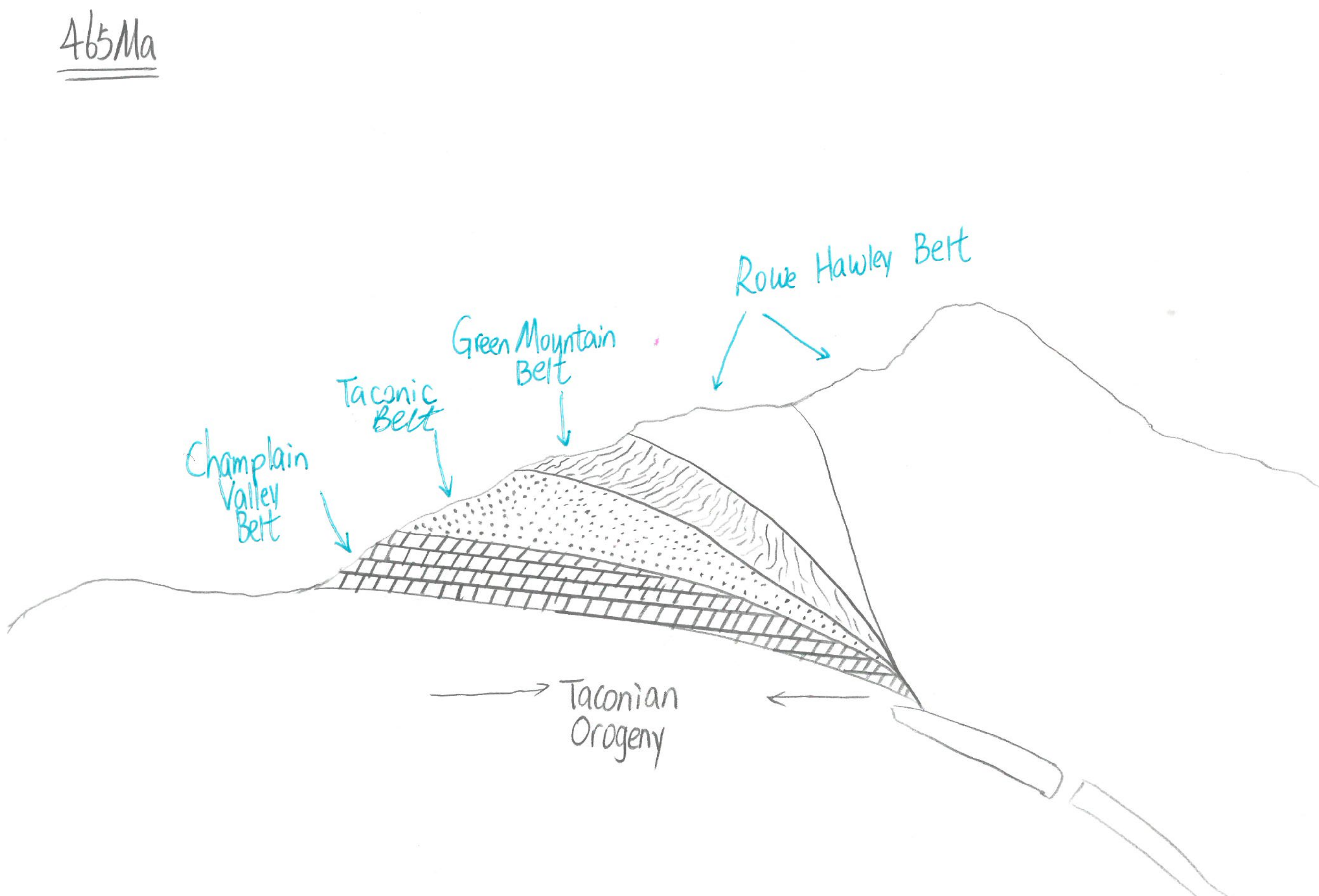


Fig. 7

Tectonic at 450Ma

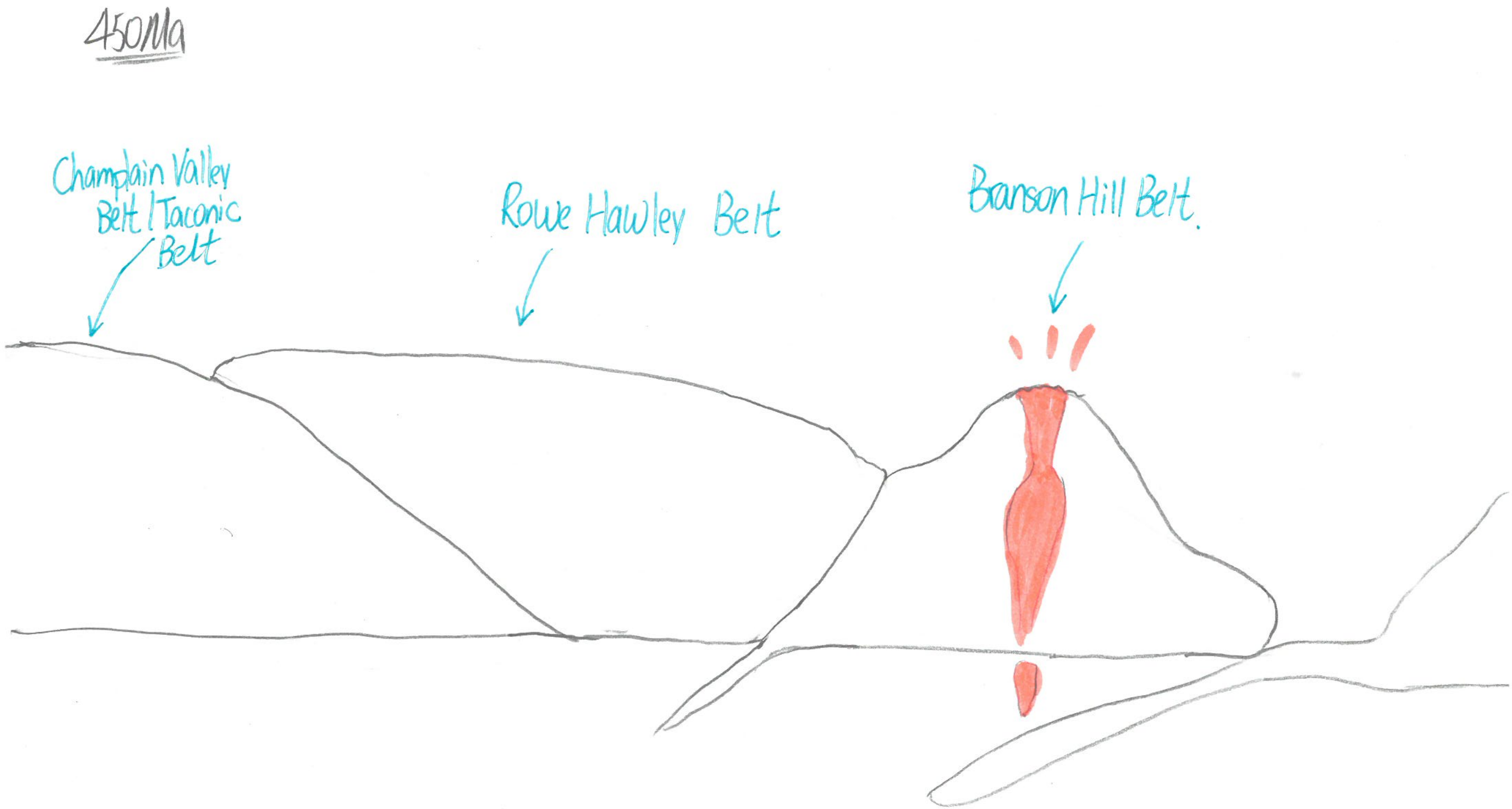


Fig 8

Tectonic at 420Ma

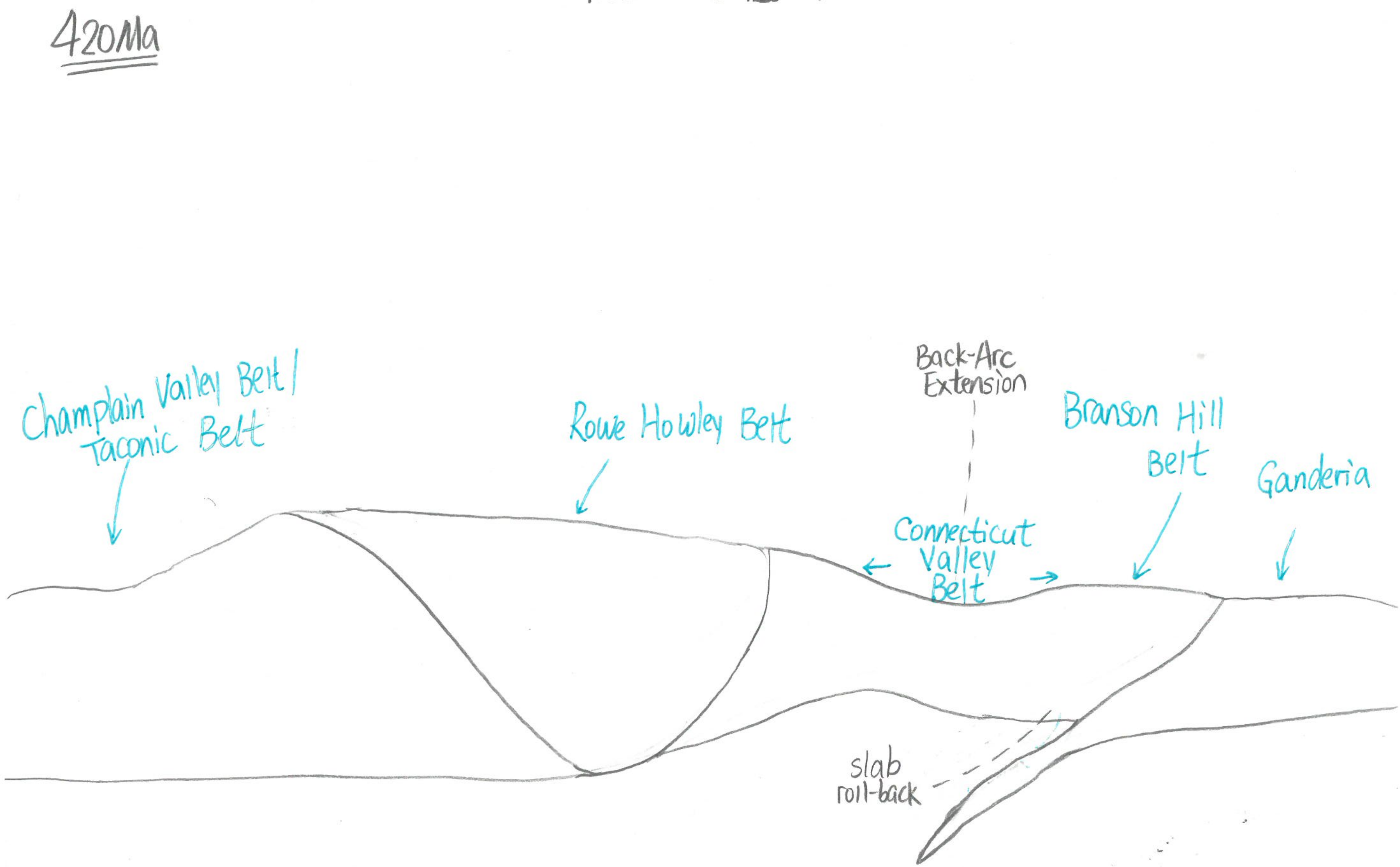


Fig. 9
Tectonic at 400 Ma

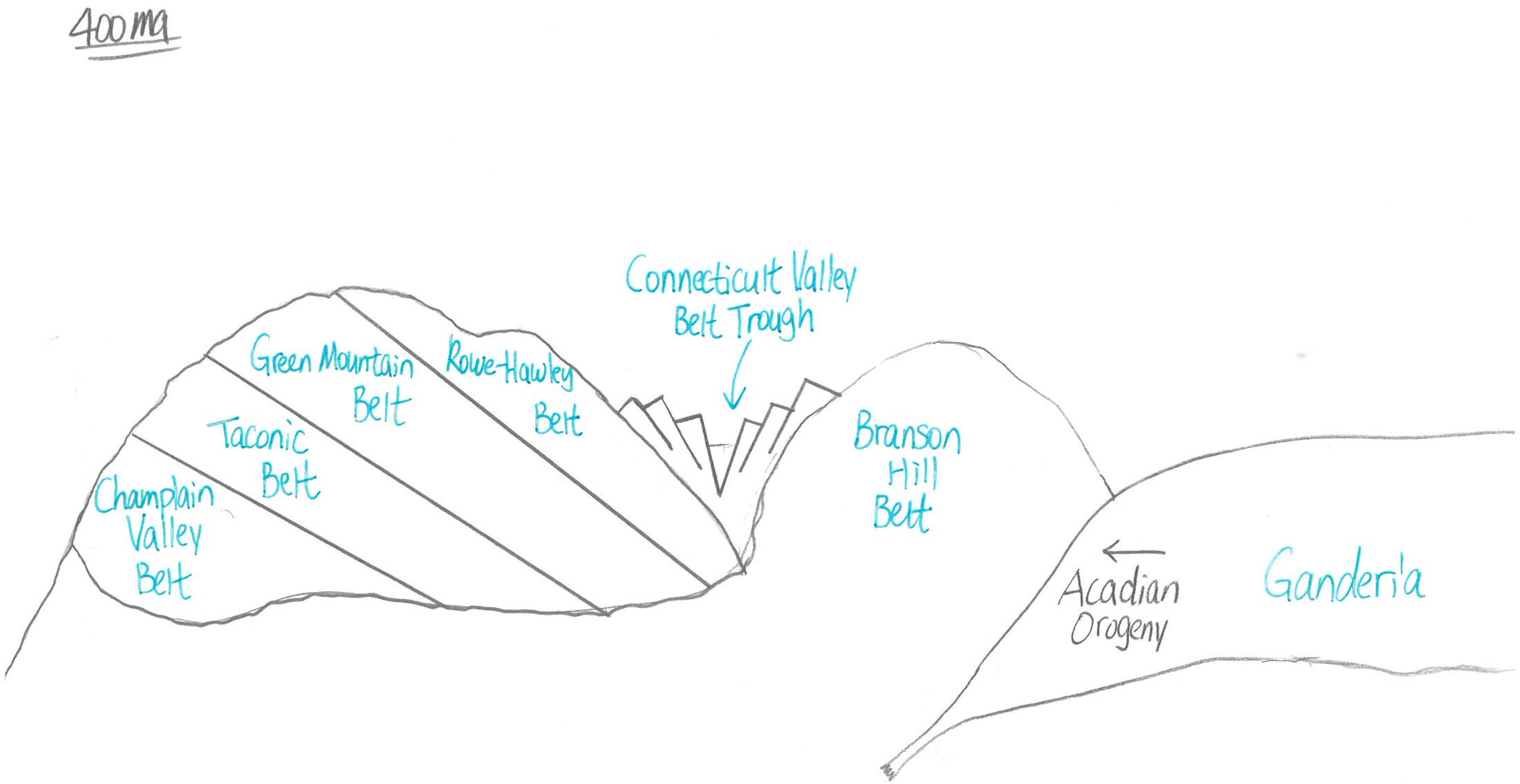
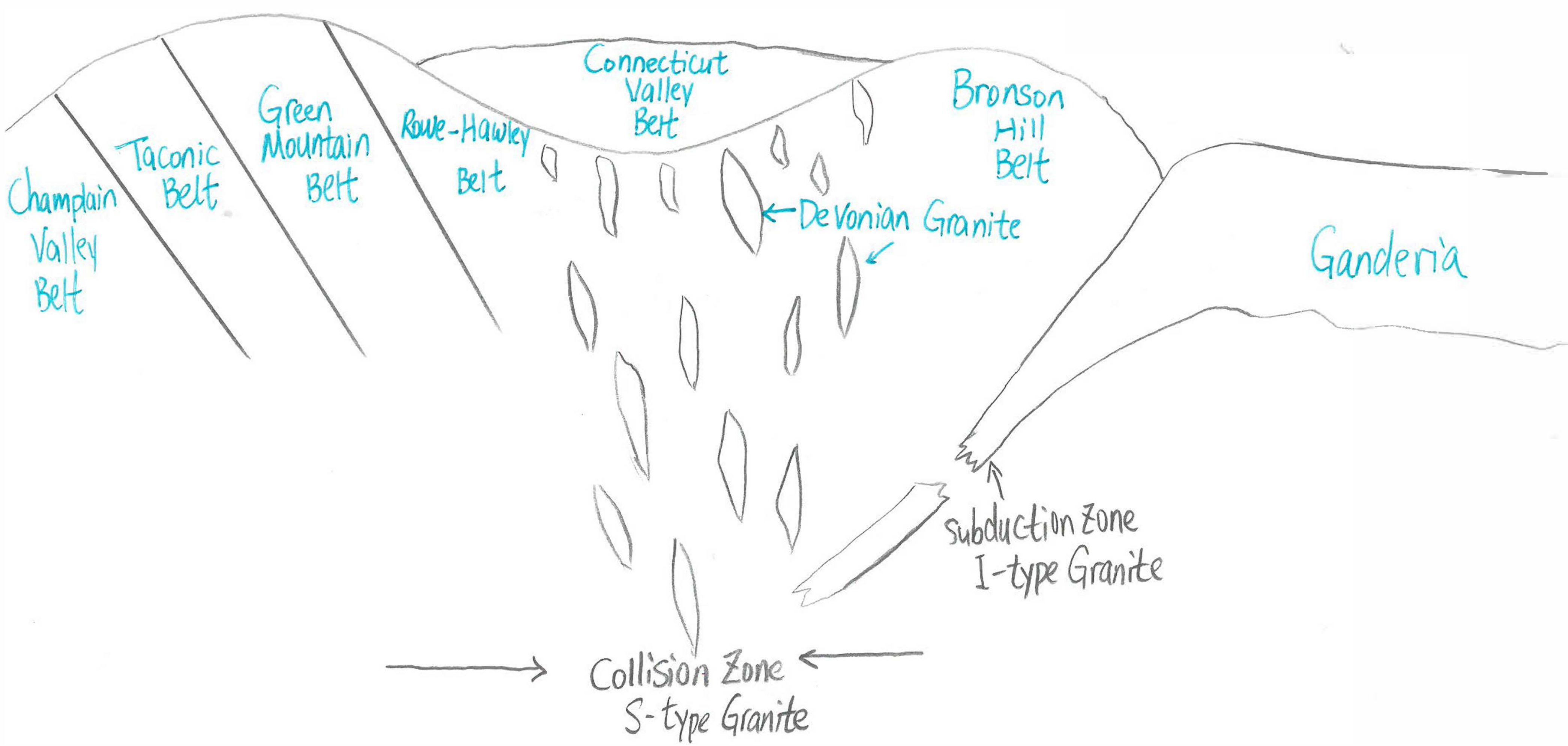


Fig. 10
Tectonic at 390Ma

390Ma



Appendix 1: Limestone in Crown Point

Introduction

Crown Point State Historical Site lies on a peninsula in the west end of the Lake Champlain, close to the Adirondacks Mountains in New York, USA. Crown Point is generally known as a state historical site, but it is also a great place to learn about depositional history of biogenic sedimentary rocks. Exposed carbonate sedimentary rocks from four different formation periods: Crown Point Formation (465-460 million years ago), Valcour Formation, Orwell Limestone and Glen Falls limestone (450-455 million years ago) were examined at Crown Point from point A (Fig. 1), which is at the southernmost tip of the site, to point J, the northwesternmost point on September 21, 2017 as a field trip for *"Geol0201: Bedrock history of Vermont"*. Data of fossils identification (Fig. 2), rock descriptions (Figs. 2, 3), and a stratigraphic column of site A (Fig. 4) were collected to interpret and understand the depositional history of limestones deposited from ~460ma to ~450ma.

Description of Rocks

The general rock type at Crown Point is biogenic grey- or blue-colored limestone formed in a shallow marine environment, though some magnesium-carbonate-rich dolostone can be seen, particularly at site A (Figs. 3, 4). The strike of all rocks in all sites is generally N20^{0}E, and the dip is 10^{0}NW. This information can be used to calculate the missing cross section from A to D on Fig. 2 (Fig. 5).

Rocks at site A and B are part of the Crown Point formation, the oldest formation type exposed at Crown Point (Fig. 1). The rock is generally fine-grained and well-sorted, with some sand-sized quartz grains. Though the thickness of the bed varies, it is generally between 2-10 cm thick. Dark-grey limestone beds make up most of the outcrop, which is interbedded with thinner, yellowish dolostone throughout (Fig. 4). Fig. 4 shows that the limestone-dolostone ratio changes through time and upsection, with an average ratio around 85%-15%. Rocks at site B are similar to those at site A, though crossbedding can be seen (Fig. 3). Although fossils are not abundant at these two sites, maclurites and girvanellas were observed in some layers.

Rocks at site D and E are part of Valcour Formation (Figs. 1, 2, 3). Unlike the Crown Point formation, bigger fossils are visible. At site D, worm borrows, brachiopods, and large maclurites were observed (Fig. 2). The rock exposed at site D has very thin -mm scale beds, with some fine-grained dark grey beds interbedded with even finer-grained light grey beds. Interestingly, some of the beds have a U-shape feature interpreted as a tidal channel (Figs. 2,3). Moreover, at site E, the thin (-mm scale beds), light-grey rock is much coarse-grained with some quartz sands sticking out, and no interbedded dark-grey beds can be seen. In the layer expose some crossbedding, and some of the beds, especially those in the northern part, have u-shape patterns, probably also formed by tidal channels.

Site F, G and H exposes rocks of the Orwell Limestone, which contains abundant fossils (Figs. 1, 2, 3). Types of fossils include Forestephylum, brachiopods (orchids), malchurites, nautoloid, Pelmatozoan stems, and of particular interest was a 50cm coral at site G (Fig. 2). The rock at site F is mostly fine-grained light-grey limestone, with beds 2-10 cm thick. The texture and structure of rocks at site G is like that of site F, except for a bed (20cm thick) of black chert. The rocks exposed at site H are also fine-grained light-grey limestone, but are not in situ, probably fallen from a quarry. The rocks are massive and contain many similar fossils found in site G (Fig. 2).

At sites I and J exposed rocks belong to the Glens Falls Limestone (Figs. 2, 3). Both sites are at the northwesternmost part of Crown Point (Fig. 1). Some fossils like gastropod, prasopora, sowerbyella, nautoloid and bryozoans can be seen, and Trilobites are uniquely present in this formation (Fig. 2). However, the quantity and size of these fossils are less than those in the Orwell Formation (Fig. 2). At site I exposes thin (10cm) fine-grained light-grey limestone that has fossils such as Prasopora, Sowerbyella, and Nautoloid. At site J, the rock is at its finest with relatively smooth surface and thin layers 2 -10cm thick.

Interpretation

Throughout these sites, the age, texture, structures, and the number of fossils of rocks change. Fig. 6 shows various depositional environments of a carbonate dominated system: tidal flat, which is very shallow and has a high energy, lagoon, barrier shelf, and deep shelf, where the depositional energy is low. While the general type of depositional environment of each of the four formations can be determined, the variations of depositional environment within a formation should also be considered.

The Crown Point formation was most likely deposited in a barrier reef environment (Fig. 6). A barrier reef environment is at the edge of the transition from a subtidal zone to the shallow shelf zone, and has sections of relatively higher energy and sections of lower energy. Indeed, Rocks at site A and B show indications of both a high energy depositional environment and a low energy depositional environment. While most of the beds are fine-grained, for example, indicating a low-energy environment, some other beds can be coarse, suggesting a high-energy environment. Crossbedding at site B indicates high energy, while the lack of fossils indicates low energy. These facts support that the general depositional of Crown Point formation is at a barrier reef. The existence of crossbedding at site B is likely due to occasional wave activity along the reef.

The rocks from Valcour formation suggests a tidal flat depositional environment (Fig. 6). A tidal flat is a shallow water environment with high energy. The U-shape patterns cross-cutting beds at D, for example, are indicative of tidal channels, which exists in tidal flat environments. These periods of tidal channels violated the horizontal pattern of deposition of the Principle of original horizontality as they passed through the materials, creating these U-shape channels whose structures were preserved by subsequent superposition of in a low-energy period. Rock at site E is also very coarse-grained, providing another indication of high energy environment. The existence of two interbedded layers at site D suggests variable water depth, indicating variations of depositional environment among a certain formation. The finer grains of site D also means that rocks at site D were deposited at a locally lower energy area of tidal flat than site E.

The Orwell limestone was likely deposited in a lagoon environment (Fig. 6). A lagoon depositional environment is relatively low energy. Because the lagoon environment is shallow, it is the optimal environment for marine creatures. The abundance of fossils at site F-H, particularly the existence of many large shallow-water organisms, like corals, suggests that the depositional environment of this period is lagoon. The rocks at site F-H are also finer than that at site E, suggesting a lower energy depositional environment than the more active tidal flat.

Finally, the rocks from the most recent formation, the Glen Falls Limestone, were deposited in a deep shelf environment (Fig. 6) . The rocks at site I and J are much finer-grained and well-sorted than those from other site, indicating a lower energy, or deeper marine environment. Though some large fossils can still be seen, the number decreases and some shallow water organisms, like corals, are not present. Therefore, the depositional environment of Glen Falls Limestone is the deepest among all formations.

Conclusion

Through analysis of texture, structure, and the fossils types of different rocks from different sites and formation, it is clear the depositional environment changes over time at Crown Point from 465-450 ma. First, the rocks at Crown Point were deposited in a barrier reef environment with moderate depth, before the sea level dropped suddenly, when deposition of the Valcour formation in a tidal flat environment with much higher environment occurred. The finer-grained beds at site D suggest a transitional period between the barrier reef environment and tidal flat environment, while site E indicates a time when the sea level was at its shallowest. After deposition of the Valcour Formation, the sea level rose again, depositing Orwell Limestone in a lagoon environment. Finally, the Glen Falls formation was deposited in a deep shelf, suggesting a stark change in sea level or tectonics movement.

Appendix 2: Monkton Quartzite

Introduction

T he Monkton Quartzite is a rock formation exposed in the Champlain Valley, Vermont, USA. Snake Mountain (marked SM on Fig. 1), Redstone Quarry (marked RQ on Fig. 1), and French Farm (marked FM on Fig. 1) are three locations this formation is exposed. At Redstone Quarry, a 1-11m section of outcrop was observed on September 28th, 2017 for "Geol0201: Bedrock history of Vermont" (Figs. 2, 3). The Snake Mountain and the French Farm were not visited, but data, including the Composite Stratigraphic Column by Janeann Rogers and a lithofacies description with geological cross-section of French Farm, were used for interpretation (Figs. 4, 5). The lithofacies distribution in and across these sites can provide valuable insight to the depositional environment of a siliciclastic dominated system, the orientation of shoreline and sea level change during deposition of the Monkton Quartzite.

Data and Rock Description

The section measured at Redstone Quarry is labelled 1-11m, though observations were also made between 11-12m (Fig. 2). The lithofacies distribution of 5-7m was also collected in a more detailed columnar section (Fig. 3). The outcrop has a strike of N2^{0}W and a dip of 10^{0}E. The data collected at Red Quarry were also compared to a 30m section at French Farm (Fig. 4), where all the beds here have a dip of 40^{0}E, and a 300m section of the Snake Mountain (Fig. 5).

The rocks exposed at the Redstone Quarry, the Snake Mountain, and the French Farm are made of several lithofacies. While some of the lithofacies are unique to one site, many share similar characteristics. Lithofacies X, Y, Z, M, and N at Red Stone Quarry, Lithofacies A, B1, B2, and C at the Snake Mountain, and lithofacies G and H at the French Farm were observed.

Lithofacies X is dominantly tan coarse-grained dolomitic sandstone interbedded with medium-grained sandstone and dark red fine-grained (clay-size) mudstone. Lithofacies X was observed throughout the Redstone Quarry, although most beds are concentrated between 3-8m (Fig. 2). While many lithofacies X beds are thin in mm-scale, four big sections of lithofacies X can be seen at 3.2-4m, 4.7-5.1m, 5.4-5.7m, and 7-8m (Fig. 2). Crossbedding can be seen at 3.2-4m and 7-8m (Fig. 2).

Lithofacies Y is a red moderate- to well-sorted, medium- to coarse-grained feldspathic sandstone interbedded with white sandstone that is present upsection regularly at 1-10 m (Fig. 2). It is thinly-bedded from mm-scale to 2 cm, with some thicker (5-15cm) beds at 2-3m (Fig. 2). Lithofacies Y is interbedded with lithofacies X at some locations, like the alternative beds of X and Y between 500-595cm (Fig. 3). Crossbedding is not as common in Y as X. Very coarse-grained quartzose lens can be seen at 2-3m, 9.25-9.5m, and 10-10.8m (Fig. 2).

Lithofacies Z is red well-sorted feldspathic sandstone interbedded with dark red mudstone. This lithofacies is finer-grained than X and Y. It is abundant at Redstone Quarry, though it is more common at 4-11m (Fig. 2). While some sections of Z expose a higher concentration of mudstone, like between 595-620cm, other sections expose very few, such as between 8-8.4m and 9-9.25m (Figs. 2, 3). Crossbedding can be seen at 400-450cm. Raindrop expressions spread through 595-620cm, and a 3cm strip of very coarse-grained quartz lenses can be seen discontinuously at 610-613cm (Fig. 3).

Unlike lithofacies X, Y, Z, lithofacies M is massive, and is mostly made up of white or grey coarse-grained and well-sorted quartzose sandstone with planar crossbreds. Only one 50cm section of it is exposed at 9.5-10m at Redstone Quarry (Fig. 2). Some ripples marks can be seen on top of the section.

Like lithofacies M, lithofacies N is not abundant at Redstone Quarry. It is also massive, and is mostly grey fine to sandy dolostone. Lithofacies N is not drawn in Fig. 2, but a 50cm bed was observed above 11m. It lies at the highest point of the outcrop we observed.

At the Snake Mountain, lithofacies A is a gray medium- to coarse-grained quartzose with trough cross-bedding. Two sections of it can be seen at between 0-75m and 100-140m of the Snake Mountain (Fig. 4).

Lithofacies B1 and lithofacies B2 can be seen interbedded with each other at the Snake Mountain between 75-100m and 140-260m (Fig. 4). Both lithofacies are red feldspathic sandstones interbedded with red mudstones in B1 or thin beds of white quartzose sandstone in B2. Rocks of B2 also exposes some local tiny channels, ripples and mudcracks (Fig. 4).

The upper 40m of the Snake Mountain is covered by lithofacies C (Fig. 4). It is a dolomitic sandstone with grey sandstone interbeds. Fig. 4 also suggests that it contains some algal laminations, mudcracks, and burrows.

At the French Farm, lithofacies H, the most abundant lithofacies studied at French Farm, is a medium- to thick-bedded gray quartzose sandstone. It is exposed between 2-3 and 6-16m (Fig. 5). Some differences can be seen between the two sections. The 2-3m section has planar crossbedding, but the 6-16m section has a graded bedding with coarser grains near base and finer grains towards top (Fig. 5).

Finally, lithofacies G is a massive medium gray to tan dolostone observed between 0-2m and 19-20m section (Fig. 5), though, like lithofacies H, there are some differences between the two sections. While it is oolitic at 0-2m, it has small channels of lithofacies H at 19-20m (Fig. 5).

Interpretation

The features of each lithofacies can provide evidence of the depositional environment. Each lithofacies was formed under a certain siliciclastic dominated source area: fluvial (alluvial fan), tidal flat, beach, or carbonate barriers, though many lithofacies share common features, suggesting a similar depositional environment (Fig. 6).

Lithofacies A is the only lithofacies studied that was deposited in a fluvial (alluvial fan) environment (Fig. 6). With trough cross-bedding and medium- to coarse-grained sand, it was deposited in a very high energy environment. Since Lithofacies A does not have features associated with a tidal flat or beach, such as mudstone, mudcracks, or ripples, it was deposited in a fluvial (alluvial fan) environment.

Lithofacies X was likely deposited in a tidal flat area (Fig. 6). Thin beds of mudstone are a characteristic of a tidal flat environment. It also has coarse-grained dolomitic sandstone and abundant crossbedding, indicating a very high energy environment. Specifically, lithofacies X was formed in subtidal to intertidal zone where high current activity exists.

Like X, lithofacies Z and lithofacies B1, were also deposited in a tidal flat area (Fig. 6). Compared to X, Z and B1 do not have much crossbedding, and contain more mud and finer red feldspathic sandstone, indicating a lower energy environment. The existence of raindrop impressions on Z also indicates that the lithofacies was sometimes above sea level (Fig. 3). Therefore, even though both lithofacies were also deposited in a tidal flat environment, a lower energy condition and raindrop impressions indicate deposition in the upper intertidal zone.

Lithofacies Y, along with lithofacies B2, was formed in a tidal flat environment that was closer to a beach (Fig. 6). Although both lithofacies have features related to a beach environment, such as a lack of mudstone, rocks that are more mature, and ripples on lithofacies B2, mudcracks on B2 and Y at 540cm, for example, suggest a tidal flat feature that was periodically exposed to air (Fig. 3). Many Y beds are also interbedded with lithofacies Z, like 10-10.8m (Fig. 2), which is dolomitic, and 640-700cm (Fig. 3), where some thin mudstone layers, a feature of lithofacies Z, can be seen. Thus, although both lithofacies share some features of a beach environment, they were most likely deposited at the edge of a tidal flat that is close to a beach.

Lithofacies C is the last lithofacies formed in a tidal flat environment (Fig. 6). It contains coarsely grained dolomitic sandstone, and mudcracks, although no mudstones can be seen in C. Therefore, lithofacies C is probably also formed in a tidal-flat area close to beach with relative high energy.

Lithofacies M and H were deposited in a beach environment (Fig. 6). Both beds lack mudstones or mudcracks that can be seen in X, Y, Z, X1, X2 or C, but on top of M exposes many ripples marks that indicate the movement of waves (Fig. 2). These facts suggest that

M and H were formed in a beach environment. The graded bedding of lithofacies H at 6-16m at French Farm may also indicate an area of beach where sand was submerged by still water for a long time, when coarser elements sank to the bottom.

Finally, lithofacies N and G were formed in a carbonate barrier (Fig. 6). Both lithofacies are basically dolostone, which, unlike other rocks which are clastic, are carbonate rocks, indicating a carbonate-rich environment. The gray massive channels of H in G at 19-20m of French Farm might also indicate a spot with higher energy which brought lithofacies H formed in a beach to this carbonate shallow marine environment.

The lithofacies diagram (Fig. 7) shows relationships of depositional environment between time and West-East direction at three locations. The diagram suggests a deepening depositional environment from the Snake Mountain in the west to the French Farm in the east. This fact prove that the ocean was to the east of the mainland. Fig. 7 also shows that the sea level dropped before it starkly rose as we move upsection at all three locations.

Conclusion

The Monkton Quartzite was exposed at the Snake Mountain, the Redstone Quarry, and the French Farm in the Champlain Valley formed dominantly in siliciclastic dominated system. Four lithofacies (A, B1, B2, and C) can be seen at the Snake Mountain, five (X, Y, Z, M, and N) at Redstone Quarry, and two (G and H) at French Farm. While tidal flat is the dominate depositional environment of six lithofacies (X, Y, Z, B1, B2, C), lithofacies A was formed in a fluvial or alluvial fan environment, M and H in a beach location, and N and H, with their carbonate-rich dolostone, in a carbonate barrier. The distribution of lithofacies over space and time also indicate that the land was to the west of the ocean and the sea level dropped before it rose over time at all three locations.

Appendix 3: Taconic Sequence in the Fair Haven Area

Introduction

Rocks of several formations of the Taconic Sequence formed in the Cambrian and Ordovician period are exposed near Fair Haven, Vermont, USA (Figs. 1, 2). Rocks from Bull Formation, Browns Pond Formation, West Castleton Formation, and Hatch Hill Formation were observed at the Poultney River (Site 1 on Fig. 1), Route 22A (Site 2 on Fig. 1), Abandoned Quarry (Site 3 on Fig. 1), and West Castleton Syncline (Site 4 on Fig. 1) on October 5th, 2017 for "Geol0200: Bedrock History of Vermont". At Poultney River, exposures of the West Castleton Formation and Hatch Hill Formation were studied. The stratigraphic column of a 60m section of outcrop and a detailed column of a 10m section were collected (Figs. 3, 4). Additionally, observations were made at Route 22A, a 90m roadcut that exposes rocks from West Castleton Formation and Bull Formation (Fig. 5), an Abandoned Quarry, which exposes rocks of the Bull Formation and Browns Pond Formation in a 50m high vertical section (Fig. 6), and at the West Castleton Syncline (Fig. 7). The observations of rocks from these four sites can provide valuable insight to the depositional environment of the Taconic sequence, and the geological history of the Fair Haven Area.

Rock Description

The oldest formation studied is the Bull Formation, which is exposed at Route 22 and the Abandoned Quarry (Figs. 5, 6). It was formed during the Lower Cambrian period (Fig. 2; Ratcliffe et al., 2011). The rock of the Bull Formation is mostly fine-grained slate in multiple colors. At Route 22A, green slate exists on the northwestern end at 0-12m (Fig. 5). At the Abandoned Quarry, the rock exposed is red slate (0-5m), purple slate (5-20m), and green slate (20-42m; Fig. 6). The units are mostly thick-bedded (30-50cm), and do not often exhibit slaty cleavage.

Rocks of the Browns Pond Formation are also exposed at the Abandoned Quarry (Figs. 6). Fig. 2 shows that the Bull Formation is not continuous. It is mainly composed of fine-grained black slate. At the Abandoned Quarry, black slate lies at 42-50m. Some thin wavy limestone beds at around 42m at the bottom separate it from rocks of the Bull Formation. The beds of the black slate are much thinner (2-15cm) than those of the Bull Formation, and slaty cleavage can be seen throughout the section.

Rocks of the West Castleton Formation, formed in lower to middle Cambrian, are exposed at the Poultney River, Route 22A, and the West Castleton Syncline. The Poultney River outcrop strikes N10^{0}E and dips 88^{0}E. Most of the beds are fine-grained, thinly-bedded (mm-scale to 3cm) grey slate interbedded with coarse-grained quartz-rich or medium- to coarse-grained tan dolomitic sandstone interbeds (Fig. 3). Grey slate is observed throughout the section, although it is concentrated at the base. Many slate layers are covered by soil and grass at 30-50m, and slaty cleavages can also be observed. The overall slate to quartz-rich or dolomitic sandstone interbeds is around 60% to 40%. While more quartz-rich sandstone interbeds are exposed at 40-50m, dolomitic sandstone is the main type of interbed in the upper sections (Figs. 3, 4). Some graded beds can also be seen in the interbeds, in addition to sandstone breccias and a discontinuous section of rock with flame structures pointing west at around 65m. At Route 22A, the West Castleton Formation naturally is in contact with green slate (Fig. 5). Fig. 5 also shows that dolomitic sandstone and limestone beds and lenses are observed in major sections of black or grey slate at around 68-70m and 21-28m, respectively. At the West Castleton Syncline, the entire outcrop exposes rocks of the West Castleton Formation. Two sections of fine-grained black slate are interbedded with two sections of medium- to coarse-grained dolostone (Fig. 7). The entire outcrop is deformed and the dip changes from near vertical to near horizontal.

The Poultney River outcrop also exposes rocks of the Hatch Hill Formation (Fig. 3). It is a small formation formed in Upper Cambrian, and can sometimes be undifferentiated from the West Castleton Formation (Fig. 2; Ratcliffe et al., 2011). Unlike the abundance of fine-grained slate in the West Castleton, the slate to interbed ratio is 10% to 90%. Coarse-grained pure dolostone and sandstone are interbedded with pebble- or cobble-sized brecciated sandstone. Many breccias are sandy sandstone, quartzite, or dolomitic sandstone.

The Poultney Formation (Opo), Indian River Formation (Oir), Mt. Merino Formation (Omm) and Pawlet/Austen Glen Formation (Opaw, Oag) are also exposed upsection in the Taconic Sequence, although rocks of these formations were not observed. However, the rock descriptions of these formations were also collected from Ratcliffe et al. (2011).

Rock of the Poultney Formation (Opo) is white and grey thinly-bedded slate and phyllite formed in Middle and Lower Ordovician (Fig. 1; Ratcliffe et al., 2011). It has distinct 1cm- to several-centimeter-thick beds of siliceous argillite and metasiltstone and local thin beds of limestone interbedded with slate near the base (Ratcliffe et al., 2011).

The Indian River Formation (Oir) was formed in the Upper Ordovician (Fig. 1; Ratcliffe et al., 2011). It is mostly bluish-green well-bedded slate with a few centimeter-thick white, red and black layers of siliceous argillite and mudstone (Ratcliffe et al., 2011).

Grey, red, and green thinly bedded siliceous argillite and mudstone formed in Upper Ordivician is the main rock type of the Mt. Merino Formation (Omm; Fig. 2; Ratcliffe et al., 2011). Unlike rocks of the Indian River Formation, rocks of the Mt. Merino Formation have many cherty siliceous layers (Ratcliffe et al., 2011).

Finally, rocks of the Pawlet/Austen Glen Formation (Opaw, Oag) formed in Upper Ordovician are the youngest rock of the Taconic Sequence studied. The rock is mostly dark-grey carbonaceous slate interbedded with light grey massive- to thinly-bedded quartz-plagioclase wacke (Ratcliffe et al., 2011). Unconformity exists between rocks of the Pawlet/Austen Glen Formation and those of the Hatch Hill Formation and the West Castleton Formation (Ratcliffe et al., 2011).

Interpretation

Going upsection through the Taconic Sequence from the rocks of Bull Formation to those of the Hatch Hill Formation, the rocks change from very fine slate, to slate interbedded with medium- to coarse-grained interbeds, and to very coarse-grained beds with pebble- or cobble-sized breccias. Especially at the Poultney River, the outcrop exposes more fine-grained slates at Eastern side, and coarse-grained dolomitic or quartz-rich sandstone towards the Western end (Fig. 3). Since the flamed structures point west, the western beds (90m end) of rock are younger than the eastern ones (30m end). Therefore, the rocks become coarser upsection and with age.

This pattern looks similar to Walker's hypothetical sequence of prograted submarine fan (1984; Fig. 8). As shown in Fig. 8, the lower fan produces mostly fine-grained rocks. The upper fan, on the other hand, produces thick beds of coarse-grained graded beds with cobble-size breccias. The Taconic Sequence, thus, is deposited in a deep-water prograding submarine fan environment.

Turbidity currents are the dominate process of a submarine fan system. The turbidity currents can bring materials from the land and shallow marine environment into the deep ocean through sediment-gravity flow. As flows move from confined channel to unconfined seafloor, they spread out, decreasing the energy of the flow. Therefore, materials with the largest grain size can settle immediately, while finer grains travel a longer distance, reducing the grain sizes in the older rocks. The settling of particles is also not disturbed, concentrating the fine-grained materials on top of the flow while settling coarse-grained sediments on the lower part. This process formed the graded layers and helped transporting clays further into the lower fan.

Fine-grained slates can possibly not be directly deposited from turbidity flow, but from fine hemipelagic elements in very low current velocities, such as suspension settling, or pelagic sediments slowly suspended and deposited in ocean water. On the other hand, the interbeds are mostly formed from turbidites, because low energy movements cannot carry these coarse grains. The abundance of different kinds of breccias in rocks of the Hatch Hill Formation suggests that materials formed under different depositional environment were brought to the submarine system. The rocks of West Castleton Formation and Hatch Hill Formation were formed when the Monkton Quartzite was formed in the nearby Champlain Valley (slightly younger). It is possible that quartzose or dolomitic sandstone of Monkton Quartzite formed in tidal flat and beach environment were then brought to the submarine system by turbidity currents.

Different oxidation condition and the existence of distinct mineral cause the color difference in slates at the Abandoned Quarry. Iron has two oxidation states, +2 and +3. The purple and red slates of Bull Formation contains hematite (Fe_2O_3), and were formed with high oxidation when iron was combined with +3-state of iron. The green slate of Bull Formation contains chlorite, and is not as oxidized as the purple and red slates when it was formed when iron was combined with +2-state of iron. The black slate of Browns Pond Formation is not oxidized at all. It may contain organic materials, making it reduced. The limestone bed between the green and black slate might indicate this change of oxidation environment.

The rocks of the West Castleton Formation have undergone deformation (Figs. 3, 7). The outcrop at the Poultney River originally had a horizontal dip, but now has near vertical dip. The West Castleton Syncline also indicates a compressional force accompanying orogenic mountain building movement. Indeed, a thrust fault exists at the border of the Taconic Sequence and the Champlain Valley in the Fair Haven area, and explains how older rocks may lay on top of younger ones (Ratcliffe et al., 2011). The West Castleton Formation in the region is possibly a klippe after the Taconic Sequence thrust on top of the Champlain.

Conclusion

Four formations of the Taconic Sequence were observed at four sites visited in the Fair Haven area, Vermont, USA. At Stop 1, a deformed section of fine-grained grey to black slate beds with quartz-rich and dolomitic sandstone interbeds of West Castleton and Hatch Hill Formation show a prograding submarine fan sequence that the older rocks are generally finer than the younger rocks. At Stop 2 exposes mostly grey to black slate of

West Castleton Formation and fine-grained green slate of Bull Formation. The 50m section of abandoned Quarry is mostly slate, although the color changes from red, purple, and green ones of the Bull Formation, to the black ones of the Browns Pond Formation, which is caused by different oxidation states. Finally, at the West Castleton Syncline, a syncline of rocks of West Castleton Formation indicates deformation caused by a thrust fault. These phenomena suggest that the rocks were deposited in a deep-water submarine fan system, where the coarse-grained sediments deposited close to channel and upper fan forming interbeds and breccias in younger beds, and fine grains such as cays deposited further away in the lower fan forming slates in older beds.

References:

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Appendix 4: Metamorphic Rocks in Central Vermont

Introduction

The Green Mountain and Rowe-Hawley belts in Central Vermont, USA, have several formations that contain metamorphic rocks of different metamorphic grade. An outcrop of Moretown Formation in Putnamville, north of Montpelier (Site 1 on Fig. 1), and greenstone road-cut of Stowe formation on VT100 south of Middlesex, (Site 2 on Fig. 1) were visited on October 12th, 2017, and an outcrop of Tyson Formation near Pleiad Lake in Middlebury College Snow Bowl (Site 3 on Fig. 1), rocks of Ottauquechee Formation in Verde Antique Quarry, Rochester (Site 4 on Figs. 1, 2), greenstone of Pinney Hollow Formation on route 100 north of Rochester (Site 5 on Figs. 1, 2), and an outcrop Brandon Gap, part of the Mount Holly Complex on route 73 (Site 6 on Figs. 1, 2), were visited on October 19th, 2017, for "Geol0200: Bedrock History of Vermont". The description of six formations and the sketch of visited outcrops of Moretown Formation and Pinney Hollow Formation were collected to understand the metamorphic nature of rocks, degree of deformation, tectonic environments of metamorphism, and the type and environments of formation of protoliths of these metamorphic rocks.

Data

The oldest formation studied is the Mount Holly Complex (Y^{3A}mb, Y^{3A}ma, Y^{2}mig) formed in Middle Mesoproterozoic period, exposed at the Brandon Gap on route 73 (Site 6 on Figs. 1, 2; Ratcliffe et al., 2011). Y^{3A}mb and Y^{3A}ma members are pinkish-gray to dark-gray coarse-grained microcline-magnetite augen gneiss and Y^{2}mig is the massive medium-grained light-gray and pinkish-gray migmatite gneiss (Ratcliffe et al., 2011). A roadcut on route 73 exposes rock that is fine-grained on one-side and much coarser on the other side with bands of light grey and dark grey foliations. The outcrop contains many minerals like quartz, garnet, muscovite, potassium-feldspsar, and biotite. At the coarser side exposes many eye-shaped potassium feldspar augens.

Rocks of the Pinnacle Formation were formed in Cambrian and Neoproterozoic period (Ratcliffe et al., 2011). The rocks of the Pinnacle Formation, when undivided, is foliated muscovite-chlorite-biotite-feldspar-blue quartz schist, phyllite, and metawacke interlayered with pebble-to-cobble-sized gneiss, feldspar, and quartz lenses (Ratcliffe et al., 2011). The formation contains a massive moderately-sorted light-grey metawacke and phyllite member, poorly-sorted cobble and boulder conglomerate member, and dark-green amphibolitic, calcareous, and feldspathic greenstone members (Ratcliffe et al., 2011).

The greenstone at Route 100, north of Rochester, is part of the Pinney Hollow Formation formed in Cambrian and Neoproterozoic period (Ratcliffe et al., 2011; Site 5 on Figs. 1, 2). Chlorite is the most abundant mineral of this light-green outcrop. Quartz is also abundant in some distinct bands that are strongly deformed and folded (Fig. 3). Actinolite, plagioclase, and some pyrite can also be seen on the outcrop. The outcrop is only foliated in some location. According to Ratcliffe et al. (2011), Pinney Hollow Formation also has the light-greenish grey or dark-grey phyllite members, the light-grayish green laminated feldspathic quartz schist member, and silvery-grey coarse-grained metawacke member.

The Fayston Formation was formed in the Lower Cambrian and Neoproterozoic period (Ratcliffe et al., 2011). It contains the greyish-green, medium-grained albite-chlorite-muscovite-quartz schist, dark-green foliated greenstone, white and tan to light-grey medium-grained quartzite, and fine-grained chlorite-quartz-sericite schist (Ratcliffe et al., 2011).

Rocks of the Hazens Notch Formation, when undivided, are a dark-brown to black schist, gneiss and quartzite formed in Cambrian and Neoproterozoic period (Ratcliffe et al., 2011). It contains the massive dark-green greenstone and amphibolite member, and chlorite-muscovite-quartz schist member (Ratcliffe et al., 2011).

The Underhill Formation was formed in Cambrian and Neoproterozoic period (Ratcliffe et al., 2011). The rock of this formation is generally silver-green quartz-muscovite-chlorite-albite-magnetite schist and phyllite with local lenses of white quartzite (Ratcliffe et al., 2011). It contains the greenstone and amphibolite member, which includes light- to dark-green carbonate-rich greenstone and massive, weakly foliated amphibolite, and the light-grey to tan quartz-laminated schist member (Ratcliffe et al., 2011).

The Tyson Formation (CZtgr) at the Pleiad Lake was formed in Lower Cambrian and Neoproterozoic period (Ratcliffe et al., 2011; Site 3 on Fig. 2). The CZtgr member is a grayish-green biotite-chlorite-quartz-pebble phyllite or schist (Ratcliffe et al., 2011). The outcrop at the Pleiad Lake is a silver to grey foliated medium-grained muscovite-biotite-chlorite-quartz-pyrite schist. Coarse-grained quartz is mostly concentrated is some distinct bands, although it is abundant throughout the outcrop. Although both greenish platy chlorite and dark biotite can be seen, these minerals do not dominate. Preferred lineation, which is broadly N15^{0}E, can be seen at some location.

The road-cut on RT 100 exposes rocks of the Stowe Formation, which is a grayish-green to bright-green chlorite-rich rock formed in Cambrian and possibly Neoproterozoic period (Ratcliffe et al., 2011; Site 2 on Fig. 1). Rocks of most members of the Stowe Formation are green in color, although some are mostly fine-grained and foliated schist and phyllite, and others are dark-green hornblende-rich amphibolite and greenstone, like the greenstone road-cut visited (Ratcliffe et al., 2011). The outcrop on VT100 is a dark-green, non-foliated, and massive greenstone. While chlorite is the most abundant, quartz crystals, actinolite, small bit of magnetite and cubic pyrite minerals can also be found. The outcrop has undergone bending and folding with two faces of deformation (Fig. 4).

The Ottauquechee Formation was formed in Cambrian period and has dark-grey carbonaceous phyllite member, silver-green coarse-muscovite or feldspathic schist members, gray quartzite member, and a dark-green greenstone member (Ratcliffe et al., 2011; Site 4 on Figs. 1,2)). The Verde Antique Quarry is part of a small unit (Site 4 on Fig. 2). Near the Verde Antique Quarry exposes some green non-foliated greenschists that are exposed. The rocks are abundant in serpentine, which give the rocks a green color and a smooth, soft and waxy texture. They also have some lighter regions with a concentration of talc and some zones of black magnetite crystals. On one piece of rock lineation and slickensides can be seen.

The rocks of the Moretown Formation, including the granofels and phyllite member at the outcrop in Putnamville, was formed in Lower Ordovician to possibly Cambrian period (Ratcliffe et al., 2011; Site 1 on Fig. 1). At Putnamville, the outcrop contains fine-grained and foliated chlorite-plagioclase-quartz-muscovite phyllite and granofels (Fig. 5). The foliation of phyllite and granofels on average strikes S28^{o}W with a near vertical dip. Dikes of young green non-foliated medium-grained Ordovician igneous diabase and brown to orange Mesozoic mafic igneous rock are intruding into the phyllite, and crosscutting each other (Fig. 5). Some quartz-rich lenses can be seen within phyllite. Vesicles can also be seen within the mafic igneous rocks. The Moretown Formation also contains rocks such as the tan to green, fine-grained massive quartzite of the Harlow Bridge quartzite member, light-gray to pale-green granofels and feldspathic biotite quartzite of "Pinstriped" granofels member, greenish-gray feldspathic garnet schist of garnet schist member, and the light-pale-green chlorotic greenstone and fine-grained of amphibolite of the amphibolite and greenstone member (Ratcliffe et al., 2011).

Interpretation

Except for the rocks of Mount Holly Complex (Y3Amb, Y3Ama, Y2mig) that was formed in the earlier Middle Mesoproterozoic period, the rocks of the Lincoln Green Mountain Massif were formed in Cambrian and Neoproterozoic period. Similarly, this fact accounts to the difference between the rocks of the Mount Holley Complex, and those of the other ones were possibly metamorphosed in a similar environment, resulting in a similar metamorphic grade and degree of deformation.

The Mount Holly Complex has undergone very high-grade metamorphism with a strong degree of deformation. It is the only formation studied that has a main rock type of gneiss, a very high-grade metamorphic rock. The outcrop also contains garnet, which is also an indicator of an intermediate- to high-grade metamorphism. The alternating light-grey and dark-grey bands of foliations at the Brandon Gap on Route 73 suggest gneissosity. The augen structures in the gneiss were formed when individual grains got sheared and rotated. The protolith of the Brandon Gap on route 73 is possibly an igneous rock, because of mineralogy. This high grade of metamorphism and deformation is not seen in other formations,and may be due to their much older age and exposure to environmental and tectonic change.

The rocks of the Stowe Formation and the Pinney Hollow Formation are low- to intermediate-grade rocks that have undergone strong degree of deformation. The two formations are similar in that the greenstone road-cuts of both formations are not foliated, rich in chlorite and actinolite, and contain quartz lenses that are deformed. Both formations contain members of schists and phyllites, indicating a low-grade metamorphism, and amphibolite facies and greenstone, an intermediate-grade metamorphism (Ratcliffe et al., 2011). The abundance of fine-grained chlorite also suggests a low- to intermediate- metamorphic grade. According to Fig. 6, the protolith for both rocks is basalt. Since basalt is a key component of the oceanic crust, it may be derived from exhumed oceanic crust. Both roadcuts have quartz folds (Figs. 3, 4), a ductile deformation, which proves that both roadcuts were metamorphosed under a deep depth in crust.

The rocks of Moretown Formation have a low grade of metamorphism and some degree of deformation. The outcrop in Putnamville is very fine-grained and rich in chlorite and muscovite, both low- to intermediate- grade minerals. Even though phyllite and granofels are foliated, no apparent folds or faults can be seen. Fig. 6 shows the protolith for the outcrop is a fine-grained sedimentary rock. The existence of intruding igneous dikes also indicates tectonic movement that created igneous environment at a later time, possibly the Ordovician and Mesosoic period.

The rocks of the Tyson Formation (CZtgr) also have an intermediate grade, and some level of deformation. Unlike the Moretown Formation, minerals of the Tyson Formation can be seen with the eye, indicating a higher grade of metamorphism. Muscovite, the most abundant mineral at the outcrop in Pleiad Lake, and biotite are also both intermediate-grade minerals. The abundance of foliation suggests schistosity, which is formed when the rock was sheared and pressured by external force and temperature. Fig. 6 shows the protolith for the outcrop is mud to sandy fine-grained silica-rich sedimentary rock.

The rocks of the Ottauquechee Formation also have an intermediate grade with some deformation. Although serpentine, the most common mineral of the rocks at Verde Antique Quarry, cannot provide information about the grade of the rock because it is stable over a wide range of temperature, contact with greenschist facies nearby suggests an intermediate metamorphic grade. Because of its abundance of serpentine and talc, the protolith for the rocks is peridotite, an ultramafic igneous rock (Fig. 6). This suggests that the protolith may be formed in the mantle. The existence of slickensides on the rock surface suggests some degree of deformation.

The tectonic environment of the formations is possibly on the ocean floor or a subduction zone. The rocks were deformed in a high temperature and pressure environment. Many of the rocks of these formations have an igneous protolith and even the Moretown Formation whose protolith is mostly sedimentary suggests a later igneous intrusion due to tectonic movement. The protolith of Stowe Formation and the Pinney Hollow Formation, for example, are basalt, which may suggest an ocean floor environment. In a subduction zone, sediments are also deposited on continental margins, which may account to the sedimentary protoliths of the Moretown Formation and the Tyson Formation (CZtgr). Furthermore, a subduction zone has regions with different temperature and pressure profiles, which may suggest the formation of different rocks in different formations.

Conclusion

Metamorphic rocks of several formations can be seen in the Green Mountain and Rowe-Hawley belts in Central Vermont, USA. The rocks of Mount Holly Complex (Y^{3A}mb, Y^{3A}ma, Y^{2}mig) are high-grade gneiss with gneissosity and augen structure formed in a much older period. The rocks of other formations, on the other hand, are mostly phyllite, schist, and greenstone that have low to intermediate metamorphic grade. Despite their difference, all rocks are deformed, like the quartz-rich folds of the greenstone roadcuts on VT100 of the Stowe and Pinney Hollow Formation, schistosity of the outcrop in Pleiad Lake of Tyson Formation, and slickenside on the rocks at Verde Antique Quarry of Qttauquechee Formation. The protoliths of some rocks are igneous rocks, either basalt or peridotite, while those of others are sedimentary rocks. Finally, the tectonic environment of metamorphism is possibly on the ocean floor or a subduction zone where rocks undergone high temperature and pressure.

References:

Ratcliffe, N. M., Stanley, R. S., Gale, M. H., Thompson, P. J., Walsh, G. J., Rankin, and D. W., McHone, J. G. (2011). Bedrock geologic map of Vermont (No. 3184). *US Geological Survey*.

Appendix 5: Rocks near Lincoln gap along New Haven River

Introduction

Four stops along the New Haven River near Lincoln, Vermont, USA, were visited on Oct. 26th, 2017 for "Geol0201: Bedrock History of Vermont". The "Crash Bridge" south of Lincoln (Site 1 on Fig. 1) exposes the Proterozoic basement known as Lincoln Massif (Y^2lg), and the Pinnacle Formation at Lincoln (Site 2 on Fig. 1), Fairfield Formation at West Lincoln (Site 3 on Fig. 1), and the Cheshire Quartzite Formation at Rocky Dale (Site 3 on Fig. 1) are the cover sequences formed in Neoproterozoic – Lower Cambrian period. The observation of the rocks from these four sites can provide insights into the depositional environments of the cover sequences, the geological history in the Lincoln region, and the deformational history of the entire sequence.

Data

The Lincoln Mountain Massif (Y^2lg), a part of the Mount Holly Complex, is the Precambrian basement of the sequence of strata exposed at the Crash Bridge (Site 1 at Fig. 1) and formed in the Mesoproterozoic period. The rock of the Lincoln Mountain Massif (Y^2lg) is mostly highly-metamorphosed gray to tan coarse-grained quartz-felspar-rich gneiss. The quartz in the rock has a subtle blue tint that indicates a micro-inclusion of rutile. It is foliated with a strike at N20^{0}W and close-to-vertical dip. Cleavage can also be seen striking in a different direction at N30^{0}E with a 50^{0}E dip. Therefore, the rock is very deformed with two deformational forces in different directions.

Rocks of the Pinnacle Formation are found at the Crash Bridge (Site 1 on Fig. 1) and site 2 (Fig. 1). The formation consists primarily schistose wacke and meta-conglomerate with quartz veins formed in the Cambrian and Neoproterozoic period. At the bridge exposes rocks of the CZpcg member. Grey foliated mica-rich phyllite to schist wacke, whose schistosity strikes at N17⁰E and dips at 46⁰E, is in contact with gneiss of the Lincoln Mountain Massif and massive quartz veins (Fig. 2). Further downstream, the schistose wacke is in contact with poorly-sorted grey rounded pebble- and elongated cobble-sized conglomerate that locally contains some boulder-sized clasts as large as 20cm in diameter (Fig. 2). Site 2 exposes quartz-feldspar pebble-sized conglomerate of the CZpw member (Fig. 1). The conglomerate here is more well-sorted with smaller clast sizes and not as deformed as that at site 1. The quartz in the conglomerate also contains rutile with the same subtle blue tint found in Mount Holley gneiss.

Rocks of the Fairfield Pond Formation, formed in Cambrian and Neoproterozoic period, were found at site 3 (Fig. 1). Site 3 exposes primarily fine- to median-grained dark green to grey phyllite of the CZfp member with very fine-grained slaty sections. Foliation and local quartz veins can be seen in the rock, and a layer of dolomitic sandstone is interbedded at an angle to the foliations of the rock (Fig. 3).

Rocks of the Cheshire Quartzite at Rocky Dale (Site 4 on Fig. 1) were formed in the Lower Cambrian period. Rocky Dale exposes massive tan-gray quartzite interbedded with some thin (mm-scale – 1cm) beds of fine- to grained well-sorted red mudstone (Fig. 4) of the Cc member. The bedding strikes N20⁰W and dips 15⁰E. The rock is not very deformed and has a well-preserved sedimentary structure.

The contact between the basement and cover sequence is an unconformity (Fig. 2). The basement was formed 1.3Ga during the Mesoproterozoic period while the Pinnacle Formation was formed around 600Ma in the Neoproterozoic period (Ratcliffe et al., 2011).

Therefore, around 700MA is represented by the unconformity that separates the basement and cover sediments.

Interpretation

The rocks of the cover sequence have preserved some sedimentary structures that indicate the nature of their protoliths. The rocks of the Pinnacle Formation preserve the boulder-, pebble-, and cobble-sized clasts within the conglomerate. These clasts suggest that the protolith of the rock of the Pinnacle Formation is coarse-grained, poorly-sorted sedimentary rock. The quartz in the Pinnacle Formation, which is also found in the Mount Holley Complex stratigraphically underneath it, also suggests that the rocks of the Pinnacle Formation may be formed due to erosion of Mount Holley Gneiss. The rocks of the Fairfield Pond Formation and the Cheshire Quartzite at Rocky Dale, on the other hand, both preserve beds of fine-grained rocks interbedded with beds of coarse-grained rocks. Therefore, the protolithes of both formations are possibly interbeds of mudstone and fine-grained to medium-grained sandstone or dolomitic sandstone.

Fig. 5 shows the stratigraphic column of rocks in the Lincoln Area with their depositional environments (Tauvers, 1982). It suggests that all the formations studied are in contact with each other, and as we move up-section, the depositional environment changed from a fluvial environment to a sub-aqueous fan environment before becoming shallower into a tidal flat environment.

The data from Fig. 5 can also be proved by observations from the field. Fig. 5 shows the Pinnacle Formation was formed in an alluvial fan or, for the CZps member only, a sub-aqueous fan environment. Sedimentary structures like the abundance of cobbles and boulders of the CZpcg member suggests formation in a fluvial high-energy depositional environment. As the river turns downstream or into an underwater environment, the depositional energy became weaker, resulting in smaller pebbled-sized clasts of the CZpq member. Subsequently, Fairfield Pond was formed in a shallowing upward sequence in the oceanic environment before Cheshire Quartzite Formation was formed in a tidal flat environment (Fig. 5). The coarse-grained dolomitic sandstone interbedded with fine beds of phyllite of the Fairfield Pond Formation resemble those of the West Castleton Formation of the Taconic Sequence formed around the same period in a submarine fan system. This provide evidence that the rocks of the Fairfield Pond Formation was formed in a submarine environment. Similarly, the massive quartzite with mud interbeds is similar to the massive white-grey quartzose in the Monkton Quartzite formed around the same period in a beach environment of a siliciclastic dominated system, although rocks of the Cheshire Quartzite Formation contains fine-grained mud layers, which is indicative of a tidal flat depositional environment.

A Precambrian-Cambrian rift model can explain the change of depositional environment (Fig. 6). During rift initiation, mantle convection and ridge-push heats up the continental crust, which extends and thins as the mantle upwells (Step 1 on Fig. 6). As the continental crust moves away from rising magma, it cools down and due to the lack of support, starts to fall down, creating a lowland region called rift valley (Step 2 on Fig. 6). Rocks of the Pinnacle Formation were possibly formed in such a rift valley, when the rocks of the Precambrian basement were eroded and deposited in an alluvial fan or fluvial environment. As the rift valley deepens, water filled the valley, creating the “Linear Sea” (Step 3 on Fig. 6). The Fairfield Formation was probably deposited in such a see when the depositional environment changes into a deep ocean environment. As the continental crust expands, the magma creates oceanic crust when it cools down. The expansion of the oceanic crust creates the Middle-ocean ridge at the divergence boundary (Step 4 on Fig. 6). The continental rift, however, cannot explain the change of depositional environment from a deep oceanic environment to a tidal flat environment because the continental rift gets deeper and deeper at a certain location as it develops. This shallowing of the depositional environment may be account to a sudden sea-level drop, tectonic movement, or development of a stable continental shelf.

Fig. 7 shows as compared to the rocks in the Middlebury Synclinorium and the Champlain Valley, rocks of all the Formations in the Lincoln region are much highly deformed with multiple folds and reverse faults through the formations. However, while the Lincoln Mountain Massif at the Crash Bridge (Site 1 on Fig. 1) has a high deformation level and metamorphic grade, the rocks in the cover sequences has a lowering metamorphic grade as they get younger. The Lincoln Mountain Massif is the only formation that exposes gneiss, a very high-grade metamorphic rock. It is also highly deformed with two directions of deformational forces and no sedimentary structures are preserved. Unlike the Lincoln Mountain Massif, the rocks of the Pinnacle Formation are conglomerates which preserves some sedimentary structures like pebbles and boulders, and schist, a intermediate-grade metamorphic rock. Although rocks of both members of the Pinnacle Formation have low- to intermediate-metamorphic grade, the elongated pebbles and larger clasts sizes of the rock of CZpcg member at the Crash Bridge suggests a higher-grade metamorphism and deformation than the CApw member at Site 2, where the smaller-sized pebbles can be easily picked up. Rocks of the Fairfield Pond Formation at Site 3 and Cheshire Quartzite at Rocky Dale has undergone low-grade metamorphism because both exposes mostly fine-grained and low-grade rocks and preserved interbeds. Since the rock of Fairfield Pond Formation at Site 3 has undergone greater deformation (foliation at an angle to bed) than that at Site 4, the rock of Cheshire Quartzite has undergone the lowest grade of metamorphism studied and very little deformation. Therefore, the younger the rocks are, the less they are metamorphosed and deformed.

Conclusion

A Precambrian basement, the Lincoln Massif (Y^2lg) of the Mount Holly Complex, and the Pinnacle Formation, Fairfield Pond Formation, and Cheshire Quartzite Formation that forms the Neoproterozoic-Lower Cambrian cover sequence are exposed along the New Have River near Lincoln, VT, USA. Rocks of all formations are in contact with each other, and a 700Ma of unconformity can be seen between the Lincoln Massif and the Pinnacle Formation. As the rocks get younger, they are also less deformed and metamorphosed. A continental rift model can explain the changing depositional environment from an alluvial or fluvial environment to a deep ocean sub-aqueous while the subsequent shallowing to a tidal flat environment may be explained by a lowering of sea level or tectonic movement.

References:

Ratcliffe, N. M., Stanley, R. S., Gale, M. H., Thompson, P. J., Walsh, G. J., Rankin, and D. W., McHone, J. G. (2011). Bedrock geologic map of Vermont (No. 3184). *US Geological Survey.*

Appendix 6: Understand the Plymouth Granite

Introduction

The Plymouth Granite is an igneous rock that is part of the New Hampshire series in Central Vermont, USA (Fig. 1). An old quarry that exposes the Plymouth granite, a Devonian granite (Dg), and its surrounding CZph member of Pinney Hollow Formation country rock were visited on Nov. 2nd, 2017 as a field trip for "Geol0201: Bedrock History of Vermont" near Plymouth, Vermont, USA (Fig. 2). After both the granite and its country rock were observed and described, the entire contact between the granite and the country rock was mapped to understand the volume of remaining granite, the nature of the contact, and the environment in which the granite was intruded.

Rock Description

The country rock surrounding the granite is part of the CZph member of the Pinney Hollow Formation formed in Cambrian and Neoproterozoic period (Ratcliffe et al., 2011; Fig. 1). The CZph member is the phyllite member that is a greenish grey chlorite-muscovite-quartz phyllite (Ratcliffe et al., 2011). The old quarry exposes foliated dark-grey fine-grained schist that strikes N75^{0}W and 25^{0}E neat point u and strikes N25^{0}W and 49^{0}E at point 12(Fig. 2). Between point 5 and 17, the schist is exposed with high abundance of biotite in contact with the granite (the star on Fig. 2). According to Ratcliffe et al. (2011), besides the CZph member, Pinney Hollow Formation includes several members, like the foliated light-green chlorite-quartz-actinolite-plagioclase-pyrite greenstone member (CZpha), the light-grayish green laminated quartz schist member (CZphq), and silvery-grey coarse-grained metawacke member (CZphw).

The Plymouth granite is part of the New Hampshire series granites formed 360-390 Ma. The old quarry exposes plutonic, equigranular coarse- to moderately-grained (2-3mm) igneous felsic boulders. Finer-grained granite can also be seen locally at near the contact with the biotite-rich schist in between point 5 and 17, and granitic dikes, for example, a 0.5m-wide dike at point 12, and dikes near point 6 and at point 9 (Fig. 2). The rock is mostly light-grey colored due to its abundance in quartz and plagioclase feldspar, with some black-colored biotite-rich sections. The rock also contains minor muscovite and epidote.

Interpretation

Fig. 3 shows a northeast cross-section of the intrusion of Plymouth Granite into the country rock through A-A' on Fig. 2. Exposed dikes and a chilled margin are the evidences of its intrusion. Fine-grained sizes, as observed at point 12 (Fig. 2), is a common intrusive texture. A baked contact between biotite-rich schist and finer-grained granite between point 5 and 17 on Fig. 2 also suggests an intrusive contact, defined by fine-grained zone along the margin. The granite in dikes and the chilled margin are much finer-grained because of the rapid crystallization of hot magma when it intrudes into the surrounding country rock near a contact. Therefore, the existence of these fine-grained dikes and chilled margin is suggestive of the Plymouth granite's intrusive nature.

The Devonian granite is also an S-type (sedimentary protolith) igneous rock because it has accessory muscovite, but no hornblende. This fact suggests that the granite formed through melting of a sedimentary rock. Unlike the I-type granite formed from partially melted igneous rock like basalt at an active margin, the S-type granite was formed due to the partial melting of sedimentary rocks at base of crust through continental collision.

Thick continental crust can also partially melt at its base after collision. This process forms granite with high amount of aluminum and a narrow range of compositions.

The volume of usable remaining granite in the outcrop is around 371,339 cubic meters, assuming 50 percent of erosion and 60 percent of waste. Figs. 4 and 5 show the granite outcrop can be considered as an eroded cylinder facing upward with its width being the diameter and its height being the height of the cylinder. Therefore, according to the volume formula of a cylinder ($V=\pi r^2 h$), the usable volume of the granite is $V= \pi * (85 * 85 * 81.8) * 0.5 * 0.4 = 371{,}339\ m^3$.

The Plymouth Granite can be a good source to build futuristic science centers, like the McCardell Bicentennial Halls in Middlebury College, Middlebury, VT. A simplified model of Bicentennial Halls, ignoring windows, doors, roofs, is shown as Fig. 6. Assuming that the wall of the building is 5cm thick, the amount of granite needed to face one hall is 1378.65 m^3 (Fig. 7). This suggests that 269 complete McCardell Bicentennial Halls can be faced with it.

Conclusion

The Plymouth Granite formed in the Devonian Period around 360-390 Ma, and intruded the surrounding Pinney Hollow Formation country rock, as observed in an abandoned quarry near Plymouth, Vermont, USA. The existence of dikes at several local locations and a chilled margin supports the intrusion and its containment of minor muscovite suggests that the granite is an S-type granite formed from the partial melting of sedimentary rocks at collision zones. This remaining 371,339-cubic-meter granite body can be used to face 269 McCardell Bicentennial Halls.