2011 Alumni College

Vermont Geology: From Mountain-Building to Ground Water Resources
Schedule

Thursday 8/25: Plate tectonics, Vermont record of sedimentation and orogenesis.

Friday 8/26: Field trip including (1) Precambrian (Grenville) record, (2) early Cambrian sedimentary record, (3) middle Ordovician sedimentary record, (4) middle-late Ordovician collision and mountain-building.

Saturday 8/27: Surficial geology including (1) stream geomorphology and surface water – ground water interactions and (2) glacial deposits and soils.

Sunday 8/28: Summary and discussion.
1915– Alfred Wegener & “Origin of Continents And Oceans” …. Continental Drift
Fossil evidence of the Triassic land reptile *Lyctosaurus*.

Fossil remains of *Cynognathus*, a Triassic land reptile approximately 3 m long.

Fossil remains of the freshwater reptile *Mesosaurus*.

Fossils of the fern *Glossopteris*, found in all of the southern continents, show that they were once joined.
Pangaea ~ 200 Ma
Continental Drift

• “Continental drift” hypothesis
  • Continents "drifted" to present positions
  • Continents plowed through the oceanic crust like boats through water

• Evidence used in support of the hypothesis
  • Fit of the continents
  • Fossil evidence
  • Rock type and structural similarities
  • Paleoclimatic evidence
Fossil remains of *Mesosaurus* have been found in Africa and South America.

*Lystrosaurus* fossils have been found in Africa, Antarctica, and India.

Fossil remains of *Cynognathus* have been found in Africa and South America.

*Glossopteris* fossils have been found on all the southern continents.
Continental Drift:
• Explanations of fossil evidence
• Island Stepping Stones
• Rafting
• Land Bridges
• Continental Drift
Matching Mountain Ranges
Paleoclimatic Evidence

Distribution of glacial deposits around the world makes sense if continents were together when they formed.
The Great Debate

- Objections to the continental drift hypothesis
  - Wegener’s hypothesis lacked a mechanism capable of moving continents
  - He incorrectly suggested that continents broke through the ocean crust, much like ice breakers cut through ice – geophysicists proved this to be impossible.
  - Although ~ accepted by geologists in S. hemisphere (strong evidence there), CD faced strong opposition from geologists and physicists from US, Europe.
The Great Debate

• Continental drift and the scientific method
  • Wegener’s hypothesis was testable and proved correct in principle, but contained incorrect details
  • A few scientists considered Wegener’s ideas plausible and continued the search … but needed the types of scientific instrumentation that ultimately were developed in WWII.
Reviving the Continental Drift Hypothesis

• Paleomagnetism
  – Magnetic minerals (e.g. magnetite) in lavas record position of magnetic poles through geologic time
  – Used to support the idea that the continents drifted
FIGURE 2.9

Lines of magnetic force

Magnetic pole

North geographic pole

Dip needle

Equator

Magnetic equator

Magnetic inclination

Horizontal
High Intensity = Earth’s Field + Normal field in rock

Low Intensity = Earth’s Field + Reversed field in rock
Paleomagnetic Reversals Recorded in Oceanic Crust

A. Period of normal magnetism

B. Period of reverse magnetism

C. Period of normal magnetism
The Vine–Matthews–Morley hypothesis, also known as the Morley–Vine–Matthews hypothesis was the first key scientific test of the seafloor spreading theory of continental drift and Plate tectonics. Geophysicist Frederick John Vine and the Canadian geologist Lawrence W. Morley independently realized that if the seafloor spreading theory was correct, then the rocks surrounding the mid-oceanic ridges should show symmetric patterns of magnetization reversals, a record of the Earth's geomagnetic reversals, captured in the cooling volcanic rocks. Morley's letters to Nature (February 1963) and Journal of Geophysical Research (April 1963) were both rejected, so Vine and his adviser Drummond Hoyle Matthews were first to publish in 1963. Later geomagnetic surveys found the patterns are in fact present, providing strong confirmation of the theory.

From wikipedia.

Yet the theory of seafloor spreading (and later, theory of plate tectonics) took many years to finally catch on.
More testing of the Sea Floor Spreading hypothesis was conducted and all data supported the hypothesis.
New Oceanic Lithosphere is created during Sea-floor spreading
Age of basaltic rocks on the seafloor?
Digital Isochrons of the Ocean Floor

If new crust is forming at spreading centers, is earth expanding? Or is crust consumed elsewhere?
Earth’s lithosphere consists of rigid plates that move over plastic-like asthenosphere … driven by flow and convection in the upper mantle (asthenosphere). Oceanic plates are consumed at subduction zones …. → Theory of Plate Tectonics
Interactions at the borders of plates causes results in major geologic activity such as earthquakes and volcanic eruptions.

Spatial distribution of earthquakes helps to map plate boundaries.
Earth’s Lithospheric Plates
Continental Rifting, and Ocean Basin Formation
Oceanic-Continental Convergence

- Trench
- Continental volcanic arc
- Oceanic crust
- Continental crust
- Asthenosphere
- Subducting oceanic lithosphere
- Continental lithosphere
- Melting

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Convergent Plate Boundaries
Cascadia Subduction Zone

1100 km long subduction of the Juan de Fuca plate beneath the Pacific Northwest

Young, bouyant ocean lithosphere is being subducted – Stress!
Continental-Continental Convergence & Collision

Figure 5.14 C
Transform Boundary
Present day distribution of lithospheric plates, but they are moving and changing size and shape. In the past the distribution of these plates was much different.
Principle of Uniformitarianism

Laws of nature have always existed … so the study of rocks in modern tectonic environments enables reconstruction of past geological environments from the preserved rock record.

*The present is the key to the past.*
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<td>Dolostone, Quartzite, dolomite</td>
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<td>Age</td>
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<td>Rock Types</td>
<td>Tectonic Setting</td>
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<td>Very Stable, Passive</td>
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<td>Cephalopods</td>
<td>Continental Margin Sediments</td>
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The Appalachians formed from the rifted remnants of an older mountain belt formed during the “Grenville Orogeny” (1.4 - 1.1 Ga). The Grenville sequence formed within a super-continent called Rodinia.
Remnants of the billion year old Grenville Orogeny.

Most evidence is in eastern Canada, but the Adirondacks and slivers within the Appalachians (e.g., Green Mtns, Birkshires) also preserve rocks of this age.
Precambrian Grenville-equivalent rocks in VT are light-brown.
Rodinia began to rift apart ~600 Ma ... sediments and volcanic rocks were deposited in a narrow ocean basin between the two blocks, Laurentia (paleo-N Am) and Baltica (paleo-NE Europe)
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Monkton Formation – Passive Margin, Peritidal
The present is the key to interpreting the past

Modern Ripples (New Jersey)  Ancient Ripples (Pennsylvania)
This ocean basin is known as Iapetus, and by about 500 Ma it was quite wide (> 1000 km). The eastern margin of North America was parallel to the equator and at low latitudes. An extensive carbonate shelf (sandstones then limestones) like the Bahamas or Great Barrier Reef/N Australia existed.

~ 540 – 455 Ma
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Beekmantown Group
Shelf carbonates (subtidal to peritidal)
Chazy Group

Maclurites Magnus

Cephalopods

Chazy Mound
Black River → Trenton groups
(black shale, deep basin sedimentation)

Middle Ordovician Paleogeography (470 Ma)

Beekmantown-Chazy Contact

463 Ma
Beekmantown-Chazy Contact
A. Early Ordovician (~490-470 Ma)

Laurentia
Humber/Octoraro Taconic Sea ~Dashwood

B. Middle Ordovician (~465-461 Ma)

W (paleo-NNW)

KB K-bentonites
Indian River Fm

E (paleo-SSE)

Obducted BHA/SFA arc system

~200 km

C. Middle-Late Ordovician (~460-450 Ma)

Trenton-Black River foredeep black shales

Thrusting in Taconic slope sequence
~ 475 Ma ... Middlebury area = a warm shallow marine environment, much like the present day Bahamas. Offshore, an encroaching volcanic arc would eventually collide (~ 460 Ma).
~460-450 Ma. Deposition and deformation of accretionary wedge. Slivers of ocean crust and mantle often get obducted and preserved in continental crust. In VT, these mantle rocks

(1) Indicate suture zone
(2) Are elevated in arsenic (serpentinite, talc-carbonate) and impact rural water supplies.
The collision of this volcanic arc with eastern North America is known as the Taconic Orogeny. This collision resulted in folding, faulting and metamorphism of the previously deposited rocks. The volcanic arc itself is preserved in eastern Vermont and western New Hampshire.
Champlain Thrust fault (formed ~455 Ma)
We will see evidence of tectonic deformation associated with the Taconian Orogeny at nearly every stop.
Fig. 1. Generalized geologic map of Vermont and adjacent southern Québec (after Doll et al., 1961; Shilts and Smith, 1981; Stanley and Ratcliffe, 1985; Van Baalen et al., 1999; Kim et al., 2003; Schroetter et al., 2006). Rock and water samples for this study were obtained from within the area outlined by the trapezoid in the north-central part of Vermont. Public water supplies in Vermont that exceed the USEPA maximum contaminant level of 10 ppb are also shown.
Tetrahedral As in Antigorite

ANTIGORITE

OCTAHEDRAL SHEET

TETRAHEDRAL SHEET

- $\text{Si}^{+4}$, $R = 0.26 \text{ Å}$
- $\text{As}^{+5}$, $R = 0.34 \text{ Å}$
- $\text{Al}^{+3}$, $R = 0.39 \text{ Å}$
- $\text{Mg}^{+2}$, $R = 0.72 \text{ Å}$

Arsenic in talc-magnesite

Fig 7. Bivariate diagram of arsenic extracted as a function of magnesite dissolution from two talc-magnesite rocks is consistent with occurrence of arsenic in magnesite. Extraction steps range from 1M NH₄NO₃ (ion exchange, step 1) to progressively stronger acids, culminating with aqua regia (step 5). The fact that not all As is released during these extractions implies that some As likely also occurs in magnetite or talc.

Fig 8. Schematic sketch depicting substitution of arsenate anion for carbonate anion in magnesite (after Alexandratos et al., 2007). As(V) in magnesite is suggested by preliminary XANES data (Fig. 5).
Late Ordovician (450 Ma)
The island arc built up by the southward-directed subduction of Iapetus lithosphere collided with Laurentia in the middle to late Ordovician, causing the Taconic orogeny.
Devondian
(~400 Ma)

Laurentia
The Taconian Orogeny was responsible for many of the faults, folds and fractures preserved in west-central Vermont, but it was just the beginning for much of the Appalachians. At least two later collisions, the Acadian Orogeny (~400 – 350 Ma) and Alleghanian Orogeny (~320 – 270 Ma) resulted in more mountain building. Evidence of some of this later deformation is also preserved Vermont (more to E than W).
Early Devonian (400 Ma)
The collision of Laurentia with the continent of Baltica caused the Caledonian orogeny and formed Laurussia. The southward continuation of the convergence caused the Acadian orogeny.
Acadian isoclinal folds, Craftsbury, VT
Acadian granite w/ xenolith, Marshfield, VT
Silurian quartzite,
Delaware Water Gap, NJ/PA
Catskill Delta
(sediments deposited W of Acadian Mtn range)
Tectonic and regional metamorphic implications of the discovery of Middle Ordovician conodonts in cover rocks east of the Green Mountain massif, Vermont

Nicholas M. Ratcliffe, Anita G. Harris, and Gregory J. Walsh

Abstract: Middle Ordovician (late Arenigian—early Caradocian) conodonts were recovered from a dolostone lens in carbonaceous schist 30 m below the base of the Punney Hollow Formation in the Eastern Cover sequence near West Bridgewater, Vermont. These are the first reported fossils from the metamorphic cover sequence rocks east of the Green Mountain, Berkshire, and Hoosatanic masses of western New England. The conodonts are recrystallized, coated with graphitic matter, thermally altered to a color alteration index (CAI) of at least 5, and tectonically deformed. The fauna is nearly monospecific, consisting of abundant Periodon aculeatus Hadd.ng and rare Protopanderodus. The preponderance of Periodon and the absence of warm, shallow-water species characteristic of the North American Midcontinent Conodont Province suggest a slope or basin depositional setting. The conodont-bearing carbonaceous schist is traceable 3 km southeast to the Plymouth area, where it had been designated the uppermost member of the Plymouth Formation, previously regarded as Early Cambrian in age. The age and structural position of the carbonaceous schist above dolostones of the Plymouth Formation but below the Punney Hollow Formation (upper Proterozoic and Lower Cambrian) suggest that this unit may be correlative or time transgressive with the Ira Formation, which underlies the Taconic allochthons in the Vermont Valley. Such a correlation supports the concept of placing the western limit of the root zone of the Taconic allochthons beneath the Punney Hollow Formation. An approximate absolute age assignment for the conodont-bearing rock is between 470 and 454 Ma. This suggests that dynamothermal metamorphism during the Taconian orogeny on the east flank of the Green Mountains was younger than early Caradocian, which is in accord with the middle Caradocian age of the Ira Formation west of the Green Mountain massif.

Résumé : Des conodontes datant de l’Ordovicien moyen (Arénigien supérieur—Caradocien précoce) ont été collectés dans des lentilles de dolomie intercalées dans un schiste carboné, à 30 m sous la limite inférieure de la Formation de Punney Hollow, dans la séquence ‘Eastern Cover’, près de West Bridgewater, Vermont. Ils représentent les premiers fossiles de ce type provenant de la séquence de roches métamorphiques à l’est des massifs des Green Mountains, Berkshire et Hoosatanic de la partie ouest de la Nouvelle-Angleterre. Les conodontes se recristallisent, recouverts de matière graphitique, altérées thermiquement et présentant un index de coloration (CAI) de 5 ou plus, et déformées par les contraintes tectoniques. La faune est fortement dominée par une seule espèce, Periodon aculeatus Hadding, et réduite par rapport aux autres conodontes de la Province de conodontes midcontinentale américaine. Elle suggère un dépôt sur pente ou dans un bassin. On peut suivre le schiste carboné et les lentilles de dolomie à 3 km au sud-est de la ville de Plymouth, où il est désigné comme le membre terminal de la Formation de Plymouth, qui était considéré auparavant comme datant du Cambrien précoce. L’âge et la position structurale du schiste carboné sont assez similaires à ceux des formations de Punney Hollow (Proterozoiens supérieurs et Cambrien inférieur), qui ont été identifiées dans des allongements tectoniques dans la Vallée du Vermont. Une telle corrélation plaide pour l’interprétation qui consiste à placer la limite occidentale de la zone de roches érosionnées aux allongements tectoniques sous la Formation de Punney Hollow. L’âge absolu approximatif assigné aux roches contenant les conodontes se situe entre 470 et 454 Ma. Ces données suggèrent que la dynamothermalisation a eu lieu pendant la phase de compression tectonique de l’ordre du 470 à 454 Ma, ce qui est en accord avec l’âge de Caradocien moyen attribué à la Formation de Ira à l’ouest du massif des Green Mountains.

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Introduction

Upper Proterozoic through Ordovician rocks of the Eastern Cover sequence form the depositional and tectonic cover of the Middle Proterozoic rocks of the Green Mountain mas-
By about 250 Ma, Appalachian mountain building was complete and the result was the formation of another super continent called **Pangaea**. Beginning about 200 Ma, Pangaea began to rift apart much like Rodinia had 400 Ma earlier (**Mesozoic rifting**). The result of this was the formation of the Atlantic Ocean. The Atlantic is currently growing at a rate of about 2.5 cm (1 inch) per year . . . .
Cw ... rifting

180 Ma ... rifting

Cm
Normal fault
Hanging wall moves down relative to the footwall
The prominence of a mountain is the minimum height of a summit above the surrounding terrain. Prominence is the elevation difference between the summit and the lowest contour that encircles it and no higher summit.

Names of summits on this map have been shortened for brevity. Wherever possible, official names are used, however some summits are not named. Where an unnamed summit is the high point of a mountain range, the name of that range is used. In other cases, the elevation of the unnamed point is given. Hollow symbols represent peaks that may have less than 2,000 ft. prominence.

The following highpoints are not established:

* Eibby Mountain ME (elev. 3,624) or Caribou Mountain ME (3,640 ft).

** Mt. Ellen (4,089) or Canaan Range (4,080 or 4,088).

*** Big Moos is formerly Big Squaw.

For more information or for a list of peaks please contact Roy Schweiker at roy.schweiker@juno.com, Andy Martin at oldbuxit@iname.com or Aaron Maislish at smilish@earthlink.net.
Barber Hill pluton, Charlotte, VT

http://www.darylstorrs.com/images/Barber_small.jpg
Glacial Shale Jurassic mafic intrusion
In addition to Paleozoic sediments, folds and faults, Vermont also possesses a well-preserved record of the much younger glacial history of the region (~20 - 10 ka).
• ~15 - 12 K …the Wisconsin Ice sheet retreated, creating successively lower-elevation proglacial lakes

Collectively known as LAKE VERMONT
Approximate extent of Lake Vermont 12,500 years ago.
Once glacier had retreated N of St Lawrence River valley, sea water rushed in → Champlain Sea
Sea level ~10 ka
Approximate extent of the Champlain Sea 10,000 years ago.
Beluga Whale (Charlotte)

Harbor Seal (Plattsburgh)
Varves – annual layers

~ 11 years
• ~15-13 ka Wisconsian Ice Sheet retreated, blocked meltwaters, and proglacial lakes (e.g. Lk Vermont) formed
• At 12 ka valley was isostatically depressed
  – St. Lawrence seaway flooded valley with marine waters
• By ~9 ka differential rebound brought valley above sea level and formed present-day Lake Champlain
Although freshwater on the surface in the form of lakes, rivers and streams is quite small when compared to the total volume of water on the planet, it is important because of its accessibility and purity.

*Green River, Wyoming*
A stream is a body of water that flows downhill along a defined channel transporting solid particles and dissolved substances.

A river is simply a large stream.
Longitudinal Profile
(similar to Middlebury River)

Base Level
(Local & Ultimate)
Sediment Transport in Streams

- Normal bed load
- Rolling
- Dissolved ions
- Suspended load (clay)
- Moves during flood
- Substrate
- Saltation
- Flow
- Clast collides and bounces another into water
Stream Deposition (Alluvium)
Meandering Stream
Point Bar          Cut Bank
Meandering Stream & Oxbow Lake
Stream Deposition (Alluvium)
Sediment Deposition -- Deltas
Niger River Delta
Delta deposit | Age (years)
--- | ---
F | 400 b.p. – present
E | 1,000 b.p. – present
C | 4,000 b.p. – 2,000 b.p.
A | 7,500 b.p. – 5,000 b.p.

**FIGURE 14.23**
Delta in mountain lake, Maroon Bells, CO
Groundwater
An extremely important hidden reserve of fresh clean water
Porosity

% empty space in a material

(a)

Water

1 mm

(b)

20 cm
Permeability – measure of the ability of a material to transmit fluids. It depends on the connectivity of the pores.
Water Table
Hydraulic gradient = \( \frac{h_1 - h_2}{d} \)