

# **The Northern Appalachians: what we know and what we would like to know, and how studies of ancient orogens can contribute to interpretation of regions of active tectonics**

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## **Introduction**

Continents are formed by amalgamation of arcs and remnants of ocean basins, and subsequent accretion of sediments, volcanic plateaus and younger arcs. They are modified by rifting, the development of continental arcs above subduction zones and continent-continent collisions, which processes occur during the Wilson Cycle (orogenesis), driven by mantle convection. Characterizing rocks from orogens yields information critical to understanding the evolution of pressure-temperature-fluid conditions (petrology), the depth-time history (tectonics) and the temperature-time evolution (thermochronology) during formation and modification of continental crust. This information includes evidence of melting, from which we retrieve data about melt distribution during orogenesis, and how extreme was the thermal perturbation involved during orogenesis.

Structural analysis of orogens enables us to predict the three-dimensional form of features, to infer kinematics and to deduce mechanics (tectonics). However, these results are derived from a two-dimensional slice through an orogen, kilometers below the original topographic surface of the active mountain belt. Therefore, they must be corroborated and complemented by information from seismic, potential field and magnetotelluric studies on the three dimensional structure and composition below the erosion surface, both at the intra-crustal (or intra-lithospheric) and at the crust-mantle (or lithosphere) scales (geophysics). For a complete understanding, orogenic analysis must be placed in a global kinematic and plate tectonic framework (geodynamics). Finally, information can be fed back into thermo-mechanical models of orogens to improve their predictive capability (data assimilation).

In the Laboratory for Crustal Petrology, our interests concern the relationship between melt-depleted lower-crustal migmatites and granulites and peraluminous leucogranites, and the evolution of rheology during orogenesis. We use the New Brunswick–New England Segment of the Northern Appalachians as one of our natural laboratories to investigate orogenic processes. The USArray component of Earthscope will be used to image in unprecedented detail crust and mantle structure of different age provinces throughout North America. In addition to a regional interest in USArray, we can use geological information from a region like the Northern Appalachians to help interpret seismic, potential field and magnetotelluric data from regions of active tectonics. We can contribute significantly to the characterization of melt distribution and the nature of melt flow networks in ancient orogens (*Brown et al.*, 1999; *Brown*, 2001; *Marchildon and Brown*, 2002), and the application of this information to the interpretation of data collected in regions of active tectonics where melt is suspected (*Nelson et al.*, 1996; *Levander et al.*, 1998; *Partzsch et al.*, 2000; *Yuan et al.*, 2000).

## **Migmatites and Granites**

The upper (above the brittle-viscous transition zone) and middle (above the transition to viscous anatectic flow) crust is undepleted, whereas the lower crust (below the transition to viscous anatectic flow) is commonly melt-depleted migmatite and granulite. In metasedimentary protoliths, melt flows from grain boundaries to bedding-parallel leucosomes to dilatant sites that link to form a melt transfer network (*Brown et al.*, 1999; *Sawyer*, 2001), unless bulk flow disrupts primary structure (*Milord et al.*, 2001). Similar features are observed from the onset of muscovite dehydration melting in the upper amphibolite facies (low melt loss, mildly residual rocks; e.g., *Milord et al.*, 2001; *Solar and Brown*, 2001) to ultra-high temperature metamorphic conditions (high melt loss, strongly residual rocks; e.g., *Raith et al.*, 1997; *Sawyer*, 2001). Leucogranites crystallized from the accumulated evolved melt extracted from both metasedimentary and metaigneous protoliths (*Sawyer*, 1998; *Pressley and Brown*, 1999; *Milord et al.*, 2001). A multistage model that involves melting, fractional crystallization and separation of residual and cumulate material from evolved liquid relates leucosomes and smaller-volume granites in lower crustal migmatites and granulites (largely composed of cumulate and residual phases) to leucogranites in plutons in the middle and upper crust (largely crystallized from evolved liquid) (*Milord et al.*, 2001; *Solar and Brown*, 2001).

## **Evolution of Rheology in Orogens**

To understand orogenesis requires knowledge of material behavior of the lithosphere and the mechanics of deformation. To address these issues we get data from rock deformation experiments (high strain rates) and qualitative and quantitative data from the field (natural strain rates). From rock deformation experiments we know that melt-bearing rocks exhibit weaker behavior than similar rocks at subsolidus conditions, behavior that has been confirmed by several recent field examples (*Handy et al.*, 2001). However, we also need to know how rock behavior

changes in three dimensional space during mountain building as geotherms evolve, as crust melts, and as melt migrates through crust, advecting heat, and accumulates at shallower levels, facilitating deformation. Data to address these issues must come from field studies. During prograde orogenic evolution, these processes cause rheological transitions to become shallower. Our work shows that partial melting, melt segregation, melt migration, melt accumulation, and crystallization cause three-dimensional spatially and temporally variable transient weakening followed by hardening. During retrograde orogenic evolution, as both the thermal perturbation and melt flow decline, the material behavior switches from weak to strong and rheological transitions move deeper.

#### **A Natural Laboratory — the Northern Appalachians**

Geological, geochemical and geophysical studies of eastern North America suggest that much of the lithosphere was formed at a convergent plate margin culminating in the Grenvillian orogeny, a late-Mesoproterozoic collisional event. This lithosphere was rifted to form the Iapetus Ocean, the complex closure of which during Paleozoic time resulted in the Appalachians. Finally, the post-Appalachian lithosphere was rifted again to form the Atlantic Ocean. The Appalachians may be divided into three segments, in which metamorphic grade and implied depth exhumed to the surface increases from north to south, whereas the age of peak metamorphism and granite magmatism decreases. These are the Newfoundland and New Brunswick–New England (NBNE) segments of the Northern Appalachians, separated by late Paleozoic basin development, and the central-southern Appalachians segment.

From hinterland to foreland (east to west), the traditional structural provinces of the Appalachians are: the Meguma terrane; the Avalonian composite terrane, composed of Lower Paleozoic rocks exotic to Laurentia, accreted to the craton by dextral transcurrent deformation along the Norumbega shear zone system; the Nashoba terrane; the Central Maine belt, composed of Siluro-Devonian basin deposits, metamorphosed in the Devonian synchronous with deformation in the dextral-reverse Central Maine belt shear zone system (Acadian orogeny); the Bronson Hill belt, composed of Ordovician volcano-sedimentary and igneous rocks of an island arc system accreted to Laurentia during the progressive closure of the Iapetus Ocean (Taconian orogeny); the Connecticut Valley belt, with similar lithostratigraphy and age of deformation and metamorphism to the Central Maine belt; the Mesozoic rift basin; the Piedmont Province, a belt of polydeformed and metamorphosed flysch-type sediments, presumed deposited in an Ordovician subduction trench; further west are the Taconic allochthons, and the Valley and Ridge Province, a foreland thrust and fold belt that enabled contraction via thrusting; and, the Allegheny Plateau.

#### **Arcs in the Northern Appalachians**

The Ordovician Taconian orogeny is commonly attributed to collision between Laurentia and an arc that formed above an east-dipping subduction zone, whereas the Devonian Acadian orogeny is commonly attributed to a collision between Laurentia and an arc that formed above a west-dipping subduction zone (present co-ordinates). However, geological, geochemical and paleomagnetic evidence indicates that a number of independent, generally short-lived arc systems were present in Iapetus outboard of the margins of both Laurentia and Gondwana during the Ordovician and Silurian, and it is clear that the tectonic evolution of the Northern Appalachians was complex.

In the north of the NBNE segment and the Newfoundland segment, amalgamation of a peri-Gondwanan microcontinent (Ganderia) and the Penobscot arc (485-480 Ma) was followed by development of the Popelogan arc on the leading edge of composite Ganderia. An ocean basin between Ganderia and a microcontinent just outboard of Laurentia (Dashwoods) closed during the Late Ordovician by double subduction at the Popelogan arc in the east and at the Notre Dame arc, which developed on the Dashwoods microcontinent, in the west. This was followed by closure of a marginal basin between the Popelogan arc and Ganderia (445-430 Ma).

In the southern portion of the NBNE segment, the Shelburne Falls arc is inferred to have formed above an east-dipping subduction zone (485-470 Ma) and to have collided with Laurentia to cause the Taconian orogeny. This event was followed by development of the Bronson Hill arc (455-440 Ma), which most likely formed above a west dipping subduction zone initiated near the Laurentia after a flip in subduction polarity.

During the Early Silurian (440-425 Ma), the remnant 'Iapetus' ocean between the leading edge of Laurentia and the Avalon Composite terrane closed diachronously, from north to south, and was followed by the early Devonian accretion of Meguma (c. 415 Ma) to North America. These events may have been the cause of Early Devonian to Early Carboniferous dextral transpressive deformation, metamorphism and plutonism (the 'Acadian' orogeny).

The polarity of subduction associated with the 'Acadian' events is contentious. The fate of subducted slabs associated with any of the Lower Paleozoic collision events is unknown. Slab detachment may be the cause of the extreme thermal perturbation implied by the diachronous (north to south) linear belt of high-grade metamorphism and associated plutonism that characterizes the Acadian orogeny.

#### **The Acadian orogen of the Maine–New Hampshire sector**

The Central Maine belt is a principal unit occupying most of the east part of the area; it is composed of a Lower Paleozoic sedimentary succession, deformed and metamorphosed at greenschist to upper amphibolite facies conditions, which exceeded the anatectic front as recorded by migmatites, and intruded by plutons of Devonian age.

Geochemical data show that migmatites are residual (e.g. *Solar and Brown, 2001b*), and isotope data indicate granite commonly was derived predominantly from a Central Maine belt source (*Pressley and Brown, 1999*). Age data suggest contemporaneous deformation, metamorphism and granite emplacement (e.g. *Solar et al., 1998*). The Central Maine belt is located between Ordovician rocks of the Bronson Hill belt (this belt includes rocks now assigned to the Shelburne Falls arc) to the west and rocks of the Avalon Composite terrane to the east, from which it is separated by the dextral-transcurrent Norumbega shear zone system. The tectonic regime in the Central Maine belt involved non-coaxial non-plane strain flow, in which the inclined vorticity vector was stretched along its length and the deformation was partitioned into alternating steeply inclined S-L and L>>S tectonite zones within the Central Maine belt shear zone system (*Solar and Brown, 2001a*). Regionally distributed asymmetric structures indicate dextral-SE-side-up kinematics. The orogeny was transpressive, driven by oblique convergence. The metamorphic field gradient is of low dP/dT type (andalusite-staurolite to sillimanite migmatite), P-T paths are clockwise and the thermal peak was late syntectonic (*Solar and Brown, 1999, 2000*), reflecting regionally elevated thermal gradients and pluton-driven thermal pulses (*Brown and Solar, 1999*); cooling progressed southward. These data suggest limited thickening, elevation of the mountain belt and collapse, perhaps reflecting limited convergence.

At higher structural levels, above the anatexis front, in the Presidential Range of eastern New Hampshire, east-verging inclined folds are superimposed on km-scale recumbent east-verging folds, consistent with structures to the south. We interpret the contrast between the simpler deformation history in Maine and the more complex sequence in New Hampshire to reflect proximity to the free surface. At this level, the effect of gravitational collapse is combined with the transpressive deformation to produce superimposed structures during ongoing deformation. The age of syntectonic metamorphism and plutonism is the same as that in Maine. To the west of the Bronson Hill belt is the Connecticut Valley belt, which most likely is a correlative of the Central Maine belt transported west. In the Connecticut Valley belt of western New Hampshire, structural relations and counterclockwise metamorphic P-T paths suggest a sequence of thrust sheets, each associated with syntectonic melt at the apparent base, emplaced from west to east, contemporaneously with deformation, metamorphism and magmatism in Maine, with cooling progressing from west to east, reflecting increasing isostatic rebound toward the orogenic core.

#### **Lithosphere Structure of the Northern Appalachians**

Our knowledge of deep crustal and upper mantle structure comes primarily from seismic refraction and reflection studies, supplemented by gravity and magnetic studies, studies of xenoliths in Mesozoic dikes, and inversion of geochemical data from magmatic rocks to identify melt source(s).

Thermobarometry combined with dating of accessory minerals (crustal xenoliths) and Re-Os isotope systematics (mantle xenoliths) can be used to constrain the depth of equilibration and age of the lower crust and upper mantle underlying the northern Appalachians. This is important since the crust and mantle components of the lithosphere may have been formed at different times and juxtaposed by tectonic activity.

Regional studies that invert geochemical data from upper crustal plutons have been used to characterize basement terranes underlying the Northern Appalachians (e.g. *Ayuso and Bevier, 1991; Whalen et al., 1994; Kerr et al., 1995; Brown and Pressley, 1999*). Grenvillian basement is unlikely on geophysical grounds (*Stewart, 1989; Zhu and Ebel, 1994*), and the low-velocity deep crust and mantle lithosphere that underlies the Central Maine belt likely is peri-Gondwanan ('Avalon-like'), consistent with the complex history of arc evolution, migration and amalgamation (above). Also based on  $V_p/V_s$  ratios, the North Appalachian crust is interpreted to be more felsic than Grenville crust (*Musacchio et al., 1997*).

The splitting of core-refracted shear waves indicates the presence of two layers of anisotropic upper mantle in this region, a lower layer related to present plate motion and a fossil fabric in the lithosphere mantle normal to the trend of the Northern Appalachians, which may reflect post-Alleghanian orogenic collapse (*Levin et al., 2000*).

#### **Acadian Magmatism in a Wider Context**

The Acadian metamorphism of New Hampshire and Maine is late syntectonic (e.g. *Solar and Brown, 1999, 2000*) and defines a linear metamorphic high, which correlates directly with a linear magmatic belt of late syntectonic plutons. One of the biggest problems still to be fully understood in orogens is the cause of the thermal perturbation responsible for metamorphism and melting.

In general, numerical models of metamorphism due to thickening and thermal relaxation do not generate conditions appropriate for melting at appropriate depths. This indicates that an additional heat source is necessary. An increase in radiogenic heat production due to high heat-producing horizons within basinal sedimentary sequences has been suggested by *Chamberlain and Sonder (1990)* for the Acadian metamorphism of the New Hampshire and Maine. Sufficient additional heat could be generated by accretion of radioactive material and concurrent erosion (*Huerta et al., 1996*). Seismic profiles that show a layer of intermediate velocity may be located between lower crust and upper mantle in some regions of Earth, which has been interpreted to indicate the presence of mafic intrusions at the apparent base of the crust. Thus, magmatic under- or intra-plating has been proposed as a

cause of additional heat, but is generally viewed as inappropriate based on petrological and volume considerations (Barboza *et al.*, 1999). In some circumstances, mafic magma may be a second order effect advecting heat into crust, such as during ridge subduction or triple junction migration (e.g. Levander *et al.*, 1998).

The most likely source of additional heat is the asthenosphere. Part of the lithosphere thermal boundary layer may be removed convectively (e.g. Platt and England, 1994), facilitated by collisional thickening of continental crust, which may be decoupled from lithospheric mantle, to generate a thick, dense and unstable orogenic root (Houseman *et al.*, 1981). Modeling studies suggest that such an orogenic root may founder, detach and sink through the asthenosphere (Houseman and Molnar, 1997). Detachment might occur by ductile necking or by delamination (Bird, 1979; Schott and Schmeling, 1998). In all scenarios, syn-orogenic lithosphere thinning, uplift, decompression melting, near-surface extension and substantial mantle strain are predicted to occur. An alternative way to bring the asthenosphere closer to the base of continental crust in convergent orogens is by slab breakoff (Davis and von Blanckenburg, 1995; Wortel and Spakman, 2000). Such a model predicts that after collision the slab may detach and sink into the mantle, allowing hot asthenosphere to be emplaced beneath thickened orogenic crust. The tectonic, metamorphic and magmatic response similar to the case of delamination, but the diachronous nature of slab detachment as the break propagates enables discrimination from delamination.

#### **Relationship to Earthscope - USArray — Scientific issues and approaches**

We can contribute to the interpretation of regions of active tectonics, based on our knowledge of the features of deep crust in ancient orogens, and to the development of experiments to test interpretations of the Northern Appalachians, which is one of our natural laboratories, in the USArray component of EarthScope. We expect to integrate measurements from USArray with complementary geologic information.

Specifically in the Northern Appalachians we would like to know more about:

- subduction, which is controversial for the Taconian and Acadian, which could be tested by high resolution images of upper mantle structure (on the order of tens of kilometers) to trace evidence of subducted slabs;
- diachronous slab break-off, which will provide information about the apparent space problem for the lithospheric mantle during orogenesis involving collisions;
- crustal structure and composition, particularly better resolution of basement terranes (lithosphere terranes?) and the extent of 'Avalon-like' basement;
- mantle anisotropy, as determined by shear wave splitting, across the Northern Appalachians;
- the Norumbega Fault System, particularly using high-resolution imaging to determine its extent at depth;
- upper crustal structure, particularly the 3-D form of plutons, derived from high-resolution images from focused investigations using portable instruments, to enable better estimates of mass transfer from mantle to crust, and between crustal melt produced and crustally-derived granite in the upper crust;
- based on magnetotelluric field studies of conductivity, *T* and fluid content of 'stable' orogenic crust.

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