Evidence for polyphase deformation in the mylonitic zones bounding the Chester and Athens Domes, in southeastern Vermont, from $^{40}Ar/^{39}Ar$ geochronology

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Abstract

The Chester and Athens Domes are a composite mantled gneiss dome in southeast Vermont. While debate persists regarding the mechanisms of dome formation, most workers consider the domes to have formed during the Acadian Orogeny. This study integrates the results of $^{40}Ar/^{39}Ar$ step-heating of single mineral grains, or small multigrain aliquots, with data from microstructural analyses from samples collected in multiple transects across the dome-bounding shear zone(s) in order to understand the relationship between metamorphism and deformation. Results from the sheared units along the north and south transects are presented from west to east. In the north, hornblende from the Barnard Gneiss yielded a weighted mean age of 406 Ma from a plateau -like segment and biotite yielded a weighted mean age of 344 Ma. Muscovite from a second sample of the Barnard gneiss yielded a weighted mean age of 388 Ma for a plateau -like segment and biotite yielded a plateau age of 334 Ma. One analysis of biotite from the Devonian Waits River Formation yielded a plateau age of 403 Ma, and muscovite yielded a plateau age of 362 Ma, consistent with microstructural evidence of muscovite growing at the expense of biotite. In this transect, the deformation ages inferred for the samples include 388 Ma in association with upper greenschist to lower amphibolite-facies metamorphism, and 362 Ma in association with greenschist-facies metamorphism. In the south, muscovite from the basement cover contact yielded a weighted mean age of 365 Ma. Biotite from this sample yielded a weighted mean age of 358 Ma. A hornblende analysis from the Missisquoi Formation yielded a weighted mean age of 392 Ma. Muscovite from another sample of the Missisquoi Formation yielded a weighted mean age of 365 Ma and biotite yielded a weighted mean age of 406 Ma. Along this southern transect, two sets of foliations were observed in thin section; an older S_1 is preserved in the microlithons of a younger, more dominant foliation. The dominant age signals in the integrated data from both transects are c. 406 Ma, 388 Ma, 365 Ma,and 344 Ma. The geochronology, along with the local preservation of an older S_1 foliation in thin section, indicates that the samples experienced multiple phases of deformation. We also analyzed muscovite from a leucocratic Acadian dike that crosscuts the dominant penetrative foliation along the W margin of the Dome. Muscovite from this sample yielded a plateau age of 344 Ma. While all samples within the attenuated mantling units appeared to exhibit a single dominant foliation in the field, the results of this study suggest a complex history of deformation based on the microstructural analysis, the variety of plateau/weighted mean ages obtained, and the complexity of age gradients in the individual age spectra.

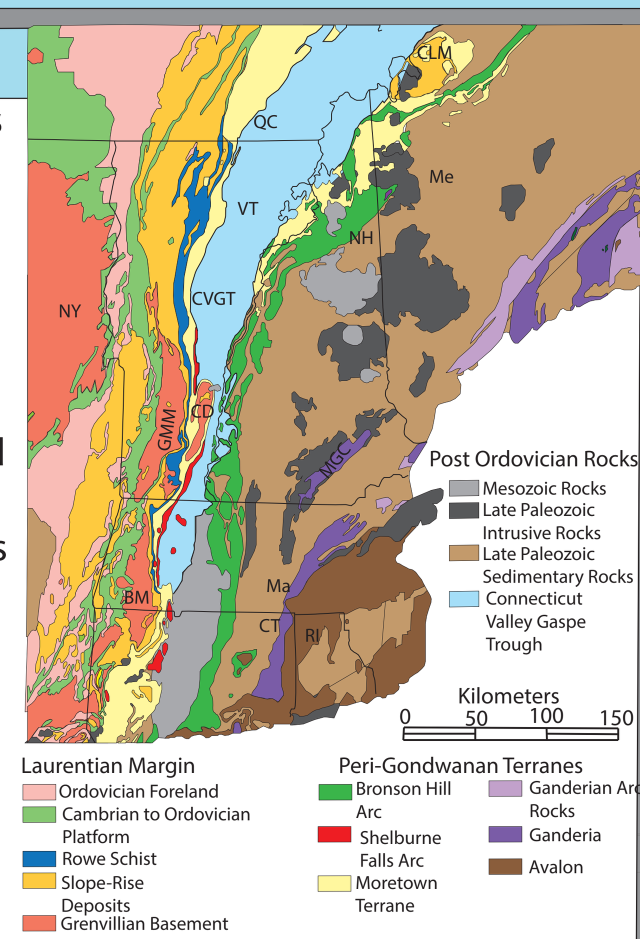


Figure 1: Tectonic map of New England modified after Karabinos and others (2017) and Hibbard and others (2006). Abbreviations include: BM – Berkshire Massif, CLM – Chain Lakes Massif, GMM – Green Mountain Massif, MGC – Massabesic Gneiss Complex, CVGT – Connecticut Valley Gaspe Trough and CD – Chester and Athens Dome. Black box represents Figure 2.

Geologic Overview

- These domes are cored by Middle Proterozoic Grenvillian basement and are separated from the metamorphic Silurian to Devonian-aged rocks of the Connecticut Valley Trough by mylonitic shear zones (Karabinos, 1999; Karabinos et al., 2010; Doll et al., 1961).
- The faults surrounding the domes are now interpreted to be low-angle normal faults (Karabinos et al., 2010) that formed during the Acadian orogeny (Vance and Holland, 1993).
- Previous work involving $^{40}Ar/^{39}Ar$ and K-Ar geochronology has been completed in New England in an effort to determine and understand the timing of deformation.
- However, despite all of the geochronological data in the region, there are very limited data that exist for the Chester and Athens Domes. Work completed by McWilliams (2008) has suggested the domes experienced a polyphase tectonic history rather than experiencing solely Acadian deformation.
- For example, deformation may have involved two folding stages including recumbent folds developing due to a nappe stage which involved shortening, followed by a doming phase (Hepburn et. al., 1984).
- In contrast, Karabinos et al. (2010) suggested extension occurred along the shear zone in between the nappe stage and the doming stage.
- Resolving between the various hypotheses and constraining the timing of the deformation, particularly the formation of the dome bounding shear zones, has yet to be completed.

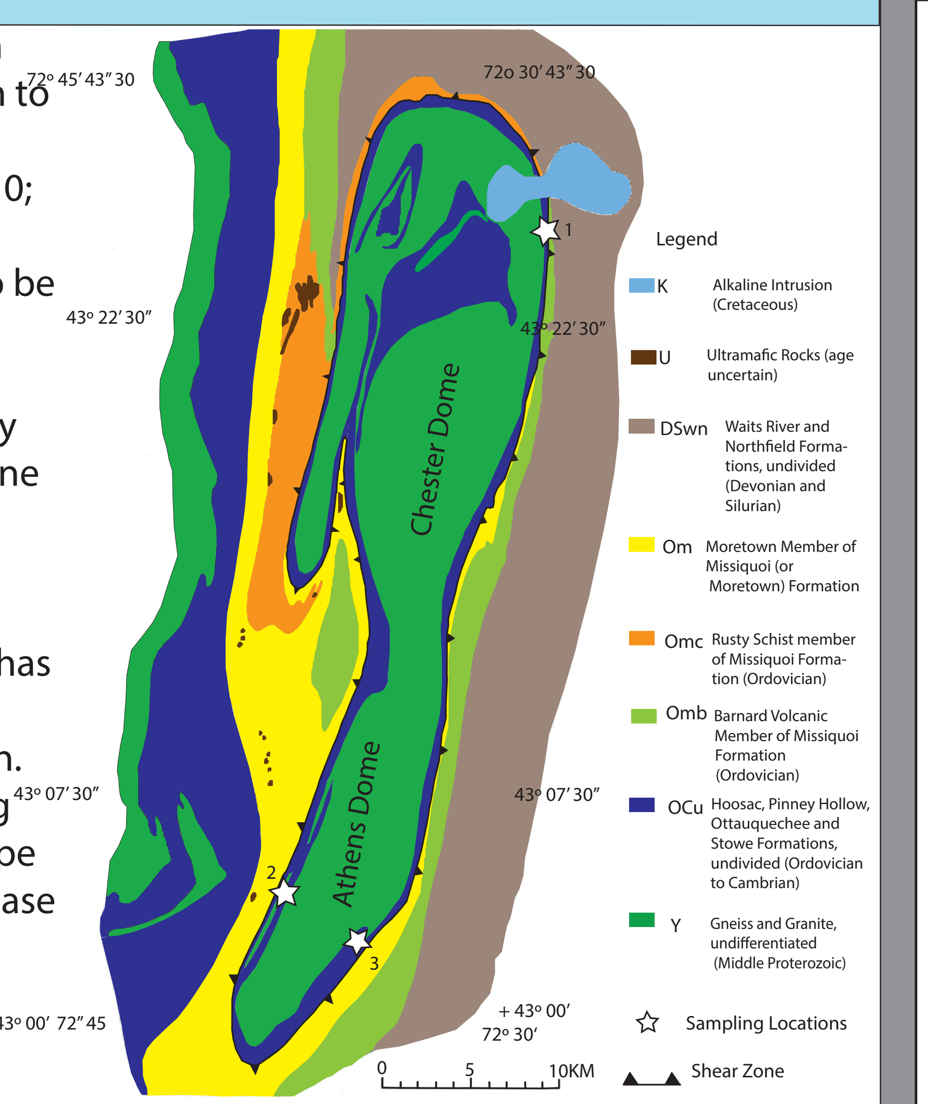


Figure 2: Geologic map modified after Ratcliffe and Armstrong (1995) showing the Chester and Athens Domes. The three white stars, one located in the northeast of the Chester Dome, one in the southeast of the Athens Dome, and one in the southwest of the Athens Dome, show the locations of the samples that were taken.

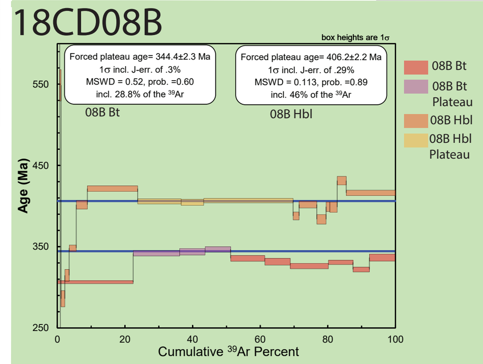
Microstructure and $^{40}Ar/^{39}Ar$ Geochronology

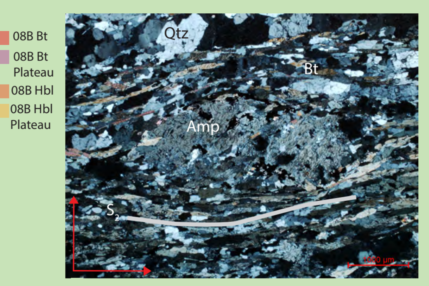
Twelve samples were collected during the fall of 2018 from the shear zones bounding the Chester and Athens Domes for microstructural analysis and $^{40}Ar/^{39}Ar$ age dating. These samples were divided between two transects, one in the northeastern section of the Chester dome and the second in the southern section of the Athens dome. These samples were analyzed by X-ray diffraction in the fall of 2018. Oriented, orthogonal thin sections were also prepared for each of the twelve samples. The thin sections named with an "X" were cut parallel to the stretching lineation (X) and normal to the foliation (Z) whereas the thin sections named with a "Y" have been cut perpendicular to the 'X-Z' thin section.

Sample	Mineral Assemblage	Metamorphic Facies
18CD08A	Quartz, Muscovite, Biotite, Feldspar, Epidote	Upper Greenschist to Lower Amphibolite
18CD08B	Quartz, Biotite, Feldspar, Amphibole	Amphibolite Facies
18CD08C	Quartz, Muscovite, Biotite, Feldspar, Epidote	Upper Greenschist to Lower Amphibolite
18CD08D	Quartz, Muscovite, Biotite, Feldspar, Garnet	Upper Greenschist to Lower Amphibolite
18CD08E	Quartz, Muscovite	Greenschist Facies
18CD09A	Quartz, Amphibole	Amphibolite Facies
18CD09B	Quartz, Biotite, Feldspar, Amphibole, Muscovite	Amphibolite Facies
18CD09C	Quartz, Amphibole, Feldspar	Amphibolite Facies
18CD10A	Quartz, Muscovite, Biotite, Feldspar, Garnet	Amphibolite Facies
18CD10B	Quartz, Amphibole, Feldspar	Amphibolite Facies
18CD10C	Quartz, Feldspar, Muscovite, Graphite	Granulite Facies
18CD10D	Quartz, Feldspar, Graphite	Granulite Facies

North Transect

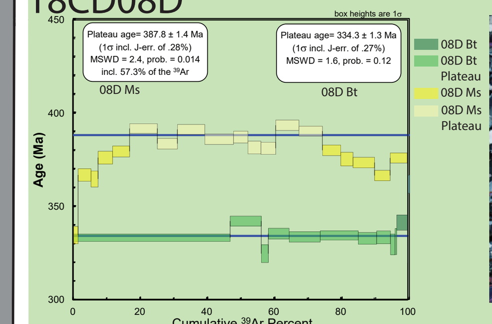
18CD08B

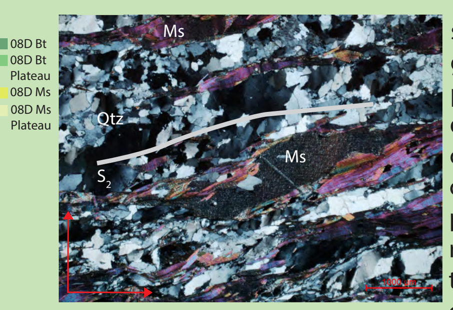




This is from the Barnard Gneiss from the shear zone. The thin section shows an amphibolite porphyroclast with quartz strain shadows. The mineralogy suggests amphibolite facies metamorphism. The quartz experienced GBM, indicating the deformation temperature is ~500°C. The hornblende has a closure temperature of ~500-600°C, and the temperature of deformation when the shear zone was active was at least 500°C. This indicates the hornblende likely constrains the timing of the high-T shearing of the sample at amphibolite facies conditions. The biotite has a closure temperature of ~300-400°C. The biotite contains a complex spectrum suggestive of resetting. Microstructural analysis suggests two generations of biotite, where the older was reset by later deformation. There is one foliation found.

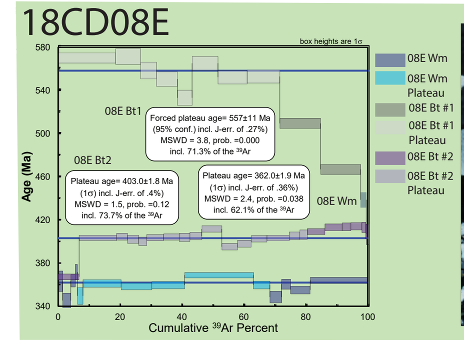
18CD08D

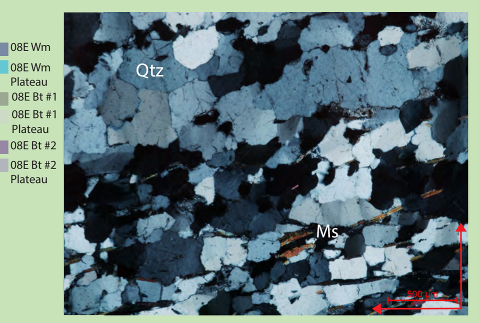




This is from the Missisquoi Formation from the shear zone. The thin section shows group 2 muscovite mica fish. The mineralogy suggests upper greenschist to lower amphibolite facies metamorphism. The quartz experienced GBM, and some SGR, indicating the deformation temperature is >500°C and the sample possibly cooled during deformation from 500-450°C. The white mica has a closure temperature of ~450-550°C. Since the deformation temperature is >500°C, this indicates the white mica constrains the minimum age for the timing of formation for the sample. The biotite has a closure temperature of ~300-400°C, so it constrains the cooling history. There is one foliation found.

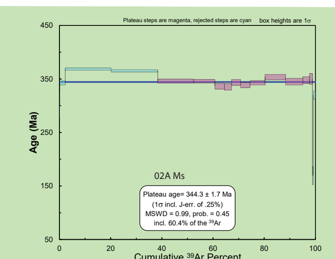
18CD08E

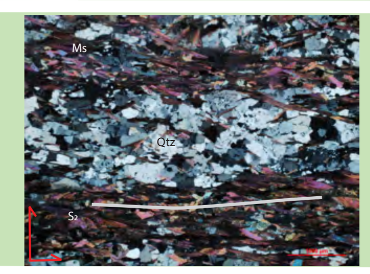




This is from the Waits River Formation outside of the shear zone. The thin sections shows quartz experiencing GBM. The mineralogy suggests greenschist facies metamorphism. Biotite #1 is 577 Ma and is interpreted to be a detrital grain. Biotite #2 is 403 Ma and may record the timing of deformation associated with greenschist facies metamorphism. The white mica is 364 Ma. There is textural evidence for the white mica growing a the expense of biotite, so it may record a later deformation related event that occurred below the closure temperature of both minerals. There is one foliation.

19CD02A Acadian Dike

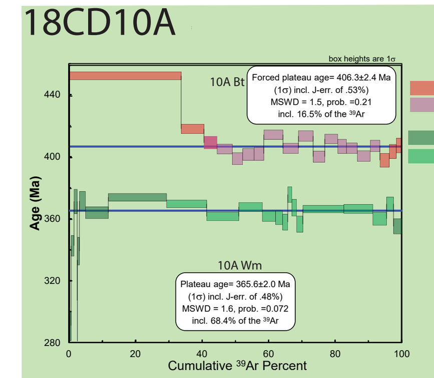


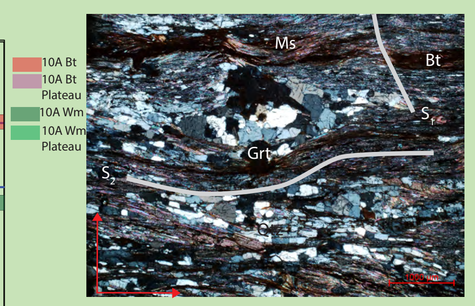


This thin section shows quartz containing GBM and GBAR. Only one deformation event. Evidence of new mineral growth during static crystallization in the quartz. Intrusion formed after the shearing event occurred and is a continuation of the existing deformation, representing the timing of the conclusion of deformation in the Dome

South Transect

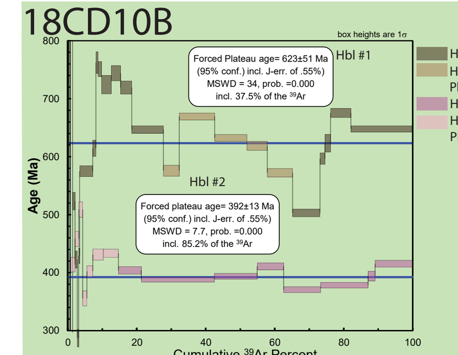
18CD10A

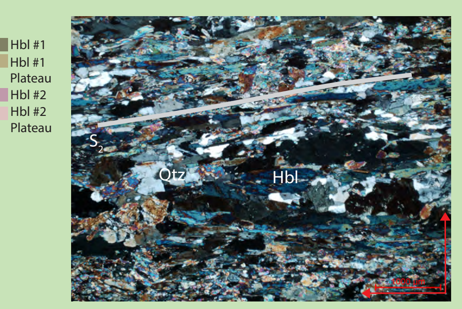




This is from the Missisquoi Formation from the shear zone. The mineralogy suggests amphibolite facies metamorphism. The thin section shows a porphyroclast with quartz wings. It also shows two foliations, S_1 and S_2. S_1 is the older overprinted foliation that is trapped in the microlithons that are defined by S_2, which is the younger more dominant foliation defined by the planar orientation of the micas and compositional layering. This indicates that there was two phases of deformation. The biotites older age might be explained by the possible older generation of biotite in the sample. The white mica was interpreted to constrain the timing of formation of the dominant foliation S_2. Conversely, the older biotite may place constraints on the minimum age of the formation of S_2.

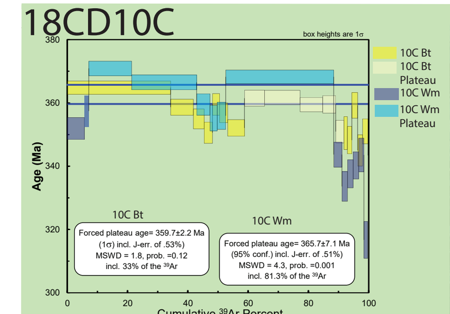
18CD10B

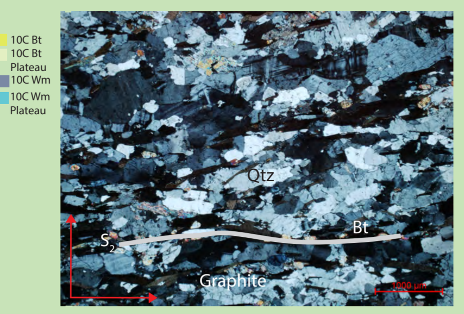




This is from the Missisquoi Formation from within the shear zone. The mineralogical composition suggests amphibolite facies metamorphism. The thin section shows only one foliation. The temperature of deformation is >500°C. Hornblende #1 was much older than the other samples from both the north and south transects. Hornblende #2 contained younger ages c. 360 Ma. This corresponds to two southern samples which also contained ages c. 360 Ma. This 392 Ma could be the minimum age for the high-temperature deformation.

18CD10C

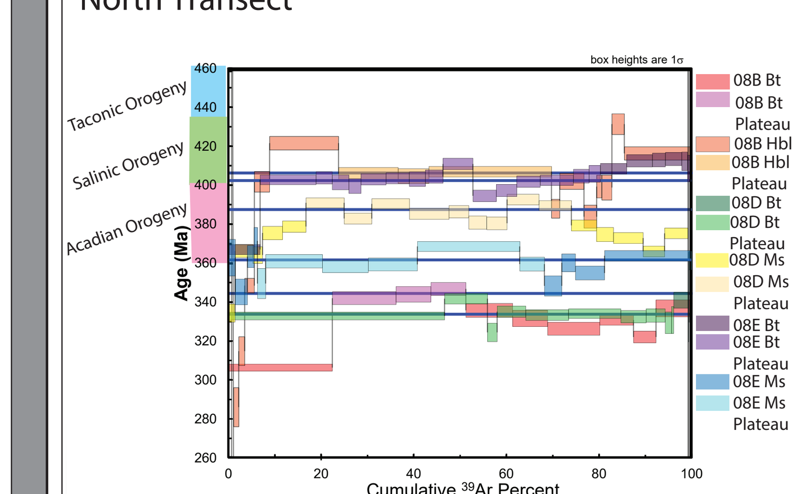




This is a sample of basement rock from the basement cover contact within the dome. The thin section shows one foliation defined by compositional layering and preferred orientation of platy minerals. The mineralogical composition suggests granulite facies metamorphism. The age of the biotite is very close to the age of the muscovite, with the biotite being slightly younger. This older younger relationship could be consistent with white mica recording the deformation age of the sample whereas the biotite records a cooling age of the sample.

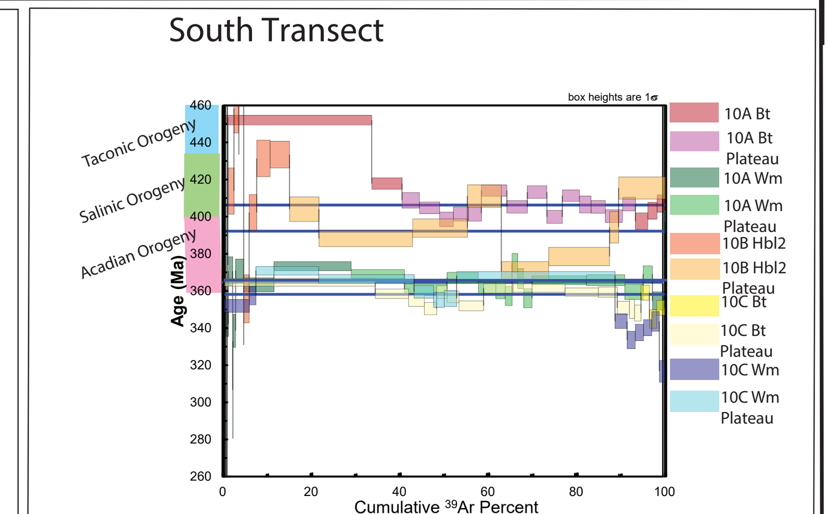
Discussion

North Transect



Data for this transect were sampled from the Missisquoi Formation and the Connecticut Valley Gaspe Trough. In the first sample, the hornblende age is interpreted to constrain an earlier phase of deformation and to constrain the formation of the dominant foliation at c. 406 Ma, whereas the biotite data constrains the timing of the later deformation event at temperatures close to its closure temperature c. 344 Ma. In the second sample, the white mica plateau age of c. 387 Ma can be interpreted as constraining the timing of deformation at mid greenschist-facies conditions and the biotite plateau age of 334 Ma likely constrains the timing of the later phase of deformation. The third sample contained a c. 362 Ma white mica interpreted to represent the deformation age whereas the second biotite containing an age of c. 403 Ma may relate to burial metamorphism.

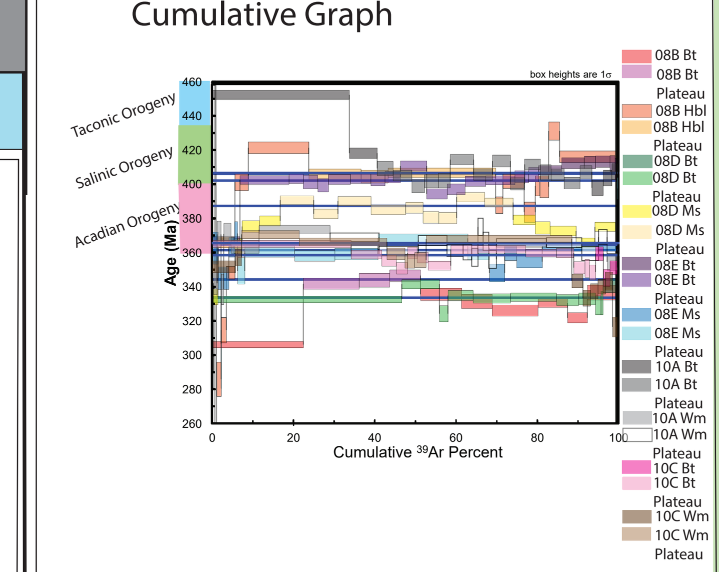
South Transect



Data for this transect were sampled from the basement cover contact in the west and from the Missisquoi Formation in the east. In the first sample, 10C, the white mica plateau was interpreted to constrain the timing of deformation that the sample experienced whereas the slightly younger biotite may reflect a cooling age. Moving eastward to sample 10B, the first old hornblende was interpreted to possibly be a detrital grain that survived metamorphism. For the second hornblende, the age gradients show some resetting around 356 Ma that may provide an estimate for the timing of deformation. The last sample had a weak overprinted foliation and evidence for two generations of biotite. The white mica was interpreted to be the age of the 365 Ma deformation event resulting in the formation of the dominant foliation, S_2. The biotite is interpreted to be part of the older population associated with S_1, for which the 406 Ma age constrains the timing of formation. Therefore, this sample experienced metamorphism during a c. 406 Ma deformation event and then experienced deformation again c. 365 Ma.

Conclusion

Cumulative Graph



Conclusions: The Domes experienced two phases of deformation, which were interpreted to have occurred during the Salinic Orogeny, due to deformation ages of 406 Ma, and during the Acadian Orogeny, due to deformation ages of 365 Ma and 344 Ma. The samples that were collected within the attenuated mantling units appeared to exhibit a single dominant foliation in the field. Upon closer examination in thin section, it could be seen that the samples from the Missisquoi Formation in the southern transect contained the dominant foliation overprinting an older weaker S_1 foliation. This supports the interpretation that the shear zone experienced multiple phases of deformation, where the S_1 formed during the first deformation event during the Salinic Orogeny, and it was then later overprinted by a second foliation during the second deformation event from the Acadian Orogeny, with a more minor overprint again c. 344 Ma. The results support the interpretation that the Chester and Athens Dome experienced a complex history of deformation.

Comparisons between the data indicate that both transects were subjected to Acadian deformation, and in some places the samples may also record evidence of Salinic deformation. Hornblende and biotite samples were collected from the Green Mountain Massif from Proterozoic gneisses for $^{40}Ar/^{39}Ar$ geochronology, and interpretations determined that the Massif experienced Taconic deformation whereas the areas to the east of the Massif (like the Chester and Athens Dome) experienced Acadian deformation (Sutter et. al., 1985). The Acadian deformation ages recorded by the white micas does agree with the interpretation that areas on the east side of the Green Mountain Massif experienced Acadian deformation. Monazite grains were dated in situ in thin section to date foliations of rocks from near the Chester and Athens Dome from the Spring Hill Synform (Bell and Welch, 2002). These grains contain ages of 405, 386, and 366 Ma (Bell and Welch, 2002), which correlates to the ages obtained from both the north and south transects. Electron microprobe dating of monazites was completed in order to constrain the age of deformation in the high-strain zone, which lead to the suggestion that the grains were recrystallized during deformation in the high-strain zone and that the shear zone was active c. 380 Ma (Karabinos et al., 2010). The 08D sample correlates with the monazites, indicating that the shear zone was active c. 380 Ma and experienced Acadian deformation.

Acknowledgments

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