Provenance of the middle-amphibolite-grade Trap Falls Formation, Connecticut

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Introduction

The Trap Falls Formation is a sequence of severely deformed amphibolite grade quartzites and schists that crops out in the southern New England Appalachians in Connecticut. The formation is characterized by beds of interlayered quartzites and pelitic schists that vary in thickness from centimeters to meters. These are likely the remnants of sands and muds (Sevigny and Hanson, 1993) that were deposited in a cyclic sedimentary environment (e.g., turbidite flows or tidal deposits). The Trap Falls Formation was deformed during the Acadian (Devonian) orogeny. It is among the goals of this projects to constrain the environment, source, and approximate age of the sediment. For example, in what tectonic setting were Trap Falls sediments deposited? Were they derived from the North American craton, a magmatic arc, or perhaps an unknown eastern island or continent?

In order to begin addressing some of these questions, we have supplemented what is known about the geology of the Trap Falls Formation with geochemical, isotopic, and geochronologic data. Although sandstone petrography is a classic tool in sedimentary studies, it usefulness is severely curtailed in recrystallized metamorphic rocks. In this case, geochemical compositions can provide information on the sedimentary history of the rock and on the average composition of the source. Nd- and Pb-isotope analysis of whole-rock samples can constrain the average provenance of the original sediment, and detrital zircon ages serve to pinpoint specific provenance ages.

Geologic Setting

The Trap Falls Formation is the name given by Rodgers (1985) for units previously called the Southington Mountain Schist (Fritts, 1962) or the Southington Mountain Formation (Crowley, 1968). It is an amphibolite grade unit that is exposed in the southern tip of the Connecticut Valley Synclinorium of the New England Appalachian Belt. In the study area (Fig. 1), pelitic schists and quartzites are interlayered on all scales (cm to meters). Minor calcite marble, calc-silicate, and amphibolite are described by Crowley (1968). We sampled two quartzites and two schists from an outcrop north of Bridgeport, Connecticut along Highway 25, and an additional schist and quartzite approximately 4 and 8 km northeast of these (Fig. 1). Based on stratigraphic arguments, the depositional age of the Trap Falls Formation has been interpreted to be Ordovician (Crowley, 1968; Rodgers, 1985). A U-Pb age from metamorphic garnet provides a minimum age for the Trap Falls Formation of 419 ± 10 Ma, at which time it was metamorphosed to the middle amphibolite facies (Lanzirotti and Hanson, 1994). The youngest detrital zircon age from this study provides a maximum age for deposition of 992 ± 2 Ma. Thus the Trap Falls, as a pre-Devonian unit, may have been derived from any rocks exposed prior to the Devonian.

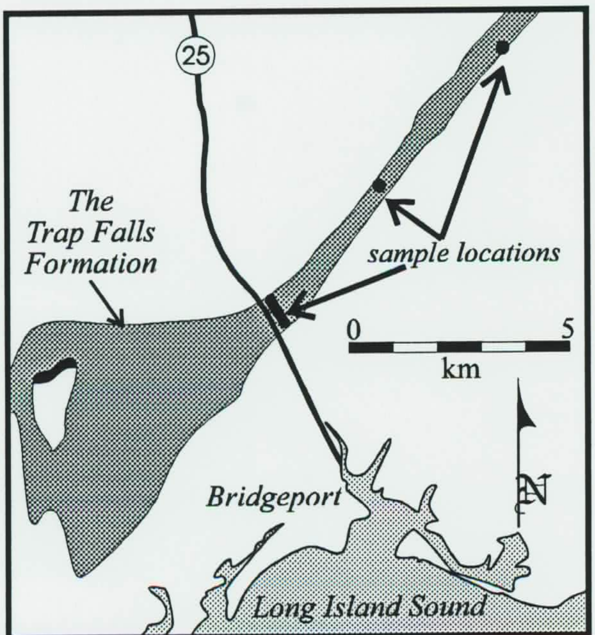

Figure 1. Location of the Trap Falls Formation in Connecticut and sample locations. Modified from Rodgers, 1985

Geochemical Composition

Quartzite layers of the Trap Falls Formation have high SiO_2 (85-91 wt%), and low abundances of Al_2O_3 (3.4-3.6 wt%), Na_2O (0.2-0.1 wt%), and K_2O (0.3-0.4 wt%). The schistose layers have SiO_2 from 61-65 wt%, and higher abundances of Al_2O_3 (16.3-19.0 wt%), Na_2O (1.0-1.2 wt%), and K_2O (4.0-5.3 wt%). The Chemical Index of Alteration (CIA; Nesbitt and Young, 1982) is used as a measure of the degree of weathering of a sediment. Fresh igneous rocks have CIA values of around or less than 50. As a rock is weathered, the CIA increases, so that average shale has a CIA of approximately 72 and kaolinite has a CIA of 100. CIA values for the schists are between 68 and 70. This is consistent with a significant weathering history in the source of the Trap Falls Formation.

Most elements are depleted in the quartzites relative to the schists, this is likely a result of quartz dilution in the sandy protolith of the quartzites. Notable exceptions include CaO and Zr. The higher abundance of CaO in the quartzites (1.3-1.8 wt%, compared to 0.6-0.9 wt% in the schists) may indicate a calcareous biogenic (?) component in the sands. Reasonable CIA values were not obtained for the quartzites because of the anomalously high CaO. Elevated Zr abundances (305 to 371 ppm, compared to 244-281 ppm in the schists), may reflect hydraulic sorting of zircon into coarser sand fractions.

Rare earth element (REE) abundances in sedimentary rocks may be employed as indicators of the average REE composition of the source. The REE composition of samples from the Trap Falls Formation are plotted normalized to C1 chondrites in figure 2. Post-Archean average Australian Shale (PAAS), used as a measure of average upper crustal abundances, is plotted for reference. REE patterns of this study approximately parallel PAAS with light (L)REE enrichment. Abundances are variable, with quartzites having lower concentrations of the REE than the shales. The quartzites exhibit a tailing upwards in the heavy (H)REE that may be attributed to heavy mineral enrichment (McLennan, 1989). REE patterns for zircon, for example, are enriched in the HREE relative to the LREE.

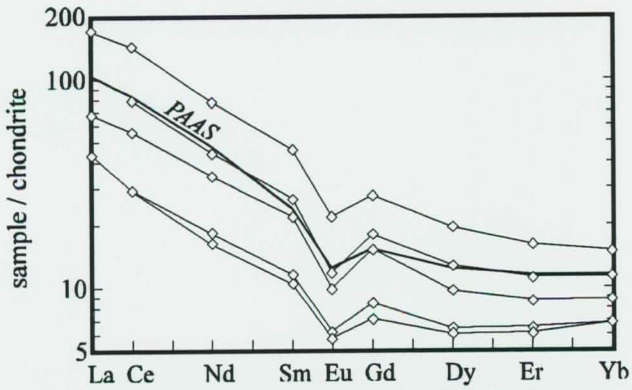

Figure 2. Chondrite normalized REE plot of Trap Falls Formation samples and PAAS (heavy line) for reference. PAAS and chondrite values from Taylor and McLennan, 1985.

Isotopic Provenance

Nd isotopes provide important information about the provenance of sedimentary rocks. Figure 3 is a plot of the Nd isotopic composition of Trap Falls Formation samples as a function of time. Each line on the graph represents a sample, where the y-intercept is the ε_{Nd} ($^{143}Nd/^{144}Nd$ normalized to CHUR, in parts per 10^4) measured today, and the slope is a function of the sample $^{147}Sm/^{144}Nd$. The evolution of a depleted mantle reservoir is plotted for reference. The intersection of a sample path with the depleted mantle evolution line provides an

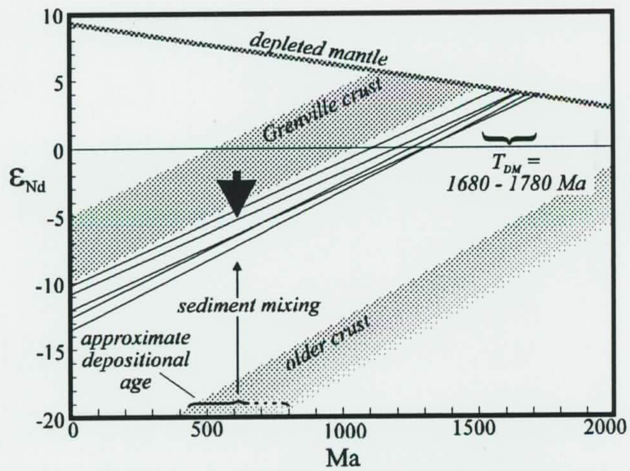

Figure 3. Plot of ε_{Nd} vs. time for samples of the Trap Falls Formation. Also plotted are approximate evolution trends for Grenville Province and older rocks. Arrows describe effect of mixing of Grenville rocks with older crust at the time of sedimentation. Width of arrow is representation of the relative proportion needed from each reservoir.

estimate of the average age of extraction of the sample source from a mantle reservoir. This model-age (T_{DM}) assumes a single-stage history for the sample, that is, that the $^{147}Sm/^{144}Nd$ has not changed appreciably since extraction from the mantle. ε_{Nd}'s for the samples are between -10.2 and -13.6, corresponding to T_{DM}'s from 1680 to 1780 Ma. The coherency in T_{DM}'s among Trap Falls Formation samples suggests that there has been no major change in $^{147}Sm/^{144}Nd$ (e.g., see McDaniel et al., 1994).

The whole-rock Pb isotopic compositions of Trap Falls samples are plotted in figure 4, a plot of $^{207}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$. Trap Falls Formation sample compositions scatter about a 1000 Ma reference isochron, a trend that might be produced by the variable addition of 1000 Ma high U/Pb phases (e.g., zircon) to sediment of less radiogenic composition. Also plotted are fields which encompass the range of whole-rock Pb isotopic analyses of the Grenville of the southern and central Appalachians (data from Sinha et al., in press) and the Adirondacks of New York (data from DeWolf and Mezger, 1994). Grenville rocks have a wide range in isotopic compositions and some terranes follow a trend similar to the Trap Falls Formation. Th central and southern Appalachian suite have high $^{207}Pb/^{204}Pb$ relative to $^{206}Pb/^{204}Pb$, suggesting that there is a component of Archean Pb incorporated in them (Sinha et al., in press).

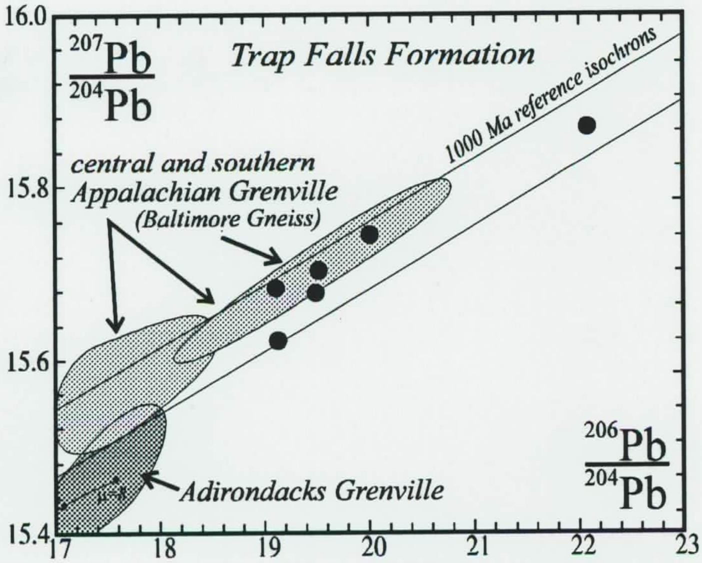

Figure 4. Plot of $^{207}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ for Trap Falls Formation samples with a 1000 Ma reference isochron. Fields of Grenville data from Sinha et al. (in press) and DeWolf and Mezger (1994).

Detrital zircon ages

Whole-rock isotopic compositions of the Trap Falls Formation indicate that it's source is dominated by old crust, possibly North American in origin, but does not provide information about specific source ages. Age determinations of single detrital zircons provide information into specific sources. We analyzed three single-grain and four multi-grain fractions of detrital zircons from the northern-most quartzite sample (Fig. 1) . The fractions were chosen to represent the morphological types. We accept the $^{207}Pb/^{206}Pb$ from single-grain analyses as a reliable measure of the minimum crystallization age (Ross and Parrish, 1991). Multi-grain fractions must be concordant within analytical uncertainty to be a reliable

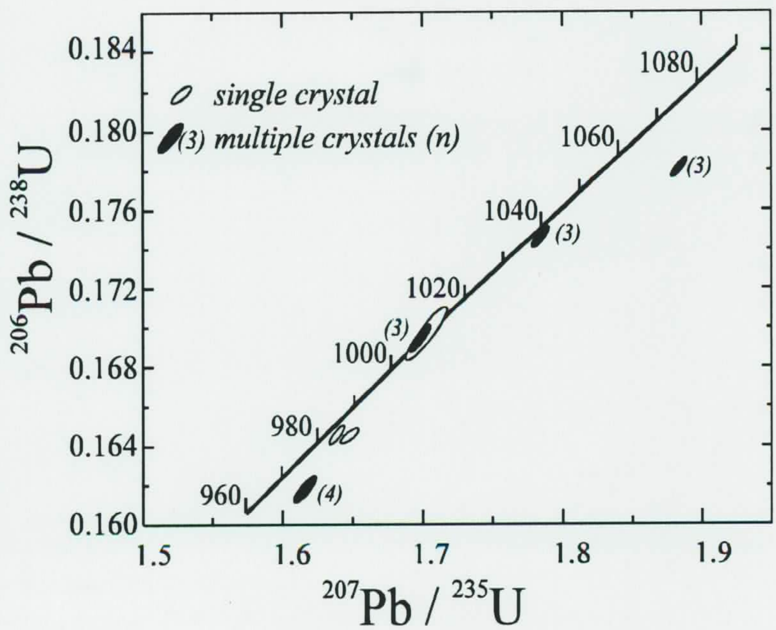

Figure 5. Concordia plot of single and multi-grain detrital zircons.

measure of crystallization age. All analyses are less than 5% discordant and yield $^{207}Pb/^{206}Pb$ ages ranging from 992 to 1113 Ma.

Two single grains from the dominant, rounded morphological population yield 992 ± 2 and 1008 ± 6 Ma ages (Fig. 5). A single crystal tip with good euhedral morphology yields a 1005 ± 4 Ma age. Two of the four multi-grain analyses are concordant and give 1005 ± 3 Ma and 1044 ± 3 Ma ages (Fig. 5). One 3.1% discordant multi-grain analysis yields a 998 ± 4 Ma $^{207}Pb/^{206}Pb$ age, which is within analytical uncertainty of one concordant fraction and the single grains. The fraction that is 4.9% discordant yields a $^{207}Pb/^{206}Pb$ age of 1113 ± 2 Ma. This fraction was selected from a morphologically subordinate population composed of elongate zircon crystals with rounded terminations. We interpret the age to result from: (1) recent Pb loss from a ca. 1113 Ma source, (2) mixing of ca. 1005 and 1750 Ma grains, or (3) some combination of 1 and 2. Based on crystal size, limited zircon morphology, and U-Pb ages from single grains and multiple crystal fractions, we interpret the detrital zircon data from this quartzite sample to suggest that a dominant component of the Trap Falls Formation was derived from a ca. 1000-1050 Ma plutonic terrane.

Discussion

The geochemistry of the Trap Falls Formation is consistent with a sedimentary protolith. High SiO_2 and elevated Zr in the quartzites are suggestive of a clean quartz sands, and the highly aluminous nature of the schists is consistent with metamorphosed muds. Thus, we consider that the Trap Falls Formation is likely the product of deformation and metamorphism of interbedded carbonate-bearing quartz sands and muds. Quartz-rich sands are often associated with tectonically quiet, trailing- edge type margins (Dickinson, 1988; McLennan et al., 1990). The composition of the Trap Falls Formation, therefore, suggests that it was deposited in a tectonically stable environment. REE patterns for the Trap Falls Formation parallel PAAS, suggesting that the composition of the source is similar to that of average upper crust (Taylor and McLennan, 1985). In contrast, sediment derived from basins marginal to island arcs tend to have patterns that are less LREE-enriched with less well-developed Eu anomalies (McLennan et al., 1990). Using sediment compositions for tectonic discrimination is not without caveats, however. Sedimentary compositions describe provenance, which in turn is used to infer tectonic environment. Sediments can be derived from sources that are not directly related to the tectonics of the depositional basin. Thus, although the composition of the samples suggests a stable cratonic depositional basin, and we favor this interpretation, we cannot exclude an active margin setting for the Trap Falls Formation.

Nd model ages for the Trap Falls Formation (T_{DM} from 1680 to 1780 Ma) are older than published model ages for the Grenville Province (1100 to 1500 Ma; Patchett and Ruiz, 1989; Daly and McLelland, 1991; McLelland et al., 1993). This suggests that there is some component of ancient crust in the source of the Trap Falls Formation, however the proportion required to produce the difference in compositions would be small (arrows, Fig. 3). The Pb isotopic composition of the Grenville Province varies widely, but in some cases compares favorably with Trap Falls Formation compositions (e.g., Sinha et al., in press). The database of Grenville Nd compositions is scarce, particularly in the Appalachian region, and it is probable that Grenville terranes with a greater incorporation of recycled basement have older Nd model ages.

Many Grenville-aged plutons consist of 1150-1100 Ma crystallization ages (Easton 1986), however in the Hudson Highlands of eastern New York, Grenville gneisses yield U-Pb zircon ages ranging from ~1170 to ~1060 Ma (Tilton et al., 1960; Aleinikoff, 1985). In addition, Karabinos and Aleinikoff (1990) have identified a small but significant suite of granites with 950 Ma U-Pb zircon age in western New England. In Quebec, the Grenville Labrieville massif yields 1010 to 1008 Ma U-Pb zircon ages (Owens et al., 1994). Thus, U-Pb ages of detrital zircons from the Trap Falls Formation are consistent with derivation from relatively young plutonic rocks of the Grenville Province.

The sum of the data for the Trap Falls Formation indicates that the provenance is dominated by approximately 1000 Ma Grenville Province rocks. We cannot rule out the possibility that there is an older crustal component within the provenance, but neither is it required. Nd isotopes, in particular, suggest an older crustal component. Given the limited database for Grenville Province Nd compositions, however, together with the wide range in Pb isotopic compositions, we consider that model ages on the order of 1700 Ma may well be present in the Appalachian Grenville Belt. The 1113 Ma multi-grain zircon age may result from a mixture of ca. 1000 Ma zircons with older, ca. 1750 Ma zircons, however it may also simply reflect recent Pb loss in a 1113 Ma zircon population. Thus, although our data suggest a mixture of Grenville and older components in the provenance, it is unclear whether the older component represents a distinct terrane or was itself incorporated within the Grenville Province.

Conclusions

From physical observations, geochemistry, Nd- and Pb- isotopic compositions, and detrital zircon ages, we make the following interpretations about the origin, age, and source of the Trap Falls Formation:

1. The protolith likely consisted of aluminous muds interlayered with clean, carbonate-bearing quartz sands, implying an environment of cyclic deposition. For example, the sediment may have been deposited as turbidites or in a tidal environment.

2. The depositional age of the Trap Falls Formation is constrained from geochronology to be between 409 Ma (garnet growth; Lanzirotti and Hanson, 1994), and 994 Ma (youngest detrital zircon age, this study).

3. The geochemistry of the samples indicates that the sediments were clean, virtually pure quartz sands, and weathered aluminous muds. This may indicate derivation from pre-existing sedimentary rocks (multi-cycle sediment), or may be the result of deposition in an environment where there is ample opportunity and means for continued chemical weathering and winnowing. The compositions are consistent with deposition in a tectonically stable cratonic environment. The possibility that the composition is inherited from a rising highlands source that consists largely of sedimentary rock (e.g., an accretionary wedge associated with the Taconian orogeny) however, cannot be discounted.

4. The provenance of the sediment consists, on average, of old crustal terranes, with crustal residence ages on the order of 1700 Ma. Pb isotopes are consistent with a source from the Grenville Province. Detrital zircons are dominated by approximately 1000 Ma U-Pb ages. If there are older or younger zircons in the sands, they are either not populous enough to be represented in the analyses (we analyzed 16 zircons), or have characteristics (e.g., size, optical clarity) that are detrimental totheir selection for analysis. The detrital zircon ages, along with the whole-rock isotopic analyses provide strong evidence that Grenville-age rocks with significant ancient crustal incorporation are the major component of the provenance of the Trap Falls Formation.

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