Postmetamorphic unroofing history deduced from petrology, fluid inclusions, thermochronometry, and thermal modeling: An example from southwestern New England

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ABSTRACT

Nonlinear unroofing rates from ~10 to <1 mm/yr following high-pressure Acadian (Devonian) metamorphism have been documented in southwestern New England by using combined petrologic, fluid inclusion, thermochronometric, and thermal modeling techniques. Thermobarometry of pelitic schists from the Rowe-Hawley belt of western Connecticut indicates peak Acadian pressure-temperature conditions of 8.2 kbar and 575 °C. Densities of CO_2- and H_2O-rich fluid inclusions require nearly isothermal decompression followed by more isobaric cooling from these conditions. Comparison of this observed path to those generated by thermal models suggests that decompression was characterized by initial rapid upward en bloc velocity (~1 cm/yr) of brief duration, followed by much slower unroofing rates (≤0.3 mm/yr). Published geochronologic ages in this region constrain the rapid uplift to the Middle Devonian, and uplift slowed dramatically by the end of the Devonian. This differential uplift has major implications for interpretation of Devonian igneous activity and sedimentation in southwestern New England.

INTRODUCTION

Studies of mineral equilibria as recorded by mineral compositions, zoning, and solid inclusions provide a powerful means of determining metamorphic pressure-temperature (*P-T*) paths (e.g., Spear et al., 1984). Application of this approach is limited by the availability of suitably constrained mineral assemblages. This is especially true for parts of *P-T* paths following peak conditions where mineral assemblages commonly do not reequilibrate. Resolution of later parts of *P-T* paths is critical because most geochronologic constraints to cooling history apply to conditions below ~500 °C (e.g., Sutter et al., 1985).

Fluid inclusions can provide a means of evaluating peak conditions of metamorphism (Crawford, 1981), *P-T* conditions during uplift (Hollister et al., 1979), and direct evidence of metamorphic fluid composition (e.g., Frey et al., 1980). These applications are limited by the tendency of inclusions to reequilibrate during decompression. However, this tendency enables fluid inclusions to record later parts of *P-T* paths, and thus combined mineral equilibrium and fluid inclusion studies can yield constraints that are not generally available when the techniques are applied singly. In this study we have evaluated the *P-T* path of part of the Rowe-Hawley belt of western Connecticut by using petrologic and fluid inclusion techniques; these data were combined with geochronologic constraints of the region to derive the *P-T-t* (time) path. We then compare this path to paths generated by thermal models to evaluate crustal processes during decompression. This approach is essentially the inverse to studies that extrapolate model paths from crustal constraints and then use them to evaluate regional geologic history (e.g., Chamberlain and England, 1985).

The Rowe-Harley belt (Fig. 1) represents part of the Iapetus eugeocline that was transported westward and variably metamorphosed during the Taconian orogeny (Stanley and Ratcliffe, 1985). Within western Connecticut, the Rowe-Hawley belt was remetamorphosed to amphibolite grade during the Acadian orogeny (Sutter et al., 1985; Dietsch and Sutter, 1987). Samples considered in this study are from the Roxbury 7½-minute quadrangle (Gates, 1959), west of the Waterbury dome, where the Rowe-Hawley belt consists of pelitic and mafic schists, quartzites, and small granitic bodies. Figure 1 is within the Acadian kyanite-staurolite zone of Robinson (1982); peak metamorphic conditions in the vicinity of the Waterbury dome were 550–600 °C and 5–8 kbar (Dietsch, 1988).

MICROSTRUCTURES AND PETROLOGY

Pelitic schists of the Rowe-Hawley belt typically contain quartz, muscovite, biotite, chlorite, and ilmenite, as well as one or more of the

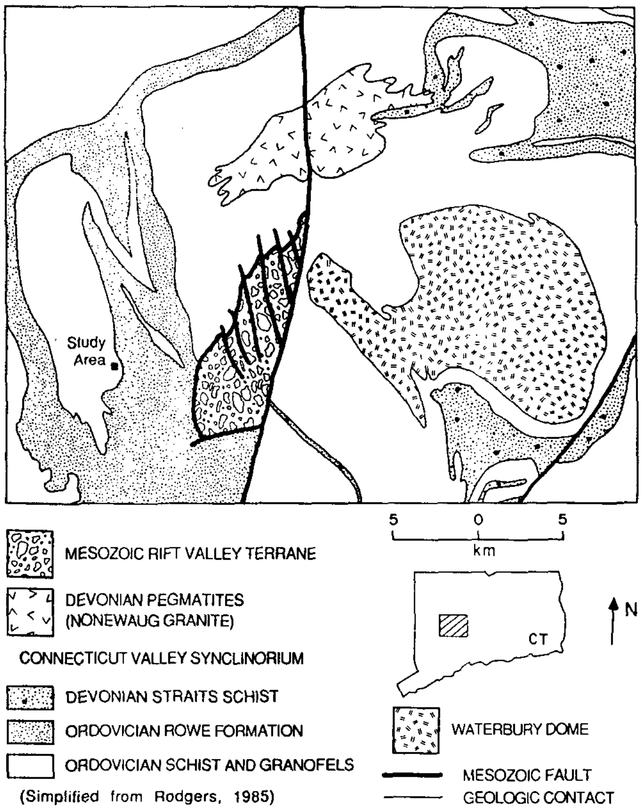

Figure 1. Location of study area within part of area of tectonic map of Connecticut.

Note: Additional material for this article is Supplementary Data 8913, available on request from the GSA Documents Secretary (see footnote 1).

phases garnet, kyanite, staurolite, and plagioclase. Garnet and staurolite occur as porphyroblasts that contain quartz and ilmenite inclusions defining a plane concordant with schistosity. These internal surfaces are locally sigmoidal, suggesting syndeformation to postdeformation porphyroblast development. Chlorite occurs as lath-shaped crystals that parallel schistosity and appear to be prograde. Kyanite is locally abundant, yet coexisting garnet and kyanite were not observed. Intracrystalline strain features (e.g., undulose extinction, subgrains) were not observed, and grain boundaries among quartz and feldspar form 120° triple junctions, indicating postdeformational annealing of minerals.

Two or three domains containing garnet + biotite or garnet + biotite + plagioclase + muscovite + quartz were analyzed for each sample. Rim compositions of adjacent minerals were averaged to obtain the components and associated uncertainties summarized in Table 1.[1] Mineral compositions were determined by using an ARL-SEMQ electron microprobe at Virginia Polytechnic Institute (analytical scheme discussed in Solberg and Speer, 1982). Mineral formulas were calculated on the basis of number of oxygens per anhydrous formula.

Compositions and textural relations in the assemblage quartz + muscovite + garnet + biotite + staurolite + chlorite suggest the reaction

$$\text{garnet} + \text{muscovite} + \text{chlorite} = \text{staurolite} + \text{biotite} + \text{quartz} + H_2O. \quad (1)$$

In the model KFMASH system, this reaction is univariant and buffers H_2O activity at either specific pressure or temperature. This suggests that the assemblage is unlikely for a rock in which fluid composition is controlled externally, but is very reasonable if fluid composition is internally controlled (e.g., Guidotti, 1974). The analyzed sample contains no carbonate minerals, and no calcareous units have been observed in the vicinity of the sample locality. The H_2O:CO_2 ratio of fluids present during metamorphism cannot be calculated because of the absence of carbon-bearing phases. However, sample occurrence and mineralogy qualitatively indicate that metamorphic fluids evolved predominantly through dehydration reactions and that fluid composition was internally controlled.

TABLE 1. DATA USED TO CONSTRAIN PEAK METAMORPHIC CONDITIONS IN FIGURE 2

Mineral*	Component	Mole fraction	Uncertainty†
Garnet	Almandine	0.7470	0.0155
n = 6	Pyrope	0.0983	0.0166
	Spessartine	0.0090	0.0059
	Grossular	0.1457	0.0257
Biotite	Annite	0.4224	0.0082
n = 16	Phlogopite	0.3894	0.0099
Muscovite	Al^{VI}	0.9290	0.0066
n = 8	K/Σ(alkalis)	0.7706	0.0221
	Na/Σ(alkalis)	0.2275	0.0214
Plagioclase	Albite	0.6966	0.0477
n = 24	Anorthite	0.2919	0.0434

* n = number of analyses.
† Uncertainty is 2σ.

Peak metamorphic temperatures were estimated by using the Hodges and Spear (1982) modification of the Ferry and Spear (1978) calibration for Fe-Mg partitioning between garnet-biotite. Peak metamorphic pressures were estimated by using the calcium exchange reaction between garnet and plagioclase expressed by

$$\text{almandine} + \text{grossular} + \text{muscovite} = \text{annite} + \text{anorthite}. \quad (2)$$

Reaction 2 was calibrated empirically by Ghent and Stout (1981) by using ideal solution models and by Hodges and Crowley (1985), who used a larger data set and solution models consistent with Hodges and Spear (1982).

Simultaneous solution of the thermobarometric equilibrium expressions of Hodges and Spear (1982) and Hodges and Crowley (1985) by using data from Table 1 yields 575 °C and 8.2 kbar. We defined a 95% confidence interval ellipse for this solution (Fig. 2) using a Monte Carlo–type propagation of uncertainties as described by Hodges and McKenna (1987); the mineral component standard deviations of Table 1 were the basis for this error propagation, and thus the ellipse represents the precision (combined analytical error and natural sample variability) of the *P-T* estimate. This treatment indicates an uncertainty of ±60 °C and 1.6 kbar (2σ), which is consistent with commonly accepted uncertainties for these equilibria and is primarily a function of the grossular and anorthite uncertainties. Also shown in Figure 2 are the *P-T* projections of reaction 1 (Guidotti, 1974), the aluminum silicate triple point (Holdaway, 1971), and fluid inclusion isochores described below.

FLUID INCLUSIONS

Doubly polished sections were examined on a petrographic microscope equipped with a gas-flow heating-freezing stage. Measured temperatures have a precision and accuracy of ±0.1 °C at temperatures $\leq$50 °C, and ±2.5 °C at temperatures around 375 °C (Sterner et al., 1988). Fluid isochores were calculated by using the modified Redlich-Kwong equations of Holloway (1981; corrected to make the *a* term temperature dependent) and data extrapolated from Potter (1977).

Matrix quartz in these samples contains inclusions of varying morphology and composition. CO_2-rich inclusions are present as equant, solitary inclusions up to 4 μm in diameter and in decrepitation clusters up to 100 μm across. H_2O-rich inclusions ranging from 1 to 5 μm in diameter are both solitary and within planes. Veins of coarse-grained quartz that locally crosscut the foliation contain only H_2O-rich inclusions.

Figure 2 shows the range of isochores defined by the different types of inclusions. All CO_2-rich inclusions homogenize to the liquid phase between −4.3 and +6.2 °C (average bulk density = 0.866 g/cm^3; *n* = 19), and melt at −59.3 to −57.0 °C (*n* = 20). The freezing point of these inclusions is depressed between 0.4 and 1.7 °C below that of pure CO_2, suggesting the presence of a phase with a freezing point lower than CO_2. This component is most likely CH_4 (assuming that it is within the C-O-H system). There is no systematic relation between the densities of the solitary and decrepitated CO_2-rich inclusions, and therefore all CO_2 inclusions appear to have reequilibrated during decompression.

Bulk densities of the H_2O-rich inclusions display systematic variations. H_2O-rich inclusions within matrix quartz homogenize to the liquid phase at 259 to 332.0 °C (*n* = 17). H_2O-rich inclusions within veins of quartz that cut the foliation are consistently of higher density and homogenize to the liquid phase in the relatively narrow range 228 to 247.8 °C (*n* = 9). This record is interpreted to reflect entrapment and/or reequilibration of H_2O-rich inclusions within the matrix over a wide range of conditions, and entrapment of H_2O-rich inclusions within veins over a relatively narrow range of conditions late in the uplift history. The H_2O-rich inclusions have freezing temperatures of −8.5 to −6.5 °C (*n* = 7), indicating an average salinity of ~10 wt% NaCl-equivalent.

CONSTRAINTS ON THE METAMORPHIC AND DECOMPRESSION HISTORY

The phenomenon commonly referred to as uplift is the decompression that may occur through rigid-block uplift and erosion, extensional deformation along low-angle normal faults, and ductile thinning of the crust, and may collectively be referred to as unroofing (Haugerud and Zen, 1989). One-dimensional modeling of metamorphic *P-T* paths commonly predicts rapid decompression and maintenance of temperatures within ~15 °C of peak metamorphic conditions for a significant part of the metamorphic history (England and Thompson, 1984), resulting from the relative inefficiency of crustal conductive heat transport. Decompression rates inferred from geochronologic studies typically vary from 0.1 to 1.0 mm/yr (e.g., Clark and Jager, 1969), reflecting combined uplift, erosion, and tectonic denudation processes integrated over tens of millions of years. In contrast, estimates of modern (instantaneous) rates of uplift are as much as ~1.0 cm/yr (e.g., Bull and Bull, 1984). The amount of tectonic denudation (through penetrative ductile strain or normal faulting) is a function of strain rate,

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[1] A complete list of mineral compositions, analysis maps of individual samples, and field coordinates, GSA Supplementary Data 8913, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301.

which is generally constrained by strain analysis and *P-T-t* path studies to ~10^{-16}/s to 10^{-14}/s (Pfiffner and Ramsay, 1982; Haugerud and Zen, 1989).

T-t parts of *P-T-t* paths are usually constrained by mineral thermochronometry, which optimally records the time of cooling to a temperature equal to the closure temperature for that mineral at a specific rate of cooling; the slower the rate of cooling, the lower the closure temperature for that mineral will be (e.g., Dodson, 1973). Conventional K/Ar and $^{40}Ar/^{39}Ar$ incremental-release dating techniques are most widely used for thermochronometry. The closure temperature for Ar diffusion in hornblende varies from ~450 to 520 °C; cooling rates are between 1 and 100 °C/m.y. (Harrison, 1981), and empirical studies indicate that for regional metamorphic cooling rates, Ar is retained in muscovite at ~300 °C (cf. Harrison and McDougall, 1980; Sutter et al., 1985). Amphibole and muscovite from staurolite-grade cover sequences that mantle the Waterbury dome record dates of 376 ±4 and 358 ±10 Ma, respectively (2σ uncertainty; Dietsch and Sutter, 1987), which indicates an average cooling rate of ~11°C/m.y. following Acadian metamorphism in this area. This rate is consistent with other studies in the Connecticut Valley synclinorium that suggest relatively rapid cooling following peak Acadian *P-T* conditions (Sutter and Hatch, 1985; Sutter et al., 1985). Dietsch and Sutter (1987) noted that there is apparently no thermal record of Alleghanian tectonics in the vicinity of the Waterbury dome.

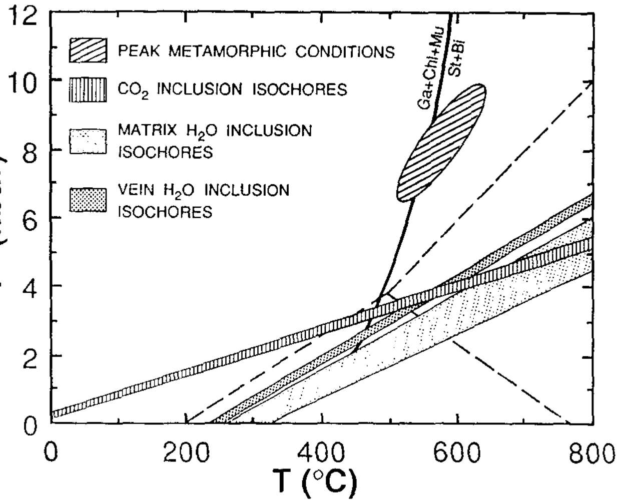

Figure 2. Estimated peak metamorphic conditions for study area, represented by 95% confidence level ellipse. Also shown are reaction 1 (Guidotti, 1974), aluminum silicate triple point (Holdaway, 1971), and fluid inclusion isochores discussed in text.

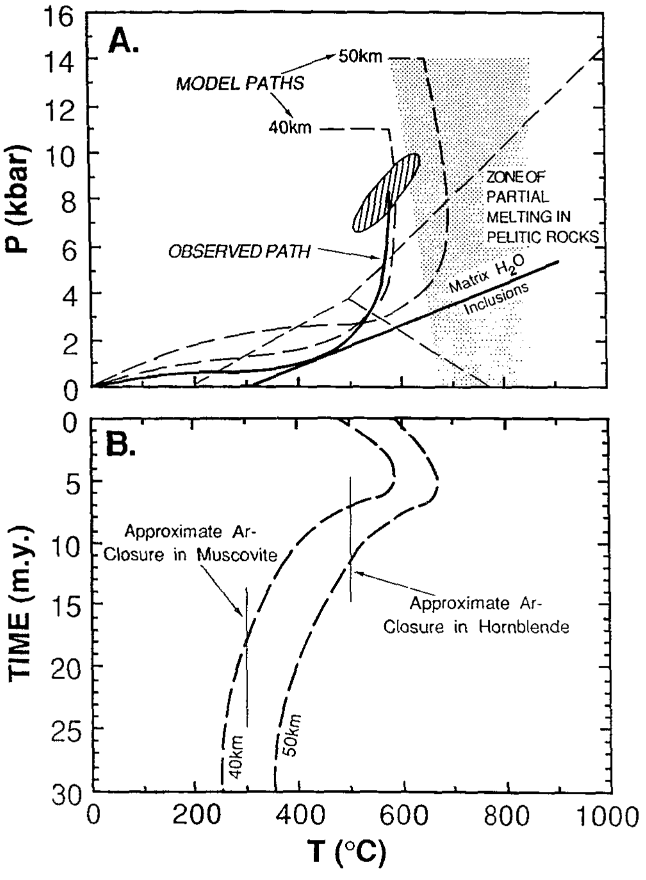

Figure 3. A: *P-T* projection of observed unroofing path indicated by petrologic and fluid inclusion data of Figure 2 and two model paths generated by one-dimensional model of Haugerud (1986). Zone of partial melting in pelitic rocks is from Thompson (1982). B: *T-t* projection of model paths.

DISCUSSION

Figure 3A shows the decompression path required by the petrologic and fluid inclusion data of Figure 2. The least dense (lowest slope) H_2O isochore provides the principal constraint to the unroofing path (see Hollister et al., 1979, for review of fluid inclusion data interpretation). Numerous paths could be drawn through this isochore, and we chose one that is consistent with the interpretation that (1) the temperature during decompression was never above that indicated by the mineral assemblage, and (2) the range of H_2O isochores reflects entrapment/reequilibration over a range of conditions, ending with vein formation. Any path drawn through these isochores will require a nearly isothermal early decompression.

Also shown in Figure 3A are two model paths generated by the one-dimensional thermal model of Haugerud (1986) by using parameters listed in Table 2, and Figure 3B presents their corresponding *T-t* paths. The model paths were constructed on the basis of available geochronologic data and *P-T* data of this study, by considering parts of crust initially emplaced at 40 and 50 km beneath a single 20-km-thick thrust slab. The model path that begins at 40 km most closely approximates the observed path and requires a maximum uplift rate of 2.0 mm/yr and a maximum internal strain rate of 1.7 × 10^{-14} · s^{-1}. The combined result of these processes (by comparison of Fig. 3A and 3B) is unroofing at ~1.0 cm/yr for an ~2 m.y. interval. The uplift rate can be decreased (or increased) without changing the model path if balanced by an increase (or decrease) in the strain rate. The prograde path is sensitive to a choice of single vs. multiple thrusts; however, any combination that reproduces the observed decompression requires a very rapid and brief initial unroofing.

Combination of the observed path with the $^{40}Ar/^{39}Ar$ data of Dietsch and Sutter (1987) indicates an average unroofing rate of ~0.3 mm/yr between the closure temperatures of hornblende and muscovite. This apparent conflict with the much greater initial unroofing rate may be resolved by noting that the cooling ages only relate to the part of the path between ~500 and 300 °C, and therefore at best provide only a minimum constraint to the initial unroofing rate. This relation is illustrated in Figure 3B, where the 40 km model path represents rapid cooling (>70 °C/m.y.) from amphibolite-grade conditions through the Ar retention temperature of hornblende and slower cooling through the Ar retention temperature in muscovite

(~10 °C/m.y.), yielding an average cooling rate of ~15 °C/m.y.

CONCLUSIONS

Combined fluid inclusion and mineral equilibrium data indicate that parts of the Rowe-Hawley belt underwent extremely rapid initial unroofing following high-pressure Acadian amphibolite-grade metamorphism. This resulted in a *P-T* path with relatively isothermal decompression followed by more nearly isobaric cooling. Comparison of the observed path with theoretical models shows that such decompression can best be accounted for by rapid uplift with concomitant erosion and tectonic denudation; the net result of these processes was a maximum unroofing rate of ~1 cm/yr. Consideration of the thermal history of the Acadian event as recorded by $^{40}Ar/^{39}Ar$ dates suggests that this rapid movement characterized only the initial part of the path, and late-stage unroofing was ≤0.3 mm/yr.

Differential uplift rates during the Devonian have several implications for interpretation of igneous activity and sedimentation in southern New England. Crust below the present erosion surface, represented by the 50 km model path, passed well within the field of partial melting in pelitic rocks during unroofing. Postdeformational pegmatitic intrusions are widespread within the Connecticut Valley synclinorium. These intrusions locally coalesced into very coarse grained plutons (Fig. 1), the largest of which (Nonewaug Granite) has a crystallization age of 383 ±10 Ma (Mose and Nagle, 1982). We believe that these intrusions represent melts formed during rapid decompression of pelitic crust along paths similar to the 50 km path, and that rapid initiation of unroofing may have prevented formation of larger plutons.

Tectonic studies in the Appalachian mountain belt have long associated Devonian clastic sedimentation with the Acadian orogeny (e.g., Rodgers, 1967). The coarsest and thickest accumulations of Devonian sediment were deposited in the northern Catskill delta as alluvial fans during the Middle and Late Devonian, and the Acadian mountain range virtually ceased to be a sediment source to the northern Catskills by the end of the Devonian (Fail, 1985). This depositional history is consistent with the differential uplift rates we report for the Acadian mountain range of southwestern New England. The overall depositional setting of the Catskill delta has been interpreted as a result of transcurrent plate motion (Ettensohn, 1985). Alternatively, this study suggests that the differential sedimentation in the northern Catskills reflects rapid Middle Devonian unroofing driven by extreme tectonic thickening in the Acadian mountain belt.

TABLE 2. DATA AND PARAMETERS USED IN FIGURE 3

The model unroofing histories are treated in five stages:

Stage	Duration (m.y.)	Uplift rate (mm/yr)	Strain rate (s^{-1})
1	1.0	1.0	1.0×10^{-15}
2	2.0	2.0	1.7×10^{-14}
3	1.0	1.0	1.0×10^{-16}
4	1.5	0.2	No tectonic thinning
5	95	0.1	" " "

Note: Thermal conductivity: 3.00 $W \cdot m^{-1} \cdot K^{-1}$;
density: 2700 $kg \cdot m^{-3}$;
basal flux: 0.035 $W \cdot m^{-2}$;
heat generation in crust: 1.7×10^{-6} $W \cdot m^{-3}$;
thickness of thrust sheet: 20 km;
lag time between thrust event and uplift: 3 m.y.

This study emphasizes that the assumptions required to extrapolate *P-T-t* paths from a single *P-T* or *T-t* technique often negate the potential to evaluate crustal processes that formed the path. This is especially true of mineral thermochronometry in medium- to high-grade metamorphic rocks if much of the *P-T-t* path resides close to peak metamorphic temperatures (above the closure temperature interval) and/or the cooling rate was nonlinear. Fluid inclusion data can be especially useful to the interpretation of decompression paths because their realm of formation is commonly within mineral-chronometer closure temperature intervals.

REFERENCES CITED

Bull, W.B., and Bull, R.P., 1984, Tectonic significance of rounded quartz pebbles on the Southern Alps of New Zealand: Geological Society of America Abstracts with Programs, v. 16, p. 458.

Chamberlain, C.P., and England, P.C., 1985, The Acadian thermal history of the Merrimac synclinorium in New Hampshire: Journal of Geology, v. 93, p. 593–602.

Clark, S.P., and Jager, E., 1969, Denudation rate in the Alps from geochronologic and heat flow data: American Journal of Science, v. 267, p. 1143–1160.

Crawford, M.L., 1981, Fluid inclusions in metamorphic rocks—Low and medium grade, *in* Short course in fluid inclusions: Mineralogical Association of Canada Short Course Handbook 6, p. 157–176.

Dietsch, C.W., 1988, Geology of the Waterbury Dome [Ph.D. thesis]: New Haven, Connecticut, Yale University, 333 p.

Dietsch, C.W., and Sutter, J.F., 1987, $^{40}Ar/^{39}Ar$ age spectrum data bearing on the polyphase thermal and tectonic evolution of the Connecticut Valley synclinorium, SW New England, U.S.A. (Evolution of metamorphic belts, metamorphic studies group, Joint Meeting with IGCP project 235): Dublin, Ireland, University College, p. 6.

Dodson, M.H., 1973, Closure temperature in cooling geochronological and petrologic systems: Contributions to Mineralogy and Petrology, v. 40, p. 259–274.

England, P.C., and Thompson, A.B., 1984, Pressure-temperature-time paths of regional metamorphism I. Heat transfer during the evolution of thickened continental crust: Journal of Petrology, v. 25, p. 894–928.

Ettensohn, F.R., 1985, The Catskill delta complex and the Acadian orogeny: A model, *in* Woodrow, D.L., and Sevon, W.D., eds., The Catskill delta: Geological Society of America Special Paper 201, p. 39–49.

Fail, R.T., 1985, The Acadian orogeny and the Catskill delta, *in* Woodrow, D.L., and Sevon, W.D., eds., The Catskill delta: Geological Society of America Special Paper 201, p. 15–38.

Ferry, J.M., and Spear, F.S., 1978, Experimental calibration of the partitioning of Fe and Mg between garnet and biotite: Contributions to Mineralogy and Petrology, v. 66, p. 113–117.

Frey, M., Bucher, K., Frank, E., and Mullis, J., 1980, Alpine metamorphism along the geotraverse Basel-Chiasso—A review: Eclogae Geologicae Helvetiae, v. 73, p. 527–546.

Gates, R.M., 1959, Bedrock geology of the Roxbury quadrangle, Connecticut: U.S. Geological Survey Geologic Quadrangle Map GQ 60-121, scale 1:24,000.

Ghent, E.D., and Stout, M.Z., 1981, Geobarometry and geothermometry of plagioclase-biotite garnet-muscovite assemblages: Contributions to Mineralogy and Petrology, v. 76, p. 92–97.

Guidotti, C.V., 1974, Transition from staurolite to sillimanite zone, Rangeley quadrangle, Maine: Geological Society of America Bulletin, v. 85, p. 475–490.

Harrison, T.M., 1981, Diffusion of ^{40}Ar in hornblende: Contributions to Mineralogy and Petrology, v. 78, p. 324–331.

Harrison, T.M., and McDougall, I., 1980, Investigations of an intrusive contact, northwest Nelson, New Zealand—I. Thermal, chronological, and isotopic constraints: Geochimica et Cosmochimica Acta, v. 44, p. 1985–2003.

Haugerud, R.A., 1986, 1DT—An interactive, screen-oriented microcomputer program for simulation of 1-dimensional geothermal histories: U.S. Geological Survey Open-File Report 86-511, 19 p. and 5/14″ diskette.

Haugerud, R.A., and Zen, E-an, 1989, Metamorphic path studies—A critique and prospectus, *in* Perchuk, L.L., ed., Advances in geochemistry (D.S. Korzhinskiy volume): New York, Springer-Verlag (in press).

Hodges, K.V., and Crowley, P.D., 1985, Error estimation and empirical geothermobarometry for pelitic systems: American Mineralogist, v. 70, p. 702–709.

Hodges, K.V., and McKenna, L.W., 1987, Realistic propagation of uncertainties in geologic thermobarometry: American Mineralogist, v. 72, p. 671–680.

Hodges, K.V., and Spear, F.S., 1982, Geothermometry, geobarometry, and the Al_2SiO_5 triple point at Mt. Moosilauke, New Hampshire: American Mineralogist, v. 67, p. 1118–1134.

Holdaway, M.J., 1971, Stability of andalusite and the aluminosilicate phase diagram: American Journal of Science, v. 271, p. 97–131.

Hollister, L.S., Burruss, R.C., Henry, D.L., and Hendel, E.M., 1979, Physical conditions during uplift of metamorphic terranes, as recorded by fluid inclusions: Bulletin de Minéralogie, v. 102, p. 555–561.

Holloway, J.R., 1981, Compositions and volumes of supercritical fluids in the Earth's crust, *in* Short course in fluid inclusions: Mineralogical Association of Canada Short Course Handbook 6, p. 13–38.

Mose, D.G., and Nagel, M.S., 1982, Chronology of metamorphism in western Connecticut: Rb-Sr ages, *in* Joesten, R., and Quarrier, S., eds., Guidebook for field trips in Connecticut and south-central Massachusetts, New England Intercollegiate Geological Conference: Connecticut Geological and Natural History Survey, Guidebook 5, p. 247–263.

Pfiffner, O.A., and Ramsay, J.G., 1982, Constraints on geological strain rates; arguments from finite strain states of naturally deformed rocks: Journal of Geophysical Research, v. 87, p. 311–321.

Potter, R.W., 1977, Pressure corrections for fluid-inclusion homogenization temperatures based on the volumetric properties of the system NaCl-H_2O: U.S. Geological Survey Journal of Research, v. 5, p. 603–607.

Robinson, P., 1982, Realms of metamorphism in southern New England, with emphasis on the eastern Acadian metamorphic high, *in* Schenk, P.E., et al., eds., Regional trends in the geology of the Appalachian-Caledonian-Hercynian-Mauritanide orogen: Dordrecht, Holland, D. Reidel, p. 249–259.

Rodgers, J., 1967, Chronology of tectonic movements in the Appalachian region of eastern North America: American Journal of Science, v. 265, p. 408–427.

—— 1985, Bedrock geologic map of Connecticut: Hartford, Connecticut Geological and Natural History Survey, scale 1:125,000.

Solberg, T.N., and Speer, J.A., 1982, QALL, a 16-element analytical scheme for efficient petrologic work on an automated ARL-SEMQ: Application to mica reference samples, *in* Heinrich, K.F., ed., Microbeam analysis: San Francisco, San Francisco Press, p. 422–426.

Spear, F.S., Selverstone, J., Hickmott, D., Crowley, P., and Hodges, K.V., 1984, *P-T* paths from garnet zoning: A new technique for deciphering tectonic processes in crystalline terranes: Geology, v. 12, p. 87–90.

Stanley, R.S., and Ratcliffe, N.M., 1985, Tectonic synthesis of the Taconian orogeny in western New England: Geological Society of America Bulletin, v. 96, p. 1227–1250.

Sterner, S.M., Hall, D.L., and Bodnar, R.J., 1988, Synthetic fluid inclusions V. Solubility relations in the system NaCl-KCl-H_2O under vapor-saturated conditions: Geochimica et Cosmochimica Acta, v. 52, p. 988–1005.

Sutter, J.F., and Hatch, N.L., 1985, Timing of metamorphism in the Rowe-Hawley zone, western Massachusetts: Geological Society of America Abstracts with Programs, v. 17, p. 65.

Sutter, J.F., Ratcliffe, N.M., and Mukasa, S.B., 1985, $^{40}Ar/^{39}Ar$ and K-Ar data bearing on the metamorphic and tectonic history of western New England: Geological Society of America Bulletin, v. 96, p. 123–136.

Thompson, A.B., 1982, Dehydration melting of pelitic rocks and the generation of H_2O-undersaturated granitic liquids: American Journal of Science, v. 282, p. 1567–1595.

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