ABSTRACT

$^{40}$Ar/$^{39}$Ar dating of hornblende, muscovite, and orthoclase from southeastern Quebec provides new constraints on the timing, grade, and regional extent of Taconian and Acadian metamorphism in the Canadian Appalachians. Muscovite ages reveal that the Taconic orogeny occurred at ca. 463 Ma throughout the region. Lack of reset amphibole indicates that the metamorphic grade did not exceed greenschist facies. Acadian metamorphism, with a peak of $<$350 °C, is recorded by an orthoclase cooling age of 377 ± 4 Ma. This later metamorphism partially reset finer-grained muscovite toward the Vermont border. The calculated 300–340 °C closure temperature of orthoclase indicates that this age currently provides the closest estimate of the timing of peak Acadian metamorphism north of New England. Despite the lower grade of Taconian and Acadian metamorphism in Quebec compared to New England, peak temperatures appear to have been achieved synchronously. In addition, investigation of the timing of pre-Taconic decoupling of the Quebec oceanic fragments suggests a protracted obduction history. Obduction may have displaced slivers of both the subducting and overthrusting oceanic plates.

INTRODUCTION

The effects of two orogenic episodes are recorded in the rocks of the Quebec Appalachians. The Taconic orogeny, caused by the attempted subduction of the Laurentian margin, resulted in ophiolite obduction and related Ordovician thrust stacking, early cleavage development, and folding (Tremblay, 1992; Pinet and Tremblay, 1995). Overprinting structural elements were imparted during the Devonian Acadian orogeny, in response to the docking of the Avalon superterrane (Cousineau and Tremblay, 1993; Tremblay and Pinet, 1994). Peak greenschist-facies metamorphism has been attributed to either the Taconic or the Acadian events (Tremblay and St-Julien, 1990; Tremblay and Pinet, 1994) depending on location in the orogen. Although pressure-temperature-time compilations have been made for the Appalachian orogen to the south and east of the Canada-U.S. border in New England (Laird et al., 1984; Osberg et al., 1989; Drake et al., 1989; Rast and Skehan, 1993), few comparative studies exist for the adjacent Quebec Appalachians, and age constraints are sparse. Rapid decreases in both Taconian and Acadian grades of metamorphism into Canada inhibit simple northward extrapolation of pressure-temperature conditions. In order to provide new constraints on the grade, timing, and regional extent of Taconian and Acadian metamorphism in southeastern Quebec (Fig. 1), several minerals have been dated by the $^{40}$Ar/$^{39}$Ar incremental heating technique. 1

REGIONAL SETTING

The samples in this study, which include hornblende, muscovite, and orthoclase, were collected from along a lineament known as the Baie Verte–Brompton line, except samples A, H, and E, which were located within 1.5 km of it (Fig. 1). The lineament separates oceanic lithologies to the southeast from continental-derived sedimentary rocks to the northwest (Williams and St-Julien, 1982). The amphibole samples (A and B) and the orthoclase sample (I) were extracted from amphibolite-facies dynamothermal soles beneath obducted oceanic fragments (Whitehead et al., 1995). These soles were formed by the accretion of overthrust rocks to the bases of displaced oceanic lithosphere during an early oceanic decoupling episode (Spray, 1984; Jamieson, 1986). The muscovite samples (E to H) were derived from continental sedimentary rocks known as the Caldwell Group, and also from emplacement-related intersheared Caldwell and sole rocks (C and D).

RESULTS

Obduction

The sole to the Thetford Mines ophiolite yields a hornblende $^{40}$Ar/$^{39}$Ar age of 477 ± 5 Ma (Whitehead et al., 1995) (Fig. 2). The similarity of this age to an ophiolite U-Pb zircon age of 479 ± 3 Ma, determined from overlying crustal plagiogranites (Dunning and Pedersen, 1988), indicates that the sole formed and cooled rapidly through the $\sim 500$ °C closure temperature of hornblende shortly after the overlying oceanic crust crystallized. The site of decoupling was therefore at or near a ridge segment. The principal heat source for the metamorphism of the accreting sole was most likely conduction from the overthrusting young, hot, displaced oceanic lithosphere (Whitehead et al., 1995). During the closure of the fore-arc
basin from which the Thetford Mines ophiolite was decoupled (Lau-
rent and Hébert, 1989), interthrusting of the oceanic crustal sheets
with the contemporary accretionary-prism units occurred. Final
continental emplacement locally juxtaposed the basal sole against
the Caldwell metasedimentary rocks, resulting in an intersheared
zone up to 6 m wide, from which muscovite samples C and D were
derived.

Two splits of an amphibole separate from amphibolites along
the Pennington sheet in the Flintkote mine were analyzed, one
unshielded to allow for the production of $^{38}\text{Ar}$ from Cl, and one with
a Cd shield. Close agreement in age spectra, isotope correlation
ages, and $^{37}\text{Ar}/^{39}\text{Ar}$ spectra is apparent in the two analyses. Mini-
mum ages of ca. 400 Ma over the first 20% of gas released may
reflect Acadian overprinting of a K-rich contaminant phase or, more
likely, overprinting of a portion of amphibole gas that is released
early in the step heating by a type of “short-circuit” diffusion (Lee,
1995). The final 70% of gas yields a near-plateau age of 496 ± 5 Ma.
The same isotope correlation age of 491 ± 11 Ma is given by the
shielded and unshielded samples. For the unshielded analysis, only
small quantities of Cl-derived $^{38}\text{Ar}$ were found, and there was no evidence of excess, Cl-correlated $^{40}\text{Ar}$.

There are no crustal rocks associated with the Pennington sheet
that can be dated so as to provide an upper limit on the timing of
the decoupling of the sheet. Consequently, no cooling rate for the
adjacent sole can be deduced, and the amphibolite age is a lower
limit to the timing of decoupling. Although the uncertainty in the
preferred age (491 ± 11 Ma) permits marginal overlap with the
Thetford Mines ophiolite sole age, it is considered probable that the
Pennington sheet was displaced from the oceanic domain before
the overlying Thetford ophiolite, consistent with a protracted obduction
period as suggested by Pinet and Tremblay (1995). In order to ex-
plain the position of the Pennington sheet to the west of and struc-
turally beneath the accretionary-prism and fore-arc ophiolite units,
we suggest that the sheet was backthrust from the subducting plate
rather than the overlying Thetford Mines fore-arc lithosphere
(Fig. 2).

Taconic Ages

Muscovite sample C yielded a plateau defined by eight steps
that make up ~80% of the gas and an age of 461 ± 3 Ma. Muscovite
sample D has a somewhat more discordant spectrum than sample C,
with an age of 464 ± 3 Ma defined by all steps except the first and
last. The spectrum for sample E has a pronounced age gradient at
low (~850 °C) extraction temperatures. At higher temperatures a
plateau is defined (nine steps, ~60% of the gas) at an age of 460 ±
3 Ma. Of the muscovites from Asbestos (samples F, G, H), only F
yielded a spectrum with a plateau. The age is 464 ± 3 Ma as defined
by ~65% of the gas over eight steps. The spectra for samples G and
H have age gradients, very pronounced in the case of sample H.

Ages defined by limited amounts of gas at the highest release
temperatures are 465 ± 5(G) and 463 ± 3 Ma (H).

These results are interpreted as cooling ages following peak
Taconic regional metamorphism. Coupled with the absence of reset
hornblends, the indication is that temperatures between ~350 °C
and 500 °C, the closure temperatures of muscovite and amphibole,
respectively, were attained (Fig. 3).

In New England, the timing of amphibolite-facies Taconic meta-
 metamorphism has been established at 465 ± 5 Ma by using $^{40}\text{Ar}/^{39}\text{Ar}$
data on hornblende ( Laird et al., 1984; Sutter et al., 1985). Monazite
in the Chain Lakes massif of Maine yielded a 468 ± 2 Ma U-Pb age
(Dunning and Cousineau, 1990). Muscovite, having a closure tem-
perature close to the greenschist-facies peak, is the best indicator of
the timing of peak-temperature conditions during the Taconic event
in southeastern Quebec. The peak temperatures thus appear to have
occurred virtually simultaneously in southeastern Quebec and New
England, despite the increase in grade into the United States
(Fig. 3).
Acadian Features

Analytical scanning-electron-microscope X-ray maps of K in low-K amphibole (0.1 wt% K) from a dynamothermal sole at Asbestos reveal orthoclase inclusions up to 0.4 by 1 μm in length (sample I). It is clear from the $^{37}$Ar/$^{39}$Ar spectrum that at low and intermediate release temperatures, the age spectrum is dominated by gas from the K-feldspar. A near-plateau age of $377^{\pm} 6^{4}$Ma for the first 85% of gas released is a strong indication that the feldspar was overprinted by the Acadian orogeny. Temperatures attained at this time were estimated as follows. The amount of feldspar gas in each heating step was first calculated by subtracting a hornblende contribution from the total $^{39}$Ar released; the hornblende component was estimated by assuming a two-component mixture and using the observed $^{37}$Ar/$^{39}$Ar ratios in conjunction with the $^{37}$Ar/$^{39}$Ar ratio of hornblende as determined from microprobe analyses of Ca and K. An Arrhenius plot, constructed by using the inferred feldspar $^{39}$Ar values along with laboratory heating times and temperatures, has a reasonably well-defined linear segment at low extraction temperatures (Fig. 2, IV). Diffusion parameters defined by this linear segment (which represents >50% of the total gas release) were used to perform a simple diffusion calculation (in which we have assumed spherical symmetry) to estimate the heating times and temperatures.

Acadian History

Pennington sheet decoupled, sole forms & cools.
TMO basin in extension - Tremadoc

II) TMO decoupling, sole formation & cooling - Arenig

III) Taconian cooling - Caradoc/Llandeilo

IV) Acadian cooling, Frasnian (Late Devonian)

Figure 2. Tectonic model and dating compilation. Lowermost plots in spectra of A, B, and I depict $^{37}$Ar/$^{39}$Ar ratios. Heights of rectangular bars in age spectra and $^{37}$Ar/$^{39}$Ar plots indicate 2σ relative uncertainties. Final ages reported to 2σ. The flux monitor used was the hornblende standard MMhb-1 (assumed age = 520 Ma; Samson and Alexander, 1987). Spectra B and I from Whitehead et al. (1995). Stage names after time scale of Harland et al. (1989). TMO—Thetford Mines ophiolite; PS—Pennington sheet.

Orthoclase closure temperature as calculated for sample I by using Dodson's (1973) formula and our diffusion parameters.
required to completely outgas the feldspar. The calculations suggest that for reasonable heating times (e.g., 1 m.y.), temperatures could have been as low as ~300 °C, but probably were at least 30–40 °C higher. Such temperatures at Acadian times appear consistent with the resetting observed in the finer-grained muscovite sample, H. However, the majority of muscovites appear unaffected or show evidence of only minor, low-temperature resetting. Thus, it appears that although Acadian structures are typically well developed in the region, the metamorphic temperatures were not high enough to disturb the coarser muscovites; i.e., probably <350 °C.

Extrapolation of the Acadian metamorphic front from Maine (Rast and Skehan, 1993) into Quebec suggests that it lies close to the ophiolites of the Baie Verte–Brompton line, which is consistent with the data presented here. Peak temperatures increase rapidly to the south, up to sillimanite–K-feldspar grade in parts of northern New England (Osberg et al., 1989). The timing of the Acadian event in western central Vermont is recorded by muscovite, biotite, and amphibole ages of 387 to 376 Ma (Lanphere et al., 1983; Laird et al., 1984) and by 376.1 ± 5 Ma hornblende in western Massachusetts (Sutter et al., 1985). These ages are comparable to our 377 Ma orthoclase age. Because the inferred resetting temperature was not above ~350 °C, our 377 Ma age appears to be a good estimate of the timing of the peak of the Acadian event in this region.

SUMMARY

The Pennington harzburgite sheet was decoupled at or before ~491 Ma, possibly from oceanic lithosphere subducting to the east beneath the concomitantly extending fore-arc basin (Fig. 2). The sheet may then have been accreted to the base of the accretionary prism unit.

Extension continued through 479 ± 3 Ma in the fore-arc basin until ca. 477 ± 5 Ma when compression decoupled this fore-arc crust at or near the ridge, accreting a sole in the process. Obduction emplaced the Pennington sheet onto the continental units, followed by the structurally higher fore-arc Thetford Mines ophiolite. Out-of-sequence thrusting juxtaposing continental units on the eastern side of the Pennington sheet was followed by the recumbent folding of the lower sheet, probably accompanying the emplacement of the Thetford Mines ophiolite.

Crustal thickening during the Taconic orogeny resulted in regional greenschist-facies metamorphism. The average cooling age of ca. 463 Ma is considered close to the peak Taconic event in southeastern Quebec and is coincident with peak metamorphism in New England.

The ensuing Acadian orogeny failed to reset the coarser mica ages. Partial resetting of finer-grained muscovites at Asbestos indicates that the green-schist-facies metamorphic front was situated close to this region. An orthoclase age of 377 ± 4 Ma represents cooling through ~300–340 °C shortly after the realization of peak temperatures and is, so far, the best age constraint on the timing of Acadian metamorphism in southeastern Quebec. There is no evidence of diachronism in the peak metamorphism in the New England–Quebec segment of the orogen.

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