Constraints on the duration of tectonic processes: Protracted extension and deep-crustal rotation in the Grenville orogen

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ABSTRACT

Geochronological data on metamorphic minerals within and outside the Bancroft shear zone, a large-scale Proterozoic shear zone, provide evidence for extensional displacement over a period of 150 m.y. This is the longest time interval yet demonstrated for any fault responding to one orogenic phase. Extensional displacement rates along the Bancroft shear zone, averaged over 150 m.y. from 1040 to 893 Ma, are 0.06 to 0.13 km/m.y. During extension, unroofing of the footwall was accompanied by rotation as 5 to 15 km of overlying crust was unloaded. Similar lower-plate rotation has been inferred for many of the Tertiary metamorphic core complexes exposed in the western United States. The protracted displacement and rotation history of the Proterozoic Bancroft shear zone contrasts with the much faster extensional unroofing of the younger metamorphic core complexes, suggesting inherent differences in the tectonic processes operating in these two geologic settings. Similarities, however, indicate that both settings may share common aspects of tectonic deformation. These findings underscore the geologic importance of large, deep-crustal faults and indicate that present-day zones of active extension, such as in the Himalayas, could remain active many millions of years into the future.

INTRODUCTION

The Grenville orogen (province), part of the well-exposed Canadian Shield, provides a rare opportunity to examine the middle to lower levels of an ancient orogenic system. The results of this examination can provide insight into the mechanics, magnitude, and duration of tectonic processes occurring deep within active orogens such as the Himalayas and the Alps. The Bancroft shear zone is an ancient extensional collapse structure (Mezger et al., 1991) that developed in response to successive overthrusting and crustal thickening. We report here ^{40}Ar/^{39}Ar data for minerals in and around the shear zone that help determine the duration and magnitude of displacement along this extensional fault and indicate that significant rotation accompanied the unroofing of rocks below the shear zone. Such footwall rotation is observed in metamorphic core complexes (e.g., Spencer, 1984; Wernicke, 1985; Buck, 1988; Wernicke and Axen, 1988; Bartley et al., 1990; Hoisch and Simpson, 1993); thus, similar styles of tectonic deformation may have been operating in the deep crust as early as the Middle Proterozoic.

In southeastern Ontario, the Grenville orogen consists of two large northeast-trending belts of metamorphic rocks, the Central gneiss belt and the Central metasedimentary belt, separated by a tectonic boundary termed the Central metasedimentary belt boundary zone (Wynne-Edwards, 1972; Davidson, 1984). The Central metasedimentary belt is further subdivided into the Bancroft, Elzevir, Mazinaw, Sharbot Lake, and Frontenac domains, located in order from northwest to southeast (Davidson, 1984, 1986; Hanmer, 1988; Ontario Geological Survey, 1991).

Metamorphic conditions in the orogen range from upper greenschist to granulite facies (5–11 ± 1 kbar; 450–900 ± 50 °C), and there is a general decrease in pressure-temperature (*P-T*) conditions from northwest to southeast (Anovitz and Essene, 1990). The increase in recorded metamorphic *P-T* conditions is probably related to large-scale, northwest-directed overthrusting during orogenesis. Evidence of such northwest-directed thrusting within the Central gneiss belt is well preserved by shear-sense indicators within a number of large, shallowly dipping, ductile shear zones (Davidson, 1984). Ductile shear zones are also present in the Central metasedimentary belt, and separate its constituent domains. Recent ^{40}Ar/^{39}Ar and U/Pb geochronological studies have underscored the tectonic significance of the shear zones in the Central metasedimentary belt, and indicate that they were sites of large-scale lateral and/or vertical displacements during the amalgamation and unroofing of the belt (Cosca et al., 1991, 1992; Mezger et al., 1991, 1993).

On the basis of U/Pb dating of igneous and metamorphic sphenes from the Bancroft domain, the Central metasedimentary belt boundary zone, the Bancroft shear zone, and the Elzevir domain, Mezger et al. (1991) showed that igneous activity occurred prior to 1041 Ma, whereas metamorphism occurred between 1045

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and 1030 Ma. Metamorphism in the Bancroft domain is delineated further by a U/Pb monazite metamorphic growth age of 1041 Ma (Mezger et al., 1991). No age difference was observed between any of the metamorphic sphenes, both large and small, from within and outside the Bancroft shear zone, which suggests that the sphenes record metamorphic growth ages. Moreover, because the sphenes dated in the shear zone are small and from a highly sheared matrix, yet record the same ages (1045 to 1032 Ma) as the larger unsheared metamorphic sphenes from outside the shear zone (Mezger et al., 1991), these ages define the time of initial shearing along the Bancroft shear zone, a time contemporaneous with metamorphism.

The sphene ages are evidence that the Bancroft shear zone became an active zone of extensional shearing at 1045 Ma and continued until at least 1032 Ma (Mezger et al., 1991). The observed $\Delta^{13}C$ values between calcite and graphite (normally a refractory thermometer) in marble mylonites of the shear zone indicate that deformation facilitated carbon isotope exchange and that in the most highly sheared marble mylonites, deformation and resetting of the stable isotope thermometer continued to temperatures of ~450 °C (van der Pluijm and Carlson, 1989). This observation indicates that a $^{40}Ar/^{39}Ar$ study of hornblendes from rocks bordering the shear zone offers the possibility of placing further absolute time constraints on continued extensional displacement along the zone.

METHODS AND RESULTS

Five samples of amphibolite were collected along a transect perpendicular to the regional strike of the Bancroft domain (Fig. 1). The amphibolites were crushed and washed in an ultrasonic cleaner, and high-purity hornblende (>99.9%) separates were obtained by magnetic separation followed by hand picking. The samples were analyzed by the $^{40}Ar/^{39}Ar$ step-heating method following the methods described in Cosca and O'Nions (1994). A summary of the $^{40}Ar/^{39}Ar$ analytical data for the hornblendes is given in Table A[1] and shown in Figure 1. The hornblendes yielded $^{40}Ar/^{39}Ar$ integrated total fusion ages of between 956 and 996 Ma and $^{40}Ar/^{39}Ar$ plateau ages range between 959 and 995 Ma. The $^{40}Ar/^{39}Ar$ plateau ages are taken as a best estimate for the time when hornblendes cooled through argon closure, or ~480 °C (Harrison, 1981). The hornblendes have a restricted compositional range (ferroedenitic to magnesian hastingsitic hornblende) similar to that of 33 previously analyzed hornblende samples (Cosca et al., 1991, 1992). The narrow compositional range, together with the fact that composition has no significant influence on argon retention in metamorphic calcic hornblendes (Cosca and O'Nions, 1994), indicates that some additional mechanism was responsible for the observed variation in $^{40}Ar/^{39}Ar$ ages of the hornblendes. Because the $^{40}Ar/^{39}Ar$ plateau ages agree well with the integrated $^{40}Ar/^{39}Ar$ total fusion ages, the possibilities of excess argon or unrepresentative cooling ages (Lee, 1993) are minimal.

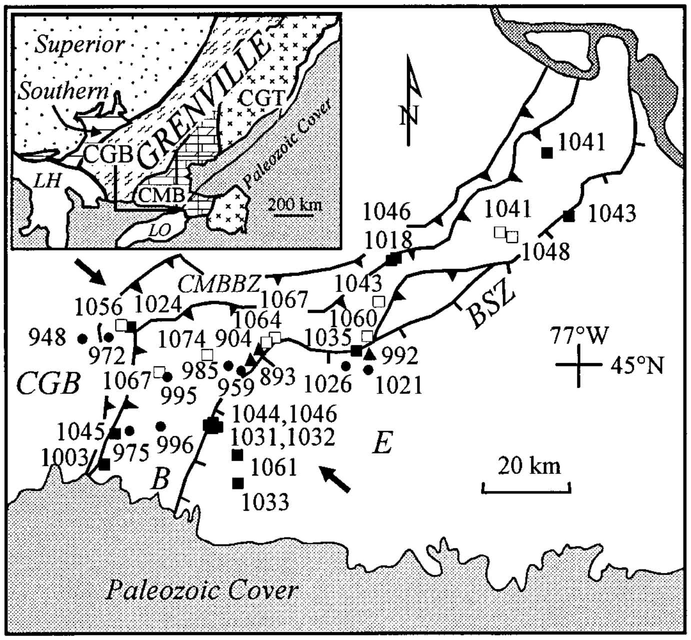

Figure 1. Simplified tectonic map of Central gneiss belt (CGB) and Central metasedimentary belt (CMB) in Ontario. Mineral ages: solid circles (Cosca et al., 1991, and this study) = $^{40}Ar/^{39}Ar$ hornblende; triangles = $^{40}Ar/^{39}Ar$ phlogopite (Cosca et al., 1992); solid squares (metamorphic) and open squares (igneous) = U/Pb sphene (Mezger et al., 1991, 1993). Arrows indicate line of cross section shown in Figure 2. B = Bancroft terrane; E = Elzevir terrane; BSZ = Bancroft shear zone; CMBBZ = Central metasedimentary belt boundary zone; CGT = Central gneiss terrane; LO = Lake Ontario; LH = Lake Huron.

DURATION AND MAGNITUDE OF EXTENSIONAL SHEARING

Amphibolites from immediately west and east of the Bancroft shear zone cooled through argon closure in hornblende at 959 Ma and 1021 to 1026 Ma, respectively. Because all the amphibolites are unsheared, coarse grained, and sufficiently distant from the shear zone, frictional heating or recrystallization is not a probable cause for the observed variation in hornblende ages. Moreover, no evidence for magmatic or hydrothermal activity after 1020 Ma was observed. Therefore, the differences in hornblende $^{40}Ar/^{39}Ar$ plateau ages, 62 to 67 Ma, are probably related directly to extensional unroofing of the Bancroft domain. During extension along the shear zone, the hanging wall (Elzevir domain) was displaced to lower structural levels relative to the footwall (Bancroft domain). Ignoring possible but unlikely variations in radiogenic heat production between the Bancroft and Elzevir domains, such displacement would juxtapose rocks from deeper, hotter levels in the Bancroft domain next to the Elzevir domain. It follows that the $^{40}Ar/^{39}Ar$ plateau age of 959 Ma for hornblende records the unroofing of this sample through its argon closure temperature of ~480 °C and prolongs the time of extensional displacement along the Bancroft shear zone to at least 959 Ma. Extensional displacement at ~480 °C is consistent with the calcite-graphite stable isotope thermometry (van der Pluijm and Carlson, 1989) and the inferred midcrustal depths of mylonitization (Mezger et al., 1991).

Phlogopites sampled from unsheared marble west and east of the Bancroft shear zone have $^{40}Ar/^{39}Ar$ plateau ages of 893 and 904 ± 3 Ma in the Bancroft domain and 992 ± 3 Ma in the Elzevir domain (Cosca et al., 1992). These data contrast to those for phlogopites, muscovite, and hornblende within the shear zone. The argon isotopic ratios in these minerals indicate excess argon, probably related to interaction with metamorphic fluids during dynamic recrystallization (Cosca et al., 1992). The phlogopites free of excess argon can be assumed reliably to record the time when the marbles cooled below argon closure (~300 °C). Thus, the pattern of phlogopite $^{40}Ar/^{39}Ar$ data indicates that the Bancroft shear zone was active, perhaps episodically, at least until the youngest phlogopite in the Bancroft domain cooled below argon closure, or 893 Ma. The overall time interval for extensional displacement along the

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[1] GSA Data Repository item 9518, Table A, analytical data for $^{40}Ar/^{39}Ar$ incremental heating experiments, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301.

shear zone is, therefore, at least 150 m.y., longer than is known for any other fault responding to one orogenic phase (in this case collapse of the orogen).

Assuming similar closure temperatures, cooling rates, and diffusional length scales, the magnitude of displacement along the shear zone can be estimated from differences in $^{40}\mathrm{Ar}/^{39}\mathrm{Ar}$ ages for the same mineral on opposite sides of the zone combined with regional cooling rates and a model retrograde *P-T* path. The differences in $^{40}\mathrm{Ar}/^{39}\mathrm{Ar}$ plateau ages of 62 to 67 Ma combined with a regional cooling rate of 2 to 4 °C/m.y. (Cosca et al., 1991) indicate a temperature difference of between 120 and 270 °C immediately following argon closure in the youngest hornblende. Applying a model retrograde path of 30 °C/km (Cosca et al., 1991), these temperature differences suggest extensional displacements along the shear zone of 4 to 9 km and time-integrated average displacement rates of 0.06 to 0.15 km/m.y. Similar calculations with the $^{40}\mathrm{Ar}/^{39}\mathrm{Ar}$ data for phlogopite yielded extensional displacements between 6 and 13 km and integrated average displacement rates of 0.06 to 0.13 km/m.y.

TECTONIC IMPLICATIONS

Compared with active orogens, the cooling and unroofing of the Grenville orogen occurred very slowly (Cosca et al., 1991, 1992). However, this is not to say that faster cooling and unroofing were not occurring in higher crustal levels during the Grenville orogeny. The upper levels of the orogen are long since eroded and only the roots are exposed, which record slower cooling rates because these rocks cooled after the crust had attained conditions of near-isostatic equilibrium. Nonetheless, growing evidence of large-scale extensional faults in the Grenville orogen indicates that locally, important differences existed in crustal thickness even during the late cooling history of the orogen (e.g., Cosca et al., 1991, 1992; Mezger et al., 1991, 1993; van der Pluijm et al., 1994). The $^{40}\mathrm{Ar}/^{39}\mathrm{Ar}$ data can be combined with the U/Pb data of Mezger et al. (1991, 1993) to model the late tectonic history of the Bancroft domain and surrounding area. Because amphibolite facies metamorphism waned after 1032 Ma, metamorphic temperatures were below those necessary to form sphene; thus there is a lack of younger sphene ages. In contrast, hornblende and phlogopite, because of their lower blocking temperatures, record additional age information related to the unroofing and cooling history.

The distribution of $^{40}\mathrm{Ar}/^{39}\mathrm{Ar}$ ages for hornblende (Fig. 2) demonstrates the heterogeneous cooling of rocks through the $\sim$480 °C isotherm at $\sim$1 Ga. In the Elzevir domain near the Bancroft shear zone, hornblendes cooled through $\sim$480 °C at $\sim$1022 Ma. In contrast, the hornblendes from the Bancroft domain indicate that closure to argon diffusion in hornblende occurred first in the west and 37 m.y. later in the east, approaching the Bancroft shear zone. No faults that might explain the age variations have been observed between sample localities in the Bancroft domain. If extensional unroofing was the sole mechanism for cooling through argon closure in the Bancroft domain, uniform but younger ages relative to the Elzevir domain would be expected. Alternatively, the progressively younger hornblende cooling ages in the eastern Bancroft domain can be related to rotation of the footwall during extensional shearing

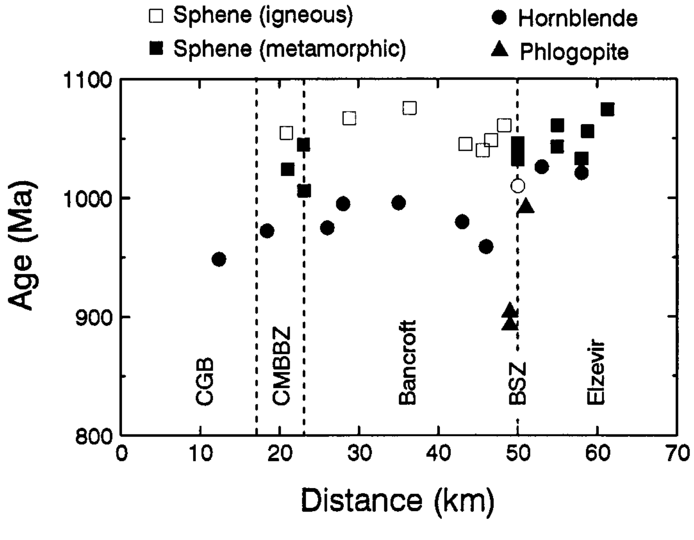

Figure 2. Plot of mineral age vs. distance for transect given in Figure 1. Progressively younger $^{40}\mathrm{Ar}/^{39}\mathrm{Ar}$ hornblende ages in Bancroft terrane toward Bancroft shear zone (BSZ) reflect crustal rotation during uplift. Young $^{40}\mathrm{Ar}/^{39}\mathrm{Ar}$ hornblende age near Central metasedimentary belt boundary zone (CMBBZ) probably records cooling associated with late thrusting and metamorphism, consistent with U/Pb metamorphic sphene data (Mezger et al., 1991, 1993; McEachern and van Breemen, 1993). Open circle on BSZ is maximum age for hornblende containing excess argon (Cosca et al., 1992). CGB is Central gneiss belt.

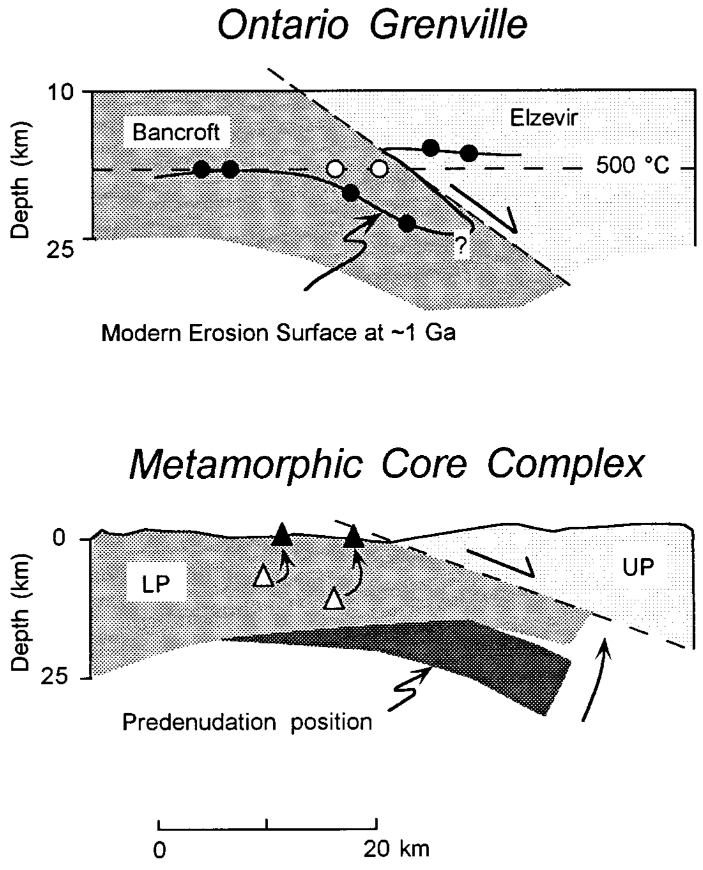

Figure 3. Comparison of tectonic models for crustal extension and tilt in Bancroft terrane (top) and metamorphic core complexes. Midcrustal slice through Bancroft and Elzevir terranes at 1 Ga shown with predicted depths for dated samples now at same surface elevation (shown by solid circles). Open circles indicate expected sample depths in footwall if no rotation occurred. 500 °C isotherm (approximate closure temperature for argon in hornblende) is projected across two terranes. Simplified model for core complex formation (bottom) suggests that deeply buried rocks (open triangles) in lower plate (LP) undergo significant rotation before arriving at surface (solid triangles) as upper plate (UP) is removed during extension (e.g., Spencer, 1984; Wernicke, 1985; Buck, 1988; Wernicke and Axen, 1988).

of the Bancroft shear zone (Fig. 3). Such a mechanism would predict that as overlying crust is tectonically unloaded during active extension, rocks in the lower plate farthest from the shear zone would be the first to be unroofed and cool through the argon closure temperature in hornblende. Continued extension and decrease of the load on the lower plate would allow lower-plate rocks closer to the Bancroft shear zone to be unroofed. A comparison of this model with models for metamorphic core complex formation reveals a similar amount of rotation of the lower plate necessary to expose differentially buried crust (Fig. 3). Footwall rotation in the Bancroft domain would be hinged in the central to western part of the domain, where the $^{40}Ar/^{39}Ar$ ages of hornblende converge at 1.0 Ga. Given a difference in calculated burial depth of 4 km between samples of the Bancroft domain, and a hinge zone located 25 km west of the Bancroft shear zone, the angle of rotation, x, calculated from the relation $x = \tan^{-1}(4/25)$, is equal to 9°. A hinge zone located 15 km west of the shear zone requires an angle of footwall rotation equal to 15°. Such low angles of rotation imply a relatively shallow dip of the extensional fault (e.g., Wernicke and Axen, 1988), which is consistent with the field observations (Carlson et al., 1990). Some rotation of hanging-wall rocks, as observed in metamorphic core complexes, may be expected in the Elzevir domain closest to the Bancroft shear zone, perhaps as a consequence of rotation of the zone with time. The limited geochronological data are insufficient to test such a model; however, of the two samples in the Elzevir domain near the Bancroft shear zone, the sample closer to the zone has the older $^{40}Ar/^{39}Ar$ cooling age and is consistent with such rotation.

The time intervals required for extension and unroofing of Tertiary metamorphic core complexes (e.g., Baldwin et al., 1993; Hoisch and Simpson, 1993) are two orders of magnitude shorter than those recorded in the Bancroft shear zone. Therefore, the shear zone is not similar to detachment faults in this respect, but it is an extensional fault that juxtaposes rocks in a manner similar to that in younger metamorphic core complexes. Thus, unroofing associated with large-scale extensional faults, even in different geologic settings, can share similar tectonic mechanisms.

CONCLUSIONS

The findings reported here provide evidence that large-scale extensional shear zones extending down to at least midcrustal levels can remain active for at least 150 m.y. Deep continental crust that is unroofed by extension may undergo rotation as overlying upper crust is removed. We conclude that crustal extension has been operating in the earth since at least Middle Proterozoic time and that today's regions of large-scale extension may well continue to be active far into the future.

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