Determining the significance of high-grade shear zones by using temperature-time paths, with examples from the Grenville orogen

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ABSTRACT

Ductile shear zones preserve essential information on processes that are active in orogenic roots, but the significance of these zones is often difficult to interpret. Structural, petrologic, and geochronologic data from shear zones yield elements of the history that are not necessarily synchronous. However, by combining these data with temperature-time (*T-t*) paths, insights are obtained into the nature of shear zones, the relation between bounding blocks, and orogenic evolution of the deep crust. This procedure is illustrated with two examples from the mid-Proterozoic Grenville orogen. *T-t* paths from ~1160 to ~900 Ma are based on U-Pb dating of metamorphic minerals—including garnet (closure temperature, T_c, > 800 °C), monazite ($T_c \simeq 725$ °C), sphene ($T_c \simeq 600$ °C), and rutile ($T_c \simeq 400$ °C)—and $^{40}Ar/^{39}Ar$ hornblende ages ($T_c \simeq 480$ °C). Comparison of *T-t* paths from adjacent blocks allows predictions about the significance, kinematics, and timing of displacement of shear zones. In the Grenville orogen, *T-t* paths can distinguish between major terrane boundaries (e.g., the Carthage-Colton shear zone) and within-terrane shear zones (e.g., the Bancroft shear zone). Thus, these data can also be used to identify individual tectonic terranes in the deep crust. This integrated approach to analysis of shear zones provides constraints needed to determine the nature and rate of deep orogenic processes in areas that are complicated by high metamorphic grades.

INTRODUCTION

Much of our knowledge of orogenic processes is derived from the study of Mesozoic-Cenozoic mountain belts that typically expose the upper levels of the crust. However, the widespread suggestion of decoupling between upper- and lower-crustal levels (e.g., Burchfiel et al., 1989; Oldow et al., 1990) also requires study of deeper-crustal levels for our understanding of orogenic dynamics. In addition to differences in deformation style, deep-crustal terranes (lithotectonic blocks with distinct geologic histories) may be different from those recognized in the upper-crustal layers of an orogen. Deeply eroded Precambrian orogens allow direct examination of deep-crustal tectonic processes, but the high metamorphic grades and old ages of these belts pose unique challenges to the study of the deep orogenic architecture that once supported the crustal levels that are exposed in modern belts.

Shear zones are widespread in high-grade belts and contain essential evidence on the spatial and temporal evolution of deep orogenic roots. However, structural, petrologic, and geochronologic studies of shear zones offer incomplete and sometimes conflicting information. First, it is often impossible from mapping alone to determine the relative significance of shear zones. Major sutures may be much less prominent than minor but better-preserved (younger?) shear zones. Second, shear-sense indicators enable determination of relative displacements, but the displacement sense observed in the field may only represent the final stages of shearing in long-lived or reactivated zones of crustal weakness. Petrologic data generally yield the peak and retrograde metamorphic history of the area and do not preserve the pressure and temperature (*P-T*) conditions during earlier and perhaps more important events. Finally, dating of shear zones may constrain the timing of deformation, but such dates often cannot be directly correlated to kinematic information. Isotopic ages of shear zones are typically determined by dating minerals in synkinematic intrusions that are considered to be unique to the shear zone, or dating minerals that are interpreted to be unique to the shear zone; however, problems exist with both approaches. The former is a highly indirect and interpretative method of dating, and the latter requires the presence of distinct mineral populations. Moreover, in the absence of suitable mineral growth or isotopic resetting, direct dating of shear zones may not be possible. Thus, we are faced with considerable problems in the interpretation of shear-zone data, while at the same time these data are essential for an understanding of orogenic processes. Therefore, additional tools are necessary to assess the tectonic significance of shear zones. Temperature-time (*T-t*) histories from individual blocks neighboring shear zones provide a powerful solution to many of these problems and require data that are less difficult to obtain than complete *P-T-t* paths of the shear zone. In this paper we discuss some of these problems and their solutions, with two examples from the mid-Proterozoic Grenville orogen of North America.

GEOLOGIC SETTING OF THE GRENVILLE OROGEN

The Grenville orogen of North America is continuously exposed in an ~2000-km-long belt from Labrador to southern Ontario and northern New York State. The orogen is characterized by a suite of metaigneous and metasedimentary rocks that yield isotopic ages of 0.9–1.5 Ga (e.g., Easton, 1992; McLelland et al., 1988; Tuccillo et al., 1992). The first-order subdivision in the southern part of the orogen is based on lithologic, metamorphic, structural, and geophysical contrasts (Fig. 1), which are, from west to east, the Gneiss belt, the Metasedimentary belt, and the Granulite belt (nomenclature modified from Wynne-Edwards, 1972; Davidson, 1986). The Gneiss belt is composed of gneisses of upper amphibolite to granulite facies and predominantly igneous origin. Peak metamorphic pressures in this belt ranged from 800 to 1100 MPa, corresponding to crustal depths of 30–45 km (Anovitz and Essene, 1990). The Metasedimentary belt is dominated by marbles, other metasedimentary rocks, and metavolcanic rocks that range in metamorphic grade from greenschist to granulite facies; pressures varied from 500 to 800 MPa, i.e., crustal depths of 18–30 km (Anovitz and Essene, 1990). The Granulite belt is characterized by metaigneous rocks of the upper amphibolite to granulite facies, which corresponds to regional pressures of 700–800 MPa and crustal depths of 25–30 km (Bohlen et al., 1985). This first-order subdivision poses the question of whether these belts are the main deep-crustal blocks (tectonic terranes) involved in the Grenville orogeny, which may be addressed with *T-t* histories.

The three belts are separated by ductile shear zones (Davidson, 1986). The Metasedimentary belt shear zone, in the western part of the Bancroft domain, separates medium-grade metasedimentary and igneous rocks of the Metasedimentary belt from high-grade gneisses of the Gneiss belt. The Carthage-Colton shear zone marks the boundary between the Metasedimentary and the Granulite belts in northern New York (Geraghty et al., 1980). Many more shear zones have been identified in the area (Fig. 1; e.g., Davidson, 1986; Easton, 1992), and the relative significance of these zones can be assessed by the approach discussed below.

TEMPERATURE-TIME PATHS

In the southwestern Grenville orogen of Ontario and New York, U-Pb geochronology has typically been used to define the timing of igneous events and the early deformation history, while $^{40}Ar/^{39}Ar$ studies have constrained the late exhumation history. These methods provide insights into the evolution of the orogen, but the tectonic information derived from them is incomplete. Identification of tectonic terranes in high-grade metamorphic regions may ideally be obtained from the determination of quantitative pressure-temperature-time (*P-T-t*) paths for the entire time between deposition and exhumation, but this is seldom possible in practice. The prograde history of most high-grade areas remains obscured, given current *P-T-t* techniques, and pressure-sensitive mineral equilibria are generally absent for much of the retrograde path. We therefore advocate using a more readily applied approach in which the cooling history after the last high-grade metamorphism is used to characterize the history of a region. For each domain, a *T-t* path based on U-Pb and $^{40}Ar/^{39}Ar$ ages determines the relation with neighboring domains and with others in the orogen (Fig. 2). For example, nonparallel *T-t* paths in neighboring domains may reflect spatial separation (i.e., different terranes) or internal vertical displacement. Alternatively, offset in time of parallel *T-t* paths between domains with corresponding pressure discontinuities may reflect different crustal levels within the same terrane. The nature of displacements is further constrained by determining shear sense within the zones.

Tectonic interpretations from *T-t* paths necessitate a distinction between growth and cooling ages; i.e., isotopic ages must be interpreted in view of thermometric data. For example, sphene in rocks of upper amphibolite facies may give the same age as monazite in spite of their different closure temperatures (T_c) (e.g., Bancroft domain; Table 1), which could reflect either very rapid cooling associated with faulting (100–150 °C within the 2–3 m.y. U-Pb error limits) or growth of monazite below its T_c. Peak metamorphic temperatures in the Bancroft domain (<650 °C) favor the latter interpretation; because monazite grew below its T_c, the ages correspond to the time of metamorphism in the area and may not be used in estimates of cooling rate.

The principle of our approach is used in $^{40}Ar/^{39}Ar$ thermochronology. However, because high temperatures characterize deeper levels of the crust, the $^{40}Ar/^{39}Ar$

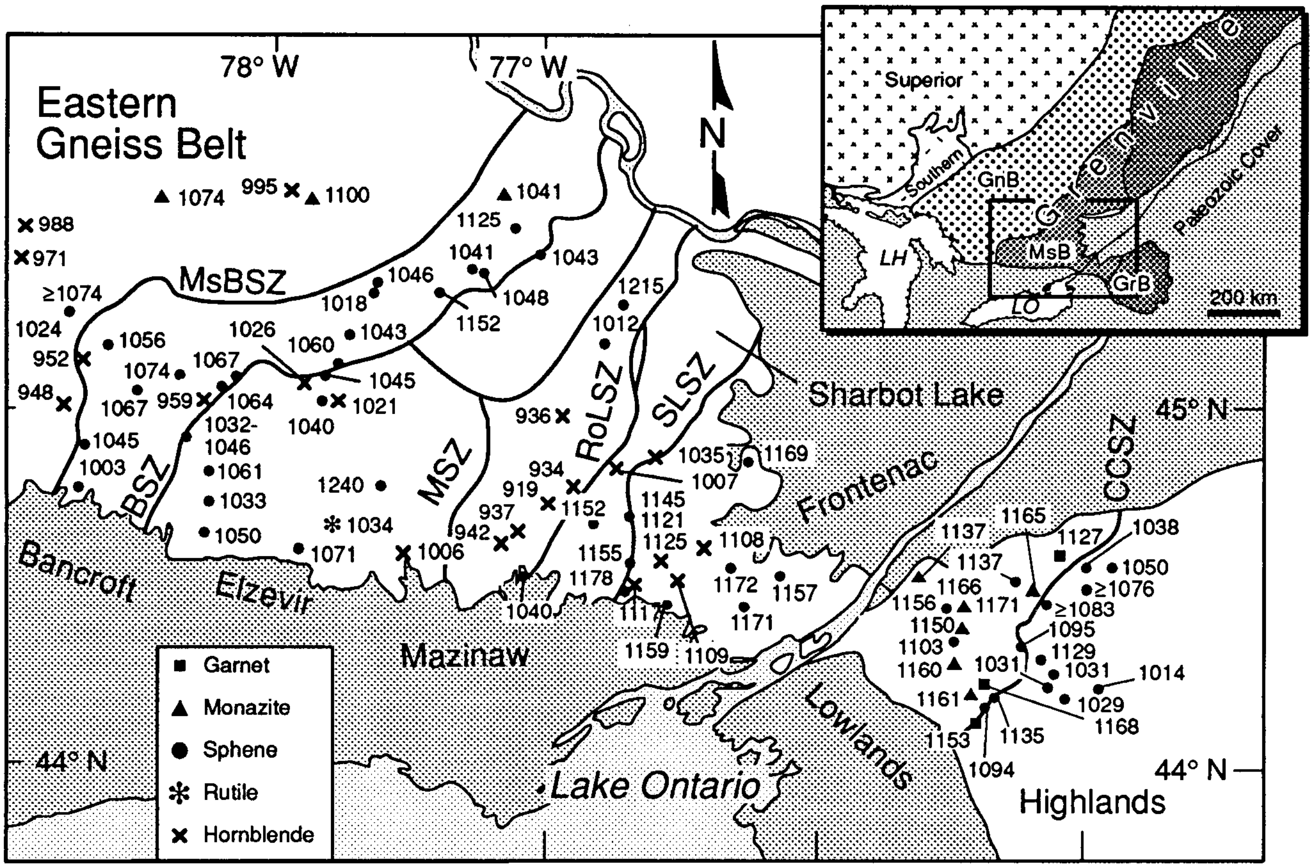

Figure 1. General subdivision of exposed Grenville orogen in North America (inset) and second-order subdivision into domains, showing U-Pb ages of rutile, sphene, monazite, and garnet and $^{40}Ar/^{39}Ar$ ages (Ma) of hornblende. Domain-bounding ductile shear zones: BSZ—Bancroft shear zone, CCSZ—Carthage-Colton shear zone, MsBSZ—Metasedimentary belt shear zone, MSZ—Mooroton shear zone, RoLSZ—Robertson Lake shear zone, SLSZ—Sharbot Lake shear zone. GnB—Gneiss belt, GrB—Granulite belt, MsB—Metasedimentary belt, LH—Lake Huron, LO—Lake Ontario. Subdivision after Easton (1992).

technique allows insight only into the late cooling history (T_c hornblende is ~480 °C for slow cooling; Harrison, 1981). Use of metamorphic minerals with U-Pb closure temperatures bridging the gap between $^{40}Ar/^{39}Ar$ ages and peak metamorphic ages (480–800 °C) allows the more complete analysis necessary for the deeper crust (Fig. 2). The metamorphic minerals rutile, sphene, and monazite are particularly useful because they are common in metamorphic rocks and allow high-precision age determinations by the U-Pb method (±2–3 m.y.). The U-Pb closure temperatures are estimated to be ~400 °C for rutile (Mezger et al., 1991a), 600–650 °C for small to large sphenes (Heaman and Parrish, 1991; Mezger et al., 1991a), and ~700–725 °C for monazite (Parrish, 1991). Among other parameters, closure temperature varies as a function of grain size and cooling rate, but these are generally sufficiently close in a given study area that an average T_c for each mineral may be considered representative. When combined with dates for peak metamorphism (i.e., U-Pb ages from garnet, zircon, and/or allanite with $T_c > 800$ °C; from monazite in rocks of the amphibolite facies; and from sphene in rocks of the greenschist to middle amphibolite facies), the retrograde *T-t* path for a given domain can be determined.

TWO EXAMPLES FROM THE GRENVILLE OROGEN

Geochronologic data from the southern Grenville orogen, including several new U/Pb and $^{40}Ar/^{39}Ar$ ages in the Metasedimentary belt, are summarized in Table 1. Analytical procedures and detailed locations of previously published ages are described in Cosca et al. (1991, 1992) and Mezger et al. (1991b, 1992, 1993). The important distinction between growth and cooling ages for each mineral is based on local geothermometry. The *T-t* paths and times of peak metamorphism vary considerably across the southern Grenville orogen, and plotting them together in a single diagram obscures much of the critical information. A more informative approach is to compare the histories of neighboring domains, which establishes any differential displacements and the timing of separation and linkage of the domains (Fig. 3). The data in Figure 3 and Table 1 can be used to make predictions on the nature and timing of shear zones in the region (cf. Fig. 1).

Bancroft Shear Zone

The eastern Gneiss belt and Bancroft domain of the Metasedimentary belt have different peak metamorphic histories, but thrusting along the Metasedimentary belt shear zone at 1080 Ma indicates that the Gneiss belt and Metasedimentary belt were already juxtaposed at that time (McEachern and van Breemen, 1993). The Bancroft domain is separated from the Elzevir domain by the extensional Bancroft shear zone (Carlson et al., 1990). Sphene ages within the Bancroft shear zone range from 1046 to 1032 Ma, overlapping with sphene ages in the neighboring blocks, which has been interpreted as evidence for synorogenic collapse (Mezger et al., 1991b). However, *T-t* paths from the Bancroft and Elzevir domains (Fig. 3a) are distinct even after 1000 Ma, on the basis of new isotopic ages. Hornblende from the Bancroft domain just to the west of the Bancroft shear zone yields a pla-

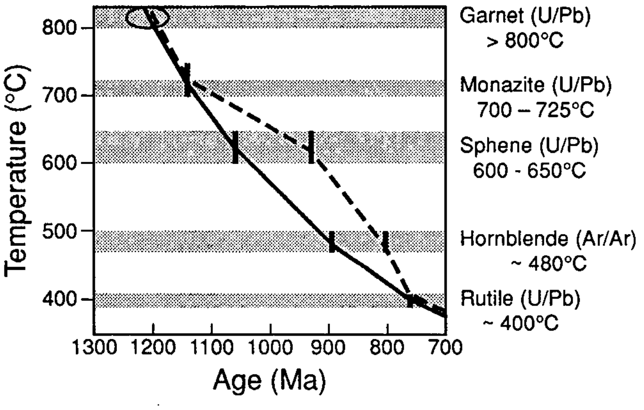

Figure 2. Schematic temperature-time (*T-t*) paths. For each domain, a *T-t* path is determined by using isotopic ages on minerals with different closure temperatures (T_c), as shown. Relation between paths of neighboring domains allows predictions about history of intervening shear zone. Significance of kinematic and temporal data from shear zone can be determined by comparison of *T-t* paths between neighboring domains.

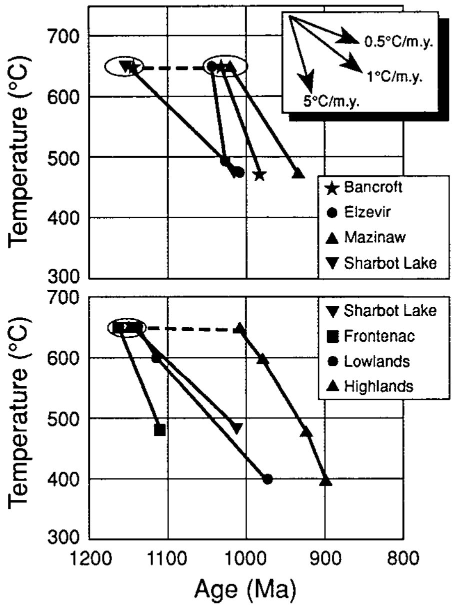

Figure 3. Generalized temperature-time paths for the Metasedimentary belt and Granulite belt (see Table 1 and Fig. 1). Representative values are used when range in ages is present. Ellipses mark times of regional metamorphism (~1160 and ~1045 Ma); horizontal dashed lines link multiple metamorphisms within a single domain, but do not imply constant temperature over that time interval.

TABLE 1. TEMPERATURE-TIME DATA FOR THE GRENVILLE OROGEN (S. ONTARIO, N. NEW YORK)

Mineral	*eastern Central Gneiss Belt*	*Bancroft domain*	*Elzevir domain*	*Mazinaw domain*	*Sharbot Lake domain*	*Frontenac domain*	*Lowlands domain*	*Highlands domain*
rutile			*1034**				*953-1008*	*885-911*
hornblende	*948-995*	*959*	*1006-1026*	*934-942*	*1007-1035*	*1108-1125*		*(900-950)*
sphene	*≥1074*	1024-1045 and 1152	1033-1061	1012-1040	1153-1158	1157-1178	1103-1156	*982-1050*
monazite	1074-1100	1041					1137-1171	1033
garnet							1127-1168	1013-1154

Note: Growth ages are indicated by upright font and cooling ages by italics; ages from domain-bounding shear zones have been omitted; Ar-Ar ages in the Highland domain (in parentheses) are from Heizler and Harrison (1986) and Onstott and Peacock (1987).

★ Large rutile (T_C ~500°C).

teau age of 959 ±3 Ma, compared with dates in the Elzevir domain of 1021–1026 Ma (Table 1). Thus, the sphenes in the shear zone record the early displacement history, but not the later history. This is most likely a consequence of the decreasing grade of metamorphism during exhumation, which inhibited further sphene growth and recrystallization.

Carthage-Colton Shear Zone

The Lowlands domain of the Metasedimentary belt is separated from the Highlands domain of the Granulite belt by the Carthage-Colton shear zone (Geraghty et al., 1980), interpretations of which vary from a major shear zone to a minor and tectonically unimportant boundary. Mezger et al. (1992) obtained sphene ages from the Carthage-Colton shear zone of 1098 ±4 Ma, but these data need to be interpreted in light of the thermal histories of bordering blocks. The Lowlands and Highlands domains have similar histories before ~1160 Ma (e.g., McLelland et al., 1988). Following similar peak metamorphic conditions at ~1160 Ma, *T-t* paths show that subsequent high-grade metamorphism at ~1000 Ma is restricted to the Highlands, whereas the Lowlands domain had cooled to the U/Pb T_c of rutile (Fig. 3b). These data show that the Lowlands escaped the later metamorphism either by being located at higher crustal levels or by being laterally separated from the Highlands. The former requires that the Lowlands initially moved up along the Carthage-Colton shear zone, followed by a similar amount of displacement back to its current structural position. In this scenario, sparse observations of northwest-directed shear sense in the zone (e.g., Heyn et al., 1987) must reflect the late, normal displacement, whereas the sphene ages must record the initial reverse displacement. More likely, the *T-t* paths reflect lateral separation of the two domains, dated by the sphene ages.

CONCLUSIONS

Isotopic ages from minerals in shear zones may not coincide with the deformation responsible for the shear-sense indicators, as shown by two examples from the Grenville orogen. However, combining structural, petrologic, and isotopic data with *T-t* paths of neighboring domains constrains the significance of shear-zone ages and clarifies the relative importance of individual shear zones for the temporal and spatial evolution of the orogen. The *T-t* paths may be used to hypothesize the nature and timing of displacement of shear zones in the absence of independent temporal and/or kinematic data, or even indicate the presence of discontinuities not (yet) identified in the field. Moreover, when *T-t* paths are sufficiently well known, they can also be used to calculate time-integrated cooling rates and provide estimates of the exhumation rate if a geothermal gradient is assumed. Thus, the study of shear zones in deeply eroded mountain belts is greatly aided by *T-t* studies, which provide a powerful method for regional tectonic analysis.

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