Heterogeneous deformation in a strong deep crust: the Proterozoic character of the Snowbird Tectonic Zone, Athabasca granulite terrane

Michael L. Williams*
Department of Geosciences, University of Massachusetts, Amherst, MA 01003, USA
mlw@geo.umass.edu

and

Gregory Dumond
Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

and

Kevin H. Mahan
Department of Geological Sciences, University of Colorado, Boulder, CO 80309, USA

and

Michael J. Jercinovic
Department of Geosciences, University of Massachusetts, Amherst, MA 01003, USA

Summary

The central segment of the enigmatic Snowbird Tectonic Zone is exposed within the Athabasca granulite terrane (AGT) (Fig. 1). The AGT, located north of Lake Athabasca in the western Canadian Shield, is North America's largest exposure of lower continental crust (>20,000 km^2). The region is underlain by orthogneisses, paragneisses, felsic granulites, mafic granulites, and rare crustal eclogite. At the latitude of Lake Athabasca, the granulite terrane can be separated into two main parts: the East Athabasca mylonite triangle (Tantato domain) to the east and tectonic domains of the Rae Province to the west (e.g., the Beaverlodge domain), separated by the >400 km-long Grease River shear zone (Fig. 1). At this latitude, the Snowbird tectonic zone has been considered to include the entire East Athabasca triangle.

The East Athabasca mylonite triangle preserves evidence for two groups of lower crustal granulite-grade events, one at ca. 2.61-2.54 Ga, and one at ca. 1.9 Ga. The earlier group of events involved intense sub-horizontal fabric development and ductile flow contemporaneous with anatexis. The second group of events generally involved sub-vertical fabric development, with a more discrete, heterogeneous style than the earlier events. The second event was also synchronous with emplacement of the Chipman mafic dike swarm - a sub-vertical, NE-striking swarm that may extend from the Canadian Rockies to Hudson Bay. The dikes are superbly exposed within the AGT, where they were emplaced into the 3.3-3.0 Ga Chipman tonalite under lower crustal conditions (~1.1 GPa). More than anything, the Chipman dike swarm helps define the present-day trace of the Snowbird Tectonic Zone (Williams and Hanmer, 2006).

This study focuses on the Proterozoic history of the Athabasca granulite terrane and also, the central portion of the Snowbird Tectonic Zone. Dumond et al. (this volume) present data about the Archean history of the terrane and the possibility that some aspects of the Snowbird Tectonic Zone may be inherited from the Neoarchean.

Proterozoic shear zones of the Athabasca granulite terrane

The AGT is cut by four major shear zones that each experienced significant Paleoproterozoic strain: the Legs Lake, Cora Lake, Grease River, and Oldman-Bulyea shear zones (Fig. 1). The

>500 km-long Legs Lake shear zone is a 5-8 km-wide dextral oblique-slip thrust-sense mylonite zone that dips moderately to the NW (Mahan et al., 2003). Stretching lineations plunge moderately to the NW. The structure juxtaposes granulite-grade lower crustal gneisses of the AGT on the NW with amphibolite-grade middle crustal paragneisses of the Hearne domain on the SE. The >200 km-long ultramylonite Cora Lake shear zone separates the Chipman domain and Chipman dike swarm from adjacent subdomains of the AGT further west (Fig. 1). The steeply NW-dipping structure contains shallowly SW-plunging stretching lineations with kinematic evidence for both sinistral and dextral strike-slip displacement (Mahan et al., 2008). The >400 km-long Grease River shear zone cuts the Legs Lake and Cora Lake shear zones and is dominated by penetrative NE-striking, steeply NW-dipping foliations with shallowly SW-plunging to sub-horizontal stretching lineations (Dumond et al., 2008; In Press). Kinematics are consistent with dextral strike-slip displacement with a component of SW-over-NE oblique thrusting. Lower crustal felsic and mafic granulites and orthogneisses are preserved on both sides of the Grease River shear zone at the latitude of Lake Athabasca (59° 20' N). The Oldman-Bulyea shear zone is a >70 km-long, moderately SW-dipping, oblique thrust-sense structure in highly retrogressed granulites (Card, 2001; this study). Kinematics are uniformly top-to-the-NE along moderately SW-plunging stretching lineations. The structure is transposed adjacent to the Grease River shear zone, as indicated by the onset of L>>S tectonite strain and a dextral deflection of foliation trajectories (Dumond et al., 2008).

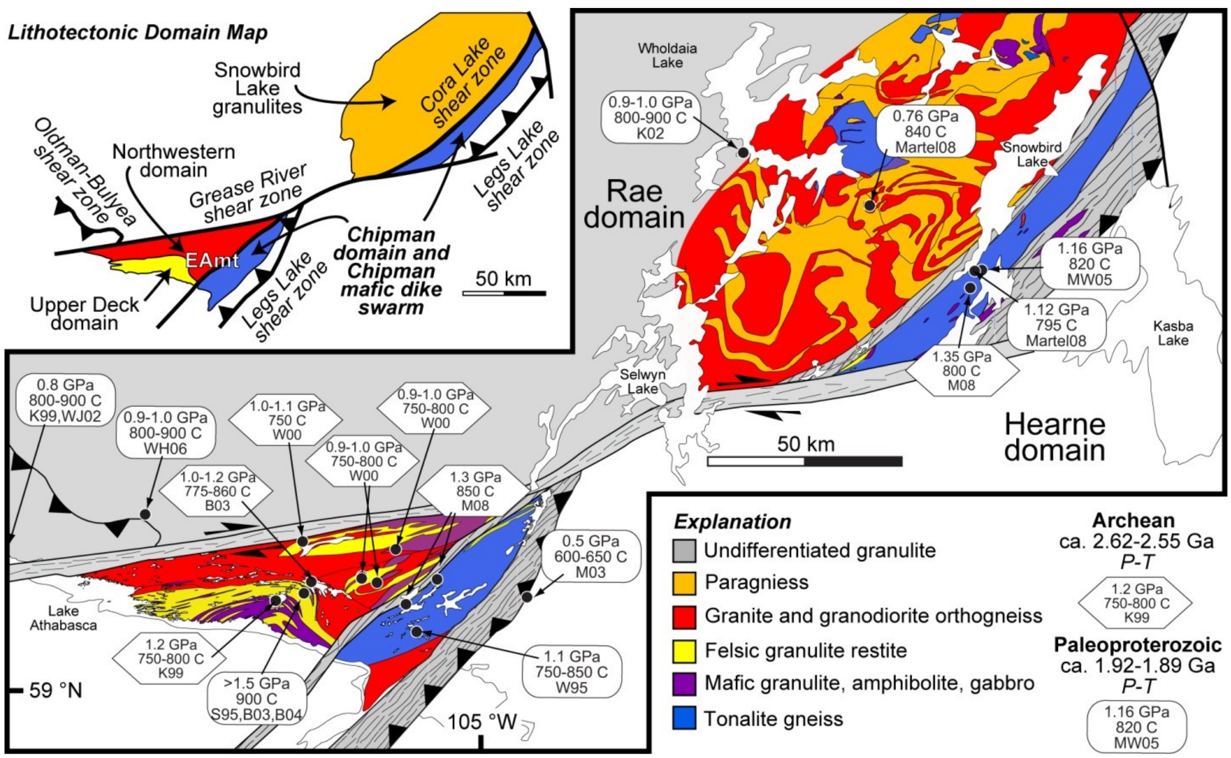

Figure 1. Geologic map of Athabasca granulite terrane after Mahan et al. (2008) and Dumond et al. (In Press). See Mahan et al. (2008) for *P-T* references. Inset litho-tectonic map in upper left corner indicates locations of major domains and shear zones within the terrane.

All four shear zones record activity at amphibolite-facies conditions. Based on field relationships, there is the following relative timing of shear zone displacement. The Legs Lake and Cora Lake shear zones are cut by the Grease River shear zone. The Oldman-Bulyea shear zone has foliation trajectories that are deflected or sole into the Grease River shear zone, implying that the Oldman-Bulyea shear zone is the youngest structure. However, both the Grease River and Cora Lake shear zones originated as granulite-facies structures – the Grease River shear zone records high-T deformation at ca. 1.9 Ga (Dumond et al., 2008), and the Cora Lake shear zone contains Cpx-anorthosite mylonites and mafic granulite boudins that originated in the Neoarchean (Mahan et al., 2008). Mahan et al. (2008) documented evidence for ca. 1.9 Ga dextral displacement and reactivation along the Cora Lake structure. Circa 1.85 Ga amphibolite-grade shearing has been constrained by electron microprobe monazite geochronology along the Legs Lake, Grease River, and Oldman-Bulyea shear zones during uplift of the AGT to middle crustal levels (Mahan et al., 2006; Dumond et al., 2008; 2009). Further reactivation at ca. 1.8 Ga resulted in offset of the terrane along the Grease River shear zone (Mahan and Williams, 2005; Dumond et al., 2008).

Deformation style in the Proterozoic

The rocks in the East Athabasca mylonite triangle were dehydrated and in many places, partially melted during the initial Neoarchean granulite-grade event followed by protracted isobaric cooling. This left the rocks restitic, rheologically strong, and less susceptible to penetrative strain in the Paleoproterozic. Proterozoic deformation at ca. 1.9 Ga was, instead, localized into discrete shear zones and regions of high heat flow (e.g., the Chipman dike swarm). Shear zones are upright with generally sub-horizontal or shallowly-plunging lineations. The shear zones generally display significant grain size reduction, strong mylonitic fabrics, and excellent kinematic indicators. The Grease River and Legs Lake shear zone contain pseudotachylite that may represent the latest stages of deformation after significant regional exhumation.

The 2.6 Ga Fehr granite is one major exception to the rheologically-strong (at 1.9 Ga) character of the East Athabasca rocks (Koteas et al., this volume). This granitoid displays variable degrees of migmatization (up to 60% or more) and intense deformational fabrics, commonly with an early shallowly dipping fabric and later upright fabric. We interpret the Fehr granite to have been relatively fertile (with respect to melting) at the end of the ca. 2.6 Ga event and thus, to be susceptible to Proterozoic melting, weakening, and intense tectonism. Rocks immediately west of the Grease River shear zone (in the Beaverlodge domain of the Rae sub-province) are also characterized by intense deformation, multiple generations of fabrics, and locally significant migmatite (see also Bethune et al., 2008; Knoz et al., 2008). Although some Archean rocks are apparently present, at least some of these rocks likely represent Proterozoic metasediments or igneous rocks that, like the Fehr granite, were more fertile for penetrative Proterozoic tectonism.

The central segment of the Snowbird tectonic zone follows the 1.9 Ga Chipman dike swarm. The swarm is tens of km in width at minimum; current boundaries are defined by younger fault and shear zones. Individual dikes are 1to 10s of meters across. High metamorphic temperatures (ca 800 C) are associated with the central part of the swarm. Previously deformed and restitic rocks such as the Chipman tonalite were not strongly tectonized during dike emplacement, but fertile rocks such as the Fehr granite or the dikes themselves were intensely deformed. Thus, fabrics interpreted as representing the Proterozoic Snowbird tectonic zone actually consist of two distinct components: (1) older, typically Archean, fabrics that have been fortuitously exposed along the trend of the Snowbird tectonic zone by shear zones such as the Legs Lake shear zone and (2) fertile rocks that have been intensely deformed during Chipman dike emplacement

Conclusions

Rocks of the Athabasca granulite terrane experienced high-pressure granulite facies metamorphism in the Paleoproterozoic (ca 1.9 Ga). Two styles of deformation are typical: rocks that experienced Archean tectonism tend to display a rheologically strong style with upright fabrics and highly partitioned, relatively narrow deformation zones. Rocks that were either not present or not strongly tectonized in the Archean exhibit a more penetrative deformation style with multiple folding events, local melting, and intense fabric development. The NE-trending Snowbird tectonic zone is essentially localized along the Chipman dike swarm and consists of older (Archean) deformation fabrics exposed by Proterozoic faulting and new Proterozoic fabrics produced in susceptible rocks during high-T dike-related heating and weakening.

Acknowledgements

Work in the Athabasca granulite terrane was partly supported by NSF Grant EAR-0609935. The authors are extremely grateful to the following people for discussions, insights about rocks of the Churchill Province: Kathy Bethune, Bernadette Knox, Ken Ashton, Chris Koteas, Simon Hanmer, Chris Kopf, and Sheila Seaman.

References

Bethune, K.M., Ashton, K.E., Berman, R.G., and Knox, B., 2008, -Pb SHRIMP geochronology of rocks in the western Beaverlodge Domain, Saskatchewan: unravelling the polyphase tectonometamorphic history of the SW Rae Province: GAC-MAC Abstract, v. 33, p. 21.

Card, C.D., 2001, Geology and tectonic setting of the Oldman-Bulyea Shear Zone, northern Saskatchewan, Canada: Regina, University of Regina, 188p.

Dumond, G., Goncalves, P., Williams, M.L., and Jercinovic, M.J., In Press, Sub-horizontal fabric in exhumed continental lower crust and implications for lower crustal flow: Athabasca granulite terrane, western Canadian Shield: Tectonics.

Dumond, G., McLean, N., Williams, M.L., Jercinovic, M.J., and Bowring, S.A., 2008, High-resolution dating of granite petrogenesis and deformation in a lower crustal shear zone: Athabasca granulite terrane, western Canadian Shield: Chemical Geology, v. 254, p. 175-196.

Dumond, G., Mahan, K. H., Williams, M. L. and Jercinovic, M. J., 2009. Orogenic float and the monazite connection. *Geological Society of America Abstracts with Programs*, vol. 41, no. 7, p. 356.

Knox, B., Bethune, K.M., Ashton, K.E., Williams, M.L., and Rayner, N., 2008, U-Pb SHRIMP and chemical monazite geochronology of rocks in the central Beaverlodge Domain, Saskatchewan: constraints on ages of rock units and implications for the tectonic evolution of the SW Rae Province: GAC-MAC Abstract, v. 33, p. 86.

Mahan, K.H., Goncalves, P., Flowers, R., Williams, M.L., and Hoffman-Setka, D., 2008, The role of heterogeneous strain in the development and preservation of a polymetamorphic record in high-P granulites, western Canadian Shield: Journal of Metamorphic Geology, v. 26, p. 669-694.

Mahan, K.H., Goncalves, P., William, M.L., and Jercinovic, M.J., 2006, Dating metamorphic reactions and fluid flow: application to exhumation of high- P granulites in a crustal-scale shear zone, western Canadian Shield: Journal of Metamorphic Geology, v. 24, p. 193-217.

Mahan, K.H., and Williams, M.L., 2005, Reconstruction of a large deep-crustal terrane: Implications for the Snowbird tectonic zone and early growth of Laurentia: Geology, v. 33, p. 385–388.

Mahan, K.H., Williams, M.L., and Baldwin, J.A., 2003, Contractional uplift of deep crustal rocks along the Legs Lake shear zone, western Churchill Province, Canadian Shield: Canadian Journal of Earth Sciences, v. 40, p. 1085-1110.

Williams, M.L., and Hanmer, S., 2006, Structural and metamorphic processes in the lower crust: evidence from a deep-crustal isobarically cooled terrane, Canada, *in* Brown, M., and Rushmer, T., eds., Evolution and Differentiation of the Continental Crust: Cambridge, Cambridge University Press, p. 231-267.