Transpressive uplift and exhumation of continental lower crust revealed by synkinematic monazite reactions

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ABSTRACT

Exposures of continental lower crust provide fundamental constraints on the thermal-mechanical behavior of continental lithosphere during orogeny. The applicability of field-based results, however, requires knowledge of whether these data pertain to deformation during lower-crustal residence or during uplift and exhumation of deep crust. Dating synkinematic monazite-producing reactions provides one way to evaluate deformation styles in the deep crust. We report on the implications of monazite reaction dating for the timing of fabric formation and movement along three crustal-scale shear zones in northern Saskatchewan, western Canadian Shield. The structures accommodated dextral transpressive strain during oblique- and thrust-sense displacement that was coeval with uplift and exhumation of >20,000 km^2 of continental lower crust (>1.0 GPa) to middle-crustal levels (<0.5 GPa). In situ Th-U–total Pb monazite data reveal that monazite rims in all three shear zones grew synkinematically at 1849 ± 6 Ma (2σ, mean square of weighted deviates = 0.8). The style of deformation involved localized strain concurrent with segmentation and translation of rheologically strong blocks of deep crust along mutually interacting shear zones during transpression.

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INTRODUCTION

Geophysical data, numerical modeling, and field-based studies indicate that continental lower crust exerts important controls on the rheology of the lithosphere during contractional and extensional tectonism (e.g., Jamieson et al., 2007; Wernicke et al., 2008). The study of rare exhumed exposures, however, provides the only way to accurately evaluate the way in which the lower crust accommodates the requisite deformation, and thus yields valuable constraints on the thermal-mechanical behavior of deep crust (Percival et al., 1992). Examples include Fiordland, New Zealand, for constraints on the evolving rheology of arc lower crust (Klepeis et al., 2007), and the Athabasca granulite terrane, Canada, for understanding the role of lower crust in the stabilization and reactivation of cratonic lithosphere (Flowers et al., 2008). The applicability of field-based data, however, depends upon accurate dating of deformation events to evaluate whether fabrics and inferred processes developed at the crustal level of interest or during subsequent uplift and exhumation.

Obtaining accurate dates that constrain the age of deformation is a first-order problem in continental tectonics. Recent work has focused on dating fabric-defining mineral phases like titanite, muscovite, and monazite (e.g., Resor et al., 1996; Mulch et al., 2005; Williams and Jercinovic, 2012). Interpretation of these dates requires constraints on the mechanisms and reactions responsible for growth and modification of the geochronometers during deformation. New research on monazite (light rare earth element phosphate) provides evidence for fluid-mediated dissolution-reprecipitation and dissolution-precipitation creep as mechanisms for producing the intragranular compositional zoning commonly observed in monazite (Harlov et al., 2011; Wawrzenitz et al., 2012). These mechanisms facilitate reactions between monazite and other phases that can be linked texturally to the tectonite fabric in the host rock (e.g., Foster et al., 2004; Williams and Jercinovic, 2012).

The role of reaction dating in constraining continental tectonics and mechanisms for uplift and exhumation of deep crust is highlighted herein with new field data and Th–U–total Pb monazite geochronology from the Athabasca granulite terrane, western Canadian Shield. We provide evidence for coeval displacement along three crustal-scale shear zones and an approach for evaluating tectonic models that assume regional kinematic compatibility. The geochronologic results are consistent with the "orogenic float" model, as defined by orogen-scale partitioning of strain on simultaneous strike-slip and thrust-sense shear zones, e.g., Oldow et al. (1990). This deformation overprinted fabrics linked to Neoarchean weak lower-crustal flow (Dumond et al., 2010). The results support a mechanism for thrust-related uplift of high-pressure rocks via transpressive strain that was distributed across interacting shear zones during segmentation and translation of rheologically strong blocks of lower crust.

BACKGROUND

The Athabasca granulite terrane is exhumed continental lower crust (0.8 to >1.5 GPa ≈ 30 to >50 km paleodepths) exposed north of Lake Athabasca, Canada (Fig. 1A; Mahan et al., 2008). The terrane is composed of Archean to Paleoproterozoic mafic and felsic granulites, orthogneisses, paragneisses, and minor eclogite bounded on its eastern margin by the 1.85 Ga Legs Lake shear zone (Fig. 1B; Mahan and Williams, 2005). Two main groups of structures have been identified throughout the terrane. The first group (D_1) includes subhorizontal to NW-striking, moderately dipping gneissic fabrics (S_1), ESE-trending stretching lineations, and recumbent isoclinal folds (F_1; Martel et al., 2008; Ashton et al., 2009; Dumond et al., 2010). These composite structures are interpreted as the result of granulite-grade lower-crustal flow at 2.60–2.55 Ga, defining a protracted episode of lower-crustal weakness (Dumond et al., 2010). Group two structures (D_2) include several generations of upright, open to tight folds of S_1 and transposition of folds and gneissic fabrics into subvertical to steeply dipping NE-striking mylonitic

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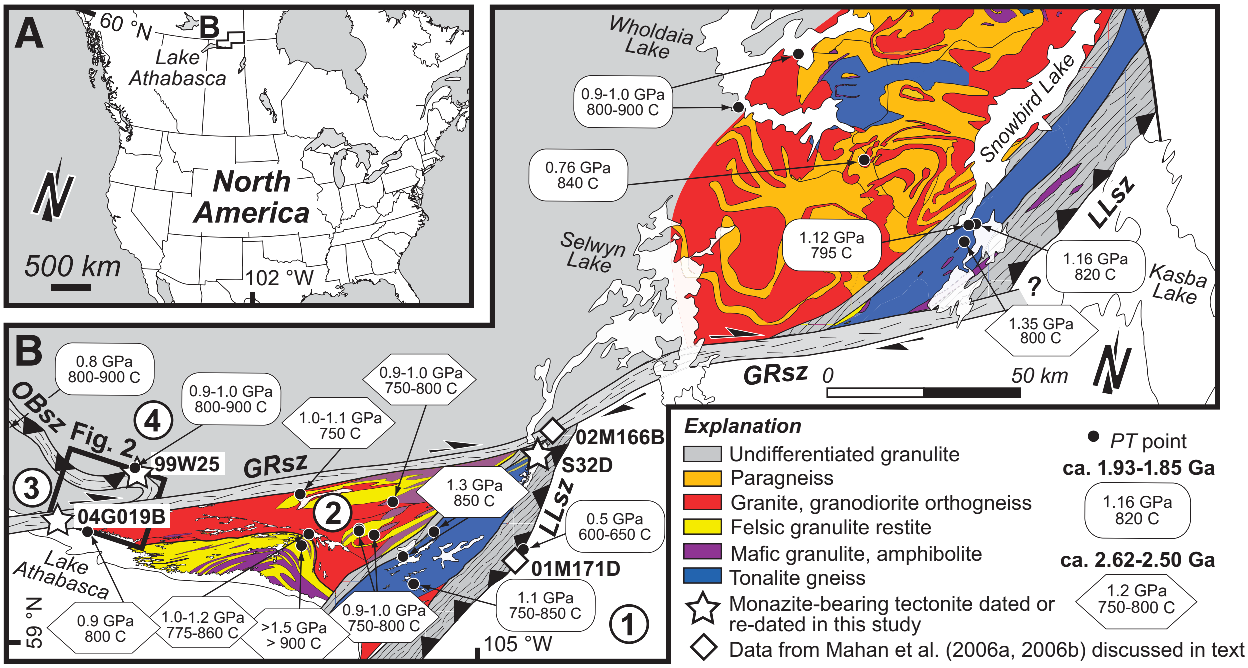

Figure 1. (A) Location of Athabasca granulite terrane in North America near the northeast end of Lake Athabasca. (B) Athabasca granulite terrane (modified after Mahan et al., 2008). Stars indicate locations of the three samples analyzed in this study. Diamonds correspond to samples dated by Mahan et al. (2006a, 2006b) referred to in the text. Abbreviations are: OBsz—Oldman-Bulyea shear zone; GRsz—Grease River shear zone; LLsz—Legs Lake shear zone. Note location of map in Figure 2. Numbered circles correspond to lithotectonic domains bounded by the shear zones illustrated in Figure 3: (1) Hearne; (2) Tantato–East Athabasca mylonite triangle; (3) Beaverlodge; and (4) Train Lake.

shear zones (S_2; Mahan et al., 2003; Martel et al., 2008; Ashton et al., 2009; Dumond et al., 2010). These structures are attributed to NW-SE subhorizontal shortening related to both the Taltson and Trans-Hudson orogenies at 1.92–1.80 Ga (Dumond et al., 2008; Ashton et al., 2009).

D_2 fabrics and structures are associated with crustal-scale shear zones that transect the Athabasca granulite terrane. Three prominent structures are the >500-km-long Legs Lake, the >400-km-long Grease River, and the >70-km-long Oldman-Bulyea shear zones (Figs. 1B, 2, and 3). The 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 SW (Fig. 3). The structure juxtaposes granulite-grade lower-crustal gneisses in its hanging wall (0.8–>1.1 GPa) with amphibolite-grade middle-crustal paragneisses in its footwall (0.4–0.5 GPa; Mahan et al., 2003; domains 2–4 over 1 in Figs. 1B and 3). The Grease River shear zone cuts the Legs Lake shear zone and is dominated by penetrative NE-striking, steeply NW-dipping foliations with shallowly SW-plunging to subhorizontal stretching lineations (Fig. 3). Kinematic indicators throughout the 5–7-km-wide structure correspond to dextral, strike-slip displacement with a component of SW-over-NE oblique-thrusting (Dumond et al., 2008, 2010). The Oldman-Bulyea shear zone is a NW-striking, 2–3-km-wide, moderately SW-dipping, oblique thrust-sense structure in highly retrogressed granulites (Card, 2001; Figs. 1B, 2, and 3).

NEW DATA FROM THE OLDMAN-BULYEA SHEAR ZONE

New mapping along the Oldman-Bulyea shear zone indicates that it was 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 (Figs. 2A and 2B). The undeflected segment of the Oldman-Bulyea shear zone dips moderately SSW and contains moderately SW-plunging stretching lineations (Fig. 2A). The deflected segment of the structure is transposed into steeply NW-dipping foliations associated with the Grease River shear zone (Fig. 2B). Outcrop-scale kinematics defined by shear bands and asymmetric porphyroclasts are uniformly top-to-the-NE along moderately SW-plunging stretching lineations (e.g., Fig. 4B; Data Repository section DR1A[1]). Garnet porphyroblasts are overgrown by biotite-rich strain shadows with sigmoidal tails defined by quartz ribbons in felsic granulites throughout the zone (e.g., Data Repository section DR1B [see footnote 1]). Stereonet analysis reveals that the two shear zones share nearly the same SW-plunging stretching lineation (Fig. 2A). Based on existing geochronology, Dumond et al. (2008) hypothesized that the Legs Lake and Grease River shear zones moved contemporaneously at ca. 1.85 Ga. The absolute timing of displacement along the Oldman-Bulyea shear zone, however, was unknown prior to this study.

MODEL FOR TRANSPRESSIVE UPLIFT AND EXHUMATION

Field relationships and existing geochronology support the following relative timing for segmentation of the Athabasca granulite terrane. The 1.85 Ga Legs Lake shear zone accommodated ~20 km of uplift and is cut by the Grease River shear zone (Mahan et al., 2003; Mahan and Williams,

[1]GSA Data Repository Item 2013323, section DR1 (field and thin-section kinematic data from the Oldman-Bulyea shear zone), section DR2 (electron microprobe analysis methods for monazite), section DR3 (table of monazite major- and trace-element data), and section DR4 (X-ray maps and backscattered-electron images of analyzed monazite grains), is available at www.geosociety.org/pubs/ft2013.htm, or on request from editing@geosociety.org, Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

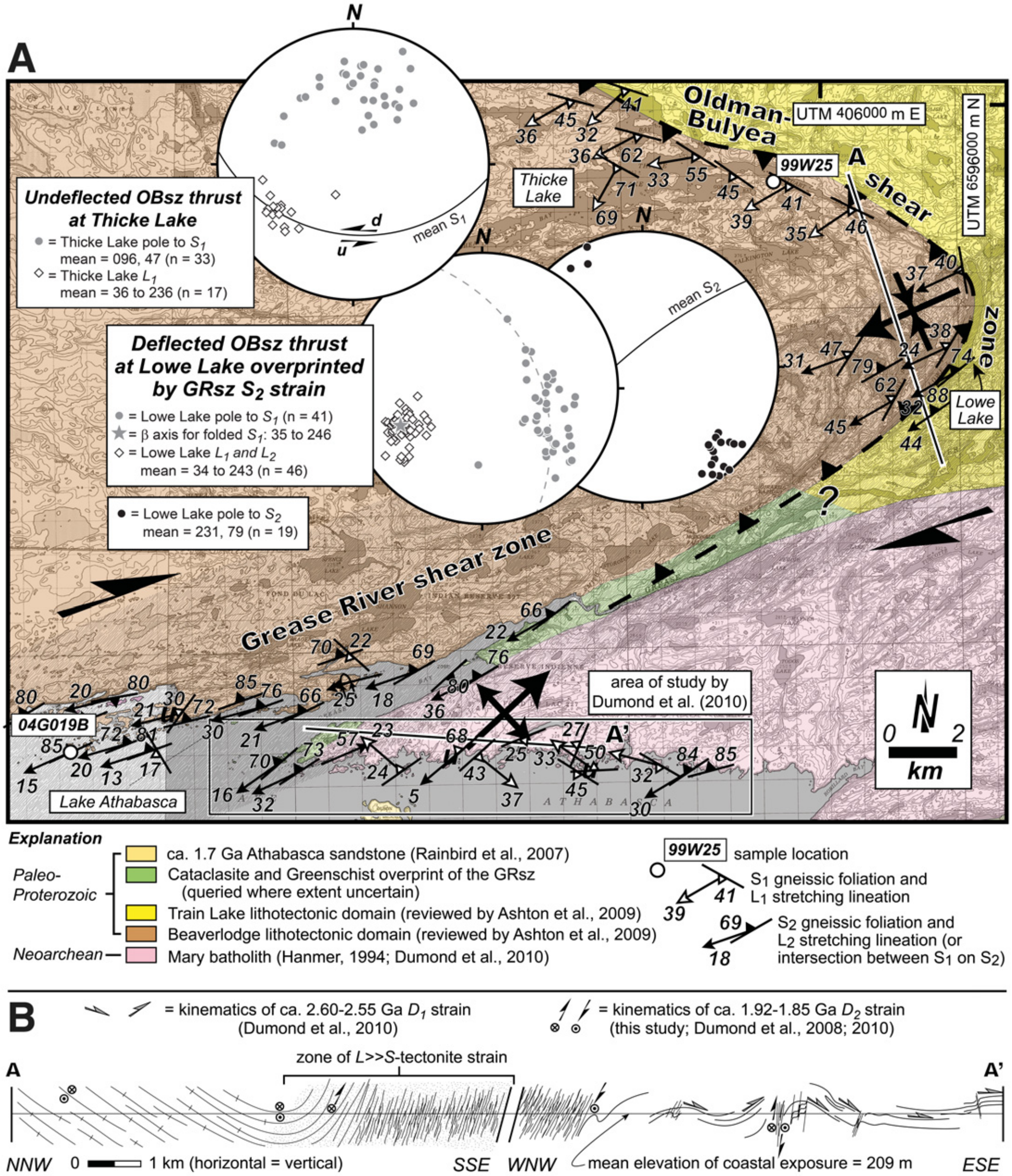

Figure 2. (A) Geologic map illustrating deflection of the Oldman-Bulyea shear zone (OBsz; defined farther NW of the area by Card, 2001) into the Grease River shear zone (GRsz). Stereonets depict gneissic foliations, stretching lineations, and intersection lineations in the area. See Figure 1 for location of map. (B) Geologic cross section across the deflected Oldman-Bulyea shear zone and the Grease River shear zone.

2005). The Oldman-Bulyea thrust-sense shear zone has foliation trajectories that are deflected into the Grease River shear zone (Fig. 2A), implying that the Grease River shear zone is the youngest structure. However, microstructural and geochronological data from a deformed granite dike indicate older (ca. 1.92–1.90 Ga) granulite-grade shearing in the Grease River shear zone that predates the amphibolite-grade Legs Lake shear zone (Dumond et al., 2008). These data are reconciled by interpreting the Grease River shear zone as the deep crustal roots of an older (≥1.92 Ga) intracontinental strike-slip shear zone that was cut, uplifted, and reactivated in the hanging wall of the 1.85 Ga Legs Lake shear zone (Fig. 3). Reactivation of the Grease River shear zone at 1.8 Ga at lower-amphibolite- to greenschist-grade conditions led to the observed ~110 km offset of the Legs Lake shear zone and the present-day geometry of the terrane (Mahan and Williams, 2005; Dumond et al., 2008). Thus, while the shear zones did not originate at the same time, the observations imply a shared history. Deformation occurred under amphibolite-grade conditions, resulting in top-to-the-NE transport along penetrative SW-plunging stretching lineations in all three zones (Fig. 3). Accurate constraints on the timing of shearing are required to validate this model.

TESTING A TECTONIC MODEL WITH SYNKINEMATIC REACTION DATING

We used Th–U–total Pb monazite geochronology to evaluate the hypothesis that all three shear zones moved simultaneously during regional transpressive uplift and exhumation of continental lower crust. Synkinematic monazite grains in retrogressed garnet-bearing felsic granulite gneisses from the Legs Lake and Oldman-Bulyea shear zones (samples S32D and 99W25, respectively) and in a granite orthogneiss (sample 04G-19B) from the Grease River shear zone were used to constrain the timing of movement (Fig. 1B). These are three among several samples chosen to test the hypothesis (samples located in Fig. 1B).

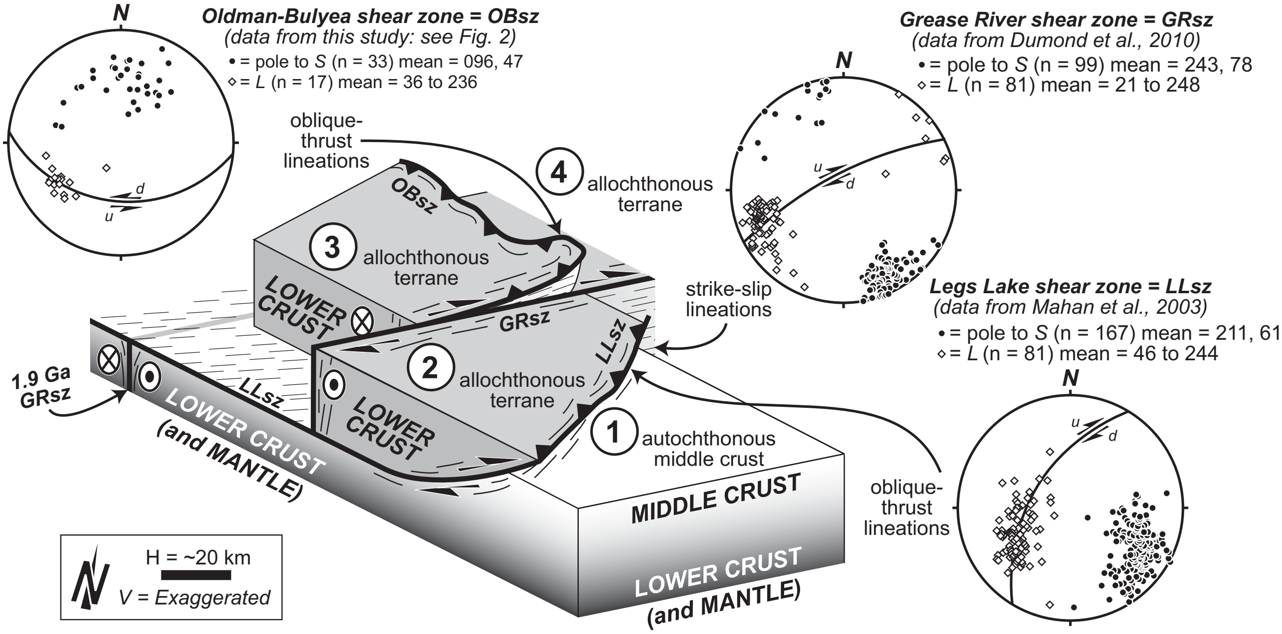

Figure 3. Vertically exaggerated block diagram depicting geometry of Legs Lake, Grease River, and Oldman-Bulyea shear zones based on maps in Figures 1B and 2 and data from Mahan et al. (2003), Mahan and Williams (2005), and Dumond et al. (2008, 2010). Lower-hemisphere equal-area stereonet projections of poles to foliations (S) and lineations (L) illustrate kinematically compatible top-to-the-NE transport. Numbered circles are same as in Figure 1B. The figure illustrates how blocks 2–4 were active in the hanging wall of the Legs Lake shear zone.

Monazite from each of the samples was dated in the context of three metamorphic and metasomatic reactions. The felsic granulites contain a penetrative foliation defined by biotite that wraps around resorbed garnet (Figs. 4A and 4B; Data Repository section DR1B [see footnote 1]). Biotite also defines asymmetric strain shadows, shear bands, and C-S fabrics. Monazite grains in these samples have distinct 5–10-µm-wide high-Y rims attributed to garnet breakdown and growth of biotite during fluid flux and synkinematic reaction 1 (Figs. 4A and 4B; mineral abbreviations after Bucher and Frey, 2002):

$$\text{Grt + Kfs + Y-poor Mnz + Fluid} \rightarrow \text{Bt + Sil + Y-rich Mnz.} \quad (1)$$

In the Oldman-Bulyea shear zone, reaction 1 produced plagioclase instead of sillimanite (Fig. 4B):

$$\text{Grt + Kfs + Y-poor Mnz + Fluid} \rightarrow \text{Bt + Pl + Y-rich Mnz.} \quad (2)$$

Breakdown of garnet to synkinematic biotite in Equations 1 and 2 is consistent with precipitation of high-Y monazite during shear zone–related uplift and coeval exhumation (Mahan et al., 2006a).

The biotite-bearing granite orthogneiss from the Grease River shear zone contains abundant elongate high-Ca monazite with asymmetric low-Ca rims associated with secondary apatite (Fig. 4C; Dumond et al., 2008). Monazite zoning is consistent with dissolution of high-Ca cores and reprecipitation of 5–30-µm-wide low-Ca rims with apatite during metasomatic reaction 3:

$$\text{High-Ca Mnz + Fluid} \rightarrow \text{Low-Ca Mnz + Ap.} \quad (3)$$

Monazite grains are aligned in the penetrative orthogneiss fabric. Low-Ca domains define σ-type geometries consistent with synkinematic reprecipitation during top-to-the-NE strain (Fig. 4C). Sigmoidal monazite grains are similar to σ-type K-feldspar–porphyroclasts in the same orthogneiss (Fig. 4D).

Geochronological Analysis

In situ Th–U–total Pb dating was performed on the Cameca® SX100 Ultrachron electron microprobe at the University of Massachusetts following the approach of Williams et al. (2006) and Jercinovic et al. (2008). Analytical methods and full results are detailed in the Data Repository (sections DR2, DR3, and DR4 [see footnote 1]). Monazite domains from the Legs Lake and Grease River shear zones were previously dated independently by Mahan et al. (2006a, 2006b) and Dumond et al. (2008), respectively, and yielded ca. 1.85 Ga dates. Newly identified monazite grains from the Oldman-Bulyea shear zone were dated for the first time here. Because sample coating effects and calibration can affect precision and accuracy (Williams et al., 2006), we minimized these potential sources of uncertainty by coating all three samples simultaneously and reanalyzing them during the same session with the same calibration. This is the most robust way to evaluate the hypothesis that the ages for shearing and reaction in all three samples are identical within uncertainty.

Figure 5A summarizes the individual results at the 95% confidence level for each shear zone. Data for the Legs Lake shear zone from sample S32D yield a weighted mean date of 1844 ± 23 Ma (mean square of weighted deviates [MSWD] = 0.32). The relatively large uncertainties are attributed to the low Th and Pb concentrations of the grains (section DR3 [see footnote 1]). Results for the Grease River shear zone from sample 04G19B provide a weighted mean date of 1847 ± 9 Ma (MSWD = 1.4). Sample 99W25 from the Oldman-Bulyea shear zone yields a weighted mean date of 1851 ± 10 Ma (MSWD = 1.2). Figure 5B summarizes results for all nine rim domains from the three shear zones that define a single weighted mean date of 1849 ± 6 Ma (MSWD = 0.82). These results are identical within the resolution of the technique, and we interpret 1849 ± 6 Ma as the age of simultaneous reaction and shearing. The age does not include all sources of systematic error, e.g., uncertainties in the decay constants (i.e., Williams et al., 2006).

REACTION DATING, OROGENIC FLOAT, AND EVOLVING LOWER CRUST

Reaction dating is a promising approach for testing kinematic compatibility and documenting the record of synkinematic reactions and ductile

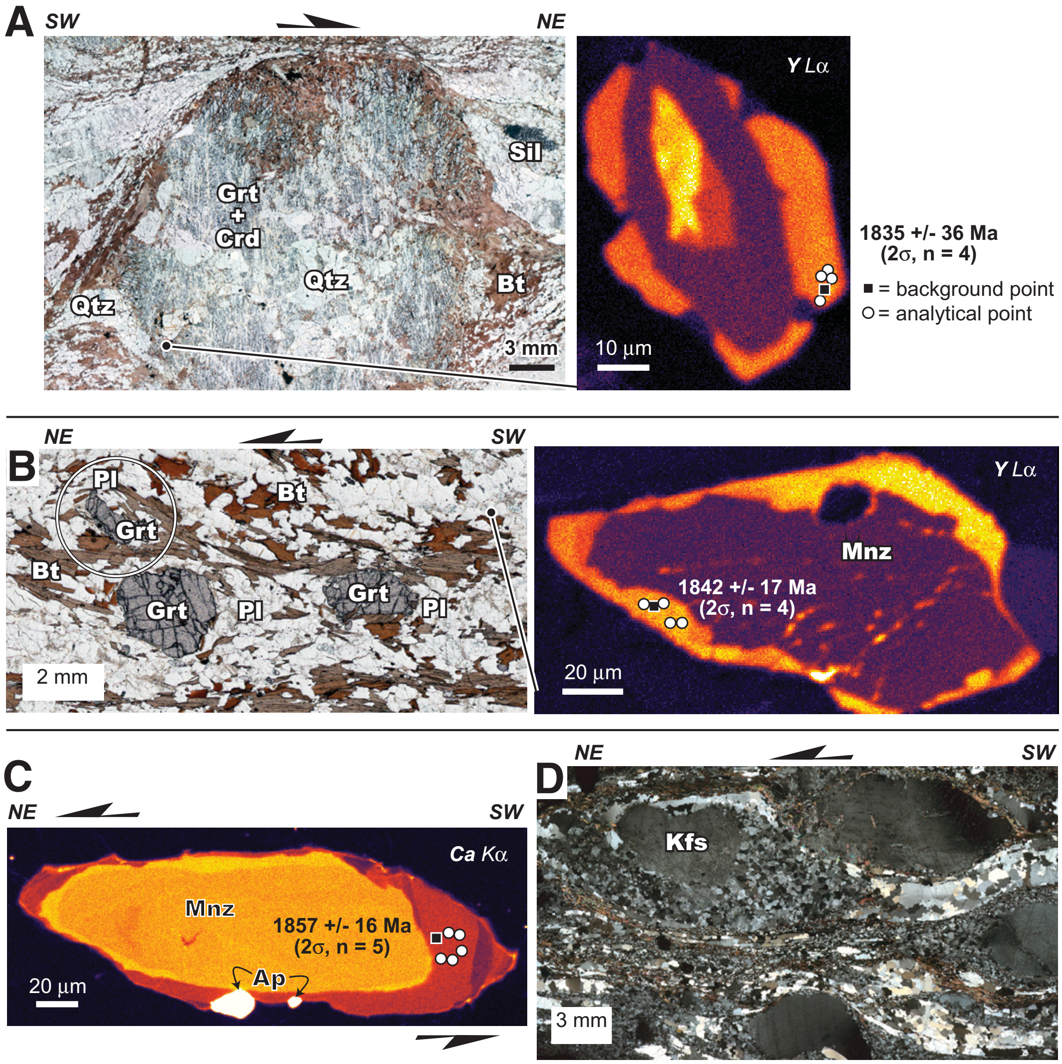

Figure 4. (A) Plane light photomicrograph of retrogressed felsic granulite. Note that biotite is synkinematic (after garnet) and strongly wraps around the garnet from sample S32D. Biotite commonly defines σ-asymmetry within the Legs Lake shear zone fabric. X-ray map shows high-Y monazite rim, interpreted to have reprecipitated during garnet breakdown and growth of synkinematic biotite. (B) Plane light photomicrograph of retrogressed felsic granulite from the Oldman-Bulyea shear zone sample 99W25. Note incipient C-S fabric defined by biotite (after resorbed garnet). Circled region highlights growth of biotite and plagioclase after garnet. X-ray map illustrates high-Y monazite rim interpreted in the same manner as for sample S32D. (C) X-ray map of monazite grain from the Grease River shear zone sample 04G-19B. Asymmetric σ-type low-Ca rims indicate top-to-the-NE sense of shear. (D) Cross-polarized light photomicrograph of biotite orthogneiss. Note K-feldspar σ-type porphyroclast (Kfs) with core-and-mantle structure indicating top-to-the-NE sense of shear. Mineral abbreviations are after Bucher and Frey (2002).

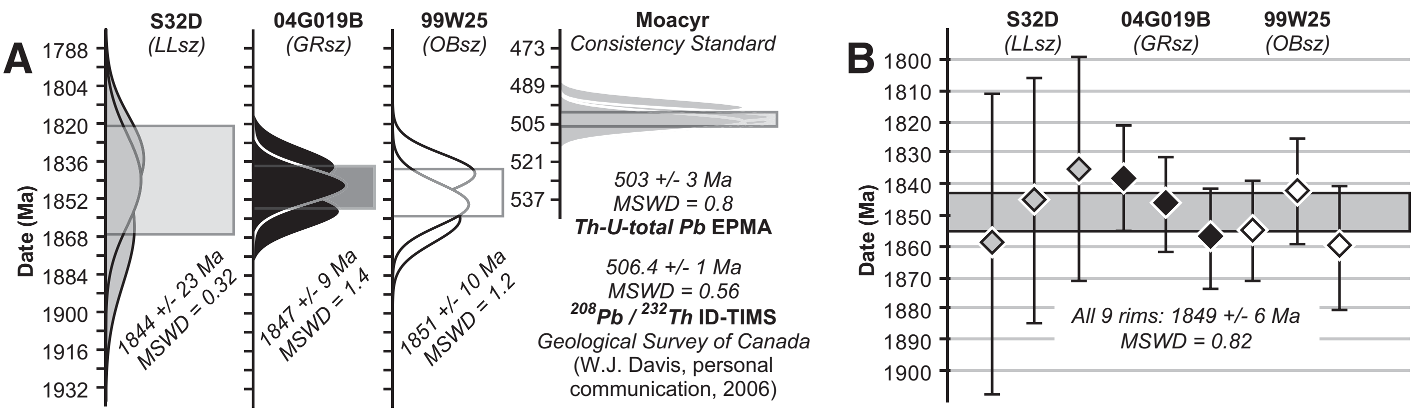

Figure 5. (A) Gaussian normalized histogram plots with weighted mean dates for monazite rims from all three shear zones. Adjacent plot shows results for multiple analyses of Moacyr monazite consistency standard obtained during the same analytical session. Abbreviations are: OBsz—Oldman-Bulyea shear zone; GRsz—Grease River shear zone; LLsz—Legs Lake shear zone; EPMA—electron microprobe analysis; ID-TIMS—isotope dilution–thermal ionization mass spectrometry. (B) Vertical 2σ error bar plot. All nine rim domains yield a weighted mean date of 1849 ± 6 Ma (mean square of weighted deviates [MSWD] = 0.8) interpreted as the age of simultaneous reaction and shearing during uplift and exhumation (at 95% confidence).

movement in regional-scale shear zone systems. Monazite is a “reactive porphyroclast” ideal for reaction dating in shear zone tectonites due to its tendency to recrystallize via dissolution-precipitation creep (Wawrzenitz et al., 2012) and fluid-mediated coupled dissolution-reprecipitation (Harlov et al., 2011). Decompression and fluid infiltration occurred during shortening at 1.85 Ga (Mahan et al., 2006a), inducing garnet breakdown to biotite ± plagioclase ± sillimanite in the Legs Lake and Oldman-Bulyea shear zones and catalyzing metasomatic reactions that promoted dissolution and reprecipitation of monazite ± apatite in the Grease River shear zone.

This study provides evidence for orogen-scale partitioning of strain on simultaneous strike-slip and thrust-sense shear zones, i.e., “orogenic float” of Oldow et al. (1990). Coeval displacement requires a basal décollement to maintain kinematic compatibility (Oldow et al., 1990). We infer that the downdip portion of the Legs Lake shear zone is the master décollement, which beheaded the older ca. 1.9 Ga Grease River shear zone and ramped up to middle-crustal levels (Fig. 3). The Oldman-Bulyea shear zone and the offset segment of the Grease River shear zone were active only in the hanging wall of the Legs Lake décollement during segmentation, uplift, and exhumation of lower crust at 1.85 Ga. At this stage, the active Grease River shear zone moved northeastward along with blocks 2–4 in the hanging wall of the Legs Lake shear zone and was dismembered from the formerly active footwall segment (1.9 Ga segment in Fig. 3). Shortening during shearing was also accommodated by folding within the blocks (Fig. 2B). Synkinematic monazite rims in each of the shear zones are compositionally and texturally linked to these events across several segments of the Grease River and Legs Lake shear zones, emphasizing the regional character of this event (samples 02M166B and 01M171D in Fig. 1B; Mahan et al., 2006a, 2006b).

Heterogeneous strain is exhibited by strong, locally isobarically cooled blocks of crust with shear zones localized between them (Fig. 2B; Williams et al., 2009). Ca. 1.85 Ga and younger strain is generally not observed outside the shear zones. This behavior contrasts with the Neoarchean weak lower-crustal flow experienced by some blocks outside the shear zones (e.g., west half of Fig. 2B; Dumond et al., 2010), highlighting the weak-to-strong rheological evolution of continental lower crust prior to uplift. The results illustrate a mechanism for uplift and exhumation of high-pressure rocks via transpressive strain distributed across interacting shear zones at the hundreds of kilometers scale (coupled to erosion and/or extension at the surface).

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