Restored transect across the exhumed Grenville orogen of Laurentia and Amazonia, with implications for crustal architecture

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ABSTRACT

New $^{40}Ar/^{39}Ar$ analyses from a transect across the major tectonic units of the southwest Amazon craton document the heterogeneous effects of the late Mesoproterozoic collision with the Grenville margin of North America. Basement rocks of the Amazon and adjacent Paragua cratons mostly preserve pre-Grenvillian ages (older than 1.3 Ga). Localized isotopic age resetting at 1.18–1.12 Ga is caused by Grenvillian activation of widespread, sinistral strike-slip shear zones in the Amazon basement. In the Nova Brasilândia belt between these two cratons, new $^{40}Ar/^{39}Ar$ data record cooling through 920 Ma after the granulite facies deformation of this suture zone. Regional cooling rates calculated from compiled U/Pb, $^{40}Ar/^{39}Ar$, and Rb/Sr thermochronologic data are used to establish post-Grenvillian exhumation patterns for the southwest Amazon and the North American belt. Paleodepths calculated for 1.0 Ga along a transect of the restored 1300-km-wide belt vary from uniformly deep levels (15–30 km) exposed in North America to shallower levels (5–15 km) observed in the southwest Amazon. We interpret this difference as reflective of a change in tectonic architecture, i.e., thrust-dominated deformation in Laurentia versus strike-slip dominated deformation in the Amazon, with a commensurate variation in crustal thickness. This interpretation explains the widespread preservation of both pre-Grenvillian ages and collisional ages from the Amazon craton, in contrast with the more homogeneous array of cooling ages from the North American Grenville Province marking the postorogenic extensional collapse of an overthickened crust. The asymmetrical orogenic architecture from the reconstructed Grenville belt mirrors cross sections proposed for modern orogenic belts where deep-crustal rocks are not yet exposed.

Keywords: Grenville Province, Amazon craton, thermochronology, orogenic structure, exhumation, asymmetry.

INTRODUCTION

The Grenville Province of North America is widely recognized as the exhumed root of a segment of a major orogenic belt (Rivers et al., 1989). The overthickened crust that typifies orogenic zones has left imprints on the southern and eastern margin of Laurentia, where a long Mesoproterozoic history of accretion of juvenile crust culminated in a continental collision (Mosher, 1998; Rivers and Corrigan, 2000). Evidence for this ca. 1.2–1.0 Ga collision includes seismic images of imbricated crust (e.g., Forsyth et al., 1994), a burial history marked by mid-crustal (800–1000 MPa) mineral assemblages exposed at the surface (e.g., Streepey et al., 1997) with a residual 40–45 km of crust locally present, extensive isotopic resetting following the relaxation of crustal isotherms (e.g., Mezger et al., 1993), and a kinematic history reconstructed from study of mylonitic shear zones (e.g., Davidson, 1984). The development of crustal overburden through thrust faulting eventually exceeded crustal strength, leading to the extensional collapse of the Grenville Province (e.g., Culshaw et al., 1991). The prolonged postorogenic phase was marked by widespread motion on normal shear zones, with coupled exhumation and erosion reducing crustal thickness (e.g., Cosca et al., 1991).

Observations of the exhumed Grenville Province are commonly cited in reference to deep-crustal processes active in younger collisional belts; the scale of this ancient belt invites comparison to the Himalayan-Tibetan system (e.g., Dewey and Burke, 1973; Windley, 1986). Conversely, the kinematic framework of the Himalayan-Tibetan orogen, with its early accretionary history succeeded by a quasi-orthogonal continent-continent collision, has influenced models of Grenville tectonics: the implication is that deformation along the ~3000 km Grenville Province was caused by individual collisions with three separate continents. These were identified by Dalziel (1991) and Hoffman (1991) as Kalahari, Amazonia, and Baltica, although recent evidence from Amazonia suggests that transpressive motion of the Amazon craton was responsible for the all of the Grenvillian deformation of Laurentia (Tohver et al., 2002, 2004). All models place the Amazon against the central Grenville Province (i.e., Ontario, Quebec, New York) by 1.0 Ga (Fig. 1).

The 1.0 Ga Grenvillian link between Amazonia and Laurentia permits us to reconstruct the tectonometamorphic history preserved on both plates of a major orogen in order to recreate the ancient belt's principal structures. We report new $^{40}Ar/^{39}Ar$ analyses from a transect of the southwest Amazon craton that are used with recently published data to establish the post-Grenvillian exhumation history for ancestral South America. These data are integrated with the thermochronological record of the North American counterpart to build a crustal model for a restored Grenville belt, with implications for field studies of ancient orogens and evolutionary models of modern mountain belts (e.g., Beaumont et al., 2001).

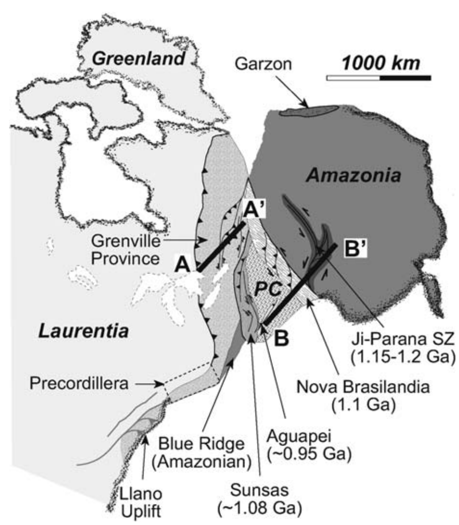

Figure 1. Reconstruction ca. 1 Ga with position of transects A-A' and B-B' across Grenvillian belts of Laurentia and Amazonia. SZ—shear zone; PC—Paragua craton.

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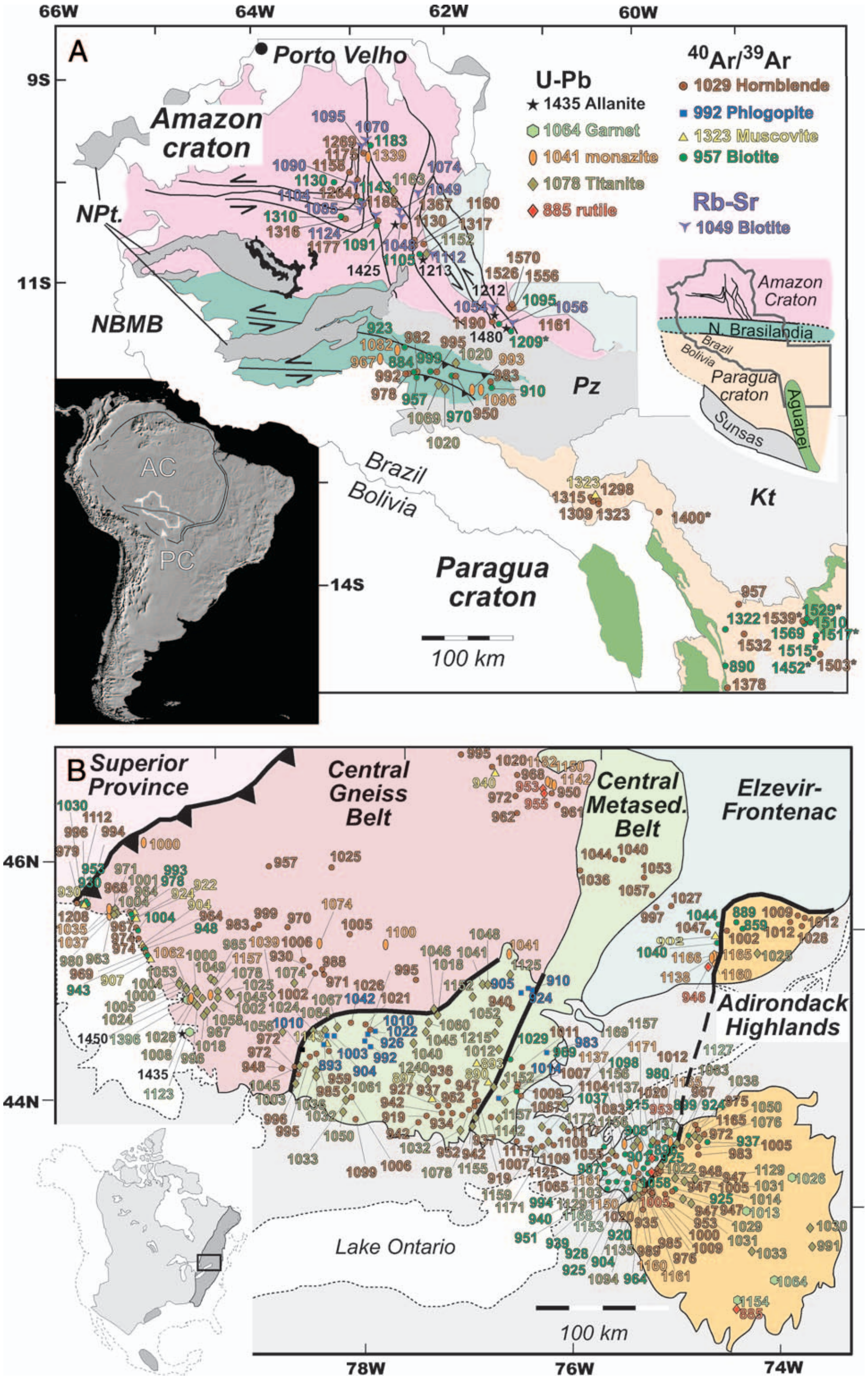

Figure 2. Summary of compiled thermochronologic age data for (A) southwest Amazon craton (AC; PC is Paragua craton) and (B) Laurentia (data sources in Appendix A; see footnote). NBMB—Nova Brasilândia metasedimentary belt; NPt.—Neoproterozoic; Pz—Paleozoic, Kt—Cretaceous.

GRENVILLIAN OROGEN OF THE AMAZON CRATON

The Grenvillian deformation of the southwest Amazon craton is observed in four separate features (from south to north): (1) the ca. 1.08 Ga Sunsas belt and adjacent regions along the southwest margin of the subcontinental Paragua craton (PC) of eastern Bolivia; (2) the ca. 0.95 Ga Aguapeí belt (AB) internal to the PC in western Brazil; (3) the 1.1 Ga Nova Brasilândia metasedimentary belt (NBMB) that sutures the Amazon craton (AC) and PC; and (4) the 1.2–1.15 Ga Ji-Paraná shear zone (JPSZ) network that affected the Amazon basement north of the NBMB (Fig. 1). The Sunsas belt along the southwest margin of the PC was first described by Litherland et al. (1989), and was marked by calc-alkaline, granitic magmatism emplaced into fold belts bordered by large strike-slip shear zones (Santa Catalina SZ and San Diablo SZ) with sinistral offsets active ca. 1.08–1.0 Ga (Litherland et al., 1989; Boger et al., 2005). This record contrasts with the sparse igneous rocks and localized low-grade deformation of the intracratonic AB. Aguapeí deformation occurred ca. 950 Ma (Geraldes et al., 1997), well after the cessation of deformation in the Sunsas belt. The northern boundary of the PC is defined by the ~2000 km, east-west–trending NBMB, where upper amphibolite to granulite metamorphism of intercalated marine sediments and mafic rocks record the transpressive suturing of the AC and PC ca. 1.09 Ga (Tohver et al., 2004). North of the NBMB suture, the AC basement rocks are chiefly metaigneous suites that record a protracted history of arc construction and remobilization throughout the Mesoproterozoic (Bettencourt et al., 1999; Payolla et al., 2002). Here, Grenvillian deformation occurred at 1.2–1.12 Ga, resulting in the JPSZ network of sinistral strike-slip shear zones that extends over hundreds of kilometers.

$^{40}Ar/^{39}Ar$ GEOCHRONOLOGY OF SOUTHWEST AMAZON CRATON

Sampling in western Brazil was carried out along a 750 km transect across the major tectonic units exposed in the states of Rondônia and Mato Grosso. Three domains were sampled: the Paleoproterozoic-Mesoproterozoic basement of the AC, including mylonitic rocks of the 1.2–1.15 Ga JPSZ; metasediments of the western exposures of the NBMB; and PC basement rocks, including the AB. Sample locations, argon age spectra, and a complete reference list for Grenville thermochronology data are included in Data Repository Appendix A.[1]

The results of the $^{40}Ar/^{39}Ar$ analyses from 34 samples can be grouped into three age brackets: (1) pre-Grenvillian ages (1.3–1.55 Ga) observed in the AC and PC basement rocks, including biotite samples in the latter; (2) 1.18–1.12 Ga ages in samples from JPSZ mylonites that crosscut the AC north of the NBMB; and (3) 1.0–0.9 Ga ages from amphibolite-grade metabasites intercalated with NBMB (Fig. 2). While widespread 1.3 Ga hornblende ages in the AC largely reflect metamorphism subsequent to igneous crystallization, AC biotite ages are all younger than ca. 1.1 Ga. Both biotite and hornblende ages

[1]GSA Data Repository item 2006136, Appendix A, sample locations, argon age spectra, and a complete reference list for Grenville thermochronology data, is available online at www.geosociety.org/pubs/ft2006.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

from the PC samples correspond closely to published U-Pb zircon ages (Geraldes et al., 2001), suggestive of undisturbed magmatic ages. The 1.18−1.12 Ga hornblende ages from the JPSZ mylonites record the timing of deformation, not regional cooling, an interpretation supported by feldspar thermometry on recrystallized grains and hornblende ages older than 1.3 Ga from undeformed samples outside the shear zones (Tohver et al., 2005). The youngest ages (ca. 1.0–0.92 Ga) come from the NBMB, exhumed from mid-crustal depths (~800 °C at 800 MPa) following the suturing of the Amazon and Paragua cratons ca. 1.09 Ga (Tohver et al., 2004).

The ~600 m.y. variation in ages observed at the modern surface of the southwest Amazon indicates the heterogeneity of Grenvillian tectonothermal effects. For example, the interior of the PC was at high crustal levels (i.e., cooler than the closure temperature of biotite) throughout the late Mesoproterozoic, with deformation confined to the marginal Sunsas and Nova Brasilândia belts. In the AC basement, extensive deformation was accommodated by strike-slip shear zones active at temperatures of ~450–550 °C, but rocks (and their pre-Grenville geochronological record) outside of shear zones were unaffected. In contrast, granulite facies deformation in the ~100-km-wide NBMB signifies deeper exhumation from mid-crustal levels, with isotopic resetting upon cooling.

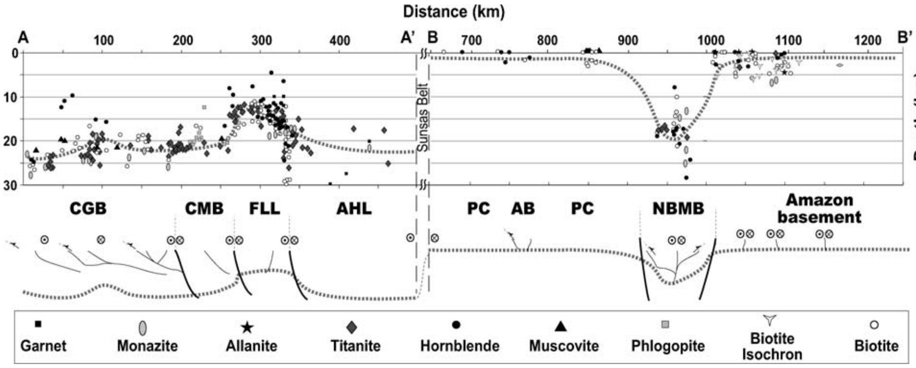

Figure 3. Top: Calculated paleodepths for 1.0 Ga from observed cooling rates with 30 °C/km geotherm. Dashed gray line (moving average) is depth of modern surface at 1.0 Ga (10× vertical exaggeration [v.e.]), e.g., rock cooling at 2 °C/m.y. through hornblende blocking temperature of 500 °C at 1.1 Ga would be ~10 km from surface by 1.0 Ga. Bottom: Paleodepth line superimposed on structure inferred from seismic and field studies (5× v.e.) Notice correlation of paleodepth and thrusting in Laurentia vs. shallow exhumation of southwest Amazonia tied to predominance of strike-slip faults. NBMB—Nova Brasilândia metasedimentary belt; AB—Aguapeí belt; PC—Paragua craton; AHL—Adirondack Highlands; FLL—Frontenac-Adirondack Lowlands; CMB—Central Metasedimentary Belt; CGB—Central Gneiss Belt.

DISCUSSION AND CONCLUSIONS

Thermochronologic data from U/Pb dating of garnet, monazite, allanite, titanite, and rutile; $^{40}Ar/^{39}Ar$ dating of hornblende, phlogopite, muscovite, and biotite; and Rb-Sr dating of biotite from studies of the central Grenville Province and southwest Amazonia were compiled with our new results (Fig. 2). The different closure temperatures (T_c) of these minerals were used to calculate regional cooling rates for the major tectonic units across the transects (Fig. 1; Appendix A [see footnote 1]). In the case of deformation ages recovered from mylonites, the deformation temperature (~450 °C; Tohver et al., 2005) is used instead of the thermal blocking temperature. Using a geotherm of 30 °C/km from calculated pressure-temperature (P-T) conditions (Streepey et al., 1997), the cooling rates yield an exhumation rate for each tectonic domain, signifying that cooling ages from different minerals (with different T_c) can be normalized for a given time to a common dimension, depth. Clearly, calculated exhumation rates have not been constant since the end of the Grenville episode; the presence of Cambrian–Ordovician sediments on top of Grenvillian metamorphic rocks in Laurentia and the Neoproterozoic–Paleozoic sedimentation in the southwest Amazon craton establish a cut-off time for postorogenic exhumation. Calculating depths at 1.0 Ga circumvents the problem of decreasing cooling and/or exhumation rates, especially below 300 °C (e.g., Streepey et al., 2001). Scatter in the calculated paleodepths using different minerals may reflect variation in the actual T_c for individual grains, localized changes in cooling rates, or deformation after cooling. However, this scatter should not significantly affect the relative paleodepth values between tectonic domains. One complication is presented by nine older Amazon samples (i.e., age ca. 1.5 Ga or older), where assumed long-lived exhumation results in negative calculated paleodepths, i.e., above the modern surface. In these cases, the paleodepth is normalized to zero.

Paleobaths calculated in this manner for the southwest Amazon at 1.0 Ga are remarkably consistent for individual tectonic domains across the sampled transect (Fig. 3). For example, the NBMB exhibits the most deeply exhumed crust of the southwest Amazon, supporting the contention that this belt represents an exhumed suture zone. The PC and AC basement rocks on either side of this suture zone were much closer to the surface by 1.0 Ga, as evidenced by the absence of thermal resetting at this time. A single hornblende sample from the PC records an age of 990 Ma, possibly reflecting the thermal aureole of the São Domingos granite. In contrast, calculated paleobaths of the central Grenville Province of Laurentia at 1.0 Ga demonstrate that much deeper crustal levels are exposed. From northwest to southeast, the average paleodepth at 1.0 Ga of the Central Gneiss Belt and Central Metasedimentary Belt is 15–25 km, versus 10–15 km for rocks of the Frontenac-Adirondack Lowlands, and 15–30 km for the Adirondack Highlands, consistent with P-T estimates (e.g., Streepey et al., 1997). Whereas relative motion between these fault-bounded domains has been documented as part of the extensional collapse of overthickened crust in a late-orogenic to postorogenic period (e.g., Culshaw et al., 1991; Cosca et al., 1991; Mezger et al., 1993; Busch et al., 1997), the contrast with the southwest Amazon data is relevant here, where Grenvillian crustal thickening was limited in both degree and geographic occurrence.

From the uneven exhumation of the restored Grenville orogen emerges a picture of an asymmetric orogenic structure, with a thick crustal stack in the thrust-dominated foreland of Laurentia and localized crustal thickening in the strike-slip dominated hinterland of the southwest Amazon craton. The widespread preservation of pre-Grenvillian metamorphic ages in the southwest Amazon contrasts with the uniform age resetting ca. 1.1–1.0 Ga of metamorphic chronometers from the North American Grenville Province. This difference is interpreted as a result of orogenic structure; whereas regionally uniform isotherms in the thrust-imbricated Laurentian crust reset all thermochronometers, the effects of predominantly strike-slip deformation in southwest Amazonia were more localized. Thus, the Laurentian belt records cooling in the post-orogenic period, in contrast with the mixture of pre-Grenvillian ages, syncollisional deformation ages, and postorogenic cooling ages observed in the southwest Amazon. A corollary for deciphering Grenvillian events is that the southwest Amazon exhibits excellent preservation of syncollisional structures, in contrast with the widespread reactivation of ductile structures in the postorogenic extensional phase in the Laurentian belt. This reactivation has not completely obliterated the record of along-strike motion in the central Grenville Province documented by the northeast-directed thrusting parallel to strike (Hanmer,

1988) or sinistral motion across prominent mylonitic shear zones (e.g., Martignole and Pouget, 1994; Busch et al., 1997; Zhao and Martignole, 1997; Martignole and Friedman, 1998; Streepey et al., 2001; O'Dowd et al., 2004).

The broad differences in strain pattern across the restored Grenville belt may reflect the deep crustal profile of other collisional belts. A similar orogenic asymmetry characterizes the Alpine-Pyrenees belt, where convergence precluded extensive strike-slip motion (Beaumont et al., 2000). Numerical models of convergent orogens predict a broad prowedge marked by late exhumation of high-grade rocks, and a confined retrowedge that undergoes early exhumation from a shallower crustal level (Jamieson et al., 2002), in keeping with our empirical model of Laurentia and southwest Amazon, respectively. This agreement leads us to speculate that the orogenic asymmetry of the Grenville belt reflects slab polarity with hinterland-directed subduction (i.e., Laurentia under the conjoined Amazon-Paragua craton). Another explanation is that the more uniform strain of Laurentia reflects its preexisting thermal structure, softened by long-lived convergence and magmatism throughout the Mesoproterozoic (e.g., Rivers and Corrigan, 2000). The older model ages of the southwest Amazon craton suggest that the colder, stronger Amazon lithosphere prevailed during the Grenvillian collision, regardless of subduction geometry.

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