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Geology 2003;31;e30-e31
doi: 10.1130/0091-7613-31.1.e30

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COMMENT

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The tectonic evolution of the Belingwe Greenstone Belt in Zimbabwe has been a matter of great controversy. In the most recent contribution to this debate, Bolhar et al. (2003) reported major element, trace element, and Nd isotope data for mafic volcanic rocks of different stratigraphic units of the greenstone belt. Three stratigraphic units of the ca. 2.9 Ga Lower Greenstones and two units of the ca. 2.7 Ga Upper Greenstones were sampled. Two groups of geochemically distinct volcanic rocks were observed in each stratigraphic unit, a group of unfractionated rocks and a group of light rare earth element–enriched rocks with negative anomalies for Nb, Ta, Ti, and P, and low ε_{Nd} values. The geochemical signatures of the second group of rocks have been attributed to processes of assimilation of continental crust, followed by fractional crystallization.

These observations are important because of the ongoing debate about whether mafic volcanic rock units in greenstone belts, and the Belingwe belt in particular, represent ophiolite-like sequences that originated in oceanic environments and were obducted onto continental crust or whether they represent continental flood basalt–like, autochthonous sequences that extruded onto continental crust. Based on the geochemical evidence, Bolhar et al. favored an ensialic origin for the Belingwe volcanic rocks and an autochthonous origin for the Upper Greenstones.

If we accept that the geochemical signatures are indeed a result of contamination by continental crust rather than related to other processes, such as the presence of an enriched mantle source, source contamination, or subduction, we think that an ensialic and autochthonous origin, i.e., deposition on the gneissic basement now surrounding the greenstone belt, cannot be inferred from the geochemical evidence presented.

1. Contacts between basement rocks and mafic volcanic sequences in greenstone belts are sheared. In the Belingwe belt, the basal contact of the Upper Greenstone volcanic sequence is a major thrust fault (Kusky and Winsky, 1995; Hofmann et al., 2003a), negating an autochthonous or para-autochthonous origin. All contacts between stratigraphic units of the Lower Greenstones are sheared.

2. Mafic volcanic greenstone sequences formed in submarine settings well below wave-base, and this is also the case for the Upper Greenstone volcanics of the Belingwe belt, which contain pillow basalts and intercalations of turbidites (Hofmann et al., 2003b). Time-equivalent continental flood basalts (Ventersdorp Group, South Africa; Nelson et al., 1992), and continental flood basalts in general, are subaerial lava flows. In addition, Archean continental flood basalts, exemplified by the Ventersdorp and Dominion Groups in South Africa and the Fortescue Group in Australia, although geochemically very similar to the enriched Belingwe volcanic rocks, completely lack unfractionated basalts. The geochemical signatures are attributed to melting of an enriched mantle source (subcontinental lithospheric mantle) rather than crustal contamination processes (references in Nelson et al., 1992).

3. Many volcanic greenstone sequences show evidence that they formed in a near-continental setting, as exemplified, for example, by gneiss bodies engulfed in mafic lava or quartzose sediments overlying pillow basalt in the Mafic Formation of the Midlands Greenstone Belt, Zimbabwe (Dirks et al., 2002). However, as in many modern tectonic settings, no clear-cut distinction can be made between a continental or oceanic origin, because modern-day oceans develop by thinning and rifting of continental crust. As such, contamination of basalts produced in infant oceans and backarc basins by continental crust can be expected. Backarc basins flanked or underlain by thinned continental crust have commonly been cited as analogues for Archean greenstone belts.

4. Bolhar et al. state that their data are inconsistent with an oceanic plateau and mid-ocean-ridge setting. However, some oceanic plateau basalts show evidence for crustal contamination (Kerguelen Plateau; Ingle et al., 2002). In addition, many ophiolites show geochemical signatures different from mid-ocean-ridge basalts; these supra-subduction zone geochemical signatures are in contrast to the lack of structural-stratigraphic evidence for subduction-related activity (Moores et al., 2000), a similar case of controversy between geochemists and field-oriented researchers.

5. An important observation by Bolhar et al. is that the volcanic rocks of each stratigraphic unit show remarkably similar geochemical signatures, so that essentially identical petrogenetic processes are implied. This is in contrast to the lithological attributes of individual stratigraphic units. For example, the 2.90 Ga Hokonui Formation of the Lower Greenstones is lithologically similar to an island-arc sequence, because it is characterized by submarine to possibly subaerial andesitic to dacitic lavas, pyroclastic and epiclastic rocks, and only minor amounts of mafic volcanic rocks. The 2.69 Ga Zeederbergs Formation is a submarine lava plain sequence of basalts and basaltic andesites, similar to the extrusive sequence of modern oceanic crust or oceanic plateaus. It thus appears that trace element geochemistry is unable to distinguish between different extrusive settings in the Belingwe belt, or that geochemically similar magmas extruded in different settings, the latter indicating a relatively strong mantle imprint on magma chemistry.

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REPLY

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Late Archean volcanic rocks of the Belingwe Greenstone Belt have long been known to contain a small continental crustal component evident in their radiogenic isotope and trace element signatures (Chauvel et al., 1993). Recently, we discovered new geochemical evidence suggesting that all volcanic units contain members with a distinctive crustal fingerprint. It was concluded that the volcanic rocks were erupted through pre-existing continental crust, although a specific tectonic interpretation was deliberately avoided. Hofmann and Dirks' claim that the new data are also compatible with an oceanic deposition, provided that enriched mantle sources were melted or that dismembered continental crust was present in the oceanic lithosphere. We wish to draw the reader's attention to the fact that when all available evidence is considered, continental emplacement of the rocks is an unavoidable conclusion.

The formation and tectonic evolution of the Belingwe Greenstone Belt has attracted considerable attention. At the heart of the debate lies the question of whether igneous assemblages of the Upper Greenstones formed in an oceanic setting and were later thrust along a major shear zone onto volcano-sedimentary sequences of the Lower Greenstones. A major structural hiatus could suggest, but not necessarily imply, that the greenstones were tectonically emplaced onto continental crust via horizontal accretion, after their formation as oceanic plateaus, arcs, or at mid-oceanic ridges (e.g., Kusky and Kidd, 1992).

The investigation of the geochemical data by Bolhar et al. (2003) revealed a ubiquitous crustal signature in volcanic rocks from all five stratigraphic units in the Belingwe Greenstone Belt, providing direct evidence for the presence of continental crust prior to or during emplacement, in agreement with previous studies:

1. Chauvel et al. (1993) reported correlated model source $^{238}U/^{204}Pb$ and initial $^{143}Nd/^{144}Nd$ ratios in Reliance Formation volcanic rocks, consistent with assimilation of 3.5 Ga continental material.

2. Wilson et al. (1995) found xenocrystic zircons in volcanic samples from various Zimbabwean greenstone belts including the Belingwe Greenstone Belt, with U/Pb ages substantially older than those of their host rocks.

3. Lower crustal garnets were recovered from Reliance Formation komatiites (Shimizu et al., 2002), consistent with assimilation of lower crust.

4. Re-Os systematics of chromites from ultramafic complexes in the vicinity of the Belingwe Greenstone Belt provide geochronological and geochemical evidence for successive growth of the Zimbabwe craton lithosphere since 3.8 Ga (Nägler et al., 1997), suggesting that the craton was already (part of?) a continental entity by the time of Belingwe Greenstone Belt basalt eruption.

5. Blenkinsop et al. (1993) summarized evidence in favor of an ensialic origin for the Upper Greenstones, including the absence of a major high-temperature shear zone at the base of the Reliance Formation. They also noted the presence of quartzose sandstones intercalated with the Reliance Formation, negating an oceanic plateau origin.

6. Hunter et al. (1998) recognized continental-type depositional facies in the Manjeri Formation underlying Upper Greenstone volcanic rocks. Highly variable rare earth element and Nd isotope compositions with model ages of 3.5–2.9 Ga imply derivation of sediment source material from basement units.

7. 2.7–2.6 Ga stromatolites in the Belingwe Greenstone Belt have distinctive Pb isotopes derived from a long-lived source with substantially higher $^{238}U/^{204}Pb$ than mantle (Bolhar et al., 2002). Pb of such isotopic character is only known from a few so-called high-μ cratons, of which the Zimbabwe craton is a prominent representative. It thus appears that the Pb isotopes were derived from the old gneisses of the Zimbabwe craton, strongly arguing against an oceanic origin. Sm/Nd isotope systematics are also consistent with derivation from water with a strong continental signature.

In view of this overwhelming body of evidence, we remain unconvinced by Hofmann and Dirks' suggestion that these greenstones formed in the oceanic realm. We re-emphasize that the existence of a major metamorphic and structural disconformity has not been verified by subsequent studies (Blenkinsop et al., 1993). The validity of inferring horizontal accretion on the basis of sheared contacts alone appears problematic too, since the extent of tectonic displacement cannot be quantified. Even tectonic transport involving large-scale displacement does not preclude extrusion onto pre-existing crust, because interaction of asthenospheric melts with crust could have occurred prior to horizontal accretion.

Finally, we refute Hofmann and Dirks' suggestion that lithological variation provides a more reliable discriminator of tectonic setting than trace element geochemistry. The remarkably coherent geochemical variations between different stratigraphic units require very similar processes of magma genesis. Once magmas are formed, lithological variation can be imposed by a variety of environmental factors that are common to many tectonic settings.

ACKNOWLEDGMENTS

This reply benefited greatly from comments by Balz Kamber and Tom Blenkinsop.

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