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Punctuated anorogenic magmatism

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ABSTRACT

The emplacement of anorogenic magmas, be they mantle-derived or crust-derived and silica-undersaturated or silica-oversaturated, marks a period of rifting or tectonic relaxation and apparent quiescence. In a given area, such magmatism commonly recurs episodically, and can yield even more strongly alkaline products than in the first cycle, in spite of the depletion that resulted from that episode of melting. Anorogenic magmatism is said to be punctuated where it recurs, in response to a triggering mechanism. The second cycle reflects an influx of heat and a fluid phase responsible for the fertilization of the depleted source-rock. In cases of an anorogenic stage after a major collision, the first cycle of magmatism, yielding an AMCG suite, arises by gravity-induced sinking of lithosphere and the diapiric rise of an asthenospheric mantle; renewed magmatism may involve localized and renewed detachment as late as 200 m.y. after the collision. Where the hiatus is much longer, as in Nigeria, we appeal to a propagating zipper-like zone of extension, possibly related to rotation of a crustal block. The economic ramifications of punctuated anorogenic magmatism are important; the second-generation magmas may well crystallize products that are mineralized in the high-field-strength elements and any other elements enriched in the source rocks. Such a model would account for the rich deposits of alluvial columbite, zircon and cassiterite associated with the Younger Granites of Nigeria.

1. Introduction

The emplacement of anorogenic magmas, be they mantle-derived or crust-derived and silica-undersaturated or silica-oversaturated, marks a period of tectonic relaxation and apparent quiescence. By definition, anorogenic magmas are those not associated with compressional forces, which lead to subduction and eventually to collision. It is in Africa that they are best displayed; as Bailey and Woolley (2005) pointed out, most of that continent has been free of orogenic magmatism for the last 550 m.y. Felsic rocks are present in 864 alkaline and carbonatitic complexes on African soil, and tholeiitic basalt is absent from all of them. It is an attribute of magma emplacement in such a context that it tends to be episodic, and repeated at a given location over long periods of time.

Initiation of a cycle of anorogenic magmatism may well follow closely an interval of crustal compression (e.g., subduction, collision), or it may mark a recurrence of igneous activity after a very long hiatus. It is not at all uncommon to find, in the younger cycle of magmatism, geochemically more evolved magmas, and rocks significantly more enriched in economically interesting elements than in the older rocks. In this review, we explore this theme of "punctuated anorogenic activity" from the point of view of geochemical enrichment potentially leading to mineralization. We attempt to answer an important question posed by many an explorationist searching for economically attractive deposits of the high-field-strength elements: why is one batch of magma inherently more promising than another in terms of its mineral potential?

2. The concept of "punctuated equilibrium", and an illustration in a case of recent rift-related mafic volcanism in Tanzania

It is in the area of the evolutionary sciences that punctuated equilibrium is very clearly displayed; evolutionary changes in some species come in spurts. By 1993, Gould and Eldredge (1993) could report that their concept of punctuated equilibrium, the opposite of gradualism, had achieved broad acceptance as a predominant pattern within the history of species. Already in 1985, however, the concept of punctuation had been applied to the field of sedimentary petrology: Morton (1985) proposed its use to signify instances of episodic diagenesis, "whereby sudden diagenesis is initiated by a change in pore-water chemistry", a pattern that he contrasted with the prevailing hypothesis of gradual transformations with progressive burial. It seems completely in keeping with the usage of Gould, Eldredge and Morton to apply the concept here to magmatic events. The concept of gradualism seems to apply perfectly to the progressive changes associated with the subduction factory (Tatsumi, 2005), at least during the lifetime of the orogenic belt. On the other hand, one can expect anorogenic igneous activity to start

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suddenly after a short or a long period of apparent dormancy, in response to some triggering factor in the mantle environment.

In an overview of his career-long involvement in northern Tanzania, Dawson (2008) described a recent example of punctuated anorogenic magmatism along the Gregory Rift. The Older Extrusives, emplaced over the interval 8.1 to 1.2 m.y., consist dominantly of nephelinite or basalt, and include minor volumes of trachytic and phonolitic differentiates. The emplacement of the Younger Extrusives in the same geographic area follows a period of quiescence and major faulting. The younger lavas, produced in small batches, are much more explosively emplaced, and tend to be volatile-rich, dominantly ultrabasic, and highly enriched in the alkalis and high-field-strength elements. Natrocarbonatitic lavas, such as at Oldoinyo Lengai, form part of this second cycle of volcanism, and are associated with alkali-enriched nephelinites free of olivine and containing combeite, $Na_2Ca_2Si_3O_9$. Lavas of the second cycle vary widely in a plot of $^{143}Nd/^{144}Nd$ versus $^{87}Sr/^{86}Sr$, some basic, felsic and carbonatitic lavas showing clear signs of involvement of crust (Dawson, 2008, Fig. 7–12). Morogan and Martin (1985) documented clear examples of the fenitization of crustal xenoliths at Oldoinyo Lengai, followed by melting of the alkali-metasomatized domains (glass is still present). The striking differences in products of volcanism in the second cycle of magmatism led J.B. Dawson to infer a surprisingly rapid and efficient refertilization of the upper mantle under northern Tanzania after the first cycle. It seems clear that 1) a mixed aqueous–carbonic fluid interacted with the mantle source to replenish it efficiently in alkalis and incompatible elements, and 2) the fluid phase continued its ascent into the Tanzanian crust, focused in the second-cycle volcanic cones like Oldoinyo Lengai, where it did induce fenitization of crustal blocks. What caused the rapid renewal and change in style of activity? As Bailey and Woolley (2005) pointed out, regional changes in the motion of plates may well be involved.

3. Punctuated anorogenic magmatism in the Chilwa Province of Malawi, East African Rift

The Chilwa Province of alkaline igneous rocks and carbonatites in Malawi and neighboring Mozambique displays three major cycles of igneous activity (Woolley, 1987). During the first cycle, between 138 and 132 m.y. ago (Eby et al., 1995, 2004), twenty intrusive complexes of carbonatite were emplaced, each associated with an extensive aureole of fenite. This was followed by renewed activity over the interval 129–123 m.y., dominated by syenite and nepheline syenite, locally with quartz syenite units. There are no obvious parental magmas. During the third cycle, over the interval 115–111 m.y. (Eby et al., 1995, 2004), peralkaline syenite, quartz syenite and A-type (i.e., ferroan) granite were emplaced. As in the previous cycle, basic rocks account for a fraction of 1% of the igneous suites (A.R. Woolley, pers. commun., 2012), and these basic rocks are not tholeiitic. The miarolitic pegmatites that appear at the end stage of the Zomba–Malosa complex are arguably the most spectacular example of the NYF category of rare-element-enriched granitic pegmatite in the world. They contain exceptional aegirine, arfvedsonite, barylite [$BaBe_2Si_2O_7$, i.e., Be in an Al-free mineralogical expression], zircon, bastnäsite-(Ce), parisite-(Ce), xenotime-(Y), caysichite, Y-rich milarite, hingganite-(Y), polycrase-(Y), Ce-rich pyrochlore, and niobophyllite–astrophyllite, among others (Guastoni et al., 2003, 2009; Martin and De Vito, 2005).

For cycle 1, Woolley (1987) proposed that a long period of focused metasomatism by a CO_2-bearing fluid led to domains of carbonated peridotite in the upper mantle; this peridotite melted to give an alkali-enriched carbonatitic magma directly, although the radiogenic isotopic values (Sr, Nd) of Simonetti and Bell (1994) also are consistent with separation of an immiscible carbonatitic fraction from a nephelinitic magma. On the other hand, their oxygen and carbon isotopic data indicate an open-system disturbance in the carbonatites of the Chilwa Island complex. The coeval silicate rocks of that complex indicate an interaction with fenitized granulitic basement.

In view of the virtual absence of basic rocks in cycle-2 complexes in Malawi, Woolley (1987) postulated that large volumes of phonolitic magma could be generated directly in the mantle at the expense of suitably transformed rocks. The fenitization–simulation experiments of Preston et al. (2003) and the field observations of contact fenitization of anorthosite by ferrocarbonatite (Drüppel et al., 2005), which both produced nepheline syenites, demonstrate the viability of the process. On a diagram of Yb/Ta versus Y/Nb, Eby et al. (2004) showed that phonolites showing a negative Eu anomaly plot in the OIB box, whereas other phonolites free of such an anomaly could have an origin tempered by a fluid-dominant process, possibly at high pressure.

For cycle 3, Woolley (1987) proposed that the fluids affecting the uppermost mantle continued their ascent into the lower crust, and caused K-feldspathization reactions and fenitization. Because there are again no basic antecedents in cycle 3, syenitic melt seems to have been generated by the virtually wholesale melting of fenitized and geochemically fertilized granulitic lower crust, which likely was then parental to the vast volumes of the Chilwa granites (Mlanje, Malosa, Zomba intrusive suites), all of the ferroan variety (Frost and Frost, 2011; Frost et al., 2001). Both the Mlanje massif and the Zomba–Malosa batholith contain metaluminous to peralkaline syenite, quartz syenite and granite; a 1-km aureole of feldspathization and fenitization of the enclosing of the Mozambique Belt granulites around Mlanje (Platt and Woolley, 1986) may well provide an example of the type of "ground preparation" that took place in the source area of the A-type felsic magma.

In these cases of punctuated rift-related magmatism, a possible triggering mechanism to initiate the youngest cycle of magmatism 20 million years after the first might be a secular change in the make-up of the fluid phase being added to the lower crust from below, from CO_2-dominant to H_2O-dominant. As carbonation reactions proceeded in the uppermost mantle, it seems likely that the supercritical fluid phase progressively became depleted in CO_2 and enriched in H_2O. The progressive transfer of an aqueous–carbonic fluid into the crust is considered the key in explaining the enrichment in high-field-strength elements and Be in syenites and A-type granites of crustal origin, and in the associated NYF-type (i.e., Nb-, Y- and F-enriched) granitic pegmatites (Martin, 2006; Martin and De Vito, 2005).

4. Punctuated anorogenic magmatism in the Gardar Province

Upton et al. (2003) reviewed the products of alkaline magmatism and their ages of emplacement in the Mesoproterozoic Gardar Province in southern Greenland. The area contains clear evidence of repeated episodes of extensional tectonics over the interval 1280–1140 m.y., related to the breakup of Pangea. Anorthositic xenoliths in several Gardar intrusive complexes imply the presence at depth of an extensive anorthositic–mangerite–charnockite–(ferroan) granite complex (AMCG; see below). There is a parallel with the events described in Malawi. The oldest dates mostly pertain to mantle-derived suites that contain "transitional" gabbro, nepheline syenite and carbonatite. The younger dates pertain largely to more evolved suites, which include agpaitic complexes. Ivigtut, at 1248 ± 25 m.y., is a relatively early manifestation of post-AMCG Gardar magmatism, but also the most strongly mineralized A-type granite (Blaxland, 1976). It also has the highest initial $^{87}Sr/^{86}Sr$ value, 0.7125. At face value, the Sr isotopes indicate a crustal origin, and could be consistent with an origin by melting of a metasomatized crust, possibly a metasomatized A-type granite of the subjacent AMCG suite. The same can be claimed for the Nunarssuit biotite granite [1162 ± 21 m.y., initial $^{87}Sr/^{86}Sr$ value 0.7068], whereas the Nunarssuit syenite [1154 ± 14 m.y., initial $^{87}Sr/^{86}Sr$ value 0.7043] is closer to a mantle value (Blaxland et al., 1978). Finally, the well-known Ilímaussaq complex contains agpaitic silica-oversaturated units that present a