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Intracontinental anorogenic alkaline magmatism and carbonatites, associated mineral systems and the mantle plume connection

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ABSTRACT

Intracontinental alkaline complexes and carbonatites commonly occur in rift-related settings, best exemplified by the Cenozoic–present day East African Rift System. Examples in the ancient geological record are more difficult to unravel due to subsequent overprinting during tectono-thermal events unrelated to the original rifting. In the present paper, with the exception of the Bayan Obo carbonatite, I have used examples of anorogenic alkaline complexes and carbonatites that are effectively pristine and unaffected or little influenced by later geological events. In this context, I report on two alkaline complexes and associated mineralisation in Namibia (Brandberg and Erongo) related to the opening of the South Atlantic and the Paraná–Etendeka large igneous province. With regard to carbonatites and associated mineralisation, I discuss the exceptionally well-preserved Kruidfontein and Goudini in South Africa, Mount Weld and Gifford Creek ferrocarbonatite complex in Western Australia, the controversial Bayan Obo in northern China and the carbonatites of the Mianning–Dechang belt in SW China. It is proposed that all these igneous systems are formed by processes of partial melting in metasomatised lithospheric mantle, induced by upwelling mantle plumes. Furthermore, it is contended that these alkaline and carbonatite igneous systems are generally formed in the distal sectors of a mantle plume due to lateral transfer of volatiles, resulting in low degrees of partial melting in the metasomatised sub-continental lithospheric mantle.

> "One thing I have learned in a long life: that all our science, measured against reality, is primitive and childlike — and yet it is the most precious thing we have."
>
> [Albert Einstein]

1. Introduction

Alkaline magmatism is generally associated, in space and time, with extensional tectonics and more specifically with rifting events. The causes and mechanisms of rifting are complex and are beyond the scope of this contribution, however the interested reader should consult Burke and Dewey (1973), Fitton and Upton (1987), White and McKenzie (1989), Wilson (1989), Kampunzu and Lubala (1991), Storey et al. (1992), Olsen (1995), Condie (1997), Şengör and Natal'in (2001) and Fourel et al. (2013).

Magma genesis in rift environments is thought to be related to the ascent of mantle melts and the effects of their interaction with lithosphere materials. The main products of rift magmatism are fissure-fed tholeiitic flood basalts (large igneous provinces — LIPs), mafic–ultramafic intrusions, dyke swarms and intracontinental alkaline provinces (Pirajno, 2000). The latter is characterised by anorogenic magmatism, which includes alkaline ring complexes, carbonatites, kimberlites, lamproites, monogenetic and central-vent alkaline volcanoes. In terms of tectonic environments, three main scenarios can be considered in which alkaline complexes and associated igneous rocks are emplaced (Bonin, 1986; Kinnaird and Bowden, 1991). They are: 1) doming of the crust, followed by rifting; 2) "hot spot" traces with time–space migrating magmatism; and 3) alkaline complexes located along crustal-scale shear zones.

In this paper, I direct my attention to the mineral systems that are related to intracontinental alkaline magmatism and associated carbonatites and examine their links with rifting processes and mantle plumes. Rift structures act as major conduits for both magmas and hydrothermal fluids and it is reasonable to assume that ore deposits are formed in which metal associations are related to both magma and interaction of the fluids with rift-related volcano-sedimentary sequences. Based on geochemical and stable isotope studies (e.g. Nelson et al., 1988; Ngwenya, 1994; Bell and Simonetti, 2010; Kogarko et al., 2010), it appears that in the first instance the origin of the mineralising fluids is essentially magmatic, although there are many cases in which the mineralisation was formed through processes of hydrothermal activity related to the influx of meteoric waters and their mixing with high-temperature fluids of magmatic origin (e.g. Kinnaird and Bowden, 1991; Lowenstern, 2001; Bell et al., 2013). The ore-forming processes are always accompanied by alteration of the

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host rocks, including alkali metasomatism (fenitisation), greisenisation, propylitisation, silicification and phyllosilicate alteration (Pirajno, 2013a).

Many, if not most of the structures associated with alkaline complexes are ancient zones of lithospheric structural weakness, which have been repeatedly reactivated during tectono-thermal events. These structures may extend deep into the crust and to the subcontinental lithospheric mantle (SCLM). Thus, several alkaline provinces are localised along crustal scale shear zones, along the margins of cratonic blocks, within Proterozoic mobile belts, and along reactivated zones of faulting and rifting (Begg et al., 2009).

Most primary alkaline magmas are mafic, rather than ultramafic, and in many cases, prolonged lithospheric and/or crustal residence time results in a wide range of rock types, including felsic derivatives far removed from compositions in equilibrium with mantle olivine. The rock types considered here range from mafic to felsic and usually contain feldspathoids (e.g. nepheline) and/or alkali-pyroxene and alkali-amphibole. The silica-oversaturated rock types (generally quartz-bearing) range from monzonite to syenite, alkali-syenite and alkali-granite, and their volcanic equivalents. Nomenclature for the silica-undersaturated rock types (generally feldspathoid-bearing) can be confusing and plagued by locality-based names. The terminology published by Le Maitre (2002) provides a sufficient guide to their classification.

The relationship between alkaline magmatism, thermal anomalies in the mantle and extensional tectonics has been mentioned above. Whether rifting is a passive or active process, the end result is thinning the crust and upper lithosphere, causing lithospheric mantle melts and the asthenosphere to rise. This may result in:

- decompression melting of the upwelled mantle;
- transfer of volatiles into the SCLM and the lower crustal regions;
- melting of the lower crust due to the addition of heat, either through conduction or through intrusion, coupled with the possible effects of introduced volatiles.

The amount of magma generated depends on the temperature of the upwelled mantle and the amount of lithospheric thinning, which are also related to the rate of extension. High rates of extension (e.g. continental break-up) are often associated with voluminous production of basaltic magmas. Lower rates of extension (e.g. intra-continental rift/graben structures) result in lower degrees of partial melting, and more alkalic and silica-undersaturated magmas. In intra-continental settings, the range of resulting rock types is often very wide and not restricted to silica-undersaturated compositions. It is quite common for alkaline complexes to consist of both silica-undersaturated and silica-oversaturated rocks, as is the case for many of the non-carbonatitic complexes of southern Africa (Woolley, 2001; Woolley and Kjarsgaard, 2008). The relationship between these has long been a point of extensive debate. The two types of rocks are separated by a thermal divide (Ab–Or join) that, in theory, cannot be crossed via closed system fractionation of magmas (e.g. Rayleigh fractionation). Hence, two separate magma types have usually been invoked to explain the presence of both silica-undersaturated and silica-oversaturated rocks in alkaline complexes, with the silica-oversaturated rocks generally regarded as products of crustal, rather than mantle or SCLM, melting. Isotopic evidence usually shows the silica-undersaturated rocks to be of mantle or SCLM origin, but does not always show the silica-oversaturated rocks to be of crustal derivation (Nelson et al., 1988; Begg et al., 2009).

In terms of mineral exploration, the recognition of the different magma types may be very important. As a generalisation, mineralisation tends to be affiliated with the silica-oversaturated, rather than the silica-undersaturated rock types. Furthermore, it is those silica-oversaturated rocks that show significant, or dominant, crustal origins which are most commonly and strongly mineralised (Pirajno, 2009 and references therein). On the other hand, silica-undersaturated magmas can host critical elements, such as rare earth elements (REE), P, U, Th, and F.

In this contribution a selection of diverse intraplate alkaline magmatic systems and carbonatites from Namibia (Brandberg, Erongo), South Africa (Kruidfontein, Goudini), Western Australia (Mount Weld and Gifford complex) and China (Bayan Obo and the carbonatites of the Mianning–Dechang belt) are examined. Except for the Mianning–Dechang belt, I have been involved in various degrees with all of the above mentioned complexes. These alkaline intrusions and carbonatites host REE, P, U, and F mineralisation ranging from non-economic to sub-economic in the present time, to economic. In the present article the emphasis is on carbonatites and related mineralisation, due to their ever increasing economic importance, as explained in the pages ahead.

2. Anorogenic alkaline plutonic and volcano-plutonic complexes

Anorogenic alkaline complexes are generally characterised by unusual concentrations of non-hydrous volatiles (CO_2, B, F), REE and LILE incompatible elements (P, Zr, Ba, Nb, U, Th, Sn, Ta and W) (Bailey et al., 1974; Bailey, 1985; Bailey and Macdonald, 1987; Edgar, 1987; Owen-Smith et al., 2013). These elements may form their own minerals, or they may enter the lattice of rock-forming minerals (e.g. micas), that have crystallised in the subsolidus range of pressure and temperature. The processes that lead to the enrichment of these elements are linked with the activity of residual alkali-rich fluids. Consequently, their concentration, either in rock-forming minerals or in their own mineral species, is largely dependent on the original magma composition and the nature of the source regions where partial melting occurred.

From the stand point of economic mineralisation, important rock associations of alkaline magmatism are: kimberlites, lamproites, mafic ultrapotassic rocks, syenite–pyroxenite–ijolite–carbonatite complexes, carbonatite plugs and dykes, alkali basalts, and peralkaline granite–syenite–gabbro assemblages (Mutschler et al., 1985; Pirajno, 2013a). These rocks occur as dykes, pipes, hypabyssal and subvolcanic intrusions and as central volcano-plutonic structures, many of which form ring complexes. Most important for economic mineral deposits are kimberlites and lamproites (diamonds), carbonatite and volcano-plutonic complexes. Carbonatites are especially significant because they constitute a major source of Nb, P, Zr, Ti, Th, Sr and REE. Most economic mineral deposits (excluding diamonds in kimberlites and ultrapotassic mafic rocks) occur associated with central vent-type complexes of which two main groups are recognised (Bowden, 1985): 1) alkali-granite–syenite (saturated–oversaturated); and 2) ijolite–carbonatite (undersaturated). They are schematically illustrated in Fig. 1. The idealised cross-sections shown in Fig. 1 also illustrate the importance of the level of erosion, and hence age, in terms of the preservation potential of the contained mineral deposits.

In this section, I discuss two alkaline plutonic and volcano-plutonic complexes, Brandberg and Erongo, respectively and both in Namibia. The reason is two-fold: one is that they do provide good examples of anorogenic intracontinental magmatism, in the specific case related to the Paraná–Etendeka flood volcanism and the Gondwana continental breakup, and the other reason is because both complexes have been the focus of my study during my work time in Namibia. The distribution and setting of alkaline complexes and carbonatites in south-western Africa is shown in Fig. 2.

2.1. Brandberg

The Brandberg alkaline complex (Hodgson, 1973; Diehl, 1989, 1990; Bowden et al., 1990; Pirajno, 1994; Watkins et al., 1994; Schmitt et al., 2000; Trumbull et al., 2004), forms a conspicuous circular topographic feature approximately 26 km across rising to 2573 m above sea level and 2000 m above the surrounding desert (Fig. 3). The complex is intruded into metasediments of the Damara Orogen and overlying

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