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An overview of monogenetic carbonatitic magmatism from Uganda, Italy, China and Spain: Volcanologic and geochemical features

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ABSTRACT

We address general features of carbonatite monogenetic volcanic fields located in continental settings which are peculiar being associated with kamafugites or melilite-bearing leucitites. Instructive examples are the Toro Ankole in Uganda, West Qinling in China, and Campo de Calatrava in Spain and the Intra-mountain Ultra-alkaline Province (IUP) of Italy. Maars are the typical volcanic forms, occurring in isolation or in clusters along fault systems. Concentric-shelled juvenile lapilli and bombs, having a upper-mantle peridotite kernel, are unique to this type of volcanism. These pyroclasts are interpreted as the result of deep-seated fragmentation of magma having a high carbon dioxide-water (CO_2/H_2O) ratio. The presence of discrete, large peridotitic nodules implies a high-velocity propagation of magma, while the associated large CO_2 emission suggests a high proportion of juvenile CO_2. Magma fragmentation is inferred to occur as a consequence of explosive CO_2 exsolution at the upper mantle level (diatresis) followed by immiscibility. Based on field evidence, carbonatitic maar formation could be due to violent CO_2 expansion and does not require phreatomagmatic phenomena. Extrusive carbonatites and associated rocks represent very primitive melts having a distinct High Field Strength Elements (HFSE) distribution, the source of which is related to enriched mantle. Carbonated peridotite is a stable paragenesis at depths of 400–600 km; thus, primary carbonatitic silicate magma can be produced at these depths as a consequence of rising deeper melt/fluids that are trapped at the transition zone. In our opinion, carbonatitic carbon is linked to the primary process of deep-mantle differentiation and Earth's core degassing.

1. Introduction

Extrusive carbonatites are often thin tuff-aprons of very fine-grained grey rocks that are easily confused with silicate tuffs or lavas or with mineralised travertine. The texture of extrusive carbonatites is aphyric or porphyritic and rarely displays the exotic minerals found in intrusive carbonatites. These rocks are subject to rapid weathering and erosion. However, the presence of phlogopite or other igneous minerals immediately distinguishes them from sedimentary limestone. Extrusive carbonatites have relatively small chemical variability; detailed study reveals a mineral chemistry which is very rare or absent among silicate igneous rocks and are distinctive of carbonatites. Considering that extrusive carbonatites are difficult to recognise, even if they are relatively abundant, it would be advantageous to reassess their main petrologic characteristics in order to discuss their origin and geological importance. Volcanic features, in particular, are useful in constraining the magma propagation towards the surface and determining its condition at the moment of the extrusion. The extrusive carbonatites are characterized by the presence of a groundmass of fine-grained carbonate and the possible presence of distinctive Sr-Ba-REE-Zr-rich phases such as garnet, apatite, perovskite, plus xenocrystic olivine, phlogopite and diopside. Only half of an extrusive carbonatites contain peridotite nodules but they are ubiquitous in the rocks here considered. These nodules are, in the order of frequency, spinel-lherzolites, garnet-lherzolites, wehrlites, veined by clinopyroxenite, and phlogopitite from the lithospheric mantle (e.g. Rosatelli et al., 2007). The chemistry of carbonates, mostly calcite and very minor dolomite also prove to be peculiar even if they are highly variable in their proportions of Sr, Ba, REE and Mn. Highly reactive nyerereite is only found in fresh lavas of the Oldoinyo Lengai volcano, except for tiny inclusions at a few localities (Stoppa et al., 2009). Extrusive carbonatites are often associated with melilitites, from which unstable melilite and other mineral debris can be derived mechanically (Bailey et al., 2005b). Co-eruptive carbonatite and kamafugite preserve primitive chemical features even if they are produced by reciprocal immiscibility. This

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genetic mechanism makes them differentiates derived from a silico-carbonatitic primary parental melt.

A significant aspect of carbonatite volcanism is the amount of CO_2 and of light elements that are carried through the lithosphere from the mantle and potentially released at the Earth's surface. Carbonatite volcanism offers a unique opportunity to investigate localised solid and fluid transfer of carbon (C) towards the surface, especially with the knowledge that an estimated 10^{20} kg of solid C may be stored deep in the Earth (Tingle, 1998; Hayden and Watson, 2008). The C content of the Earth's metallic core may be quite high (5 wt%), raising the possibility that the core supplies carbon to the mantle (Hayden and Watson, 2008). The areas investigated in this study are among the most productive for CO_2 on a global scale. For example, CO_2 vents at Calatrava produce 4860 kg CO_2 per day in the La Sima volcano (Calvo et al., 2010; Gosálvez et al., 2010); the geyser of Bolaños de Calatrava issues up to 40 tonnes of CO_2 per day. The Italian carbonatite area has an average CO_2 discharge of up to 10×10^6 mol yr^{-1} km^{-2}, with the Vulture volcano alone producing 3.7×10^6 mol yr^{-1} km^{-2} of CO_2, one of the biggest producers of continuous deep-seated CO_2 in the world (Gambardella et al., 2004). The mefite d'Ansanto is located 40 km west of the Vulture area and emits ~800 tonnes per day of CO_2 (Rogie et al., 2000). Due to complex water–rock interaction, most of the CO_2 released from the carbonatitic areas, if not lost in the atmosphere, is confined to ground waters and travertine, a rock that frequently occurs in association with this type of volcanism.

In this paper, we focus on typical geological, volcanological, and petrological features of four areas in Uganda, Italy, China and Spain where extrusive carbonatites form co-eruptive, conjugate pairs with kamafugite (Barker and Nixon, 1989; Stoppa and Woolley, 1997; Yu et al., 2003b, 2004; Bailey, 2005). In these areas, the rocks of this association contain abundant peridotite nodules. The geodynamic context and geochemistry of rocks of the four investigated areas have been considered important to an understanding of the tectonic setting of carbonatites (Bailey and Collier, 2000; Stoppa, 2003). Notably, sub-lithospheric earthquakes are found to be absent in the four carbonatite regions and this rules out a direct link with active subduction. Earthquake activity in these areas is typically related to extensional focal mechanisms confined into continental crust (e.g. Lavecchia et al., 2006). However, in three cases, no crustal thinning was found and the lithosphere showed a normal thickness (80–110 km). Only the Ugandan carbonatites were clearly associated with intra-continental rifting.

We present our own data based on field surveys of the investigated areas dating from 1997 to 2010 and give new analyses of rocks from Uganda, China and Spain. New data are compared with older data from the literature.

2. Background

Up until the late 1950s, only intrusive carbonatites were known, until Dawson (1964) suggested that the Olduvai "calcretes" were carbonatite tuffs from Oldoinyo Lengai. However, most geologists remained sceptical about their igneous nature. A firm link between carbonatites and mantle melts was established in the 1970s (e.g. Bell and Powell, 1970). However, the study of extrusive carbonatites only became prevalent in the 1980s, beginning with a paper demonstrating that lapilli associated with the Kaiserstühl occurrence were of volcanic nature (Keller, 1989). At that time, Dawson (1964), had already described the Oldoinyo Lengai material and Deans and Roberts (1984) described a number of extrusive carbonatite localities. The sum of knowledge in the field of carbonatite volcanism was summarised in books edited by Bell (1989) and Bell and Keller (1995). Woolley and Church (2005 and references therein) gave an overview of extrusive carbonatites, stressing their petrological association with melilitites and mantle nodule occurrences. Finally, Bailey (2005) noted that large extrusive carbonatite fields occur in Europe. At present, there remains an open debate on the nature and origin of the metasomatic agent of the carbonatite mantle source, as well as the eruption triggers for carbonatite volcanism. In Italy, Prof. Locardi was the first to suggest that a mantle derived, carbonatitic component could be implicit in Italian mafic, ultra-potassic magmatism (Locardi, 1990). In the late 1980s, Stoppa (1988) proposed that some extremely silica-undersaturated rocks of central Italy were possibly of a carbonatitic nature, and subsequently described the monticellite Ca-carbonatite diatreme at Polino, Terni (Stoppa and Lupini, 1993). The presence of carbonatites in Italy has prompted several comprehensive studies which have enabled significant advances in this field. Since the 1990s other extrusive carbonatites at Cupaello, San Venanzo, Oricola, Grotta del Cervo, and Mount Vulture have been described (Stoppa and Cundari, 1995; Stoppa, 1996; Stoppa and Principe, 1998; Stoppa et al., 2005; Stoppa, 2007). Other carbonatitic rocks have also been identified in Italy, including those associated with Cretaceous-Tertiary lamprophyric magmatism (Vichi et al., 2005).

3. Extrusive carbonatite provinces

3.1. Uganda: Fort Portal and Katwe Kikorongo

The Quaternary Fort Portal and Katwe Kikorongo volcanic fields lie north of the Western Rift in Uganda (Fig. 1a). Sample locations and rock-type features are addressed in Table 1. Fort Portal is a prehistoric volcanic field, with a total area of approximately 150 km^2, mantled by carbonatitic lapilli-tuffs that are 4–6 m thick. Two maar and scoria cone clusters, Fort Portal and Kasekere, are aligned northeast–southwest (NE–SW) following the main fracture system of the area (Fig. 2a,b). The large carbonatite tuff blanket shows two main units deposited by a pyroclastic surge, including preserved dunes with a rippled surface (Fig. 2d,e). The tuff appears to have been deposited and welded at high temperatures, with lapilli moulded to each other. A number of pseudo-hornitos, showing open vents orientated downwind, are pipes formed by the distillation of vegetation on a marshy area where hot tuff was deposited (Fig. 2c). Melilitite lapilli are frequent in the blanket tuff but contain groundmass carbonate and amoeboid carbonate segregations (Bailey et al., 2005b). Crustal xenoliths have also been incorporated mechanically and do not show any sign of reaction. About 50 scoria cones up to 150 m high were formed by highly vesiculated carbonatite lapilli and bombs, with mantle and crustal xenoliths making up 25% of the ejecta volume. The summit area of the cones is covered by very fluidal spatter, lava slurries and Pele's tears (Fig. 2g), indicating very fluid lava fountain. Kalyango is a tuff-ring which is composed of several metres of laminated ash tuffs, inverse graded lapilli tuffs with impact blocks and accidental breccia. Ephemeral carbonatites flows formed by top rheomorphic spatters and lower lava flow originated in the east section of the ring and moved SW. The only subvolcanic facies consists of small, fine-grained dykes having combe textures found in the Kasekere area.

Katwe-Kikorongo (K-K, Fig. 1a) has a carbonatite blanket similar to Fort Portal but most of the volcanoes here are large maars and tuff rings. The silicate component is a kamafugite (i.e. kalsilite-leucite melilitite), which is much more abundant here than at Fort Portal, and forms tuffs and some short lava flows. The K-K carbonatitic lapilli tuffs are composed of small pelletal, micro-porphyritic lapilli showing melilitite and phlogopite laths that are concentrically arranged around the lapilli core often formed by a diopside xenocryst. The carbonate droplets (Fig. 3d,e) range in size from ~0.3–2 mm and are spherical or, more frequently, plastically deformed because of being moulded against each other. Carbonate forms a micritic