Earth-Science Reviews 139 (2014) 145–167

Contents lists available at ScienceDirect

Earth-Science Reviews

journal homepage: www.elsevier.com/locate/earscirev

Towards a new model for kimberlite petrogenesis: Evidence from unaltered kimberlites and mantle minerals

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A R T I C L E I N F O

Article history:
Received 31 July 2013
Accepted 9 September 2014
Available online 22 September 2014

Keywords:
Kimberlite
Melt inclusions
Mantle
Carbonatite
Geochemistry
Petrology

A B S T R A C T

Kimberlites represent magmas derived from great mantle depths and are the principal source of diamonds. Kimberlites and their xenolith cargo have been extremely useful for determining the chemical composition, melting regime and evolution of the subcontinental mantle. The late-Devonian Udachnaya (means *Fortuitous*) pipe hosts the largest diamond deposit in Russia (>60% diamond quantity and value) and one of the largest in the world, supplying gem-quality diamonds (~12% of world production). Since its discovery in 1956, the Udachnaya kimberlite pipe has become a "type locality" for geochemists and petrologists studying mantle rocks and mantle physical–chemical conditions. Apart from hosting a diverse suite of extremely well-preserved mantle xenoliths, the host kimberlite (East body) is the only known occurrence of fresh kimberlite, with secondary serpentine almost absent and uniquely high Na_2O and Cl (up to 6.2 wt.%) and low H_2O (<1 wt.%) contents. The discovery of such compositional features in the only unaltered kimberlite has profound implications for models of parental kimberlite magma compositions, and the significance of the high Na and Cl abundances in the Udachnaya-East pipe has therefore been subjected to vigorous criticism. The main argument against a primary magmatic origin of high Na-Cl levels involves the possibility of contamination by salt-rich sedimentary rocks known in the subsurface of the Siberian platform, either by assimilation into the parental magma or by post-intrusion reaction with saline groundwaters.

In this paper we review evidence against crustal contamination of Udachnaya-East kimberlite magma. This evidence indicates that the kimberlitic magma was not contaminated in the crust, and the serpentine-free varieties of this kimberlite owe their petrochemical and mineralogical characteristics to a lack of interaction with syn- and post-magmatic aqueous fluids. The groundmass assemblage of this kimberlite, as well as earlier-formed melt inclusions, contains alkali carbonate, chloride and other Na- and Cl-bearing minerals. This mineralogy reflects enrichment of the parental melt in carbonate, chlorine and sodium. The combination of low H_2O, high alkali-Cl abundances, lack of serpentine, and the presence of alteration-free mantle xenoliths all indicate that the Udachnaya-East kimberlite preserves pristine compositions in both kimberlite and mantle xenoliths. Evidence for broadly similar chemical signatures is found in melt inclusions from kimberlites in other cratons (South Africa, Canada and Greenland in our study). We demonstrate that two supposedly "classic" characteristics of kimberlitic magmas – low sodium and high water contents – relate to postmagmatic alteration.

A "salty" carbonate composition of the kimberlite parental melt can account for trace element signatures consistent with low degrees of partial melting, low temperatures of crystallisation and exceptional rheological properties that enable kimberlite magmas to rise with high ascent velocities, while carrying a large cargo of entrained xenoliths and crystals. Our empirical studies are now supported by experimental data which suggest that carbonate-chloride fluids and melts derived by liquid immiscibility are a crucial factor of diamond formation.

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http://dx.doi.org/10.1016/j.earscirev.2014.09.004

Contents

1. Introduction

Although occurrences of kimberlite are rare and of small volume, the unusually deep-seated mantle sources of kimberlite magmas and the association with diamonds and mantle xenoliths has long generated a disproportionate interest in the scientific and exploration communities. Significant effort has gone into characterising styles of emplacement, ages, petrography, mineralogy, textural and compositional characteristics, and the tectonic setting of kimberlites. However, a full understanding of kimberlite petrogenesis has been hampered by effects of pre-emplacement contamination, syn-emplacement stratification and syn/post-emplacement alteration of kimberlite rocks, all of which tend to hinder recognition of primary/parental kimberlite magma compositions. The prevailing practice of using bulk kimberlite compositions to derive parental compositions has been challenged by research on exceptionally fresh kimberlite specimens from the Devonian Udachnaya-East pipe (Kamenetsky et al., 2004; Kamenetsky et al., 2007a; Kamenetsky et al., 2009c; Kamenetsky et al., 2012b) and other relatively fresh kimberlites (Kamenetsky et al., 2009b; Kamenetsky et al., 2013), detailed mineralogical studies and related mass-balance calculations (e.g., Brett et al., 2009; Patterson et al., 2009; Pilbeam et al., 2013) and thoughtfully designed experiments (e.g., Sparks et al., 2009; Brooker et al., 2011). A review of existing data and interpretations, combined with new results and ideas, is presented in this paper.

2. Udachnaya-East kimberlite: common and unique properties

2.1. Location, host rocks and petrography

The Udachnaya diamondiferous kimberlite pipe is located in the northwestern part of the Daldyn–Alakit kimberlite province in Siberia (Fig. 1). At the surface, two adjacent kimberlite bodies (East and West) are recognised, and these can be traced to separate pipes in underground workings beyond ~250–270 m. Based on stratigraphic relationships both intrusions formed near the Devonian–Carboniferous boundary (~350 Ma), and radiometric age estimates vary from 389 to 335 Ma (Maslovskaja et al., 1983; Burgess et al., 1992; Maas et al., 2005). The most robust age constraints suggest kimberlite emplacement at ~367 Ma, based on perovskite U–Pb and phlogopite RbSr dates presented by Kinny et al. (1997) and Kamenetsky et al. (2009c).

The Udachnaya pipes are emplaced within thick (up to 2.5 km) terrigenous-carbonate and carbonate rocks along the western flank of the Olenek artesian basin (Fig. 1 in Pavlov et al., 1985; Fig. 1 in Alexeev et al., 2007). The stratigraphy of the sedimentary cover around the pipes is well known from >30 exploration holes to 700–1700 m depth, and from three geotechnical holes (KCC-1,2,3 to 1100–1500 m) drilled adjacent to the pipe, ~ 800–1000 m south from the open pit (Fig. 1B). Furthermore, a complete stratigraphic record of this part of the Daldyn–Alakit kimberlite province was recovered in two deep holes which intersected crystalline basement at ~2500 m. These deep drillholes (#703 and # 2531, Figs. 1B, 2) are located 1.5 km to the southeast and 4 km to the northeast from the pipe and recovered limestones, dolomites, siltstones, mudstones and sandstones (Fig. 2B).

The eastern and western bodies of the Udachnaya kimberlite pipe differ in terms of mineralogy, petrography, composition, and degree of alteration. While alteration in the western pipe is typical of kimberlites globally, alteration within the Udachnaya-East pipe is much weaker, and parts of this pipe are unique in showing no serpentinisation of olivine and groundmass. The occurrence of "unaltered kimberlite" in the Udachnaya-East (UE) pipe (Figs. 1A, 3D, E, 4) was first reported by Marshintsev et al. (1976), followed by more detailed descriptions a decade later (Marshintsev, 1986). In these reports, "unaltered kimberlite", intersected by drilling at depths below 350 m, is described as a dense, dark-grey rock with olivine unaffected by serpentinisation, unusually low H_2O^+ (1.95 wt.%) and relatively high Na_2O (0.52 wt.%), compared to the dominant serpentinised kimberlites in the pipe. Marshintsev's "unaltered kimberlites" were subsequently studied by other Russian researchers (e.g., Kornilova et al., 1981; Egorov, 1986; Egorov et al., 1986, 1988; Sobolev et al., 1989; Egorov et al., 1991; Kharkiv et al., 1991) but failed to gain attention outside the former USSR.

Information on weakly altered and unaltered UE kimberlites published prior to early 2000s is difficult to relate to any specific rock type