Kimberlitic olivine – a proxy to kimberlite petrogenesis and ascent process

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ABSTRACT. In kimberlite, olivine is an important constituent and it is found as mineral grains of different sizes, which can be of xenocrystic and magmatic origin. To know the processes, that are involved and controls the compositional variations of olivine, can provide distinct understanding into the genesis and evolution of kimberlites. In addition to this the textural features of kimberlitic olivine, which are recorded as textural events during magma ascent constrains the ascent of kimberlite and the processes involved. Unambiguous identification of kimberlitic olivine and its textural features require careful petrographic examination combined with mineral compositional analysis and use of high magnification images (BSE-SEM), all this is integrated to know the origin of olivine grain which in turn constrain the process involved in ascent of kimberlite and its petrogenesis. In this study we review the use of kimberlitic olivine in deducing the upper mantle conditions and process for kimberlite petrogenesis.

1. Introduction:

Olivine, the most profuse mineral phase in the upper mantle and, a major mineral constituent of mantle derived rocks such as Kimberlite. In kimberlites olivine forms as 50% of total volume and sometime exceeds up to 60%, in case of coherent kimberlite [1, 2, 3, 4, 5]. Therefore, can be used as proxy for kimberlite petrogenesis, ascent process and also for diamond quality or grade of a kimberlite pipe. Kimberlitic olivine, includes three parageneses based on crystal morphology and size [6, 7] and accordingly are termed as megacryst (coarse grain, rounded crystal of > 10mm size); macrocryst (medium grain, rounded to sub-rounded crystal of 5-10mm); and phenocryst (medium to fine grain less then 5mm size) (Figure 1).

Various, theories and processes has been suggested for the origin of kimberlitic olivine, as expressed by their paragenesis: the macrocryst & xenocryst are of foreign origin to that of kimberlite magma and the phenocrust is considered to have crystallized from the kimberlite melt. Olivine in Kimberlite shows zoning between core and rim, and crystallise in three distinct phases (1) in the mantle from earlier kimberlite melts; (2) in the ascending kimberlite; (3) after emplacement [8]. There is a considerable debate regarding the nature of the mantle source of the olivine cores and the proposed origins ranges from kimberlite related dunites, megacryst and sheared peridotite, and an early magmatic origin [8, 9]. Hence, olivine contains rich repository of information on petrogenesis, metasomatism and process related to kimberlite evolution. Here, we review the implication and utility of kimberlitic olivine as a proxy to the evolution of kimberlite melt, upper mantle condition, metasomatism, kimberlite ascent process, which is mostly based on the extract of the recent studies, publications and research articles available on the internet on the subject.
Figure 1. (a) Photomicrographs of olivine hosted by kimberlite; xenocrystic olivine (macrocrysts) with distinct rims formed by overgrowth of olivine [after 31], (b) Phenocryst-like, olivines comprising core of rounded olivine xenocryst and euhedral rim of olivine overgrowth

2. Kimberlitic Olivine – a monitor of upper mantle condition:

Olivines from kimberlite provides important information’s, on the nature and evolution of kimberlitic melt, as its formation can persist from earliest stage to the latest stages of crystallisation [9] and witnesses the complete processes of kimberlite evolution. Olivine contain mantle lithologies and phases as inclusion, which provide clues to kimberlitic metasomatism during the early stages, zoning and textures of olivine grains contain information on the effects of mantle metasomatism at mantle depths. In addition to this zones and rims of kimberlitic olivine also testify the various processes involves in ascent and emplacement of kimberlite magmas.

2.1. Origin of Olivine:

Magmatic origin has been suggested for kimberlitic olivine, recently studies based on high precision analytical techniques such as BSE, EPMA, LA-ICPMS etc. indicated that the cores of olivine have inclusions of lithospheric mantle phases i.e., orthopyroxene, garnet, clinopyroxene, Cr-spinel [10, 11, 12] and challenges the magmatic origin. Based on the experimental and petrographic studies, it is evident that these minerals are unstable at low pressure within a melt [13, 14, 15, 16, 17] and, advocates the xenocrystic origin of olivine grain in kimberlite.
The core composition of olivine plays vital and important role in deducing information on kimberlite evolution and upper mantle conditions. Most of the core compositions from kimberlitic olivine plots in the area designated for peridotite (i.e., 89-94 of Mg# value; 0.30-0.45 wt% NiO value and CaO < 0.1% wt%).

Olivine grains showing decreasing Mg#; Ni and Ca trends and high Mn, low Ca cores with Mg# 84-88 are believed to be formed from metasomatism of the lithospheric mantle by precursor kimberlite (or kimberlite-related) melts not long before entrainment in the ascending kimberlite [18, 19, 20, 21, 22]. Early metasomatism at depths may also result the, olivine cores with high Mg# > 89 and CaO more than 0.1 wt% is attributed to the process of early metasomatism by Ca rich kimberlitic melt within the mantle [12, 23]. Similarly, Fe rich olivine cores are considered to be formed by deep metasomatic products of early kimberlitic melt [24]. Hence, the composition of olivine core provides an estimate of the degree of metasomatism along the magmatic conduit sampled by kimberlite magmas.

2.2. Kimberlitic olivine-its implication to melt evolution:

Proportion of magmatic and xenocrystic olivine in kimberlite is essential in calculating kimberlite melt composition. Relative proportion of both the olivines (magmatic and xenocrystic) within a kimberlite is variable, this variation can be due to paragenesis of olivine within a particular kimberlite or may be also due to different methods used for estimation. Higher and lower concentration of xenocrystic and magmatic olivine respectively, within bulk kimberlite is attributed to low Mg and Si concentration of parent kimberlite melt [1,13].

For its, antecrystic and xenocrystic nature, cores of kimberlitic olivine furnish significant insights into the conditions ranging from mantle to kimberlite magma conduits.

The information when integrated with thermometry data, based on olivine, garnet, diopside etc. can be applied for constraining the depth of olivine entrainment and offer a complementary approach for mantle compositional variation with depth [25,26].

Olivine Rim Composition: Rims of olivine in kimberlite, exhibits a trend of homogenous Mg# values and variable concentration of miner and trace element. It shows constant values Mg# in rims are constant, Ni values decreases and Mn and Ca values are variable. Fractional crystallisation of olivine and chromite during early stage of kimberlite crystallisation has been suggested for the above trend. In addition to this, different theories such as higher distribution coefficient of Fe-Mg between olivine and melt [2]; combination of fractionation and assimilation of olivine & orthopyroxene respectively in Ca-Mg carbonate melt has also been suggested for the olivine rim composition. (Figure 1 & 2).

However, to explain the composition pattern and constant Mg# of olivine rims, needs contribution of other additional processes. The process involving high Si and low Co2 contents through assimilation of orthopyroxene [27, 2, 13, 14] and other mantle phase; and increasing oxygen fugacity during kimberlite crystallisation has been proposed for the composition of olivine rims worldwide. The study of olivine rim composition and associated process during kimberlite crystallisation can provide a profound in depth sights into the petrogenesis of kimberlite melts.

3. Kimberlite Ascent- as olivine reflects:

The rapid movement of kimberlite from the depths of mantle to the upper surfaces of lithosphere have been studied by various workers in details [28, 29]. Various models like, the propagation of a volatile rich magma-filled cracks upward through the mantle lithosphere [29]; deep seated exsolution of Co2-rich fluids [30] have been suggested for this rapid phenomenon. Textural features within the olivine
Figure 2. Photomicrographs showing different types of texture and their relationship in a Kimberlitic Olivine [after, 31]. (a) network of sub-parallel sealed cracks carbonate filled sealed crack, (b) Network of sub-parallel Healed cracks, fractures, overgrowth and carbonate filled crack (c) healed cracks defined by discontinuous trails of fluid inclusions, (d) Olivine overgrowth and shapes of olivine (rounded and ellipsoidal).
record and experiences physical and chemical changes of the ascending magma. These textural features can constrain the process operative during the kimberlite ascent and eruption (Figure 2).

3.1 Texture features within olivine

-Olivine Overgrowths: Development of growth rims on a larger olivine grain and the interface of this trapped fluids, melt inclusion, mineral phase can be seen in form of discontinuous trails, which are parallel to margins of core.

-Fractures: It host a network of sub parallel to micro cracks, these are of different types.

-Sealed cracks: Sets of fractures, cracks filled with inclusions, mostly of carbonate and oxide.

-Healed cracks: They are in form of discontinuous fractures or trails of fluids and mineral inclusion, representing later event of fracturing. These fractures are filled melt and fluid inclusion.

-Sealed cracks: They are continuous and discontinues segments and patches as elongated carbonate.

-Shapes and surfaces: Olivine grains are rounded to elliptical and the surfaces are texturally distinct, they appear penetrative flaky and curving smooth when seen in high magnification.

The implication of above textural relationship can be utilised and a sequence of events occurring within the rising magma can be established. Within, the rising magma xenocrystic / xenolith minerals are not in equilibrium and react with the melt at different rates depending on their composition [3]. The textures observed in olivine are the results of the process involved during the ascent and interaction of the magma. The fractures sealed with carbonate rich fluids can develop during development of partially digested olivine. A later set of fractures filled with more sialic and hydrous magma can also develop which may be attributed to olivine saturation event, which is followed by overgrowths and capping of the sealed cracks. Rounded to ellipsoidal olivine grains may represent the last textural event. Rough and pitted textures in olivine grains may be due to the abrasion and attrition during the transport of kimberlitic magmas of a turbulent nature [31, 32].

4. Conclusion

Olivine grains in a Kimberlite is a depository of details on the composition, metasomatism and thermal conditions of the mantle sampled by kimberlites. Important constraints on the evolution of kimberlitic melts are made as it is present from the earliest stage up to last stage of crystallisation. It requires a careful point selection and detailed textural identification under the microscope and high magnifying images (BSE-SEM). To address the petrogenesis of kimberlite melt, it is essential to include and integrate the information based on textural relationship and analytical data. Studies suggest that olivine cores are the product of different types of disaggregate mantle rocks and large portions of the core is derived from megacryst, sheared peridotite and other lithologies. Textural information recorded by olivine, coupled with the intrinsic properties of olivine such as bulk modulus, viscosity and tensile strength can constrain magma ascent rates.

Overall, Olivine from kimberlite provide a complete information on the evolution of kimberlitic magma and its systems. It provides clues to the early metasomatic process operating within the upper mantle. Zoning and rims of kimberlitic olivine indicate the evidences of early crystallisation at mantle depths and also the process involved in ascent and emplacement of kimberlite.
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