Geochemistry of circum-craton eclogites and other mafic xenoliths from the Kaapvaal craton, southern Africa, and their comparison to on-craton equivalents

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Major and trace element and isotope geochemistry of constituent minerals from eclogites and related mafic xenoliths (garnet clinopyroxenites, garnet websterites) from five circum-craton localities (Lovedale, Roodekraal, Jachtfontein, Markt and Goedehoop) situated along the southwestern margin of the Kaapvaal craton, southern Africa, are reported. A comparison is made to equivalent lithologies from the on-craton localities of Roberts Victor (Hatton, 1978), Jagersfontein and Jwaneng.

Major element chemistry

Clinopyroxenes in circum-craton eclogites sensu largo are omphacites, with high jadeite contents (14.3-50.4 mole%), corresponding to high Na_2O contents (2.60-7.15 wt.%). In contrast, clinopyroxenes in circum-craton garnet clinopyroxenites and garnet websterites are diopsides, with lower Na_2O contents (0.25-2.85 wt.%). Al_2O_3 contents are higher in omphacites (5.36-14.13 wt.%) than in diopsides (0.78-5.35 wt.%), while FeO* contents are similar (2.00-8.62 wt.% for omphacites and 1.89-6.99 wt.% for diopsides). Diopsides have higher CaO (19.3-24.6 wt.%) and MgO (13.2-17.7 wt.%) contents than omphacites (11.6-19.5 wt.% and 6.55-13.1 wt.%, respectively). Mg#'s vary between 0.661 and 0.913 for omphacites and between 0.781 and 0.942 for diopsides. When compared to on-craton clinopyroxenes, the circum-craton clinopyroxenes in both eclogites and clinopyroxenites/websterites show similar composition in all major elements except MgO, for which circum-craton clinopyroxenes have lower values at similar sodium content. Omphacites from circum-craton kyanite eclogites show lower Al_2O_3 contents than omphacites from on-craton kyanite eclogites, at a given Na_2O content. Garnets in equilibrium with diopsides have low and restricted range in CaO contents (4.13-5.79 wt.%), compared to garnets in equilibrium with omphacites (4.21-12.94 wt.%). Garnets in the two lithologies have similar FeO* contents (11.3-25.8 wt.% and 12.4-23.6 wt.% when in equilibrium with omphacite or diopside, respectively), with garnets in kyanite eclogites having a more restricted range in FeO* (12.7-16.5 wt.%). All garnets have low amounts of Na_2O (< 0.21 wt.%), and display a large variation in MgO contents (7.2-16.2 wt.% and 10.0-16.2 wt.% when in equilibrium with omphacite and diopside, respectively), which leads to a large, and overlapping, variation in Mg# values for both lithologies (35.5-69.7 and 43.9-69.8, respectively). All garnets have low Cr_2O_3 contents (<0.28 wt.%), except those that equilibrated with significant amounts of orthopyroxene, which have higher Cr (0.21-2.14 wt.% Cr_2O_3). When compared to garnets from on-craton xenoliths, garnets from off-craton settings show similar contents in Ca but slightly higher contents in Fe and/or lower contents in Mg.

Trace element mineral composition

Most off-craton clinopyroxenes exhibit convex-upward chondrite-normalized REE patterns, with LREE being higher in omphacites (La_N = 1.40-81.4) than in diopsides (La_N = 1.65-33.7). MREE enrichment is variable (Sm_N: 5.12-86.1 for omphacites and Sm_N: 8.88-94.9 for diopsides), whereas HREE contents are low in clinopyroxene from all lithologies (Yb_N = 0.14-1.57 for omphacites and Yb_N = 0.14-0.90 for diopsides). When compared to on-craton clinopyroxenes (La_N = 0.76-47.9 and Sm_N = 1.26-32.9), off-craton clinopyroxenes appear enriched in LREE and especially in MREE (figure 1).

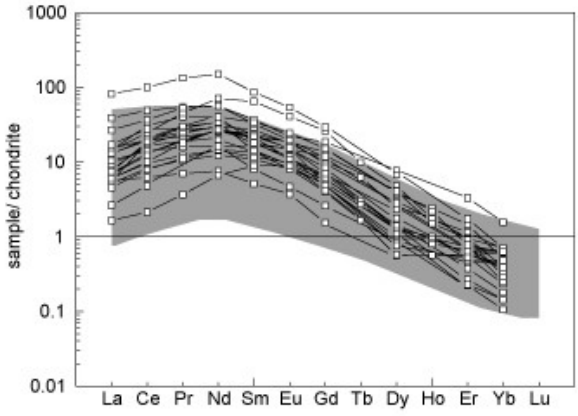

Fig.1: Chondrite-normalized REE patterns for cpx from circum-craton xenoliths. The grey field represents the REE patterns for on-craton cpx from Jagersfontein, Jwaneng and Roberts Victor.

Chondrite-normalized REE patterns for garnets in equilibrium with diopsides exhibit a rather steep positive slope from LREE to MREE [$(Ce/Nd)_N$ = 0.04-0.52] that flattens down from MREE to HREE [with

$(Gd/Yb)_N$: 0.26-1.61], whereas garnets in equilibrium with omphacites exhibit a strong positive slope from LREE to MREE [$(Ce/Nd)_N$ = 0.04-0.17], a "hump" towards Sm and Eu (Sm abundances of 6 to 48 times chondrites) and a slight negative slope from Gd to Yb [$(Gd/Yb)_N$ = 0.84-4.9]. Significant positive Eu anomalies in garnets are observed in eclogites from Roodekraal and Jachtfontein (Eu/Eu* = 1.24-1.84). Both groups of garnets are strongly depleted in LREE (Ce_N: 0.032-1.6), and enrichment in HREE is variable (Yb_N: 4.8-32.2 and Yb_N: 8.9-39.8 for garnets in equilibrium with omphacites and diopsides, respectively, with garnets from one sample from Roodekraal having a Yb_N value of 91.6). When compared to on-craton garnets (Sm_N: 0.98-10.5, Yb_N: 2.20-22.3), off-craton garnets appear enriched in MREE and HREE (figure 2).

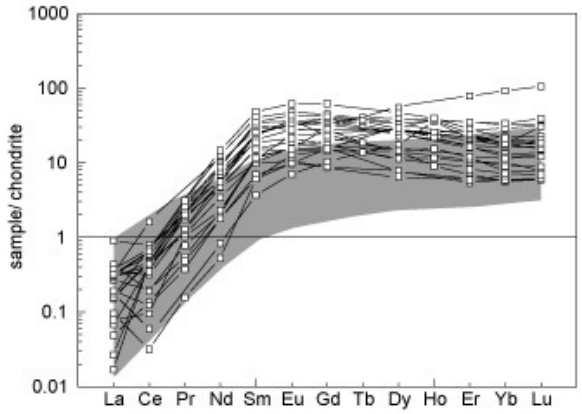

Fig. 2: Chondrite-normalised REE patterns for garnets from circum-craton xenoliths. The grey field represents the REE patterns for on-craton garnets from Jagersfontein, Jwaneng and Roberts Victor.

Stable and radiogenic isotopes

Oxygen isotope analyses on garnets from circum-craton localities yield $\delta^{18}O$ values ranging between 5.15 and 6.78‰ for eclogites and between 5.24 and 7.03‰ for garnet clinopyroxenites. In comparison, garnets from the on-craton Roberts Victor, Jwaneng and Jagersfontein localities give $\delta^{18}O$ values ranging from 4.68 to 6.70‰, although published data from Roberts Victor give a range of 2.2-8.0‰. Present-day Sr isotope compositions determined on circum-craton clinopyroxenes give overlapping, to slightly higher, values for eclogites ($^{87}Sr/^{86}Sr$: 0.70352-0.70708) than for garnet clinopyroxenites ($^{87}Sr/^{86}Sr$: 0.70254-0.70620). Clinopyroxenes in garnet websterites yield lower $^{87}Sr/^{86}Sr$ values of 0.70267-0.70345. In comparison, on-craton eclogitic clinopyroxenes exhibit a wide range of $^{87}Sr/^{86}Sr$ values (0.70277-0.70889), garnet clinopyroxenites have a narrower overlapping range (0.70353-0.70518), and the single garnet websterite gives a value of 0.70734. Low Rb contents in the clinopyroxene result in minimal age correction even over 2 Ga. Ranges in $^{143}Nd/^{144}Nd$ ratios for clinopyroxenes are low and similar between the circum-craton eclogites (0.51191-0.51268) and the circum-craton garnet clinopyroxenites (0.51181-0.51264). Clinopyroxenes from the circum-craton websterites overlap to slightly higher values of 0.51207-0.51271. $^{143}Nd/^{144}Nd$ ratios for on-craton eclogitic clinopyroxenes (0.51209-0.51259) are within the range of values defined by the circum-craton equivalents, and clinopyroxene from on-craton garnet clinopyroxenites show a limited range of $^{143}Nd/^{144}Nd$ values (0.51272-0.51276) similar to their circum-craton counterparts. Among circum-craton xenoliths, eclogitic clinopyroxenes exhibit higher present-day $^{206}Pb/^{204}Pb$ ratios (17.26-19.45) and $^{208}Pb/^{204}Pb$ ratios (37.11-41.93) than clinopyroxenes from clinopyroxenites ($^{206}Pb/^{204}Pb$: 16.85-17.78 and $^{208}Pb/^{204}Pb$: 36.77-37.45). Clinopyroxenes from on-craton garnet clinopyroxenites show higher $^{206}Pb/^{204}Pb$ values (19.01-20.69) and $^{208}Pb/^{204}Pb$ values (38.94-38.97) than their circum-craton counterparts. In contrast, both $^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ ratios are higher for circum-craton eclogitic clinopyroxenes than for their on-craton counterparts ($^{206}Pb/^{204}Pb$: 15.00-17.50 and $^{208}Pb/^{204}Pb$: 35.24-37.38, respectively).

Geothermobarometry

Equilibrium temperatures were estimated using thermometers of Ellis and Green (1979) and Krogh (1988). For the orthopyroxene-bearing samples, equilibrium temperatures and pressures were estimated using the geobarometer of Brey and Köhler (1990). An assumed pressure of 30 kb was used in the calculations. Temperatures obtained for the garnet websterites are the lowest with all thermometers (T_{EG}: 742-781°C, T_K: 669-697°C, and T_{BK}: 739-820°C), whereas garnet clinopyroxenites appear to have equilibrated at slightly higher temperatures (T_{EG}: 715-830°C and T_K: 635-748°C). Ranges in temperature obtained for the eclogite xenoliths are wide, with T_{EG} = 707-1056°C (mean 913°C) and T_K = 633-1064°C (mean 887°C), and results for kyanite eclogites (T_{EG}: 940-1010°C and T_K: 930-1001°C) indicate equilibration at the high end of this temperature range. Equilibration pressures obtained for the orthopyroxene-bearing samples range from 16 kb to 33 kb. Temperatures of equilibration estimated on eclogites from Roberts Victor by Harte and Kirkley (1997) at an assumed pressure of 50 kb give T_{EG} values ranging from 947 to 1285°C, and temperatures obtained for eclogites from Jagersfontein with the same geothermometer are more restricted in range (1020-1072°C; at 50 kb). Temperatures obtained for the two eclogites from Jwaneng give an average value of 960°C.

Discussion and conclusions

Mafic mantle xenoliths brought to the surface along the southwestern margin of the Kaapvaal craton can be subdivided into two lithological groups, namely omphacite-bearing (eclogites sensu largo) and diopside-bearing rocks (garnet clinopyroxenites, garnet websterites). When compared to their cratonic counterparts, clinopyroxenes and garnets in circum-cratonic eclogites exhibit lower MgO contents and higher MREE abundances, with garnets sowing a flatter HREE pattern. Temperatures of equilibration for

the different circum-craton xenoliths (at P = 30 kb) increase from the garnet websterites (T_{EG} = 742-781°C) through the garnet clinopyroxenites (T_{EG} = 715-830°C) to eclogites (T_{EG} = 707-1056°C, mean value of 913°C). Pressures of equilibration obtained for the orthopyroxene-bearing samples vary between 16 and 33 kb (corresponding to depths of ~50-100 km). Based on geophysical studies indicating the occurrence of 45 to 50 km of crust underneath this circum-cratonic region, we argue that the circum-craton suite as a whole originate from the upper mantle rather than from the lower Proterozoic crust. The temperatures and pressures of equilibration obtained for these xenoliths correspond to shallower depths than those at which the on-craton xenoliths equilibrated, believed to be within the diamond stability field.

Raised oxygen isotope values in garnets from circum-craton eclogites and clinopyroxenites, are interpreted as resulting from the low-temperature alteration of the protolith at crustal depths. A low pressure protolith is supported by the common occurrence of positive Eu anomalies in garnets, clinopyroxene and in many recalculated bulk-rock chondrite-normalized REE patterns. Low but variable $^{87}Sr/^{86}Sr$ ratios, MORB to HIMU-like Pb isotope ratios and depleted, although in some cases complex, chondrite-normalised bulk rock REE patterns, are consistent with derivation from a geochemically depleted protolith, interpreted to be oceanic crust. In contrast, the very low $^{143}Nd/^{144}Nd$ ratios of the clinopyroxenes require an episode of enrichment (metasomatism) undergone by the xenoliths or their protoliths, the former supported by the presence of secondary phlogopite observed in many samples. Noteworthy is the presence of minerals with mixed geochemical signature which is indicative of the complex interactions between the mantle and the melts/fluids percolating through it in subcontinental environment.

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