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A Metamorphic Petrologist's View on Gemstone Formation: An Example from Sri Lanka

LUKAS P. BAUMGARTNER, FERNANDO G.W.A.R., HAUZENBERGER C.A., HOFMEISTER W.
Institute of Geosciences Johannes Gutenberg-University, D-55099 Mainz, Germany
e-mail: lukas@mail.Uni-Mainz.de

Abstract

The growth of gem quality metamorphic minerals is most likely in fluid rich systems, where growth rate exceed the rate of nucleation. This condition typically occurs when crystallizing is close to equilibrium. This communication discusses metasomatic growth of corundum crystals at the boundary between ultramafic and acidic granulites. The phase petrology of the formation of corundum at the Rupaha deposit is presented Corundum forms due to desilification of the acidic granulite during peak granulite facies.

Introduction

Some of the world's most productive gemstone provinces lie within Precambrian rocks forming the basements of the southern continents which formed the Gondwana super continent. Sevral different mineral species of gem quality are found in these granulite facies (high-temperature) terranes. Uncut gemstones owe their values to their size, color, luster, transparency, lack of fractures and unsightly inclusions, and the absence of alteration. The focus of this presentation is on metamorphic gemstone formation.

Gem quality crystals are formed either by recrystallization or by net transfer reactions. The formation of large crystals by recrystallization requires a very long time of high temperature annealing. The surface energy reduction due to grain size increase is very small (Joesten, 1991; Lasaga 1998). Hence the formation of large gems through recrystallization only seems unlikely. The crystallization of new crystals requires nucleation of the crystal, its growth, and transport of the constituents of the gem to the reaction site. Formation of individual, large crystals only occurs in systems where growth dominates over nucleation. Growth and nucleation of crystals can be viewed as parallel processes, once first nucleation has occurred.. Growth dominated systems are typically observed close to equilibrium, where nucleation densities are small (Roselle and Baumgartner, 1997; Lasaga, 1998). Transport of constituents always acts in series with nucleation and growth (Kerrick et al., 1991; Roslle 1997). The formation of large crystals requires rapid transport of constituents to the growth or nucleation site. Equally important is the removal of components not included into the crystal originally present at the growth location. The mobility of ions and complexes is facilitated by the presence of a typically aqueous fluid phase, rich in complexing agents like fluorine and chlorine.

A high surface free energy of the crystal both helps preventing the formation of inclusions, as well as rampant nucleation. Post-peak metamorphic fluid-rock interactions will form retrograde minerals, which may destroy the gem quality of original minerals.

This and the companion paper by Hauzenberger et al. (this volume) describe two different types of metamorphic corundum deposits: one of metasomatic origin, one of sedimentary-metamorphic origin. Corundum is a relatively rare oxide, since it is only stable in quartz-absent, aluminum rich rocks at elevated temperatures and pressures. Its metamorphic formation is restricted to sediments with unusual high aluminum and low quartz contents (bauxites, some carbonates). See Hauzenberger et al. (this volume) for an example. Alternatively, silica rich rocks can become silica under saturated due to mobilization of silica out of an aluminum rich protholith. This second case will be dealt with in more detail here.

Sri Lanka has long been renowned for the variety and abundance of its gemstones, most notably those of oxide group minerals, found in gem bearing gravels. Corundum and spinel found in many *in-situ* deposits in Sri Lanka is reported to form due to either metasomatism or skarn-type mineralization (see Fernando 1995). Our study draws attention to an apparently significant connection between gemstone formations in Sri Lanka and the high temperature granulite facies during the Pan-African Thermo-Tectonic Episode, dated at around 600 - 500Ma. Special emphasis is placed on the recently discovered corundum-spinel-sapphirine occurrence at Rupaha.

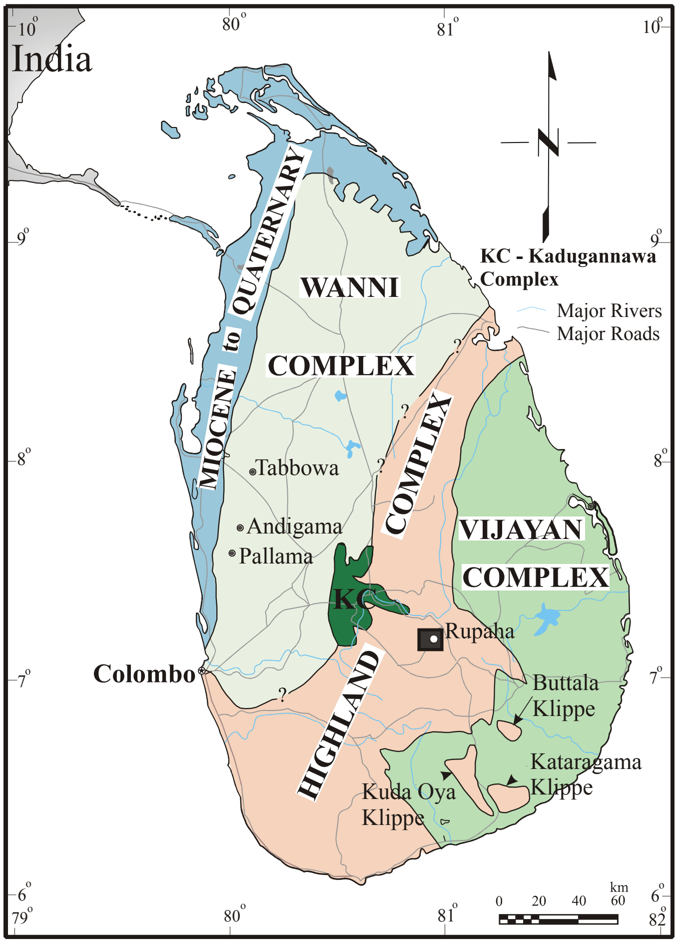

Fig. 1: The simplified geological map of Sri Lanka shows the major tectonic units (after Cooray 1994). The study area is outlined by a box.

Field relationships of the study area

Rupaha is located in the Highland Complex of Sri Lanka, which represents a small, but important fragment of the super-continent Gondwana (Fig. 1).

Excellent exposures of ultramafic rocks embedded in granulites were found at 10 localities. The ultramafic and the granulite rocks separated by a reaction zone, which locally reaches a thickness of 50cm. Starting at the ultramafic contact, the following zones have been observed: phlogopite; phlogopite + spinel; phlogopite + spinel + sapphirine; sapphirine + corundum + biotite; and corundum + biotite + plagioclase (Fig 2).

Metamorphic conditions

The mineral assemblages from both ultramafic rocks and granulites indicate granulite facies metamorphic conditions. A maximum temperature of 875 ± 20°C (Opx-Cpx thermometer) and at a peak pressure of 9.0 ± 0.1 kbar (Grt-Cpx-Pl.Qtz) was calculated for the granulites. The ultramafic rocks recorded a peak temperature of 840 ± 70°C (Opx-Cpx thermometer) at an adopted pressure of 9 kbar. Coexisting spinel and sapphirine from the reaction zone yield a temperature estimate of 820 ± 40°C. Hence all units have experienced the same peak metamorphic conditions. Relict textures, like corundum surrounded by spinel in the sapphirine-spinel zones further supports growth of the metasomatic zones during metamorphism.

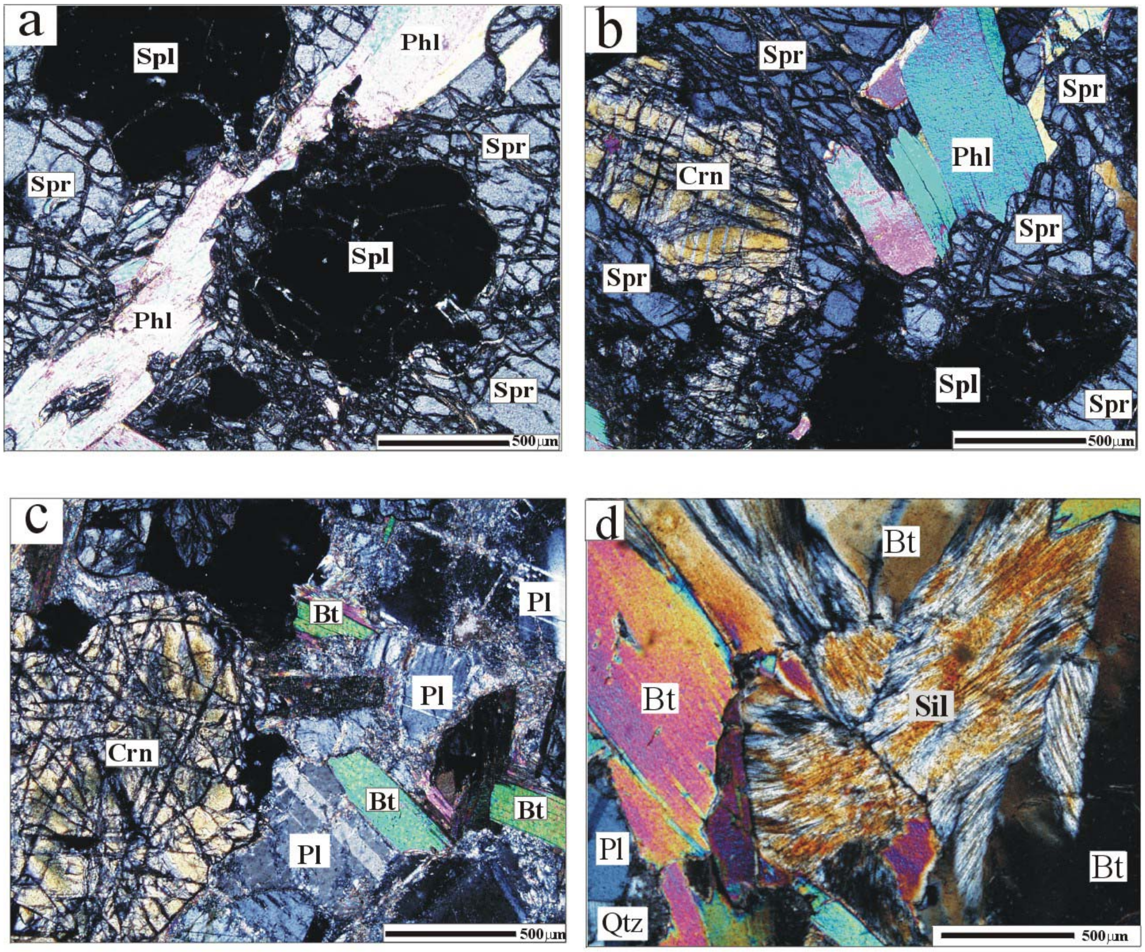

Fig. 2 The photographs show the mineral assemblages of the reaction zones: (a). phlogopite-spinel-sapphirine zone, (b). relict corundum in the sapphirine-spinel zone, (c). corundum-biotite-plagioclase gneiss, (d) sillimanite-biotite-quartz-plagioclase in sillimanite-bearing granulites.

The stability field of sapphirine and the assemblages spinel-corundum is shown in a chemical potential diagram of MgO (μ[MgO]) in Figure 3). The activity corrected T-μMgO diagram is calculated for the system MgO-Al_2O_3-SiO_2-H_2O-CO_2 at 9kbar condition using the thermodynamic database of Holland and Powell (1998) , assuming $X_{CO2} = 0$. The activity models for spinel and sapphirine are those of Holland and Powell (1998). The shaded area marks the stability field of sapphirine. The sapphirine field is enlarged somewhat by decreasing the water activity to 0.5, assuming dilution by CO_2 (Fig. 3). Hence the stability of sapphirine also suggests a high temperature origin.

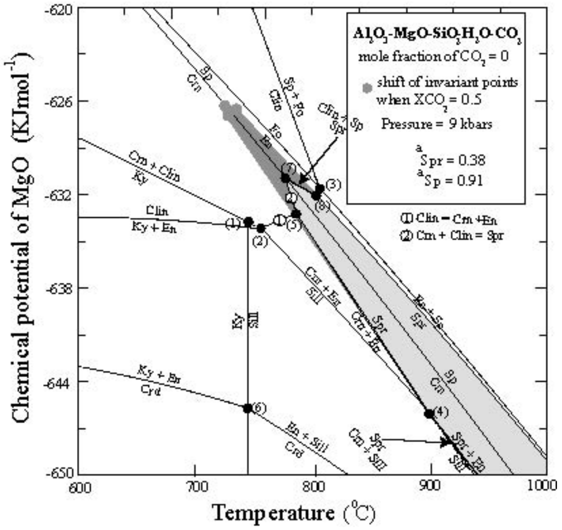

Fig. 3 Chemical potential (μMgO) versus temperature diagram was calculated for the system Al_2O_3-SiO_2-MgO at 9kbar and X_{CO2} = 0, using the thermodynamic data of Holland and Powell (1998). The light shaded area is the stability limit of sapphirine. The stability field of sapphirine extends towards lower temperatures for decreasing water activity (X_{CO2}=0.5).

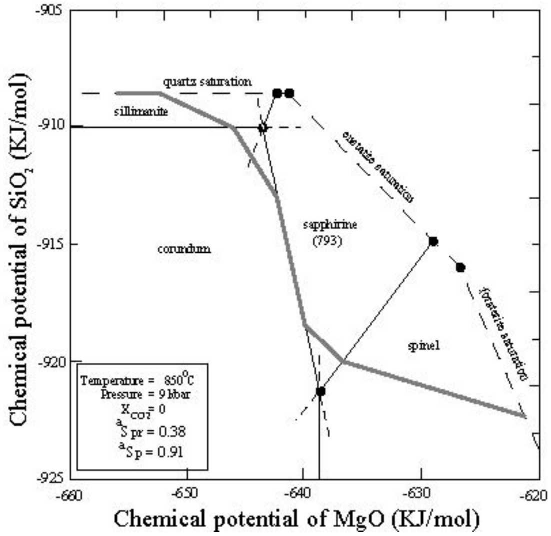

Fig. 4 Phase field boundaries were calculated by balancing the mineral reactions with Al_2O_3. The thick line indicates schematically the chemical potential gradient between the granulites and the ultramafic rocks which lead to the formation of the corundum and spinel-bearing mineral assemblages.

Growth of the Reaction Zones

Equilibrium phase relations among pertinent minerals are shown in the Fig. 4 for the system Al_2O_3-SiO_2-MgO-H_2O at 850°C, 9kbar fluid and solid pressure. The univariant boundaries and the phase saturation limits were calculated with the thermodynamic database of Holland and Powell (1998). The assemblage spinel and forsterite found in the ultramafic rocks define a high chemical potential of MgO at low SiO_2 values. Sillimanite and quartz, the assemblage of the granulitic rocks, in turn require a high SiO_2 potential at low MgO values. The thick black line drawn in the Fig. 4 schematically illustrates the chemical potential gradients defined by the mineral zones observed in the reaction zones between the ultramafic rocks and the surrounding granulites.

The corundum and spinel occurrences at Rupaha were overprinted during cooling by several retrograde fluid events, and local deformation. Many of the corundum grains were partially altered to diaspore, which fills fractures and rims, whereby the quality of the gems were greatly reduced.

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