# Clinopyroxene phenocryst formation in an alkaline magma: Interpretations from oscillatory zoning

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Oscillatory zoning is observed in a large variety of igneous mineral species and reflects changes in the crystal-melt system. Theoretical (numerical modelling) and experimental investigations of this common phenomenon lag behind the ability to accurately measure oscillating chemical compositions on a micro-scale. For this reason only general models for the production of oscillatory zoning exist (Shore and Fowler, 1996). Although the formation of oscillatory zoning patterns (OZP) commonly observed in accessory minerals such as zircon probably require a complex feed-back mechanism between the crystal and melt, major element OZPs in most rock forming minerals can be adequately explained without a feed-back mechanism and, therefore, probably reflect true oscillations in the broad chemical environment. These oscillations may occur as changes in the system's pressure, temperature, or composition (e.g. Simonetti *et al.*, 1996).

The sample for the present study is from the eastern Pontides, near the city of Trabzon, Turkey. Volcanic rocks from the region formed during three cycles of Phanerozoic eruptive activity in the Liassic, Upper Cretaceous and ?Eocene. The third stage coincides with maximum regional crustal thickening, during which time alkaline volcanism was dominant between Tonya and Trabzon, along the modern coastline. Exposed ?Eocene alkaline rocks at Trabzon and include a range of lava and pyroclastic compositions. The rocks are generally microlitic porphyritic to hyalo-prophyritic, and contain clinopyroxene, plagioclase, analcite, olivine and phlogopite as major phases, and sanidine, nepheline, cancrinite, apatite and Fe-Ti oxides as minor phases. In addition, the rocks from Trabzon area often contain cognate or cumulate xenoliths. The magmas derived from an E-type MORB source which experienced low degrees of melt segregation, rising to shallow depths (~1 kbar) and evolving during ascent by fractionation of garnet (residual), olivine, clinopyroxene, and plagioclase (Arslan *et al.*, 1997).

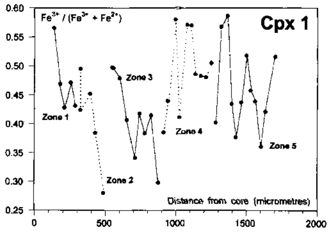
## Diopside chemistry

Two large (~3 mm long) euhedral clinopyroxene crystals 1 cm apart in thin-section (alkaline basalt from Trabzon) were selected for investigation. They have different habits, prismatic (cpx 1) and equant (cpx 2); both display spectacular oscillatory and sector zoning. Cpx 1, in particular, contains many large and small apatite inclusions. Cpx chemistry was determined by electron microprobe analysis (major oxides) and SIMS (trace elements). Analytical traverses were performed parallel to {100} or {110}.

The cpx crystals have a diopside stoichiometry, $Wo_{47-51}En_{43-48}Fs_{2-8}$, and are relatively enriched in $TiO_2$ (0.53–1.98 wt.%), $Al_2O_3$ (2.74–9.36 wt.%), P (42–2454 ppm), V (160–268 ppm), Zr (298–681 ppm), Ni (542–954 ppm) and the *LREE*. Figure 1 shows the pattern of $Fe^{\#}$ ($Fe^{3+}/[Fe^{3+}+Fe^{2+}]$) with distance ($x$) from core to rim. Different 'zones' are recognised in the cpx's OZPs based on bright horizons along the OZP. In some instances this clearly correlates with a high $Fe^{\#}$ (cpx 2). The two patterns are different; that of cpx 1 appearing to randomly oscillate whereas that of cpx 2 seems periodic, especially in zones 3–5. Similar patterns are observed for $Mg^{\#}$, $TiO_2$, and Al although there is a general trend in cpx 1 from core to rim of decreasing $Mg^{\#}$ and $^{[6]}Al$, and increasing $TiO_2$. Amongst other elements, zones 1, 2, and 5 of cpx 1 have high concentrations of Ni and Cr whilst zones 3 and 4 are low.

## Fractal analysis

Fractal statistics allows quantification of OZPs, taking the description of such patterns beyond the qualitative. The slope of the line in Fig. 2 yields the Hurst exponent, $H$, which is related to the Fractal dimension (Holten *et al.*, 1997). Figure 2 was constructed from $Mg^{\#}$ *vs* distance for cpx 1. The $H$ value of 0.42 indicates that the OZP does not



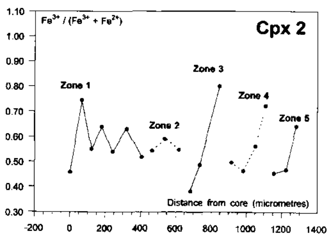


FIG. 1. $Fe^{\#}$ *vs* distance (core–rim) for cpx 1 and cpx 2.

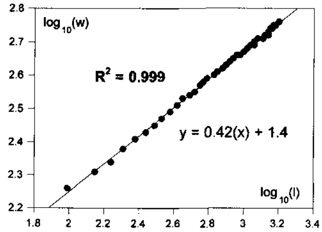


FIG. 2. Log-log plot of width *vs* length of the $Mg^{\#}$ function (value *vs* distance) in cpx 1. The slope of the line is the Hurst exponent, *H*.

represent ordinary Brownian motion, but reflects an underlying structure to the OZP. Both cpx 1 and cpx 2 yield values of *H* about 0.42 for chemical and grey-scale (image) analysis of their OZPs.

Also measured is the Lyapounov exponent, $\lambda$, (Halden, 1996) of the OZPs using grey-scale digital images. A positive $\lambda$ value indicates a chaotic OZP, whilst a negative value indicates a non-chaotic pattern. As discussed by Halden (1996) a non-chaotic pattern can still be an oscillatory pattern. We used two different trajectory lengths (10 and 30 ?m) and obtain these $\lambda$ ranges: cpx 1, 0.0046–0.0183; cpx 2, −0.1298– −0.0419. Cpx 1's OZP is, therefore, weakly chaotic, whilst cpx 2's is non-chaotic.

## Discussion

The titanium-bearing aluminian diopsides described above from Trabzon, Turkey, are similar to occurrences reported from other alkaline igneous provences. Two populations of diopside phenocryst are chemically distinguishable at Napak volcano, Uganda, interpreted by Simonetti *et al.* (1996) to occur by the mixing of at least two different magmas. Although the close chemical similarities of the Trabzon crystals, cpx 1 and 2 suggest shared origins, their zoning patterns are different and reflect different crystallisation paths.

The decrease in $^{[6]}Al$ from core to rim in cpx 1 probably reflects decreasing *P*. This crystal probably began crystallising from the melt at depth and continued crystallising during magma ascent into the upper crust and a shallow magma chamber. The occurrence of cognate and cumulate xenoliths in the lavas support the interpretation of crystallisation over a wide *P* range. The central zones of cpx 1 are enriched in Ni and Cr reflecting early crystallisation, which may have occurred over a longer duration than cpx 2 based on a larger crystal size. The origin of the OZP may reflect changing *P*, providing a (one-way) forcing on the system which may be reflected by an *H* value < 0.5 (ordinary Brownian motion = 0.5). The weakly-chaotic OZP of cpx 1 may result from local effects, such as changes in $f_{O_2}$ due to co-crystallisation of apatite.

Core-rim chemical trends are not measured for cpx 2. Quantities such as $Mg^{\#}$ and $^{[6]}Al$ are variable but show no general trend. Unlike cpx 1, this crystal is interpreted to have crystallised at constant *P* over a shorter duration, probably at shallow depths in a magma chamber. The periodicity of major element features ($Mg^{\#}$ and $Fe^{\#}$) in the outer zones must represent an open system where new magma pulses or eruption are the most likely processes. The $H < 0.5$ may reflect melt differentiation or decreasing *T* (both generally represent one-way system forcing), which is also likely to produce the observed OZP.

Eruption of the magma containing cpx 1 and cpx 2 may have been triggered by a new magma batch, responsible for higher Ni and Cr in the rim of cpx 1, and a sharp rise of $Mg^{\#}$ in both cpx 1 and cpx 2 at their rim. Despite different origins within a larger open magmatic system, the crystals were frozen near eachother after eruption, preserving evidence of different crystallisation paths in their chemical and optical zoning patterns.

## References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