MINOR ELEMENT ZONING OF OLIVINE IN TYPE IIA CHONDRULES IN SEMARKONA. R. H. Hewins[1,2], [1]Department of Earth and Planetary Sciences, Rutgers University, 610 Taylor Rd., Piscataway, NJ 08854-8066, USA; [2]Muséum National d'Histoire Naturelle & CNRS, 61 rue Buffon, 75005 Paris, France (hewins@rci.rutgers.edu).

Introduction: The detailed interpretations of chondrule thermal histories are difficult and controversial. The olivine in Type IA chondrules may be relicts of granular olivine aggregates or formed by fractional crystallization [1,2]. Type IIA chondrules may have been heated and cooled once or multiple times [3,4]. Criteria in addition to texture would be useful for determining the extent of melting, number of events and cooling history. A new tool that can clarify how olivine crystals formed is X-ray intensity mapping of minor elements such as P [5,6,7] and it reveals unexpected features in many chondrules investigated.

Experimental Techniques: We used a section of Semarkona MNHN ns2 and made X-ray scanning images of chondrule olivine using the Cameca SX100 at the Université Paris VI. We used 15keV, high beam current (500nA) and high dwell times (100 ms) with 1μm spacing. BSE intensities and P, Cr, Ca, and Al or Mn counts were measured simultaneously using LTAP, LLIF, LPET and TAP crystals to form images.

Quantitative analyses of olivine were done on the Cameca SX100 microprobe at the Université Blaise Pascal, along traverses with 1μm spacing. We used 15 keV, and 150nA for less abundant elements. The lowest detection limits were 71 ppm (P), 76 ppm (Na), 93 ppm (Al) 140 ppm (Ca) and 210 ppm (Cr).

Results: Mean P_2O_5 concentrations in olivine grains in Type IIA chondrules range from 0.013 to 0.115 wt.%, always above the detection limit. The maximum values, occurring both in interior zones and at edges for P_2O_5 are 0.11 to 0.53 wt.%. The data are consistent with those of [3], <0.06 to 0.17 wt.% for chondrule mean olivine and <0.06 to 0.5 wt.% for chondrule maxima. By contrast, Type IA olivine has less than the detection limit of 71 ppm for P.

Maps of PK_α intensity in Type IIA chondrules in Semarkona MNHN ns2 reveal several kinds of zonation not evident in maps for other elements. The zonation varies from obvious (Fig. 1,2) to very faint, and from fairly continuous to sharply discontinuous. P maps also reveal the presence of relict grains.

Concentric-hourglass zoning. Many olivine crystals show discontinuous concentric zoning in hourglass form for P, whereas other elements e.g. Cr show a much simpler pattern (Fig. 1).

Oscillatory concentric zonation. P zonation is very common, especially as oscillatory concentric zonation,

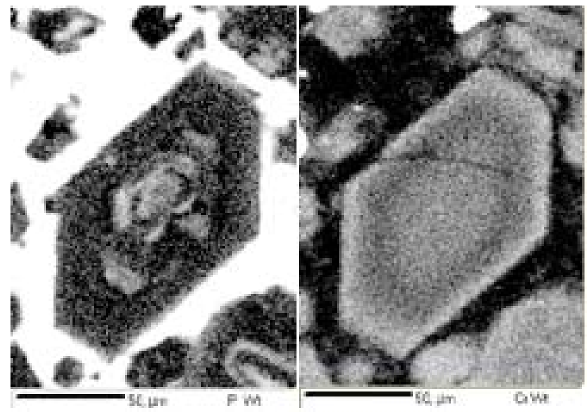

Fig. 1 Concentric-hourglass zoning in P (left); reverse/normal zoning in Cr (right).

which documents stages in olivine growth. In many cases P zoning shows that the central region has the form of a hopper crystal (Fig. 2), which has subsequently filled in. Melt inclusions (white in Fig. 2) are common in such grains.

Fig. 2 Concentric oscillatory zoning in P reveals that the core initially had a hopper form.

Micron-scale concentric zoning. Fine-scale oscillatory zoning in many elements is absent in most cores but common near crystal rims (though hardly visible for P in X-ray images). The amplitude of the composition oscillations increases towards the rim. The zoning is obvious in quantitative analyses, provided that the traverse step is equal to the wavelength of the oscillatory zoning (Fig. 3). Here P correlates with Fe, Cr, Mn and Ca but anticorrelates with Mg.

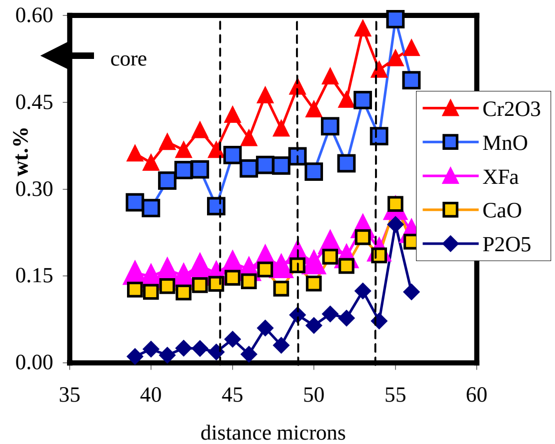

Fig. 3 Micron-scale oscillatory zoning at olivine rim.

Al zoning. In Fig. 4, the large hopper olivine grain shows, in addition to faint oscillatory zoning, a nearly continuous ring in P marking a growth surface around a late patch of olivine enriched in Al (& Ca) and connected to a finger of mesostasis.

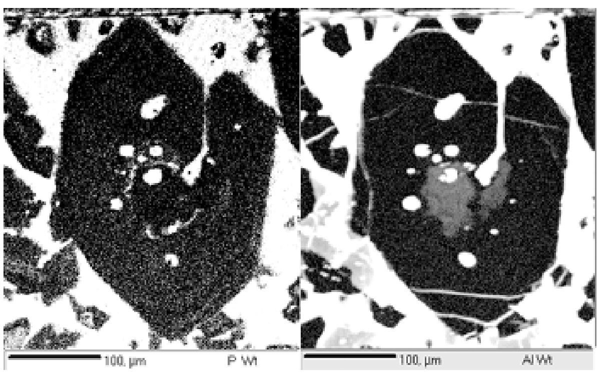

Fig. 4 Left P, right Al. Al-rich patch surrounded by P-rich zone; faint oscillatory zoning.

Relict grains. Forsteritic relict grains in Type II chondrules are very obvious in BSE images, though the boundary between core and relict is not sharp, because of diffusion. In P maps the boundary is sharp, because P is zero in the relict, and it is often marked by a P-rich boundary layer. This helps diffusion work [8].

Ferroan relict olivine grains in Type IIA are very hard to recognize in BSE images. However, they are obvious in P X-ray images (Fig. 5).

Discussion: Minor element zoning in olivine and pyroxene in chondrules has already given valuable information on their formation [e.g. 3]. However, X-ray mapping of minor element zonations in olivine has barely been exploited at all [6,7]. Trace elements that diffuse more slowly than Fe and Mg, especially phosphorus, reveal details (e.g., overgrown relicts as phenocryst cores, skeletal cores, oscillatory zoning) that allow us to distinguish easily the nature of any igneous growth history or resorption. None of these features seen in P K_{α} could be seen in BSE, optical microscope or cathodoluminescence images.

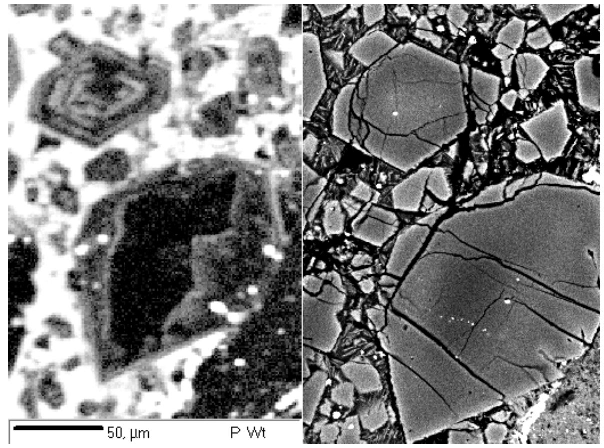

Fig. 5 Relict grain in P X-rays (left) and BSE (right).

It is striking that P in Type IIA olivine shows oscillatory zoning in the core (Fig. 1,2,5), while Cr and other elements for the same grains shows simple broad zoning patterns. The P-rich zones correspond to greater than equilibrium partitioning between olivine and melt. Since it is implausible that the bulk liquid experienced fluctuations in P concentration, we infer periods of rapid growth and fluctuations in liquid boundary layer composition. Similar variations for other elements may have been erased by diffusion (except in lower temperature rims (Fig. 3). P-rich zones coating anhedral relict cores suggest that initial overgrowth is rapid and such grains may show only smooth pseudo-igneous (Fe-Mg) zoning in BSE (Fig. 5).

Conclusion: Zoning in P persists in chondrule olivine because it is a slow-diffusing element. P-rich zones mark periods of rapid growth and also mark onset of growth on resorbed relict grains, including ferroan relicts otherwise difficult to recognize. P maps can resolve many questions about the evolution of individual chondrules, and generally show continuous crystallization of olivine grains.

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