SHORT COMMUNICATIONS

MINERALOGICAL MAGAZINE, DECEMBER 1984, VOL. 48, PP. 547–50

Recognition of simple and complex zoning in olivine and orthopyroxene phenocrysts using laser interference microscopy

ALTHOUGH much critical petrogenetic information is contained within zoned phenocrysts in volcanic rocks, the common orthorhombic minerals olivine and orthopyroxene normally appear homogeneous under the microscope. This is a reflection of their modest change of birefringence with chemical composition, and of their high symmetry which precludes the application of extinction angle measurement to determine composition. Petrogenetically important zoning may, of course, be defined by electron probe analysis, but in practice a very large number of spot analyses is required to delineate even simple zoning, and complex zoning may be overlooked.

The technique of Multiple Frequency Laser Interference Microscopy, recently developed by one of us (Pearce, 1984), offers a practical, rapid, and relatively inexpensive method for the detection of mineral zoning in thin section. On a single interferometric photograph it is possible to recognize, with a high degree of resolution, zoning of various types over an entire thin section. In this technique a laser light source is combined with a Mach Zhender interferometer as part of a microscope. Using a doubly polished thin section (necessary for these high-relief minerals), an interferogram is produced in one of two modes: wide fringe and narrow fringe. In the former, an 'image' is produced which is contoured with respect to refractive index gradients within the sample. In the narrow fringe mode, the interferogram comprises a series of interference fringes which traverse the mineral grain, thereby forming a profile of the refractive index. As examples of usefulness of the technique, we cite the following.

Simple zoning in olivine. A Quaternary intracanyon olivine basalt from central Arizona contains numerous olivine phenocrysts, generally not exceeding 300×100 μm in size. In figs. 1*a–c* a typical phenocryst is shown in, respectively, crossed-nicols transmitted light, a wide-fringe interferogram, and a narrow-fringe interferogram. A compositional profile determined by electron probe analysis (line A–A′ in fig. 1*a*) is illustrated in fig. 1*d*. Whereas the phenocryst appears essentially homogeneous in transmitted light, fig. 1*a*, almost two orders of interference are evident in fig. 1*b*, corresponding to a refractive index contrast between core and margin equivalent to *c*. 12 mole % forsterite (Pearce, 1984; Pearce *et al*., 1983). In the narrow-fringe interferogram, fig. 1*c*, the fringes are smoothly curved, conforming to the refractive index profile (and hence compositional gradient) of the grain. The interference is the same as in the wide-fringe mode but the resolution of the zoning is more precise. The simple, continuous zoning evident from the interferograms is corroborated by the electron probe traverse (fig. 1*d*).

Complex zoning in orthopyroxene. Absarokitic and shoshonitic lavas of the Permian Mitu Group of Puno Department, SE Peru (Kontak *et al*., 1984), contain remarkably fresh phenocrysts of olivine and orthopyroxene. Both minerals show complex zoning but this is more evident in the case of the orthopyroxene in the shoshonites, as described below.

In figs. 2*a–c*, a representative phenocryst is illustrated in the same fashion as the preceeding olivine. The transmitted light photograph (fig. 2*a*) reveals a semi-continuous, annular, darkened zone, pale-brown in colour, in a crystal which otherwise appears unzoned. Both broad- and narrow-fringe interferograms reveal complex refractive index zoning in the grain. In the former, the aforementioned zone is clearly outlined by a bilaterally symmetrical trough of approximately one order of interference. In fig. 2*b*, this appears as a pale band bordered by darker selvages. In this grain, however, the refractive index zoning is more clearly shown by the narrow-fringe interferogram in fig. 2*c*. Here, the pale-brown zone corresponds to a well-defined trough in the fringe pattern which is readily followed around the grain.

The indicated compositional variation is confirmed by the electron probe profile in fig. 2*d*: the pale-brown zone of contrasted refractive index is shown to be a zone depleted in enstatite relative to adjacent zones towards both the core and the

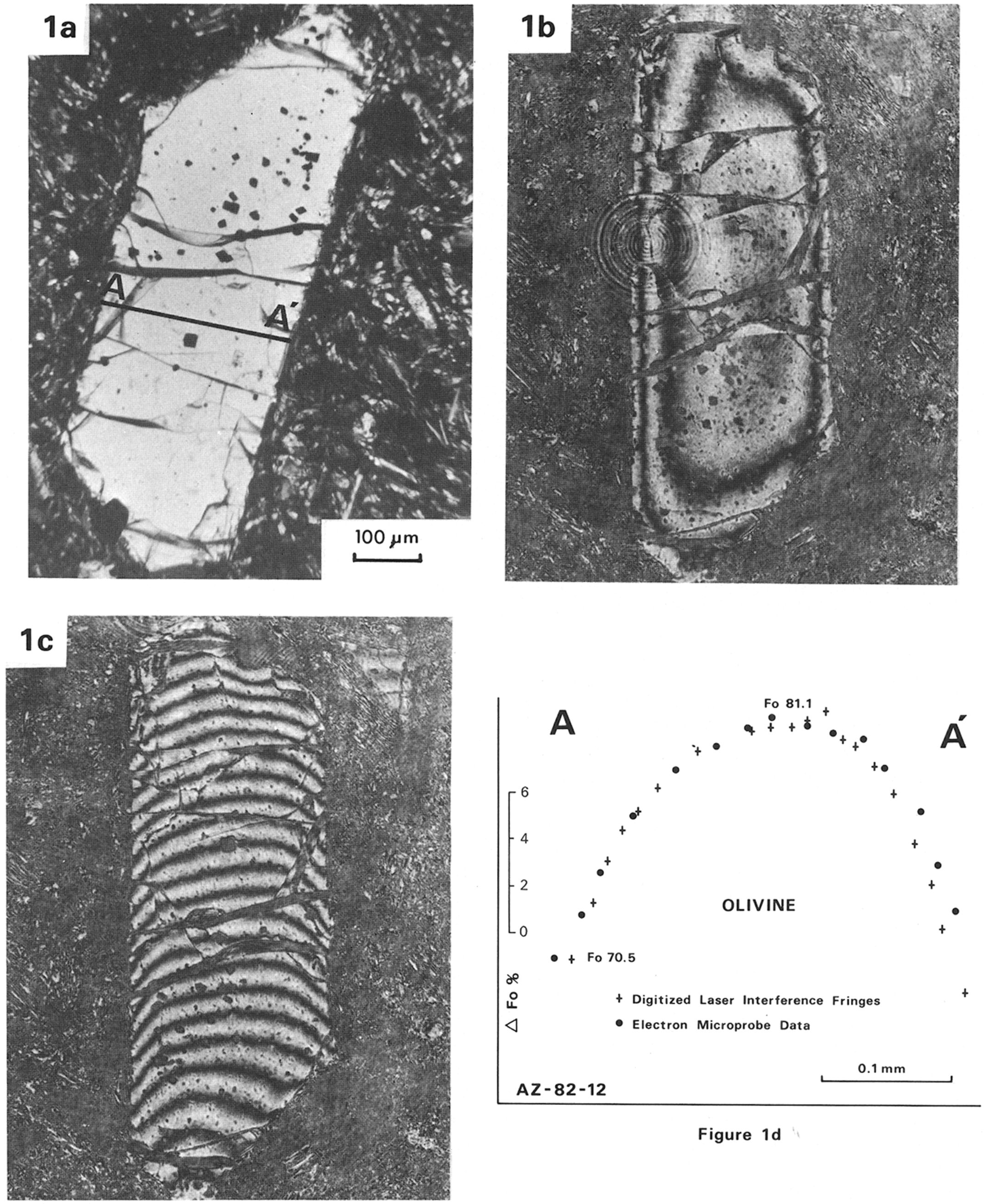

FIG. 1. Olivine phenocryst in Quaternary intra-canyon olivine basalt from Arizona: (*a*) crossed-nicols transmitted light; (*b*) wide-fringe interferogram; (*c*) narrow-fringe interferogram; (*d*) compositional profiles (line A–A′ in fig. 1*a*) of the olivine phenocryst determined by electron microprobe analyses and digitized laser interferometry. The indicated compositions (i.e. $Fo_{81.1}$ and $Fo_{70.5}$) are the maximum and minimum values determined by electron microprobe analysis.

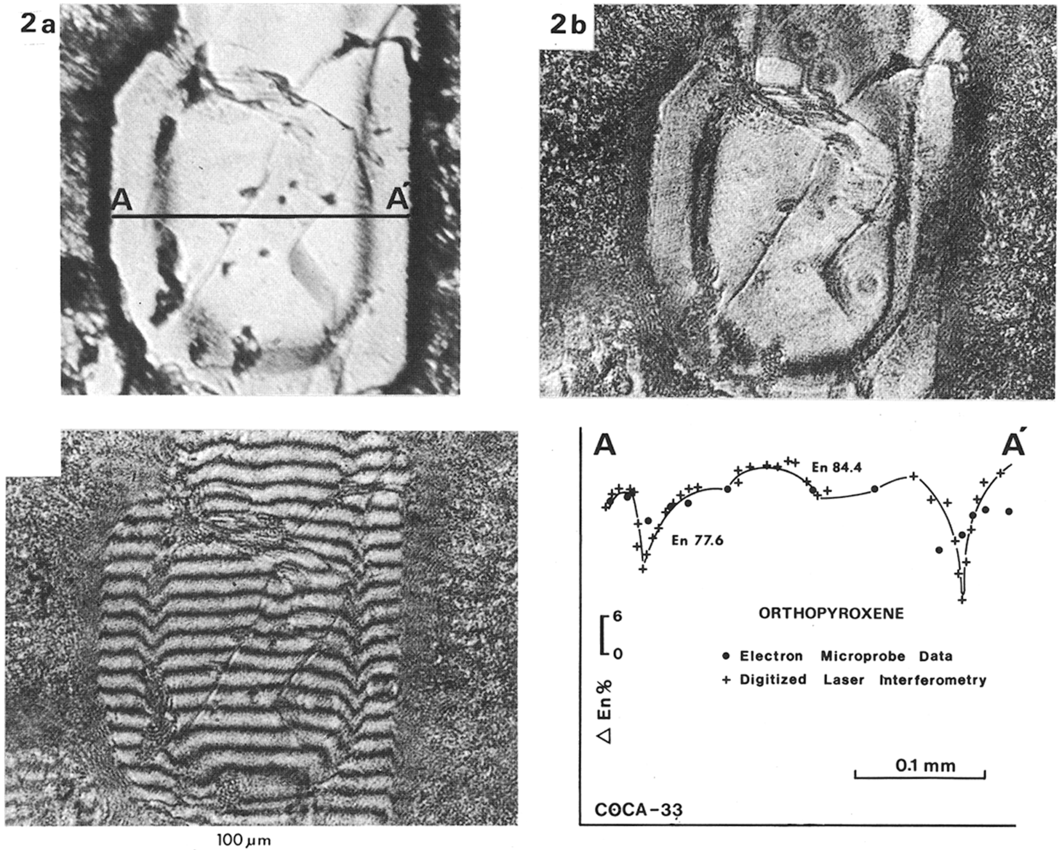

Figure 2d

FIG. 2. Orthopyroxene phenocryst in shoshonitic lava of the Permian Mitu Group of SE Peru: (*a*) plane-polarized transmitted light; (*b*) wide-fringe interferogram; (*c*) narrow-fringe interferogram; (*d*) compositional profiles (line A–A' in fig. 2*a*) of the orthopyroxene phenocryst determined by electron microprobe analyses and digitized laser interferometry. The indicated compositions (i.e. $En_{84.4}$ and $En_{77.6}$) are the maximum and minimum values determined by electron microprobe analysis.

margins of the grain. This zone, shown to be continuous by interferometry, is only some 10 μm in width and would probably be missed in routine microanalysis of phenocryst rims and cores. Interferometric imaging readily confirms that comparable refractive index zoning is typical of the orthopyroxene phenocrysts in this rock.

Discussion. We suggest that interferometry may be a useful adjunct to petrographic studies of volcanic and other rocks, arising from its ability to define cryptic zoning in minerals at the scale of optical resolution of the light microscope. In the present instance, the simple zoning of the olivine in the intra-canyon basalt contrasts strongly with the complex pattern of the Peruvian orthopyroxene. The latter 'double-rim zoning' is, we consider, a feature of considerable petrogenetic significance. Three mechanisms could be invoked to explain the 'double rim': namely magma mixing; fluctuations in f_{O_2} and f_{H_2O}; and a pressure-dependent variation in K_d for the opx/liquid equilibrium. The first two cases are considered unlikely in the present case, for reasons which have been presented elsewhere (Kontak *et al.*, 1984). We therefore tentatively propose that the K_d for opx/liquid may vary with pressure, and, further, that the outward transition from the relatively Fe-rich annular zone to the contiguous, more Mg-rich zone, records movement of the host magma from a higher to a lower pressure environment.

In this context, it is of interest to note that olivine phenocrysts in absarokites intercalated with the Mitu Group shoshonites also display 'double-rim zoning', albeit less clearly. Several authors (e.g.

Ford *et al.*, 1983; Takahasi and Kushiro, 1983) have recently argued on experimental grounds that the olivine K_d is pressure-dependent. Whereas there are no comparable experimental data for the opx/liquid K_d relationship, available data (for example, Frey and Prinz, 1978) suggest that the K_d relationships vary sympathetically in these two mineral groups. Therefore, both olivine and orthopyroxene would be expected to become more Mg-rich with reduced pressure. We envisage that the orthopyroxene phenocrysts grew Mg-rich cores zoned to relatively Fe-rich rims at depth, were abruptly transported to a much lower pressure (sub-volcanic?) regime, then developed Mg-rich overgrowths which again became zoned to relatively Fe-rich rims. Thus a double-rim is developed in these phenocrysts.

Acknowledgements. Laboratory and field expenses for this work were covered by Natural Sciences and Engineering Research Council of Canada operating and equipment grants to T.H.P. and A.H.C.

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[*Manuscript received 13 February 1984*]

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MINERALOGICAL MAGAZINE, DECEMBER 1984, VOL. 48, PP. 550-2

Kornerupine in a sapphirine-spinel granulite from Labwor Hills, Uganda

NIXON *et al.* (1973) report kornerupine in an ore-rich specimen from the Labwor refoliation zone, a belt of granulite-facies rocks where sapphirine-quartz and sillimanite-orthopyroxene-quartz assemblages are also found. While kornerupine is known from about thirty-five or forty localities world-wide, only at one other locality, Paderu, India, does kornerupine occur where sapphirine-quartz is also reported (Grew, 1982, 1983*a*). This communication reports mineralogical and chemical details on Nixon *et al.*'s (1973) kornerupine-bearing rock and considers the conditions of kornerupine formation in the Labwor refoliation zone.

The kornerupine-bearing rock (sample No. PHN 984) is an eluvial cobble presumed to represent an iron-rich lens in granulites that contain sapphirine, garnet, sillimanite, orthopyroxene, spinel, and cordierite. The cobble consists of a cellular aggregate of green spinel which contains abundant streaks and fine dust of magnetite. In parts of the cobble, interstices between the spinel aggregate are mostly filled with sillimanite in prisms up to nearly 1 mm across and several millimetres long. This sillimanite is pale yellow in hand specimen and in part chatoyant from fine acicular inclusions. In other parts of the cobble the interstices are largely filled with kornerupine in prisms several millimetres across, having a crude parallel orientation. The kornerupine is distinctly pleochroic: γ-pale brown, β-blue. Sillimanite prisms mostly 0.05 to 0.2 mm across occur sparingly in kornerupine. Sapphirine in platelets and irregular grains up to 2 mm across is found throughout the cobble and is best developed along boundaries between spinel and kornerupine grains. Sapphirine is markedly pleochroic in brown and blue colours. Oxides besides spinel are magnetite and an ilmenite-hematite intergrowth, which is dominantly hematite with blebs, lamellae, and margins of ilmenite. Biotite flakes 0.1-0.5 mm