American Mineralogist, Volume 66, pages 1233–1236, 1981

Olivine orientation in the ALHA77005 achondrite

JOHN L. BERKLEY[1] AND KLAUS KEIL

Department of Geology and Institute of Meteoritics
University of New Mexico, Albuquerque, New Mexico 87131

Abstract

ALHA77005, a unique achondrite found in the Allan Hills area, Antarctica, contains cumulus olivine and chromite phenocyrsts poikilitically enclosed by pyroxene and maskelynite. Petrofabric analysis on olivine shows a weak preferred orientation primarily consisting of a *YZ* foliation plane containing a weak [001] lineation. Secondary maxima are attributed to the development of exaggerated {110} forms in some olivine grains. Olivine microstructures suggest an approach to equilibrium grain orientation in response to laminar flow lines in a fluid medium. Orientation effects caused by grain-to-grain contact are probably of minimal importance. ALHA77005 is an example of a cumulate rock solidified in the act of flow and accumulation. Olivine orientations closely mimic patterns in porphyritic, tabular bodies (dikes, sills, flows).

Introduction

ALHA77005 is a unique achondrite recovered from the Allan Hills area of Antarctica (King *et al.*, 1980; McSween *et al.*, 1979). It is composed of olivine, low-Ca and high-Ca pyroxene, maskelynite, and opaques (chromite, ilmenite, and trace amounts of nickel–iron and troilite). Olivine and chromite occur as phenocrysts poikilitically enclosed by pyroxene. The purpose of this study is to determine the collective three-dimensional orientation of olivine grains in ALHA77005 and to evaluate the implications of this microstructure on its origin. Our results show that ALHA77005 was formed by flow and cumulus processes that produced a weak foliation and lineation of mineral elongation. This rock may represent an early differentiate related by a common magmatic parent to the shergottites (Stolper *et al.*, 1979), two-pyroxene achondrites that are also believed to be of cumulate origin (Stolper and McSween, 1979).

General petrography

Olivine in ALHA77005 is anhedral to subhedral and has a pale brown color. Many grains display rounded habits (Fig. 1a), possibly caused by reaction with intercumulus liquid or from subsolidus reaction with poikilitic pyroxenes. Olivine grain size varies from less than 0.1 mm to over 2.0 mm in long dimension. The average grain diameter is about 1.0 mm which lies in the lower range of cumulus olivine crystals in terrestrial layered complexes (1–4 mm; Jackson, 1971). Most grains display varying degrees of shock deformation mainly manifested as blotchy, undulatory extinction patterns. This unquestionably introduces some error in universal stage measurements of grain orientations, but we consider this error to be negligible for our purposes.

Fabric analysis

Methods

The indicatrix axes of olivine grains in three orthogonally cut thin sections were measured on a four-axis universal stage, and the results plotted on equal area stereonet diagrams. The data points in two of these diagrams were rotated into the plane of the first to improve counting statistics (Fig. 2). The three thin sections were cut from three perpendicular sides of an approximately 1 cm^3 cube of the meteorite, and 100 individual olivine grains were measured from each section.

Results

Olivine grains in ALHA77005 display orthogonal maxima for *X*, *Y*, and *Z* with *X* normal to the

[1] Current address: Lunar and Planetary Laboratory, University of Arizona, Tucson, Arizona 85721.

0003–004X/81/1112–1233$02.00

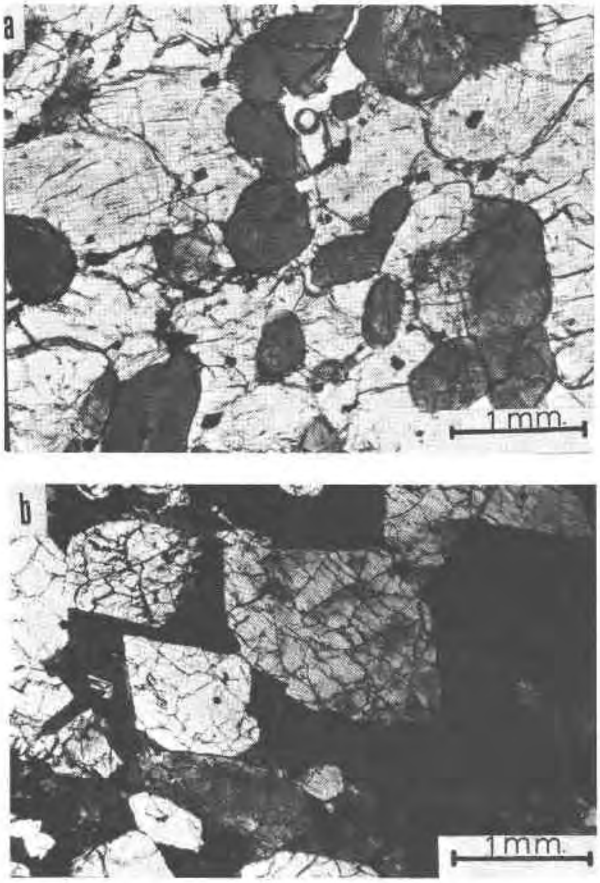

Fig. 1. Transmitted light photomicrographs: (a) rounded olivine grains (dark) poikilitically enclosed by pyroxene. Small cubic grains (black) are cumulus chromite. Most olivine grains are "free-floating" individuals, not in contact with other grains. Plane polarized light (b) Olivine grains (enclosed by large, nearly extinct poikilitic pyroxene grain which is dark), some of which display pronounced development of {110}, especially in rhomb-shaped grains near the center. Dark grain (lower half, just left of center) displays the most common habit with flattened {010}. Foliation plane (S) trends NW and lineation of mineral elongation (determined from Fig. 2 but not visible here) is approximately normal to the plane of the photograph. Crossed polarizers.

foliation (Fig. 2). Y and Z lie in a girdle that corresponds to the visible foliation plane(s). This YZ foliation girdle is strongly shaped as determined by the flattened {010} form which is well-developed in many subhedral olivine grains (Fig. 1b). The Y maximum (vertical in Fig. 2) probably constitutes an elongation lineation of prismatic olivine grains.

In addition to the principal concentration maxima mentioned above, a set of minor maxima also occurs. Although many grains display pronounced {010} flattening, a significant number of grains show pronounced development of {110} pinacoids with {010} greatly diminished in size and area. The latter grains display pseudo-rhombic cross sections when viewed along [001] zone axes (Figs. 1b and 3). These crystals are effectively flattened parallel to (100) (a face not observed in most cases) and lie with large crystal faces (110) and ($1\bar{1}0$) symmetric to the foliation plane (S, Fig. 3). Because Z bisects the low interfacial angle between (110) and ($1\bar{1}0$), a minor Z maximum occurs normal to S and, accordingly, a minor X maximum occurs in or near S (Figs. 2.3). These maxima occur approximately 90° from the strongest X and Z maxima, and well-developed XZ girdles show that intermediate positions are easily obtainable (Figs. 2,3). The large variety of olivine crystal habits in ALHA77005 helps to explain why concentration maxima do not exceed 8%, a characteristically weak pattern (Fig. 2).

Interpretation of olivine microstructure

Olivine crystals settling in a magma under laminar flow should become aligned with broad crystal faces parallel to the boundary surface and with pronounced zone axes parallel to the flow direction (Den Tex, 1969). The critical role of current deposition as opposed to simple crystal settling in producing mineral layering in cumulates has been stressed recently by Irvine (1978) and is emphasized in the present case. In ALHA77005 olivine grains commonly appear to occur as free-floating individuals, although many grains maintain contact with one or more adjacent crystals (Fig. 1). Thus, instead of having settled on the stagnant floor of a cumulate magma reservoir, these olivine grains appear "frozen" in the act of flowage with poikilitic pyroxene grains and interstitial maskelynite representing the former intercumulus material. Equilibrium positioning relative to flow lines, therefore, was more important than rest positions on an accumulation surface (or other grain-to-grain contact effects) in determining the ultimate orientations of olivine grains.

In terrestrial examples the preservation of olivine flow orientations in mafic intrusions is not universal but is dependent on particular environmental conditions during igneous crystallization. For instance, Huang and Merritt (1952) described a single troctolite body in which preferred orientations are well preserved in some localities and totally lacking in others. The principal requirement for development and maintenance of flow patterns is high viscosity during intrusion (Shaw, 1969; Jackson, 1971). Rela-

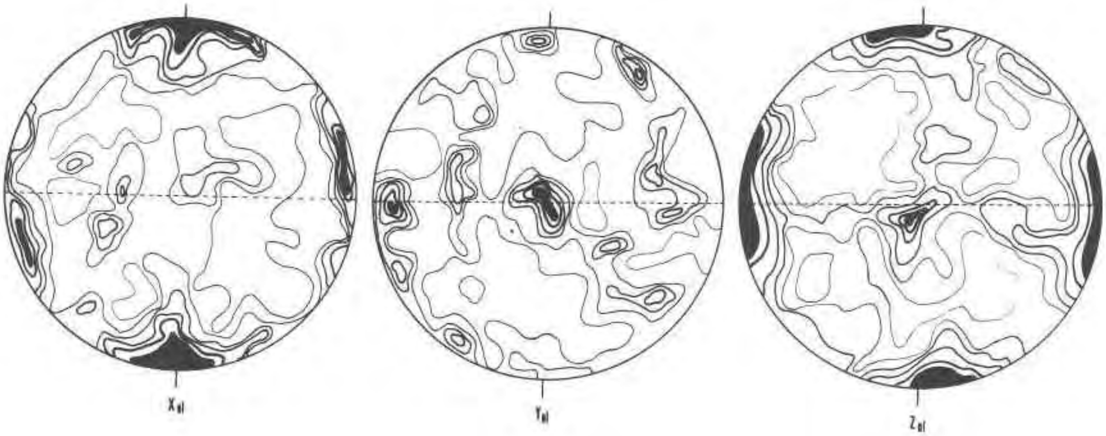

Fig. 2. Stereograms of orientations of olivine indicatrices: 300 points total. The horizontal line represents the approximate trace of the foliation. The lineation of elongate olivine grains is approximately vertical (normal to the page) and lies in the foliation. Contour lines represent 1,2,3,4,5, and 6% in 1% of the area for all diagrams. Black areas represent > 6% in 1% of the area.

tively quick cooling is probably the most effective process for causing increased viscosity. Other factors that would contribute to the preservation of olivine flow patterns within a dike (or other tabular body) are: narrow width, steady rate of intrusion, and rigid confining country rocks to prevent dilation by loss of hydrostatic pressure (Brothers, 1959). Most of these parameters cannot be applied to massive, layered intrusives which may account for the rarity of mineral lineations in terrestrial cumulate bodies (Jackson, 1971).

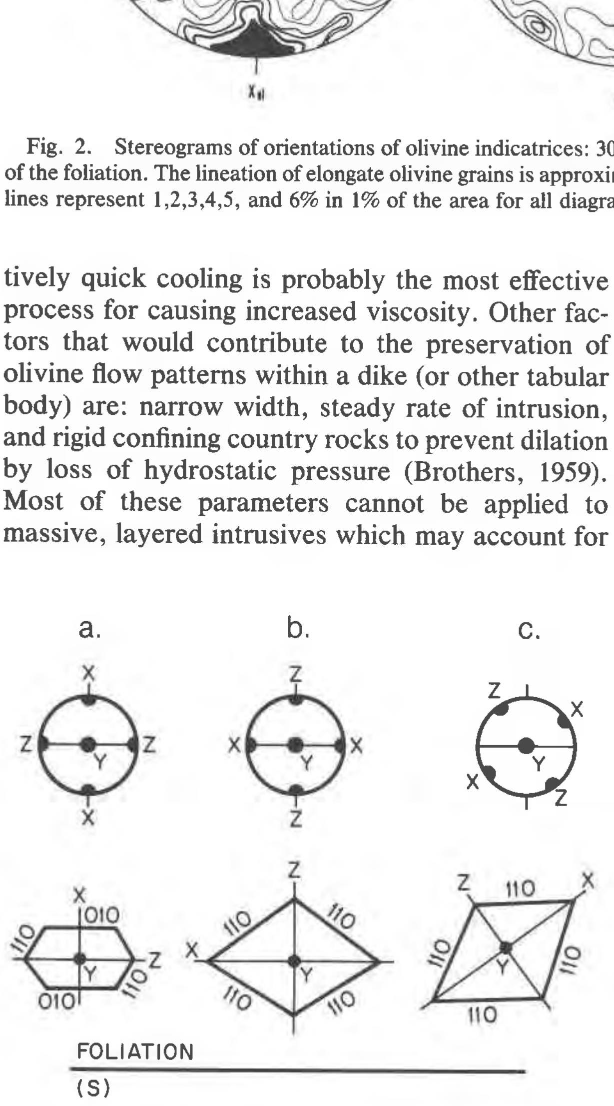

Fig. 3. Schematic diagrams showing the preferred orientation of common olivine habits in ALHA77005 relative to foliation (S) and the resultant orientations of the indicatrix on stereograms. (a) flattened {010} giving *X* concentration normal to S. This pattern dominates in Fig. 2. (b) exaggerated {110} development producing secondary maxima in Fig. 2 (*Z* normal S). (c) intermediate orientation for crystal habit similar to b. Other positions are possible for this habit as well as for that shown in a. Orientations a and b are preferred over c.

The packing density of tabular olivine in terrestrial cumulates averages approximately 80% (Jackson, 1971) which implies a high proportion of cumulus relative to intercumulus crystals. Although not confirmed by quantitative modal analysis, the proportion of intercumulus to cumulus material in ALHA77005 is sufficiently high (Fig. 1a) to suggest less-than-optimum packing of cumulus crystals in the crystal–liquid mush. If rapid cooling were responsible for preserving high intercumulus to cumulus ratios as well as preferred olivine orientations, it is difficult to account for the necessary rapid loss of heat in a massive magma reservoir except near the margins of this body. Heat loss to country rocks should be more efficient in a thin dike or sill (Jaeger, 1968) and this environment (including surface lava flows) is more likely to facilitate the preservation of the textural features displayed in ALHA77005. In fact, we note many essential similarities between olivine fabrics in this meteorite (Fig. 2). and those measured in basaltic dikes and flows studied by Brothers (1959). However, we cannot unequivocally rule out an origin by accumulation in a massive, convecting intrusive body. For example, a plausible scenario might include an early accumulate stage followed by extrusion of crystal–liquid mush along narrow auxiliary conduits.

Summary: cumulate history

ALHA77005 represents an ultramafic cumulate rock. Olivine, the principal cumulus phase (in addition to chromite), displays an orientation pattern that is characteristic of tabular minerals in a fluid laminar flow regime. This rock apparently solidified while in the act of magmatic flow, thus preserving weak lineation of mineral elongation parallel to the flow direction and an associated foliation caused by the alignment of broad crystal faces relative to flow lines. Orientation effects attributable to interaction with adjacent mineral grains are minimal. Other than shock-related strain features, ALHA77005 displays no evidence of tectonic shear that might otherwise influence olivine fabrics. We conclude that textural features in this meteorite resulted from intrusion of phenocryst-bearing mafic magma in a thin tabular body, although we cannot conclusively rule out an origin in a massive intrusive body.

Acknowledgments

We thank Karen Denomy and Gil McLaughlin for technical assistance. Reviews by Drs. Edward Stolper, John Wood, and Cornelis Klein helped to improve the final manuscript. The Antarctic Meteorite Working Group (National Science Foundation, Division of Polar Programs) kindly provided samples of ALHA77005. The project was supported in part by NASA grant NGL 32-044-064 (Klaus Keil, principal investigator).

References

Brothers, R.N. (1959) Flow orientation of olivine. American Journal of Science, 257, 574–584.

Den Tex, E. (1969) Origin of ultramafic rocks, their tectonic setting and history: A contribution to the discussion of the paper "the origin of ultramafic and ultrabasic rocks" by P.J. Wyllie. Tectonophysics, 7, 457–488.

Huang, W.T., and Merritt, C.A. (1952) Preferred orientation of olivine crystals in troctolite of the Wichita Mountains, Oklahoma. American Mineralogist, 37, 865–868.

Irvine, T.N. (1978) Density current structure and magmatic sedimentation. Carnegie Institute of Washington, Yearbook 77, 717-725.

Jackson, E.D. (1971) The origin of ultramafic rocks by cumulus processes. Fortschritte der Mineralogie, 48, 128–174.

Jaeger, J.C. (1968) Cooling and solidification of igneous rocks. In H.H. Hess and A. Poldervaart, Eds., Basalts, 2, p. 503–537. John Wiley and Sons, New York.

King, T.V.V., Score, R., Gabel E.M. and Mason, B. (1980) Meteorite descriptions. In U.B. Marvin and B. Mason, Eds., Catalog of Antarctic Meteorites, 1977-1978, p. 12–44, Smithsonian Institution, Washington.

McSween, H.Y., Jr., Taylor, L.A. and Stolper, E.M. (1979) Allan Hills 77005: A new meteorite type found in Antarctica. Science, 204, 1201–1203.

Shaw, H.R. (1969) Rheology of basalt in the melting range. Journal of Petrology, 10, 510–535.

Stolper, E., McSween, H.Y. and Hays, J.F. (1979) A petrogenetic model of the relationships among achondritic meteorites. Geochimica et Cosmochimica Acta, 43, 589–602.

Stolper, E., and McSween, H.Y. (1979) Petrology and origin of the shergottite meteorites. Geochimica et Cosmochimica Acta, 43, 1475–1498.

Manuscript received, March 16, 1981;
accepted for publication, June 15, 1981.