# Hourglass Chondrules

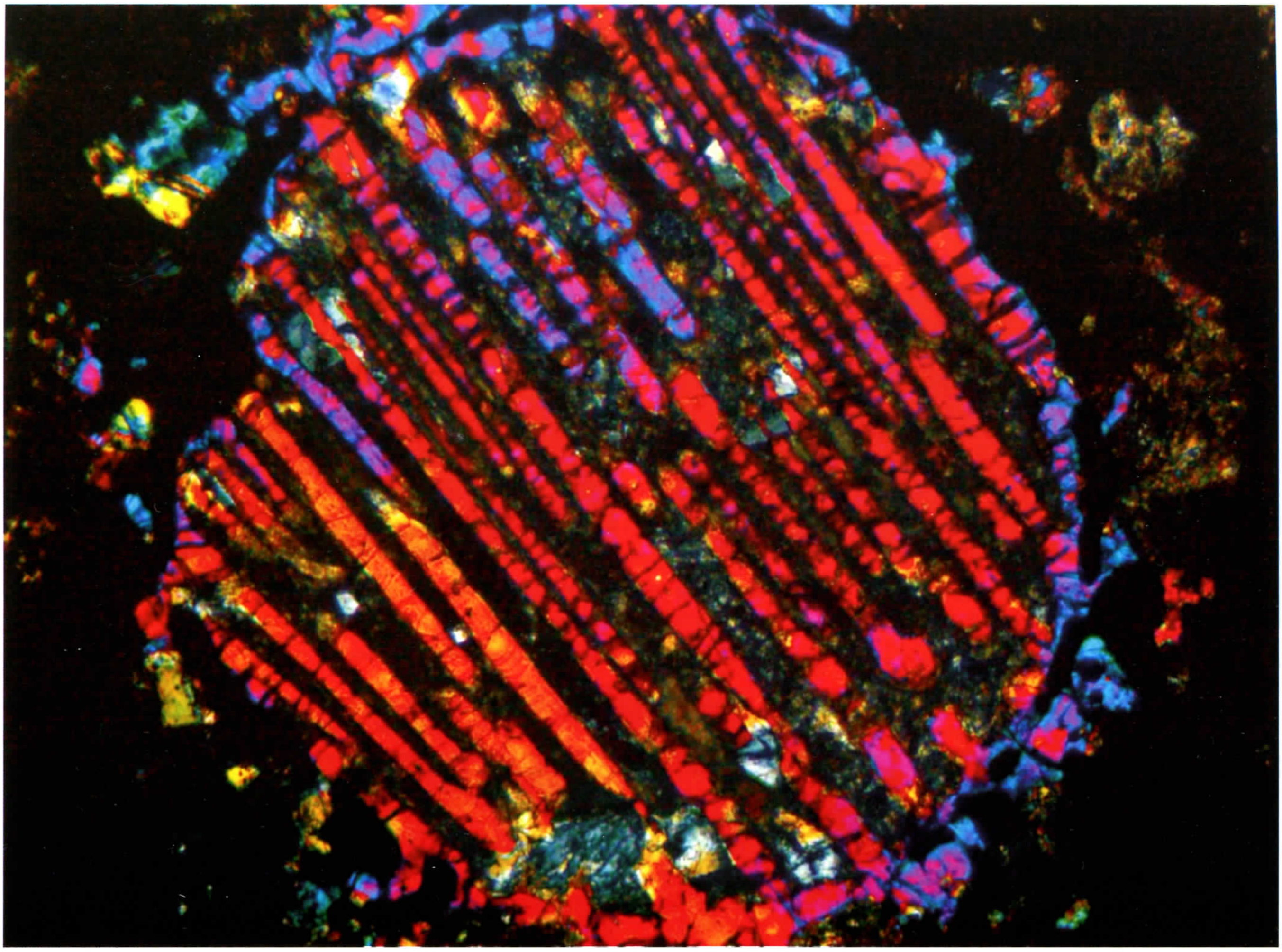


*Figure 1. A barred olivine chondrule in the Allende CV3 meteorite. Polarizing microscope, crossed polars, field of view 1.1 mm wide.*

*by Roger Warin, Frédéric Hatert and John Kashuba*

Barred olivine chondrules constitute one of the most intriguing petrographic features observed in meteorites. There is one type that we occasionally see that deserves closer study: hourglass chondrules. For the record, chondrules lend their name to chondrites, the most plentiful type of meteorite currently falling to earth. Chondrules are solid bits of minerals that retain the spherical shape they acquired when they were molten droplets. The source of their raw material and the heating mechanisms involved are still debated. We know that their


*Figure 2. We suggest that hourglass chondrules are spheres with four diagonally associated sections of olivine plates and that the relationship of these sections is that of crystallographic twins. Imagine an interpenetration twin in spherical form*

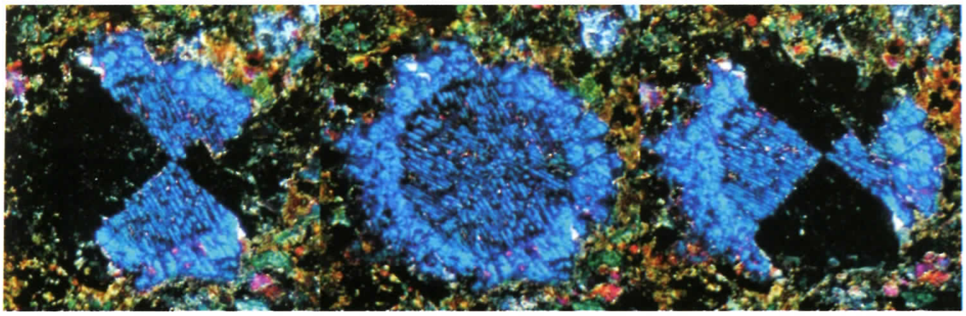


*Figure 3. Sequence showing progressive optical extinction and illumination in an hourglass chondrule from the DaG 412 CK5 meteorite. Polarizing microscope, rotating crossed polars, chondrule diameter is 1.1 mm.*

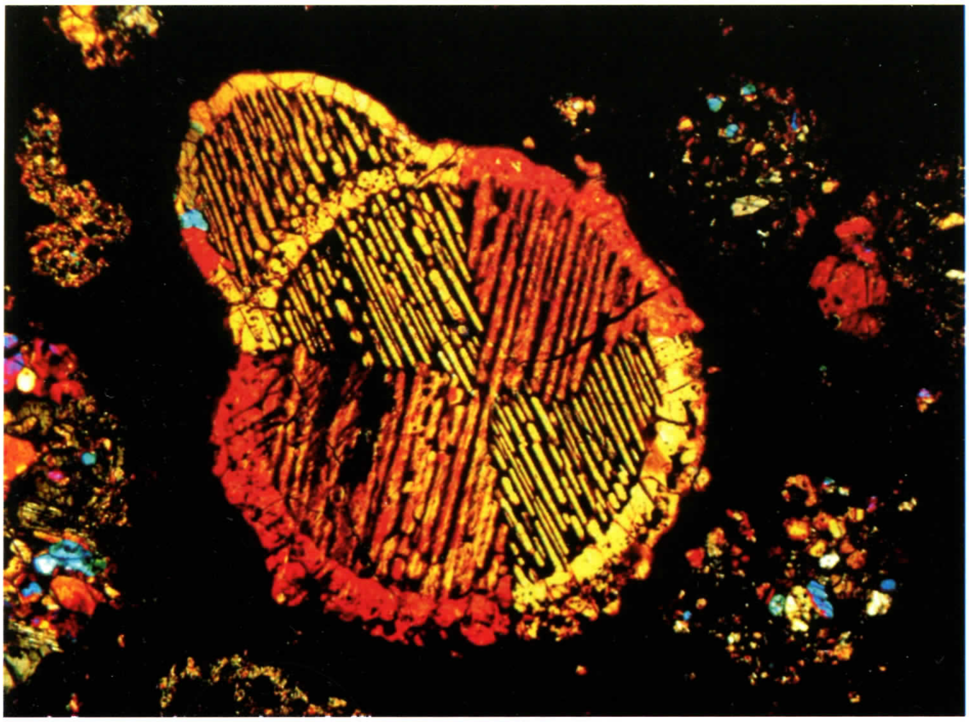
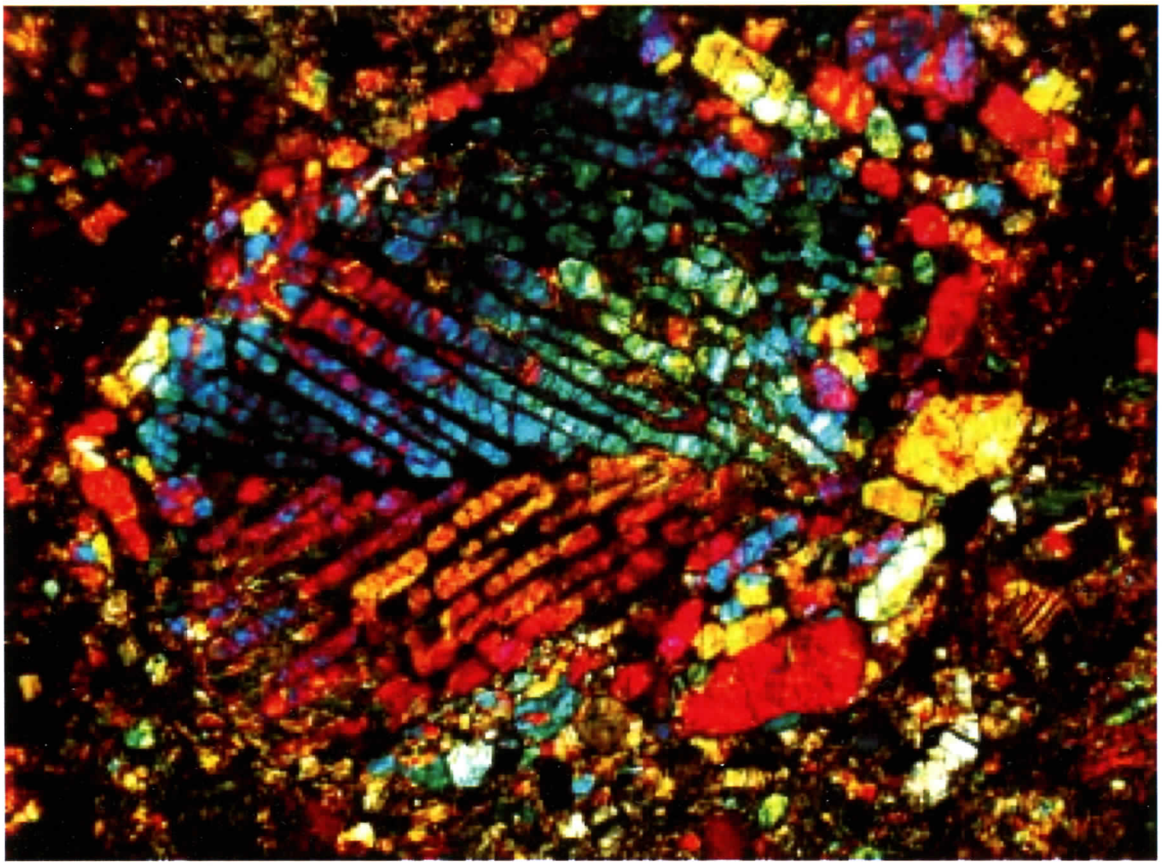


*Figure 4. Hourglass chondrule from the Allende CV3 meteorite. Polarizing microscope, crossed polars, field of view 4.8 mm wide.*

*Figure 5. (below) Chondrule characterized by a single twin in the NWA 4436 (L4) meteorite. Polarizing microscope, crossed polars, field of view 2.4 mm wide.*



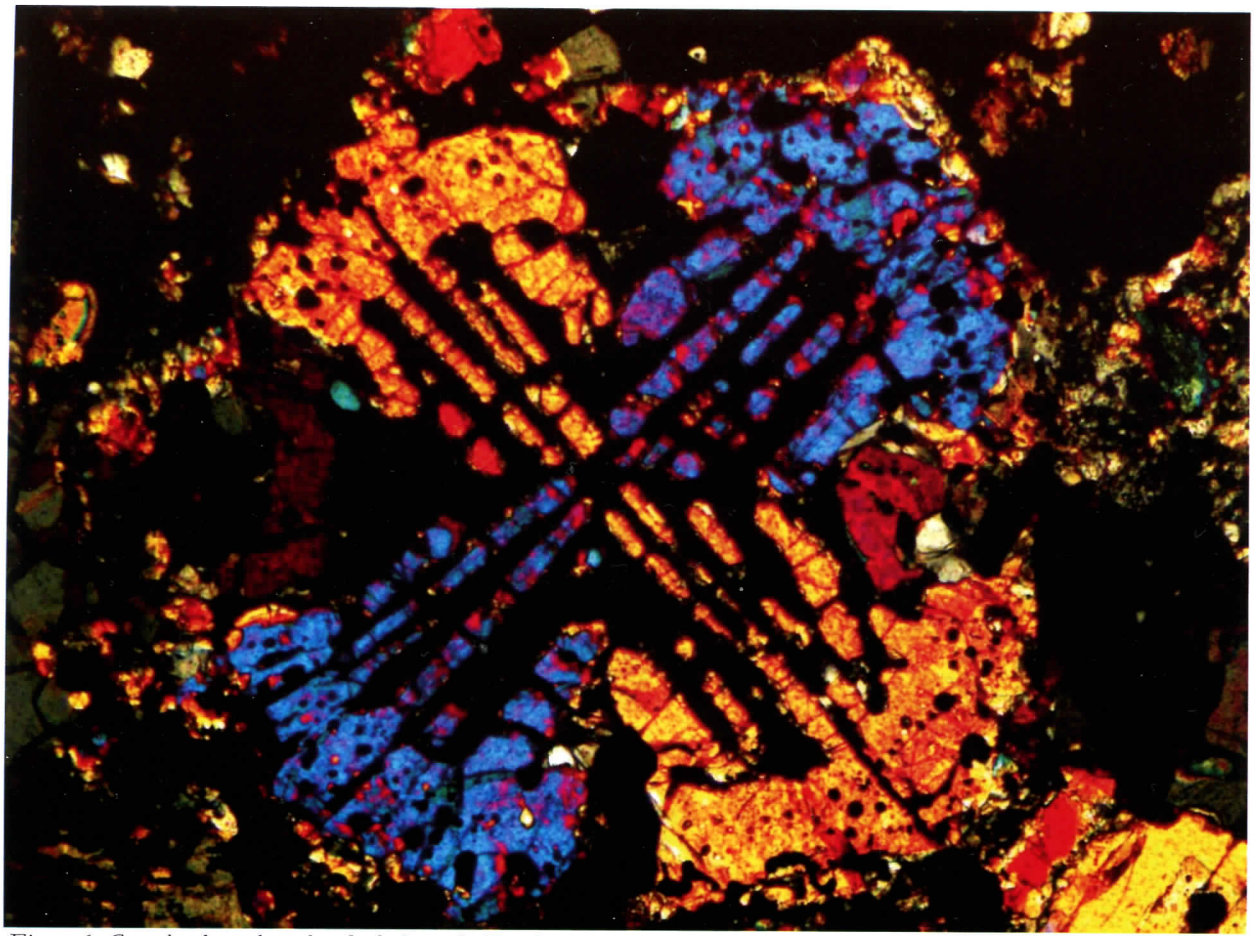
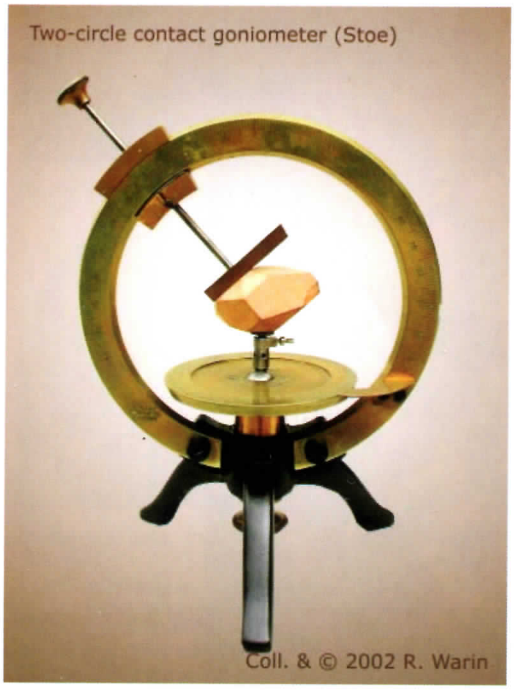


*Figure 6. Complex hourglass chondrule from the Twodot (H6) meteorite. Polarizing microscope, crossed polars, field of view 1.2 mm wide.*




*A two circle brass goniometer, Stoe model, with a wood model crystal of datolite.*

# Goniometers

A goniometer is an instrument used to measure angles between mineral crystal faces. It was an effective technique for identifying minerals before the advent of X-ray spectrometers.

Essentially there are two types of goniometers, those that contacted the face of crystals and those that use reflected light. As the technology of goniometers advanced from 1815 through 1920 they became more precise while they became more difficult to use.

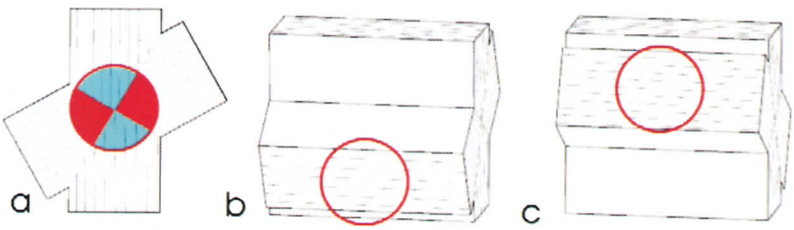



*Figure 7. Drawing showing a (011) twin between two olivine crystals. The lines on the crystal faces represent the trace of the (010) olivine lamellae observed in chondrules and the red circle represents the field delimited by a chondrule. A twin observed perpendicular to the common a axis shows the typical morphology of an hourglass chondrule (a), whereas the other orientations approximately along the b (b) or the c (c) axes only show a single set of lamellae.*

| Meteorite | Measured angles (°) | Average values (°) | Calculated twin angle (°) | Twin law |
|---|---|---|---|---|
| **Allende** | 14.5 | | | |
| | 15.7 | 15 ± 1* | | |
| | 68.4 | | | |
| | 71.0 | 70 ± 1 | 73.7 | (012) ? |
| | 36.6 | | | |
| | 35.0 | 36 ± 1* | | |
| | 58.0 | | | |
| | 61.1 | 60 ± 2 | 59.6 | (011) |
| **DaG-412** | 75.8 | | | |
| | 73.5 | | | |
| | 72.2 | | | |
| | 75.4 | 74 ± 1 | 73.7 | (012) |
| | 15.2 | | | |
| | 17.8 | | | |
| | 14.3 | | | |
| | 17.0 | 16 ± 1* | | |
| **NWA-4436 (a)** | 27.4 | | | |
| | 34.7 | | | |
| | 30.4 | 31 ± 3* | | |
| | 64.1 | | | |
| | 55.2 | | | |
| | 63.6 | 61 ± 4 | 59.6 | (011) |
| **NWA-4436 (b)** | 37.0 | | | |
| | 45.3 | 41 ± 4 | 40.5 | (021) |
| **Twodot** | 50.4 | | | |
| | 50.5 | | | |
| | 54.0 | | | |
| | 44.2 | 50 ± 4* | | |
| | 42.8 | | | |
| | 40.9 | | | |
| | 42.7 | | | |
| | 43.4 | 42 ± 1 | 40.5 | (021) |

* Complementary angle.

*Table 1. Goniometric measurements on olivine lamellae from hourglass chondrules and resulting twin laws.*

final form depends on their composition, the extent of their melting and their rate of cooling. Barred olivine chondrules are olivine rich; they were fully melted and cooled moderately fast.

Such a moderately fast cooling causes rapid crystallization that can produce skeletal forms. Terrestrial skeletal examples include dendritic water crystals (snowflakes and hoar frost) and hopper shaped mineral crystals where conditions favored molecular deposition at crystal edges over deposition on crystal faces. In meteorites, the d'Orbigny and Sahara 99555 angrites contain hollow blades of anorthite.

The normal barred olivine chondrule is a single skeletal crystal formed of parallel blades of olivine separated by a feldspathic glass (Fig. 1). The blades tie into an enclosing shell, all of which is in crystallographic continuity. We stress that the olivine is in parallel plates or, if you like, blades. The term "barred" refers only to the two dimensional appearance of the crystal on the cut surface of a meteorite slice or thin section, where it has the appearance of parallel prison bars.

Over the years we have found several barred olivine chondrules with a striking symmetry between two sets of plates. In thin section each set occupies two diagonally opposite quadrants of a circle. They appear as two hourglasses, or like a pizza cut into four slices, where two slices of pepperoni touch only their points at the center and two slices of anchovy, likewise, touch each other only at the center.

These pizza slices or hourglass shapes are, like the "bars", the two dimensional manifestation of cross sectioned solids. We suggest that these solids are spherical chondrules with four diagonally associated sections of plates (Fig. 2). Various cuts through such a sphere will generate many of the otherwise oddly configured fields of bars seen in sectioned chondrules. Returning to the pizza analogy, we noticed that, when viewed in cross-polarized light and rotated, each set goes to extinction in turn, now the pepperoni and now the anchovy (Fig. 3). This configuration is so distinct that we wondered if we were seeing crystallographic twins.

In nature, olivine twins are extremely rare, and are observed only on well-faced gem-quality crystals. In order to confirm

## Twinning

There are many ways minerals twin but they are always orderly. Twinning introduces symmetry. This may be reflection across a twin plane, rotation about a twin axis (sometime 60 degrees often 180 degrees) or it may be about a point, a twin center.

Contact twins usually derive from the first of these. The twin plane is a "composition surface" where lattice positions are shared by the crystal on each side of it. Quartz and orthoclase have well known forms in this mirror-like style. Penetration twins derive from twin axes and twin centers. Portions of crystals appear to have passed inside the body of another of the same species. Pyrite and fluorite often do this.

Contact twins that repeat with parallel composition planes are called polysynthetic. If the composition planes are not parallel they are cyclical twins. Twins occur as accidents during growth, during transformation of existing crystal structures by temperature or pressure changes and by mechanical deformation.

Twin "laws" state the plane or axis around which the twinning occurs and hence define the forms that can result. Each is specific to one of the crystal systems. For example, in the triclinic system the albite law, {010}, indicates that twinning can be on a plane perpendicular to the b axis. In meteorite thin sections we see plagioclase where this repeats. The polysynthetic twinning appears as parallel, differently colored zones in individual mineral grains.

the presence of twins in hourglass chondrules, we investigated the optical orientation of olivine lamellae occurring in five chondrules from four different meteorites. These observations, which are given below, allowed us to confirm the presence of olivine twins and to determine the twin laws responsible for these unusual petrographic textures.

## *Petrographic Description*

The samples investigated in this study are from the Allende CV3, DaG 412 CK5, NWA 4436 L4 (two samples, a and b) and Twodot H6 meteorites.

Olivine is orthorhombic, meaning it has three axes of unequal length, all of which are at 90° to each other. It is biaxial and optically negative, except when extremely magnesian. In all samples, we observed that one axis was essentially perpendicular to the plane of the thin section. This might seem extraordinary but it must be remembered that we were looking at a selected population of cut chondrules, chondrule sections with a particular appearance. The student of optical mineralogy will appreciate that this orientation was determined by our viewing the samples under the petrographic microscope with crossed polars and in conoscopic illumination and observing obtuse bisectrix interference figures.

Further, we determined that it is the higher refraction index, $\gamma$, that is approximately perpendicular to the plane of the thin section and that the intermediate index, $\beta$, is parallel to the elongation of olivine lamellae. As a consequence, the a crystallographic axis (corresponding to $\gamma$) is approximately perpendicular to the thin section plane, the c axis (corresponding to $\beta$) is parallel to the elongation of olivine lamellae and the b axis is perpendicular to this elongation. Generally, the olivine lamellae are exactly parallel to the c crystallographic axis, as shown by a right optical extinction, except in the Allende and NWA 4436 (b) chondrules where the extinction angles range between 3.5 and 15.2°.

The investigated chondrules are generally constituted by four optically distinct portions (Figs. 3, 4), except in the NWA 4436 (b) chondrule where only two portions occur (Fig. 5). In the Twodot chondrule, each quadrant is further divided in two optically distinct parts, separated by a small angle varying between 1.5 and 10°. These slightly different optical orientations, however, are not visible without careful goniometric measurements (Fig. 6).

Another interesting feature concerns the interference colors, which are generally different for adjacent quadrants (Figs. 4, 5, 6) due to slightly distinct optical orientations, but can also be identical (Fig. 3) when the a axis is exactly perpendicular to the thin section. This observation clearly shows that the optical orientations, as described above, are approximate. More accurate measurements with the universal stage would be necessary to exactly determine the position of optical axes.

## *Optical Orientation of Olivine Crystals and Determination of Twin Laws*

Four different types of twins are known in olivine. These are characterized by the (100), (011), (012) and (031) twin planes (Dana, 1895; Dodd & Calef, 1971; Tröger, 1979). Whereas the (100) twin would produce parallel sets of lamellae indistinguishable from non-twinned chondrules, the three other types of twins are potential candidates to produce hourglass chondrules. All these twins are of {0kl} type and are consequently best observed in planes approximately perpendicular to the a axis (Fig. 7a). This feature explains why all investigated hourglass chondrules systematically show the same orientation, with a approximately perpendicular to the thin section plane. An orientation perpendicular to b or c would not produce an hourglass chondrule (Figs. 7b, c).

Goniometric measurements performed on the investigated samples have shown the presence of the (011), (012) and (021) twins. The good fit between the angles measured under the microscope and the angles calculated with the SHAPE software (Dowty, 1994) (Table 1), confirm that hourglass chondrules effectively correspond to olivine twins. This result is somewhat different from the measurements performed by Dodd & Calef (1971), who investigated composite olivine chondrules in which several set of plates occur without any particular angular relationship. Such composite chondrules are not due to twinning and the random orientations of olivine plates confirm a rapid crystallization in a low-pressure environment.

The careful optical examination of hourglass chondrules, described in the present paper, has consequently confirmed that this beautiful petrographic texture was effectively produced by olivine twins. It also allowed the identification of the new (021) olivine twin, which was never previously described in the literature.

## *References*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Errata – The careful reader of our Karoondites article might have noticed a contradiction. Here is the offending sentence as it should be corrected: Cryptocrystalline Porphyritic chondrules are the dominant type.


About the Authors

Frédéric Hatert is a Research Fellow of the Fund for Scientific Research, FNRS, at the University of Liège, Belgium, where he received his PhD in Mineralogy in 2002. He was also a Research Fellow of the Alexander von Humboldt Foundation in Germany. He is Vice- Chairman of the Commission on New Minerals, Nomenclature and Classification of the International Mineralogical Association, since 2006.

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