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Evidence of shock-metamorphic effects in the Ergheo meteorite

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SUMMARY. The Ergheo meteorite was inspected both by transmitted and reflected light in order to look for evidence of shock metamorphism by petrological observations. The stone is a well-recrystallized olivine-hypersthene chondrite that shows features of severe fracturing, prominent veining, and diffused cracking. The presence of several shock-transformed components is described in some detail. Ergheo is a meteorite that suffered particularly by shock in full agreement with Heymann's (1967) and Turner's (1968) statements.

IN July 1889 a meteorite was seen to fall in Ergheo, Brava, Somaliland (approx. 1° 10′ N., 44° 10′ E.). The meteorite, a stone of about 20 kg, remained for five years lying in the ground and only in 1898 was it first described (Artini and Melzi, 1898*a*, *b*; with an incomplete analysis by Boeris). Some years later the stone was sawn and the fragments were distributed to museums and collections.

Ergheo has been recently the object of several investigations: Keil (1962) made a planimetric analysis on 30 cm^2; Mason (1963), by X-ray, determined the olivine composition as Fa_{25}; Keil and Fredriksson (1964) established the composition of olivine ($Fa = 23{\cdot}7$) and pyroxene ($Fs = 20{\cdot}5$), in a systematic study of the relations between the coexisting minerals; and Bunch *et al.* (1967), using electron microprobe techniques, analysed the composition of the chromite present in the stone.

Material of the Ergheo meteorite has been extensively used for trace-element determinations: C, 0·11 % (Moore and Lewis, 1965); N, 73 ppm (Moore and Gibson, 1969); Li, 1·21 ppm, B, 0·60 ppm, and Cl, 212 ppm (Quijano-Rico and Wanke, 1968); Ga, 5·9 ppm, Ge, 9·7 ppm, In, 0·31 ppb, Ir, 0·49 ppm (Tandom and Wasson, 1967, 1968); Te, 0·48 ppm, I, 90 ppb, and U, 21 ppb (Goles and Anders, 1962).

The Ergheo meteorite was classified as a crystalline olivine-hypersthene chondrite by Hey (1966) and as an L5-chondrite by Van Schmus and Wood (1967). Heymann (1967) listed Ergheo as a probable black chondrite, judging from its appearance.

Recently Turner (1968), by the ^{39}Ar-^{40}Ar method, demonstrated in Ergheo evidence for thermal outgassing events, which occurred some 530±10 Myr ago. In view of these findings we decided to study the Ergheo stone in some detail for independent petrological evidence of shock effects. Our petrological observations could result in a further demonstration of the role played by optical inspection as correlated to other types of experimental evaluations.

A piece weighing 199 g and nine thin sections, from Artini's collection, preserved in the Museo Civico di Storia Naturale in Milan, Italy, were studied. For comparison and more exhaustive investigation we also used a thin section cut from the British Museum (Natural History) fragment BM 85838. We would like to express our appreciation to the Directors of the Museums for the opportunity to examine and study this interesting material.

Petrological texture

General considerations. Various situations arise in which meteorites appear to be altered both by temperature and pressure: actually, according to present ideas, metamorphism in chondrites is primarily connected with phenomena usually known as 'recrystallization' processes. But a detailed investigation of the petrological texture of the ordinary chondrites may reveal fracturing, veining, and some types of microdeformations (cracking), that may be as well ascribed to shock-induced alterations. We have then to consider several connected features, subjects of speculations about the preterrestrial history of the meteorites.

Let us therefore assume the Ergheo chondrite to be an heterogeneous body, its components, the lithic portion and the metallic phases, exhibiting 'brittle' or 'ductile' response to stress. Ergheo has an average composition of 92·19 % silicates, 1·56 nickel-iron, 5·87 troilite, and 0·38 chromite as determined by Keil (1962). Its petrological texture is fundamentally fine-grained and the wavy extinction is evident and generalized. Chondrules are rarely well-discernible (fig. 1), they have vague distorted contours, which often blend gradually into the surrounding groundmass. In some regions it is, however, possible to note close-packed chondrules having polyhedral shapes. Several authors (see, e.g. Baldanza and Pialli, 1968) have emphasized that the origin of this structure is undoubtedly dependent on high pressures exerted in certain zones of the meteorite over an ill-defined period of time.

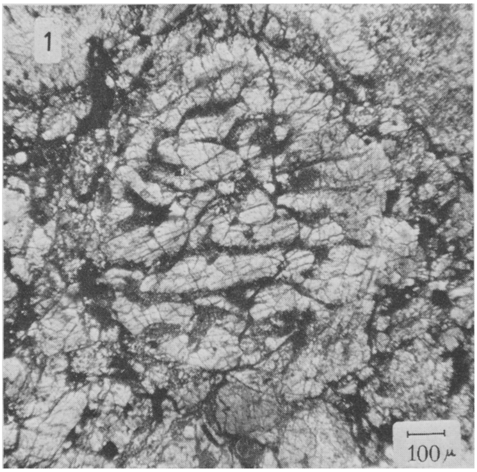
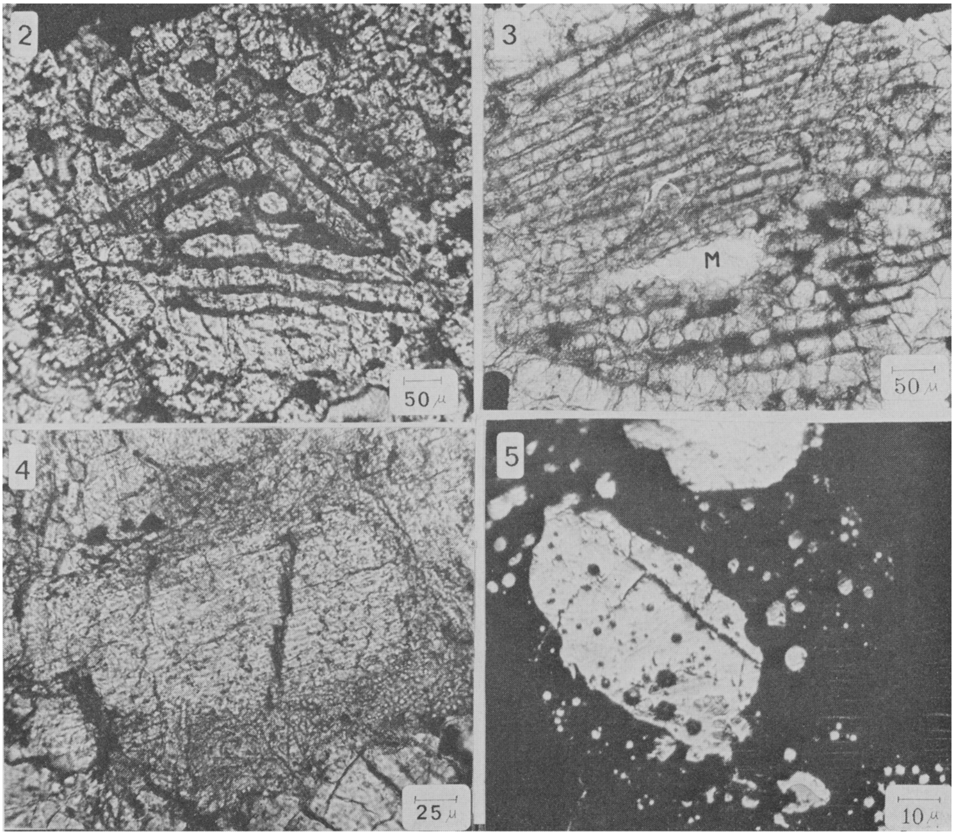


FIG. 1. A porphyritic olivine chondrule in the Ergheo meteorite. The contours are not clearly defined. Chondrule and ground mass are crossed by a zigzag metallic veinlet (ordinary light).

All these considerations are peculiar to a well-recrystallized chondrite, but some further speculations may be made about the single components of the stone, which in several cases present unambiguous features of shock effects.

The shock-transformed components. We present here some observations made during the study of thin and polished sections of the Ergheo meteorite. The lithic portions and the metallic phases of the stone were separately investigated, in order to establish the deformation history of this chondrite.

The important role played by some plagioclasic feldspars and their metamorphic products, minor constituents in the mineralogical composition of some chondrites, has been emphasized by several meteorite petrographers (e.g. Van Schmus and Wood, 1967). Among the lithic components of Ergheo, the presence of maskelynite, the well-known metastable strained mineral, is, in our opinion, significant and it might be chosen as a primary diagnostic criterion for shocking (fig. 2).



Figs. 2–5: Fig. 2. Maskelynite and olivine bars as observed by crossed nicols in a chondrule with vague distorted contours. Fig. 3. A maskelynite grain (M) in a barred olivine chondrule (ordinary light). Fig. 4. Heavily deformed olivine crystal: a mylonitization ring and severe cracking are evident (ordinary light). Fig. 5. Grains and globules of opaque components (reflected light).

This component is quite often interstitial, colourless, isotropic or weakly birefringent, with very low relief (fig. 3). Wood (1962) pointed out that there is at least a strong possibility that the presence of such a mineral could be attributed to a rapid secondary heating, or impulsive pressure and shearing stress. More recently Bunch *et al.* (1967)

stated that the formation of maskelynite is probably due to shocks from low to moderate in intensity. Barth (1969), following Milton and De Carli (1963), emphasized that the plagioclasic feldspar components are transformed into a diaplectic glass, maskelynite, in a span of time from several microseconds to seconds, by shocks giving rise to transient peak pressures in the range of 250–500 kb, with peak temperatures around 600 °C. As a consequence we may argue that the presence of maskelynite in Ergheo may be attributed to shock. Our speculations are in full agreement with Van Schmus and Ribbe's (1968) results: they state that there is a close correlation between observed maskelynite abundances and K-Ar ages of chondrites, and with Heymann's (1967) conclusions that L-group chondrites were involved in a cosmic collision. The ages of chondrites containing maskelynite would be essentially much lower than the $4{\cdot}0$–$4{\cdot}5\times 10^9$ yr ages reported for chondrites containing little or no maskelynite. Actually Ergheo has an average K-Ar age around $1{\cdot}0\times 10^9$ yr (Heymann, 1967) and $1{\cdot}1\times 10^9$ yr (Turner, 1968) and the petrographic appearance of the deformed feldspar crystals could be attributed to subdivisions D or E as proposed by Van Schmus and Ribbe (1968).

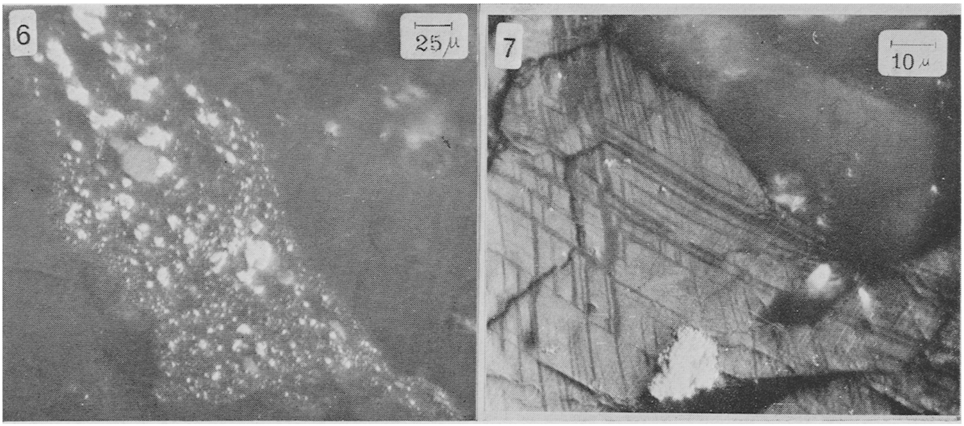
The degree of deformation exhibited by the olivine grains in our Ergheo thin sections (fig. 4) is, following the terminology proposed by Carter *et al.* (1968), MH (moderate-heavy) in some cases, H (heavy) in several others. These findings correspond to shock conditions of 200–300 kb. The mineral presents intense cracking, undulatory extinction, and local mosaicism. All data are then in reasonable agreement and their correlation confirms that shock is the main agent responsible for these features.

Some other indications of shock transformation processes may be found by inspection of the opaque components. Several grains, on rotation of the microscope stage, do not go to extinction uniformly, owing to distortion of the crystal lattice. Globules of nickel-iron and sulphide (fig. 5) occur within well-defined regions between and around the silicate chondrules; similar globules have been produced experimentally by Fredriksson *et al.* (1962) with shock pressures ranging from 150 to 800 kb.

Heymann *et al.* (1966) used the recrystallization of troilite as a qualitative shock indicator. Troilite in Ergheo (fig. 6) is recrystallized into polycrystalline masses; many of the recrystallized mosaics retain their original grain outlines, while others are incorporated, together with chromite and other minerals, into veinlets of melted silicates, in form of droplets, grains, or flakes. Grain sizes of troilite are quite variable, generally smaller in specimens showing more severe deformations.

The presence in Ergheo of a quite rare form of ilmenite may be considered as a significant evidence of transient peak-temperatures and severe strains. Fig. 7 shows that ilmenite observed in magnetite apparently developed a peculiar twinning along three planes, whilst it is well known that in 'primary ilmenite' lamellar twinning is generally restricted to one single direction. At very high temperatures, as pointed out by several authors (e.g. Correns, 1969) magnetite can take up in solid solution considerable amounts of titanium, forming mixed crystals with ulvöspinel, Fe_2TiO_4. Upon cooling and at fairly high partial pressures of oxygen, exsolution occurs: oxidation takes place and ilmenite unmixes in form of lamellae ordered along planes parallel to $\{111\}$ of magnetite.

In other grains, as shown in fig. 8, the ilmenite exsolution process and lamellar twinning developed along only one direction, following {100} of magnetite. In this case it is evident that the unmixing of ilmenite proceeded less regularly than in the above illustrated case, owing to the existence of tension cracks, almost perpendicular to the twin plane, which originated before twinning and exsolution. An arrow shows one of these cracks and its effects on the exsolution process, which is clearly different on the two sides of the fracture. While on one side of the crack ilmenite lamellae are observed in quite regular alternation with magnetite, both having about the same thickness, on the opposite side of the crack only one relatively thick lamella of ilmenite originated.

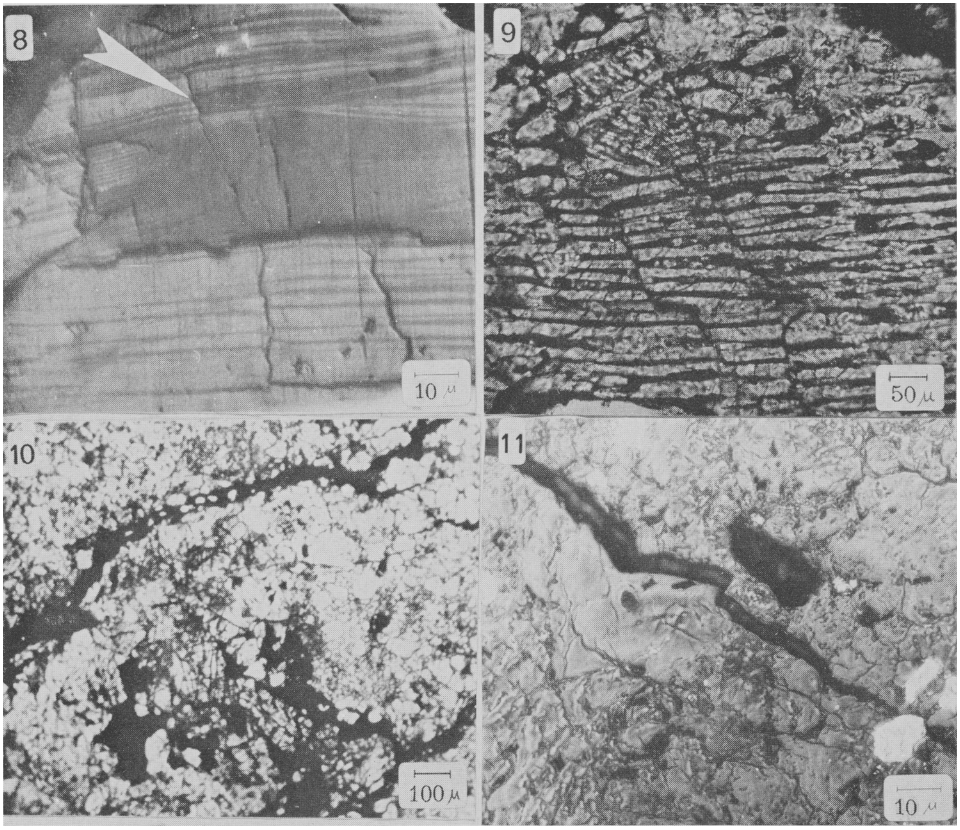


FIGS. 6 and 7: Fig. 6. Mosaic recrystallization of troilite, incorporating fragments of chromite. Fig. 7. Under high magnification: a magnetite grain and exsolution ilmenite lamellae (reflected light; oil immersion).

Fracturing[1] phenomena are evident; several chondrules display fractures cutting both olivine and groundmass (fig. 1), so that, in our opinion and in agreement with Dodd *et al.* (1967) they occurred after solidification of the latter. In some cases fracturing was followed by faults, as in fig. 9, where the olivine and the plagioclase bars of the chondrule display a sort of displaced wedge.

Veining is extensive in Ergheo and quite probably subsequent to the fracturing phenomenon. Practically all the mass of the stone is crossed by veins of various width. The large veins (50–100 μm) are generally sinuous; they are filled by metallic components, which often exhibit inclusions of olivine grains (fig. 10). Others (10–30 μm) have sharp boundaries and consist of dark brown glassy material (fig. 11). Metallic veins of such width cross some chondrules or the matrix or both; their structure is

[1] By '*fracturing*' we mean an extensive phenomenon that involves the whole structure of the stone breaking through many crystals, possibly as a consequence of propagation of cracks.

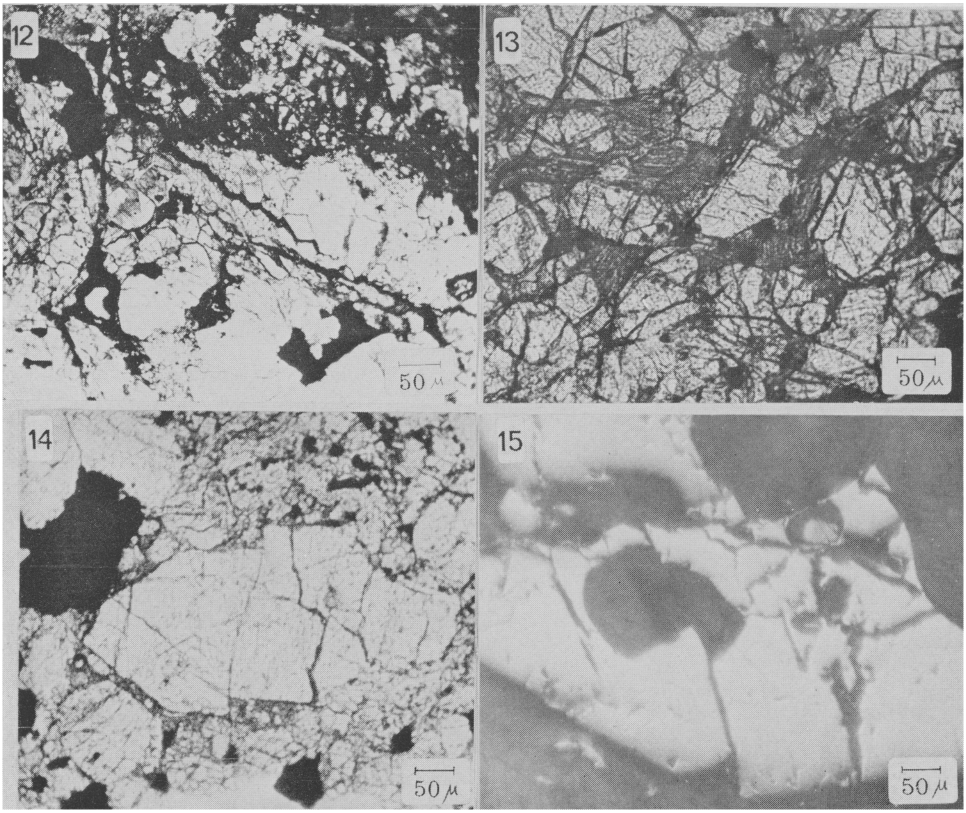


FIGS. 8–11: Fig. 8. Evidence of deformation: lamellar twinning of ilmenite in magnetite. The arrow shows a crack and its effects on the exsolution process (reflected light; oil immersion). Fig. 9. Severe fracturing and faults in a barred olivine chondrule (crossed nicols). Fig. 10. Large veins in the Ergheo meteorite filled with metallic components (ordinary light). Fig. 11. Vein of dark brown glassy material (reflected light).

characteristically zigzag; this feature may be attributed to a certain extent to shock phenomena in a low pressure conditioned environment (fig. 12).

Cracking. The brittle response to stress of olivine and chromite grains, resulting in an extensive cracking, is easily seen at high magnification. Olivine is present, as usual in ordinary chondrites, in form of euhedral and subhedral crystals (fig. 13) and in some cases coalesces into randomly oriented mosaic structures. The presence of extensive cleavage is easily noted in olivine: it may be connected with the passage of a shock wave, causing fracture, and particularly with the tensional phase. We like to consider this cleavage only 'apparent', as it often appears slightly sinuous; such a deformation, however, may be explained by the same mechanical agent. If we observe the crystal in fig. 14 it clearly shows the results of shocking: in this particular case cracking was followed by evident thrusting and faulting, recognizable as secondary phenomena.

Chromite is present in Ergheo as a minor opaque component and it occurs usually as 'coarse chromite', following the definition of Ramdohr (1967). This mineral has an extraordinarily brittle response to stress and it appears always strongly cracked, as shown in fig. 15. Sliding of the material gives in some cases additional evidence of shock.



FIGS. 12–15: Fig. 12. Zigzag metallic veins in the Ergheo meteorite (ordinary light). Fig. 13. Apparent cleavage and cracking in olivine subhedral crystals (ordinary light). Fig. 14. Euhedral crystal of olivine clearly showing the results of shocking. Cracking was followed by thrusting and faulting (ordinary light). Fig. 15. Brittle response to stress in a coarse chromite grain. Cracking and faulting are evident (reflected light).

Conclusions

Every meteorite fallen on the earth may be considered as a 'survivor' from an unknown, much larger parent body, which during its preterrestrial history suffered several metamorphic events. From this point of view it could be tentatively assumed that most meteorites are to be regarded as metamorphic rock. Many authors emphasize (Wood, 1963; Van Schmus and Wood, 1967) that there are different degrees of metamorphism in chondrites; however, we would add that by petrological examination we may tentatively go back to the causes of metamorphism, which impressed their marks both on the silicate and on the metallic phases.

Ergheo, then, belongs to a class of chondrites that suffered particularly by shock, as is testified by inspection of the mass of the stone and of its components. In particular we found the following evidence of shock: extensive recrystallization, severe fracturing, prominent veining, and diffused cracking. Undoubtedly, in addition to the mechanical shock, other types of metamorphism[1] extending their action over long periods of time occured in Ergheo, but these considerations are beyond the field of our present interest.

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[1] Mylonitization domains, strictly connected with thermal metamorphism, may give a good example of such effects.