17. THE FORMATION OF CHONDRULES AND CHONDRITES AND SOME OBSERVATIONS ON CHONDRULES FROM THE TIESCHITZ METEORITE

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Abstract. Analyses of coexisting minerals and interstitial groundmass in a few chondrules of the Tieschitz and Mezö-Madaras chondrites show that these chondrules are the products of several complex and overlapping processes. Comparison of these chondrules with so-called 'equilibrated' chondrules from these and other meteorites makes clear that the chondrules of the so-called 'unequilibrated' chondrites have been formed under special circumstances. Probably they represent a border-facies of the ordinary process of chondrule formation. Formation of 'equilibrated' chondrules from 'unequilibrated' ones through thermal metamorphism is thought to be impossible.

The Tieschitz meteorite shows no sign of metamorphism. In spite of this, several chondrules display some alterations which they clearly sustained after their agglomeration. Some process – probably circulating water or water vapour – led to selective dissolution of the nepheline and feldspar component, mainly near the surface and along cracks in finegrained pyroxene chondrules and glass-bearing chondrules. No redeposition of this material has been observed.

1. Introduction

Detailed investigations of some chondrites and their chondrules which have been performed during recent years, have tended to clear up some of the questions concerning the formation of chondrules and chondrites. It is the purpose of this paper to summarize briefly the knowledge of this subject.

According to [1] the chondrites can be divided into two groups: the so-called 'equilibrated'* and the 'unequilibrated' ones. The former are characterized by a constant Fe/Mg ratio of their olivines and orthopyroxenes, and both of them can be found in all chemical groups, i.e. H, L, and LL [2, 3].

On the other hand the chondrites cover a wide range of structures with all transitions between loosely bound, friable tuffs and consolidated, crystalline, 'recrystallised' chondrites where only by chance some sparse remains of chondrules can be found. These differences in structure led to the early assumption that they had been caused by thermal treatment of different strength and duration [4]. This idea on the 'metamorphism' of chondrites has been taken up again and used to explain the 'equilibration' of chondrites [1]. These efforts led to a 'petrological' classification of chondrites [5]. Because of its simplicity, this classification scheme has gained wide acceptance among non-petrological meteoriticists, only a few criticisms having been made [6]. There is a danger in interpreting non-petrological data by correlating them with the 'metamorphic grades' of Van Schmus and Wood, since a proof that meta-

* This designation has become quite common and will therefore also be used in this paper. Nevertheless it should be pointed out that it is misleading to use this term because the so-called 'equilibrated' chondrites are petrologically far from equilibrium.

Millman (ed.), Meteorite Research.

morphism is responsible for 'equilibration' and 'recrystallization' is still lacking.

It is not the purpose of this paper to treat the above-mentioned theme extensively. What follows is an attempt to summarize briefly recent conceptions on the formation of chondrules and chondrites from the petrological point of view.

2. The Formation of Chondrules

The information on chondrules which is available is still too meager to construct a comprehensive theory. There exist, however, several indications that some special processes have been involved [7–10]. If the theory outlined in this paper is correct then it is also necessary to postulate a homogeneous reservoir – solid, liquid or gas – of pre-chondritic origin from which the chondrules of the 'equilibrated' chondrites could have been derived.

The result of the processes which occurred after the formation of liquid droplets is observable and measurable in meteorites and, in principle, can be recognized. This concerns the solidification and agglomeration of chondrules.

The crystallization of the silicate droplets created by some unknown process is, after the formation, the second important process which characterized the chondrules. These appear to have frozen rapidly and started to crystallize after they have been more or less undercooled. Depending on whether the supercooling is strong or not the phases will start crystallizing within the field of crystal plus liquid stability or outside. In the first case there will be a fractional crystallization with continual change in liquid and crystal composition. The chondrules of the 'unequilibrated' chondrites may have solidified in this manner. The weak supercooling could have been caused by

(1) slow cooling,

(2) early crystallization of the phases induced by foreign nuclei,

(3) lower liquidus and solidus temperatures because of a low melting composition.

If the droplets are undercooled beneath the solidus, then they should theoretically crystallize with a constant composition. The phases present will tend to have a special composition which will depend only on the composition of the system and the temperature of crystallization. As has been shown the partitioning of oxidized iron between olivine and orthopyroxene is very insensitive to temperature [11]. Therefore, the composition of the phases crystallizing under these conditions will roughly depend only on the composition of the system, providing that the diffusion rates for the ions involved are high enough. At the very least the main phases, olivine and orthopyroxene, will thus appear to be 'equilibrated'.

The composition of phases not as abundant as olivine and pyroxene will further depend on local inhomogeneities caused by the rapid change in composition of the melt during the crystallization of the main phases. Also, the nucleation of these phases will be prevented until the residual melt reaches the critical degree of supersaturation. Therefore these minerals have to crystallize while all parameters which affect their final composition are changing. It is not surprising then to find them 'unequilibrated' even in 'equilibrated' chondrites [10, 12].

3. The Formation of Chondrites

The more or less solidified chondrules agglomerated after their formation, thus forming a chondrule tuff or chondrite. We can assume, in analogy to similar terrestrial processes, a wide range in agglomeration temperature. Accordingly the appearance of the different chondrites, similar to terrestrial tuffs and ignimbrites, should be quite different. The grade of welding (recently often confused with 'metamorphism') should increase with increasing agglomeration temperature, agglomeration rate, and/or the physical state of the chondrules (liquid, partly liquid, or solid). Thus the different 'grades of metamorphism' of VAN SCHMUS and WOOD [5] can easily be explained. The postulation of a re-heating event as being responsible for the wide range in structure of chondrites is unnecessarily complicating.

4. Alteration of Chondrules and Chondrites

After they were formed the chondrules suffered a great variety of alterations. Probably many chondrules from the 'unequilibrated' chondrites have been mutually affected by the gaseous environment in which they were suspended. The processes involved thereby like oxidation, reduction, evaporation, and condensation can sometimes be traced directly [8]. Possibly they are at least partly responsible for the formation of the 'unequilibrated' chondrites.

On the other hand we have to assume that the chondrules of the 'equilibrated' chondrites have been prevented from interaction with any environment, or that very low temperatures existed [9]. Otherwise the Fe/Mg ratio in different chondrules of a chondrite should be different for the different composition of chondrules.

Further, there appear to be important alterations which the chondrules frequently undergo when they agglomerate. As pointed out in the foregoing section we can assume that agglomeration took place under conditions which appear to be similar to high-temperature conditions. The more or less solidified chondrules will be deformed and welded together when they meet each other. It is reasonable to assume that while they agglomerate some of them are still crystallizing. Thus they set free heat of crystallization which cannot radiate into space because of the shielding by the following chondrules. This may cause a high temperature to last for minutes (instead of seconds in the case of isolated droplets). Thereby also the feldspar will have a chance to crystallize. Because it is generally easier to crystallize a phase from a melt, or from a strongly undercooled melt, than from a glass it is unnecessary to assume a tempering process ('metamorphism') to explain the meteoritic feldspars as products of recrystallization of meteoritic glasses.

This view is supported by analyses of glasses and matrices [8, 13] which showed that the appearance of glass or 'recrystallized' glass seems to depend on the composition of the system (Figure 1).

There are several other alterations to be observed in chondrules and chondrites, which are mainly caused by shock. They are well known and therefore need not be treated here.

A phenomenon observed on some chondrules of the Tieschitz meteorite has not been mentioned before and will be described briefly. Fibrous pyroxene chondrules usually show on their surfaces and along cracks alterations which could be explained

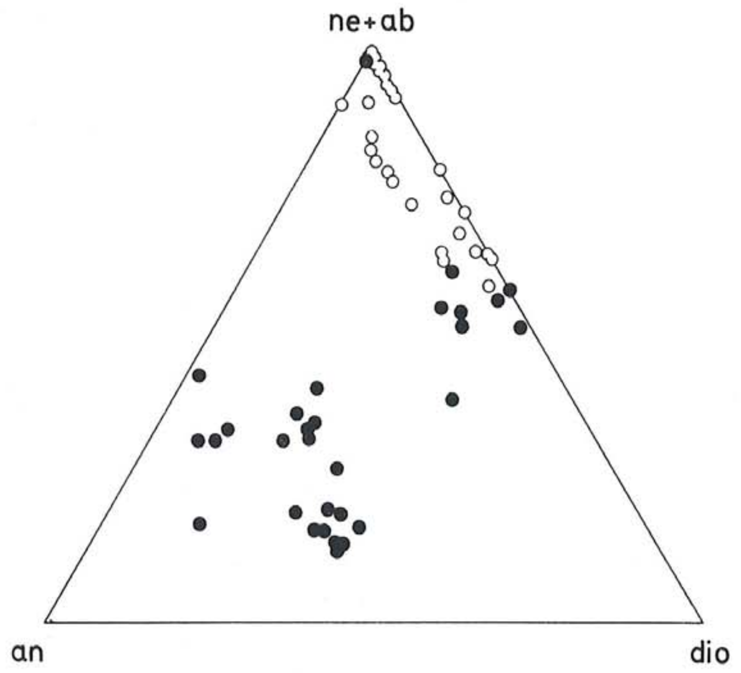

Fig. 1. Mole percents of ne + ab – an – dio (CIPW norm) of analyses of glasses and matrices from the Chainpur, Bjurböle [13], Mezö-Madaras, and Tieschitz meteorites [8, 14]. Black dots represent matrices, rings are for glasses. The black point on top of the graph is the projection of the nepheline analyses made in chondrule MMXXXII [8]. This is a monomineralic 'matrix' and therefore an exception to the rule (the same would hold for the plagioclase in chondrules).

by selective leaching of the feldspar component primarily, sometimes followed by recrystallization of the remaining material through the action of some solvent [14] (Figure 2). Microprobe checks gave as a result that Na, Al, Si, and to a lesser extent Mg, gradually decrease towards the surface of the chondrules. This leaching corresponds qualitatively to the leaching ability of plain water [15]. On the other hand the carbonaceous matrix between the chondrules has been enriched in Na, Al, and K by a factor of 2–3 if compared with carbonaceous chondrites [16]. The material removed from these chondrules has not been replaced. Therefore the altered parts are very porous and could have acted as a reservoir for liquids and/or gases. Active liquid circulation has until now only been known from carbonaceous chondrites [17]. The Tieschitz meteorite thus appears to be something like the 'missing link' between the carbonaceous chondrites and all other chondrites. This view is also supported by the bulk composition [18].

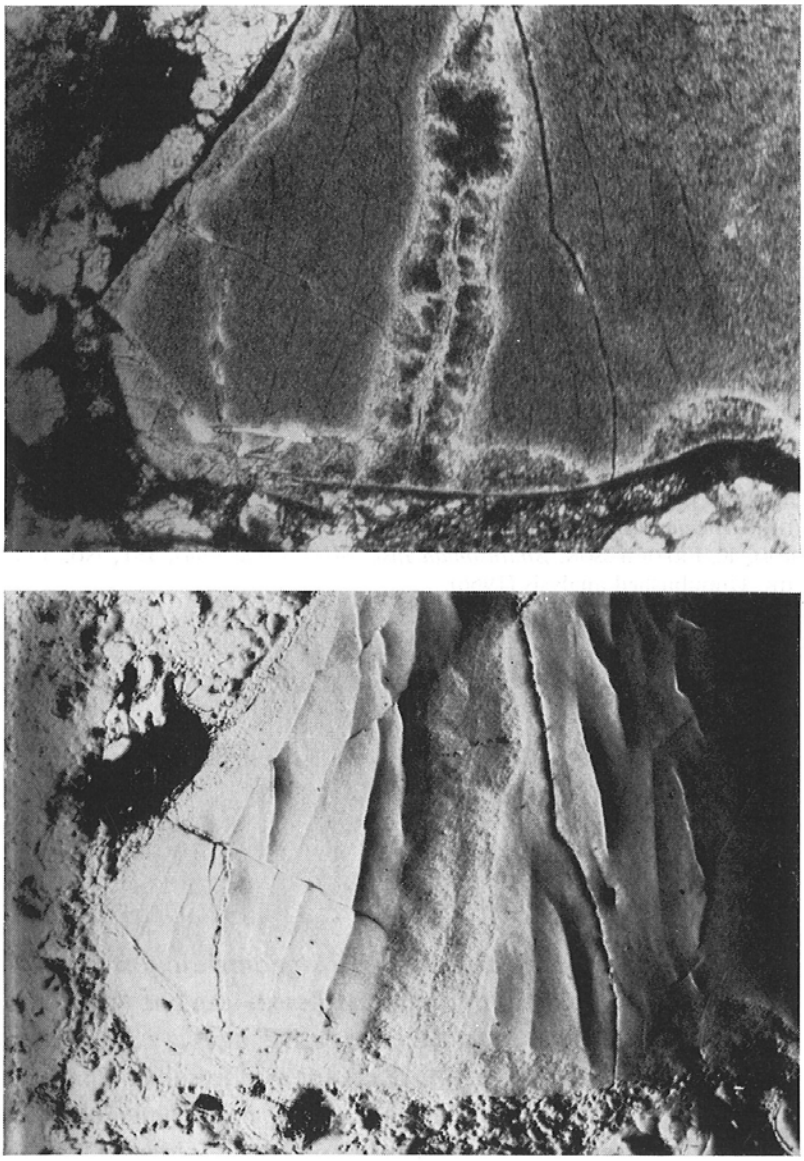

Fig. 2. Part of a fibrous pyroxene chondrule from the Tieschitz meteorite. Top: Transmitted light. Bottom: Incident light. Magnification approximately 180 ×. Note the porous appearance of the altered parts.

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