TRANSMISSION ELECTRON MICROSCOPE STUDY OF SOME MINERALS OF THE METEORITE ALLENDE. W.F.Müller, TH Darmstadt, FB 11, FG Mineralogie, D 6100 Darmstadt, Germany

The carbonaceous chondrite Allende provides a wealth of information and numerous papers on this meteorite have already been published. This mineralogical study by means of transmission electron microscopy (TEM) combined with energy dispersive X-ray microanalysis (EDS) has been started in order to learn about the microstructure of the constituents of this meteorite. The aim is lastly to help answer questions on the genesis and history of Allende as formulated in (1), e.g. Precipitates and defects of crystals reflect the formation conditions and their thermic and mechanical history. However, a conclusive interpretation of the observations presented in this paper is severely hampered by the lack of comparative experimental data. The minerals studied occurred in a Mg-rich chondrule, in a Ca-Al-rich inclusion and in the matrix of the meteorite. Previous TEM studies of Allende were only concerned with the matrix and chondrules (2,3).

Chondrule. This chondrule probably corresponds to the type "granular olivine plus clinoenstatite" described in (4). The prevalent minerals are olivine crystals (Fa3 to 25) which are almost free of dislocations. In addition, low-Fe (<Fs4) clinopyroxenes along the join $MgSiO_3$-$CaMgSi_2O_6$ occur (5,6): clinoenstatite (~Wo 5), pigeonite (Wo7 to 12), submicroscopic intergrowth of pigeonite and diopside on (001), diopside. The pigeonite, space group $P2_1/c$, displays antiphase domains with the displacement vector 1/2 [110]. The clinoenstatite which is untwinned does not show antiphase domains; it contains orthopyroxene lamellae parallel to (100) which are only one or a few lattice units along $\underset{\sim}{a}^*$ in width. In addition to olivine and clinopyroxene, the following minerals have been identified: bytownite with antiphase domains of the displacement vector 1/2 [110], pentlandite, sodalite, FeNi, spinel minerals of the composition $(Fe,Mg)(Al,Cr)_2O_4$ which are usually very fine grained (<µm).

Ca-Al-rich inclusion. The inclusion studied is about 10 mm in size and contains predominantly melilite crystals up to 2 mm in length. The other minerals identified are spinel, perovskite, hibonite, anorthite, wollastonite, grossularite, hedenbergite, diopside, Ti-Al-augite. The inclusion apparently corresponds to type A of (7).

Melilite: According to EDS its akermanite contents is below 10 mole percent. The melilite crystals contain numerous dislocations which are partly arranged in dislocation walls. These grain subboundaries lie parallel to (100) and are probably tilt boundaries made up by edge dislocations with the Burgers vector b = [100]. The dislocation walls can be correlated with the deformation lamellae about parallel to (100) seen in the petrographic microscope. These have also been mentioned in (7).

TEM STUDY OF THE METEORITE ALLENDE

MÜLLER, W.F.

Spinel: Most spinels studied were free of dislocations. However, in two larger grains, about 20 to 30 μm in size, dislocations have been found. Contrast experiments showed that their Burgers vector is 1/2⟨110⟩. In one case, two systems of long parallel edge dislocations lying parallel to {111} were seen. Thus, the slip system is 1/2⟨110⟩ {111} as observed in stoichiometric spinel deformed at high temperatures (8). In some spinels, dark field images have been obtained which show contrast phenomena similar to strain contrast of very small precipitates of of domains with a size in the order of 50 Å. It is not yet clear which kind of defects is present.
Perovskite: One perovskite grain fragmented into domains was found. The domains are apparently orientation variants due to the solid state phase transition of the high temperature cubic to the low temperature orthorhombic phase (cf.9).
Anorthite: In agreement with microprobe analyses (4,7), the anorthite was found to be chemically almost pure $CaAl_2Si_2O_8$. Electron diffraction patterns revealed sharp and relatively strong reflections of the type h+k=2n, l=2n+1. The crystals display polysynthetic twinning of the albite law and antiphase domains with the displacement vector 1/2 [111]. The domain walls are up to several μm apart. Antiphase domains with the displacement vector 1/2 [110] have not been seen (for literature on TEM studies of anorthite, see (10)). The lack of 1/2 [110] antiphase domains suggests that the anorthite crystals of Allende did not crystallize from the melt. However, it is possible that also anorthite formed from the melt with the proper heat treatment at temperatures just below the melting point may be free of these domains. The question if the anorthite of Allende formed from the vapour cannot be answered, because no information is available on the presence, nature and texture of antiphase domains in such anorthites.
Wollastonite: hk0 electron diffraction patterns of wollastonite needles revealed almost continous streaks parallel to a^* in the layers k=2n+1. The streaks indicate a high degree of stacking disorder with faults parallel to (100). The displacement vector of the faults is 1/2 [010]. Stacking faults of this type have also been found in terrestrial wollastonites (11,12,13,14) which display different degrees of disorder. There is experimental evidence that stacking disorder in wollastonite can be produced by deformation (15). The high degree of stacking disorder as observed here, however, may also be a growth phenomenon. In view of the occurrence of Allende wollastonite as needles in cavities (see Fig.1 in 16), this explanation is favoured.
Grossularite: This mineral occurred as aggregate of small grains about 0.5 to 1.5 μm in size which formed large angle grain boundaries among each other.
Hedenbergite (Wo50 to 55, Fs5 to 50, En<3) showed twinning on

TEM STUDY OF THE METEORITE ALLENDE

MÜLLER, W.F.

(100). The twin lamellae were 150 to 700 Å in width and 0.03 to 0.5 µm apart. Diopside and Ti-Al-augite are twinned on (001), too. An origin of the twins due to mechanical deformation is not excluded.
Hibonite: Only one grain was found. It showed dislocations near the grain boundary to melilite.

Matrix. The minerals observed in the matrix are olivine (Fa~50, in agreement with (4)), diopsidic clinopyroxene, sulfides and spinels of various compositions. The olivine crystals usually show long screw dislocations with the Burgers vector [001]. Dislocations of this type are characteristic of deformation processes at low temperatures and high strain rates (17) and have been observed in shocked lunar olivine (18).

References: (1)Haggerty S.E. and Merkel G.A.(1976).In Lunar Sci.VII,p.342-345. The Lunar Science Institute, Houston, Texas. (2)Ashworth J.R. and Barber D.J.(1975)Earth Planet.Sci.Lett.27, 43-50. (3)Green II H.W. et al.(1971)Science 172,936-939. (4)Clark Jr. S.P. et al.(1970)Smithson.Contrib.EarthSci.5. (5)Müller W.F. (1976)Naturwiss.63,432. (6)Müller W.F.(1977)Fortschr.Mineral.55, Beiheft 1,172-173. (7)Grossman L.(1975)Geochim.Cosmochim.Acta 39, (8)Mitchell T.E. et al.(1976)J.Mat.Sci. 11,264-272. (9) Kay H.F. and Bailey P.C.(1957) Acta Cryst.10,219-226. (10)Heuer A.H. and Nord Jr. G.L.(1976). In Electron Microscopy in Mineralogy (H.-R. Wenk,ed.),p.274-303. Springer-Verlag, Berlin,Heidelberg, New York.(11)Müller W.F. and Wenk H.-R.(1975)Acta Cryst.A31 part S3,S294. (12)Wenk H.-R. et al.(1976).In Electron Microscopy in Mineralogy (H.-R.Wenk, ed.),p.324-331. Springer-Verlag Berlin, Heidelberg, New York.(13)Akai J.(1975) Mem.Fac.Sci.Kyoto Univ. Series of Geology and Mineralogy,vol.XLI,No.2,1-14. (14) Jefferson D.A. and Thomas J.M.(1975)Acta Cryst.A31 part S3,S295. (15)Wenk H.-R.(1969)Contr.Mineral.Petrol.22,238-247.(16)Fuchs L. H.(1971)Am.Mineralog.56,2053-2068. (17)Phakey P.P. et al.(1972). In Flow and Fracture of Rocks (H.C.Heard et al., eds.).Geophys. Monogr.16, 117-138. (18)Engelhardt W.v. et al.(1971) Proc.Lunar Sci.Conf. 2nd,p.833-854.