# MINERALOGY AND CHEMISTRY OF THE ASHMORE CHONDRITE

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*The Ashmore olivine-bronzite chondrite is a group H, type 5 stone which differs from other H5 chondrites mainly in its higher proportion of chromite (0.9 wt %) and in the relatively lower iron and higher magnesium content of the chromite. The modal proportions of opaque phases were obtained by point-counting in reflected light, and the modal proportions of nonopaque silicate phases in the matrix were estimated from traverses of a selected small area by electron microprobe. The consistency between the bulk chemical analysis and the chemical composition calculated from the modal mineral proportions implies that the bulk silicate composition of the chondrules is very similar to that of the silicate matrix and suggests a common source for both chondrules and matrix.*

## INTRODUCTION

The Ashmore chondrite was found in February 1969 in a plowed field in Gaines County, Texas. A preliminary description of the 55.4 kg stone, an olivine-bronzite chondrite, was given by Craig *et al.* (1971). The site of the find is close to that of the Loop chondrite, to which Ashmore was originally attributed, but it is now clear that Ashmore is distinct from Loop (E. P. Henderson, personal communication, 1970). Although a surface zone 2 to 3 mm thick is rather badly oxidized and weathered, the interior of the stone is almost unaltered and is suitable for more detailed mineralogical and chemical study. In this paper we give the results of detailed petrographic studies and microprobe analyses of major mineral phases, and the relation of the modal mineralogy to the bulk chemical composition is discussed. A preliminary account of the modal and mineralogical composition was given by Bryan and Kullerud (1971).

Chondritic meteorites constitute over 80% of all known falls and are of special petrologic interest because of their tendency to fall rather neatly into one of several well-defined types, which are readily distinguished by certain key chemical and mineralogical parameters combined with a few simple textural features (Van Schmus and Wood, 1967). It is perhaps this tendency

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of chondrites to define a "natural" classification scheme that makes them rewarding subjects for petrographic study. Van Schmus (1969) has summarized the characteristics of chondritic meteorites and the theories of their origin. He noted that only about half of the known chondritic meteorites have been classified. Knowledge of the degree of homogeneity within the compositional groups and of the nature and extent of chemical and mineralogical variations within and between groups is clearly essential to an understanding of chondrite petrogenesis. Thus, we have tried to provide all data for Ashmore that may be critical to its proper classification.

## METHODS

The major mineral phases were analyzed by electron microprobe, using standards and correction procedures that have been described previously (Boyd, 1968; Boyd *et al.*, 1969). Preliminary scans with the probe beam showed little variation from grain to grain of a given mineral phase, and thus all mineral analyses except that of plagioclase were carried out on single grains, chosen for freedom from impurities or cracks and for sufficient surface area to avoid overlapping of analyzed spots. The feldspar analysis, however, is a composite of counts taken from a dozen very small grains chosen at random, because only one or two sets of counts could be obtained from each grain without overlapping of analyzed areas.

Modal analysis of the opaque phases and total silicate matrix was carried out in reflected light. The silicate matrix was then scanned by the microprobe beam while count levels for Ca, Mg, and Si were recorded on chart paper. The sample traverse rate was $60\,\mu$m per minute, with a corresponding chart rate of one inch per minute. Each mineral was identified from its characteristic peak heights on the chart paper, and the sum of the traverse lengths within each phase, divided by the total traverse length, gives the estimated volume percentage of the mineral. The area used to estimate silicate mineral proportions was limited to about 5 mm$^2$ because of both mechanical restrictions on traverse length (about 4 mm) and the time required (about one hour) for a complete traverse. Three traverses, totaling about 11 mm, were run across this area, which was selected as being reasonably representative of the finer grained matrix on the basis of optical examination. Thus, the silicate proportions should be regarded as representative only of the matrix; a similar area selected within a large chondrule or including a large olivine grain could be expected to give different results. However, the remarkable consistency between the modal and chemical data, discussed subsequently, suggests that the measured values are representative of the whole sample.

## PETROGRAPHY AND MINERALOGY

The Ashmore chondrite contains a few well-defined chondrules of the barred olivine and radial pyroxene type, but most of the chondrules are extensively recrystallized and are recognized only with difficulty. The matrix is recrystallized to grains generally larger than 0.1 mm in diameter. Olivine and bronzite are abundant and readily identified. Feldspar is not conspicuous optically but may be detected by its characteristic fluorescence under the electron beam of the microprobe. Augite could be identified only from the characteristic count rates for Ca, Mg, and Si when scanned with a finely-focused electron beam. Individual mineral phases show very little grain-to-grain variation. Mineral compositions (Table 1) and proportions (Table 2) correspond closely to the H-group averages.

Kamacite tends to form irregular amoeboid grains with sutured boundaries against the silicate matrix. Some of it contains irregular patches of taenite. Troilite and chromite tend to form more rounded grains with relatively smooth boundaries. The most conspicuous minor mineral phase is lawrencite, which is readily identified from its deliquescence on a freshly-cut surface. It appears to be concentrated along the boundaries of kamacite. Decomposition of lawrencite and adjacent kamacite to limonite and HCl rapidly produces rusty patches and stains the silicate matrix on fresh surfaces.

Other minor mineral phases observed in polished section include a phosphate mineral, graphite, blue ilmenite, copper, pentlandite, magnetite, and goethite. Graphite (microcliftonite) may be observed at high magnification in many grains of kamacite, oriented along the octahedral (111) planes of the metal. It probably formed by breakdown of cohenite ($Fe_3C$). Some ilmenite grains enclosed by troilite contain bluish areas, resembling the blue ilmenite produced when stoichiometric synthetic ilmenite is heated with sulfur. The blue color may be due to loss of iron to form iron sulfide. Metallic copper occurs in tiny grains associated with kamacite and troilite and may

### Table 1

Compositions of analyzed minerals compared with average mineral compositions of group H chondrites (Van Schmus, 1969)

|  | Olivine | | Orthopyroxene | | | Feldspar | | | Chromite | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
|  | Fo | Fa | En | Fs | Wo | Or | An | Ab | Fe | Mg | Mn |
| Ashmore chondrite | 80.9 | 19.1 | 81.9 | 16.6 | 1.5 | 5.6 | 12.1 | 82.3 | 80.2 | 17.3 | 2.5 |
| Average group H | 80.7 | 19.3 | 81.6 | 16.8 | 1.6 | 5.8 | 12.3 | 81.9 | 83.1 | 14.0 | 2.9 |

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result from breakdown of chalcopyrrhotite. Pentlandite occurs between grains of kamacite and troilite and in tiny fissures in troilite. It apparently formed by reaction between troilite and the Fe-Ni alloy. The latter two minerals also extend into fractures in the silicate matrix, indicating the relative mobility of the nickel-iron and sulfide phases in comparison with the silicates. Magnetite and goethite are restricted to the weathered rim on the outer surface of the meteorite.

Microprobe analyses of the major minerals are given in Table 3. Binns (1970) found little or no $Fe_2O_3$ in chondritic pyroxenes, so our inability to determine $Fe_2O_3$ by microprobe analysis does not invalidate comparisons of our analysis with his pyroxene data. It is interesting that our orthopyroxene does show about the same Z-group deficiency as that noted by Binns, although one might well question whether either the microprobe or gravimetric analysis is sufficiently precise to detect such subtle departures from stoichiometry. Additional careful analysis of chondritic orthopyroxenes by other workers may eventually establish whether this apparent Z-group deficiency is a consistent and measurable property of some, or of all, chondritic orthopyroxenes. The similarity in Fe/Mg ratio of orthopyroxene and olivine, with olivine being slightly more iron-rich, is also characteristic of terrestrial harzburgites (see, for example, Himmelberg and Coleman, 1968).

The chromite in Ashmore is present in two to three times the quantity usually reported for H-group chondrites (Keil, 1962; Van Schmus, 1969). In composition it is on the low-iron and high-magnesium end of the range

### Table 2
### Modal mineral proportions*

| | Ashmore | | | Typical group H, wt % | |
| | Vol % | | Wt % | Van Schmus, 1969 | Keil, 1962 |
|---|---|---|---|---|---|
| Orthopyroxene | 24.1 | | 22.0 | 23-27 | |
| Olivine | 38.1 | | 35.4 | 33-37 | |
| Augite | 7.1 | 87.2 | 6.5 | 4-5 | 77.95 |
| Feldspar | 11.1 | | 8.0 | 9-10 | |
| Apatite | 0.4 | | 0.4 | 0.6 | |
| Other | 6.4 | | 5.2 | — | |
| Metal | 7.3 | | 15.3 | 15-17 | 16.80 |
| Troilite | 4.8 | 12.8 | 6.3 | 5-6 | 5.03 |
| Chromite | 0.7 | | 0.9 | 0.5 | 0.22 |

*Ashmore modal volume % estimated from point count and microprobe traverses. Weight % calculated, using the following assumed densities: metal, 8.0; troilite, 5.0; chromite, 4.8; orthopyroxene, 3.35; olivine, 3.40; plagioclase, 2.65; augite, 3.35; apatite, 3.2; other, 3.00. Count area = 13 $mm^2$, 4354 points.

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## Table 3
### Microprobe analyses of major mineral phases

#### a. Silicate and oxide

| | Bronzite | Olivine | Plagioclase | Chromite |
|---|---|---|---|---|
| $SiO_2$ | 56.7 | 39.6 | 64.6 | 0.14 |
| $Al_2O_3$ | 0.19 | 0.0 | 21.5 | 6.19 |
| $TiO_2$ | 0.19 | — | — | 2.28 |
| FeO | 11.3 | 17.9 | 0.21 | 29.3 |
| MnO | 0.55 | 0.51 | — | 0.87 |
| MgO | 31.3 | 42.6 | 0.07 | 3.47 |
| CaO | 0.81 | 0.01 | 2.58 | — |
| $Na_2O$ | 0.0 | — | 9.70 | — |
| $K_2O$ | — | — | 1.01 | — |
| $Cr_2O_3$ | — | — | — | 56.4 |
| Totals | 101.04 | 100.62 | 99.67 | 99.73* |

| | Bronzite | | Olivine | | Plagioclase | | Chromite | |
|---|---|---|---|---|---|---|---|---|
| O | 6.000 | | 4.000 | | 32.000 | | 32.000 | |
| Si | 1.984 | } 1.997 | 0.999 | } 0.999 | 11.473 | | 0.040 | |
| Al | 0.008 | | — | | 4.488 | | 2.069 | |
| Ti | 0.005 | | — | | — | } 15.992 | 0.487 | |
| Fe | 0.331 | | 0.380 | | 0.031 | | 6.815 | |
| Mn | 0.016 | | 0.019 | | — | | 0.209 | |
| Mg | 1.632 | } 2.009 | 1.603 | } 2.002 | 0.018 | | 1.466 | |
| Ca | 0.030 | | 0.000 | | 0.491 | } 4.078 | Cr 12.633 | |
| Na | 0.000 | | — | | 3.340 | | V 0.164 | |
| K | 0.000 | | — | | 0.229 | | Zn 0.076 | |
| | 4.006 | | 3.001 | | 20.070 | | 23.959 | |

#### b. Metal and sulfide

| | Kamacite | Troilite |
|---|---|---|
| Fe | 93.2 | 63.2 |
| Mn | 0.02 | 0.00 |
| Ni | 5.79 | <0.03 |
| Co | 0.69 | 0.09 |
| Si | 0.05 | 0.18 |
| P | 0.01 | 0.0 |
| S | — | 35.8 |
| Totals | 99.76 | 99.30 |

*Includes $V_2O_3$, 0.72; ZnO, 0.36.

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previously reported for H5 and H6 chondrites (Bunch *et al.*, 1967), and in this respect it shows a greater departure in composition from the group average than the other major nonmetallic phases (Table 1). Although Bunch *et al.* (1967) showed that chromites tend to fall into a trimodal compositional grouping corresponding to H, L, and LL groups, their data do show a rather wide range (29.8 to 32 wt %) of FeO and a similarly wide range (2.03 to 3.10 wt %) of MgO in equilibrated H-group chromites. However, relatively low FeO and high MgO are features of the H group as compared with groups L and LL, and the Ashmore chromite data are consistent with this tendency. There have been relatively few reports of ZnO in chondritic chromites, although zinc is a common constituent of terrestrial chromite. Bunch *et al.* (1967) reported 1.09% ZnO in chromite in Pultusk, an H5 chondrite. Other cation oxides ($MnO$, $TiO_2$, $Al_2O_3$) are close to the values previously reported and are typical of type 5 chondritic chromite.

A careful search for daubréelite with the probe beam, while counts for Cr and S were recorded, gave negative results. Chromite appears to be the only Cr-bearing phase. Partitioning of Cr between oxide and sulfide phases may account for the lower content of chromite in other H-group chondrites. The total amount of $Cr_2O_3$ in Ashmore is toward the high end of the range reported for chondrites, although high values are not uncommon. Urey and Craig (1953, p. 80) showed a bimodal distribution for $Cr_2O_3$ in 37 samples of H-group chondrites, with peaks close to 0.05 and 0.40 wt % and a mean of 0.27 wt %, which is, however, not a typical value as it falls close to the frequency minimum of the distribution. Keil (1962, p. 4059) obtained much lower average modal weight proportions for chromite and other opaque phases than those given by Urey and Craig (1953), but he noted that his data seemed consistent with chemical analyses by Wiik (1956). These differences could reflect errors in the assumptions about mineral densities used to convert volume percentages to weight percentages, or errors in older chemical procedures, or both.

A few phosphate grains were positively identified optically; because of the similarity of apatite, whitlockite, and merrillite in hardness and other optical properties the three minerals cannot be readily distinguished. Also, we have not definitely established that all phosphorus expressed in the bulk chemical analysis (Table 4) is confined to distinct phosphate phases; some could be present in silicates (Urey and Craig, 1953, p. 52). In subsequent discussion we have referred to this mineral as "apatite" and have assumed that all phosphorus is present in that phase (Moss *et al.*, 1967). Although this assumption is adequate for present purposes, the need for more exact work on this mineral should be recognized.

## CHEMICAL COMPOSITION

The chemical composition of the Ashmore chondrite is given in Table 4. Details of the analytical procedure have been given by Jarosewich

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(1966). The chemical parameters by which chondrites are conventionally compared and classified are given in Table 5. It is immediately evident that in chemical composition, also, Ashmore is very close to the average for group H chondrites. The ratio of metallic to total iron was calculated after all $Fe_2O_3$ was converted to metallic iron, as petrographic study indicates that most of the oxidation has taken place along the boundaries of kamacite grains as a result of reaction with the decomposition products of lawrencite. Some small amount of iron and chlorine may have been lost from the sample through the very rapid deliquescence of lawrencite. Although the effect is believed to be too small to seriously alter the chemical parameters, the tendency would be to give slightly low figures for total iron and metallic iron and a slightly low total because chlorine has not been determined. Assuming all $Fe_2O_3$ as Fe, the amount of metallic iron becomes 15.55 wt %. Craig *et al.* (1971) reported 27.5 wt % Fe in a sample of the Ashmore. They also reported 1.82 wt % Ni. The Ni content listed in our Table 4 is 1.70 wt %. The difference in Fe/Ni ratio between the value of 27.5/1.82 = 15.11 obtained by Craig *et al.* (1971)

### Table 4
### Chemical analysis of Ashmore chondrite

| | |
|---|---|
| Fe | 14.36 |
| Ni | 1.70 |
| Co | 0.08 |
| FeS | 5.92 |
| $SiO_2$ | 36.43 |
| $TiO_2$ | 0.11 |
| $Al_2O_3$ | 2.00 |
| $Cr_2O_3$ | 0.55 |
| $Fe_2O_3$ | 1.70* |
| FeO | 10.20 |
| MnO | 0.29 |
| MgO | 22.88 |
| CaO | 1.60 |
| $Na_2O$ | 0.81 |
| $K_2O$ | 0.10 |
| $P_2O_5$ | 0.20 |
| $H_2O(+)$ | 0.44 |
| $H_2O(-)$ | 0.09 |
| C | 0.02 |
| Total | 99.48 |
| Total Fe | 27.24 |

*$Fe_2O_3$ due to terrestrial oxidation. When calculated as metal, Fe (metal) is 15.55%.
Analyst: Eugene Jarosewich, Department of Mineral Sciences, Smithsonian Institution.

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and 15.55/1.70 = 9.15 obtained in the present study is not readily explained. The sample analyzed by Craig *et al.* (1971) was small, perhaps not representative, and possibly oxidized (J. Craig, oral communication, September 5, 1974). It seems that the value of 9.15 is the more representative Fe/Ni ratio in the Ashmore.

The close correspondence in chemical composition between Ashmore and other group H chondrites is not surprising in view of the very close similarity in composition and proportion of individual mineral phases. In order to compare the bulk chemical composition with the modal mineralogy, the contributions of each oxygen-bearing mineral to the major cation oxides have been calculated and are presented in Table 6. There is a remarkably close

### Table 5
#### Chemical paramaters of Ashmore chondrite*

|  | $Fe/SiO_2$ | $Fe°/Fe$ | $SiO_2/MgO$ |
|---|---|---|---|
| Average group H† | 0.77±0.97 | 0.63±0.07 | 1.55±0.05 |
| Ashmore | 0.75 | 0.57[+] | 1.59 |

*See text for discussion of estimate of metallic iron.

†Van Schmus and Wood (1967).

[+]All Fe in $Fe_2O_3$ converted to $Fe°$.

Fe = total $Fe°$, plus Fe in ($FeO+Fe_2O_3$) calculated as wt % Fe.

Note that $Fe/SiO_2$ is *total iron as Fe* divided by $SiO_2$. This parameter is *not* seriously affected by oxidation.

### Table 6
#### Comparison of calculated and observed oxide wt %
#### of silicate, oxide, and phosphate in the Ashmore chondrite*

|  | Calculated | Observed (Table 4) |
|---|---|---|
| $SiO_2$ | 35.5 | 36.43 |
| $TiO_2$ | 0.06 | 0.11 |
| $Al_2O_3$ | 1.84 | 2.00 |
| $Cr_2O_3$ | 0.51 | 0.55 |
| FeO | 9.46 | 10.20 |
| MnO | 0.31 | 0.29 |
| MgO | 23.21 | 22.88 |
| $Na_2O$ | 0.81 | 0.81 |
| $K_2O$ | 0.08 | 0.10 |
| $P_2O_5$ | 0.17 | 0.20 |

*Mineral phases used in calculation are olivine, bronzite, augite, plagioclase, chromite, and apatite. Except as noted in text, mineral compositions used are those in Table 3 and weight percentages used are those given in Table 2, Col. 2.

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correspondence between the composition derived from the mode and that obtained by bulk analysis. As it was not possible to analyze the very finely dispersed augite in Ashmore, we have used the average augite composition for group H chondrites given by Van Schmus (1969, p. 168-9). The apatite composition was computed from the ideal formula; otherwise the mineral compositions are those given in Table 3.

As noted previously, the modal proportions of the silicate minerals were estimated from a very small area of fine-grained matrix, and there is no reason to suppose that the proportions there would be representative of the modal composition of the whole sample. That the matrix is apparently representative implies that the overall bulk silicate phase composition of the recrystallized chondrules is virtually identical with that of the matrix. This phase homogenization could possibly be related to the recrystallization and equilibration that have clearly been extensive in Ashmore, but one normally would expect equilibration to homogenize phase compositions without redistributing their proportions between chondrules and matrix. The possibility of phase homogenization in Ashmore by brecciation and mechanical mixing at some early stage cannot be ruled out, but there is certainly no definite textural evidence for such an event. The alternative explanation, that the fine matrix and the chondrules both had the same initial overall bulk composition and hence would equilibrate to mineral assemblages identical in both composition and proportion, has important implications for the genesis of chondritic meteorites. Such an identity in bulk composition might arise if chondrules and matrix both are derived from a common dust cloud, perhaps from a solar nebula in which lightning-like discharges fused portions of the dust cloud into spherical chondrules, as advocated by Whipple (1966).

## ACKNOWLEDGMENTS

## REFERENCES

Binns R.A., 1970. Pyroxenes from non-carbonaceous chondritic meteorites. *Min. Mag.* 37, 649-669.

Boyd F.R., 1968. Quantitative electron-probe analysis of pyroxenes. *Carnegie Institution Washington Year Book* 66, 327-334.

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Boyd F.R., L.W. Finger, and F. Chayes, 1969. Computer reduction of electron-probe data. *Carnegie Institution Washington Year Book* 67, 210-215.

Bryan W.B. and G. Kullerud, 1971. Meteorites. *Carnegie Institution Washington Year Book* 69, 245-249.

Bunch T.E., K. Keil, and K.G. Snetsinger, 1967. Chromite composition in relation to chemistry and texture of ordinary chondrites. *Geochim. Cosmochim. Acta* 31, 1569-1582.

Craig J.R., D.A. Howe, R.L. Harris, and G. Kullerud, 1971. The Ashmore: A new olivine-bronzite chondrite. *Meteoritics* 6, 33-37.

Himmelberg G.R. and R.G. Coleman, 1968. Chemistry of primary minerals and rocks from the Red Mountain-Del Puerto ultramafic mass. *U.S. Geol. Surv. Prof. Paper* 600-C, 18-26.

Jarosewich E., 1966. Chemical analyses of ten stony meteorites. *Geochim. Cosmochim. Acta* 30, 1261-1265.

Keil K., 1962. On the phase composition of meteorites. *J. Geophys. Res.* 67, 4055-4061.

Moss A.A., M.H. Hey, C.Y. Elliott, and A.Y. Easton, 1967. Methods for the chemical analysis of meteorites: II. The major and some minor constituents of chondrites. *Min. Mag.* 36, 101-119.

Urey H.C. and H. Craig, 1953. The composition of the stone meteorites and the origin of the meteorites. *Geochim. Cosmochim. Acta* 4, 36-82.

Van Schmus W.R., 1969. The mineralogy and petrology of chondritic meteorites. *Earth Sci. Rev.* 5, 145-184.

Van Schmus W.R. and J.A. Wood, 1967. A chemical petrologic classification for the chondritic meteorites. *Geochim. Cosmochim. Acta* 31, 747-765.

Whipple F.L., 1966. A suggestion as to the origin of chondrules. *Science* 153, 54-56.

Wiik H.B., 1956. The chemical composition of some stony meteorites. *Geochim. Cosmochim. Acta* 9, 279-289.

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