

## Chapter 6

### MARTIAN METEORITES

**Harry Y. McSween, Jr.**

*Department of Geological Sciences  
University of Tennessee  
Knoxville, Tennessee 37996  
mcsween@utk.edu*

**Allan H. Treiman**

*Lunar and Planetary Institute  
3600 Bay Area Boulevard  
Houston, Texas 77058  
treiman@lpi.jsc.nasa.gov*

### INTRODUCTION

Mars, as revealed by observations from spacecraft, has had a unique geologic history with many intriguing parallels to that of the Earth. Imaging results from the Mariner 4, 6, and 7 flyby missions in the 1960s were misleading, giving an impression of a lunar-like surface because they returned images of only the ancient, heavily cratered southern highlands. Global mapping by the Mariner 9 orbiter in 1971 revealed the full surface of Mars, which includes vast, younger volcanic plains and huge volcanic constructs in the northern hemisphere, a yawning canyon system, seasonally changing polar caps, and geomorphic evidence of drainage and catastrophic flooding by water early in the planet's history. Viking orbiters and landers in 1976 and the Mars Pathfinder lander in 1997 provided much rich detail about martian geology, and the Mars Global Surveyor mission promises more insights. Comprehensive summaries of martian geophysics, geology, surface properties, and atmosphere have been published previously in *Mars* (Kieffer et al. 1992).

The dozen presently recognized *SNC* (*shergottite-nakhlite-chassignite*) meteorites are generally accepted to be martian igneous rocks. These basaltic and ultramafic rocks define a common oxygen isotope mass fractionation line (Clayton and Mayeda 1996) distinct from those of other solar system bodies and share other geochemical characteristics (McSween 1994) that indicate their formation by partial melting of evolved source regions with broadly similar compositions and redox states (Longhi et al. 1992, Bertka and Fei 1997). Because the assortment of meteorite lithologies has now expanded beyond the bounds of the original SNC classification and is likely to become even broader as more martian meteorites are discovered, the meteoritic (SNC) nomenclature has become somewhat archaic. To minimize confusion, we will describe these meteorites using both the traditional meteorite nomenclature and petrologic classifications in the IUGS-approved terminology for igneous rocks.

These meteorites provide critical constraints on the geochemical and geophysical properties of the martian core and mantle (Dreibus and Wänke 1985, Treiman et al. 1986, Longhi et al. 1992, Collinson 1997, Gaetani and Grove, 1997), the chronology of planetary differentiation, magmatism, and bombardment (Shih et al. 1982, Chen and Wasserburg 1986a, Jagoutz 1991, Ash et al. 1996, Lee and Halliday, 1997), the global volatile inventory and outgassing history (Carr and Wänke 1992, McSween and Harvey

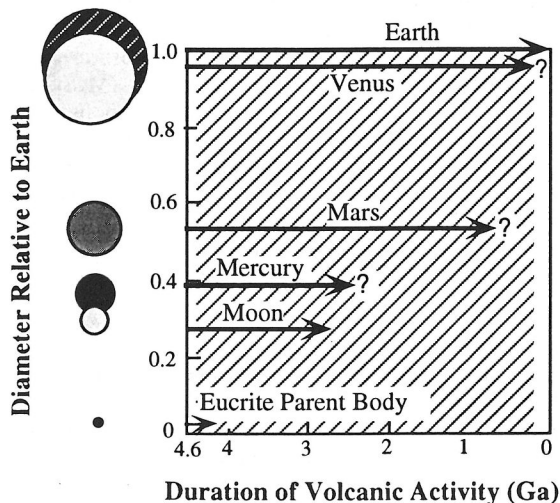
1993), interactions between the atmosphere, hydrosphere, and lithosphere (Wright et al. 1990, Karlsson et al. 1992, Watson et al. 1994), and near-surface weathering processes (Gooding 1992). One meteorite has also been suggested to provide evidence for possible biologic activity on Mars (McKay et al. 1996), a proposal that has sparked great interest and debate.

This review focuses specifically on the mineralogy and petrology of martian meteorites, which relate directly to the planet's magmatism, impact history, and weathering. Although this work touches on some of the implications of these samples for understanding other aspects of martian geology (and possibly biology?), it does not attempt to duplicate other reviews which address that broader subject (e.g. McSween 1985 1994 1997). We will, however, reiterate the evidence that links these meteorites to Mars, as well as describe their removal from Mars and delivery to Earth. We will also compare the mineralogy of these meteorites to that inferred for martian rocks and soils based on interpretations of remote-sensing spectral and chemical data. This paper does not include a discussion of CI carbonaceous chondrites as possible martian sedimentary rocks (Brandenburg 1996), as we consider that hypothesis to be unsubstantiated and implausible (Treiman 1996a). Further information on the SNC meteorites, including sample availability as well as a listing of the minerals occurring in them, can be found in the *Mars Meteorite Compendium* (Meyer 1996). Representative compositions of minerals in SNC meteorites are tabulated in an appendix at the end of this chapter.

## SOURCE AND DELIVERY OF SNC METEORITES

### Evidence for a Martian origin

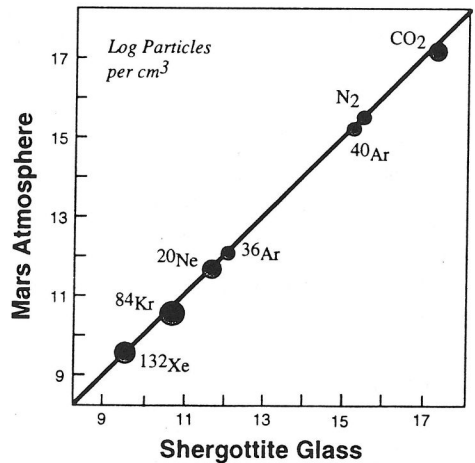
Shoemaker et al. (1963) were prescient in suggesting the possibility that impact ejecta might be liberated from Mars and ultimately collide with the Earth, and they wondered whether such materials could ever be recognized. The first suggestions that SNC meteorites were from Mars (McSween et al. 1979a, Walker et al. 1979, Wasson and Wetherill 1979) were based on the relatively young crystallization ages (<1.3 Ga) of the few meteorites then available. The duration of igneous (volcanic) activity on a body is directly related to its size (Fig. 1) because large bodies have low surface-to-volume ratios and so lose internal heat more slowly than small bodies. Bodies of asteroidal size, like 4 Vesta and other achondrite



**Figure 1.** The duration of planetary igneous activity, as judged from crater-counting ages of volcanic surfaces and radiometric ages of samples, is related to planet size. The ages of SNC meteorites, ranging from ~4.5 Ga to as young as 180 Ma (cross-hatched area), suggest their derivation from a planetary body (modified from McSween 1994).

parent bodies (see Chapter IV), experienced melting very early in solar system history but have not apparently produced magmas since ~4.4-4.5 Ga. The ages of currently known martian meteorites extend from ~4.5 Ga to at least 330 Ma, and possibly to 180 Ma (discussed below). Igneous activity on the SNC parent body ranging over most, if not all, of geologic history demands that these meteorites were derived from a large planetary body (Fig. 1), or one like Io with an extrinsic heat source. Although this argument does not link these meteorites specifically to Mars, that planet is an attractive option because of its modest size and proximity to Earth. Another observation made at the time was that chemical analyses of martian duracrust-free soil by Viking landers were remarkably similar to those of shergottites (Walker et al. 1979).

The idea that meteorites could come from Mars remained alive (e.g. Wood and Ashwal 1981, Vickery and Melosh 1983) but highly disputed until Bogard and Johnson (1983) discovered Ar trapped within impact-melted glass in shergottite EETA79001. The isotopic compositions and relative abundances of Ar and other noble gases, N<sub>2</sub>, and CO<sub>2</sub> (Becker and Pepin 1984, Swindle et al. 1986), are a remarkable match for martian atmospheric abundances (Fig. 2). The composition of the atmosphere of Mars is unique, so far as we know, and serves as a geochemical fingerprint linking EETA79001 to its parent planet. Moreover, shock experiments have demonstrated that noble gases implanted during impact melting are not isotopically fractionated (Weins and Pepin 1988). Similar trapped gases have now been found in other highly shocked SNC meteorites (e.g. Marti et al. 1995, Turner et al. 1997), convincing most skeptics that these meteorites are from Mars. Although comparison of shock-implanted gases with the *modern* martian atmosphere may be criticized, the gas-implanting shock events are thought to have occurred recently, perhaps as the meteorites were ejected from the planet's surface.



**Figure 2.** The abundances of N<sub>2</sub>, CO<sub>2</sub>, and various noble gas isotopes trapped in impact-melted glass from the EETA79001 shergottite match measurements of the martian atmosphere by Viking spacecraft (modified from Pepin and Carr 1992). Uncertainties in the analyses are encompassed within the circles.

Other arguments for a martian origin of the SNC meteorites fall into the category of plausibility tests. For example, the low remanent magnetization recorded in the shergottites (Collison 1986), thought to have formed 330 to 180 Ma ago, is consistent with what is known about the present-day magnetic field of Mars. The highly fractionated rare earth element (REE) patterns of SNC meteorites appear to require garnet in the source region (Nakamura et al. 1982, Longhi 1991), which implies a planet with substantial internal pressures. Also, the presence of pre-terrestrial hydrous minerals and salts in these meteorites (Gooding 1992) is consistent with photogeologic evidence for abundant water on Mars in its distant past.

### Removal from Mars and delivery to Earth

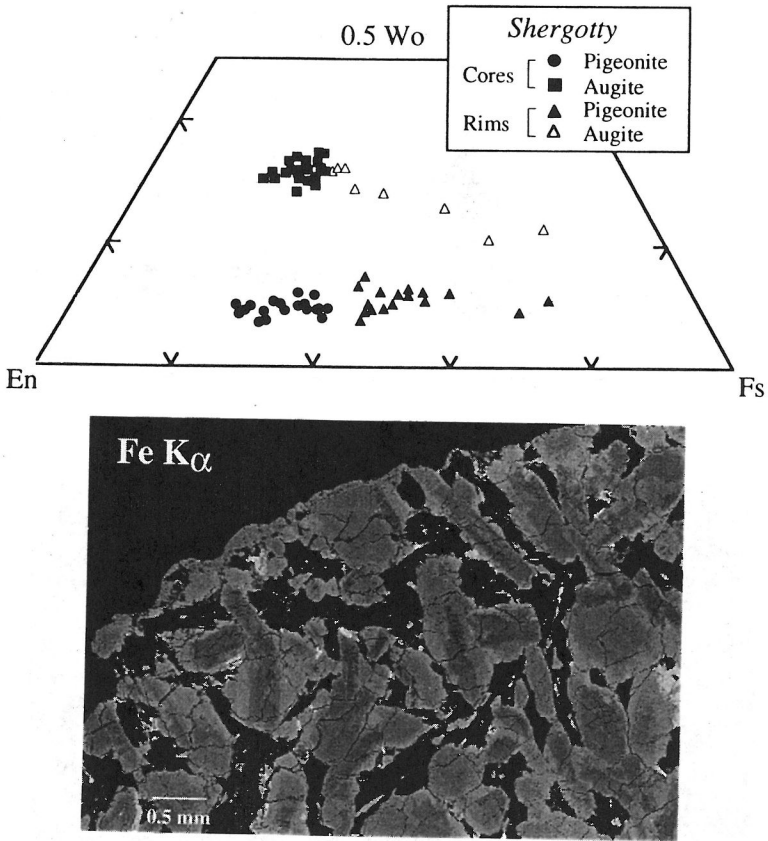
A major difficulty initially encountered by the hypothesis that SNC meteorites are from Mars was that no known mechanism could remove rocks from the surface of a planet without totally melting or vaporizing them (Wetherill 1976). This difficulty was underscored by the apparent absence of meteorites from the Moon—if there were no meteorites from the nearest, relatively modest-sized body, how could one expect to find meteorites from a larger, more distant planet? The discovery in Antarctica of a lunar highlands breccia, first reported in 1983, demonstrated that meteorites could be ejected from large bodies and opened the way for serious consideration of martian meteorites.

The only plausible event with sufficient energy to launch rocks at martian escape velocity (~5 km/sec) is a large meteor impact. After a number of inventive attempts to model the ejection of modest-sized rocks without completely destroying them (e.g. Wasson and Wetherill 1979, Nyquist 1983), an explanation by Melosh (1984) gained favor. In this model, shock waves from large impacts accelerate fragments at or near the surface to the required velocity. Given the violent process for extracting meteorites from Mars, it is not surprising that some of them have experienced severe shock metamorphism and, in some cases, shock melting. In fact, it is astonishing that a few of them exhibit little or no discernable shock effects.

The fate of rocks escaping Mars orbit has been explored by numerical integration of their orbital histories (Wetherill 1984, Gladman et al. 1996). The efficiency of the delivery of martian ejecta to Earth may be as high as ~7.5%, with about a third of terrestrial encounters occurring within 10 Ma. These results are consistent with the measured cosmic-ray exposure ages for SNC meteorites, which vary from 3 to 16 Ma (Eugster et al. 1997). The exposure ages cluster into groups that are consistent with petrology and other characteristics (Treiman 1995a), implying that cosmic-ray exposure was initiated at launch and that the ejected rocks were meter-sized or smaller.

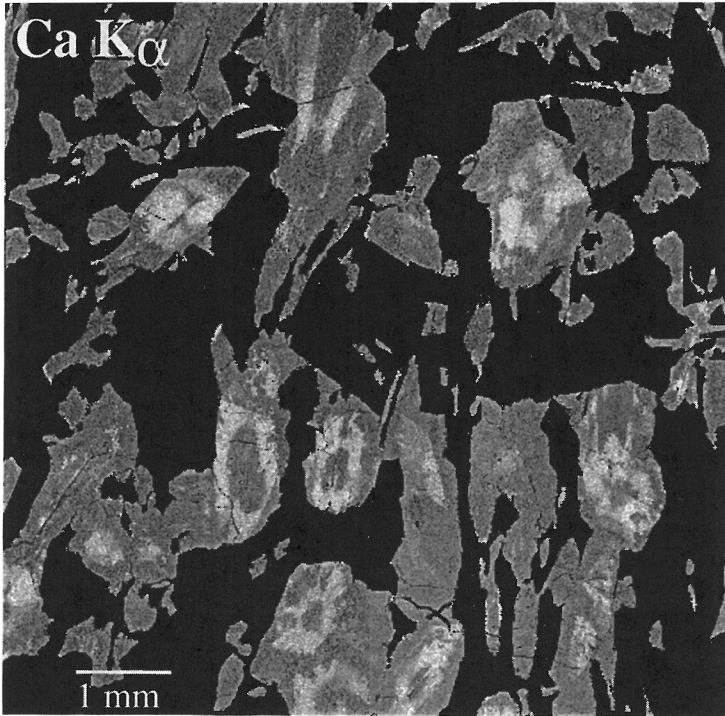
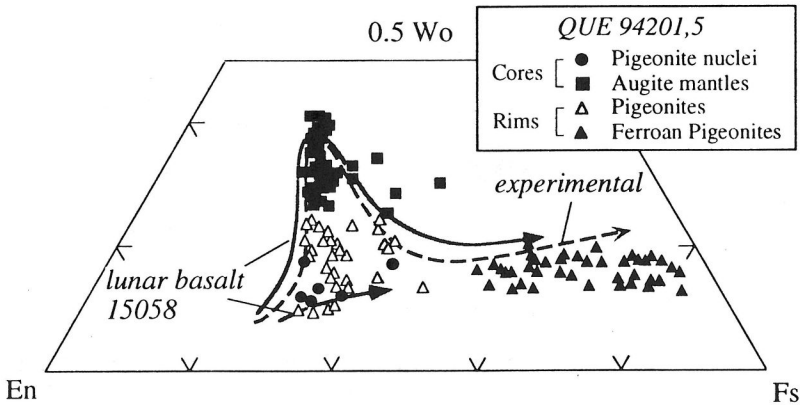
### BASALTIC SHERGOTTITES (BASALTS)

The basaltic shergottites are named for Shergotty, a ~5 kg meteorite which fell in the Bihar State of India in 1865 (originally described by Tschermak, 1872). The Zagami meteorite (~18 kg) fell in Katsina Province, Nigeria, in 1962. Other basaltic shergottites were recovered in Antarctica: EETA79001 (7.9 kg found at Elephant Moraine in 1979), and QUE94201 (12 g found in the Queen Alexandria Range in 1994). EETA79001 actually consists of two lithologies, termed A and B, that appear to represent distinct magmas.



**Figure 3.** Pyroxenes in Shergotty consist of relatively homogeneous magnesian cores of pigeonite and augite with Fe-rich rims (analyses by Stöffler et al. 1986). The accompanying FeK $\alpha$  map of Shergotty clearly shows the magnesian cores, interpreted to be cumulus crystals.

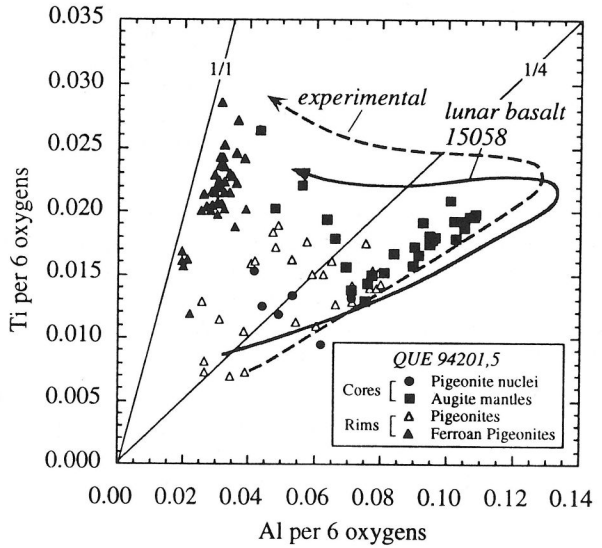
grains exhibit more irregular zoning. Typical core and rim compositions are given in Table A1, and zoning trends in Shergotty are illustrated in Figure 3. The homogeneous magnesian cores of pigeonite (En<sub>57-60</sub>Wo<sub>12</sub>) and augite (En<sub>48</sub>Wo<sub>32</sub>) have been interpreted as cumulus crystals (Stolper and McSween 1979, McCoy et al. 1992, Treiman and Sutton 1992), possibly representing phenocrysts crystallized at depth and physically concentrated in the magma. In contrast, pyroxenes in QUE94201 and EETA79001 lithology B display complex zoning patterns that are similar to those formed by continuous crystallization of lunar basaltic melts (McSween et al. 1996, Mikouchi et al. 1997). Pyroxene cores have nuclei of magnesian pigeonite mantled by augite, in turn rimmed by strongly zoned ferroan pigeonite and pyroxferroite (Table A1 and Fig. 4). Mantling of pigeonite by augite reflects increasing Ca concentration in residual liquids due to suppression of plagioclase crystallization, and the subsequent replacement of augite by ferroan pigeonite is correlated with the onset of plagioclase crystallization. Thus EETA79001 lithology B and QUE94201 may represent liquid compositions without cumulus pyroxenes. Some portions of the Zagami meteorite, termed the dark mottled lithology by McCoy et al. (1995), may be similar to QUE94201.



**Figure 4.** Pyroxenes in the QUE94201 basaltic shergottite show complex zoning, consisting of magnesian pigeonite cores mantled by augite, in turn mantled by ferroan pigeonite and pyroxferroite (after McSween et al. 1996). The accompanying Ca K $\alpha$  map of QUE94201 clearly illustrates the augite mantles. The observed trend mimics that of pyroxenes in lunar basalt 15058 and in continuous crystallization experiments on the same lunar basalt composition.

The Mn/Fe ratios of shergottite pyroxenes (and other SNC pyroxenes) are slightly higher than those in HED achondrites and considerably higher than those in lunar

pyroxenes (Stolper and McSween 1979, McSween et al. 1996). This abundance ratio is useful in distinguishing martian meteorites from other samples. Both Fe and Mn have similar volatilities, so it is thought that various bodies accreted with essentially the same (i.e. chondritic) Fe/Mn ratio. These elements also fractionate similarly during melting, so the Fe/Mn ratio of a basalt is nearly identical to that of its source mantle. However, during core separation Fe is fractionated from Mn, so core formation imprints a characteristic Fe/Mn ratio on the complementary silicate portion of the planet. That ratio is readily determined from pyroxenes in basalts.



**Figure 5.** Molar Ti versus Al in pyroxenes of the QUE94201 shergottite (after McSween et al. 1996). With progressive crystallization, Al first increases and then decreases, the latter representing the onset of plagioclase crystallization. This trend, seen in all basaltic shergottites, is similar to that measured in pyroxenes of lunar basalt 15058 and in continuous crystallization experiments

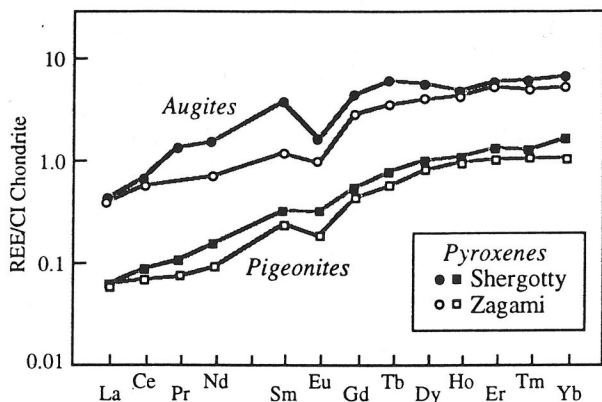


Figure 6. REE abundances in pyroxenes of basaltic shergottites (after Wadhwa et al. 1994).

pigeonite and augite lamellae in both cores and rims record equilibration temperatures of  $\sim 950^{\circ}\text{C}$ . Based on comparison with microstructural studies of pigeons in lunar and terrestrial basalts, the thicknesses of exsolution lamellae in pigeonites suggest cooling rates of 0.05 to  $0.5^{\circ}\text{C}/\text{day}$ . The faster rate is similar to that inferred for QUE94201 based on calculation of the rate necessary to prevent diffusive modification of Mg-Fe zoning in pigeonite rims (Mikouchi et al. 1996).

Plagioclase in the basaltic shergottites has been converted to *maskelynite*. Most grains retain their original morphologies and normal zoning patterns, generally ranging from cores of  $\text{An}_{57-66}$  in the cores to  $\text{An}_{52-43}$  in the rims (Table A2). Maskelynites also contain small amounts of K, Fe, and Mg, with  $\text{Fe}/(\text{Fe}+\text{Mg})$  increasing with albite content.

*Magnesian olivine* and *orthopyroxene* occur only in EETA79001, lithology A. These phases are xenocrysts similar to the major minerals in lherzolithic shergottites, so they will be described in that section. *Fayalitic olivine* ( $\text{Fa}_{90-98}$ ) occurs as an accessory mineral in the late-stage mesostasis of Shergotty and Zagami (Smith and Hervig 1979, Stolper and McSween 1979, McCoy et al. 1993) and QUE94201 (McSween et al. 1996). Olivine was noted in the Mössbauer spectra of Zagami by Vistisen et al. (1992).

The oxide minerals in basaltic shergottites are normally *ilmenite* ( $\text{Ilm}_{95}\text{Hm}_5$ ) and *titanomagnetite* ( $\text{Mt}_{37}\text{Usp}_{63}$ ). Ilmenite occurs both as anhedral grains intergrown with titanomagnetite and as thin lamellae within titanomagnetite. The oxide compositions (Table A4) define a temperature of  $860^{\circ}\text{C}$  and an  $f\text{O}_2$  of  $10^{-14}$ , corresponding approximately to the quartz-fayalite-magnetite buffer assemblage (Stolper and McSween 1979). However, QUE94201 contains virtually hematite-free ilmenite and magnetite-free ulvöspinel (Table A4), indicating more reducing conditions near the iron-wüstite buffer (McSween et al. 1996). The primary ulvöspinel grains in QUE94201 now consist of mosaic intergrowths of titanomagnetite and ilmenite, resulting from subsolidus oxidation-exsolution. Lithology A of EETA79001 also contains chromite xenocrysts (described later).

Sulfide minerals are primarily *pyrrhotite* ( $\text{Fe}_{0.92-0.94}\text{S}$ ) containing minor Ni and Cu (Smith and Hervig 1979). Small grains of pure magnetite associated with pyrrhotite in QUE94201 allow the possibility that the primary sulfide in this meteorite may have been troilite, which underwent secondary oxidation or weathering (McSween et al. 1996). The sulfur isotopic compositions ( $\delta^{34}\text{S} = -1.9$  to  $+0.8\%$ ) of pyrrhotites in basaltic shergottites are unfractionated from the chondritic ratio (Greenwood et al. 1997). *Pentlandite* was also noted in EETA79001 (McSween and Jarosewich 1983).



Phosphates include both *merrillite* and *chlorapatite*, but merrillite is by far the dominant phosphate phase. (The term “whitlockite” is often used interchangeably with “merrillite” in describing meteoritic phosphate, and “whitlockite” has been used almost exclusively in literature on martian meteorites. However, Rubin (1997b) noted that structural differences between these phases indicate that “merrillite” is the appropriate name.) REE abundances in phosphates were analyzed by Wadhwa et al. (1994) and McSween et al. (1996). Merrillite is the primary carrier of REE, and mass balance calculations indicate that bulk-rock REE concentrations can be accurately accounted for with 0.5 to 1.5 wt % merrillite, the approximate modal abundance of this phase. Apatite in Zagami has a very high D/H ratio ( $\delta D = +3000$  to  $+4300\%$ ) approaching that of the martian atmosphere (Watson et al. 1994).

Glassy mesostasis in the basaltic shergottites commonly contains silica in addition to fayalite. Stöffler et al. (1986) described a 200  $\mu\text{m}$  grain of  $\alpha$ -quartz in Shergotty. *Baddeleyite* has been described in Shergotty (Smith and Hervig 1979) and QUE94201 (McSween et al. 1996).



**Figure 7.** Magmatic inclusion (~0.16 mm across) in the core of a Shergotty pyroxene, viewed in plain light. Hercynitic spinel with magnetite cores (opaque cubes at bottom), kaersutite (dark grain at center), and sulfide (opaque grain at top) are set in glass.

Trapped magmatic inclusions in the cores of pyroxenes in Shergotty, Zagami, and EETA79001 (Fig. 7) commonly contain glass, amphibole, and hercynitic spinel (Treiman 1985 1997). The amphibole is *ferro-kaersutite* or *titano-alumino-ferro-tschermakite* (terminology of Leake et al. 1997), with high concentrations of Ti and Al, very low OH (~1/10 of that expected), and  $\delta D = +500$  to  $+1670\%$  (Watson et al. 1994). The spinel is approximately  $\text{FeAl}_2\text{O}_4$  and has a distinctive green color. Treiman (1985) suggested that the crystallization of these minerals in trapped melt inclusions required pressures of at least 0.1 GPa, but more recent studies (Popp et al 1995a 1995b) imply that low-OH kaersutite may be stable at lower pressures.

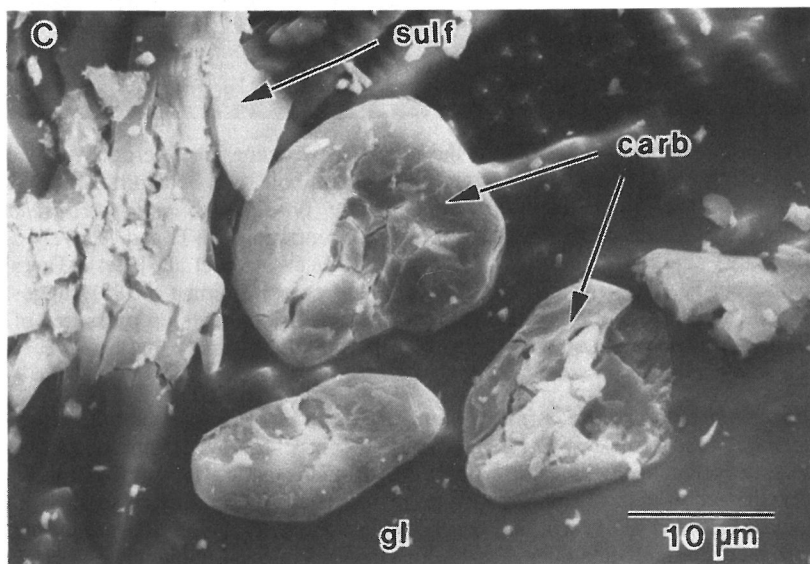
**Shock metamorphic minerals and effects.** Shergotty is the type specimen for *maskelynite* (Tschermak, 1872), a diaplectic glass formed from plagioclase. The maskelynite generally lacks crystal structure, as indicated by its isotropism. However, powder diffraction of maskelynite separates reveals small amounts of coherently diffracting plagioclase (Hörz et al. 1986), and thermoluminescence studies of Shergotty and Zagami likewise indicate small quantities of crystalline material in maskelynite (Hasan et al. 1986). El Goresy et al. (1997) described two kinds of “maskelynite” in Shergotty: Type 1 grains are smooth and anhedral with no detectable chemical zoning, whereas Type 2 grains have

remnant birefringence and twinning and exhibit fractures and zoning. They interpreted the Type 1 grains to be shock melts rather than diaplectic glasses.

The shock pressures required to form maskelynite vary with plagioclase composition. Shergotty and Zagami have experienced equilibrium shock pressures of ~29 GPa, as determined from index of refraction measurements of maskelynite calibrated to shock pressure (Stöffler et al. 1986, Langenhorst et al. 1991), although small pockets and veins of impact melt suggest higher local pressures of 60-80 GPa. EETA79001 experienced a slightly higher equilibrium shock pressure of ~34 GPa (Stöffler et al. 1986), and some maskelynite grains show evidence of flow structures suggesting melting (McSween and Jarosewich 1983). Shock melt pockets and veins are also more prominent in this meteorite. The shock melts consist of brown vesicular glass containing relict crystals and secondary skeletal olivine and pyroxene crystals. The compositions of shock-melted glasses are similar to the bulk composition of the host lithology, but are slightly enriched in the plagioclase component (McSween and Jarosewich 1983). Shock melt has also been reported in QUE94201 (Mikouchi et al. 1996).

*Ringwoodite* and *majorite*, the high-pressure polymorphs of olivine and pyroxene, respectively, were tentatively reported within shock veins in EETA79001 (Steele and Smith 1982). Stöffler et al. (1986) also reported a possible grain of *stishovite* in Shergotty. Other shock effects in all basaltic shergottites include mosaicism, polysynthetic twinning, and planar features developed in pyroxenes, mechanical twinning in ilmenite, and mosaicism and strongly reduced birefringence in quartz (Stöffler et al. 1986, Müller 1993).

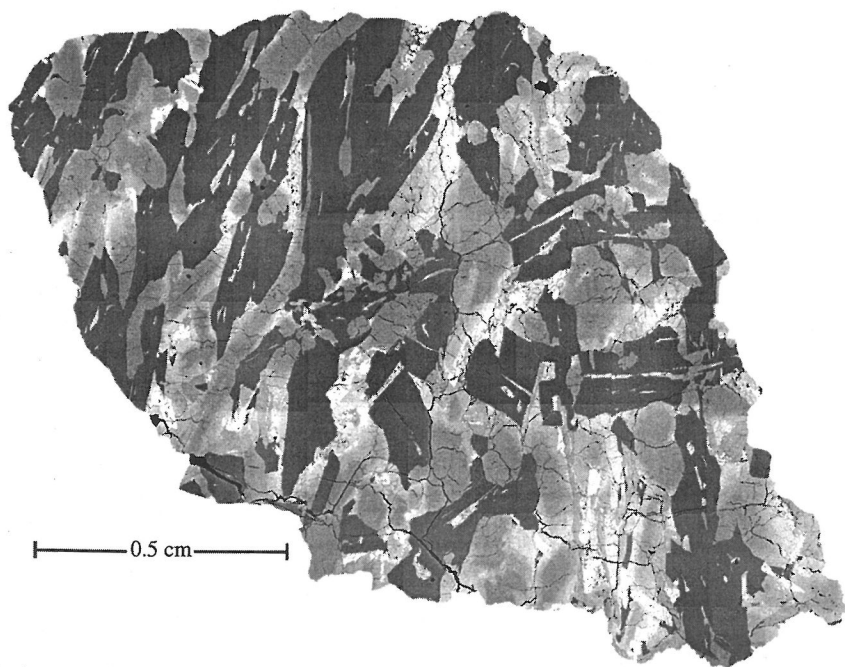
**Alteration minerals.** Small quantities of secondary alteration minerals in SNC meteorites formed by reaction with aqueous fluids, either within the shallow crust or as weathering products on the surface of Mars. Small platy grains of an Fe-rich, Al-poor illite-like *clay* occur in EETA79001, and sulfur pyrolysis experiments suggest the presence of S- and Cl-rich aluminosilicate *mineraloids* (Gooding and Muenow 1986). Tiny veins and disseminated grains of granular *calcite* (Fig. 8), sometimes associated with laths of *gypsum*



**Figure 8.** Secondary alteration phases in EETA79001 shergottite glass include carbonate and Ca-sulfate. This SEM photomicrograph was taken by Gooding et al. (1988).

and *Mg-phosphate*, occur within impact-melted glass (Gooding et al. 1988). A portion of the water extracted from basaltic shergottites has O isotopic compositions that are distinct from those of the igneous silicates (Karlsson et al. 1992), implying that the alteration fluid was not in equilibrium with the lithosphere. The isotopic compositions of C and O extracted from the calcite are distinct from terrestrial carbonates (Wright et al. 1988), supporting an extraterrestrial origin. Sulfates, aluminosilicate clays, and secondary silica have been found in QUE94201 (Wentworth and Gooding 1996), but it has not yet been established that these phases are extraterrestrial.

Most of the secondary minerals in shergottites occur as isolated grains either along fractures or partially included in impact glasses. A few vesicles in EETA79001 contain fluffy white deposits of *Ca carbonate*, *Ca sulfate*, and unidentified *phosphates*, the so-called "white druse" (Martinez and Gooding 1986, Gooding et al. 1988, Gooding and Wentworth 1991). The origin of this material is unclear; its O isotopes appear to be martian (Clayton and Mayeda 1988, Wright et al. 1988), but it contains sufficient  $^{14}\text{C}$  to suggest a terrestrial origin (Jull et al. 1992).



**Figure 9.** Backscattered electron image of QUE94201, showing preferred orientation of pyroxene grains with interstitial maskelynite and other phases.

### **Petrology, geochemistry, and geochronology**

**Petrology.** The basaltic shergottites exhibit foliated textures produced by the partial alignment of pyroxene prisms (Fig. 9), with interstitial maskelynite and other phases. This fabric was initially attributed to crystal accumulation in a shallow intrusion or thick flow (Duke 1968, Stolper and McSween 1979), a conclusion supported by phase equilibrium experiments demonstrating that Shergotty and Zagami are not multiply saturated with pyroxenes and feldspar at low pressure (Stolper and McSween 1979). Although most workers accept a crystal accumulation model for these meteorites, the foliation is now

commonly attributed to flow alignment in extruded lavas (e.g. McSween 1994). The confinement of melt inclusions containing amphibole and spinel to the magnesian cores of pyroxene crystals in Shergotty and Zagami supports the idea that the cores are cumulus and crystallized under differing conditions (McCoy et al. 1992), but there is now doubt that the presence of amphibole requires a high confining pressure. Petrographic and experimental estimates of the proportion of cumulus pyroxene cores in these meteorites give conflicting results (Stolper and McSween 1979, McCoy et al. 1992, Treiman and Sutton 1992, McCoy and Lofgren 1996, Hale et al. 1997). As already noted, QUE94201 and EETA79001 lithology B may not contain cumulus pyroxenes.

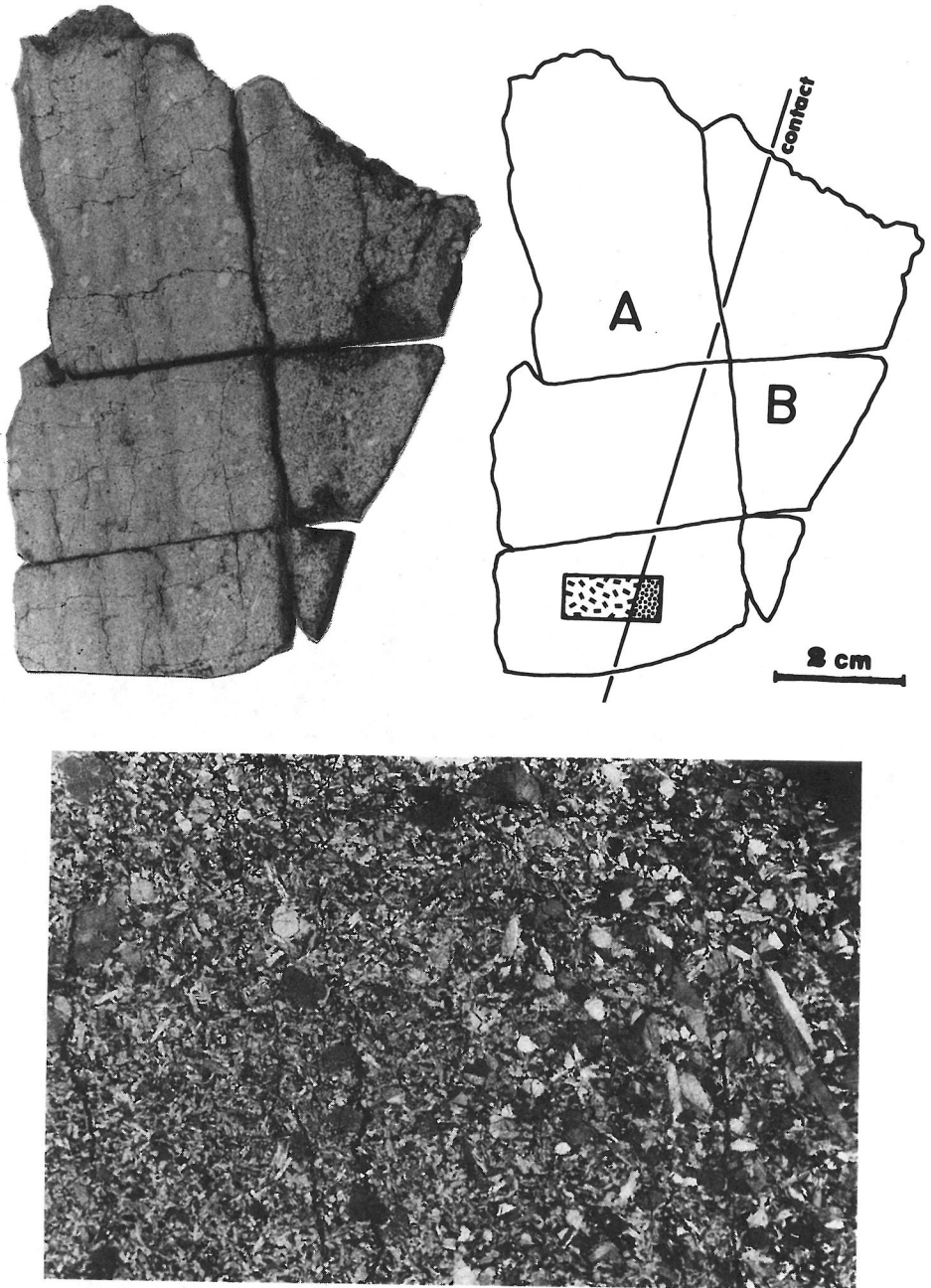
EETA79001 contains two igneous lithologies joined along a diffuse, planar contact (Fig. 10). McSween and Jarosewich (1983) interpreted these lithologies as flows, but Mittlefehldt et al. (1997) suggested that lithology A might be an impact melt. This scenario is consistent with the partially resorbed clasts (occurring mostly as xenocrysts) of ultramafic lherzolite in this basalt, which are difficult to explain on thermal grounds (Wadhwa et al. 1994). However, it seems unlikely that igneous activity and impact would occur so closely in time that both lithologies would have the same crystallization ages (Wooden et al. 1982).

Zagami contains pockets (up to cm-size) of a distinct, "dark mottled lithology," rich in fayalite, oxides, phosphate, and mesostasis (Vistisen et al. 1992, McCoy et al. 1993). This material represents the last dregs of melt during the fractional crystallization of this magma. This unusual differentiate has not been found as pockets in other basaltic shergottites, but it is petrographically similar to the small QUE94201 shergottite (McSween et al. 1996).

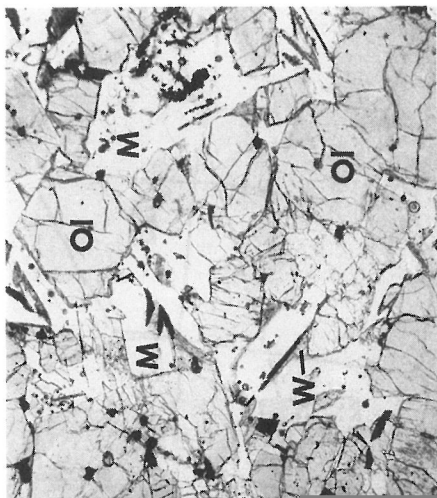
**Geochemistry.** Complete elemental analyses of all basaltic shergottites except QUE94201 were tabulated by Treiman et al. (1986); an analysis of QUE94201 was published by Warren and Kallemeyn (1997), and analyses from other sources are available in abstract form (see Meyer 1996). All these basalts are Fe-rich and Al-poor compared to terrestrial basaltic counterparts, and their compositions are thought to reflect the composition and redox state of the martian mantle (Longhi et al. 1992). Samples tend to be heterogeneous in trace element abundances, because these elements are distributed among a few rare phases. The abundances of chalcophile elements in shergottites and those inferred for the martian mantle are low, reflecting segregation of sulfide into the core (Treiman et al. 1986). Conversely, moderately volatile element abundances are fairly high (Laul et al. 1986), implying that Mars accreted abundant volatiles. Certain element ratios appear to be uniform in these meteorites, or nearly so, and may serve as geochemical fingerprints to identify members of this group: Fe/Mn and K/U (McSween et al. 1979a); K/La, Al/Ti, and Na/Ti (Treiman et al. 1986); and Ga/Al (Warren and Kallemeyn 1997).

It is difficult to relate Shergotty and Zagami to the Antarctic shergottites based on trace element and radiogenic isotope systematics. The initial Sr, Nd, and Pb isotopic compositions for Shergotty and Zagami are different enough from those of EETA79001 to require that they formed from separate magmas (Jones 1989). Assimilation of an isotopically distinct crustal component rich in incompatible elements by the parent magma of Shergotty and Zagami provides a possible explanation for these differences (Shih et al. 1982, Longhi and Pan 1989). Rare earth element patterns for all basaltic shergottites are LREE-depleted and lack Eu anomalies (e.g. Smith et al. 1984). The LREE depletion in QUE94201 is more extreme than for other basaltic shergottites (McSween et al. 1996), and its initial Nd isotope ratio of  $\epsilon^{143}\text{Nd} = +48$  (Borg et al. 1997) implies that the extreme LREE depletion occurred early in Mars' history.

**Geochronology.** The crystallization ages of most basaltic shergottites have been difficult to interpret. Whole-rock Rb-Sr and U-Th-Pb "isochrons" of ~4.5 Ga and Sm-Nd "isochrons" of ~1.3 Ga are commonly interpreted as mixing lines between different



**Figure 10.** A slab of the EETA79001 meteorite contains two lithologies, labelled A and B, joined along a diffuse, planar contact. The sketch illustrates the location of a thin section bridging the contact; a photomicrograph of the thin section is shown below (from McSween 1985). Lithology A has a finer-grained groundmass and contains xenocrysts of olivine, orthopyroxene, and chromite. Lithology B is more typical of a basaltic shergottite.



Micrographs showing olivines (Ol) and chromite (Ch) in some areas of the impact melt. (b) Pockets of impact melt consist of brown glass and small clusters of chromite euhedra.

reservoirs (e.g. Jones 1986), although that is not universally accepted. Rb-Sr and U-Th-Pb mineral isochrons for Shergotty, Zagami, and EETA79001 give virtually identical ages of  $180 \pm 20$  Ma (Shih et al. 1982) and  $190 \pm 30$  Ma (Chen and Wasserburg 1986), which are usually interpreted to indicate the time of crystallization. Various controversies related to attempts to disentangle crystallization and shock ages for these meteorites were summarized by McSween (1994). On the other hand, QUE94201 yields identical Rb-Sr and Sm-Nd crystallization ages of  $327 \pm 12$  Ma and  $327 \pm 19$  Ma respectively (Borg et al. 1997).

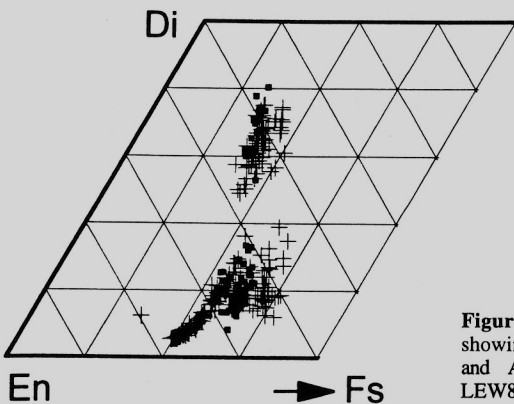
## LHERZOLITIC SHERGOTTITES (LHERZOLITES)

All known lherzolitic shergottites were recovered in Antarctica. The group consists of ALHA77005 (a 482 g sample found in the Allan Hills in 1977), Y793605 (a 16 g meteorite found in the Yamato Mountains in 1979), and LEW88516 (a 13 g specimen recovered at Lewis Cliff in 1988). Xenocrysts and largely disaggregated xenoliths of lherzolite also occur within lithology A of the EETA79001 basaltic shergottite.

### Mineralogy

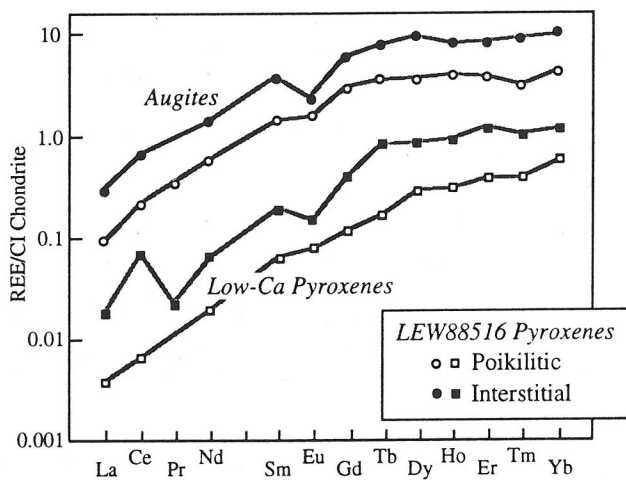
**Igneous minerals.** Mineralogical descriptions of the lherzolitic shergottites can be found in McSween et al. (1979b), Smith and Steele (1984), Harvey et al. (1993), Ikeda (1994 1997), Treiman et al. (1994), Mikouchi and Miyamoto (1996 1997), and Gleason et al. (1997).

**Olivine** varies in composition from  $Fo_{76-60}$  (Table A3) within the meteorites of this group, although different meteorites show different mean values. Olivines poikilitically enclosed by pyroxenes are rounded and slightly more magnesian than the euhedral to subhedral grains in non-poikilitic areas (Fig. 11a,b). Most grains contain minor Mn, Ca, and Ni. The olivines in all three lherzolites have a distinctive brown color, apparently caused by oxidation ( $\sim 4.5\%$  of the total Fe in ALHA77005 olivine is trivalent, and charge transfer produces an absorption band that results in the color—Ostertag et al. 1984). In all three meteorites, the olivines are too Fe-rich to be in equilibrium with coexisting pyroxenes, apparently because subsolidus reequilibration of olivine is faster than pyroxene (Harvey et al. 1993).



**Figure 12.** A portion of the pyroxene quadrilateral, showing pyroxene analyses for LEW88516 (crosses) and ALHA77005 (filled squares). Pyroxenes in LEW88516 span a greater range in Wo and En contents. From Treiman et al. (1994).

A variety of pyroxenes occur in the lherzolites. Magnesian low-Ca pyroxene, possibly orthopyroxene (although its structural state is unknown), mostly forms large oikocrysts (Fig. 11a). These crystals are monotonically zoned from  $En_{78}Wo_4$  to  $En_{65}Wo_{15}$  (Fig. 12).

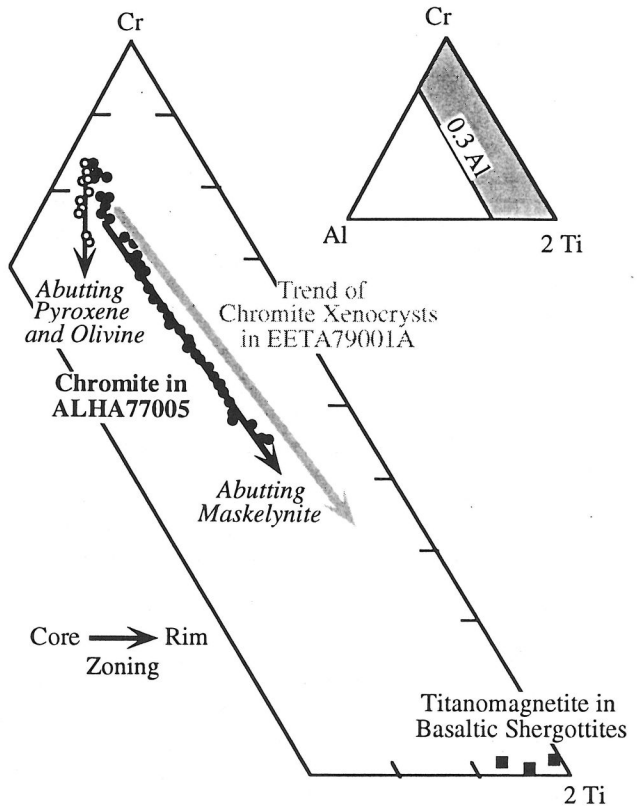


**Figure 13.** REE abundances in pyroxenes of the LEW88516 lherzolithic shergottite. After Wadhwa et al. 1994.

Magnesian *pigeonite* forms a broad scatter of compositions at the end of this trend (Fig. 12). The pigeonite grains occur as smaller grains in interstitial areas. *Augite* forms exsolution lamellae in low-Ca pyroxenes, as well as small interstitial grains. The augites are apparently zoned from  $En_{45}Wo_{40}$  to lower Ca contents (Fig. 12), although this trend may represent overlap of the electron beam on exsolved phases. Representative pyroxene analyses are given in Table A1. Application of two- and three-pyroxene geothermometry to all three meteorites gives equilibration temperatures of  $\sim 1150^{\circ}\text{C}$  (Ishii et al. 1979, Harvey et al. 1993, Mikouchi and Miyamoto 1996). Pyroxene compositions in LEW88516 are slightly more Fe-rich than those in ALHA77005 and Y953605 (Harvey et al. 1993, Treiman et al. 1994, Mikouchi and Miyamoto 1996).

Minor and trace elements in pyroxenes were analyzed by Lundberg et al. (1990), Harvey et al. (1993), and Wadhwa et al. (1994 1997). Poikilitic low- and high-Ca pyroxenes show increases in Ti, Al, Sc, Y, Zr, Cr, and V and decreases in Cr with increasing Fe/(Fe+Mg), and their REE patterns are LREE-depleted with small, negative Eu anomalies. REE abundances in low-Ca pyroxenes are consistently lower than in augites, and the slopes of their patterns are generally steeper (Fig. 13). Trace element zoning in





**Figure 14.** Molar compositions of spinels in ALHA77005 (modified from McSween et al. 1979b, and Ikeda 1994). Chromites in contact with pyroxene and olivine have slightly aluminous rims, whereas those abutting maskelynite have Ti-rich rims. The zoning trend for chromite xenocrysts in EETA79001 (McSween and Jarosewich 1983), and compositions of titanomagnetites in the basaltic shergottites Shergotty (Stolper and McSween 1979), EETA79001 (McSween and Jarosewich 1983), and QUE94201 (McSween et al. 1996) are also illustrated.

virtually hematite-free (Table A4) but contains significant Mg and minor Mn and Cr (Ikeda 1994).

Other phases include *merrillite* and sulfides, both *pyrrhotite* and *pentlandite*. Pyrrhotite contains minor Ni, Co, Cu, and Zn (Ikeda 1994). Merrillite is the major REE carrier in lherzolites, as it is in basaltic shergottites. The REE patterns for merrillites are LREE-depleted with small negative Eu anomalies (Wadhwa et al. 1994). Pyrrhotite in LEW88516 contains S with similar isotopic composition ( $\delta^{34}\text{S} = -1.9\%$ ) to that in basaltic shergottites (Greenwood et al. 1997).

Magmatic inclusions in the centers of olivine grains contain glass and augite rich in Al, Ti, and Ca compared to other augites in lherzolites. Other accessory minerals in the inclusions are chromite, spinel, low-Ca pyroxene, sulfide, ilmenite, and phosphate, but amphibole has not been reported (Harvey et al. 1993). The inclusions have been analyzed by INAA for trace element abundances (Lindstrom et al. 1993).

**Shock metamorphic minerals and effects.** Plagioclase has been converted to maskelynite in all the lherzolitic shergottites. In ALHA77005, Ikeda (1994) described some grains of feldspathic glass with thin plagioclase rims, which he attributed to shock melting and subsequent crystallization of plagioclase. Thermoluminescence measurements on this meteorite (Hasan et al. 1986) support the identification of small quantities of plagioclase. Some maskelynite grains show flow lines and vesicles (Treiman et al. 1994).

Olivine shows closely spaced planar elements, and pyroxenes exhibit twinning and mosaicism (Treiman et al. 1994). Oxidation of Fe in olivine to produce its distinctive

Xenocrysts of low-Ca pyroxene, olivine, and chromite in lithology A of EETA79001 have compositions that are the same as in their lherzolite counterparts, leading to the hypothesis that this basaltic shergottite magma intruded lherzolite and incorporated pieces of it as xenoliths (McSween and Jarosewich 1983, Steele and Smith 1983). Thus, this meteorite is possibly derived from the same geographic area as the lherzolic shergottites, and plausibly liberated in the same impact event. The younger cosmic-ray exposure age of EETA79001 (~0.5 Ma) may indicate breakup of a larger rock in space at that time.

**Geochemistry.** Chemical analyses for lherzolic shergottites were tabulated by Treiman et al. (1986 1994), Meyer (1996), Warren and Kallemeyn (1996 1997), and Gleason et al. (1997). Compared to basaltic shergottites, these meteorites have lower abundances of Si and Al, and higher Fe and Mg, reflecting the abundance of olivine. The lherzolites have similar diagnostic element ratios to those in basaltic shergottites (Treiman et al. 1986), but their absolute trace element abundances are generally lower by an order of magnitude (McSween et al. 1979a).

Accurate REE abundances in whole-rock samples are difficult to obtain, because of the problem in obtaining representative samples of these coarse-grained, heterogeneous rocks. However, a whole-rock REE pattern for ALHA77005 (Smith et al. 1984) is in good agreement with calculated REE abundances using ion microprobe analyses of phases and modal analyses (Lundberg et al. 1990). REE abundances in this and other lherzolites (e.g. Treiman et al. 1994) are much lower than in basaltic shergottites, and their patterns are strongly LREE-depleted with distinctive "humps" at Tb that trail off towards lower HREE abundances.

**Chronology.** Crystallization ages for the lherzolic shergottites suffer from the same uncertainties that plague the basaltic shergottites. Rb-Sr ages of  $187 \pm 12$  Ma (Shih et al. 1982) and  $154 \pm 6$  Ma (Jagoutz 1989) have been accepted as the crystallization age for ALHA77005, although the Sm-Nd age is ~325 Ma (Shih et al. 1982). Radiogenic isotope dates for other lherzolites are not available.

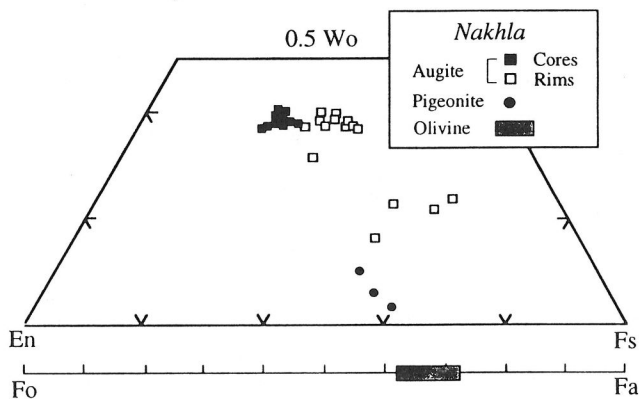
## NAKHLITES (CLINOPYROXENITES/WEHRLITES)

There are three known nakhlite meteorites. The type meteorite, Nakhla, fell in 1911 at El-Nakhla el-Bahariya, an oasis in northern Egypt. It fell as many individual stones; the known mass is approximately 10 kg, but some reports have put the total mass at ~40 kg. Lafayette is a single stone of 0.8 kg, and was recognized in 1931 at Purdue University. Its pristine fusion crust would seem to imply that it was collected soon after it fell, but  $^{14}\text{C}$  measurements give a fall date of ~8,000 years ago (Jull et al. 1997a). Governador Valadares, a single stone of 0.16 kg, was found in Minas Geras province, Brazil, in 1958. It is unweathered and was probably found soon after it fell. Considering the uncertain histories of Lafayette and Governador Valadares, it remains possible that they are all pieces of the Nakhla fall.

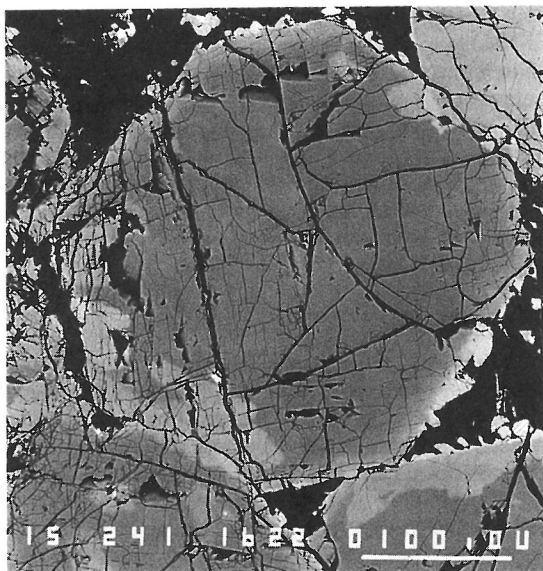
### Mineralogy

**Igneous minerals.** The nakhlites are igneous rocks, and their mineralogy is dominated by phases common in basaltic igneous rocks on Earth and throughout the solar system. Augite is by far the most abundant mineral, olivine is second, and all other minerals are minor. Mineralogical descriptions of nakhlites, and tabulations of mineral compositions, can be found in: Bunch and Reid (1975), Boctor et al. (1976), Berkley et al. (1980), Smith et al. (1983), Treiman (1986 1990 1993), Gooding et al. (1991), Harvey and McSween (1992 a,b), and Treiman et al. (1993).

Sub-calcic *augite* (Table A1 and Fig. 15) is present as euhedra and subhedra of 0.5 mm length on average. The augite is black in hand sample, and very pale green in thin section. Simple twins on {100} are common. In Nakhla and Governador Valadares, the bulk of each augite grain is a nearly homogeneous core of  $\sim\text{Wo}_{38.5}\text{En}_{37.5}$  (Smith et al. 1983, Treiman 1990, Harvey and McSween 1992b). Outside the core is a rim of nearly constant Wo content but monotonically increasing Fe/Mg ratio to  $\sim\text{Wo}_{33}\text{En}_{23}$ . The pattern of Fe/Mg change is consistent with igneous fractionation from a reservoir of limited volume, e.g. a magma pocket trapped in a cooling cumulate (Treiman 1990). Ferroan low-Ca pyroxene of variable composition discontinuously surrounds the rim zone, and sometimes replaces portions of both rim and core zones (Figs. 15 and 16). This late low-Ca pyroxene ranges in composition from  $\sim\text{Wo}_{02}\text{En}_{38}$  to  $\text{Wo}_{11}\text{En}_{24}$  to  $\text{Wo}_{24}\text{En}_{16}$  (Berkley et al. 1980, Treiman 1990, Harvey and McSween 1992b). Lafayette has a comparable range of pyroxene compositions, although the distinction between core and rim is weak (Harvey and McSween 1992b).



**Figure 15.** Pyroxene and olivine compositions in Nakhla (modified from Harvey and McSween 1992b). Augite cores have more Fe-rich rims, and pigeonite of variable composition replaces augite. Olivine is too Fe-rich to be in equilibrium with augite and is thought to have suffered subsolidus re-equilibration.



**Figure 16.** Backscattered electron image of Nakhla augite, showing the homogeneous core and a higher Z (higher Fe) rim and replacement zones. The horizontal bar is 100  $\mu\text{m}$  long.

Minor and trace element zoning patterns in nakhlite pyroxenes are complex. Although the augite cores have nearly constant Ca-Mg-Fe contents, their abundances of trivalent and tetravalent elements can vary by factors of two or three (Treiman 1990, Wadhwa and Crozaz 1995). McKay et al. (1994) found a bimodal distribution of Al contents in the cores and suggested that they might be sector-zoned. Outside the cores, minor and trace element abundances are consistent with fractional crystallization: Al, Ti, Zr, and the REE increase together while Mg and Cr decrease (Treiman 1990, Wadhwa and Crozaz 1995a).

There appear to have been no TEM, electron diffraction, or X-ray diffraction studies of pyroxenes from the nakhrites.

*Olivine* is the second most abundant mineral in the nakhrites. It is most apparent as postcumulus infillings among euhedral augite grains, but is also prominent in some sections as subhedral grains up to 4 x 3 mm. It is clear and olive-green in hand sample, and colorless in thin section; compared to augite, olivine has higher birefringence, contains rounded magmatic inclusions, and contains feathery chromite inclusions. The chemical compositions of olivine in Nakhla and Governador Valadares (Table A3) are somewhat variable, from Fo<sub>30</sub> to Fo<sub>17</sub> and CaO from 0.20 to 0.60% (Berkley et al. 1980, Treiman 1990, Harvey and McSween 1992b). This variability appears as a slight normal zoning in Fe/Mg from core to rim, and as oscillatory zoning in CaO (Treiman 1990, Harvey and McSween 1992b). The zoning in Fe/Mg probably reflects continuous diffusive exchange with late (evolving) magma (Longhi and Pan 1989, Harvey and McSween 1992b); variations in CaO content may reflect original growth zoning. Olivine in Lafayette is effectively of constant composition, Fo<sub>23</sub>, with CaO contents ranging only from 0.15 to 0.35% (Berkley et al. 1980, Harvey and McSween 1992b). Nakhlite olivines contain significant Ni (~ 200 ppm; Bunch and Reid 1975, Smith et al. 1983), but extremely low abundances of the REE (Wadhwa and Crozaz 1995).

1976). These oxide minerals (Table A4) are consistent with an oxidation state near the quartz-fayalite-magnetite buffer assemblage, 740°C and  $fO_2 = 10^{-17}$  (Reid and Bunch 1985). The intrinsic oxygen fugacity measurements of Delano and Arculus (1980) imply much more reduced conditions, somewhat above the iron-wüstite buffer.

Sulfide minerals in the nakhlites are poorly characterized. *Pyrite* is the apparently the most abundant sulfide in Lafayette, and it contains lamellae of *marcasite* (Bunch and Reid 1975, Boctor et al. 1976, Berkley et al. 1980). Minor *chalcopyrite* is also present (Bunch and Reid 1975, Bunch and Reid 1975, Meyer 1996). Iron monosulfide is common, and has been called *troilite* or FeS (Bunch and Reid 1975, Boctor 1976, Weincke 1978, Berkley et al. 1980). However, it is much more likely to be *pyrrhotite*, given the oxidation state of the nakhlites and the presence of pyrite and marcasite. In fact, Weincke's (1978) chemical analysis of 'troilite' from Nakhla appears to be pyrrhotite of composition  $Fe_{0.97}S$ .

Other minor minerals in the nakhlites include *chlorapatite*, a *silica* phase, and alkali-silica glass (Bunch and Reid 1975, Berkley et al. 1980). Wadhwa and Crozaz (1995a) have analyzed the chlorapatite for REE, and it is a significant contributor to the rare earth budgets of the nakhlites.

Magmatic inclusions in the nakhlite olivines (Fig. 17) have a slightly different mineralogy than the bulk rock (Harvey et al. 1992a, Treiman 1993). The inclusions consist principally of aluminous augite, silica-rich glass, and Ti-magnetite (ilmenite exsolutions not reported); less abundant minerals include pigeonite, silica, chlorapatite, alkali feldspar, Ti-Al chromite, pyrrhotite, and hercynite spinel (Harvey and McSween 1992a, Treiman

**Shock metamorphic minerals and effects.** The nakhlites show little evidence of shock. The plagioclase in the nakhlites remains crystalline and has not been converted to maskelynite. To our knowledge, no high-pressure phases, such as ringwoodite or majorite, have been reported from the nakhlites. Shock effects seem to be limited to polysynthetic twinning of augite on {001} (Berkley et al. 1980), minor granulation along fracture ('gouge') zones, and possibly some minor local shock melts.

**Alteration minerals.** The nakhlites contain a complex assemblage of low-temperature alteration minerals, first recognized and suggested to be extraterrestrial by Bunch and Reid (1975) and Reid and Bunch (1975). Gooding et al. (1991) proved the case by showing that alteration materials in Nakhla were transected by, and decomposed at, the meteorite's fusion crust; Treiman et al. (1993) demonstrated the same relationship for Lafayette. Stable isotope and noble gas studies have confirmed that the hydrous alteration products are martian (Karlsson et al. 1992, Drake et al. 1994, Swindle et al. 1995, Leshin et al. 1996, Romanek et al. 1996).

'Iddingsite' is the prominent alteration material—rusty red veinlets and patches in grain boundaries and replacing olivine (Bunch and Reid 1975, Boctor et al. 1976, Berkley et al. 1980). Nakhlite 'iddingsite' consists principally of ferroan *smectite* and *iron oxides* (Ashworth and Hutchison 1975, Gooding et al. 1991, Treiman et al. 1993). The smectite is poorly crystalline and variable in composition, and the iron oxides include two-ring ferrihydrite and magnetite (Gooding et al. 1991, Treiman et al. 1993). Chemical compositions of the iddingsite and its constituent phases are given by Bunch and Reid (1975), Boctor et al. (1976), Gooding et al. (1991), Treiman et al. (1993), and Treiman and Lindstrom (1997). Swindle et al. (1995, 1997) dated its formation by K-Ar methods as a few hundred Ma.

The iddingsite is accompanied by many ionic salt minerals, including *Ca-sulfate* (gypsum?), *Ca-carbonate* (calcite?), *siderite*, *Mg-phosphate* (epsomite? or kieserite?), and *halite* (Chatzitheodoridis and Turner 1990, Gooding et al. 1991, Treiman et al. 1993, Saxton et al. 1997, Vicenzi et al. 1997).

## **Petrology, geochemistry, and geochronology**

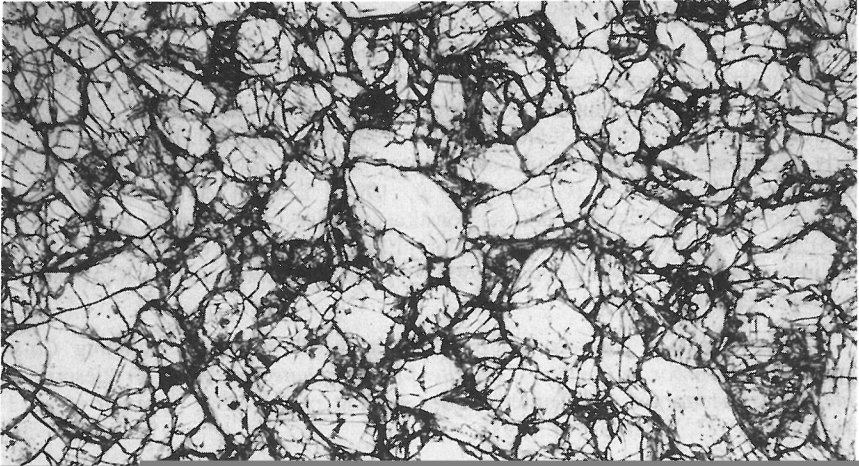
**Petrology.** The nakhlite meteorites (Fig. 18) are considered to be cumulate igneous rocks, enriched in augite and olivine relative to their parental magma (Reid and Bunch 1975, Berkley et al. 1980, Treiman 1986, 1990, 1993; Harvey and McSween 1992b). Berkley et al. (1980) showed that the nakhlite pyroxenes are weakly aligned, consistent with flow or crystal settling. Considering the sharp chemical zoning in the nakhlite pyroxenes and the acicular habit of its plagioclase, Treiman (1986) proposed that the nakhlites were surface flows or near-surface intrusions.

In fact, rocks of comparable mineralogy, compositions, and textures do occur in thick flows and sills on Earth (Treiman 1987). Friedman et al. (1995) studied the crystal size distributions (CSD) of the augites. They inferred that the augites grew rapidly from magma, and that the nakhlite cumulates formed by settling of crystal clusters or of crystal mush. Following accumulation and crystallization of intercumulus liquids, the nakhlites experienced varying degrees of subsolidus annealing, which caused olivines to reequilibrate (Harvey and McSween 1992b).

**Geochemistry.** Elemental analyses of the nakhlites were tabulated by Treiman et al. (1986) and Meyer (1996). As befit augite-olivine cumulates, the nakhlites are relatively rich in Ca, Mg, and Fe, and relatively poor in many incompatible elements like Al and Ti. Bulk abundances of incompatible elements are not far different from those of Shergotty and Zagami, but the nakhlites are relatively enriched in highly incompatible elements, e.g.

LREE/HREE =  $3 \times$  CI. As with the shergottites, moderately volatile elements are relatively abundant and chalcophile elements are quite depleted; some element abundance ratios appear to be essentially identical in nakhlites and shergottites (McSween et al. 1979a, Treiman et al. 1986, Laul et al. 1986, Warren and Kallemeyn 1997).

Because the nakhlites are cumulates, the compositions of their parent magmas have been difficult to retrieve. Various geochemical and experimental treatments have yielded a range of estimated compositions (Treiman 1986, Longhi and Pan 1989, Harvey and McSween 1992a, Treiman 1993, Kaneda et al. 1997), but all are ferroan basalts with low alumina content —  $\text{Al}_2\text{O}_3$  between 5 and 9% wt. This low  $\text{Al}_2\text{O}_3$  is manifested as the late crystallization and low abundance of plagioclase, and early crystallization of augite. Such Al-depleted magmas represent melts from a mantle previously depleted in Al (Longhi and Pan 1989, Treiman et al. 1995).





**CHASSIGNY (DUNITE)**

The Chassigny meteorite is unique, the only martian dunite. It was seen to fall in Haute-Marne, France, on October 3, 1815. It is not known if Chassigny fell as a single stone or several, but its total mass was about 4 kg (Meyer 1996).

**Mineralogy**

***Igneous minerals.*** Chassigny is interpreted as an igneous rock, an olivine-chromite cumulate (Fig. 19), possibly with some cumulus augite and pigeonite (Mason et al. 1975, Floran et al. 1978, Boynton et al. 1976, Wadhwa and Crozaz 1995). Among the cumulus minerals is an intercumulus assemblage of pyroxenes, plagioclase, and minor phases. Modern mineralogical descriptions of Chassigny, and tabulations of its mineral compositions, can be found in Floran et al. (1978), Johnson et al. (1991), and Wadhwa and Crozaz (1995).



**Figure 19.** Chassigny, viewed in plain light (2 mm across). This view shows euhedral to subhedral olivine, pyroxene, and plagioclase (upper left), opaque chromite, and a magmatic inclusion (lower left).

*Olivine* is by far the most abundant mineral in Chassigny, comprising approximately 90% of its volume (Prinz et al. 1974, Wadhwa and Crozaz 1995). It occurs as euhedra and subhedra averaging 1.5 mm long among the intercumulus phases, and commonly includes euhedral chromite grains (Floran et al. 1978). The chemical composition of Chassigny olivine is essentially constant, and rather ferroan compared to terrestrial dunites (Table A3). The olivines show no preferred orientation (Floran et al. 1978).

The olivines contain rounded inclusions, as large as 200  $\mu\text{m}$  diameter, with a unique minerals assemblage (at least for a meteorite): silicate glass, augite, low-Ca pyroxene, kaersutite, chorapatite, pyrrhotite, chromite, pentlandite and biotite, but no feldspars (Floran et al. 1978, Johnson et al. 1991). The inclusions have been interpreted as magmatic, partially crystallized droplets of magma trapped in the olivine as it grew. Inclusion pyroxenes are distinctly more aluminous and titanian than those in the bulk rock (e.g. 4.9%  $\text{Al}_2\text{O}_3$  in inclusion augite vs. 1.2% in intercumulus augite) and slightly more magnesian (Floran et al. 1978). Righter et al. (1997) analyzed the inclusion glass and biotite for trace elements.

*Augite* and *orthopyroxene* account for ~5% of Chassigny. The pyroxenes form poikilitic and interstitial grains among and around the cumulus olivines; at least some of the pyroxenes may have been cumulus themselves (Boynton, et al. 1976, Floran et al. 1978, Wadhwa and Crozaz 1995). The original igneous minerals appear to have been augite and pigeonite, the latter inferred from regions of orthopyroxene with abundant fine exsolution lamellae of augite (Wadhwa and Crozaz 1995). This exsolved pyroxene is associated with regions of homogeneous, unexsolved orthopyroxene and augite. The pyroxenes all have essentially the same molar  $\text{Fe}/(\text{Fe}+\text{Mg})$  (Table A1); variations in Ca content can be ascribed to mixing of end-member augite and orthopyroxene in the analytical volume. Despite the constancy of their divalent cation composition, pyroxenes in Chassigny preserve significant variations in abundances of tri- and tetravalent cations (Wadhwa and Crozaz 1995). Abundances of Al, Ti, Y, and Ce (and other rare earths) are positively correlated in both augite and orthopyroxene; augites show a 2-fold range in Ti content correlated with and 8-fold range in Ce content (Wadhwa and Crozaz 1995). There appear to have been no TEM, electron diffraction, or X-ray diffraction studies of pyroxenes from Chassigny.

*Feldspars* are present as intercumulus grains among the olivine and pyroxenes. Individual feldspars are chemically homogeneous, but there is a wide continuous range of compositions. Most of the analyzed grains are *plagioclase* (oligoclase/anorthoclase,  $\sim\text{An}_{10}\text{Ab}_{80}\text{Or}_{10}$ ), but individual analyses extend to labradorite,  $\sim\text{An}_{60}\text{Ab}_{30}\text{Or}_{10}$ , and *sanidine*,  $\text{An}_{02}\text{Ab}_{28}\text{Or}_{70}$  (Floran et al. 1978; Table A2). Wadhwa and Crozaz (1995) analyzed the plagioclase for rare earth elements.

The Chassigny *kaersutite* was the first find of a hydrous amphibole in a meteorite, and the first find of amphibole in the martian meteorites (Prinz et al. 1974, Floran et al. 1978). In cation content it is a typical kaersutite: rich in Ca, Ti and Al, and with an incompletely filled A site. Analyzed  $\text{OH}^- + \text{F}^- + \text{Cl}^-$  sum to  $\sim 0.40$  anions per formula unit, while their O(3) site must contain 2.000 total anions. The deficit in this site must be filled by  $\sim 1.60$   $\text{O}^{2-}$  anions, making this amphibole an oxy-kaersutite (Hawthorne 1981). Popp et al. (1995a,b) shown that the oxy substitution in kaersutite can be charge balanced by trivalent and tetravalent cations in the C (or 'M') sites.

A single grain of *trioctahedral mica* in Chassigny is the only documented occurrence of this mineral group in the martian meteorites (Johnson et al. 1991, Rubin 1997). The mica was described as biotite, but its molar  $\text{Mg}/\text{Fe}$  ratio of 2.07 places it nearly on the (arbitrary) boundary between biotite and phlogopite. If any of its iron is trivalent, as seems likely, Chassigny's mica should probably be classified as *phlogopite*. The mica is quite rich in

titanium, comparable in many respects to those in terrestrial alkaline rocks. The normalized formula has less Si+Al than required for the tetrahedral sites of a biotite; this may suggest  $Ti^{4+}$  in tetrahedral sites. Analyzed  $OH^- + F^- + Cl^-$  sum to  $\sim 1.70$  anions per formula unit, while the formula should contain 4.00 total anions. The deficit in this site must be filled by  $\sim 2.30 O^{2-}$  anions, making this mica an *oxy-titan-phlogopite*.

*Chromite* is the principal oxide mineral in Chassigny (Table A4), and is present as euhedra to 40  $\mu m$  across in olivine and as larger subhedra associated with feldspar and pyroxene among the olivines (Tschermak, 1885, Floran et al. 1978). Chassigny chromites contain significant ferric iron, constant  $Fe^{2+}/(Fe^{2+} + Mg)$ , and constant  $Cr/(Cr + Al)$ . However, Ti and  $Fe^{3+}$  contents are somewhat variable, and present an inverse relationship between  $[2 Ti^{4+} + Fe^{3+}]$  and  $[Cr^{3+} + Al^{3+}]$  content (Floran et al. 1978). Other oxide phases include *ilmenite*, *baddelyite*, and *rutile*, which are always found together associated with intercumulus feldspar (Floran et al. 1978).

Sulfide minerals are reported to include *pyrrhotite*, *marcasite*, and *pentlandite* (Floran et al. 1978). The 'troilite' analyzed by Floran et al. (1978) is apparently pyrrhotite,  $(Fe_{0.87}Ni_{0.01})S$ . Floran et al. (1978) suggested that the marcasite is a terrestrial weathering product, but the nakhlites and ALH 84001 contain preterrestrial (martian) marcasite and/or pyrite. Pentlandite has only been found in the magmatic inclusions.

The phosphate in Chassigny is *chlorapatite*, which occurs as slender prisms. Floran et al. (1978) and Wadhwa and Crozaz (1995) analyzed the chlorapatite for REE, and it is a significant contributor to Chassigny's rare earth budget.

**Shock metamorphic minerals and effects.** Chassigny shows variable effects of shock metamorphism, ranging from slightly perceptible to melting. Most of the olivine appears little shocked, with some undulatory extinction and with fractures radiating from magmatic inclusions. Elsewhere, the olivine is cut by planar deformation lamellae, principally oriented near  $\{130\}$ ,  $\{100\}$  and  $\{010\}$  (Sclar and Morzenti 1971, Floran et al. 1978, Greshake and Langenhorst 1997). Locally, olivine shows intense mosaicism and reduced birefringence. Olivine-composition melts were produced in pools and along fractures; this material is now glassy or devitrified to fine feathery crystals (Melosh et al. 1983); Tschermak (1885) may have described a similar assemblage. Pyroxenes appear to be little deformed, save fracturing and local recrystallization (Floran et al. 1978, Greshake and Langenhorst 1997). Feldspars show undulatory extinction and reduced birefringence; maskelynite and feldspar-composition melts are rare to absent (Floran et al. 1978, Melosh et al. 1983).

Overall, shock effects in plagioclase and olivine are consistent with a shock stage of S4 (moderately shocked) corresponding to shock pressures of 15 to 35 GPa (Stöffler et al. 1991). However, the presence of planar deformation features suggests a shock stage of S5, and olivine-composition melts suggest S6, consistent with local shock pressures in excess of 55 GPa (Stöffler et al. 1991).

**Alteration minerals.** Chassigny contains very little aqueous or low-temperature alteration material. Wentworth and Gooding (1994) found discrete grains of Ca carbonate (calcite), Mg-sulfate (gypsum or bassanite), and Mg-carbonate (magnesite and hydromagnesite?) in veinlets crossing the primary igneous minerals. No clays or ferric oxides were found, but traces of P and Cl are consistent with low-temperature materials in the other martian meteorites (e.g. Treiman et al. 1993). It is not certain that these materials are martian, though Wentworth and Gooding (1994) infer that they probably are. Surprisingly, bulk Chassigny contains a significant amount of water,  $\sim 0.1\%$   $H_2O$  (Karlsson et al. 1992, Leshin et al. 1996), far beyond the contributions from its amphibole

and biotite (Watson et al. 1994). The D/H ratio of this water is indistinguishable from terrestrial water (Leshin et al. 1996).

### **Petrology, geochemistry, and geochronology**

**Petrology.** Chassigny is interpreted as a cumulate igneous rock, enriched in olivine, chromite, and pyroxenes relative its parental magma (Prinz et al. 1974, Floran et al. 1978, Longhi and Pan 1981, Wadhwa et al. 1995). Initial crystallization was rapid enough to allow the olivines in Chassigny to entrap droplets of magma, which eventually became the magmatic inclusions. Cooling was, however, slow enough to permit the olivines and pyroxenes to diffusively equilibrate, and for the pigeonite to exsolve to orthopyroxene and augite. The integrated compositions of exsolved pigeonites and the compositions of the most ferromagnesian augites suggest magmatic temperatures around 1200°C (Wadhwa and Crozaz 1995). The compositions of the most calcian augites suggest temperatures as low as ~700°C (Floran et al. 1978).

Among the martian meteorites, Chassigny has been associated with the nakhlites in having the following characteristics: a LREE-enriched parent magma, a parent magma with liquidus olivine and augite, and a comparable crystallization age (see below). However, this association has been questioned by Wadhwa and Crozaz (1995), based in part on the finding of possibly cumulate pigeonite. They suggest that Chassigny is more closely related to

**Geochronology.** Unlike the shergottites, the geochronology of Chassigny appears simple. All chronometric systems ( $^{87}\text{Rb}$ - $^{87}\text{Sr}$ ,  $^{147}\text{Sm}$ - $^{143}\text{Nd}$ , K-Ar) yield ages near 1.3 Ga, which are generally interpreted as its time of crystallization (Lancet and Lancet 1971, Bogard and Nyquist 1979, Nakamura et al. 1982b, Jagoutz 1996). An event near 4.5 Ga, presumably silicate differentiation, is recorded as an excess of  $^{142}\text{Nd}$ , the decay product of the short-lived isotope  $^{146}\text{Sm}$  (Harper et al. 1995, Jagoutz et al. 1996).

### ALH84001 (ORTHOPIROXENITE)

The ALH84001 meteorite (1.9 kg) was found in the Allan Hills, Antarctica, in 1984. It was originally classified as a diogenite. Using a strictly non-genetic classification, this meteorite is a diogenite—a pyroxenite composed mostly of low-Ca pyroxene. Its identification as a martian meteorite was not made until a decade after its recovery (Mittlefehldt 1994). This meteorite does not fit into any of the previously established SNC categories.

### Mineralogy

**Igneous minerals.** Mineralogical descriptions of ALH84001 are given by Berkley and Boynton (1992), Mittlefehldt (1994), Treiman (1995b) and Harvey and McSween (1996).

ALH84001 consists predominantly of coarse *orthopyroxene* crystals of uniform composition ( $\text{En}_{70}\text{Wo}_3$ ) (Table A1). Contents of Al, Ti, and Cr also show very limited variation (Mittlefehldt 1994). As for other martian meteorites, the REE patterns in orthopyroxene are LREE-depleted with small negative Eu anomalies (Papike et al. 1994), but they do not show the trace element zoning characteristic of other SNC pyroxenes (Wadhwa and Crozaz 1994). No exsolution of clinopyroxene has been observed optically or in microprobe analyses, but minor *augite* ( $\text{En}_{45}\text{Wo}_{43}$ ) occurs in interstitial regions. Two-pyroxene geothermometry indicates equilibration temperatures of  $\sim 875^\circ\text{C}$  (Treiman 1995b).

Harvey and McSween (1996) found a few small patches of embayed *olivine* ( $\text{Fo}_{35}$ ) within some orthopyroxene grains. Like the olivine in lherzolithic shergottites, this olivine is apparently too Fe-rich to be in equilibrium with the host pyroxene. They suggested that the olivines were relics from a reaction with a  $\text{CO}_2$ -rich fluid to produce orthopyroxene, but they could also be relics from a magmatic reaction to form orthopyroxene.

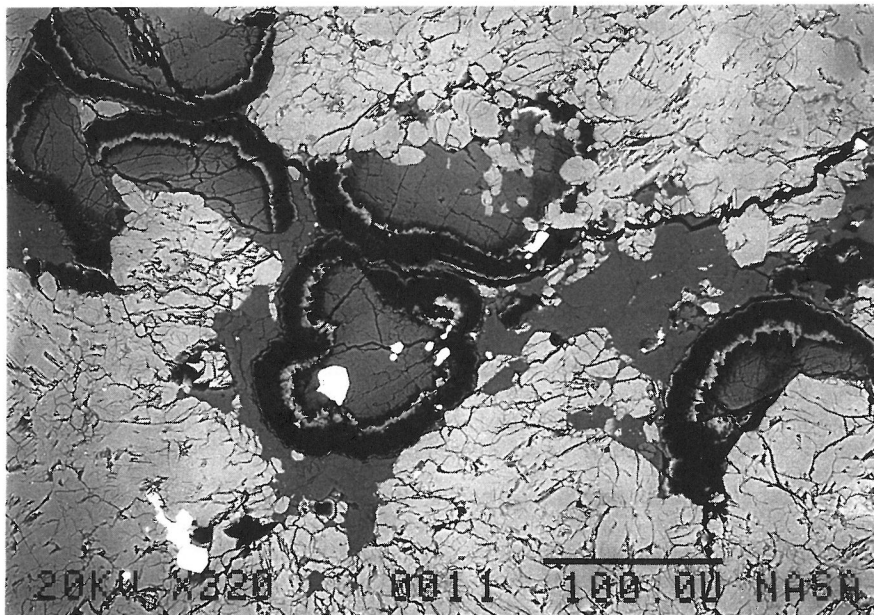
*Maskelynite* occurs interstitially, with compositions generally varying between  $\text{An}_{31}$  and  $\text{An}_{37}$  (Table A2). However, some maskelynites have much higher concentrations of Na and K, varying from  $\text{Ab}_{66}\text{Or}_7$  to  $\text{Ab}_{67}\text{Or}_{17}$ . Mittlefehldt (1994) noted that some maskelynite analyses were non-stoichiometric, and argued that they were mixtures of feldspar and silica. REE concentrations in maskelynite are LREE-enriched with pronounced positive Eu anomalies. Wadhwa and Crozaz (1994) attributed differences in the REE patterns of melts in equilibrium with maskelynite and orthopyroxene to metasomatism, but Treiman (1996b) suggested that the difference reflected subsolidus chemical equilibration.

Euhedral *chromite* occurs throughout the rock. These grains contain 5 to 8 wt %  $\text{Fe}_2\text{O}_3$ , as well as minor Al and Ti (Berkley and Boynton 1992, Mittlefehldt 1994) (Table A4). Some chromites show slight zoning, although the variations are not consistent. Another igneous accessory phase is *apatite*, which occurs as small interstitial grains. Its REE pattern is LREE-enriched, like the maskelynite (Wadhwa and Crozaz 1994). Although the apatite has the highest REE abundances in the rock, it is not the major REE carrier because of its low modal abundance. Igneous sulfides are very uncommon in ALH84001.

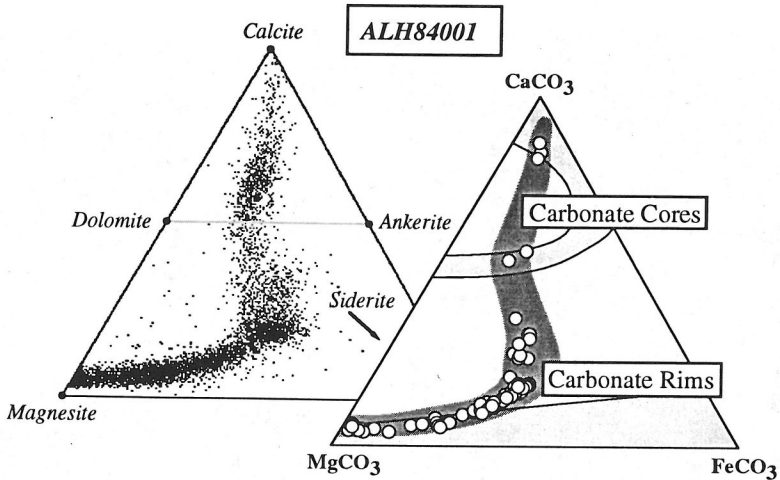
Kirschvink et al. (1996) have interpreted magnetic susceptibility measurements as indicating the presence of *pyrrhotite*, but this phase appears to be quite rare, at least as can be detected using optical and electron microbeam methods.

### Alteration and putative biogenic minerals

Fracture zones in ALH84001 contain a rich variety of secondary phases that have been attributed to alteration by hydrothermal or CO<sub>2</sub>-rich fluids and to possible biogenic processes. McKay et al. (1996) presented a number of arguments for biologic activity, and we will address only those that are mineralogic in nature. Most prominent are rounded globules of *carbonate* (Fig. 20), consisting of orange cores of ankerite with minor calcite and rims of strongly zoned magnesite and breunnerite (Fig. 21). The magnesite-breunnerite sequence is repeated twice on the rims. Carbonate is also found as irregular patches (Treiman 1995b) in fracture zones and within veins of plagioclase melt glass (Scott et al. 1997). The microstratigraphy in all carbonates is the same, except where it was terminated because the open spaces became occluded. Descriptions of the textural relationships between the carbonate and host rock are conflicting; for example, Treiman (1995b) observed carbonate replacing maskelynite, McKay and Lofgren (1997) and McKay et al. (1997) noted carbonate being intruded by plagioclase glass, and Scott et al. (1997) proposed that carbonate crystallized from impact melts now represented by plagioclase glass. Romanek et al. (1994) argued that these carbonates formed at low temperatures (<80°C) by reaction of an aqueous fluid with the rock. Noting the unusual carbonate compositions and the absence of hydrous silicates, Harvey and McSween (1996) supported the suggestion of Mittlefehldt (1994) that the carbonates formed at high temperatures (>650°C), possibly by reaction of a CO<sub>2</sub>-rich fluid with the rock. Treiman (1995b) and Valley et al. (1997) criticized the application of carbonate geothermometry and phase equilibria to these carbonates, instead favoring the formation of metastable carbonates at low temperatures. The oxygen isotopic compositions of carbonates correlate



**Figure 20.** Backscattered electron image of carbonate globules in ALH84001. Ankerite cores are rimmed by multiple zones of magnesite (black) and siderite-rich carbonate (white). Scale bar is 100 microns.

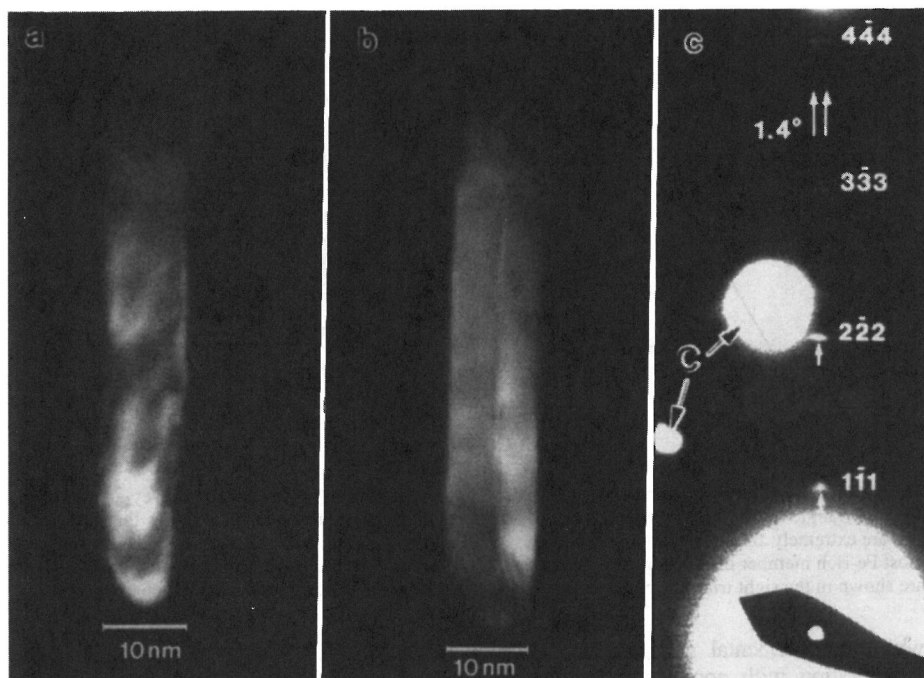


**Figure 21.** Compositions of zoned carbonate globules in ALH84001 (modified from Harvey and McSween 1996). Triangle on the left shows more than 6,700 semi-quantitative analyses, illustrating that the carbonates are extremely fine-grained; overlaps suggest that calcite coexists with ankerite, and ankerite abuts the most Fe-rich member of the magnesite-siderite solid solution series. Fully quantitative microprobe analyses are shown in the right triangle, which is the 700°C phase diagram for the Ca-Mg-Fe carbonate system.

with their elemental compositions (Leshin et al. 1997), which may suggest either equilibration with aqueous fluids during temperature excursions of at least 250°C, or Raleigh fractionation of CO<sub>2</sub>-rich fluids at an even wider range of temperatures. However, C isotopic compositions may not support these scenarios (Eiler et al. 1997). Carbon isotopic compositions demonstrate that they are extraterrestrial, but imply some exchange with terrestrial carbon (Jull et al. 1997b). REE patterns for carbonates were measured by Wadhwa and Crozaz (1995b) and Shearer et al. (1997), and were attributed to metasomatizing fluids to account for differences in these patterns from those of the primary minerals.

When examined under TEM, the carbonates are seen to contain a variety of *magnetite* and *sulfide* morphologies that were suggested by McKay et al. (1996) to be biogenic minerals. Nanophase magnetites were noted to be similar in size (20-100 nm diameter, magnetically “single domain” crystals) and shape to those produced by terrestrial magnetotactic bacteria, and sulfides (pyrrhotite and greigite) were suggested to have formed by sulfate-respiring organisms. Monoclinic 4C pyrrhotite was identified by its composition and (111) basal spacing of 0.57 nm (although the basal spacing of this phase, corresponding to (002), is 0.53 nm, and the (111) spacing is 0.47 nm), but greigite was identified only by its morphological similarity to terrestrial biogenic greigite. In addition, McKay et al. (1996) described minute “ovoid and elongated forms” seen in SEM as possible nanofossils.

Bradley et al. (1996) attempted to replicate these observations using TEM. They discovered nanophase whiskers and platelets of magnetite (Fig. 22), sometimes with axial screw dislocations, internal structures not characteristic of biogenic magnetite. The unusual assortment of magnetite morphologies and the spiral growth mechanism are consistent with their formation by vapor deposition. Bradley et al. (1996) argued that these grains were deposited at high temperatures, by analogy with magnetite whiskers found in sublimes from volcanic fumaroles. Moreover, they noted that the platelets and whiskers were similar



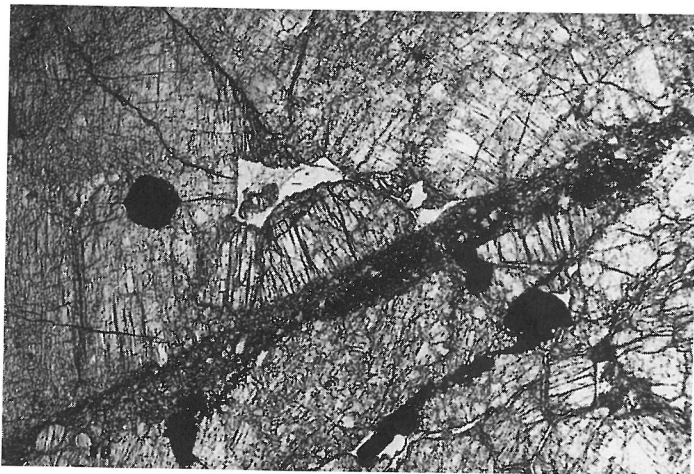
**Figure 22.** TEM darkfield images of two nanophase magnetite whiskers in ALH84001 carbonate (from Bradley et al. 1996). The whisker in (a) appears twisted and free of internal dislocations, whereas the whisker in (b) has an axial screw dislocation. Splitting of hkl diffractions, seen in the selected area diffraction pattern (c), is caused by helical lattice distortions resulting from the screw axis. Diffractions from the surrounding carbonate are labelled "C."

in size and morphology to the ovoid and elongated forms described by McKay et al. (1996), and the absence of other similar materials in the carbonates suggested that these might be the nanofossils. However, no study has yet identified a nanofossil in the SEM and then sectioned the same particle for TEM analysis. Bradley et al. (1997) found that some magnetite whiskers without screw dislocations had grown epitaxially onto the carbonate substrate and on other magnetites. Epitaxial growth is another mechanism common in vapor deposition.

Other minerals associated with carbonate and believed to be part of the alteration assemblage include *pyrite* and other trace sulfides. The pyrite occurs as small euhedral grains in the fracture zones. Its sulfur is isotopically heavy ( $\delta^{34}\text{S} = +2.0$  to  $+7.3\%$ ; Shearer et al. 1996, Greenwood et al. 1997), which appears to be inconsistent with its formation by reduction of sulfate through chemosynthetic pathways used by known terrestrial organisms. The occurrence of *pentlandite* was reported by Shearer et al. (1997), and Wentworth and Gooding (1995) described feathery grains of ZnS within carbonates.

*Silica* has been reported at the juncture where some carbonate globules have growth together (Harvey and McSween 1996), in shock-melted veins (Scott et al. 1997, Valley et al. 1997), and also as euhedra within orthopyroxene (Kring and Gleason 1997). As noted above, non-stoichiometric maskelynite analyses have also been attributed to mixture of feldspar and silica (Mittlefehldt 1994).





**Figure 23.** Photomicrograph of ALH84001 showing fracture zones crosscutting orthopyroxenite. The image measures approximately 2 mm (courtesy of D. Mittlefehldt).

**Shock metamorphic minerals and effects.** ALH84001 is cut by numerous deformation zones a few mm wide (Fig. 23), composed of fine grains of the same minerals that compose the host rock. Mittlefehldt (1994) termed these “crush zones,” emphasizing their cataclastic origin. Treiman (1995b) used the term “granular bands” to call attention to their granulitic (recrystallized) texture. Some areas of these zones exhibit mortar or augen textures, with swirled stringers of chromite traceable to chromites in the adjacent rock. Treiman (1995b) interpreted these zones as melt-breccia dikelets or crystalline cataclasites.

Maskelynite occurs as small, irregularly shaped grains. Veins of plagioclase glass formed by impact melting also occur (McKay and Lofgren 1997, Scott et al. 1997). Carbonates are commonly cut by microfaults with offsets, and radial fractures occur around chromite and maskelynite. Orthopyroxene exhibits strain birefringence.

### **Petrology, geochemistry, and geochronology**

**Petrology.** ALH84001 is a coarse-grained orthopyroxenite cumulate with homogeneous pyroxene, suggesting crystallization in a plutonic environment. Interstitial phases apparently represent material crystallized from intercumulus liquid. The meteorite now consists of coherent clasts up to a few cm across bounded by recrystallized fracture zones. The petrologic history of this meteorite, as envisioned by Mittlefehldt (1994), was as follows: Crystallization and accumulation of orthopyroxene and chromite from basaltic magma was followed by crystallization of plagioclase from intercumulus liquid, and then succeeded by formation of carbonate and pyrite. Shock metamorphism then formed fracture zones, and additional carbonate was deposited. Treiman’s (1995b) petrogenesis differs in having only one period of carbonate deposition, but two shock events. His order of events after formation of the cumulate rock was as follows: Shock metamorphism produced fracture zones, followed by thermal metamorphism that resulted in textural annealing and equilibration of all minerals. Subsequently, fluids were introduced, which precipitated carbonates and pyrite. Following that, the rock experienced a second shock metamorphism, possibly the ejection event, which converted plagioclase to maskelynite and deformed carbonates.

The oxygen isotopic composition of this stone (Clayton and Mayeda 1996) clearly

links it to SNC meteorites, and it has certain mineralogical properties, such as the presence of sodic maskelynite and Fe<sup>3+</sup>-bearing chromite, that resemble SNC minerals. However, the basaltic parent magma for ALH84001 is probably not related to the parent magmas of other martian meteorites. This meteorite is, after all, 3 to 4 billion years older than other members of this clan (see below).

**Geochemistry.** Major, minor, and trace elements were analyzed by Dreibus et al. (1994), Mittlefehldt (1994), and Warren and Kallemeyn (1996). The meteorite has high Mg/(Mg+Fe) and relatively high abundances of volatile elements. The abundances of the siderophile elements Ni, Ir, Au, and Os are very low compared to other martian meteorites. The REE pattern exhibits a depletion in LREE and a negative Eu anomaly, as expected for a cumulate orthopyroxenite. The La/Lu ratio is higher than would be predicted for a parent magma with chondritic REE ratios, but can be explained by inclusion of a small amount intercumulus liquid in the rock.

**Geochronology.** The crystallization age of ALH84001 is  $4.5 \pm 0.13$  Ga, based on a Sm-Nd isochron (Nyquist et al. 1995). Argon isotope dating gives a shock age of  $4.0 \pm 0.1$  Ga (Ash et al. 1996, Turner et al. 1997). The time of formation of the carbonates is unclear and disputed. From <sup>40</sup>Ar/<sup>39</sup>Ar measurements, Knott et al. (1995) suggested that the carbonate formed at ~3.6 Ga, which was cited by McKay et al. (1996). On the other hand, the Rb-Sr data of Wadhwa and Lugmair (1996) suggested an age of ~1.4 Ga.

## MARTIAN MINERALOGY INFERRED FROM REMOTE SENSING AND SPACECRAFT DATA

Beyond inferences from the SNC meteorites, the mineralogy of Martian surface materials is known only indirectly. Reflection spectra, both telescopic and spacecraft, can be interpreted in terms of mineralogy—absorption bands in the spectra can be assigned to specific minerals or mineral groups. The chemical composition and magnetic properties of the martian soil, or dust, were analyzed in situ by the Viking lander spacecraft, and those analyses provide some indirect constraints on the soil mineralogy. From imagery and reflection spectra, the surface of Mars can be characterized in terms of three spectrally distinct units: low-albedo (dark), gray, Fe<sup>2+</sup>-rich regions interpreted to be mixtures of dark rocks and residual soils; high-albedo (bright), red, Fe<sup>3+</sup>-rich regions thought to be covered with aeolian dust; and intermediate albedo regions thought to be indurated soils (Presley and Arvidson 1988, Murchie et al. 1993). Images from the Viking landers (Fig. 24) indicate rock abundances covering 10 to 20% of the surface, and thermal emissivity measurements (Christensen 1986) suggest that some dark areas may contain proportions of rock as high as 35%. In this section we compare what is inferred about the mineralogy of the martian surface, especially the dark rocky regions, from remote sensing spectral measurements and chemical data from the Viking and Mars Pathfinder landers with what has been learned from the study of martian meteorites.

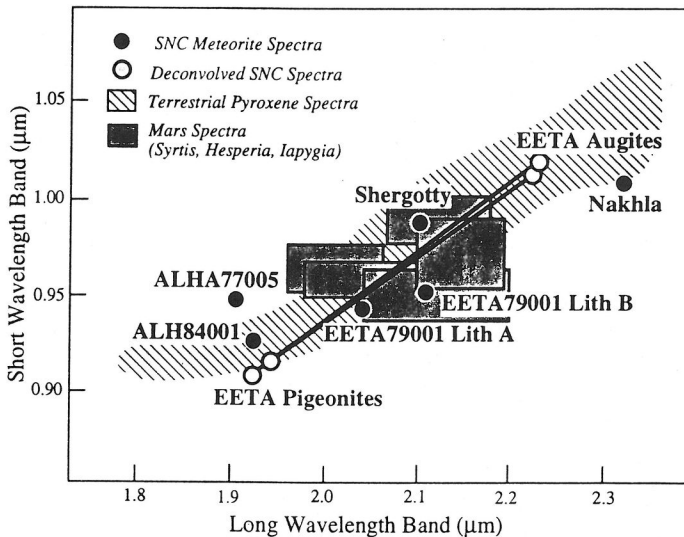
### Igneous rocks

Near-infrared reflectance spectra of the dark regions exhibit two crystal-field absorption bands (near 1 and 2 μm) that indicate the presence of pyroxenes with variable Ca and Fe<sup>2+</sup> contents (Soderblom 1992). As illustrated in Figure 25, the spectra of three low-albedo areas on Mars (Hesperia, Iapygia, and two measurements for Syrtis Major taken at different times—Singer et al. 1980, Mustard et al. 1993) are similar to spectra for basaltic shergottites, but not to lherzolitic shergottites, nakhlites, or ALH84001 (McFadden 1987, Sunshine et al. 1993, Bishop et al. 1994). The 2 μm absorption band is partly masked by martian atmospheric CO<sub>2</sub>, as indicated by the widths of the boxes, and both



**Figure 24.** Photograph of the martian surface at the Viking 2 landing site in Utopia Planitia, taken in 1979. The abundant rocks are partly covered by frost.

absorption bands are probably broadened by compositional scatter in pyroxenes. The absorption bands for Mars and for the SNC meteorites are actually composite spectra of more than one pyroxene phase; however, Sunshine et al. (1993) deconvolved the overlapping spectral bands of pigeonite and augite in EETA79001, as shown by open symbols with tie-lines in Figure 25. High-resolution orbital spectra of Mars obtained by future orbiting spacecraft may be able to similarly deconvolve pyroxene spectral components and thus identify coexisting pyroxenes in surface rocks. As an example, Mustard and Sunshine (1995) determined differences in the modal proportions of pigeonite



**Figure 25.** Long- and short-wavelength band positions for SNC meteorites, low-albedo regions of Mars, and terrestrial pyroxenes of varying composition (modified from McSween 1994). The martian spectra are similar to those of basaltic shergottites, suggesting that these meteorites may represent widespread lavas. The deconvolved spectra for EETA79001 (Sunshine et al. 1993) separate overlapping bands for pigeonite and augite, whose individual spectra are joined by tie-lines.

and augite in comparing high-resolution spectra from Phobos II for Eos Chasma (within Valles Marineris) and Nili Patera (a caldera in Syrtis Major). In any case, the spectral properties of all regions examined so far suggest that basaltic shergottites are probably common lava types on the martian surface (Singer and McSween 1993, Mustard and Sunshine 1995).

The spectral field defined by terrestrial pyroxenes with various compositions and crystal structures is illustrated in Figure 25 by the cross-hatched area (Cloutis and Gaffey 1991). Orthopyroxene plots at the lower left corner of this distribution, and augite plots at the upper right. The spectra of ALHA77005 and ALH84001, both of which contain appreciable orthopyroxene, plot in the appropriate corner, and EETA79001 lithology A, which contains xenocrysts of orthopyroxene, plots closer to this corner than does lithology B. Likewise, the Nakhla spectra plot in the augite field. High-resolution spectra of Mars may thus be able to locate possible source craters for these lithologies. It is noteworthy, however, that the meteorites for which plutonic origins are inferred do not appear to be common surface rocks.

None of the areas surveyed show spectra features indicative of olivine or plagioclase, although abundant pyroxenes could mask limited amounts of these minerals. Magnetite or other opaque phases are inferred to be present in the dark regions, based on their low albedos and other spectral details (Mustard et al. 1993).

The chemical composition of martian duracrust-free soil at the Viking landing sites is similar to that of basaltic shergottites (Baird and Clark 1981, Warren 1987). This may imply derivation from a widespread volcanic protolith, and supports the inference from spectra that shergottites are common surface rocks.

Specific craters on the martian surface have been proposed as the sites from which SNC meteorites were ejected (e.g. Nyquist 1983, Mougins-Mark et al. 1992). These studies were based on a consensus that only the Tharsis volcanic terrain is young enough to have supplied meteorites with ages  $< 1.3$  Ga. Trieman (1995a) used the properties of SNC meteorites to argue that at least three crater sites are required. Consideration of the size of the crater necessary to eject fragments of the required size and velocity appears to restrict choices to craters of at least 12 km diameter (Vickery and Melosh 1987). The location of specific launch sites for these meteorites would provide ground truth for interpreting martian spectra.

Preliminary chemical analyses from the Mars Pathfinder landing site (Rieder et al. 1997) indicate the presence of rocks with andesitic compositions. These rocks share certain chemical characteristics, such as high Fe/Mg, with SNC meteorites, but their compositions are considerably more fractionated. The Pathfinder site at the mouth of an outflow channel was originally selected because floods may have carried samples of the ancient martian crust from the heavily cratered southern highlands. Compositional similarity between the Pathfinder rocks and mean composition of the Earth's crust might imply parallel differentiation patterns.

### **Soils and weathering products**

The mineralogy of the martian soil is poorly known, with limited and ambiguous data coming from Viking lander instruments (magnetic properties, life sciences, and major element composition), from Mars Pathfinder chemical analyses, and from reflectance spectral measurements in the visible and near-infrared. Future spacecraft missions will attempt to fill this void in our knowledge, both with landed mineralogic instruments and with remote sensing in different wavelength ranges, notably the thermal infrared.

Iron oxide minerals are prominent in the martian soil, as suggested by its red-orange color. Reflection spectral studies suggest that the soil contains nanophase hematite and minor crystalline hematite (Morris et al. 1989, 1993; Bell et al. 1990, Bell 1992, Murchie et al. 1993). The soil also contains a few percent of a highly magnetic mineral which is probably titanomagnetite (Hargraves et al. 1977, Baird and Clark 1981). Other iron minerals may also be present, including schwertmannite (a hydroxylated ferric sulfate) and ferrihydrite-intercalated clays (Bishop et al. 1993, Bishop and Murad 1996).

Salt minerals are also important. The Viking lander XRF and Pathfinder APXS analyses of martian soil show high and variable abundances of S which are correlated with those of Mg; both elements are anticorrelated with Si (Clark 1993). Both S and Mg are more abundant in crusted soil samples, which suggests the presence of a water-soluble Mg-sulfate salt; its identity is not known, but possible choices include kieserite  $\text{MgSO}_4 \cdot \text{H}_2\text{O}$ , bloedite  $\text{MgNa}_2(\text{SO}_4)_2 \cdot 4\text{H}_2\text{O}$ , and loweite  $\text{MgNa}_2(\text{SO}_4)_2 \cdot 2.5\text{H}_2\text{O}$  (Clark and van Hart 1981). Sulfate might also be present as ferric sulfate intercalations in smectitic clays or as schwertmannite (Bishop et al. 1995, Bishop and Murad 1996). Infrared light absorptions characteristic of sulfate (or bisulfate) minerals are observed in reflection spectra of Mars, but the mineralogic hosts for these anions are not clear (Pollack et al. 1990, Blaney and McCord 1995, Bell et al. 1996). Detectable chorine in the soil suggests the presence of chloride salts, NaCl seems likely (Clark and van Hart 1981), and the positive correlation of Mg and Cl in soil analyses may suggest a Mg-bearing chloride (Clark 1993). The Viking XRF analyses admit the possibility of Mg carbonate minerals in the soil, but probably not Ca carbonates (Clark 1993). Anhydrous carbonates have not been detected spectroscopically, although there is some evidence for hydrous magnesium carbonate minerals (e.g. Calvin et al. 1994). Current interpretations of the Viking life science experiments are not consistent with abundant carbonate minerals (Banin et al. 1992).

The silicate mineralogy of the martian soil is known poorly. Reflection spectra show no absorptions characteristic of olivine or pyroxenes, although the bulk composition of the soil is close to that of basaltic shergottites (Baird and Clark 1981, Banin et al. 1992). The bulk composition and color of the soil have suggested that it is palagonite, or altered basaltic glass (Banin et al. 1992). Palagonite on Earth consists of principally of nanophase phyllosilicates and ferric iron oxides (e.g. Banin et al. 1992), and some palagonites have reflection spectra (visible through near-infrared) that are essentially identical to that of the martian soil (e.g. Morris et al. 1993). This model for the soil silicate is attractive in its simplicity, but cannot explain all available data. Results from the Viking life science and soil reactivity experiments are more consistent with crystalline clays than with palagonite (Banin et al. 1992), and near-infrared absorptions attributable to metal—OH bonds (as in clays) are weak and unusually sharp for known phyllosilicates on Earth (Bell et al. 1994, Bell 1996). The mineral scapolite has been suggested as a significant component of the martian soil, but the spectral absorptions that suggested scapolite are also consistent with other sulfate or carbonate minerals (Clark et al. 1990, Bell 1996).

The nature of the martian soil is one manifestation of chemical weathering on Mars, which has been explored by Gooding (1978) and Siderov and Zolotov (1986) from theoretical thermodynamic bases. The martian meteorites contain some low-temperature alteration minerals of martian origin, as described above, which can be used as constraints on weathering and soil mineralogy (Gooding 1992). A mixture of smectite and illite such as occur in the martian meteorites, plus salt and iron oxide minerals, matches the chemical composition of the martian soil and is perhaps more consistent with the Viking life science experiment results than is palagonite (Gooding 1992). On the other hand, the Viking XRF analyses can be accommodated as a mixture of a single silicate component, a single salt component, and an Fe-Ti oxide (Clark 1993).

## ACKNOWLEDGMENTS

We appreciate helpful discussions with J.H. Jones and D.W. Mittlefehldt, the photography assistance of Debra Reub, and constructive reviews by R.P. Harvey and T.J. McCoy. This work was partly supported by NASA grants NAG-54541 to HYM and NAGW-5098 to AHT.

## REFERENCES

- Ash RD, SF Knott, G Turner (1996) A 4-Gyr shock age for a martian meteorite and implications for the cratering history of Mars. *Nature* 380:57-59
- Ashworth JR, R Hutchison (1975) Water in non-carbonaceous stony meteorites. *Nature* 256:714-715
- Baird AK, BC Clark (1981) On the original igneous source of martian fines. *Icarus* 45:113-123
- Banin A, BC Clark, H Wänke (1992) Surface chemistry and mineralogy. In: Mars. HH Kieffer, BM Jakosky, CW Snyder, MS Matthews (eds) p 594-625. Univ Arizona Press, Tucson, AZ
- Becker RH, RO Pepin (1984) The case for a martian origin of the shergottites: Nitrogen and noble gases in EETA79001. *Earth Planet Sci Lett* 69:225-242
- Bell JF III (1992) Charge-coupled device imaging spectroscopy of Mars. 2. Results and implications for martian ferric mineralogy. *Icarus* 100:575-597
- Bell JF III (1996) Iron, sulfate, carbonate, and hydrated minerals on Mars. In: Mineral Spectroscopy: A Tribute to Roger G. Burns. MD Dyar, C McCammon, MW Shaefer (eds) *Geochemical Soc Spec Pub* 5:359-380
- Bell JF III, TB McCord, PD Owensby (1990) Observational evidence for crystalline iron oxides on Mars. *J Geophys Res* 9:14,447-14,461
- Bell JF III, JB Pollack, TR Geballe, DP Cruickshank, R Freedman (1994) Spectroscopy of Mars from 2.04 to 2.44  $\mu\text{m}$  during the 1993 opposition: Absolute calibration and atmospheric vs mineralogic origin of narrow absorption features. *Icarus* 103:103-123
- Berkley JL, NJ Boynton (1992) Minor/major element variation within and among diogenite and howardite orthopyroxenite groups. *Meteoritics* 27:387-394
- Berkley JL, K Keil, M Prinz (1980) Comparative petrology and origin of Governador Valadares and other nakhlites. *Proc Lunar Planet Sci Conf* 11:1089-1102
- Berkley JL, K Keil (1981) Olivine orientation in the ALHA77005 achondrite. *Am Mineral* 66:1233-1236
- Bertka CM, Y Fei (1997) Mineralogy of the martian interior up to core-mantle boundary pressures. *J Geophys Res* 102:5251-5264
- Binns RW (1967) Stony meteorites bearing maskelynite. *Nature* 211:1111-1112.
- Bishop JL, E Murad (1996) Schwertmannite on Mars? Spectroscopic analyses of schwertmannite, its relationship to other ferric minerals, and its possible presence in the surface of Mars. In: Mineral Spectroscopy: A Tribute to Roger G. Burns. MD Dyar, C McCammon, MW Shaefer (eds) *Geochemical Soc Spec Pub* 5:227-358
- Bishop JL, CM Pieters, RG Burns (1993) Reflectance and Mössbauer spectroscopy of ferrihydrate-montmorillonite assemblages as Mars soil analog materials. *Geochim Cosmochim Acta* 57:4583-4595
- Bishop J, C Pieters, J Mustard, S Pratt, T Hiroi (1994) Spectral analyses of ALH84001, a meteorite from Mars (abstr). *Meteoritics* 29:444-445
- Bishop JL, CM Pieters, RG Burns, JO Edwards, RL Mancinelli, H Fröschl (1995) Reflectance spectroscopy of ferric sulfate-bearing montmorillonites as Mars soil analog materials. *Icarus* 117:101-119
- Blaney, D. L., T. B. McCord (1995) Indications of sulfate minerals in the martian soil from Earth-based spectroscopy. *J Geophys Res* 100:14,433-14,441
- Boctor NZ, HOA, G Kullerud (1976) Lafayette meteorite: Petrology and opaque mineralogy. *Earth Planet Sci Lett* 32:6
- Bogard DD, LE Nyquist (1979)  $^{39}\text{Ar}$ - $^{40}\text{Ar}$  chronology of related achondrites (abstr). *Meteoritics* 14:356
- Bogard DD, P Johnson (1983) Martian gases in an Antarctic meteorite. *Science* 221:651-654
- Boynton WV, PM Starzyk, RA Schmitt (1976) Chemical evidence for the genesis of the ureilites, the achondrite Chassigny, and the nakhlites. *Geochim Cosmochim Acta* 40:1439-1477
- Borg LE, LE Nyquist, LA Taylor, H Wiesmann, C-Y Shih (1997) Rb-Sr and Sm-Nd isotopic analyses of QUE94201: Constraints on martian differentiation processes (abstr). *Lunar Planet Sci XXVIII*:133-134
- Bradley JP, RP Harvey, HY McSween Jr (1996) Magnetite whiskers and platelets in the ALH84001 martian meteorite: Evidence of vapor phase growth. *Geochim Cosmochim Acta* 60:5149-5155

- Bradley JP, HY McSween Jr, RP Harvey (1997) Epitaxial growth of single-domain magnetite in martian meteorite ALH84001 (abstr). *Met Planet Sci* 32:A20
- Brandenburg JE (1996) Mars as the parent body of the CI carbonaceous chondrites. *Geophys Res Lett* 23:961-964
- Brearley AJ (1991) Subsolidus microstructures and cooling history of pyroxenes in the Zagami shergottite (abstr). *Lunar Planet Sci XXII*:135-136
- Bunch TE, AM Reid (1975) The nakhlites, part 1: Petrography and mineral chemistry. *Meteoritics* 10:303-315
- Calvin WM, TVV King, RN Clark (1994) Hydrous carbonates on Mars? Evidence from Mariner 6/7 infrared spectrometer and ground-based telescopic spectra. *J Geophys Res* 99:14,659-14,675
- Carr MH, H Wänke (1992) Earth and Mars: Water inventories as clues to accretional histories. *Icarus* 98:61-71
- Chatzitheodoridis E, G Turner (1990) Secondary minerals in the Nakhla meteorite (abstr). *Meteoritics* 25:354
- Chen JH, GJ Wasserburg (1986a) Formation ages and evolution of Shergotty and its parent planet from U-Th-Pb systematics. *Geochim Cosmochim Acta* 50:955-968
- Chen JH, GJ Wasserburg (1986b) S =/ N =? C (abstr). *Lunar Planet Sci XVII*: 113-114
- Christensen PR (1986) The spatial distribution of rock on Mars. *Icarus* 68:217-238
- Clark BC (1993) Geochemical components in Martian soil. *Geochim Cosmochim Acta* 57:4575-4581
- Clark BC, DC van Hart (1981) The salts of Mars. *Icarus* 45:370-378
- Clark RN, GA Swayze, RB Singer, JB Pollack (1990) High-resolution reflectance spectra of Mars in the 2.3- $\mu$ m region: Evidence for the mineral scapolite. *J Geophys Res* 95:14,463-14,480
- Clayton RN, TK Mayeda (1988) Isotopic composition of carbonate in EETA79001 and its relation to parent body volatiles. *Geochim Cosmochim Acta* 52:925-927
- Clayton RN, TK Mayeda (1996) Oxygen isotope studies of achondrites. *Geochim Cosmochim Acta* 60:1999-2017
- Cloutis EA, MJ Gaffey (1991) Pyroxene spectroscopy revisited: Spectral-compositional correlations and relationships to geothermometry. *J Geophys Res* 98:10,973-11,016
- Collinson DW (1986) Magnetic properties of Antarctic shergottite meteorites EETA79001 and ALHA77005: Possible relevance to a martian magnetic field. *Earth Planet Sci Lett* 77:159-164
- Collinson DW (1997) Magnetic properties of Martian meteorites: Implications for an ancient Martian magnetic field. *Met Planet Sci* 32:803-811
- Delano JW, RJ Arculus (1980) Nakhla: Oxidation state and other constraints (abstr). *Lunar Planet Sci XI*:219-221
- Drake MJ, TD Swindle, T Owen, DS Musselwhite (1995) Fractionated martian atmosphere in the nakhlites? *Meteoritics* 29:854-859
- Dreibus G, H Wänke (1985) Mars, a volatile-rich planet. *Meteoritics* 20:367-381
- Dreibus G, A Burgele, KP Jochum, B Spettel, F Wlotzka, H Wänke (1994) Chemical and mineral

- Gleason JD, DA Kring, DH Hill, WV Boynton (1997) Petrography and bulk chemistry of Martian ilmenite LEW 88516. *Geochim Cosmochim Acta* 61:4007-4014
- Gooding JL (1978) Chemical weathering on Mars: Thermodynamic stabilities of primary minerals (and their alteration products) from mafic igneous rocks. *Icarus* 33:483-513
- Gooding JL (1992) Soil mineralogy and chemistry on Mars: Possible clues from salts and clays in SNC meteorites. *Icarus* 99:28-41
- Gooding JL, DW Muenow (1986) Martian volatiles in shergottite EETA79001: New evidence from oxidized sulfur and sulfur-rich aluminosilicates. *Geochim Cosmochim Acta* 50:1049-1059
- Gooding JL, SJ Wentworth (1991) Origin of "white druse" salts in EETA79001 (abstr). *Lunar Planet Sci XXII*:461-462
- Gooding JL, SJ Wentworth, ME Zolensky (1988) Calcium carbonate and sulfate of possible extraterrestrial origin in the EETA79001 meteorite. *Geochim Cosmochim Acta* 52:909-915
- Gooding JL, SJ Wentworth, ME Zolensky (1991) Aqueous alteration of the Nakhla meteorite. *Meteoritics* 26:135-143
- Greenwood JP, LR Ricuputi, HY McSween Jr (1997) Sulfur isotopic compositions in shergottites and ALH84001, and possible implications for life on Mars. *Geochim Cosmochim Acta* 61:4449-4453
- Greshake A, F Langenhorst (1997) TEM characterization of shock defects in minerals of the martian meteorite Chassigny (abstr). *Met Planet Sci* 32:A52
- Hale VPS, HY McSween Jr, GA McKay (1997) Cumulus pyroxene in Shergotty: The discrepancy between experimental and observational studies (abstr). *Lunar Planet Sci XXVIII*:495-496
- Hargraves, R. B., D. W. Collinson, R. E. Arvidson, C. R. Spitzer (1977) The Viking magnetic properties experiment: Primary mission results. *J Geophys Res* 82:4547-4558
- Harper CL Jr, LE Nyquist, B Bansal, H Wiesmann, C-Y Shih (1995) Rapid accretion and early differentiation of Mars indicated by  $^{142}\text{Nd}/^{144}\text{Nd}$  in SNC meteorites. *Science* 267:213-217
- Harvey RP, HY McSween Jr (1992a) The parent magma of the nakhlite meteorites: Clues from melt inclusions. *Earth Planet Sci Lett* 111:467-482
- Harvey RP, HY McSween Jr (1992b) The petrogenesis of the nakhlites: Evidence from cumulate mineral zoning. *Geochim Cosmochim Acta* 56:1655-1663
- Harvey RP, HY McSween Jr (1996) A possible high-temperature origin for the carbonates in martian meteorite ALH84001. *Nature* 382:49-51
- Harvey RP, M Wadhwa, HY McSween Jr, G Crozaz (1993) Petrography, mineral chemistry, and petrogenesis of Antarctic shergottite LEW88516. *Geochim Cosmochim Acta* 57:4769-4783
- Hasan FA, M Haq, DWG. Sears (1986) Thermoluminescence and the shock and reheating history of meteorites—III. The shergottites. *Geochim Cosmochim Acta* 50, 1031-1038
- Hawthorne FC (1981) Crystal chemistry of the amphiboles. In: *Amphiboles and other hydrous pyroxenes—Mineralogy*. Veblen DR (ed). *Rev Mineral* 9A:1-102
- Hörz F, R Hanss, C Serna (1986) X-ray investigations related to the shock history of the Shergotty achondrite. *Geochim Cosmochim Acta* 50:905-908
- Ikeda Y (1994) Petrography and petrology of ALH-77005 shergottite. *Proc NIPR Symp. Antarctic Met* 7:9-29
- Ikeda Y (1997) Petrology of the Y-793605 ilmenitic shergottite (abstr). *Met Planet Sci* 32:A64-A65
- Ishii T, H Takeda, K Yanai (1979) Pyroxene geothermometry applied to a three-pyroxene achondrite from Allan Hills, Antarctica and ordinary chondrites. *Mineral J* 9:460-481
- Jagoutz E (1989) Sr and Nd isotopic systematics in ALHA77005: Age of shock metamorphism in shergottites and magmatic differentiation of Mars. *Geochim Cosmochim Acta* 53:2429-2441
- Jagoutz E (1991) Chronology of SNC meteorites. *Space Sci Rev* 56:13-22.
- Jagoutz E (1996) Nd isotopic systematics of Chassigny (abstr). *Lunar Planet Sci XXVIII*:597-598
- Jérémine E, J Orcel, A Sandréa (1962) Étude mineralogique et structural de la météorite de Chassigny. *Bull Soc franc Mineral Cristal* 85:262-266
- Johnson MC, MJ Rutherford, PC Hess (1991) Chassigny petrogenesis: Melt compositions, intensive parameters, and water contents of Martian (?) magmas. *Geochim Cosmochim Acta* 55:349-366
- Jones JH (1986) A discussion of isotopic systematics and mineral zoning in the shergottites: Evidence for a 180 m.y. igneous crystallization age. *Geochim Cosmochim Acta* 50:969-977
- Jones JH (1989) Isotope relationships among the shergottites, the nakhlites and Chassigny. *Proc Lunar Planet Sci Conf* 19:465-474
- Jull AJT, DJ Donahue, TD Swindle, MK Burkland, GF Herzog, A Albrecht, J Klein, R Middleton (1992) Isotopic studies relevant to the origin of the "white druse" carbonates on EETA79001 (abstr). *Lunar Planet Sci XXXIII*:641-642
- Jull AJT, CJ Eastoe, S Cloutd (1997a) Terrestrial age of the Lafayette meteorite and stable isotopic composition of weathering products (abstr). *Lunar Planet Sci XXVIII*:685-686
- Jull AJT, CJ Eastoe, S Cloutd (1997b) Isotopic composition of carbonates in the SNC meteorites, Allan Hills 84001 and Zagami. *J Geophys Res* 102:1663-1669



- Kaneda K, GA McKay, L Le (1997) Synthetic and natural nakhlite pyroxenes: Minor elements composition (abstr). *Lunar Planet Sci XXVIII*:693-694
- Karlssohn HR, RN Clayton, EK Gibson Jr, T. K. Mayeda (1992) Water in SNC meteorites: Evidence for a martian hydrosphere. *Science* 255:1409-1411
- Kieffer HH, BM Jakosky, CW Snyder, MW. Matthews, eds (1992) *Mars*. Univ Arizona Press, Tucson, AZ, 1498 p
- Kirschvink JL, A Maine, H Vali (1997) Paleomagnetic evidence of a low-temperature origin of carbonate in the martian meteorite ALH84001. *Science* 275:1629-1633
- Knott SF, RD Ash, G Turner (1995)  $^{40}\text{Ar}/^{39}\text{Ar}$  dating of ALH84001: Evidence for the early bombardment of Mars (abstr). *Lunar Planet Sci XXVI*:765-766
- Kring DA, JD Gleason (1997) Magmatic temperatures and compositions on early Mars as inferred from the orthopyroxene-silica assemblage in Allan Hills 84001 (abstr). *Met Planet Sci* 32:A74
- Lancet MS, K Lancet (1971) Cosmic ray and gas retention ages of the Chassigny meteorite. *Meteoritics* 6:81-85
- Langenhorst F, D Stöffler, D Klein (1991) Shock metamorphism of the Zagami achondrite (abstr). *Lunar Planet Sci XXII*:779-780
- Laul JC, MR Smith, H Wänke, E Jagoutz, G Dreibus, H Palme, B Spettel, A Burghele, ME Lipschutz, RM Verkooren (1986) Chemical systematics of the Shergotty meteorite and the composition of its parent body (Mars). *Geochim Cosmochim Acta* 50:909-926
- Leake BE and 21 coauthors (1997) Nomenclature of amphiboles: Report of the Subcommittee on Amphiboles of the International Mineralogical Association, Commission on New Minerals and Mineral Names. *Am Mineral* 82:1019-1037
- Lee D-C, AN Halliday (1997) Core formation on Mars and differentiated asteroids. *Nature* 388:854-857
- Leshin LA, S Epstein, EM Stolper (1996) Hydrogen isotope geochemistry of SNC meteorites. *Geochim Cosmochim Acta* 60:2635-2650
- Leshin LA, KD McKeegan, PK Carpenter, RP Harvey (1997) Oxygen isotopic constraints on the genesis of carbonates from martian meteorite ALH84001. *Geochim Cosmochim Acta* (in press)
- Lindstrom DS, AH Treiman, RR Martinez (1993) Trace element analysis of magmatic inclusions in ALHA77005 by micro-INAA (abstr). *Met Planet Sci* 28:386-387
- Longhi J (1991) Complex magmatic processes on Mars: Inferences from the SNC meteorites. *Proc Lunar Planet Sci Conf* 21:695-709
- Longhi J, V. Pan (1989) The parent magmas of the SNC meteorites. *Proc Lunar Planet Sci Conf* 19:451-464
- Longhi J, E Knittle, JR Holloway, H Wänke (1992) The bulk composition, mineralogy and internal structure of Mars. In: *Mars*. HH Kieffer, BM Jakosky, CW Snyder, MS Matthews (eds) p 185-208. Univ Arizona Press, Tucson, AZ
- Lundberg LL, G Crozaz, G McKay, E Zinner (1988) Rare earth element carriers in the Shergotty meteorite and implications for its chronology. *Geochim Cosmochim Acta* 52:2147-2163
- Lundberg LL, G Crozaz, HY McSween Jr. (1990) Rare earth elements in minerals of the ALHA77005 shergottite and implications for its parent magma and crystallization history. *Geochim Cosmochim Acta* 54:2535-2547
- Marti K, JS Kim, AN Thakur, TJ McCoy, K Keil (1995) Signatures of the martian atmosphere in glass of the Zagami meteorite. *Science* 267:1981-1984
- Martinez RR, JL Gooding (1986) New saw-cut surfaces of EETA79001. *Antarctic Meteorite Newsletter* 9:23
- McCoy TJ, GE Lofgren (1996) The crystallization of the Zagami shergottite: A 1 atm experimental study (abstr). *Lunar Planet Sci XXVII*:839-840
- McCoy TJ, GJ Taylor, K Keil (1992) Zagami: Product of a two-stage magmatic history. *Geochim Cosmochim Acta* 56:3571-3582
- McCoy TJ, K Keil, GJ Taylor (1993) The dregs of crystallization in Zagami (abstr). *Lunar Planet Sci XXIV*:947-948
- McCoy TJ, M Wadhwa, K Keil (1995) Zagami: Another new lithology and a complex, near-surface magmatic history (abstr). *Lunar Planet Sci XXVI*:925-926
- McFadden LA (1987) Spectral reflectance of SNC meteorites: Relationships to martian surface composition. *Lunar Planet. Inst. Tech. Rept.* 88-05:88-90
- McKay DS, EK Gibson Jr, KL Thomas-Keptra, H Vali, CS Romanek, SJ Clement, XDF Chillier, CR Macchling, RN Zare (1996) Search for past life on Mars: Possible relic biogenic activity in martian meteorite ALH84001. *Science* 273:924-930
- McKay GA, GE Lofgren (1997) Carbonates in ALH84001: Evidence for kinetically controlled growth (abstr). *Lunar Planet Sci XXVIII*:921-922
- McKay GA, T Mikouchi, G. E. Lofgren (1997) Carbonates and feldspathic glass in ALH84001: Additional complications (abstr). *Met Planet Sci* 32:A87-A88

- McSween HY Jr (1985) SNC meteorites: Clues to martian petrologic evolution? *Rev Geophys* 23:391-416
- McSween HY Jr (1994) What we have learned about Mars from SNC meteorites. *Meteoritics* 29:757-779
- McSween HY Jr (1997) Evidence for life in a martian meteorite? *GSA Today* 7:1-7
- McSween HY Jr and RP Harvey (1993) Outgassed water on Mars: Constraints from melt inclusions in SNC meteorites. *Science* 259:1890-1892
- McSween HY Jr, E. Jarosewich (1983) Petrogenesis of the Elephant Moraine A79001 meteorite: Multiple magma pulses on the shergottite parent body. *Geochim Cosmochim Acta* 47:1501-1513
- McSween HY Jr, EM Stolper, LA Taylor, RA Muntean, GD O'Kelley, JS Eldridge, S Biswas, HT Ngo, ME Lipschutz (1979a) Petrogenetic relationship between Allan Hills 77005 and other achondrites. *Earth Planet Sci Lett* 45:275-284
- McSween HY Jr, LA Taylor, EM Stolper (1979b) Allan Hills 77005: A new meteorite type found in Antarctica. *Science* 204:1201-1203
- McSween HY Jr, DD Eisenhour, LA Taylor, M Wadhwa, G Crozaz (1996) QUE94201 shergottite: Crystallization of a martian basaltic magma. *Geochim Cosmochim Acta* 60:4563-4569
- Melosh HJ (1984) Impact ejection, spallation, and the origin of meteorites. *Icarus* 59:234-260
- Melosh HJ, AH Treiman, RAF. Grieve (1983) Olivine composition glass in the Chassigny meteorite: Implications for shock history. *EOS* 64:254
- Meyer C (1996) Mars Meteorite Compendium—1996. Report 27672, NASA/Johnson Space Center, Houston, TX, 175 p [Available on the Internet at <http://www-curator.jsc.nasa.gov/curator/antmet/mmc/mmc.htm>]
- Mikouchi T, M Miyamoto (1996) A new member of lherzolithic shergottite from Japanese Antarctic meteorite collection: Mineralogy and petrology of Yamato 793605. *Proc NIPR Symp Antarctic Met* 21:104-106. Nat'l Inst Polar Res, Tokyo
- Mikouchi T, M Miyamoto (1997) Major and minor element distributions in pyroxene and maskelynite from martian meteorite Yamato-793605 and other lherzolithic shergottites: Clues to their crystallization histories (abstr). *Antarctic Meteorites XXII:109-112*
- Mikouchi T, M Miyamoto, GA McKay (1996) Mineralogy and petrology of new Antarctic shergottite QUE94201: A coarse-grained basalt with unusual pyroxene zoning (abstr). *Lunar Planet Sci XXVII:879-880*
- Mikouchi T, M Miyamoto, GA McKay (1997) Similarities in zoning of pyroxenes from QUE94201 and EETA79001 martian meteorites (abstr). *Lunar Planet Sci XXVIII:955-956*
- Mittlefehldt DW (1994) ALH84001, a cumulate orthopyroxenite member of the martian meteorite clan. *Meteoritics* 29:214-221
- Mittlefehldt DW, DJ Lindstrom, MM Lindstrom, RR Martinez (1997) Lithology A in EETA79001—Product of impact melting on Mars (abstr). *Lunar Planet Sci XXVIII:961-962*.
- Morris RV, DG Agresti, HV Lauer Jr, JA Newcombe, TD Shelfer, AV Murali (1989) Evidence for pigmentary hematite on Mars based on optical, magnetic, and Mössbauer studies of superparamagnetic (nanocrystalline) hematite. *J Geophys Res* 94:2760-2778.
- Morris RV, DC Golden, JF Bell III, HV Lauer Jr, JB Adams (1993) Pigmenting agents in Martian soils: Inferences from spectral, Mössbauer, and magnetic properties of nanophase and other iron oxides in Hawaiian palagonitic soil PN-9. *Geochim Cosmochim Acta* 57:4597-4609
- Mouginis-Mark PJ, TJ McCoy, GJ Taylor, K Keil (1992) Martian parent craters for the SNC meteorites. *J Geophys Res* 97:10,213-10,225
- Müller WF (1993) Thermal and deformational history of the Shergotty meteorite deduced from clinopyroxene microstructure. *Geochim Cosmochim Acta* 57:4311-4322
- Murchie S, J Mustard, J Bishop, J Head III, C Pieters (1993) Spatial variations in the spectral properties of bright regions on Mars. *Icarus* 105:454-468
- Mustard JF, JM Sunshine (1995) Seeing through the dust: Martian crustal heterogeneity and links to the SNC meteorites. *Science* 267:1623-1626
- Mustard JF, S Erard, J-P Bibring, JW Head, S Hurretz, Y Langevin, CM Pieters, CJ Sotin (1993) The surface of Syrtis Major: Composition of the volcanic substrate and mixing with altered dust and soil. *J Geophys Res* 98 (E2):3387-3400
- Nakamura N, DM Unruh, M Tatsumoto, R Hutchison (1982a) Origin and evolution of the Nakhla meteorite inferred from the Sm-Nd and U-Pb systematics and REE, Ba, Sr, Rb abundances. *Geochim Cosmochim Acta* 46:1555-1573
- Nakamura N, H Komi, H Kagami (1982b) Rb-Sr isotopic and REE abundances in the Chassigny meteorite (abstr). *Meteoritics* 17:257-258
- Nyquist LE (1983) Do oblique impacts produce martian meteorites? *J Geophys Res* 88 (suppl):A785-A798
- Nyquist LE, B Bansal, H Weissmann, C-Y Shih (1995) "Martians" young and old: Zagami and ALH84001 (abstr). *Lunar Planet Sci XXVI:106-1066*
- Ostertag R, G Amthauer, H Rager, HY McSween Jr (1984) Fe<sup>3+</sup> in shocked olivine crystals of the ALHA787005 meteorite. *Earth Planet Sci Lett* 67:162-166

- Papanastassiou DA, GJ Wasserburg (1974) Evidence for late formation and young metamorphism in the achondrite Nakhla. *Geophys Res Lett* 1:23-26
- Papike JJ, GW Fowler, GD Layne, MN Spilde, CK Shearer (1994) ALH84001 A "SNC orthopyroxenite": Insights from SIMS analysis of orthopyroxene (abstr). *Lunar Planet Sci XXV*:1043-1044
- Pepin RO, MH Carr (1992) Major issues and outstanding questions. In: Mars. HH Kieffer, BM Jakosky, CW Snyder, MS Matthews (eds) p 120-146. Univ Arizona Press, Tucson, AZ
- Podosek, F.A., J. C. Huneke (1973) Argon 40-argon 39 chronology of four calcium-rich achondrites. *Geochim Cosmochim Acta* 37:667-684
- Pollack JB, TL Roush, R Witteborn, J Bregman, D Wooden, C Stoker, OB. Toon, D Rank, B Dalton, R Freedman (1990) Thermal emission spectra of Mars (5.4 - 10.5  $\mu\text{m}$ ): Evidence for sulfates, carbonates, and hydrates. *J Geophys Res* 95:14,595-14,627
- Presley MA, RE Arvidson (1988) Nature and origin of materials exposed in the Oxia Palus - Western Arabia - Sinus Meridiani region, Mars. *Icarus* 75:499-517
- Popp RK, D Virgo, MW Phillips (1995a) H deficiency in kaersutitic amphiboles: Experimental verification. *Am Mineral* 80:1347-1350
- Popp RK, D Virgo, HS Yoder Jr, TC Hoering, MW Phillips (1995b) An experimental study of phase equilibria and Fe oxy-component in kaersutitic amphibole: Implications for the  $f_{\text{H}_2}$  and  $a_{\text{H}_2\text{O}}$  in the upper mantle. *Am Mineral* 80:534-548
- Prinz M, PH Hlava, K Keil (1974) The Chassigny meteorite: A relatively iron-rich cumulate dunitite (abstr). *Meteoritics* 9:393-394
- Reid AM, TE Bunch (1975) The nakhlites part II: Where, when, and how. *Meteoritics* 10:317-324
- Reider R, T Economou, H Wänke, A Turkevich, J Crisp, J Brückner, G Dreibus, HY McSween (1997) The chemical composition of martian soil and rocks returned by the mobile alpha proton x-ray spectrometer: Preliminary results in x-ray mode. *Science* 278:1771-1774
- Righter K, RL Hervig, DA Kring (1997) Ion microprobe analyses of SNC meteorite melt inclusions (abstr). *Lunar Planet Sci XXVIII*:1181-1182
- Romanek CS, MM Grady, IP Wright, DW Mittlefehldt, RA Socki, CT Pillinger, EK Gibson Jr (1994) Record of fluid-rock interactions on Mars from the meteorite ALH84001. *Nature* 372:655-657
- Romanek CS, AH Treiman, JH Jones, EK Gibson Jr, R Socki (1996) Oxygen isotope evidence for aqueous activity on Mars:  $\delta^{18}\text{O}$  of Lafayette iddingsite (abstr). *Lunar Planet Sci XXVII*:1099-1100
- Rubin AE (1997a) Mineralogy of meteorite groups. *Met Planet Sci* 32:231-247
- Rubin AE (1997b) Mineralogy of meteorite groups: An update. *Met Planet Sci* 32:733-734.
- Saxton JM, IC Lyon, E Chatzitheodoridis, G Turner (1997) Oxygen isotopic composition of Nakhla carbonate (abstr). *Met Planet Sci* 32:A114-A115
- Sclar CB, SP Morzenti (1971) Shock-induced planar deformation features in olivine from the Chassigny meteorite. *Meteoritics* 6:310-311
- Scott ERD, A Yamaguchi, AN Krot (1997) Petrological evidence for shock melting of carbonates in the... martian meteorite ALH84001. *Nature* 387:377-379
- Shearer CK, GD Layne, JJ Papike, MN Spilde (1996) Sulfur isotopic systematics in alteration assemblages in martian meteorite ALH84001. *Geochim Cosmochim Acta* 60:2921-2926
- Shearer CK, MN Spilde, M Wiedenbeck, JJ Papike (1997) The petrogenetic relationship between carbonates and pyrite in martian meteorite ALH84001 (abstr). *Lunar Planet Sci XXVIII*:1293-1294
- Shih C-Y, LE Nyquist, DD Bogard, GA McKay, JL Wooden, BM Bansal, H Wiesmann (1982) Chronology and petrogenesis of young achondrites, Shergotty, Zagami, and ALHA77005: Late magmatism on a geologically active planet. *Geochim Cosmochim Acta* 46:2323-2344
- Shih C-Y, LE Nyquist, H Wiesmann (1996) Sm-Nd systematics of the nakhlite Governorador Valadares (abstr). *Lunar Planet Sci XXVII*:1197-1198
- Sidorov Yu I, MYu Zolotov (1986) Weathering of martian surface rocks. In: Chemistry and Physics of Terrestrial Planets. S Saxena (ed) p 191-223. Springer, New York
- Shoemaker EM, RJ Hackman, RE Eggleton (1963) Interplanetary correlation of geologic time. *Adv Astronautical Sci* 8:70-89
- Singer RB, HY McSween Jr (1993) The igneous crust of Mars: Compositional evidence from remote sensing and the SNC meteorites. In: Resources of Near-Earth Space. JS Lewis, MS Matthews, MMI Guerrieri (eds) p 709-736. Univ Arizona Press, Tucson, AZ
- Singer RB, RN Clark, PD Owensby (1980) Mars: New regional near-infrared spectrophotometry (0.65-2.50  $\mu\text{m}$ ) obtained during the 1980 apparition (abstr). *Bull Am Astron Soc* 22:680
- Smith JV, RL Hervig (1979) Shergotty meteorite: Mineralogy, petrology, and minor elements. *Meteoritics* 14:121-142
- Smith JV, IM Steele (1984) Achondrite ALHA77005: Alteration of chromite and olivine. *Meteoritics* 19:121-133
- Smith JV, IM Steele, CA Leitch (1983) Mineral chemistry of the shergottites, nakhlites, Chassigny, Brachina, pallasites and ureilites. *J Geophys Res* 88 (suppl): B229-B236

- Smith MR, JC Laul, M-S Ma, T Huston, RM Verkoouteren, ME Lipschutz, RA Schmidt (1984) Petrogenesis of the SNC (shergottites, nakhlites, chassignites) meteorites: Implications for their origin from a large, dynamic planet, possibly Mars. *J Geophys Res* 69:B612-B630
- Soderblom LA (1992) The composition and mineralogy of the martian surface from spectroscopic observations: 0.3  $\mu\text{m}$  to 50  $\mu\text{m}$ . In: Mars. HH Kieffer, BM Jakosky, CW Snyder, MS Matthews (eds) p 557-593. Univ Arizona Press, Tucson, AZ
- Steele IM, JV Smith (1982) Petrography and mineralogy of two basalts and olivine-pyroxene-spinel fragments in achondrite EETA79001. *J Geophys Res* 87:A375-A384
- Stöffler D, R Ostertag, C Jammes, G Pfannschmidt, PR Sen Gupta, SB Simon, JJ Papike, RH Beauchamp (1986) Shock metamorphism and petrography of the Shergotty achondrite. *Geochim Cosmochim Acta* 50:889-913
- Stöffler D, K Keil, ERD Scott (1991) Shock metamorphism of ordinary chondrites. *Geochim Cosmochim Acta* 55:3845-3867
- Stolper EM, HY McSween Jr (1979) Petrology and origin of the shergottite meteorites. *Geochim Cosmochim Acta* 43:1475-1498
- Sunshine JM, LA McFadden, CM Pieters (1993) Reflectance spectra of the Elephant Moraine A79001 meteorite: Implications for remote sensing of planetary bodies. *Icarus* 105:79-91
- Swindle TD, MW Caffee, CM Hohenberg (1986) Xenon and other noble gases in shergottites. *Geochim Cosmochim Acta* 50:1001-1015
- Swindle TD, MK Burkland, JA Grier, DJ Lindstrom, AH Treiman (1995) Noble gas analysis and INAA of aqueous alteration products from the Lafayette meteorite: Liquid water on Mars < 350 Ma ago (abstr). *Lunar Planet Sci XXVII*:1385-1386
- Swindle TD, JA Grier, B Li, E Olson, DJ Lindstrom, AH Treiman (1997) K-Ar ages of Lafayette weathering products: Evidence for near-surface liquid water on Mars in the last hundred million years (abstr). *Lunar Planet Sci XXVIII*:1403-1404
- Treiman AH (1985) Amphibole and hercynite spinel in Shergotty and Zagami: Magmatic water, depth of crystallization, and metasomatism. *Meteoritics* 20:229-243
- Treiman AH (1986) The parental magma of the Nakhla achondrite: Ultrabasic volcanism on the shergottite parent body. *Geochim Cosmochim Acta* 50:1061-1070
- Treiman AH (1987) Geology of the nakhlite meteorites: Cumulate rocks from flows and shallow intrusions (abstr). *Lunar Planet Sci XVIII*:1022-1023
- Treiman AH (1990) Complex petrogenesis of the Nakhla (SNC) meteorite: Evidence from petrography and mineral chemistry. *Proc Lunar Planet Sci Conf* 20:273-280
- Treiman AH (1993) The parent magma of the Nakhla (SNC) meteorite, inferred from magmatic inclusions. *Geochim Cosmochim Acta* 57:4753-4767
- Treiman AH (1995a) S  $\neq$  NC: Multiple source areas for martian meteorites. *J Geophys Res* 100:5329-5340
- Treiman AH (1995b) A petrographic history of martian meteorite ALH84001: Two shocks and an ancient age. *Meteoritics* 30:294-302
- Treiman AH (1996a) Comment on "Mars as the parent body of the CI carbonaceous chondrites" by J. E. Brandenburg. *Geophys Res Lett* 23:3275-3276
- Treiman AH (1996b) The perils of partition: Difficulties in retrieving magma compositions from chemically equilibrated basaltic meteorites. *Geochim Cosmochim Acta* 60:147-155
- Treiman AH (1997) Amphibole in martian meteorite EET 79001 (abstr). *Met Planet Sci* 32:A129-A130
- Treiman AH, DJ Lindstrom (1997) Trace element geochemistry of martian iddingsite in the Lafayette meteorite. *J Geophys Res* 102:9,153-9,164
- Treiman AH, SR Sutton (1992) Petrogenesis of the Zagami meteorite: Inferences from synchrotron X-ray (SXRF) microprobe and electron microprobe analyses of pyroxenes. *Geochim Cosmochim Acta* 56:4059-4074
- Treiman AH, MJ Drake, J Hertogen, MJ Janssens, R Wolf, E Ebihara (1986) Core formation in the earth and shergottite parent body (SPB): Chemical evidence from basalts. *Geochim Cosmochim Acta* 50:1071-1091
- Treiman AH, RA Barrett, JL Gooding (1993) Preterrestrial aqueous alteration of the Lafayette (SNC) meteorite. *Meteoritics* 28:86-97
- Treiman AH, GA McKay, DD Bogard, DW Mittlefehldt, M-S Wang, L Keller, ME Lipschutz, MM Lindstrom, D Garrison (1994) Comparison of the LEW88516 and ALHA77005 martian meteorites: Similar but distinct. *Meteoritics* 29:581-592
- Treiman AH, GJ Taylor, R Friedman (1995) Nakhla and its look-alikes: Al-depleted magmas and mantle differentiation on Mars and the Earth (abstr). *Lunar Planet Sci XXVI*:1419-1420
- Tschermak G (1872) Die Meteoriten von Shergotty und Gopalpur. *Sitzungsber. Akad. Wiss. Wien Math Naturwiss. Kl.* 65:122-146
- Tschermak G (1885) *The Microscopic Properties of Meteorites* (translated 1964 by JA Wood, EM Wood). *Smithsonian Contrib Astrophys* 4:6, Smithsonian Institution, Washington, DC

- Turner G, SF Knott, RD Ash, JD Gilmour (1997) Ar-Ar chronology of the Martian meteorite ALH84001: Evidence for the early bombardment of Mars. *Geochim Cosmochim Acta* 61:3835-3850
- Valley JW, JM Eiler, CM Graham, EK Gibson, CS Romanek, EM Stolper (1997) Low-temperature carbonate concretions in the martian meteorite ALH84001: Evidence from stable isotopes and mineralogy. *Science* 275:1633-1638
- Vicenzi EP, K Tobin, PJ Heaney, TC Onstott, J Chun (1997) Carbonate in Lafayette meteorite: A detailed microanalytical study (abstr). *Met Planet Sci* 32:A132-A133
- Vickery AM, HJ Melosh (1983) The origin of SNC meteorites: An alternative to Mars. *Icarus* 56:299-318
- Vickery AM, HJ Melosh (1987) The large crater origin for the SNC meteorites. *Science* 237:738-743
- Vistisen L, D Petersen, MB Madsen (1992) Mössbauer spectroscopy showing large scale inhomogeneity in the presumed martian meteorite Zagami. *Physica Scripta* 46:94-96.
- Wadhwa M, G Crozaz (1994) First evidence for infiltration metasomatism in a martian meteorite, ALH84001 (abstr). *Meteoritics* 29:545
- Wadhwa M, G Crozaz (1995a) Trace and minor elements in minerals of nakhlites and Chassigny: Clues to their petrogenesis. *Geochim Cosmochim Acta* 59:3629-3645
- Wadhwa M, G Crozaz (1995b) Constraints on the rare earth element characteristics of metasomatizing fluids in the martian meteorite ALH84001 (abstr). *Lunar Planet Sci XXVI*:1451-1452
- Wadhwa M, GW Lugmair (1996) The formation age of carbonates in ALH84001 (abstr). *Met Planet Sci* 31:A145
- Wadhwa M, HY McSween Jr, G. Crozaz (1994) Petrogenesis of shergottite meteorites inferred from minor and trace element microdistributions. *Geochim Cosmochim Acta* 58:4213-4229
- Wadhwa M, G McKay, G Crozaz (1997) Trace element distributions in Yamato 793605, a chip off the "martian lherzolite" block (abstr). *Antarctic Meteorites XXII*:197-199
- Walker D, EM Stolper, JF Hays (1979) Basaltic volcanism: The importance of planet size. *Proc Lunar Planet Sci Conf* 10:1995-2015
- Warren PH (1987) Mars regolith versus SNC meteorites: Possible evidence for abundant crustal carbonates. *Icarus* 70:153-161
- Warren PH, GW Kallemeyn (1996) Siderophile trace elements in ALH84001, other SNC meteorites and eucrites: Evidence of heterogeneity, possibly time-linked, in the mantle of Mars. *Met Planet Sci* 31:97-105
- Warren PH, GW Kallemeyn (1997) Yamato-793605, EET79001, and other presumed martian meteorites: Compositional clues to their origins. *Proc NIPR Symp Antarctic Met* (in press)
- Wasson JT, GW Wetherill (1979) Dynamical, chemical, and isotopic evidence regarding the formation locations of asteroids and meteorites. In: *Asteroids*. T Gehrels (ed) p 926-974. Univ Arizona Press, Tucson
- Watson LL, ID Hutcheon, S Epstein, EM. Stolper (1994) Water on Mars: Clues from deuterium/hydrogen and water contents of hydrous phases in SNC meteorites. *Science* 265:86-90
- Weincke HH (1978) Chemical and mineralogical examination of the Nakhla achondrite. *Meteoritics* 13: 660-664
- Weins RC, RO Pepin (1988) Laboratory shock emplacement of noble gases, nitrogen, and carbon dioxide into basalt, and implications for trapped gases in shergottite EETA79001. *Geochim Cosmochim Acta* 52:295-307
- Wentworth SJ, JL Gooding (1993) Weathering features and secondary minerals in Antarctic shergottites ALHA77005 and LEW88516 (abstr). *Lunar Planet Sci XXIV*:1507-1508
- Wentworth SJ and JL Gooding (1994) Carbonate and sulfate minerals in the Chassigny meteorite: Further evidence for aqueous activity on the SNC parent body. *Meteoritics* 29:860-863
- Wentworth SJ., JL Gooding (1995) Carbonates in the martian meteorite, ALH84001: Water-borne but not like the SNCs (abstr). *Lunar Planet Sci XXVI*:1489-1490
- Wentworth SJ., JL Gooding (1996) Water-based alteration of the martian meteorite, QUE94201, by sulfate-dominated solutions (abstr). *Lunar Planet Sci XXVII*:1421-1422
- Wetherill G (1976) Where do meteorites come from? *Geochim Cosmochim Acta* 40:1297-1317
- Wetherill G (1984) Orbital evolution of impact ejecta from Mars. *Meteoritics* 19:1-12.
- Wood CA, LD Ashwal (1981) SNC meteorites: Igneous rocks from Mars? *Proc Lunar Planet Sci Conf* 12:1359-1375
- Wooden JL, LE Nyquist, DD Bogard, BM Bansal, H Wiesmann, C-Y Shih, GA McKay (1979) Radiometric ages for the achondrites Chervony Kut, Governador Valadares, Allan Hills 77005 (abstr). *Lunar Planet Sci X*, 1379-1380
- Wooden JL, C-Y Shih, LE Nyquist, BM. Bansal, H Wiesmann, GA McKay (1982) Rb-Sr and Sm-Nd isotopic constraints on the origin of EETA79001: A second Antarctic shergottite (abstr). *Lunar Planet Sci XXIII*:879-880
- Wright IP, MM Grady, CT Pillinger (1988) Carbon, oxygen, and nitrogen isotopic compositions of possible martian weathering products in EETA79001. *Geochim Cosmochim Acta* 52:917-924

- Wright IP, MM Grady, CT Pillinger (1990) The evolution of atmospheric CO<sub>2</sub> on Mars: The perspective from carbon isotope measurements. *J Geophys Res* 95:14,789-14,794
- Yamada I, T Mikouchi, M Miyamoto, T Murakami (1997) Lamellar inclusion in olivine from Nahkla (SNC) meteorite (abstr). *Lunar Planet Sci XXVIII*:1597-1598

## APPENDIX

### **Representative Mineral Compositions in SNC Meteorites**

The Tables on the following pages contain electron microprobe analyses of pyroxenes (A1), feldspars (or maskelynite) (A2), olivines (A3), and oxides (A4) in basaltic and lherzolitic shergottites, nakhlites, Chassigny, and ALH84001.

Table A.1. PYROXENES

	Shergotty				Zagami				EETA79001				QUE94201			
	Pig Core	Rim	Aug Core	Rim	Pig Core	Rim	Aug Core	Rim	Pig Core	Rim	Aug Core	Rim	Low-Ca Px	Pig Core	Aug Core	Pyrox Rim
	<i>Chemical Composition (Weight Percent)</i>															
SiO <sub>2</sub>	54.6	49.7	53.6	50.5	51.94	49.29	52.08	50.33	53.8	49.9	52.1	50.7	54.7	51.7	50.8	47.9
Al <sub>2</sub> O <sub>3</sub>	0.74	0.66	0.96	0.87	0.69	0.53	0.97	0.93	0.70	0.83	1.50	1.21	0.60	1.39	2.33	0.66
TiO <sub>2</sub>	0.08	0.40	0.20	0.52	0.13	0.59	0.17	0.77	0.11	0.59	0.26	0.66	0.11	0.52	0.69	0.93
Cr <sub>2</sub> O <sub>3</sub>	0.43	0.10	0.70	0.17	0.41	0.03	0.72	0.15	0.45	0.27	0.62	0.44	0.49	0.46	0.84	0.06
FeO	16.9	31.1	11.9	25.8	18.90	31.67	12.09	21.18	16.7	27.5	15.0	16.9	15.2	20.5	12.3	34.2
MnO	0.53	0.78	0.41	0.68	0.66	0.91	0.42	0.59	0.63	0.84	0.52	0.59	0.60	0.58	0.43	0.90
MgO	21.8	11.0	16.9	9.62	19.17	11.09	16.00	11.00	23.0	12.6	17.6	13.6	24.5	17.9	14.5	7.48
CaO	6.11	6.64	16.7	12.2	6.35	6.50	16.59	15.46	4.38	7.41	11.8	14.5	3.03	6.98	17.9	7.86
Na <sub>2</sub> O	0.07	0.09	0.15	0.11	0.09	0.08	0.18	0.16	0.08	0.11	0.20	0.19	0.04	0.08	0.19	0.05
Total	101.28	100.03	101.42	100.51	98.34	100.69	99.22	100.57	99.85	100.05	99.60	98.79	99.27	100.11	99.98	100.04
	<i>Cation Formula Based on 6 Oxygens (Ideal Pyroxene = 4 Cations per 6 Oxygens)</i>															
Si	1.975	1.967	1.972	1.990	1.977	1.955	1.962	1.949	1.979	1.955	1.953	1.958	1.998	1.95	1.91	1.95
Al	.025	.031	.028	.010	.023	.025	.038	.042	.021	.039	.047	.042	.002	.05	.09	.03
Total tet	2.000	1.998	2.000	2.000	2.000	1.980	2.000	1.991	2.000	1.994	2.000	2.000	2.000	2.000	2.000	1.98
Ti	.002	.012	.006	.015	.004	.018	.005	.023	.002	.017	.006	.018	.002	.01	.02	.03
Al	.007	.007	bd	.030	.008	bd	.005	bd	.009	bd	.019	.012	.023	.01	.01	bd
Cr	.013	.003	.020	.005	.012	.001	.021	.004	.013	.008	.018	.012	.014	.01	.03	.00
Fe	.514	1.030	.366	.846	.602	1.050	.381	.686	.513	.898	.470	.550	.465	.65	.39	1.16
Mn	.016	.026	.013	.023	.021	.031	.013	.019	.019	.027	.015	.018	.018	.02	.01	.05
Mg	1.182	.650	.923	.561	1.088	.656	.899	.635	1.260	.737	1.985	.784	1.333	1.01	.81	.45
Ca	.239	.282	.658	.514	.259	.276	.670	.641	.171	.310	.472	.599	.118	.28	.72	.34
Na	.005	.007	.011	.009	.007	.006	.013	.012	.005	.008	.014	.013	.002	.01	.01	.00
Total Cations	3.978	4.008	4.011	4.003	4.001	4.018	4.007	4.011	3.992	3.945	3.999	4.006	3.975	4.00	4.00	3.99
	<i>Cation Ratios: Ca: Mg: Fe and Fe/(Fe+Mg)</i>															
Ca	.124	0.144	0.338	0.268	0.133	0.139	0.344	0.327	0.088	0.088	0.245	0.310	0.062	.34	.38	.17
Mg	.611	.331	.474	.292	.558	.331	.461	.324	.648	.379	.511	.406	.696	.52	.42	.23
Fe	.265	.525	.188	.440	.309	.530	.195	.350	.264	.462	.244	.284	.242	.34	.20	.60
Fe/(Fe + Mg)	.303	.613	.284	.621	.356	.615	.298	.519	.289	.549	.323	.412	.259	.39	.33	.72

Table A1. PYROXENES (Cont'd)

	EETA79001			QUES4201			Nakhla			Lafayette Valadares			Gov.					
	Pig	Aug	Aug	Pig	Aug	Aug	Pig	Aug	Aug	Pig	Aug	Aug						
	Core	Rim	Core	Core	Rim	Core	Core	Rim	Core	Core	Rim	Core						
	McSween & Jarosewich (1983)												Treiman (1989)			Harvey & McSween (1992a)		
	Chemical Composition (Weight Percent)																	
SiO <sub>2</sub>	55.2	53.4	53.6	52.5	55.05	52.17	52.21	52.48	49.64	52.68	49.82	51.36	51.51					
Al <sub>2</sub> O <sub>3</sub>	0.48	0.83	1.29	1.72	0.62	1.34	1.68	1.44	0.69	1.03	1.45	0.85	0.74					
TiO <sub>2</sub>	0.11	0.47	0.32	0.39	0.07	0.43	0.36	0.28	0.37	0.34	0.44	0.23	0.20					
Cr <sub>2</sub> O <sub>3</sub>	0.52	0.48	0.89	0.84	0.58	0.49	0.77	0.67	0.01	0.47	0.03	0.39	0.37					
FeO	14.0	16.3	9.21	9.62	14.37	16.28	10.64	10.07	36.17	14.18	25.57	14.12	13.98					
MnO	0.40	0.47	0.22	0.25	0.50	0.59	0.47	0.38	1.03	0.44	0.71	0.41	0.40					
MgO	25.9	23.4	17.6	16.9	25.59	20.01	17.60	17.60	7.73	12.97	7.27	12.79	13.16					
CaO	3.84	4.07	16.5	17.0	3.02	8.24	15.59	16.40	5.15	18.35	14.86	18.50	18.48					
Na <sub>2</sub> O					0.06	0.12	0.17	0.18	0.12	0.22	0.23	0.21	0.18					
Total	100.45	99.42	99.63	99.22	99.85	99.67	99.48	99.49	100.91	100.67	100.38	98.87	98.91					
	Cation Formula Based on 6 Oxygens (Ideal Pyroxene = 4 Cations per 6 Oxygens)																	
Si	1.985	1.975	1.975	1.953	1.99	1.95	1.94	1.95	1.965	1.969	1.994	1.972	1.97					
<sup>iv</sup> Al	0.15	0.25	0.25	0.47	0.01	0.05	0.06	0.05	0.24	0.320	0.006	0.028	0.03					
Total tet	2.000	2.000	2.000	2.000	2.00	2.00	2.00	2.00	2.000	2.000	2.000	2.000	2.000					
Ti	0.003	0.013	0.009	0.11	0.00	0.01	0.01	0.01	0.010	0.013	0.011	0.007	0.01					
<sup>vi</sup> Al	0.005	0.011	0.031	0.028	0.02	0.01	0.01	0.01	0.022	0.035	0.027	0.011	0.00					
Cr	0.015	0.014	0.026	0.025	0.02	0.01	0.02	0.014	0.001	0.001	0.000	0.012	0.01					
Fe	0.421	0.504	0.284	0.299	0.44	0.51	0.33	0.31	0.446	0.445	0.445	0.454	0.45					
Mn	0.012	0.015	0.007	0.008	0.02	0.02	0.02	0.014	0.014	0.024	0.0350	0.013	0.01					
Mg	1.388	1.290	0.967	0.937	1.38	1.11	0.98	0.98	0.429	0.463	1.153	0.732	0.75					
Ca	0.148	0.138	0.651	0.677	0.12	0.33	0.62	0.65	0.629	0.222	0.18	0.761	0.76					
Na	nd	nd	nd	nd	0.00	0.01	0.01	0.01	0.018	0.010	0.016	0.015	0.01					
Total Cations	3.992	3.985	3.975	3.985	3.99	4.01	4.01	4.00	4.015	3.993	3.982	4.005	4.01					
	Cation Ratios: Ca, Mg, Fe and Fe/(Fe+Mg)																	
Ca	0.076	0.071	0.342	0.354	0.06	0.17	0.32	0.34	0.117	0.386	0.331	0.392	0.385					
Mg	0.709	0.668	0.508	0.354	0.71	0.57	0.51	0.51	0.244	0.382	0.227	0.376	0.381					
Fe	0.215	0.261	0.149	0.156	0.23	0.26	0.17	0.16	0.640	0.237	0.443	0.232	0.234					
Fe/(Fe + Mg)	0.233	0.281	0.227	0.242	0.24	0.32	0.25	0.24	0.724	0.378	0.661	0.382	0.380					



Table A1. PYROXENES (Cont'd)

	Chassigny		ALH84001		
	Aug Wadhwa & Crozaz (1996)	Pig Opx	Aug Treiman (1995)	Opx Treiman (1995)	
<i>Chemical Composition (Weight Percent)</i>					
SiO <sub>2</sub>	53.11	53.74	53.50	53.72	54.41
Al <sub>2</sub> O <sub>3</sub>	1.03	0.61	0.72	0.56	0.56
TiO <sub>2</sub>	0.28	0.14	0.19	0.30	0.18
Cr <sub>2</sub> O <sub>3</sub>	0.77	0.41	0.30	0.49	0.29
FeO	9.33	15.90	17.89	7.48	17.50
MnO	0.34	0.50	0.59	0.27	0.51
MgO	16.71	22.98	24.35	15.94	25.59
CaO	17.87	5.21	1.87	21.01	1.52
Na <sub>2</sub> O	0.32	0.11	0.05	0.37	0.02
Total	99.77	99.60	99.47	100.14	100.58
<i>Cation Formula Based on 6 Oxygens</i>					
<i>(Ideal Pyroxene = 4 Cations per 6 Oxygens)</i>					
Si	1.969	1.979	1.973	1.981	1.975
<sup>iv</sup> Al	.031	.021	.027	.019	.024
Total IV	2.000	2.000	2.000	2.000	1.999
Ti	.008	.004	.005	.008	.005
<sup>vi</sup> Al	.014	.005	.003	.005	.000
Cr	.022	.012	.009	.014	.009
Fe	.290	.490	.552	.231	.531
Mn	.010	.015	.019	.009	.016
Mg	.923	1.262	1.339	.876	1.384
Ca	.710	.205	.074	.830	.059
Na	.023	.008	.001	.026	.002
Total Cations	4.000	4.001	4.002	4.000	4.000
<i>Cation Ratios: Ca: Mg: Fe and Fe/(Fe+Mg)</i>					
Ca	.369	.105	.038	.425	.003
Mg	.480	.645	.681	.452	.701
Fe	.151	.250	.281	.119	.269
Fe/(Fe + Mg)	.239	.279	.292	.209	.277

Table A2. MASKELYNITE and FELDSPAR

	EETA 79001 (1983)		QUE94201 McSween et al. (1996)		ALHA77005 McSween et al. (1979a)		LEW88516 Harvey et al. (1993)		Nakhta Weinke (1978)		Chassigny Floran et al. (1978)		ALH84001 Mittlefehldt (1994)
	Mask Core McSween & Jarosewich	Mask Rim	Mask Core McSween et al. (1996)	Mask Rim	Mask Core McSween et al. (1979a)	Mask Rim	Mask Core Harvey et al. (1993)	Mask Rim	Plag Weinke (1978)	Plag Floran et al. (1978)	Sanid	Mask	
SiO <sub>2</sub>	52.5	55.8	53.0	56.3	54.0	55.8	55.69	60.14	62.6	64.7	61.9		
Al <sub>2</sub> O <sub>3</sub>	29.8	27.5	29.2	27.2	28.4	26.5	27.67	23.78	24.1	20.5	24.7		
FeO	0.72	0.61	0.37	0.57	0.26	0.57	0.34	0.92	0.51	0.61	0.29		
MgO	nd	nd	nd	nd	nd	nd	nd	0.06	nd	nd	0.05		
CaO	12.7	10.5	12.9	10.6	10.7	8.96	10.25	6.44	6.3	0.95	6.29		
Na <sub>2</sub> O	4.38	5.16	4.11	5.02	5.20	6.00	5.41	7.37	7.0	5.0	7.07		
K <sub>2</sub> O	0.15	0.32	0.04	0.17	0.20	0.40	0.26	0.91	0.61	7.5	0.97		
Total	100.25	99.89	99.62	99.86	98.76	98.23	99.61	99.62	101.1	99.17	101.27		
<i>Chemical Composition (Weight Percent)</i>													
<i>Cation Formula Based on 8 Oxygens (Ideal Plagioclase = 5 Cations per 8 Oxygens)</i>													
Si	2.381	2.519	2.41	2.54	2.467	2.556	2.52	2.716	2.749	2.927	2.721		
<sup>IV</sup> Al	1.594	1.463	1.56	1.45	1.530	1.431	1.47	1.266	1.247	1.093	1.278		
Total tet	3.975	3.982	3.97	3.99	3.997	3.987	3.99	3.982	3.996	4.020	3.999		
Fe	0.026	0.022	0.01	0.02	.010	.022	.01	.004	.019	.023	.011		
Mg	nd	nd	nd	nd	nd	nd	nd	.004	nd	nd	.002		
Ca	.616	.504	0.63	0.50	.524	.440	.50	.312	.296	.046	.296		
Na	.385	.451	0.37	0.44	.461	.533	.47	.645	.596	.439	.603		
K	.008	.018	.00	.01	.012	.023	.01	.052	.034	.433	.054		
Total Cations	5.010	4.977	4.97	4.97	5.004	5.005	4.99	4.999	4.941	4.960	4.966		
<i>Molecular Proportion of Orthoclase (Or), Albite (Ab), and Anorthite (An)</i>													
Or	.008	.018	.00	.01	.526	.442	.51	.052	.036	.473	.057		
Ab	.382	.464	.37	.44	.462	.535	.48	.639	.644	.472	.632		
An	.610	.518	.63	.50	.012	.023	.01	.309	.320	.050	.311		

Table A3. OLIVINE

	BETA79001 McSween & Jarosewich (1983)	ALHA77005 McSween et al. (1979a)	LEW88516	Nakhla	Lafayette	Gov. Valadares	Chassigny
			Harvey et al. (1993)	Treiman (1993)	Harvey & McSween (1992a)		Floran et al. (1978)
	<i>Chemical Composition (Weight Percent)</i>						
SiO <sub>2</sub>	38.3	37.5	37.0	33.46	31.94	32.00	37.1
Al <sub>2</sub> O <sub>3</sub>	0.02	nd	nd	0.05	nd	nd	0.08
FeO	24.0	24.4	27.47	48.42	52.09	52.61	27.6
MgO	36.8	37.1	34.7	17.36	13.41	13.16	34.0
MnO	0.55	0.67	0.58	0.95	0.97	1.01	0.53
Cr <sub>2</sub> O <sub>3</sub>	0.07	0.07	nd	0.02	nd	nd	0.04
CaO	0.26	0.25	0.14	0.37	0.19	0.36	0.19
Total	100.00	99.99	99.89	100.63	98.63	99.17	99.54
	<i>Cation Formula Based on 4 Oxygens (Ideal Olivine = 3 Cations per 4 Oxygens)</i>						
Si	1.005	.990	.99	0.994	.99	.99	.997
Al	.000	nd	nd	0.002	nd	nd	.003
Fe	.527	.532	.62	1.203	1.36	1.37	.620
Mg	1.437	1.460	1.39	.769	.62	.61	1.362
Mn	.011	.015	.01	.024	.03	.03	.012
Cr	.001	.001	.00	.001	nd	nd	.001
Ca	.007	.007	.01	.012	.01	.01	.001
Total Cations	2.988	3.005	3.02	3.005	3.01	3.01	2.996
	<i>Cation Ratio Fe/(Fe+Mg)</i>						
Fe/(Fe+Mg)	.268	.267	.308	.610	.69	.70	.313

Table A4. OXIDES

	EET79001			QUE94201			ALH77005			LEW88516		
	Ulvospinel	Ilmenite	Chromite	Ulvospinel	Ilmenite	Chromite	Chromite	Chromite	Chromite	Chromite	Chromite	Chromite
	McSween & Jarosewich (1983)			McSween et al. (1996)			McSween et al. (1979a)			Harvey et al. (1993)		
	<i>Chemical Composition (Weight Percent)</i>											
TiO <sub>2</sub>	30.7	51.1	0.81	30.6	52.6	1.02	11.1	54.3	0.90	8.67	53.71	
Al <sub>2</sub> O <sub>3</sub>	1.72	0.19	7.11	2.07	0.08	6.95	7.14	0.18	5.62	6.39	0.09	
Cr <sub>2</sub> O <sub>3</sub>	0.04	0.34	57.8	0.26	0.04	58.3	38.5	0.62	58.04	40.50	0.76	
FeO	67.0	45.4	32.3	64.5	46.4	28.9	37.6	39.4	30.31	38.78	39.79	
MgO	0.26	1.76	2.35	0.06	0.14	5.04	5.39	5.52	3.59	3.66	4.56	
MnO	0.66	0.74	0.53	0.58	0.73	0.62	0.72	0.7	0.48	0.53	0.78	
Total	100.38	99.53	100.90	98.07	99.99	100.83	100.45	100.72	98.94	98.53	99.69	
	<i>Cation Formula Based on 4 Oxygens (Ideal Spinel = 3 Cations per 4 Oxygens)</i>											
Ti	.869	.907	.021	.87	1.00	.027	.292	.988	0.02	0.23	1.98	
Al	.075	.005	.294	.09	.00	.286	.294	.005	0.23	0.27	0.00	
Cr	.000	.006	1.612	.01	.00	1.607	1.063	0.012	1.63	1.13	0.03	
Fe	2.109	.958	.954	2.01	.98	.842	1.098	.797	0.91	1.16	1.63	
Mg	.014	.066	.123	.00	.01	.262	.281	.199	0.19	0.19	0.33	
Mn	.021	0.16	.015	.02	.02	.013	.016	.015	0.01	0.02	0.03	
Total	3.088	1.895	3.019	3.00	3.01	3.037	3.044	2.016	2.99	3.07	4.00	
Fe <sup>2+</sup> /Fe <sup>3+</sup>	7.61	bd	13.45	11.5	bd	9.94	11.5	bd	9.85	7.78	bd	

Table A4. OXIDES (Cont'd)

	Nakhla		Chassigny		ALH84001
	Magnetite Treiman (1993)	Ilmenite Boctor et al. (1978)	Chromite	Ilmenite	Chromite Mittlefehldt (1994)
			Floran et al. (1978)		
	<i>Chemical Composition (Weight Percent)</i>				
TiO <sub>2</sub>	14.81	51.3	3.6	51.2	2.23
Al <sub>2</sub> O <sub>3</sub>	6.83	0.24	6.6	0.70	8.53
Cr <sub>2</sub> O <sub>3</sub>	0.34	0.12	45.8	0.29	47.7
Fe	75.00	44.56	37.3	39.6	36.0
MgO	0.48	0.86	3.8	5.5	3.85
MnO	0.41	0.62	0.61	1.56	0.39
Total	97.87	97.70	97.71	98.85	98.70
	<i>Cation Formula Based on 4 Oxygens (Ideal Spinel = 3 Cations per 4 Oxygens)</i>				
Ti	0.622	1.974	.150	1.857	.058
Al	0.045	0.015	.417	.038	.350
Cr	0.008	0.005	1.940	.011	1.313
Fe	2.063	1.871	1.592	1.599	1.037
Mg	0.040	0.063	.304	.396	.202
Mn	0.020	0.027	.027	.640	.012
Total	2.798	3.955	4.430	4.541	2.972
Fe <sup>3+</sup> /Fe <sup>2+</sup>	1.59	56.6	3.65	7.30	4.21

