Mineralogy of meteorite groups

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Abstract–Approximately 275 mineral species have been identified in meteorites, reflecting diverse redox environments, and, in some cases, unusual nebular formation conditions. Anhydrous ordinary, carbonaceous and R chondrites contain major olivine, pyroxene and plagioclase; major opaque phases include metallic Fe-Ni, troilite and chromite. Primitive achondrites are mineralogically similar. The highly reduced enstatite chondrites and achondrites contain major enstatite, plagioclase, free silica and kamacite as well as nitrides, a silicide and Ca-, Mg-, Mn-, Na-, Cr-, K- and Ti-rich sulfides. Aqueously altered carbonaceous chondrites contain major amounts of hydrous phyllosilicates, complex organic compounds, magnetite, various sulfates and sulfides, and carbonates.

In addition to kamacite and taenite, iron meteorites contain carbides, elemental C, nitrides, phosphates, phosphides, chromite and sulfides. Silicate inclusions in IAB/IIICD and IIE iron meteorites consist of mafic silicates, plagioclase and various sulfides, oxides and phosphates. Eucrites, howardites and diogenites have basaltic to orthopyroxenitic compositions and consist of major pyroxene and calcic plagioclase and several accessory oxides. Ureilites are made up mainly of calcic, chromian olivine and low-Ca clinopyroxene embedded in a carbonaceous matrix; accessory phases include the C polymorphs graphite, diamond, lonsdaleite and chaoite as well as metallic Fe-Ni, troilite and halides. Angrites are achondrites rich in fassaitic pyroxene (*i.e.*, Al-Ti diopside); minor olivine with included magnesian kirschsteinite is also present. Martian meteorites comprise basalts, lherzolites, a dunite and an orthopyroxenite. Major phases include various pyroxenes and olivine; minor to accessory phases include various sulfides, magnetite, chromite and Ca-phosphates. Lunar meteorites comprise mare basalts with major augite and calcic plagioclase and anorthositic breccias with major calcic plagioclase.

Several meteoritic phases were formed by shock metamorphism. Martensite (α_2-Fe,Ni) has a distorted body-centered-cubic structure and formed by a shear transformation from taenite during shock reheating and rapid cooling. The C polymorphs diamond, lonsdaleite and chaoite formed by shock from graphite. Suessite formed in the North Haig ureilite by reduction of Fe and Si (possibly from olivine) *via* reaction with carbonaceous matrix material. Ringwoodite, the spinel form of $(Mg,Fe)_2SiO_4$, and majorite, a polymorph of $(Mg,Fe)SiO_3$ with the garnet structure, formed inside shock veins in highly shocked ordinary chondrites.

Secondary minerals in meteorite finds that formed during terrestrial weathering include oxides and hydroxides formed directly from metallic Fe-Ni by oxidation, phosphates formed by the alteration of schreibersite, and sulfates formed by alteration of troilite.

INTRODUCTION

The number of minerals recognized in meteorites has continued its dramatic increase since the beginning of the nineteenth century when Howard (1802) identified "martial pyrite" (troilite) and metallic Fe-Ni and inferred the presence of magnesian silicate from chemical analyses. Toward the end of the nineteenth century, Tschermak (1885) identified 16 minerals including "pure iron" (kamacite), nickel-iron (taenite), graphite, schreibersite, troilite, daubréelite, oldhamite, osbornite, chromite, magnetite, tridymite, olivine, bronzite (low-Ca pyroxene), augite, plagioclase and "breunnerite" (ferroan magnesite), as well as maskelynite (shock-disordered plagioclase glass) and igneous glass. By the middle of the twentieth century, the list had been augmented only modestly, allowing Krinov (1960) to list 26 meteoritic minerals and Mason (1962) to list 38. However, with the widespread use of reflected light microscopy, the advent of new analytical techniques (*e.g.*, x-ray diffraction, electron microprobe analysis and scanning and transmission electron microscopy) and the recovery of large numbers of meteorites (including members of new meteorite groups; Table 1) from hot and cold deserts, the list expanded rapidly in the ensuing decades. Mason (1967, 1972) listed ~60 and more than 80 meteoritic minerals, respectively. Ramdohr (1973) identified ~40 opaque minerals

in stony meteorites alone, although ~15 of these were insufficiently described to be given names. El Goresy (1976) and Buchwald (1984) reviewed the occurrences of meteoritic oxides and phosphates. Gomes and Keil (1980) reported a total of ~86 minerals in stony meteorites. Olsen (1981) expanded the total number of meteoritic minerals to ~100. Yudin and Kolomenskiy (1987) listed ~200 meteoritic minerals, and Kerridge and Matthews (1988) listed ~130. Ulyanov (1991) compiled a massive list of more than 350 minerals and their varieties in meteorites, interplanetary dust particles and tektites. Although Table 2 is based to some extent on the compilations by Kerridge and Matthews (1988) and Ulyanov (1991), it is restricted to meteorites, includes many previously overlooked and subsequently described minerals and excludes trivial mineral varieties and doubtful identifications. Today, the number of mineral species identified in meteorites (~275) is ~7% of the total number of well-characterized minerals.

The importance of minerals, mineral compositions and textural relationships for understanding the genesis of meteorites has long been recognized. Howard (1802) devoted an appreciable part of his seminal report on the chemical analysis of meteorites to Count Jacques-Louis Bournon's mineralogical descriptions. The large variety of stable and metastable mineral species reflects wide variations

TABLE 1. Meteorite classification.

Chondrites		
Carbonaceous chondrites		
	CI	aqueously altered; chondrule-free; volatile-rich
	CM	aqueously altered; minichondrule-bearing
	CR	aqueously altered; primitive-chondrule-bearing; metal-bearing
	CO	minichondrule-bearing; metal-bearing
	CV	large-chondrule-bearing; abundant CAIs; partially aqueously altered
	CK	large-chondrule-bearing; darkened silicates
	CH*	microchondrule-bearing; metal-rich; volatile-poor
	Ungrouped	(e.g., Coolidge; LEW 85332)
Ordinary chondrites		
	H	high total iron
	L	low total iron
	LL	low total iron; low metallic iron
	"HH"	(chondritic silicates in Netschaevo IIE-an iron)
R chondrites		
	R	highly oxidized; $\Delta^{17}O$-rich
Enstatite chondrites		
	EH	high total iron; highly reduced; minichondrule-bearing
	EL	lower total iron; highly reduced; moderately sized chondrules
	Ungrouped	(e.g., LEW 87223)
IAB/IIICD silicates		subchondritic composition; chondrule-free; planetary-gas-bearing
Ungrouped chondrites		(e.g., Deakin 001)
Primitive achondrites		
	acapulcoites	chondritic abundances of plagioclase and troilite; medium-grained
	lodranites	subchondritic abundances of plagioclase and troilite; coarse-grained
	winonaites	IAB-silicate-related
	ungrouped	(e.g., Divnoe)
Ungrouped meteorites		(e.g., Bencubbin; Weatherford)
Differentiated meteorites		
Asteroidal achondrites		
	eucrites	basalts
	diogenites	orthopyroxenites
	howardites	brecciated mixtures of basalts and orthopyroxenites
	angrites	fassaitic-pyroxene-bearing basalts
	aubrites	enstatite achondrites
	ureilites	olivine-, pyroxene- and carbonaceous-matrix-bearing
	brachinites	equigranular; olivine-, clinopyroxene- and orthopyroxene-bearing
Martian meteorites		
	shergottites	basalts and lherzolites
	nakhlites	cumulus-augite-bearing pyroxenites
	Chassigny	dunite
	ALH 84001	orthopyroxenite
Lunar meteorites		
	Mare basalts	
	Impact breccias	anorthositic- and mare-dominated regolith and fragmental breccias
Stony irons		
	Pallasites	metal plus olivine; core/mantle boundary samples
		Main-group pallasites
		Eagle-Station-trio pallasites
	Mesosiderites	metal plus basaltic, gabbroic and orthopyroxenitic silicates
	Ungrouped	(e.g., Enon; Mt. Egerton)
Irons		
	magmatic groups	(IC, IIAB, IIC, IID, IIF, IIIAB, IIIE, IIIF, IVA, IVB)
	nonmagmatic groups	(IAB/IIICD, IIE)
	Ungrouped	(e.g., Britstown; Denver City; Guin; Sombrerete)

*Controversial group (cf., Grossman et al., 1988; Scott, 1988; Weisberg et al., 1988; Wasson and Kallemeyn, 1990).

TABLE 2. Minerals in meteorites.

Mineral	Formula	References
native elements and metals		
awaruite	Ni_3Fe	B17,K10,M13,R8
chaoite	C	V2,V3
copper	Cu	R1,R9
diamond	C	A5,B16,K16
gold-dominated alloys	(Au,Ag,Fe,Ni,Pt)	B12,G3,S4
graphite	C	A5,B16,R1
kamacite	α-(Fe,Ni)	A1,R1,R8
lonsdaleite	C	B16,B17,F5
martensite	α_2-(Fe,Ni)	D4
molybdenum	Mo	E4
nickel	Ni	N3
niobium	Nb	E4
platinum	Pt	E4
PGE-dominated alloys	(Pt,Os,Ir,Ru,Re,Rh,Mo, Nb,Ta,Zr,Ge,W,V,Pb, Cr,Fe,Ni,Co)	A7,B8,E4,W1
rhenium	Re	E4
ruthenium	Ru	E4
sulfur	S	B17
taenite	γ-(Fe,Ni)	R1
tetrataenite	FeNi	C2
wairauite	CoFe	H3
carbides		
cohenite	$(Fe,Ni)_3C$	B16,R1
haxonite	$(Fe,Ni)_{23}C_6$	B16,S5
iron carbide	$Fe_{2.5}C$	S7
molybdenum carbide	MoC	B6
silicon carbide	SiC	A3,A5,B6,H4
titanium carbide	TiC	B6,O11
zirconium carbide	ZrC	B6,O11
nitrides and oxynitrides		
carlsbergite	CrN	B16,B23
nierite	α-Si_3N_4	A3,A4,L1
osbornite	TiN	B11,R1
roaldite	$(Fe,Ni)_4N$	B16,N2
β-silicon nitride	β-Si_3N_4	L1
sinoite	Si_2N_2O	A6
phosphides		
barringerite	$(Fe,Ni)_2P$	B17,B29
schreibersite	$(Fe,Ni)_3P$	R1
silicides		
perryite	$(Ni,Fe)_5(Si,P)_2$	W5
suessite	Fe_3Si	K7
sulfides and hydroxysulfides		
bornite	Cu_5FeS_4	E5
brezinaite	Cr_3S_4	S2,W3
caswellsilverite	$NaCrS_2$	O1
chalcocite	Cu_2S	Y3
chalcopyrite	$CuFeS_2$	G3,R1
cinnabar	HgS	U2
cooperite	PtS	G3
covellite	CuS	E5
cubanite	$CuFe_2S_3$	D4,Z3
daubréelite	$FeCr_2S_4$	K3,R1
djerfisherite	$K_6Na_9(Fe,Cu)_{24}S_{26}Cl$	F7
erlichmanite	OsS_2	G1,G2,G3
ferroan alabandite	(Mn,Fe)S	K3
galena	PbS	N3

Mineral	Formula	References
sulfides and hydroxysulfides (continued)		
gentnerite	$Cu_8Fe_3Cr_{11}S_{18}$	U2
greigite	Fe_3S_4	E5
heazlewoodite	Ni_3S_2	B17,M13
heideite	$(Fe,Cr)_{1+x}(Ti,Fe)_2S_4$	K4
idaite	Cu_5FeS_6	E5
isocubanite	$CuFe_2S_3$	B16
laurite	RuS_2	G1,G2,G3
mackinawite	FeS_{1-x}	B28
marcasite	FeS_2	M16
millerite	NiS	G3
molybdenite	MoS_2	E4
monosulfide solid solution	$(Fe,Ni)_{1-x}S$	G3
niningerite	(Mg,Fe)S	K3,K6
oldhamite	CaS	K3
pentlandite	$(Fe,Ni)_9S_8$	R1,B17
pyrite	FeS_2	R1,N3
pyrrhotite	$Fe_{1-x}S$	Z3
schöllhornite	$Na_{0.3}(H_2O)[CrS_2]$	O3
smythite	Fe_9S_{11}	E5
sphalerite	(Zn,Fe)S	D4,E5
tochilinite group		B1,Z3
tochilinite	$2[(Fe,Mg,Cu,Ni[\ ])S\cdot1.57-1.85$ $[(Mg,Fe,Ni,Al,Ca)(OH)_2]$	Z3
haapalaite	$4(Fe,Ni)S\cdot3(Mg,Fe^{+2})(OH)_2$	Z3
troilite	FeS	R1
tungstenite	WS_2	E4
violarite	$FeNi_2S_4$	U2
wurtzite-2H	β-ZnS	Y3
tellurides		
chengbolite	$PtTe_2$	G3
arsenides and sulfarsenides		
cobaltite	CoAsS	N3
gersdorffite	NiAsS	N3
iridarsenite	$(Ir,Ru)As_2$	G3
löllingite	$FeAs_2$	G3
maucherite	$Ni_{11}As_8$	N3
nickeline	NiAs	N3
omeiite	$(Os,Ru)As_2$	G3
orcelite	$Ni_{5-x}As_2$	N3
rammelsbergite	$NiAs_2$	N3
safflorite	$CoAs_2$	N3
sperrylite	$PtAs_2$	G3
halides		
halite	NaCl	B1,B5
sylvite	KCl	B1,B5
oxides		
anatase	TiO_2	W13
armalcolite	$(Mg,Fe)Ti_2O_5$	L4
baddeleyite	ZrO_2	D1,D3,K12
bunsenite	NiO	B17
Ca-armalcolite	$CaTi_2O_5$	L4
calcium oxide	CaO	G10,G11,M2
chromite	$FeCr_2O_4$	R1,Z3
corundum	Al_2O_3	G10,G11,M2
coulsonite	FeV_2O_4	A7,U2
cuprite	Cu_2O	U2
eskolaite	Cr_2O_3	G9
geikilite	$MgTiO_3$	L4
grossite	$CaAl_4O_7$	W7,W8
hematite	α-Fe_2O_3	B17

Mineral	Formula	References
oxides (continued)		
hercynite	$(Fe,Mg)Al_2O_4$	T5,Z3
hibonite	$CaAl_{12}O_{19}$	D4,M2
ilmenite	$FeTiO_3$	R1,S10
maghemite	$Fe_{2.67}O_4$	B17,Z3
Magnéli phases	Ti_5O_9 and Ti_8O_{15}	B13,B14
magnesiochromite	$MgCr_2O_4$	G9
magnesioferrite	$MgFe_2O_4$	Y3
magnesiowüstite	$(Mg,Fe)O$	C1
magnetite	Fe_3O_4	B17,K9,R1,Z3
periclase	MgO	G10,G11,M2
perovskite	$CaTiO_3$	L4,M2
pleonaste	$(Mg,Fe)Al_2O_4$	M1
pseudobrookite	Fe_2TiO_5	R3,R5
pyrophanite	$MnTiO_3$	K13
rutile	TiO_2	G10,G11,L4,M2
spinel	$MgAl_2O_4$	M2,Z3
thorianite	ThO_2	M2
Ti-rich magnetite	$(Fe,Mg)(Al,Ti)_2O_4$	D4
trevorite	$NiFe_2O_4$	B17
ulvöspinel	Fe_2TiO_4	P1
V-rich magnetite	$(Fe,Mg)(Al,V)_2O_4$	B8,E4,W1
wüstite	FeO	B17
zirconolite	$(Ca,Th,Ce)Zr(Ti,Nb)_2O_7$	M2
hydroxides		
akaganéite	$\beta\text{-}FeO(OH,Cl)$	B17,B21,B22
amakinite	$(Fe^{+2},Mg)(OH)_2$	Z3
brucite	$Mg(OH)_2$	B1
ferrihydrite	$Fe_{4-5}(OH,O)_{12}$	T4
goethite	$\alpha FeO(OH)$	B1,B17
hibbingite	$\gamma\text{-}Fe_2(OH)_3Cl$	B19,S1
hollandite	$(Fe_{15}Ni)(O_{12}(OH)_{20})Cl(OH)_2$	U2
lepidocrocite	$\gamma\text{-}FeO(OH)$	B1,B17
portlandite	$Ca(OH)_2$	O2
pyrochlore	$(Na,Ca)_2Nb_2O_6(OH,F)$	L6
zaratite	$Ni_3CO_3(OH)_4\cdot4H_2O$	B24
carbonates		
ankerite	$Ca(Fe^{+2},Mg,Mn)(CO_3)_2$	Z3
aragonite	$CaCO_3$	E6
barringtonite	$MgCO_3\cdot2H_2O$	U2
calcite	$CaCO_3$	D4,O2,Z2
dolomite	$CaMg(CO_3)_2$	Z3
hydromagnesite	$Mg_5(CO_3)_4(OH)_2\cdot4H_2O$	V4,Z1
kutnohorite	$Ca(Mn,Mg,Fe^{+2})(CO_3)_2$	Z3
magnesite	$(Mg,Fe)CO_3$	Z3
nesquehonite	$Mg(HCO_3)(OH)\cdot2H_2O$	V4,Z1
nyerereite	$Na_2Ca(CO_3)_2$	U2
reevesite	$Ni_6Fe_2(CO_3)(OH)_{14}\cdot4H_2O$	B17,W12
rhodochrosite	$MnCO_3$	U2
siderite	$FeCO_3$	B17
vaterite	$CaCO_3$	O2
zaratite	$Ni_3(CO_3)(OH)_4\cdot4H_2O$	B17
sulfates		
anhydrite	$CaSO_4$	B13,B14
barite	$BaSO_4$	N3
bassanite	$CaSO_4\cdot\tfrac{1}{2}H_2O$	O2,W11
blödite	$Na_2Mg(SO_4)_2\cdot4H_2O$	Z3
copiapite	$Fe_5(SO_4)_6(OH)_2\cdot20H_2O$	U2
epsomite	$MgSO_4\cdot7H_2O$	Z3
gypsum	$CaSO_4\cdot2H_2O$	Z3
hexahydrite	$MgSO_4\cdot6H_2O$	Z3
honessite	$(Ni,Fe)_8SO_4(OH)_{16}\cdot nH_2O$	B17

Mineral	Formula	References
sulfates (continued)		
jarosite	$KFe_3(SO_4)_2(OH)_6$	B17
melanterite	$FeSO_4\cdot7H_2O$	U2
starkeyite	$MgSO_4\cdot4H_2O$	V4,Z1
molybdates		
powellite	$CaMoO_4$	U2
tungstates		
scheelite	$CaWO_4$	M2
phosphates		
apatite	$Ca_5(PO_4)_3(F,OH,Cl)$	M2,N3
arupite	$Ni_3(PO_4)_2\cdot8H_2O$	B17,B20
beusite	$(Mn,Fe,Ca,Mg)_3(PO_4)_2$	U2
brianite	$Na_2CaMg(PO_4)_2$	B17,B27,F11
buchwaldite	$NaCaPO_4$	B17,O9
carbonate-fluorapatite	$Ca_5(PO_4,CO_3)_3F$	N3
cassidyite	$Ca_2(Ni,Mg)(PO_4)_2\cdot2H_2O$	B17,W12
chlorapatite	$Ca_5(PO_4)_3Cl$	B17
chladniite	$Na_2CaMg_7(PO_4)_6$	M10
collinsite	$Ca_2(Mg,Fe,Ni)(PO_4)_2\cdot2H_2O$	B17
farringtonite	$Mg_3(PO_4)_2$	B17,B29
fluorapatite	$Ca_5(PO_4)_3F$	D3
graftonite	$(Fe,Mn)_3(PO_4)_2$	B17,O5
hydroxyapatite	$Ca_5(PO_4)_3OH$	F8
johnsomervilleite	$Na_2Ca(Fe,Mg,Mn)_7(PO_4)_6$	O5
lipscombite	$(Fe,Mn)Fe_2(PO4)_2(OH)_2$	B17
maricite	$NaFePO_4$	C5
monazite-(Ce)	$(Ce,La,Th)PO_4$	Y1
panethite	$(Ca,Na)_2(Mg,Fe)_2(PO4)_2$	B17,B27,F11
sarcopside	$(Fe,Mn)_3(PO_4)_2$	B17,O5
stanfieldite	$Ca_4(Mg,Fe)_5(PO_4)_6$	B29
vivianite	$Fe_3(PO_4)_2\cdot8H_2O$	B17
whitlockite (merrillite)	$Ca_9MgH(PO_4)_7$	B17,B29
silicates		
nesosilicates (independent SiO_4 tetrahedra)		
almandine	$Fe_3Al_2(SiO_4)_3$	U2
andradite	$Ca_3Fe_2(SiO_4)_3$	K10
beckelite	$(Ce,Ca)_5(SiO_4)_3(OH,F)$	M2
fayalite	Fe_2SiO_4	K14
forsterite	Mg_2SiO_4	D4
grossular	$Ca_3Al_2(SiO_4)_3$	K10
kirschsteinite	$CaFe(SiO_4)$	K10,K14
majorite	$Mg_3(MgSi)Si_3O_{12}$	C1,D4
monticellite	$CaMgSiO_4$	M2
olivine	$(Mg,Fe)_2SiO_4$	B17,D4,R8
pyrope	$Mg_3Al_{22}(SiO_4)_3$	C1
ringwoodite	$(Mg,Fe)_2SiO_4$	D4,P5
sapphirine	$(Mg,Al)_7(Mg,Al)O_2[(Al,Si)_6O_{18}]$	U2
titanite	$CaTiSiO_5$	D3
wadsleyite	$(Mg,Fe)_2SiO_4$	U2
zircon	$ZrSiO_4$	B17,I2,M5
sorosilicates (two isolated SiO_4 tetrahedra sharing one O)		
åkermanite	$Ca_2MgSi_2O_7$	M2
Ca-aluminosilicate*	$Ca_3Ti(Al,Ti)_2(Si,Al)_3O_{14}$	B2,P2
gehlenite	$Ca_2Al(Si,Al)_2O_7$	M2
melilite	$(Ca,Na)_2(Al,Mg)(Si,Al)_2O_7$	M2
pumpellyite	$Ca_2(Mg,Fe^{+2})Al_2(SiO_4)(Si_2O_7)(OH)_2\cdot H_2O$	U2,Z3

Mineral	Formula	References
cyclosilicates (closed rings of SiO₄ tetrahedra)		
cordierite	$Mg_2Al_4Si_5O_{18}$	M2,P4
merrihueite	$(K,Na)_2Fe_5Si_{12}O_{30}$	D5,D6,K12
osumilite	$(K,Na)(Fe,Mg)_2(Al,Fe)_3$ $[(Si,Al)_{12}O_{30}]$	U2
roedderite	$(K,Na)_2Mg_5Si_{12}O_{30}$	B17,F6,K12
yagiite	$(K,Na)_2(Mg,Al)_5(Si,Al)_{12}O_{30}$	B17
inosilicates (continuous single or double chains of SiO₄ tetrahedra)		
anthophyllite	$(Mg,Fe)_7Si_8O_{22}(OH)_2$	B15
augite	$Mg(Fe,Ca)Si_2O_6$	D4
clinopyroxene	$(Ca,Mg,Fe)SiO_3$	B17,D4
diopside	$CaMgSi_2O_6$	D4
enstatite	$Mg_2(SiO_3)_2$	D4,K3
fassaite (Al-Ti diopside)	$Ca(Mg,Ti,Al)(Al,Si)_2O_6$	D4,M2
ferrosilite	$Fe_2(SiO_3)_2$	K15
fluor-richterite	$Na_2Ca(Mg,Fe)_5Si_8O_{22}F_2$	B7,B17,O8
hedenbergite	$CaFeSi_2O_6$	K10
jadeite	$Na(Al,Fe)(Si_2O_6)$	U2
jimthompsonite	$(Mg,Fe)_5Si_6O_{16}(OH)_2$	B15
kaersutite	$Ca_2(Na,K)(Mg,Fe)_4Ti(Si_6Al_2)$ $O_{22}(OH,F,Cl)_2$	T5
krinovite	$NaMg_2CrSi_3O_{10}$	B17,O6
orthopyroxene	$(Mg,Fe)SiO_3$	B17,D4
pigeonite	$(Fe,Mg,Ca)SiO_3$	D4
pyroxferroite	$(Fe,Mn,Ca)SiO_3$	P1
rhodonite	$CaMn_4(Si_5O_{15})$	U2
rhönite	$Ca_2(Mg,Al,Ti)_6(Si,Al)_6O_{20}$	F9
Sc-fassaite	$Ca(Sc,Ti,Al)(Al,Si)_2O_6$	D1
ureyite (kosmochlor)	$NaCrSi_2O_6$	B17,G9
wollastonite	$CaSiO_3$	F9
phyllosilicates (continuous sheets of SiO₄ tetrahedra)		
biotite	$K(Mg,Fe)_3(Si_3Al)O_{10}(OH,F)_2$	F2,J3
chlorite group		K14
chamosite	$(Fe^{+2},Mg,Fe^{+3})_5Al(Si_3Al)$ $O_{10}(OH,O)_8$	B1,Z3
clinochlore	$(Mg,Fe^{+2})_5Al(Si_3Al)O_{10}(OH)_8$	B1
clintonite	$Ca(Mg,Al)_3(Al,Si)_4O_{10}(OH,F)_2$	K14
illite	$(K,H_3O)Al_2(Si_3Al)O_{10}$ $(H_2O,OH)_2$	G6
margarite	$CaAl_2(Si_2Al_2)O_{10}(OH)_2$	K14
mica	$(K,Na,Ca)(Al,Mg,Fe)_{2-3}$ $(Si,Al,Fe)_4O_{10}(OH,F)_2$	V4,Z1

Mineral	Formula	References
phyllosilicates (continuous sheets of SiO₄ tetrahedra) (continued)		
pecoraite	$Ni_3Si_2O_5(OH)_4$	F1
serpentine group		B1,K14
amesite	$Mg_2Al(SiAl)O_5(OH)_4$	Z3
antigorite	$Mg_3Si_2O_5(OH)_4$	B1
berthierine	$(Fe^{+2},Fe^{+3},Mg)_{2-3}(Si,Al)_2$ $O_5(OH)_4$	B1
chrysotile	$Mg_3Si_2O_5(OH)_4$	B1
cronstedtite	$Fe_2^{+2}Fe^{+3}(SiFe^{+3})O_5(OH)_4$	Z3
ferroan antigorite	$(Mg,Fe,Mn)_3(Si,Al)_2O_5(OH)_4$	B1
greenalite	$(Fe^{+2},Fe^{+3})_{2-3}Si_2O_5(OH)_4$	B1
lizardite	$Mg_3Si_2O_5(OH)_4$	B1
smectite group		A2,H8,K15
montmorillonite	$(Na,Ca)_{0.3}(Al,Mg)_2Si_4O_{10}$ $(OH)_2 \cdot nH_2O$	K14,Z3
nontronite	$Na_{0.3}Fe_2^{+3}(Si,Al)_4O_{10}$ $(OH)_2 \cdot nH_2O$	Z3
saponite	$(Ca,Na)_{0.3}(Mg,Fe^{+2})_3(Si,Al)_4$ $O_{10}(OH)_2 \cdot 4H_2O$	B14,K14
sobotkite	$(K,Ca)_{0.3}(Mg_2Al)(Si_3Al)O_{10}$ $(OH)_2 \cdot 5H_2O$	B1
sodium-phlogopite	$(Na,K)Mg_3(Si_3Al)O_{10}(F,OH)_2$	K14
talc	$Mg_3(Si_4O_{10})(OH)_2$	B1,B15
vermiculite	$(Mg,Fe^{+2},Al)_3(Al,Si)_4O_{10}$ $(OH)_2 \cdot 4H_2O$	U2,Z3
tectosilicates (continuous framework of SiO₄ tetrahedra)		
albite	$NaAlSi_3O_8$	K3
anorthite	$CaAl_2Si_2O_8$	M2
celsian	$Ba(Al_2Si_2O_8)$	M2,D4
cristobalite	SiO_2	D4
feldspar group	$(K,Na,Ca)(Si,Al)_4O_8$	B17
haüyne	$Na_3Ca(Si_3Al_3)O_{12}(SO_4)$	
nepheline	$(Na,K)AlSiO_4$	M2
opal	$SiO_2 \cdot nH_2O$	B17
orthoclase	$KAlSi_3O_8$	K8
plagioclase	$(Na,Ca)(Si,Al)_3O_8$	D4
quartz	SiO_2	D4
sanidine	$KAlSi_3O_8$	F2,J3
sodalite	$Na_4(Si_3Al_3)O_{12}Cl$	M2
tridymite	SiO_2	D4
zeolite group	$(Na,K)_{0-2}(Ca,Mg)_{1-2}$ $(Al,Si)_{5-10}O_{10-20} \cdot nH_2O$	M2
oxalates		
whewellite	$CaC_2O_4 \cdot H_2O$	F12

*Unknown structure, probably melilite-like.

in the oxidation state of meteorites. Meteoritic minerals include phosphides and phosphates, sulfides and sulfates, carbides and carbonates and silicides and silicates. Although the vast majority of meteoritic minerals also occur in terrestrial rocks, many meteoritic minerals, particularly those that occur in reduced samples, are extremely rare or absent on the Earth (*e.g.*, schreibersite, daubréelite, heideite). A number of refractory meteoritic minerals (*e.g.*, hibonite, perovskite, PGE-dominated alloys) occur within carbonaceous chondrite refractory inclusions that formed at high temperatures in the solar nebula. Such minerals are relatively rare on Earth, occurring in metamorphosed limestones (as is the case for hibonite), nepheline syenites and carbonatites (perovskite) and assorted ultramafic rocks (PGE-dominated alloys). Some meteoritic minerals that are absent from terrestrial rocks are products of shock metamorphism (*e.g.*, ringwoodite; majorite); others form as a result of terrestrial weathering of primary meteoritic minerals (*e.g.*, cassidyite; schöllhornite).

Some well-known terrestrial minerals have not been identified in meteorites. Some of these phases contain rare elements as major components (*e.g.*, beryl-$Be_3Al_2Si_6O_{18}$; stibnite-Sb_2S_3; borax-$Na_2B_4O_5 \cdot 8H_2O$); without the invocation of exotic concentration mechanisms, these species would not be expected on asteroids. Other terrestrial minerals are composed of abundant elements but form under conditions of high static pressure and temperature unlikely to have occurred on asteroids (*e.g.*, kyanite-Al_2SiO_5; staurolite-$(Fe,Mg)_4Al_{17}(Si,Al)_8O_{44}(OH)_4$). Nevertheless, it is conceivable that meteorites derived from planetary bodies could contain these phases.

METEORITE GROUPS

Anhydrous (Type 3–6), Not Highly Reduced Chondrite Groups: H, L, LL, CO, CV, CK, CH, R

Silicates, metal, sulfides and oxides constitute the major and minor minerals in these chondrite groups; phosphates and carbides

occur in accessory amounts. In unequilibrated (type 3.0–3.5) samples, the major silicate phases are olivine and low-Ca pyroxene; in chondrules, olivine, low-Ca pyroxene and, in some cases, calcic plagioclase, occur in conjunction with siliceous igneous glassy mesostases and minor pigeonite and augite. Rare silica-roedderite- and silica-merrihueite-bearing chondrules and clasts also occur in type-3 ordinary chondrites (OC) (Dodd *et al.*, 1965, 1966; Krot and Wasson, 1994). The more metamorphosed chondrites (especially ordinary chondrites of type 5 and 6) contain diopside and sodic plagioclase instead of chondrule glass. In equilibrated OC and R chondrites, the plagioclase is sodic (An9–14; Van Schmus and Ribbe, 1968; Rubin and Kallemeyn, 1994); in CK4-6 chondrites, the plagioclase is much more calcic and exhibits large grain-to-grain compositional variations (*e.g.*, An45-78 in CK6 LEW 87009; Kallemeyn *et al.*, 1991). Besides anorthite in CO and CV refractory inclusions, some chondrules, and coarse-grained (*i.e.*, igneous) chondrule rims in CV chondrites, plagioclase is essentially absent in CO and CV chondrites. Smectite occurs in the matrices of some LL3 chondrites in association with calcite and magnetite, which is indicative of minor-to-moderate aqueous alteration (*e.g.*, Hutchison *et al.*, 1987; Alexander *et al.*, 1989; Krot *et al.*, 1997).

A new, as yet unnamed, Ti-bearing calcium aluminosilicate phase $[Ca_3Ti(Al,Ti)_2(Si,Al)_3O_{14}]$ was reported from several refractory inclusions in CV3 Allende (Paque *et al.*, 1994; Barber *et al.*, 1994). Other refractory inclusions in Allende contain different silicates including wollastonite, rhönite and andradite (Fuchs, 1971).

With increasing oxidation state, mafic silicates acquire more FeO as Fe from metal phases becomes oxidized. This leads to higher $(FeO+MgO)/SiO_2$ ratios, thus favoring the production of olivine. Hence, as oxidation state increases, the olivine/low-Ca-pyroxene ratio increases (*e.g.*, this ratio is 1.5 in H and 2.1 in L chondrites; Table 4.1 of Dodd, 1981). The mean olivine/low-Ca-pyroxene ratio in the (highly oxidized) R chondrites is 16 (Table 2 of Kallemeyn *et al.*, 1996).

Late-stage, preterrestrial alteration of oxidized CV chondrites has led to the replacement of plagioclase and/or glass by feldspathoids (nepheline and sodalite), the replacement of melilite in refractory inclusions by anorthite and feldspathoids, and the replacement of enstatite phenocrysts in chondrules by ferroan olivine (*e.g.*, Ikeda and Kimura, 1995). During alkali-Ca exchange reactions, CaO was released from anorthite and produced a number of Ca-rich phases including hedenbergite, andradite, grossular and kirschsteinite (e.g., Kimura and Ikeda, 1995). Andradite broke down at high O fugacities to produce wollastonite and magnetite. Kirschsteinite has also been observed in the rims around dark inclusions in CV Allende (Krot *et al.*, 1995).

Phyllosilicates occur in the matrices, chondrules and refractory inclusions of CV chondrites; phases include margarite, clintonite, saponite, Na-phlogopite, montmorillonite, chlorite and serpentine (Table 8 of Krot *et al.*, 1995). Mild thermal metamorphism of phyllosilicates produced ferroan olivine along with some sulfides and spinels (Zolensky, pers. comm., 1996).

Preterrestrial aqueous alteration of pyroxene-rich chondrules in Allende has been inferred from recent HRTEM (high-resolution transmission electron microscopy) by Brearley (1996). He observed incipient alteration of clinoenstatite grains that resulted in the formation of 30 nm size grains of talc and smaller grains of anthophyllite, jimthompsonite and disordered biopyriboles. This assemblage is characteristic of retrograde hydration of magnesian

silicates on Earth and thus supports the model of parent-body aqueous alteration of CV chondrites (*e.g.*, Krot *et al.*, 1995).

The major metallic phases in OC are kamacite and taenite; tetrataenite (Clarke and Scott, 1980) is rare, and awaruite (with an empirically determined compositional range in meteorites of 63–72 wt% Ni) is very rare. With increasing oxidation state, the metal abundance decreases and the taenite/kamacite ratio increases; the mean taenite/kamacite ratios in H, L and LL chondrites are ~0.1, ~0.3 and ≥0.9, respectively (calculated from Tables 3 and 5 of Afiattalab and Wasson, 1980). Although CO3 Kainsaz contains ~15 wt% metallic Fe-Ni (mainly kamacite), average CO chondrites contain only ~6 wt% (Table 1 of Rubin *et al.*, 1985). Metal is extremely rare in CK and R chondrites; where it is present, awaruite is the dominant phase. The CH chondrites are extremely metal-rich; ALH 85085 contains ~43 wt% metallic Fe-Ni (Grossman *et al.*, 1988). Phases include kamacite, taenite, tetrataenite and plessite (a fine-grained intergrowth of kamacite and taenite).

Another rare metal phase has low Ni and ~37 wt% Co and occurs primarily at the interface between sulfide and Ni-rich metal in highly oxidized LL and R chondrites (Afiattalab and Wasson, 1980; Rubin and Kallemeyn, 1989; Rubin, 1990). It also occurs in association with massive magnetite and Ni-rich metal in some type-3 H, L and LL chondrites that have experienced significant oxidation, possibly as a result of fluid alteration and Na metasomatism (Krot *et al.*, 1997). Hua *et al.* (1995) reported a wairauite-like phase (although with ~39 wt% Co instead of the stoichiometric 51 wt%) in association with troilite and pentlandite in the Ningqiang CK3-an chondrite. It is unclear if this phase is identical to the Co-rich metal phase in LL and R chondrites.

The oxidized subgroup of CV chondrites contains <0.5 wt% metallic Fe-Ni, dominantly awaruite. Taenite and tetrataenite are also present, but kamacite is rare, primarily occurring inside chondrules. The reduced subgroup averages 5–6 wt% metallic Fe-Ni, mainly kamacite. Taenite is minor, tetrataenite is rare, and awaruite is absent (Fig. 3 of McSween, 1977a).

Metallic Cu is a rare but ubiquitous phase in OC; its modal abundance is $~10^{-4}$ wt%, but it occurs in at least 66% of the OC (Ramdohr, 1963, 1973; Rubin, 1994). Minute amounts of metallic Cu have been identified in the matrix of Allende (Clarke *et al.*, 1970) and in an R chondrite (Rubin and Kallemeyn, 1994), but no Cu has been reported in CO or CK chondrites.

Two small metal grains with high concentrations of Au were reported in R chondrites; one grain is alloyed with major Ag and Fe, and the other with minor Fe, Ni and Pt (Bischoff *et al.*, 1994; Schulze et al., 1994). Tiny (<1 μm) noble-metal-rich alloys with high concentrations of Au and Fe were found in a CK chondrite (Geiger and Bischoff, 1995). Previous reports of Au in enstatite chondrites (Ramdohr, 1963) were misidentifications of osbornite (Mason, 1966); similarly, the report of Au in the Wedderburn IIICD iron (Edwards, 1953) is considered to be erroneous (Buchwald, 1975).

Platinum-group-element- (*i.e.*, PGE-) rich metal nuggets containing alloys of various combinations of Pt, Os, Ir, Ru, Re, Rh, Mo, Nb, Ta, Zr, Ge, W, V, Pb, Cr, Fe, Ni and Co occur inside petrographically complex metal-, sulfide-, phosphate-, silicate- and V-magnetite-bearing objects known as Fremdlinge ("strangers") within refractory inclusions in CV carbonaceous chondrites (El Goresy *et al.*, 1978; Wark and Lovering, 1978; Bischoff and Palme, 1987). In many cases, the PGE themselves have approximately cosmic interelement ratios (*e.g.*, Armstrong *et al.*, 1987).

The major sulfide phase in OC is troilite; pentlandite occurs as an accessory phase in some oxidized LL chondrites. Troilite and Co-bearing pentlandite are the major sulfide phases in CV chondrites. Troilite is more abundant in the reduced subgroup while pentlandite is more abundant in the oxidized subgroup. Rare heazlewoodite also occurs among oxidized CV chondrites. In R chondrites, troilite (and/or pyrrhotite) and pentlandite are the dominant sulfide phases; rare pyrite and chalcopyrite also occur. In CK chondrites, pentlandite is the most abundant sulfide; other phases include troilite, mackinawite, monosulfide solid solution [(Fe,Ni)$_{1-x}$S] and rare pyrite, chalcopyrite and millerite. Sulfides are relative rare (<1 wt%) in CH chondrites; phases include troilite and rare pentlandite and heazlewoodite.

Rare PGE-bearing sulfides and tellurides (*e.g.*, laurite, erlichmanite, chengbolite) have been reported in CK chondrites (Geiger and Bischoff, 1989, 1990, 1995). Some chengbolite grains contain dissolved Fe and Au. Rare grains of PGE-bearing sulfides were also identified in R chondrites (Bischoff *et al.*, 1994) and CK chondrites (Geiger and Bischoff, 1995).

Chromite is the dominant oxide in OC; ilmenite and rutile occur as rare phases. Some highly oxidized type-3 OC also contain magnetite (*e.g.*, Taylor *et al.*, 1981; Krot *et al.*, 1997). Chromian spinel is the dominant oxide phase in R chondrites; magnetite and ilmenite are rare. Ferroan chromian spinel and isolated grains of spinel occur in CH chondrites. Magnetite is the principal oxide phase in CK chondrites; many of the large magnetite grains contain ilmenite and spinel lamellae formed during oxidation and exsolution (Geiger and Bischoff, 1990, 1995). Among CO chondrites, oxide phases are essentially absent except for spinel, perovskite, hibonite and rare grossite inside refractory inclusions. Along with spinel and chromite, a wide variety of Ti oxides occurs in a moderately refractory, plagioclase-olivine inclusion in CK3-an Ningqiang: armalcolite, Ca-armalcolite, geikilite, perovskite, rutile and unidentified titanian phases (Lin and Kimura, 1996). Pleonaste occurs along with fassaite (*i.e.*, Al-Ti diopside), olivine and rare plagioclase in a refractory inclusion in CK4 Karoonda (MacPherson and Delaney, 1985). Although magnetite is the dominant oxide phase in both oxidized and reduced CV chondrites, its mean modal abundance is ~5× higher in the oxidized subgroup. Framboidal magnetite (believed to have formed *via* aqueous alteration in CI and CR chondrites; see below) occurs in the matrices of CV3 Mokoia and Bali and in carbonaceous chondrite clasts in CH ALH 85085 (*e.g.*, Krot *et al.*, 1995; Grossman *et al.*, 1988). Accessory grains of chromite and hercynite occur in dark inclusions in Allende (Clarke *et al.*, 1970; Zolensky and Krot, 1996) and micrometer-size grains of anatase have been reported in an acid residue of Leoville (Wopenka and Swan, 1985). Oxide phases in refractory inclusions in CV chondrites and the unique Acfer 094 carbonaceous chondrite include perovskite, rutile, periclase, Ca oxide, grossite, hibonite, spinel and corundum (*e.g.*, MacPherson *et al.*, 1988; Weber and Bischoff, 1994b; Greshake *et al.*, 1996a,b). Grossite is relatively common in refractory inclusions in CH chondrites (*e.g.*, Grossman *et al.*, 1988; Weber and Bischoff, 1994a,b). Tiny grains of the hydroxide pyrochlore were found within a refractory inclusion in Allende (Lovering *et al.*, 1979). Additional details of the mineralogy of refractory inclusions and their rims, including descriptions of primary and secondary phases, can be found in MacPherson *et al.* (1988). A separate list of minerals in refractory inclusions constitutes Table 3.

Chlorapatite and whitlockite (*i.e.*, merrillite) are the major phosphates in OC, CV and R chondrites. In CO chondrites, whitlockite is probably significantly more abundant than chlorapatite (Rubin

TABLE 3. Minerals in refractory inclusions, rims and Fremdlinge.

anorthite	grossite	PGE-dominated alloys
apatite	grossular	powellite
armalcolite	hedenbergite	pyrochlore
baddeleyite	hercynite	pyrrhotite
beckelite	hibonite	rhenium
Ca-armalcolite	kamacite	rhönite
calcite	kirschsteinite	ruthenium
Ca-aluminosilicate	low-Ca pyroxene	rutile
calcium oxide	melilite	scheelite
celsian	molybdenite	sodalite
chromite	molybdenum	spinel
cordierite	monticellite	thorianite
corundum	nepheline	Ti-magnetite
coulsonite	niobium	troilite
diopside	pentlandite	V-magnetite
fassaite	periclase	whitlockite
forsterite	perovskite	wollastonite
gehlenite	platinum	zeolite group minerals
geikilite	pleonaste	zirconolite

and Grossman, 1985). Rubin *et al.* (1988) reported chlorapatite in CK3-an Ningqiang, but little data are available on phosphates in other CK chondrites. Phosphates are rare in CH chondrites (Bischoff *et al.*, 1993).

The abundance of carbides in these groups is very low. It occurs in type-3 OC mainly as cohenite and, to a lesser extent, haxonite (Scott, 1971); in some chondrites, cohenite and haxonite occur along with poorly described carbide phases in association with magnetite (*e.g.*, Taylor *et al.*, 1981; Krot *et al.*, 1997). Presolar graphite, diamond and silicon carbide (all containing isotopically anomalous noble gases) have been found in unequilibrated OC, CO and CV chondrites (*e.g.*, Huss and Lewis, 1995; Table 4).

Two nitrides (nierite and associated β-Si$_3$N$_4$) were found in acid-resistant residues of three type-3 OC (Lee *et al.*, 1995). Osbornite occurs as a rare phase in CH chondrites (Bischoff *et al.*, 1993).

Among type-4–6 OC, the mean chemical compositions of olivine, low-Ca pyroxene, chromite, ilmenite and kamacite change systematically with increasing oxidation state, thus yielding the following mean mineral compositions in H, L and LL chondrites: olivine (Fa18.8, 24.7, 29.4 mol%; Rubin, 1990); low-Ca pyroxene (Fs17.2, 21.3, 24.1 mol%; Gomes and Keil, 1980); chromite (FeO: 31.2, 33.0, 34.5 wt%; MgO: 2.7, 2.0, 1.6 wt%; MnO: 0.94, 0.74, 0.63 wt%; TiO2: 2.3, 2.8, 3.2 wt%; Bunch *et al.*, 1967); ilmenite (FeO: 41.1, 42.2, 43.9 wt%; MgO: 3.8, 2.9, 2.0 wt%; MnO: 2.8, 1.3, 1.1 wt%; Snetsinger and Keil, 1969); kamacite (Co: 0.47, 0.80, 7.7 wt%; Ni: 6.9, 6.5, 5.0 wt%; Rubin, 1990).

Anhydrous, Highly Reduced Meteorites: EH, EL, Aubrites

The EH and EL enstatite chondrites and the enstatite achondrites (aubrites) contain enstatite with very little FeO and a wide variety of unusual minerals formed under highly reducing conditions. Silicates in type 4–6 enstatite chondrites include orthoenstatite, albitic plagioclase, free silica (cristobalite, tridymite and quartz) and rare fassaite, fluor-richterite, roedderite (Fuchs, 1966a) and calcic plagioclase. The EH3 and EL3 chondrites contain ortho-

TABLE 4. Presolar minerals.

corundum	lonsdaleite	silicon nitride
diamond	molybdenum carbide	titanium carbide
graphite	silicon carbide	zirconium carbide

enstatite and clinoenstatite (including some grains with up to 12 mol% Fs), free silica (tridymite and cristobalite), minor forsterite and accessory fassaite, diopside and calcic plagioclase; feldspathic Cl-bearing glass occurs as chondrule mesostases. Aubrites contain essentially the same set of silicate minerals (but no Cl-bearing glass): orthoenstatite, clinoenstatite, albitic plagioclase, diopside and forsterite; rare fluor-amphibole (probably fluor-richterite) has been reported in Mayo Belwa (Bevan *et al.*, 1977).

Oxides other than free silica are extremely rare in enstatite chondrites and achondrites. However, Lin *et al.* (1991) reported a spinel-rich chondrule in the MAC 88136 EL3 chondrite and Bischoff *et al.* (1985) reported spinel-, hibonite- and perovskite-bearing refractory inclusions and irregular fragments in EH3 chondrites.

The dominant metal phase in EH and EL chondrites is kamacite, averaging 3.3 wt% Si in EH and 1.3 wt% Si in EL chondrites (Keil, 1968). Aubrites contain little kamacite (<0.1 to 0.7 wt% in typical aubrites; Table 2 of Watters and Prinz, 1979), but the kamacite is also Si-rich (~0.1 to 2.4 wt% Si). Rare grains of taenite occur in EL3 and EL6 chondrites (Rubin, unpublished data, 1982; Lin *et al.*, 1991). Some metallic Fe-Ni grains of martensitic composition (8–14 wt% Ni) occur in the EH chondrites Abee and Adhi Kot, EL6 Hvittis and the Shallowater aubrite; these grains are products of shock metamorphism.

Accessory metallic Cu has been reported in EL6 chondrites and aubrites (Ramdohr, 1963; Keil and Fredriksson, 1963); the phase is absent from EH chondrites.

Associated with kamacite in EH3 and EL3 chondrites is perryite, schreibersite, cohenite and graphite; perryite is absent in equilibrated enstatite chondrites but present in the Norton County aubrite (Wasson and Wai, 1970).

The sulfide minerals in enstatite meteorites include phases containing elements that are lithophile under more oxidizing conditions (*e.g.*, Mg, Mn, Ca, Cr, Na, K, Ti). The EH4 and EH5 chondrites contain major niningerite (*e.g.*, Keil and Snetsinger, 1967; Keil, 1968) and Ti-bearing troilite and minor to accessory oldhamite and Zn-bearing daubréelite; EL5 and EL6 chondrites contain titanian troilite, ferroan alabandite, zincian daubréelite and oldhamite. The EH3 chondrites also contain minor caswellsilverite (Okada and Keil, 1982) and accessory sphalerite (including some Ga-bearing sphalerite grains), smythite, greigite and djerfisherite. Djerfisherite (Fuchs, 1966b) mainly occurs outside of chondrules and, in Qingzhen and Y-6901, is associated with a variety of reaction products including troilite, covellite, idaite, bornite, sphalerite and some unidentified phases (El Goresy *et al.*, 1988). The modal abundance of djerfisherite decreases from EH3 to EH5 chondrites (El Goresy, pers. comm., 1996). Ivanov *et al.* (1996) reported evidence for Na_2S_2 within metal nodules in an EH3-4 fragment in the Kaidun polymict breccia; if confirmed, this would be the first simple alkali-metal sulfide in nature. The EL3 sulfides include titanian troilite, ferromagnesian alabandite, daubréelite, sphalerite, oldhamite, djerfisherite and, in MAC 88136, pentlandite (Lin *et al.*, 1991). Aubrites contain minor titanian troilite and rare oldhamite, ferromagnesian alabandite, zincian daubréelite, djerfisherite and heideite (*e.g.*, Keil and Brett, 1974).

Four nitride phases are present in enstatite meteorites: accessory sinoite (Si oxynitride) occurs as highly birefringent grains in many EL6 chondrites (*e.g.*, Andersen *et al.*, 1964), rare grains of osbornite occur in a few EH and EL chondrites and aubrites, and nierite and associated β-Si_3N_4 have been reported in acid-resistant residues of EH3 Qingzhen and EH4 Indarch (Alexander *et al.*, 1991, 1994; Lee *et al.*, 1995).

Presolar grains of diamond and silicon carbide occur in EH3 Qingzhen (Huss and Lewis, 1995).

Aqueously Altered Carbonaceous Chondrites: CI, CM, CR

Although CI chondrites contain no intact chondrules, there are rare grains of olivine (Fa_{0-42}), low-Ca pyroxene and diopside that are most likely derived from aqueously altered chondrules (*e.g.*, McSween, 1977b; Leshin *et al.*, 1997). Presolar grains of graphite, diamond, silicon carbide and corundum have also been identified in CI Orgueil (*e.g.*, Anders and Zinner, 1993).

Average bulk CI chondrites contain ~17 wt% H_2O (Jarosewich, 1990), which is a reflection of the high proportion ($\geq$90 vol%) of fine-grained hydrous phyllosilicates and associated phases that were formed by aqueous alteration on the parent body. The phyllosilicates include serpentine-group minerals and probably chamosite and montmorillonite (Zolensky and McSween, 1988). Associated material includes poorly characterized complex organic compounds. Late-stage sulfate veins containing major epsomite and minor hexahydrite, gypsum and blödite occur.

Sulfides include minor cubanite and abundant hexagonal platelets of pyrrhotite; rare grains of elemental S are associated with pyrrhotite.

The principal oxide phase is magnetite that occurs as euhedral crystals, platelets, spherulites and framboids (also indicative of preterrestrial aqueous alteration; Kerridge *et al.*, 1979). The hydroxide, ferrihydrite, occurs as tiny (<8 nm diameter) grains in Orgueil (Tomeoka and Buseck, 1988). Other oxide phases include accessory magnesiochromite and eskolaite (Greshake and Bischoff, 1996) and rare grains of spinel and hibonite (probably derived from aqueously altered refractory inclusions) and presolar corundum (Huss *et al.*, 1995).

Carbonates occur as veins and aggregates in CI chondrites; the aggregates probably formed from fragmented carbonate veins. The principal phases are ferran magnesite, siderite, dolomite and a pure Ca carbonate (vaterite and/or calcite) (Richardson, 1978; Fredriksson and Kerridge, 1988; Johnson and Prinz, 1993; Endress and Bischoff, 1996). In many cases, the Ca carbonate is associated with magnetite. Measurements of excess ^{53}Cr (formed by the decay of ^{53}Mn) in carbonate fragments from Orgueil and Ivuna show that carbonate formation *via* parent-body aqueous alteration processes occurred within ~16 Ma of nebular formation of the oldest CV refractory inclusions (Endress *et al.*, 1996; Hutcheon and Phinney, 1996).

In contrast to CI chondrites, CM chondrites contain 6–16 vol% chondrules and chondrule fragments (McSween, 1979). Mafic silicates in the chondrules are mainly low-FeO olivine and low-Ca pyroxene, although grains with much higher FeO contents also occur (up to $Fa_{\sim 50}$ and $Fs_{\sim 50}$). Isolated mafic silicate grains include olivine, low-Ca pyroxene and rare grains of diopside. Silicates in CM refractory inclusions include diopside and fassaite as well as forsterite, anorthite and, in a few rare cases, gehlenitic melilite. Oxides are present in the refractory inclusions (*e.g.*, hibonite, perovskite, spinel, and, in a few rare inclusions, corundum and Ca-aluminosilicate). Presolar grains consisting of graphite, diamond and silicon carbide have been identified in CM Murchison (*e.g.*, Huss, 1990); some of the silicon carbide grains contain small grains of titanium carbide, molybdenum carbide and zirconium carbide (Bernatowicz *et al.*, 1991; Ott, 1996; Table 4).

Phyllosilicates within CM matrices include serpentine-group minerals (chrysotile, lizardite, antigorite, cronstedtite, ferroan antigorite, greenalite and berthierine), saponite, clinochlore, talc and, probably, chamosite. Also associated with the phyllosilicates are intergrowths of serpentine and the hydroxysulfide tochilinite, as well as troilite, several hydroxide phases (brucite, goethite, and lepidocrocite) and rare grains of apatite and halides (halite and sylvite; Barber, 1981).

The matrix of the ungrouped, CM-related chondrite, Bells, consists of fine-grained saponite and interlayered serpentine; accessory phases include pentlandite, pyrrhotite, magnetite, anhydrite, calcite and rare grains of the Magnéli phases Ti_5O_9 and Ti_8O_{15} (i.e., members of the homologous series Ti_nO_{2n-1}; Brearley, 1993, 1995).

About 70% of the C in CM chondrites occurs as insoluble macromolecular material; the soluble remainder contains diverse organic compounds including aliphatic and aromatic hydrocarbons, alcohols, carbonyl compounds and more than 70 amino acids with enantiomeric equivalence (Cronin et al., 1988).

Additional phases within CM matrices include sulfates (mainly gypsum), carbonates (mainly calcite and aragonite), hydrous oxalate (whewellite), pentlandite, rare grains of Cr- and P-rich kamacite (with some associated schreibersite), several oxides (chromite, hercynite and magnetite) and shards of Ca-, Al- and Si-rich glass (e.g., Fuchs et al., 1973; Olsen et al., 1973a; Barber, 1981).

The CR chondrites contain abundant chondrules and chondrule fragments (typically 50–60 vol%; Weisberg et al., 1993). Mafic silicate minerals in these objects include olivine, low-Ca pyroxene (mainly clinoenstatite) and, in unaltered chondrules, rare crystallites of high-Ca pyroxene within feldspathic glassy mesostases.

The CR chondrites also contain 0.1–2.6 vol% refractory inclusions (Weisberg et al., 1993). Silicates in these objects include olivine, low-Ca pyroxene, diopside, fassaite, anorthite and gehlenitic melilite. Associated oxides include spinel, perovskite and grossite.

Phyllosilicates occur in the matrix and in the interiors of some chondrules. These phases include Fe-rich serpentine-group minerals, saponite and chlorite-group minerals (e.g., Zolensky et al., 1993). Associated with the phyllosilicates are Ca-carbonates and magnetite (the latter phase occurs as framboids and platelets).

The CR chondrites contain ~5–8 vol% metallic Fe-Ni; metal grains have a positive Co-Ni trend. They range in composition from 3.7 to 22 wt% Ni (Lee et al., 1992; Weisberg et al., 1993) and span the compositional range from kamacite to taenite. Associated sulfide phases include pyrrhotite and pentlandite.

Although CV chondrites have also experienced some aqueous alteration, they are described together with anhydrous, not highly reduced chondrite groups in a previous section.

Differentiated Meteorites: Irons And Pallasites

Detailed discussions of the mineralogy of iron meteorites can be found in Buchwald (1975, 1977). The major minerals in irons are kamacite and taenite; the intergrowth of these two phases in the octahedrites is the Widmanstätten pattern, the most characteristic feature of most irons. Besides kamacite and taenite, metallic Fe-Ni occurs as martensite (e.g., in the ungrouped irons Lime Creek and Tishomingo).

Metallic Cu occurs adjacent to troilite in some IAB and IIIAB irons.

Associated with kamacite and taenite in some irons (including ungrouped samples) are carbides (cohenite and haxonite), elemental C phases (graphite, diamond and lonsdaleite), nitrides (carlsbergite

and roaldite; Buchwald and Scott, 1971; Nielsen and Buchwald, 1981), schreibersite, chromite and sulfides (troilite, daubréelite, brezinaite, mackinawite, sphalerite, djerfisherite, chalcopyrite, ferromagnesian alabandite and pentlandite). (Another sulfide, isocubanite, formerly chalcopyrrhotite, occurs in irons as a terrestrial weathering product, Buchwald, 1975.) Most of these sulfides occur in nodules consisting mainly of graphite, graphite-troilite, or troilite (El Goresy, 1965). Silicates and oxides inside the graphite and graphite-troilite nodules include olivine, clinoenstatite, plagioclase, krinovite, richterite, roedderite, ureyite (i.e., kosmochlor), rutile and chromite (El Goresy, 1965; Olsen et al., 1973b); secondary magnetite and maghemite, formed by terrestrial weathering, also occur.

The Wedderburn IIICD iron contains a carbide of formula $Fe_{2.5}C$ that forms plates a few micrometers thick inside kamacite (Scott and Agrell, 1971); it is the only carbide present in Wedderburn.

Phosphates are present in some IIIAB irons as graftonite, sarcopside and johnsomervilleite in association with schreibersite, troilite, metallic Fe-Ni and, in the case of a few troilite inclusions in Grant, pentlandite (e.g., Olsen and Fredriksson, 1966). Buchwaldite occurs within troilite nodules in Cape York (Olsen et al., 1977). The ungrouped Antarctic iron HOW 88403 contains scattered inclusions of maricite in association with chromite, schreibersite and free silica (probably quartz; Clarke et al., 1990). Chlorapatite has been reported within the graphite of IAB Youndegin (Fuchs and Olsen, 1965). Brianite, panethite, chlorapatite and whitlockite are present in silicate inclusions in IAB/IIICD irons (e.g., Fuchs et al., 1967); chladniite was reported as a single grain within a silicate inclusion in the Carlton IIICD iron (McCoy et al., 1994).

Silicate inclusions in IAB/IIICD irons have subchondritic bulk compositions and contain planetary noble gases. In addition to phosphate, mineral phases in these inclusions include metallic Fe-Ni, graphite, schreibersite, metallic Cu, troilite, daubréelite, ferroan alabandite, sphalerite, chlorapatite, cohenite, magnesiochromite, olivine, low-Ca pyroxene, diopside and albite; in rare cases, roedderite and richterite also occur. Inclusions in IIE irons contain metallic Fe-Ni, schreibersite, graphite, chlorapatite, whitlockite, sanidine, albite, feldspathic glass, low-Ca pyroxene, augite, yagiite, tridymite, chromite, ilmenite and rutile. Olsen et al. (1992) described the only known silicate inclusion in a IIIAB iron (Puente del Zacate); this inclusion contains olivine, low-Ca pyroxene, augite, sodic plagioclase, chromite, troilite and graphite. Two IVA irons (Gibeon and Bishop Canyon) contain accessory tridymite; Steinbach and São João Nepomuceno (both IVA-an) contain abundant silicates–orthorhombic and monoclinic low-Ca pyroxene and tridymite (Ulff-Møller et al., 1995). Silicate inclusions in ungrouped irons include olivine, low-Ca pyroxene, diopside, plagioclase, tridymite, chromite, rutile, troilite, daubréelite, ferroan alabandite, metallic Fe-Ni, schreibersite, graphite, chlorapatite, whitlockite and metallic Cu (Bunch et al., 1970). Cristobalite occurs in the Carbo IID iron (Marvin, 1962). Although zircon was reported in the Toluca IAB iron (Marvin and Klein, 1964), the low Pb-Pb age of the zircon (~2 Ma) indicates that it is a terrestrial contaminant (T. R. Ireland, pers. comm., 1996).

Pallasites consist mainly of kamacite and taenite (forming a Widmanstätten structure) and olivine (occurring either as single crystals or polycrystalline aggregates of angular or rounded grains). There are two groups of pallasites (actually one group and a grouplet) with distinct O-isotopic compositions (Clayton and Mayeda, 1978): main-group pallasites and the Eagle-Station trio (i.e., Eagle Station, Cold Bay, Itzawisis). Each group is presumed to be from a separate parent body.

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Olivine in main-group pallasites ranges from Fa_{11-19}; a few grains contain appreciable P (up to ~5 wt%; Buseck, 1977) replacing Si^{4+} in the lattice. Minor minerals include troilite, schreibersite, chromite, and, in some pallasites, low-Ca pyroxene. Rutile occurs as exsolution lamellae in rare chromite grains in Rawlinna, magnetite occurs as a primary phase in Giroux (Ramdohr, 1965) and pentlandite occurs as a primary phase inside troilite in a few pallasites (Buseck, 1968). Phosphates in main-group pallasites include farringtonite, stanfieldite and whitlockite. Additional accessory minerals include mackinawite, metallic Cu, sphalerite, daubréelite, barringerite and graphite. Tiny grains of Cu-sulfides in some pallasites may be products of terrestrial weathering (Buseck, 1977).

Olivine in the Eagle-Station-trio pallasites is more ferroan (Fa_{20-21}) than in the main group. Minor to accessory Eagle-Station-trio minerals include diopside, chromite, stanfieldite, whitlockite, schreibersite, sphalerite, daubréelite and mackinawite.

Differentiated Meteorites: Eucrites, Diogenites, Howardites, Mesosiderites

The three varieties of eucrites (noncumulate, cumulate and polymict) have different textures and mineral proportions but are mineralogically very similar. Their main minerals are inverted pigeonite (orthopyroxene with augite exsolution lamellae), calcic plagioclase (generally bytownite) and minor free silica (tridymite, cristobalite and quartz). Accessory phases include kamacite, troilite, ilmenite, chromite, fayalitic olivine (Fa_{80-90}), K-feldspar, fluorapatite, whitlockite, titanite (i.e., sphene), zircon, baddeleyite and glass (Delaney et al., 1984). Noncumulate eucrites (e.g., Juvinas, Pasamonte) typically have ophitic or subophitic textures (although thermal and shock metamorphism have caused primary textures to become recrystallized in some rocks, e.g., Ibitira); they all contain appreciably more modal pyroxene than plagioclase. Cumulate eucrites (e.g., Moama, Moore County) have gabbroic textures and petrofabrics and contain subequal modal abundances of pyroxene and plagioclase. Polymict eucrites (e.g., Malvern, ALHA76005) are fragmental breccias containing a variety of lithic and glassy clasts (e.g., Delaney et al., 1984).

Diogenites are magnesian orthopyroxenites consisting almost entirely of Fs_{23-28} orthopyroxene; some grains contain augite exsolution lamellae. Minor phases include calcic plagioclase (An_{85-90}), tridymite, troilite and chromite; accessory phases include ilmenite, kamacite, tetrataenite (in Ibbenbüren) and phosphate. A few diogenites also contain minor to accessory olivine.

Howardites are essentially polymict breccias consisting of eucritic and diogenitic material. Clast types include mafic rocks, impact-melt rocks and carbonaceous chondrites (mainly CM2 and CR2). The major mineralogy of howardites is a reflection of these constituents. Nevertheless, unusual minerals do occur: Yagi et al. (1978) described rare grains of the phosphate monazite-(Ce) in Y-7308.

Mesosiderites are stony-iron breccias that consist of ~50 vol% basaltic, gabbroic and orthopyroxenitic silicates and ~50 vol% metallic Fe-Ni and troilite. The major minerals in the various types of silicate clasts (Rubin and Mittlefehldt, 1992) include orthopyroxene, inverted pigeonite (orthopyroxene with augite exsolution lamellae), calcic plagioclase, tridymite and olivine. The anomalous mesosiderite, Chaunskij, contains a fine-grained lithology consisting of low-Ca pyroxene, whitlockite and cordierite (Petaev et al., 1992, 1993). Minor amounts of chromite (including titanian chromite and chromian ülvospinel), apatite and whitlockite are present in most

mesosiderites. Other phases (i.e., zircon, ilmenite, rutile, metallic Fe-Ni, troilite) occur in accessory amounts (e.g., Ireland and Wlotzka, 1992).

The metallic regions of mesosiderites contain kamacite and taenite (in some cases forming a Widmanstätten structure), tetrataenite and associated troilite and schreibersite. Martensitic and plessitic structures occur in some portions of a few mesosiderites. Hassanzadeh et al. (1990) described a metal-rich nodule in Crab Orchard with accessory pentlandite, and one in Veramin containing silicate clumps with minor diopside.

Differentiated Meteorites: Ureilites, Angrites, Martian Meteorites, Lunar Meteorites

Ureilites constitute one of the most enigmatic meteorite groups (Goodrich, 1992). They consist mainly of calcic, chromian olivine (averaging 0.33 wt% CaO and 0.58 wt% Cr_2O_3; Berkley et al., 1980) and low-Ca clinopyroxene (pigeonite in most ureilites, clinobronzite in Haverö) embedded in a carbonaceous matrix. In some cases, augite is also present. Interstitial silicates include low-Ca pyroxene, augite and free silica surrounded by Si-Al-alkali glass (Goodrich, 1992). Mafic silicates are arranged in lineations and foliations, which are characteristic of cumulate rocks. The matrix contains the C polymorphs graphite, diamond and lonsdaleite (and, in Novo Urei and Haverö, chaoite; Vdovykin, 1969, 1972), minor metallic Fe-Ni, troilite and chromian Fe-sulfide, and accessory halite, sylvite and glass. Ramdohr (1972) reported rare grains of oldhamite and niningerite. Several ureilites contain metallic spherules rich in cohenite (Goodrich and Berkley, 1986). The unusual ureilite, LEW 88774, contains augite, orthopyroxene, Cr-rich cohenite and Cr-Al spinels surrounded by brezinaite, Cr-Fe metal and skeletal crystals of a corundum-eskolaite solid solution (Warren and Kallemeyn, 1994; Satterwhite et al., 1993). The silicide, suessite, occurs in North Haig where it formed by shock metamorphism (Keil et al., 1982); another shock-produced phase (martensite) occurs in ALHA77257 (Berkley et al., 1980). Melt pockets in Kenna contain micrometer-size grains of diopside and chromite (Berkley et al., 1976). Although ureilites have extremely low abundances of feldspar, a few ureilites (e.g., Nilpena, North Haig, EET 83309) are polymict breccias containing feldspathic melt-rock clasts and basaltic and angritic clasts (e.g., Prinz et al., 1988).

The angrites comprise a grouplet of four compositionally similar igneous meteorites and a clast of similar mineralogy in the North Haig polymict ureilite; all contain abundant fassaitic pyroxene. Angra dos Reis is an ultramafic rock containing 93 vol% fassaitic pyroxene and minor calcic, ferroan olivine (averaging Fa_{47}; 1.3 wt% CaO); some of the olivine grains contain small inclusions of magnesian kirschsteinite (Prinz et al., 1977). Accessory phases include homogeneously distributed hercynitic spinel and heterogeneously distributed whitlockite. Rare grains include those of titanian magnetite, baddeleyite, celsian, bytownitic plagioclase, and troilite containing tiny blebs of low-Ni kamacite. Lewis Cliff 86010 is a moderately coarse-grained rock with a gabbroic or granular texture containing major fassaite, calcic olivine (Fa_{69}; 1.7–2.2 wt% CaO) with kirschsteinite exsolution lamellae, and anorthite; minor to accessory phases include whitlockite, hercynite/pleonaste spinel, titanian magnetite, troilite and metallic Fe-Ni (e.g., Delaney and Sutton, 1988). Lewis Cliff 87051 is a porphyritic rock containing coarse grains of magnesian olivine (Fa_{9-21}) surrounded by a fine-grained groundmass containing major anorthite, fassaite, fayalitic olivine and kirschsteinite, and minor ilmenite, whitlockite, titanian

magnetite and troilite (McKay *et al.*, 1990; Prinz *et al.*, 1990). Asuka 881371 is very similar to LEW 87051 (*e.g.*, Yanai, 1994; Warren and Davis, 1995). In addition to major olivine, fassaite, kirschsteinite and anorthite and minor to accessory spinel, ilmenite, troilite, apatite, metallic Fe-Ni and Ti-rich magnetite (Mikouchi *et al.*, 1995; Prinz and Weisberg, 1995), Asuka 881371 contains a new silicophosphate with cation proportions of $Si_3FeCa_{12}P_6$ (Warren and Davis, 1995; Prinz and Weisberg, 1995).

Martian meteorites comprise basaltic shergottites (Shergotty, Zagami, QUE 94201, and two distinct lithologies in EET 79001), lherzolitic shergottites (ALH 77005, LEW 88516, Y-793605), nakhlites (Nakhla, Lafayette, Governador Valadares), a dunite (Chassigny) and an orthopyroxenite (ALH 84001). The basaltic shergottites are fine-grained rocks consisting of major pigeonite, augite and maskelynite, minor titanian magnetite, ilmenite, pyrrhotite and whitlockite, and accessory fayalite, quartz, baddeleyite and chlorapatite within the mesostasis (McSween, 1994). Fuchs (1969) reported the occurrence of hydroxyapatite in Shergotty. Secondary phases (formed by preterrestrial alteration) in the basaltic shergottites include calcite, gypsum, Mg-sulfate, Mg-phosphate and illite (*e.g.*, Gooding, 1992). Small melt inclusions in these meteorites contain tiny grains of kaersutite, hercynitic spinel, pyrrhotite, magnetite, ilmenite and whitlockite (Treiman, 1985). The lherzolitic shergottites consist of olivine (Fa_{27}) and ferrian chromite grains poikilitically enclosed by large grains of orthopyroxene; interstitial regions contain maskelynite, pigeonite, augite, chromite and whitlockite (McSween, 1994). The preferred crystallographic orientations of the olivine grains indicate that these are cumulate rocks (Berkley and Keil, 1981). The nakhlites consist of major cumulus magnesian augite and minor ferroan olivine (Fa_{65-68}) surrounded by a microcrystalline mesostasis consisting of plagioclase (An_{27}), K-feldspar ($Ab_{22}Or_{75}$), pigeonite, ferroaugite, free silica, titanian magnetite with ilmenite lamellae (formed by oxidation-exsolution), troilite, pyrite, chalcopyrite, fluor-chlorapatite and K-rich glass (Bunch and Reid, 1975; McSween, 1994). Secondary phases in the nakhlites include calcite, siderite, gypsum, Mg-sulfate, ferrihydrite, smectite and halite. Chassigny contains 88 vol% cumulus ferroan olivine (Fa_{32}) with 120° triple junctions, minor pigeonite, poikilitically enclosed orthopyroxene, cumulus augite, sanidine, ferrian chromite, ilmenite, rutile, baddeleyite, troilite, marcasite and pentlandite (Floran *et al.*, 1978; McSween, 1994); small feldspathic and silicic melt inclusions contain kaersutite, augite, low-Ca pyroxene, chromite, sulfide and rare biotite (Floran *et al.*, 1978; Johnson *et al.*, 1991). Small grains of Ca-carbonate (probably calcite), magnesite and Ca-sulfate (gypsum or bassanite) in Chassigny are probably preterrestrial, reflecting weathering of the dunite in the martian environment (Wentworth and Gooding, 1994). Allan Hills 84001 is a coarse-grained, cataclastic orthopyroxenite consisting mainly of orthopyroxene grains ($Fs_{27.3}Wo_{3.3}$), many with 120° triple junctions, poikilitically enclosing ferrian chromite; minor to accessory phases include maskelynite, augite, apatite, pyrite and other Fe-sulfides, sphalerite, magnetite, Fe-sulfate and Mg-Fe-Ca-(Mn) carbonate (*e.g.*, Mittlefehldt, 1994; McKay *et al.*, 1996). Tubular-shaped, ~100 nm long, magnetite and Fe-sulfide objects, associated with carbonate globules in ALH 84001, were interpreted as possible martian microfossils by McKay *et al.* (1996). Table 5 provides a list of minerals identified in the martian meteorites.

In principle, the minerals in lunar meteorites can encompass all those identified in returned Apollo and Luna samples. These phases have been reviewed in great detail by Frondel (1975) and Papike *et*

al. (1991). Lunar meteorites include mare basalts and various kinds of impact breccias (Table 1). The mare basalts have ophitic and subophitic textures and contain major augite (in some cases, hedenbergite) and calcic plagioclase (in some cases, maskelynite), minor olivine (typically Fa_{30-50}), free silica (tridymite and cristobalite) and ilmenite, and accessory ulvöspinel, chromite, troilite, kamacite, whitlockite, taenite and glass. Anorthositic breccias consist mainly of calcic plagioclase (including maskelynite) with subordinate amounts of augite, orthopyroxene, olivine, hercynitic spinel, ilmenite, chromite, troilite, kamacite, taenite and other phases. Calcalong Creek is a polymict KREEP-rich breccia containing a variety of clasts including anorthosite, gabbroic anorthosite, spinel troctolite and mare basalt (Marvin and Holmberg, 1992). Constituent phases in the anorthositic and troctolitic clasts in lunar meteorites include calcic plagioclase, augite, low-Ca pyroxene, olivine, zircon, baddeleyite, ilmenite, troilite, whitlockite and chlorapatite; those in the mare basaltic clasts include plagioclase, fayalite, ferrohedenbergite, pyroxferroite, ferroaugite, ilmenite, chromian ulvöspinel, free silica, troilite and glass.

Although aubrites also are differentiated meteorites, they are described together with enstatite chondrites in a previous section.

SHOCK METAMORPHISM

Shock effects in meteorites have been reviewed by Rubin (1985), Stöffler *et al.* (1988, 1991), Scott *et al.* (1992) and Bischoff and Stöffler (1992). Some shock effects are mechanical in nature and do not involve mineral transformations.

Shock effects involving mineral transformations occur in metallic Fe-Ni, elemental C, olivine, orthopyroxene, plagioclase and zircon (Table 6). Martensite (α_2-iron) has a distorted body-centered cubic structure and typically contains 8–15 wt% Ni and forms by a shear transformation from taenite during shock heating and quenching. If shock loads exceed 13 GPa, kamacite (body-centered cubic α-iron) transforms into hexagonal close-packed ϵ-iron that has a high density (8.81 *vs.* 7.86 g cm^{-3} in kamacite). Upon pressure release, ϵ-iron reverts to kamacite with cross-hatched texture (*e.g.*, Fig. 103 of Buchwald, 1975) or to densely hatched martensite during very rapid ϵ-α transformations.

In addition to tiny (~2 nm) presolar Cδ diamond grains in unmetamorphosed chondrites (*e.g.*, Huss and Lewis, 1995), diamonds occur in ureilites (*e.g.*, Berkley *et al.*, 1980), IAB irons (Canyon Diablo, ALHA77283 and Chuckwalla; *e.g.*, Ksanda and Henderson, 1939; Clarke *et al.*, 1981) and the Abee enstatite chondrite (Russell *et al.*, 1992). Lonsdaleite, the hexagonal (2H) dimorph of diamond, also occurs in association with diamonds in ureilites and IAB irons (*e.g.*, Frondel and Marvin, 1967). These phases formed by shock

TABLE 5. Minerals in martian meteorites.

augite	hercynite	plagioclase
baddeleyite	hydroxyapatite	pyrite
biotite	illite	pyrrhotite
calcite	ilmenite	quartz
chalcopyrite	kaersutite	rhodochrosite
chlorapatite	magnetite	rutile
chromite	marcasite	sanidine
fayalite	Mg-carbonate	siderite
ferrihydrite	Mg-sulfate	smectite
ferroaugite	olivine	sphalerite
fluor-chlorapatite	orthopyroxene	Ti-magnetite
gypsum	pentlandite	troilite
halite	pigeonite	whitlockite

TABLE 6. Minerals formed by transformations during shock metamorphism.

baddeleyite	lonsdaleite	martensite
chaoite	magnesiowüstite	ringwoodite
diamond	majorite	suessite

transformation of primary graphite at pressures exceeding 13 GPa. The small whole-rock sizes of the shocked ureilites and most of the IAB irons indicate that the diamond- and lonsdaleite-forming shock events occurred on the meteorite parent bodies (*e.g.*, Clarke *et al.*, 1981) and not during collisions of the meteorites with Earth.

Chaoite, a hexagonal polymorph of graphite, differs from lonsdaleite in unit-cell size and density. It was reported in the Novo Urei and Haverö ureilites by Vdovykin (1969, 1972) where it occurs in graphite-diamond aggregates. Although experimental confirmation is lacking, it is very probable that chaoite forms from graphite by shock metamorphism.

Suessite (Fe_3Si) in the North Haig polymict ureilite was modeled by Keil *et al.* (1982) as having formed by reduction of Fe and Si (possibly from olivine) *via* reaction with carbonaceous matrix material; the extreme rarity of kamacite in North Haig implies that kamacite also may have been involved in the formation of suessite.

Ringwoodite, a polymorph of olivine, is the spinel or γ-form of $(Mg,Fe)_2SiO_4$. Majorite, a polymorph of $(Mg,Fe)SiO_3$ orthopyroxene, has the garnet structure. These two high-pressure phases occur inside shock veins in highly shocked ordinary chondrites (*e.g.*, L6 Tenham; Price *et al.*, 1979) and the martian meteorite EET 79001. Chen *et al.* (1996) found that ringwoodite and majorite in shock veins in L6 Sixiangkou were produced by solid-state transformation of olivine and low-Ca pyroxene at high shock pressure. A second shock vein assemblage in Sixiangkou, consisting of a majorite-pyrope solid solution plus magnesiowüstite, was modeled as having formed from a dense impact melt of bulk L chondrite composition at high pressures and temperatures.

Maskelynite is diaplectic plagioclase glass, a high-density, high-refractive-index phase that forms by disordering crystalline plagioclase at a shock pressure $\geq$30 GPa for oligoclase and $\geq$26 GPa for bytownite (Bischoff and Stöffler, 1992). It occurs in many severely shocked plagioclase-bearing meteorites, particularly ordinary chondrites, shergottites and lunar meteorites.

Baddeleyite (monoclinic ZrO_2) has been reported in the Y-75015 polymict eucrite, Chassigny, Angra dos Reis and a Mg-Al-chromite fragment in H3.8 Raguli (Delaney *et al.*, 1984; Floran *et al.*, 1978; Prinz *et al.*, 1977; Krot *et al.*, 1993). It forms by the thermal decomposition of zircon (tetragonal $ZrSiO_4$) at very high temperatures (~1680 °C) and low (*i.e.*, atmospheric) pressure (Fig. 1 of Butterman and Foster, 1967) *via* the reaction:

$$ZrSiO_4 \rightarrow ZrO_2 + SiO_2$$
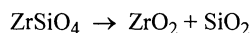
Although normally a shock product, baddeleyite has also been found in refractory inclusions in Allende and CO3 Ornans (Lovering *et al.*, 1979; Davis, 1991) where it is probably a primary nebular phase.

TERRESTRIAL WEATHERING

Terrestrial alteration of meteorites begins during atmospheric passage when a meteoroid can lose >95% of its initial mass. The surface of a falling meteoroid melts to depths of ~0.3–1.0 mm due to friction with the surrounding atmosphere; this surface ablates,

exposing a fresh surface. By the time a stony meteorite reaches the ground, its fusion crust consists of three distinct zones: an opaque glassy outer zone containing submicrometer magnetite, an intermediate zone containing partly melted silicate grains, and an inner zone containing unmelted silicate and rapidly solidified metal-sulfide intergrowths (Sears, 1978). Among secondary phases in these fusion crusts are the oxides eskolaite (formed by the reduction and breakdown of chromite), pseudobrookite (formed by the breakdown of ilmenite) and magnetite and wüstite (formed by the oxidation of metallic Fe; Ramdohr, 1967, 1973). Secondary phases that occur in iron-meteorite fusion crusts include magnetite and wüstite (Buchwald, 1977).

After meteorites reach the Earth's surface, they are subjected to weathering and the formation of additional secondary phases. Buddhue (1957) described secondary minerals in meteorites and found that the most important are goethite and magnetite. However, not all meteoritic magnetite formed by terrestrial weathering; many occurrences (*e.g.*, in CI, CR, CV and LL chondrites) probably resulted from preterrestrial aqueous alteration. The origin of ferrihydrite in CI and CM chondrites is unclear; some grains may have formed by terrestrial aqueous alteration, although preterrestrial alteration is also possible.

Surveys of iron meteorites have revealed that secondary minerals that formed by terrestrial weathering include (a) oxides and hydroxides formed directly from metallic Fe-Ni by oxidation and the incorporation of H_2O, Cl^- and, in one case, CO_3^{2-} from the terrestrial environment (Cl-bearing akaganéite, bunsenite, goethite, hematite, hibbingite, lepidocrocite, maghemite, magnetite, trevorite, and, perhaps, zaratite), (b) graphite and kamacite formed by the decomposition of iron carbide (either cohenite or haxonite), (c) phosphates formed from schreibersite (apatite, arupite, cassidyite, collinsite, lipscombite, vivianite) and (d) sulfates formed by weathering of troilite (honessite, jarosite). Additional phases in irons that formed by terrestrial alteration include metallic Cu, opal, several sulfides (pentlandite, bornite, chalcopyrite, heazlewoodite, isocubanite), at least two carbonates (reevesite, siderite), a Ni-rich phyllosilicate (pecoraite) and elemental S (*e.g.*, White *et al.*, 1967; Buchwald, 1975, 1977, 1989, 1990; Faust *et al.*, 1973; Buchwald and Clarke, 1989; Saini-Eidukat *et al.*, 1994; Table 7).

Although lawrencite [$(Fe,Ni)Cl_2$] is listed in previous compilations of meteoritic minerals as well as in the authoritative *Mineral Reference Manual* (Nickel and Nichols, 1991), it appears to be a "mineralogical chimera" (Buchwald and Clarke, 1989) and is not included in Table 2. The name lawrencite is applied to "semiliquid efflorescences" observed among iron meteorite corrosion products. However, Buchwald and Clarke (1988) found that, in every case, x-ray diffraction of dried residues of typical lawrencite occurrences resulted in the pattern characteristic of akaganéite. Thus, akaganéite is the principal Cl-bearing corrosion product of meteoritic metal, and lawrencite appears not to exist. Although a minor fraction of the Cl in akaganéite may be derived from the decomposition of meteoritic chlorapatite, most comes from the terrestrial environment (*e.g.*, snow, ice, rocky soil); Cl^- ions are readily incorporated into tunnel sites in the akaganéite crystal structure.

The unusual sulfide minerals in the highly reduced enstatite meteorites are unstable at the Earth's surface and can produce an assortment of secondary minerals upon weathering. Schöllhornite (a hydrated, alkali-bearing chalcogenide) occurs in association with caswellsilverite ($NaCrS_2$) in the Norton County aubrite (Okada *et*

TABLE 7. Minerals formed by terrestrial weathering of primary meteoritic minerals.

akaganéite	gypsum	pecoraite
apatite	heazlewoodite	pentlandite
arupite	hematite	portlandite
barite	hibbingite	pseudobrookite
bassanite	honessite	pyrite
bornite	hydromagnesite	quartz
bunsenite	illite	rammelsbergite
calcite	isocubanite	reevesite
cassidyite	jarosite	safflorite
chalcopyrite	kamacite	schöllhornite
cobaltite	lepidocrocite	siderite
collinsite	lipscombite	sphalerite
copper	maghemite	starkeyite
epsomite	magnetite	sulfur
eskolaite	maucherite	titanium dioxide
fluorapatite-carbonate	nesquehonite	trevorite
galena	nickel	vaterite
gersdorffite	nickeline	vivianite
goethite	opal	wüstite
graphite	orcelite	zaratite

al., 1985); it formed directly from caswellsilverite by weathering. Other secondary phases in Norton County formed by the weathering of oldhamite (CaS) include Ca-sulfate, Ca-carbonate and Ca-hydroxide (bassanite, vaterite, calcite and portlandite; Okada *et al.*, 1981).

Evaporite deposits have been observed on the surfaces of chondritic, achondritic and metal-rich Antarctic meteorites. Evaporite phases include carbonates (nesquehonite, hydromagnesite, amorphous Mg-carbonate) and sulfates (epsomite, starkeyite, gypsum, hydronium jarosite and a poorly characterized K-Fe sulfate; Zolensky and Gooding, 1986; Velbel, 1988). These phases probably are derived from both terrestrial redistribution of primary meteoritic carbonates and sulfates (*e.g.*, in CM chondrites) and terrestrial contamination (*e.g.*, in ordinary chondrites, achondrites and irons). The fusion crusts of Antarctic stony meteorites also contain poorly ordered clay minerals similar in composition to smectite and mica. These phases probably form in less than a million years even with only limited supplies of H_2O (Gooding, 1986).

Extreme alteration of an ordinary chondrite is illustrated by Brunflo, an H4-5 chondrite that fell in calcareous mud ~460–470 Ma ago during the Ordovician period (Thorslund and Wickman, 1981; Thorslund *et al.*, 1984). Except for relict chromite, all of the primary minerals have been replaced. Secondary minerals include major calcite, barite and a strongly disordered illite-type phyllosilicate, rare grains of native Ni, spongy aggregates of the sulfarsenides cobaltite and gersdorffite, tiny grains of arsenides (rammelsbergite, safflorite, nickeline, maucherite and orcelite), assorted sulfides (chalcopyrite containing small amounts of sphalerite, galena replacing arsenide, rare pyrite, and several incompletely characterized Cu sulfides), numerous grains of TiO_2 (probably anatase or brookite), and quartz (Nyström and Wickman, 1991). One radial-pyroxene-chondrule pseudomorph has been entirely replaced by carbonate-fluorapatite (*i.e.*, francolite) containing small TiO_2 inclusions. The complex assemblage of secondary minerals in Brunflo varies on millimeter-size scales, reflecting disequilibrium during metasomatism and diagenesis. Nevertheless, the preservation of the chondritic structure in many regions of the meteorite attests to the gradual replacement of the primary minerals during alteration.

Another Ordovician "fossil" meteorite (Österplana), found within a limestone slab, consists of calcite, Cr-bearing layered silicate, barite, apatite, tiny grains of chromite and a TiO_2 mineral (Nyström *et al.*, 1988). The object is compositionally dissimilar to every meteorite except Brunflo and is probably a highly altered ordinary chondrite.

Kyte (1996) described a ~5 mm lithic fragment surrounded by Cretaceous/Tertiary (KT) boundary sediments in a deep-sea drill core. The fragment is probably a piece of the meteorite that produced the Chicxulub impact structure in the Yucatán. The fragment consists of hematite, mixed-layer smectite/illite clays and micrometer-size grains of metallic Fe-Ni and sulfide. One metal grain is very rich in Ni ($Ni_{87}Fe_{13}$).

The mineralogical descriptions of Brunflo, Österplana and the probable KT projectile will aid in the recognition of additional fossil meteorites likely to be recovered from sediments and sedimentary rocks in the future (*e.g.*, Schmitz *et al.*, 1996, which appeared while this paper was in press, reported 13 new fossil meteorites in Ordovician limestone). These, in turn, will help constrain the nature of the meteoroid fluence over the last 500 Ma (or more) of Earth history.

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