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ASTEROID SURFACE MINERALOGY: EVIDENCE FROM EARTH-BASED TELESCOPE OBSERVATIONS

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Surface mineralogy of asteroids can be inferred in many cases using a variety of spectroscopic remote sensing techniques. Through the application of these techniques, mainly over the past ten years, mineral assemblages analogous to most meteorite types have been found as surface materials of asteroids. Conspicuously rare or absent from the main asteroid belt are ordinary chondrite-like assemblages, while carbonaceous materials are common as are metal-silicate assemblages. The distribution of mineral assemblages with asteroid size and distance from the Sun reveals heterogeneity which is surely informative of early accretionary and evolution processes, but the precise meanings are yet to be agreed on.

Low temperature assemblages are relatively more abundant with increasing distance from the Sun. All assemblages generally can be found inside 3.0 AU and metal plus orthopyroxene assemblages are concentrated inside 2.5 AU.

INTRODUCTION

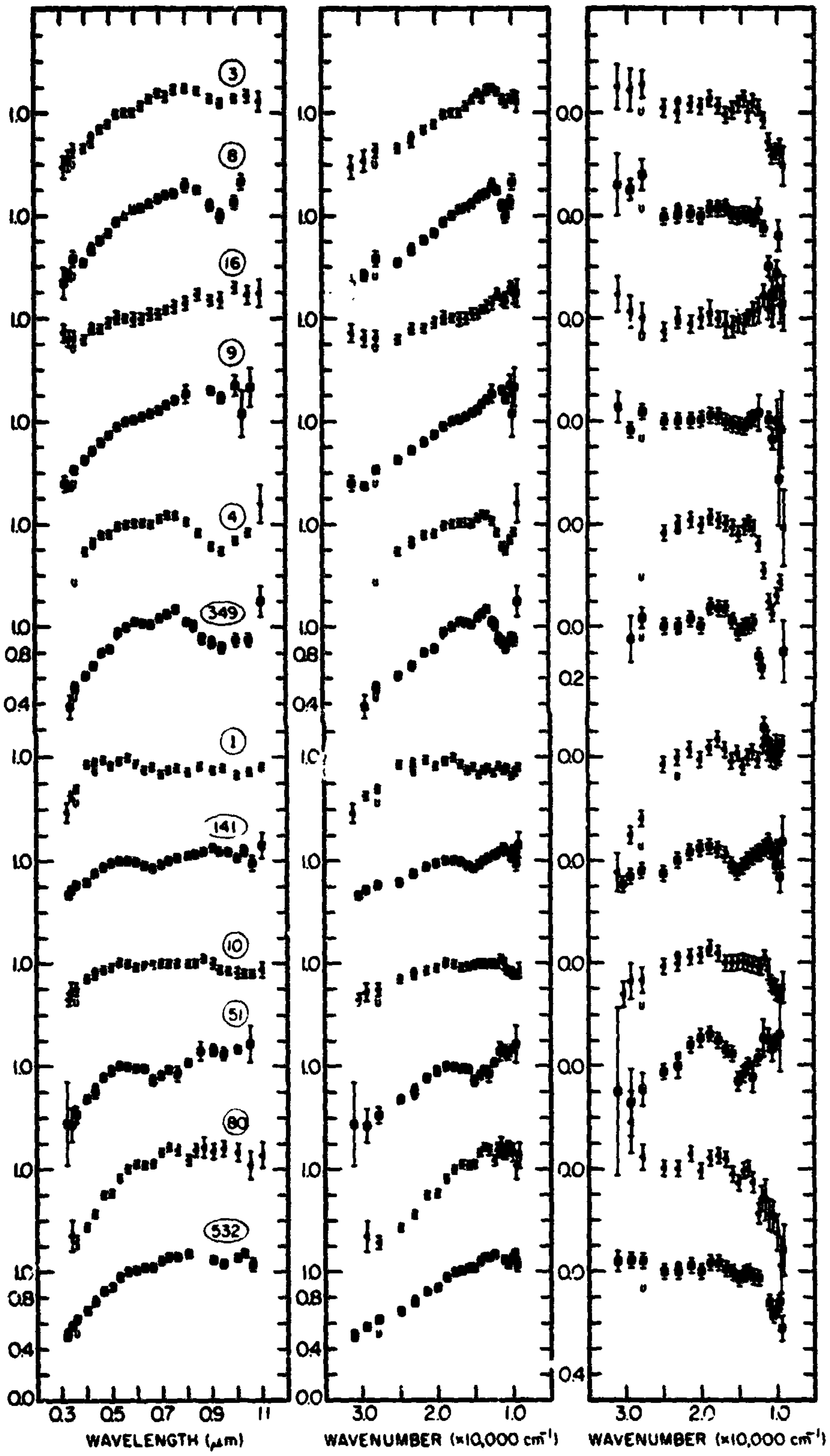
Surface mineralogy is one of the most revealing types of information obtainable about asteroids, since direct evidence of the compositional and thermal evolution of the objects is derivable. The mineral assemblages present are more informative than elemental abundances, for the exact combinations of elements in a mineral and the crystal structure are very sensitive to the composition of the parent material and to the temperature and pressure history.

Near ultraviolet, visible, and near-infrared reflectance spectroscopy is the most definitive available technique for the remote determination of asteroid surface mineralogies and petrologies. Electronic absorption features present in the reflectance spectra of asteroids (Figure 1) are directly related to the mineral phases present (Adams, 1975; McCord *et al.*, 1978).

Polarimetry, infrared radiometry and several other techniques (Morrison, 1978) provide complementary information, such as albedo, which, although not a unique function of mineralogy, is very useful in differentiating between mineralogic groups and in resolving ambiguities.

PREVIOUS CHARACTERIZATIONS OF ASTEROID SURFACE MATERIALS

McCord *et al.* (1970) measured the first 0.3-1.1 μm spectrum of an asteroid, 4 Vesta, and identified an absorption feature near 0.9 μm (see Figure 1) as due to the mineral pyroxene. They suggested that the surface material was similar to basaltic achondritic



3
8
16
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4
349
1
141
10
51
80
532
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0.3
0.5
0.7
0.9
1.1
WAVELENGTH (μm)
3.0
2.0
1.0
WAVENUMBER (×10,000 cm⁻¹)
3.0
2.0
1.0
WAVENUMBER (×10,000 cm⁻¹)

meteorites. Hapke (1971) compared the UBV colors of a number of asteroids to a variety of lunar, meteoritic and terrestrial rocks and rock powders. He concluded that the surface material of these asteroids could be matched by powders similar to a range of the comparison materials but not by metallic surfaces. Chapman and Salisbury (1973) indicated that some matches between asteroid and meteorite spectra were found for several meteorite types including enstatite chondrites, a basaltic achondrite, an optically unusual ordinary chondrite and, possibly, a carbonaceous chondrite. Johnson and Fanale (1973) showed that the albedo and spectral characteristics of some asteroids are similar to C1 and C2 carbonaceous chondrites and others to iron meteorites. The latter two sets of authors noted the problem of defining precisely what constituted a 'match,' and both raised the question of subtle modification of asteroid surface materials by *in situ* space weathering processes. Salisbury and Hunt (1974) raised the question of the effects of terrestrial weathering on meteorite specimens and the validity of matches between the spectra of such specimens and the asteroids.

McCord and Gaffey (1974) utilized absorption features and general spectral properties to characterize surface materials of 14 asteroids. They identified mineral assemblages similar to carbonaceous chondrite, stony-iron, iron, basaltic achondrite and silicate-metal meteorites. At that time it was possible to establish the general identity of the spectrally important minerals in an assemblage, but very difficult to establish their relative abundances.

Chapman *et al.* (1975) utilized spectral, albedo and polarization parameters to define two major asteroid groups. The first group was characterized by having low albedos ($\leq$0.09), strong negative polarizations (>1.1%) at small phase angles and relatively flat, featureless spectral reflectance curves. These parameters were similar to those for carbonaceous chondrites and these asteroids were designated as 'carbonaceous' or C type. The second group was characterized as having higher albedos ($\geq$0.09), weaker negative polarizations (0.4-1.0%) and reddish, sometimes featured spectral curves. These parameters were comparable to those for most of the meteorites which contain relatively abundant silicate minerals so this group was designated 'siliceous or stony-iron' or S types. A small minority (~10%) of the asteroids could not be classified in this system and were designated 'unclassified' or U types. This classification system has been redefined recently by Bowell *et al.* (1978). (In this volume, see Morrison, 1978.)

This simple classification scheme can be quite useful since it does seem to often separate these two major types of objects and the observational parameters on which the scheme is based can be measured at present for objects fainter than those for which complete spectra can be obtained. The choice of terminology is unfortunate, however, since it implies a specific definition of surface materials in meteoritic terms, which was not intended. Any 'flat-black' spectral curve would be designated C type whether or not the surface material would be characterized as carbonaceous by any other criteria. A similar objection can be raised with respect to the 'siliceous' terminology since it implies a degree of specificity not present in the classification criteria.

Thus, while the C and S classification of asteroids cannot be viewed as a description of mineralogy or petrology, it does provide valid characterization with respect to the chosen parameters. Since the groups appear in each of the parameters used (albedo, polarization, color), a single measurement such as UBV color can be used to classify the asteroid (Zellner *et al.*, 1975; Zellner *et al.*, 1977b; Zellner and Bowell, 1977; Morrison, 1977a,b).

Fig. 1. Typical spectral reflectance curves for the various asteroid spectral groups: 3 Juno, RA-1; 8 Flora, RA-2; 16 Psyche, RR; 9 Metis, RF; 4 Vesta, A; 349 Dembowska, A; 1 Ceres, F; 141 Lumen, TA; 10 Hygiea, TB; 51 Nemausa, TC; 80 Sappho, TD; and 532 Herculina, TE. Spectral curve for each asteroid is displayed in several formats: left--normalized reflectance versus wavelength (μm); center--normalized reflectance versus energy (wavenumber, cm^{-1}; and right--difference between spectral curve and a linear 'continuum' fitted through 0.43 μm and 0.73 μm points. (From Gaffey and McCord, 1978.)

This approach can also be utilized to identify anomalous objects (Zellner, 1975; Zellner *et al.*, 1977a) or to establish possible genetic relationships between members of asteroid dynamical families (Gradie and Zellner, 1977). Chapman (1976) utilized the basic CSM classification system but identified subdivisions based on additional spectral criteria ('slope,' 'bend' and 'band depth'; McCord and Chapman, 1975a,b) which are mineralogically significant.

Johnson *et al.* (1975) measured the near-infrared reflectance of three asteroids through the broad bandpass J, H, and K filters (1.24, 1.65 and 2.2 μm) and concluded that these were consistent with the infrared reflectance of suggested meteoritic materials. Matson *et al.* (1977a,b) utilized infrared H and K reflectances to infer that space weathering processes were relatively inactive on asteroid surfaces in contrast to the surfaces of the Moon and Mercury.

A very favorable apparition in early 1975 permitted the measurement of a variety of spectral data sets for the Earth-approaching asteroid 433 Eros. Pieters *et al.* (1976) measured the 0.33-1.07 μm spectral reflectance of Eros through 25 narrow bandpass filters. This curve was interpreted as indicating an assemblage of olivine, pyroxene and metal, with metal abundance equal to or greater than that in the H-type chondrites. Veeder *et al.* (1976) measured the spectrum of Eros through 11 filters from 0.65-2.2 μm and concluded that their spectral data indicated a mixture of olivine and pyroxene with a metal-like phase. Wisniewski (1976) concluded from a higher resolution spectrum (0.4-1.0 μm) that this surface was best matched by a mixture of iron or stony-iron material with ordinary chondritic material (*e.g.*, iron + pyroxene + olivine), but suggested that olivine is absent or rare. Larson *et al.* (1976) measured the 0.9-2.7 μm spectral reflectance curve for Eros and identified Ni-Fe and pyroxene, but found no evidence of olivine or feldspar. The dispute over the olivine content arises because of slight differences in the observed spectra near 1 μm, and the uncertainty in the metal abundance is due to incomplete quantitative understanding of the spectral contribution of metal in a mixture with silicates.

In a comprehensive article, Gaffey and McCord (1977) presented a detailed mineralogical analysis of 65 asteroid reflectance spectra and arrived at the most complete description existing of the mineral assemblages present on asteroid surfaces. They also gave a review of the field and a detailed discussion of the interpretive techniques applied to derive mineralogy. Much of the material in the present article is derived from this paper and the reader is referred to it for more detailed and comprehensive information.

The evolving characterization of the surface mineralogy of the asteroid 4 Vesta is illustrative of the improving sophistication of the interpretative process.

a. McCord *et al.* (1970) measured the reflectance spectrum of Vesta with moderate spectral resolution and coverage (0.40-1.08 μm, ∿24 filters). They identified a deep absorption band (∿0.92 μm) which they interpreted as diagnostic of a pigeonite (pyroxene with moderate calcium content). The spectrum was matched to that of a eucritic basaltic achondrite (pyroxene + plagioclase). A second pyroxene band was predicted near 2.0 μm.

b. Chapman (1972) obtained a spectral curve of Vesta with the absorption feature centered near 0.95 μm which was interpreted to indicate a more calcium- or iron-rich pigeonite.

c. Chapman and Salisbury (1973) compared this spectrum to a range of meteorites and concluded that it was best matched by a laboratory spectrum of the howarditic basaltic achondrite, Kapoeta.

d. Veeder *et al.* (1975) measured a high-resolution (~50 Å) 0.6-1.1 μm reflectance spectrum of Vesta, determined the absorption band position to be 0.92 ± 0.02 μm and interpreted this to represent a calcic pyroxene or eucritic basaltic achondrite.

e. Johnson *et al.* (1975) measured the broad bandpass reflectance of Vesta at 1.65 and 2.20 μm (H and K filters) and concluded that the data matched that expected for a basaltic achondritic surface material. They emphasized the need for higher-resolution spectra beyond 1.0 μm.

f. Larson and Fink (1975) determined the 1.1-3.0 μm reflectance of Vesta relative to the Moon. They identified the predicted second pyroxene band and confirmed the existence of pyroxene in the surface material. They indicated that no absorption bands for olivine, feldspar or ices were seen in the spectrum.

g. McFadden *et al.* (1977) measured the high-resolution (20-40 Å) 0.5-1.06 μm spectrum and determined the band position to be 0.924 ± 0.004 μm. They inferred the presence of a 10-12 mole% Ca pyroxene and suggested that the symmetry of the absorption feature indicated little or no olivine.

h. Larson (1977) presented the 1.0-2.5 μm reflectance curve of Vesta relative to the Sun. The band minimum (2.00 ± 0.05 μm) is within the field of eucrite meteorites, although it may overlap with the howardite field.

Improvements in the mineralogical and petrological characterization of the surface materials of 4 Vesta result partly from improvements in spectral resolution and coverage. Perhaps most important has been the improved understanding of the mineralogical significance of absorption features in reflectance spectra. The recent effort has concentrated on characterizing the mineral absorption features more precisely, but the original interpretation (McCord *et al.*, 1970) still appears valid.

SUMMARY OF ASTEROID MINERALOGICAL INFORMATION

Mineralogical interpretation of the observed spectra of approximately sixty asteroids has been made utilizing the wavelength dependent optical properties of meteoritic and meteorite-like mineral assemblages (see Gaffey and McCord, 1978) and a summary is given in Tables 1 and 2. The albedos (radiometric) and the depth of the negative branch of the polarization-phase curve have been used to provide an indication of the bulk optical density of the surface material, which constrains the interpretation of the surface mineralogy and petrology. A wide variety of mineralogical assemblages have been identified as asteroid surface materials. These assemblages are mixtures of the minerals found in meteorites. However, the relative abundance of mineral assemblage types present on main belt asteroid surfaces differs radically from the relative abundance of meteoritic mineral assemblages arriving at the Earth's surface. The relative abundances of various assemblages as discussed here are uncorrected for observational bias against the smaller, darker, and more distant asteroids as described by Chapman *et al.* (1975), Morrison (1977b), and Zellner and Bowell (1977).

Table 1. Asteroid Surface Materials: Characterizations[a]

Asteroid	Spectral Type	Mineral Assemblage (b)	Meteoritic Analogue (c)	CSM Type (d)
1 Ceres	F	Sil(O), Opq(M)*	C4 (Karoonda)	C (C*)
2 Pallas	F	Sil(O), Opq(M)*	C4 (Karoonda)	U (C*)
3 Juno	RA-1	NiFe $\sim$ (Ol$\sim$Px)	Ol-Px Stony-Iron	S
4 Vesta	A	Cpx	Eucrite	U
6 Hebe	RA-2	NiFe $>$ Cpx	Mesosiderite	S
7 Iris	RA-1	NiFe, Ol, Px	Ol-Px Stony-Iron	S
8 Flora	RA-2	NiFe $\geq$ Cpx	Mesosiderite	S
9 Metis	RF	NiFe, (Sil(E))	E. Chon. Iron	S
10 Hygiea	TB	Phy, Opq(C)	C1-C2	C (C*)
11 Parthenope	RF	NiFe, (Sil(E))	E. Chon. Iron	S
14 Irene	RA-3	NiFe, Px	Px Stony-Iron	S
15 Eunomia	RA-1	NiFe $\sim$ (Ol$\gg$Px)	Ol-Px Stony-Iron	S
16 Psyche	RR	NiFe, Sil(E)	E. Chon. Iron	M
17 Thetis	RA-2	NiFe, Cpx	Mesosiderite	S
18 Melpomene	TE	Sil(O), Opq(C)	C3	S
19 Fortuna	TA	Phy, Opq(C)	C1-C2	C
25 Phocaea	RA-2	NiFe, Px, Cpx	Px Stony-Iron	S
27 Euterpe	RA-2	NiFe, Px, Cpx	Px Stony-Iron	S
28 Bellona	TE	Sil(O), Opq(C)	C3	S
30 Urania	RF (?)	---	---	S
39 Laetitia	RA-1	NiFe $\sim$ (Ol$\sim$Px)	Ol-Px Stony-Iron	S
40 Harmonia	RA-2	NiFe $>$ Px	Mesosiderite	S
48 Doris	TA	Phy, Opq(C)	C1-C2	C
51 Nemausa	TC	Phy, Opq(C)	C1-C2	C
52 Europa	TA	Phy, Opq(C)	C1-C2	C
58 Concordia	TABC	Phy, Opq(C)	C1-C2	C
63 Ausonia	RA-3	NiFe, Px	Px Stony-Iron	S
79 Eurynome	RA-2	NiFe $\sim$ Cpx	Mesodiderite	S
80 Sappho	TD	Sil(O), Opq(C)	C3	U
82 Alkmene	TE	Sil(O), Opq(C)	C3	S
85 Io	F	Sil(O), Opq(M)*	C4 (Karoonda)	C
88 Thisbe	TB	Phy, Opq(C)	C1-C2	C
130 Elektra	TABC	Phy, Opq(C)	C1-C2	U
139 Juewa	TB	Phy, Opq(C)	C1-C2	C
140 Siwa	RR	NiFe, Sil(E)	E. Chon. Iron	C
141 Lumen	TA	Phy, Opq(C)	C1-C2	C
145 Adeona	TA	Phy, Opq(C)	C1-C2	C
163 Erigone	TA	Phy, Opq(C)	C1-C2	C
166 Rhodope	TC	Phy, Opq(C)	C1-C2	U
176 Iduna	TA	Phy, Opq(C)	C1-C2	C
192 Nausikaa	TA-2	NiFe $\sim$ (Px$>$Ol)	Px-Ol Stony-Iron	S
194 Prokne	TC	Phy, Opq(C)	C1-C2	C
210 Isabella	TABC	Phy, Opq(C)	C1-C2	C
213 Lilaea	F	Sil(O), Opq(M)*	C4 (Karoonda)	C

Table 1 (continued)

Asteroid	Spectral Type	Mineral Assemblage (b)	Meteoritic Analogue (c)	CSM Type (d)
221 Eos	TD	Sil(O), Opq(C)	C3	U
230 Athamantis	RF	NiFe, (Sil(E))	E. Chon., Iron	S
324 Bamberga	TABC	Phy, Opq(C)	C1-C2	C
335 Roberta	F	Sil(O), Opq(M)*	C4 (Karoonda)	U
349 Dembowska	A	Ol, (NiFe)	Ol. Achondrite	O
354 Eleonora	RA-1	NiFe ∿ Ol	Pallasite	S
433 Eros (e)	--	Px ∿ Ol, NiFe	H Chondrite	S
462 Eriphyla	RF (?)	---	---	S
481 Emita	TABC	Phy, Opq(C)	C1-C2	C
505 Cava	TA	Phy, Opq(C)	C1-C2	C
511 Davida	TB	Phy, Opq(C)	C1-C2	C (C*)
532 Herculine	TE	Sil(O), Opq(C)	C3	S
554 Peraga	TA	Phy, Opq(C)	C1-C2	C
654 Zelinda	TC	Phy, Opq(C)	C1-C2	C
674 Rachele	RF (?)	---	---	S
704 Interamnia	F	Sil(O), Opq(M)*	C4 (Karoonda)	U
887 Alinda	TD	Sil(O), Opq(C)	C3	S
1685 Toro (f)	--	Px, Ol	L Chondrite (?)	U

(a) From Gaffey and McCord (1978).

(b) Mineral assemblage of asteroid surface material determined from interpretation of reflectance spectra: NiFe (nickel-iron metal); Ol (olivine); Px (pyroxene, generally low calcium orthopyroxene); Cpx (clinopyroxene, calcic pyroxene); Sil(O) (mafic silicate, most probably olivine); Si(E) (spectral neutral silicate, most probably iron-free pyroxene (enstatite), or iron-free olivine (forsterite); Phy (phyllosillicate, layer lattice silicate, meteoritic clay mineral, generally hydrated, unleached with abundant subequal Fe^{2+} and Fe^{3+} cations); Opq(C) (opaque phase, most probably carbon or carbon compounds); Opq(M) (opaque phase, most probably magnetite or related opaque oxide).

Mathematical symbols ('>', greater than; '>>', much greater than; '∿', approximately equal) are used to indicate relative abundance of mineral phases. In cases where abundance is undetermined, order is of decreasing apparent abundance.

Asteroidal spectra which are ambiguous between 'TDE' and 'RF' are not characterized mineralogically.

(c) Meteoritic analogues are examples of meteorite types with similar mineralogy but genetic links are not established. For example, objects designated as analogous to mesosiderites could be a mechanical metal-basaltic achondritic mixture.

(d) Asteroidal spectral type as defined by Chapman *et al.* (1975) and as summarized by Zellner and Bowell (1977). C* designation from Chapman (1976).

(e) Pieters *et al.* (1976).

(f) Chapman *et al.* (1973).

Table 2$^{(a)}$

Asteroid	Orbital Parameters			Albedo (b) (%)	Pmin (c) (%)	Diameter (b) (km)
	a (AU)	e	i (deg)			
1 Ceres	2.767	0.08	10.6	5.4	1.67	1003
2 Pallas	2.769	0.24	34.8	7.4	1.35	608
3 Juno	2.670	0.26	13.0	15.1	0.75	247
4 Vesta	2.362	0.09	7.1	22.9	0.55	538
6 Hebe	2.426	0.20	14.8	16.4	0.80	201
7 Iris	2.386	0.23	5.5	15.4	0.70	209
8 Flora	2.202	0.16	5.9	14.4	0.60	151
9 Metis	2.386	0.12	5.6	13.9	0.70	151
10 Hygiea	3.151	0.10	3.8	4.1	-	450
11 Parthenope	2.453	0.10	4.6	12.6	0.70	150
14 Irene	2.589	0.16	9.1	16.2	-	158
15 Eunomia	2.642	0.19	11.7	15.5	0.70	272
16 Psyche	2.920	0.14	3.1	9.3	0.95	250
17 Thetis	2.469	0.14	5.6	10.3	0.65	109
18 Melpomene	2.296	0.22	10.1	14.4	-	150
19 Fortuna	2.442	0.16	1.6	3.2	1.65	215
25 Phocaea	2.401	0.26	21.6	18.4	-	72
27 Euterpe	2.347	0.17	1.6	14.7	0.60	108
28 Bellona	2.776	0.15	9.4	13.2*	-	126*
30 Urania	2.365	0.13	2.1	14.4	0.75	91
39 Laetitia	2.769	0.11	10.4	16.9	0.70	163
40 Harmonia	2.267	0.05	4.3	12.3	0.75	100
48 Doris	3.114	0.06	6.5	-	-	-
51 Nemausa	2.366	0.07	10.0	5.0	1.95	151
52 Europa	3.092	0.11	7.5	3.5	-	289
58 Concordia	2.699	0.04	5.0	-	-	-
63 Ausonia	2.395	0.13	5.8	12.8	0.65	91
79 Eurynome	2.444	0.19	4.6	13.7	-	76
80 Sappho	2.296	0.20	8.7	11.3	-	83
82 Alkmene	2.763	0.22	2.8	13.8	-	65
85 Io	2.654	0.19	11.9	4.2	-	147
88 Thisbe	2.768	0.16	5.2	4.5	-	210
130 Elektra	3.111	0.21	22.9	5.0*	-	173*
139 Juewa	2.783	0.17	10.9	4.0	1.30	163
140 Siwa	2.732	0.21	3.2	4.7	-	103
141 Lumen	2.665	0.21	11.9	2.8	1.75	133
145 Adeona	2.674	0.14	12.6	-	-	-
163 Erigone	2.367	0.19	4.8	-	-	-
166 Rhodope	2.686	0.21	12.0	-	-	-
176 Iduna	3.168	0.18	22.7	-	-	-
192 Nausikaa	2.403	0.25	6.9	16.5	-	94
194 Prokne	2.616	0.24	18.5	2.7	-	191
210 Isabella	2.722	0.12	5.3	-	-	-
213 Lilaea	2.754	0.15	6.8	-	-	-

Table 2 (continued)

Asteroid	Orbital Parameters			Albedo (b) (%)	Pmin (c) (%)	Diameter (b) (km)
	a (AU)	e	i (deg)			
221 Eos	3.014	0.10	10.8	-	-	-
230 Athamantis	2.383	0.06	9.4	10.0	-	121
324 Bamberga	2.682	0.34	11.2	3.2	1.45	246
335 Roberta	2.473	0.18	5.1	-	-	-
349 Dembowska	2.925	0.09	8.3	26.0	0.35	144
354 Eleonora	2.797	0.12	18.4	14.8	0.[illegible]	153
433 Eros	1.458	0.24	10.8	17.4	0.70	23
462 Eriphyla	2.872	0.09	3.2	-	-	-
481 Emita	2.743	0.16	9.8	-	-	-
505 Cava	2.686	0.24	9.8	-	-	-
511 Davida	2.187	0.17	15.8	3.7	1.70	323
532 Herculina	2.771	0.17	16.3	10.0	0.75	150
554 Peraga	2.375	0.15	2.9	3.9*	-	101*
654 Zelinda	2.297	0.23	18.2	3.2*	-	128*
674 Rachele	2.921	0.20	13.6	-	-	-
704 Interamnia	3.057	0.15	17.3	3.3	-	350
887 Alinda	2.516	0.54	9.1	16.6	0.75	4
1566 Icarus	1.078	0.83	23.0	16.6*		1*
1685 Toro	1.368	0.44	9.4	12.4*		3*

(a) From Gaffey and McCord (1978).

(b) Albedos and diameters by the radiometric technique as summarized by Morrison (1977b). Those indicated by an asterisk are regarded as of marginal certainty.

(c) Depth of the negative branch of the phase-polarization curve (P_{min}) as summarized by Chapman *et al.* (1975).

A large fraction ($\sim$40%) of the interpreted spectra indicate surface materials composed of an abundant (spectrally) opaque phase (*e.g.*, carbon, carbonaceous compounds and/or magnetite) mixed with an Fe^{2+}-Fe^{3+} silicate (*e.g.*, low temperature hydrated silicate or clay minerals as found in the C1 and C2 meteorites). A range of subtle variations of these spectra indicates that a variety of these opaque-rich clay mineral assemblages exist on asteroid surfaces.

Approximately a quarter of the interpreted spectra imply surface materials composed of mafic silicates (olivine, pyroxene) mixed with an opaque phase. These materials are comparable to the C3 and C4 carbonaceous chondritic assemblages. The majority ($\sim$15% of total) of these spectra are characterized by a significant but not overwhelming spectral contribution by the opaque phases. These assemblages are comparable to the 'olivine + opaques' C3O and C3V meteoritic assemblages. About 10% of the total objects studied apparently represent similar silicates (olivine) with a spectrally dominant opaque phase. Recent studies of Ceres by Lebofsky (1978) and Gaffey (1978) suggest that anomalous iron-free clay minerals, not yet observed in meteorites, may be an important surface component of these asteroids.

Most of the remaining spectra (about a third of the interpreted spectra) exhibit characteristics of a significant spectral contribution from metallic iron or nickel-iron. The surface materials of these asteroids appear to consist of assemblages of Ni-Fe, either alone or with a variety of silicates, including metal or metal plus a transition metal-free silicate (*e.g.*, enstatite or forsterite), metal plus olivine, metal plus pyroxene and metal plus olivine plus pyroxene. The majority of these metalliferous objects appear to have surface materials with abundant (∿25-75%) metal. The apparent metal abundances in these surface materials are comparable to those in the stony-iron meteorites and represent a significant enrichment over the cosmic abundance.

The range of mineral assemblages present on asteroid surfaces is an indication of the range of processes that have acted on the asteroids and asteroid parent bodies. Most modern cosmological models assume that the solid bodies of the solar system accreted from grains precipitated by a cooling nebula of solar composition (*e.g.*, Cameron, 1973; Cameron and Pine, 1973; Lewis, 1972). The sequence of condensation with decreasing temperature in a solar nebula has been discussed extensively (*e.g.*, Larimer, 1967; Grossman, 1972; Grossman and Larimer, 1974). In a condensation sequence which does not involve the large scale removal of condensed matter from contact and further reaction with the nebular gas (equilibrated or quasi-equilibrated condensation model), the unmetamorphosed chondritic meteoritic assemblages (C1, C2, C3, LL 3-4, L 3-4, H 3-4, E 3-4) and the high temperature calcium-aluminum inclusions of the C-type meteorites (*e.g.*, Allende) can be formed by accretion of direct condensation products. While the detailed sequence of mineral condensation and reaction is a function of nebular pressure, a major factor to bear in mind is that the oxidation of iron (Fe^0) to Fe^{2+} begins to take place near 750°K, well below the temperature at which essentially all the silicate and metal phases will have condensed. In these models, the magnesium end members of the olivine and pyroxene materials condense near 1300°K but do not incorporate the Fe^{2+} cations until the nebula has cooled below 750°K. The sensitivity of final product mineralogy (*e.g.*, Fe^{2+} distribution) to nebular conditions and processes (*e.g.*, isolated regions, gas-dust fractionation) and to accretionary and post-accretionary processes, can provide a key to utilizing mafic silicate mineralogy as a probe of the evolutionary history of certain regions of the solar system.

There is evidence from these remote sensing techniques for three definable asteroid populations, with different condensation, accretion or thermal histories.

1. The opaque + Fe^{2+}-Fe^{3+} assemblages (spectral types TA, TB, TC, see Table 1) and their meteorite analogues, C1 and C2 chondrites, accreted from material apparently condensed at low temperature (<400°K) from the solar nebula. These materials have experienced weak or minimal post-accretionary thermal events.

2. The opaque + mafic silicate assemblages (spectral types TD, TE, F) and their meteoritic analogues, the C3 and C4 chondrites, accreted from nebular condensate between 750°K and 350°K. The C4 meteoritic materials (type F asteroidal surface materials) appear to have experienced some post-accretionary metamorphism.

3. The metal-rich differentiated asteroid surface assemblage (and most of the differentiated meteorites) accreted from material condensed below 750°K, and have experienced intense heating events permitting magmatic differentiation to occur.

DISTRIBUTION OF ASTEROID MATERIALS

The distribution of the types of mineral assemblages with respect to orbital elements or size of body can provide insight into the nature of the asteroid formation and modification processes. Chapman *et al.* (1975), Chapman (1976, 1977), and Zellner and Bowell (1977) have drawn several conclusions based on these distributions of C- and S-type asteroids.

The distribution of the mineralogic groups with respect to semimajor axis is shown in Figure 2. These assemblages can be grouped according to post-accretionary thermal history into two groups: (a) apparently unmodified low temperature, surface materials (Types TA, TB, TC = C2) and intermediate temperature surface materials (Types TD, TE = C3), and (b) apparently metamorphosed or differentiated assemblages (Types RA, A, F). The distribution of these materials with respect to semimajor axis is shown in Figure 3.

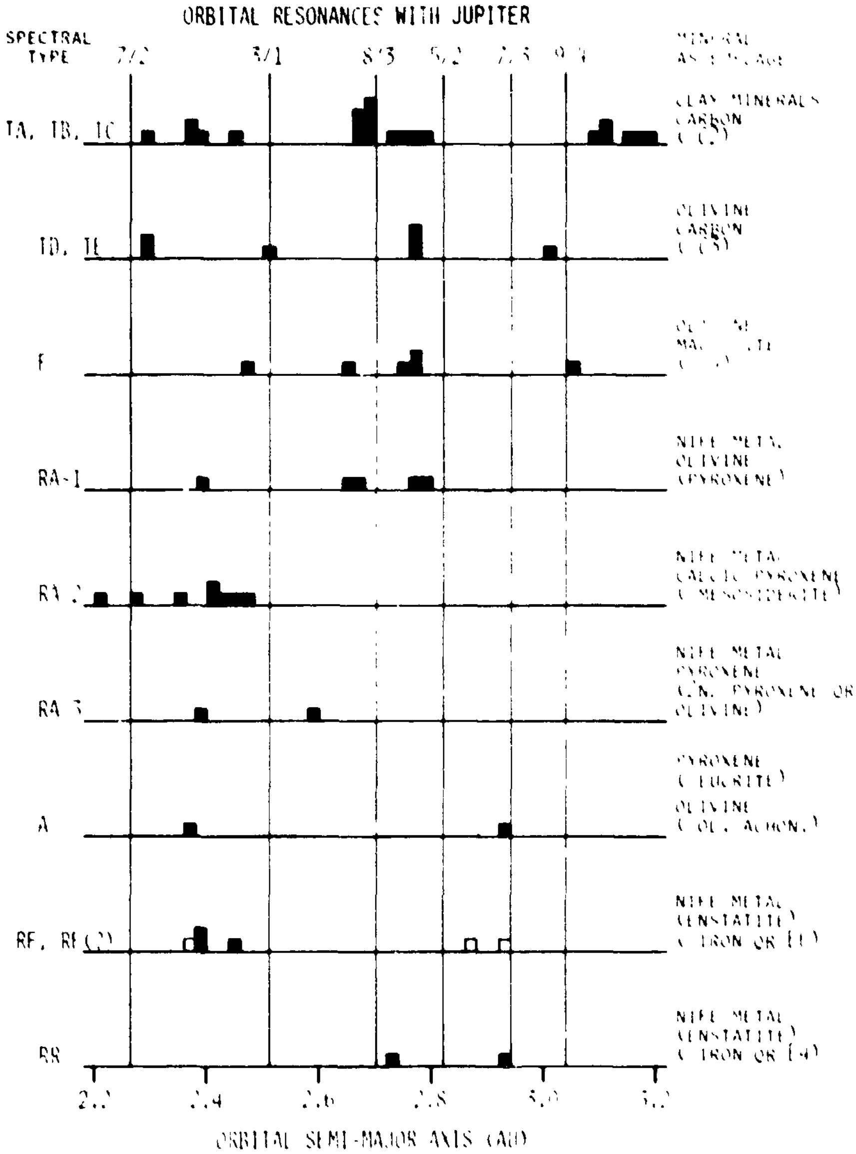

Fig. 2. Distribution of asteroid surface material groups as a function of the semimajor axis of their orbits (uncorrected for observational bias) for the members of each spectral group discussed in the text (from Gaffey and McCord, 1978).

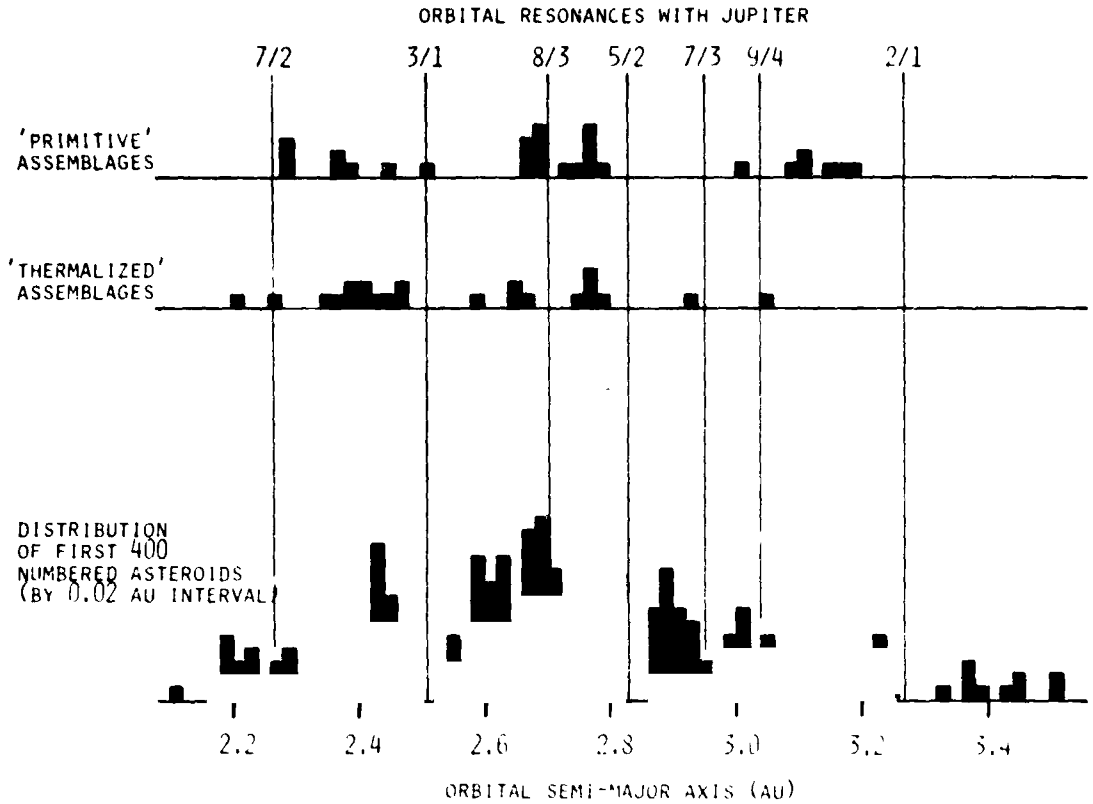

Fig. 3. Distribution of asteroid surface material groups as a function of the semimajor axis of their orbits (uncorrected for observational bias) for groups with diverse thermal histories (Primitive - apparently unaltered by any post-accretionary heating events - TA-TB-TC, TD-TE and Thermalized - apparently heated and modified or melted and differentiated by some strong post-accretionary heating episode) and the distribution of the first 400 numbered asteroids (as a histogram per 0.02 AU) (from Gaffey and McCord, 1978).

These distributions have not been corrected for observational bias, which favors brighter objects over darker objects; that is, objects with high albedos are favored over those with low albedos or objects with small semimajor axes are favored over those with large. Thus, for example, the number of TA-TB-TC objects should be multiplied by some factor depending on size and semimajor axis to compensate for their low albedos. Zellner and Bowell (1977) have discussed this bias correction process in detail.

These distributions verify the increase in relative abundance of the low temperature assemblages with increasing distance from the Sun reported by Chapman *et al.* (1975), but they also show that inside about 3.0 AU, all types generally can be found in a region. The particular concentration of the metal plus orthopyroxene assemblage contained in spectra type RA-2 inside 2.5 AU is a distribution which should be considered in light of models for differentiating these objects.

The distribution of surface mineralogies with respect to the size of the bodies is of interest (Figure 4). Two significant factors should be noted. First, the largest sized

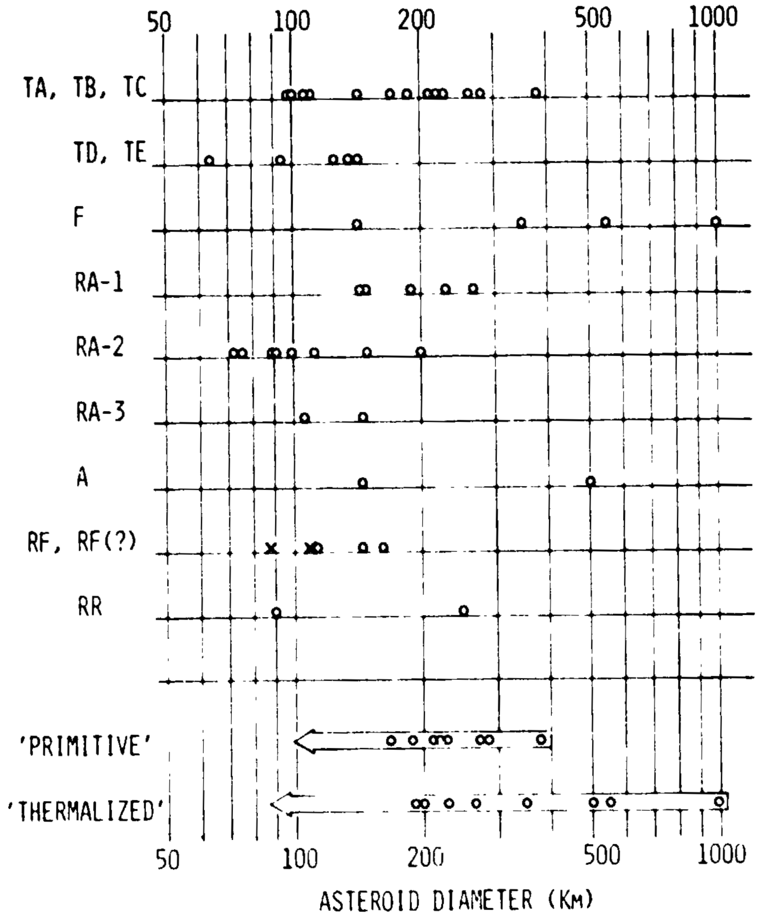

Fig. 4. Distribution of asteroid surface material groups as a function of asteroid diameters (uncorrected for observational bias). Primitive materials (TA-TB-TC and TD-TE) are compared to thermalized materials (RA-1, RA-2, RA-3, A, F) to provide an indication of the upper limits to the size distributions of the original populations (from Gaffey and McCord, 1978).

object of the TD and TE ($\sim$C3) groups is significantly smaller than that of the TA-TB-TC ($\sim$C2) group. This would tend to support the concept that the C3-type material was isolated in the interiors of bodies with C2-type surfaces (inhomogeneous accretion). Second, the largest sized body among 'thermalized' objects (RA, A, F) is significantly larger than that of the 'unthermalized' or 'primitive' objects (TA-TB-TC, TD, TE). This would imply that the size of the parent body may have an influence over post-accretionary heating. The cut-off in size below which heating did not take place appears to be approximately 300-500 km. Observational bias correction should enhance this discrepancy.

The C2-like surface materials which dominate the main asteroid belt population appear to be relatively rare on the Earth-crossing and Earth-approaching asteroids (Apollo and Amor objects). Spectral reflectance curves have been interpreted for two Amor asteroids

(433 Eros $\sim$ H5-6 or L5-6 assemblage; Pieters *et al.*, 1976 and 887 Alinda $\sim$ C3 assemblage) and for one Apollo asteroid (1685 Toro $\sim$ L6(?); Chapman *et al.*, 1973). Gehrels *et al.* (1970) utilized several indirect methods to define a wavelength dependent brightness curve for the Earth-crossing asteroid 1566 Icarus which indicated the presence of an absorption feature in the region of 1 μm (pyroxene?). Zellner *et al.* (1975) provided the UBV colors for two additional objects (1620 Geographos and 1864 Daedalus), both Type S. Zellner and Bowell (1977) indicate that of about 12 Apollo or Amor objects, one is of Type C. While some have reservations with regard to the meteoritic specificity of the CSM classification system, one can view C and S as approximately 'C2' and 'not-C2.'

It is evident that the dominant C2-type assemblages of the main belt are under-represented among the Apollo and Amor objects by about two orders of magnitude ($\sim$1/10 instead of $\sim$10/1). This discrepancy implies that the Apollo and Amor asteroids are not randomly derived from the population of the main belt. If this population anomaly is not a recent or temporary event, then the source region which replenishes this inner solar system population must be both restricted and strongly depleted in C2-type asteroidal materials. This suggests that these asteroids may be derived from the innermost portions of the belt, perhaps inside 2.0 AU. Wetherill (1977) has suggested that objects formed closer in to the Sun (*e.g.*, ordinary chondritic assemblages) may have been stored at the inner edge of the belt and may represent the source of these objects. The cometary hypothesis (Öpik, 1963, 1966; Wetherill and Williams, 1968) for the origin of the Apollo and Amor asteroids cannot be ruled out on the basis of the available spectral data. Chapman (1977) reaches similar conclusions with respect to the origin of these asteroids.

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DISCUSSION

ARNOLD: Is it correct that no two of the spectra in Figure 1 are identical? If so, then I suggest again there is great variety among asteroid surfaces.

McCORD: That is right. It is felt that each one in this sample is significantly different and reveals some difference in the surface material.

MATSON: Your expectation of a continuum of properties seems to be unlike the clear divisions seen in some other parameters, like albedo.

McCORD: In part, you are right. There won't be a continuum between all of the various dimensions.

MORRISON: When you lump the asteroids together into thermalized and unthermalized groups, but without correcting for observational bias, I don't think this really adds much information. One might as well use the bias-corrected C and S data that Zellner reported here.

CHAPMAN: Not true, because it turns out there are both thermalized and unthermalized interpretations within the S classification. In other words, although there is a general association between the McCord/Gaffey groups and the C and S classifications, their individual spectra have been interpreted in such a way that the C and S are heterogeneous with respect to thermal evolution.

McCORD: That doesn't mean the C and S classification is useless. In individual cases it could lead you widely astray, but as a statistical tool probably not.

ARNOLD: I note that you reinforced the conclusion derived by other workers that there are no close analogs of an ordinary chondrite in this group. I also note that the ones which have C3 as the closest meteoritic analogs are Ss, and I wondered if you would comment on that?

McCORD: Well, that is quite possible because C3 is a modified metamorphosed material that can have a spectral continuum which would give you an S classification when you look at it using UBV photometry.

ARNOLD: Do you take albedo into account? A laboratory scientist knows that C3s are dark objects, but not as dark as C2s.

McCORD: That is taken into consideration. In fact, sometimes albedo is necessary in order to resolve ambiguities.

CHAPMAN: The TE class that you associated with C3s falls in the S class defined by Bowell *et al.* I don't think the TE spectra differ substantially from others which you have assigned to other classifications, and secondly, the albedo of those TEs is 0.13, which is pretty bright compared to C3 meteorites.

McCORD: These TEs may be too bright; in any individual classification errors are possible. But I would like to emphasize that the classifications are not capricious and should not be judged according to a single parameter. One has to spend a great deal of time working with both the asteroid spectra and the laboratory spectra before one begins to get a feeling for which differences are important and which are not.

WETHERILL: There is a feature at 0.65 μm. It appears in what others call an S-type asteroid; it does not appear in an ordinary chondrite, nor does it appear in any actual meteorites. So in regard to comparing meteorites with asteroids, I think it is worthwhile to place similar emphasis on the things that don't agree as well as the things that do agree.

McCORD: That feature is not well understood. I think it is real and that it means something. We are going to have to go to the laboratory and work on that. At the very beginning it was felt it might be spurious, a problem with comparison of standard stars, but the calibrations have been checked. It is not as though the feature is uniformly there. It is not there in some, it is there weakly in others, strongly in still others. That indicates it is real.

GROSSMAN: When you look at the broken surfaces of C1 and C2 meteorites in the laboratory, the human eye can certainly see the difference. I'm puzzled as to why the TA-type spectrum stands for C1-C2. Is it difficult to tell the difference spectrally between a C1 and a C2 in the laboratory or is it just that the asteroid spectra fall somewhere in-between them?

CHAPMAN: There are only three C1 samples available, and they are not in pristine optical condition. The problem is that no one has had believable samples of a C1 to measure in the laboratory.

GROSSMAN: What is in store for us as far as an improvement beyond what we see in Table 1? Is there any technological breakthrough that is going to happen?

McCORD: There is not a technological breakthrough, but more hard work. One has to measure the spectrum better with higher signal-to-noise, with larger spectral range, and with higher spectral resolution. It should be done for asteroids which have strong spectral features. Then one has to have available laboratory and theoretical material that allows one to interpret the features. For example, we need data on cold hydrated materials, materials we really don't know very much about. We are setting up to do that now. The emphasis of the work now that this survey is concluded is to do better interpretations for some specific main belt objects as well as for the Earth-approaching objects.