IMPLICATIONS OF THE INFERRED COMPOSITIONS OF ASTEROIDS FOR THEIR COLLISIONAL EVOLUTION

Clark R. Chapman
Planetary Science Institute
Suite 201, 2030 E. Speedway
Tucson, AZ 85719 USA

ABSTRACT

The inferred compositions of mainbelt asteroids set constraints on the nature and degree of collisional evolution of the asteroids. The existence of a basaltic crust on 4 Vesta seems to require that there has been very little collisional evolution since the presumably ancient solidification of its crust, which is consistent with most recent models of collisional evolution. But interpretations of the compositions of M- and S-type asteroids as collisionally stripped cores of differentiated parent bodies argue for much more extensive collisions. A major problem is presented by the extreme rarity of olivine-rich asteroids and olivine meteorites. Studies of the compositions of members of dynamical families suggest that most supposed families are either not real, or at least are not genetically related fragments of a cosmochemically reasonable precursor body. The mutual incompatibilities among various "accepted" traits of the asteroids deserve further study in order to develop a self-consistent scenario for the chemical and physical evolution of the asteroids.

INTRODUCTION

There are some reasonably strong constraints on the probable mineralogical compositions of mainbelt asteroids derived from spectral reflectance, radar, and other remote-sensing data, interpreted in the context of meteorite mineralogies. In this short paper, I describe some of these constraints, consider plausible scenarios for the geochemical and collisional evolution of asteroids, and raise questions related to current collisional models. I conclude that there are severe mutual inconsistencies among several of the "preferred" interpretations of asteroids. Remote-sensing data provide constraints on the mineralogy of the **optical surfaces** of asteroids. To the degree that dynamical ("Hirayama") families of asteroids represent the products of collisional disruption of a precursor body, such remote-sensing data actually permit us to peer "inside" an asteroidal body. Our ideas about plausible mineral assemblages for asteroids, and about their distribution within parent-bodies, are strongly constrained by our knowledge of meteorites -- which, with good reason, are thought to be derived primarily from mainbelt asteroidal parent bodies -- and by our knowledge of how to apply geochemical and geophysical principles to constrain the possible evolution of asteroidal bodies. The inconsistencies that I will discuss may call any of these ideas and principles into question, but in this paper I will stress the potential difficulties with currently accepted scenarios for collisional evolution.

VESTA AND PSYCHE

Let me begin by illustrating the kind of inconsistency that arises from the interpretation of asteroid compositions. Consider the large, well-known asteroids 4 Vesta and 16 Psyche. Vesta, the second largest asteroid at about 550 km diameter, is universally thought to exhibit a surface extensively -- and perhaps solely -- covered by basaltic lava. Its reflectance spectrum exhibits characteristic features of the silicate minerals pyroxene and plagioclase, but **no evidence for olivine** (cf. review of evidence by Gaffey and McCord, 1979). Our understanding of cosmochemical processes suggests that chondritic -- i.e. solar -- composition material subjected to heating within an asteroid-sized body will differentiate into a body with a metallic core, an olivine-rich silicate mantle, and a pyroxene- and plagioclase-rich basaltic crust. Vesta is also the leading candidate for being the original parent-body of the basaltic achondritic meteorites (cf. Drake, 1979). Eucrites -- basaltic achondritic meteorites believed to represent surficial lava flows on the parent-body -- have been dated by a variety of techniques to be ~4.6 b.y. old. Davis **et al.** (1985) have addressed the question of whether the relatively thin basaltic crust of Vesta could have survived intact, in the face of collisional bombardment subsequent to the solidification of the basaltic rocks 4.5 - 4.6 b.y. ago. By "intact", it is meant that Vesta must have avoided a "catastrophic collision," one large enough to mix its presumably olivine-rich mantle materials into the surface layers of the body; also it must have avoided such a thorough "gardening" of its crust by smaller impacts for olivine to become admixed with the basalt. Davis **et al.** conclude that the preservation of Vesta's crust requires that the asteroidal population never had (since the solidification of Vesta's crust) more than several times its present mass, and that it had very few bodies -- beyond those still remaining -- of sizes larger than 85 km diameter. The collisional evolution of such an initial population, as studied by Davis **et al.**, yielded catastrophic disruption (i.e. more than half of their mass removed) of no bodies larger than about 150 km diameter. Farinella **et al.** (1982) have considered collisional evolution from the viewpoint of asteroidal spins and have obtained results compatible with those of Davis **et al.**

Now consider 16 Psyche. Ostro **et al.** (1985) report a high probability that this 250 km diameter asteroid has a surface composed of metal. This inference from radar reflection data is consistent with the less diagnostic inferences based on spectral reflectance data. The reflectance spectrum of Psyche shows no hint of the prominent absorption features of olivine or pyroxene, indicating that if silicates ever existed on this body, they have been thoroughly eroded away. Psyche, which is approximately the 15th or 20th largest asteroid, appears to be a perfect candidate for being the nickel-iron core of a precursor body very similar to (though a bit smaller than) Vesta. In order to look like Psyche, such a precursor body would have to have suffered one or more collisions sufficient not only to catastrophically fragment the body but also to disrupt it (i.e. launch the extensive mantle rocks at greater than escape velocity). Thus the Psyche precursor body, which would have looked much like Vesta, must have suffered one or more impacts **much more energetic** than the largest impact Vesta could have sustained while still preserving its crust intact. Despite the somewhat different locations of Psyche and Vesta in the asteroid belt, the expected impact fluxes on the two bodies are similar. Also, for a projectile population with a size distribution similar to the present asteroids, every impact by a projectile of a given size should be statistically accompanied by numerous impacts of projectiles half as big. Therefore, if Psyche were stripped of its mantle by a catastrophic collision, we cannot appeal to chance to explain how Vesta could have avoided thorough rearrangement (at least) of its mantle rocks.

How do we escape this dilemma? Perhaps Psyche was struck by an anomalously large or energetic projectile, not accompanied by a fragmental-like size distribution of smaller bodies. But, as we will see, Psyche is not alone as an inferred stripped core; at least according to some interpretations of the numbers of stripped cores in the asteroid belt, there have been numerous disruptive collisions involving reasonably large precursor bodies. Another conceivable alternative is that Vesta's crust has **not** survived since 4.5 b.y. ago, but rather was created rather recently. Certainly Vesta, unlike Psyche, is a unique body. Almost certainly, based on observational completeness statistics, no other asteroidal body with more than 0.05% the mass of Vesta (i.e. >40 km diameter) exists bearing a basaltic surface. There does exist one very small, Earth-approaching asteroid (1915 Quetzalcoatl) with a Vesta-like composition (McFadden **et al.**, 1984). It could well be the immediate parent-body for the basaltic achondritic meteorites. If Quetzalcoatl was melted 4.6 b.y. ago, or if it was derived from a large, now-disrupted parent-body that was melted long ago, then we need not require Vesta to be old. How Vesta could have been melted in comparatively recent epochs would still be a large mystery, however. Such processes as giant-impact melting of asteroids were considered several years ago in the context of an alternative to deriving the unusual SNC meteorites from the planet Mars; although formation of large impact melt sheets may be possible (Vickery and Melosh, 1983), whole body melting in recent epochs is difficult to support (Ashwal **et al.**, 1982). Even if an anomalously energetic impactor could work, we would once again have to assume, just as in the case of Psyche, that it was not accompanied by a fragmental size distribution of smaller bodies. In conclusion, the presence of both a basaltic Vesta and a metallic Psyche in the asteroid belt is very difficult to understand.

S-TYPE ASTEROIDS AND THE OLIVINE PROBLEM

There is an unresolved question about the nature of the S-type asteroids that has an important bearing on our understanding of the collisional evolution of the asteroid population. The nature of the problem was outlined by Chapman (1979); despite further work, there remains considerable doubt about the nature of the S-types. There is broad agreement that the spectra reflect a mixture of pyroxene, olivine, and NiFe metal. What is uncertain is the relative percentages of these phases and the precise compositions of the component minerals. To first order, two very different kinds of meteorites are composed of mixtures of these three phases. Ordinary chondrites (types H, L, and LL) are mixtures of these phases and are believed to be primitive meteorites. Stony-iron meteorites (e.g. pallasites and mesosiderites) are also mixtures of these three phases, but represent highly differentiated assemblages. The pallasites, in particular, were presumably derived from the vicinity of the core-mantle interfaces in parent-bodies of roughly chondritic original compositions, which were heated to the point of at least partial melting, permitting formation of a metallic core and a basaltic crust, with an intervening mantle of olivine composition.

The precise mineral chemistries differ for these two different interpretations, and there are considerable differences in the relative percentages of the three phases. But a combination of imprecise spectral reflectance data and inherent complications in the interpretation of the spectra result in ambiguous interpretations of the compositions of most S-types. Feierberg **et al.** (1982) argued that most S-types are of ordinary chondritic composition. Gaffey (1984) has made a detailed study of the S-type inner-belt asteroid 8 Flora, including the shape of its reflection spectrum and the variations of that spectrum with Flora's spin. He concludes that Flora is not chondritic, but rather achondritic; by extension, he argues that most or all S-types are also differentiated assemblages, presumably the stony-iron cores of differentiated asteroids "stripped" by catastrophic collisions, as originally proposed by Chapman (1974). A variety of studies are in progress that may shed further light on this matter, including radar observations, close-up study of 29 Amphitrite (another S-type) by the Galileo spacecraft, and laboratory studies of the metal component of ordinary chondrites. But the answer is still not in as to whether S-types are nearly all of ordinary chondrite-like composition, nearly all of differentiated stony-iron composition, or some mixture of the two types.

The reason this debate is important for the subject of collisional evolution is that the exposure, by stripping, of numerous stony-iron cores requires much more extensive collisional evolution than is permitted by most recent studies of asteroid collisional evolution. For example, Gaffey (1985) has concluded that for the inner asteroid belt, where S-type asteroids predominate, "collisional disruption has been extremely effective and...most objects present in this region are indeed pieces of fragmented and dispersed parent bodies." Since the larger S-type bodies exceed 200 km in diameter, to be stripped cores they must have been derived from catastrophically disrupted bodies originally 300 km or larger in diameter. Apart from intact Vesta (and possibly 349 Dembowska, which is an olivine-rich, metal-poor body: possibly a rubble-pile of crustal and mantle rocks **not** stripped to the metallic core), there is no evidence of large differentiated bodies in the inner half of the asteroid belt that have **not** been catastrophically disrupted, by Gaffey's interpretation. Yet studies of collisional evolution by Farinella **et al.** (1982) and Davis **et al.** (1985), as reaffirmed by both groups in their presentations at the Pisa Workshop, do not permit such extensive collisional disruption as Gaffey requires. Either Gaffey's interpretation of the S-types as stony-iron cores is wrong, or the recent collisional modelling of spins and size-distributions is wrong (or both).

Another asteroid composition question related to the extensiveness of asteroid collisional evolution concerns olivine. Chondritic, solar-abundance material, if differentiated within a parent-body by processes of partial-to-complete melting, should result in large volumetric quantities of very olivine-rich silicates. Approximately half the volumes of the interiors of well-differentiated asteroids should consist of olivine, with only modest admixtures of other components. (Let me emphasize the word "well-differentiated", by which I mean that the iron has substantially segregated into a core and the low-melting plagioclase/pyroxene silicates have formed a crust; although one can imagine that a few bodies could be warmed to the point that a core forms only incompletely, or there is only a small percentage of partial melting, it is difficult to believe that such a wide diversity of asteroidal bodies would all just "barely" melt.) The question is: where is all the olivine? There are two sources of evidence that the abundant olivine is not there to be seen, or sampled, near the surfaces of asteroids.

First, we see very few olivine-rich asteroids. Olivine has a prominent, diagnostic reflectance spectrum. Indeed, several olivine-rich asteroids have been discovered, defined as "A-type" by Veeder **et al.** (1983). The spectral signature of pure olivine entirely lacking pyroxene absorption features was found by Cruikshank and Hartmann (1984) for the A-type asteroid 246 Asporina. In his analysis of the 8-color survey, Tholen (1984) found that only 1% of the ~400 asteroids with high-quality spectra are of the A type. Since A types have relatively high albedos (>0.2, distinctly higher than for S-types), observational biases tend to select for these objects, so they are, in fact, much rarer even than their 1% representation in the observed sample. There are other asteroids with reflectance spectra showing a substantial quantity of olivine. 349 Dembowska is a large, olivine-rich asteroid but it prominently shows the two near-infrared absorption features due to pyroxene. Some S-type or S-like asteroids (including those, like 354 Eleonora, recently reported on by Cruikshank **et al.**, 1985) have been long known to have a 1-micron absorption feature dominated by olivine rather than pyroxene; but these asteroids all show the prominent spectral signature of metal, which implies (in the Gaffey-type interpretation) that they represent the near-core pallasitic layer, rather than a purely olivine mantle.

In addition to the near-absence of observed olivine-rich asteroids, there are very few meteorites that could have come from the olivine mantles of differentiated asteroidal parent bodies. The very rare chassignite meteorites are the only nearly-pure olivine meteorites, and most of them are young and are now thought to have been derived from Mars. A single chassignite meteorite, Brachina, has an old enough age (4.6 Gy) so that it plausibly is a sample of the mantle of a partially differentiated asteroid (Nehru **et al.**, 1983). Much more common than olivine-rich stones are the (still relatively rare) olivine-metallic pallasites. Of course, olivine-bearing ordinary chondrites -- like the L and LL-types -- are very numerous in our meteorite collections, which is a major reason why some researchers expect that they are derived from the populous S-type asteroids. Otherwise, one must postulate that the processes of meteorite delivery to Earth from the asteroid belt is extremely selective and non-representative, which seems incompatible with the latest studies of meteorite excavation processes and dynamical delivery mechanisms (Greenberg and Chapman, 1983; Wetherill, 1985). To return to the main point, there is an extreme rarity of mantle-olivine both as remotely-sensed on the surfaces of mainbelt asteroids and as sampled via meteorites.

The absence of olivine is readily understood in terms of the relatively modest amount of collisional evolution of the asteroids envisioned by Davis **et al.** and Farinella **et al.** It is all the more readily understood if it is assumed that only a minority of large asteroids were ever heated to the point of differentiation (e.g. Vesta and Nysa) but that most S-type asteroids are ordinary chondritic in composition and were heated only to the point of metamorphism (as reflected in the petrologic varieties of ordinary chondrites). Without the latter point -- the rarity of differentiation -- even the modest collisional evolution calculated by Davis **et al.** would have created rubble piles of many large asteroids and olivine-rich rocks would be exposed (mixed with crustal silicates) on the surfaces of many asteroids; but only 349 Dembowska seems a possible example of this configuration and the virtual absence of olivine meteorites argues against the prevalence of differentiated rubble piles, as well.

An alternative explanation for the absence of olivine is that the collisional evolution has been **so extensive** that the olivine mantle material of differentiated S-type precursor bodies in the inner asteroid belt has nearly all been lost, presumably by being ground down to dust. This is the argument of Gaffey (1985), who writes that "the rarity of the volumetrically more common olivine-rich fragments (A-type) relative to the metal-rich S-type suggests that much of the mass...has been lost and that only the largest and/or strongest fragments survive to the present time." Gaffey has extended his thinking and reported at the 1985 AAS/DPS meeting a model for a strong gradient in the collisional evolution of the asteroids, with modest collisional evolution in the outer belt but extensive evolution in the inner belt. He now suggests that Jupiter-scattered planetesimals -- perhaps mostly of a similar size, rather than a fragmental size distribution -- could have caused the catastrophic depletion of the inner belt very early in solar system history. A now--decayed flux of Uranuus-Neptune zone planetesimals, or inner Oort cloud comets, as discussed by Fernandez and Ip (1983), is another potential population of projectiles for fragmenting asteroids. Gaffey's reliance on a strong collisional gradient seems required in order to preserve the supposedly weaker, more primitive, and undifferentiated outer belt asteroids. However, collision velocities in the inner belt are not that much higher than in the outer belt for the hypothesized population of planetesimals or comets scattered by the outer planets. While collisional modelling of such a scenario is in order, I do not feel this is likely to work in the way Gaffey has described his model to date. Nevertheless, there is an important feature of Gaffey's approach that deserves more scrutiny because of the Vesta/Psyche conundrum. A projectile population not accompanied by a steep fragmental size distribution of smaller projectiles is just what is required to smash up most bodies, while leaving (by chance) a small number of bodies (e.g. Vesta and Dembowska) relatively unscathed.

HIRAYAMA FAMILIES

Asteroid families (groups of asteroids with orbital elements a, e, and i more similar than expected by chance) have long been interpreted to represent the product of collisional fragmentation of precursor asteroids. If this is true, then they provide us a unique capacity to "see into the insides" of a planetary body. Proper elements have been computed by many researchers over the years, and various lists of asteroid families have been published (see review by Carusi and Valsecchi, 1982). It would be particularly interesting to study the fragments of a disrupted differentiated body; we could then study the processes of segregation by direct observation. Attempts have been made, but without notable success, to "piece back together" members of particular heterogeneous families to see if the aggregate has a reasonable geometry and distribution of minerals to make cosmochemical sense as a precursor body (Chapman, 1976; Zellner **et al.**, 1977; Gradie **et al.**, 1979). Even making allowances for substantial loss of material due to preferential collisional destruction of some components, no satisfying reconstruction has yet been made for the well-known heterogeneous families. The only reconstructed families that do make sense (cf. Gradie **et al.**) are those composed of bodies of similar or identical inferred composition.

Asteroid families can provide independent insight into several of the questions discussed so far in this paper. For example, the sheer number of families provides a lower limit on the number of catastrophic fragmentations that have occurred in the asteroid belt, and hence an estimate of the degree of collisional evolution. If families provide a sample of asteroid interiors, we could estimate the fraction of differentiated precursors. A simple example of a family formed by catastrophic disruption of a differentiated precursor would be one having a large M-type (metallic) core body, perhaps some S-types from the core-mantle interface, numerous A-types from the olivine-rich mantle, and a fair number of basaltic asteroids representing the fragmented crust. As the reader can imagine from earlier discussions (of the rarity of A-types, for example), no such families have been recognized.

A serious question has been raised (e.g. by Carusi and Valsecchi) concerning the reality of the families in the published lists. While most researchers have recognized the original half-dozen families of Hirayama, there is comparatively little agreement on the smaller, less-populated families. Williams (cf. Gradie **et al.**, 1979) used a strict statistical criterion to identify more than 100 families. He believes that his calculations of proper elements are more sophisticated than earlier studies and he is not too concerned about the lack of agreement with earlier lists. I have been conducting a preliminary study of the spectral types in each of the families listed by Williams and also of the families listed by Kozai (1979), using the most extensive spectral reflectance datasets: the 24-color spectra of Chapman and Gaffey (1979) and the 8-color survey of Zellner **et al.** (1985). This work differs from the study of Gradie **et al.** not only by including the 8-color survey and by considering Kozai's families, but it employs a different criterion of comparison. Gradie **et al.** tabulated those families that seemed to be composed of asteroids having similar spectra, as would be expected for the fragments of an undifferentiated body of homogeneous composition. Only for the most populous families did Gradie **et al.** consider the question of a cosmochemically plausible heterogeneous (differentiated) precursor.

In my recent study, I have been asking the question: does the sampling of spectral types within a family differ significantly from a random sampling of spectral types **at that distance from the sun** (i.e. taking into account the variations with semi-major axis in the relative proportions of types, as determined by Gradie and Tedesco, 1982). In general, there are very few families that pass this test. Naturally, this criterion is most helpful in the inner-middle and middle of the asteroid belt (~2.3 to 2.8 AU), where the Gradie-Tedesco distribution provides reasonable frequencies of more than one distinguishable type. It is not useful, for example, in the Flora region where nearly all asteroids are S-types (which represents a continuation of the S-type trend, rather than a compositional anomaly).

Relatively few families passed the criterion of having members noticeably different from a random sampling of types. Those that did were generally the well-known, often most-populous, families such as the Eos, Koronis, and Nysa families. This result could be taken to confirm the conclusion of Carusi and Valsecchi that there is a problem concerning the reality of many of the published families. To suggest that the smaller families are "not real" may mean that the statistical tests adopted by Williams are somehow very faulty, despite his very conservative criterion of 1 chance in 3000 that a supposed family could be due to chance. It seems more likely that the statistics are correct, but that the orbital clusterings are either (a) due to some subtle problems with the calculation of proper elements or (b) due to some subtle heretofore unrecognized dynamical processes. It is well-known, for example that the Phocaea "family" is a statistically recognized cluster only because it is separated from other asteroids by some now-well-understood resonance gaps. Perhaps there is a suite of "higher order" resonances, or analogous dynamical processes, that serve to cluster genetically unrelated asteroids. If that were the case, then it would be senseless to view most families as necessarily the products of collisional disruption. If most of the families truly are of collisional origin, the findings of my preliminary study would indicate that they make little or no sense from a cosmochemical perspective, even allowing for collisional losses. Consider, for example, the prevalence of families containing roughly equal numbers of C and S objects: Whether S-types are viewed as ordinary chondrites or as stony-irons, none of the parent-body models discussed in the modern meteoritical literature would associate either material with roughly equal proportions of carbonaceous material (the universally inferred composition for C-types). A rare family of C's and S's might be ascribed to a collision between a C asteroid and a similar-sized S object, but the steep size-frequency relation of asteroids requires that such events are orders of magnitude less frequent than collisions in which the projectile contributes < 1% of the mass.

Whatever the explanation is for the apparent unreality of most asteroid families as collisional products, the existence of several real families is confirmed. Why are there not more of them? And why are there not more of the less-populated families? Perhaps the largest Hirayama families (Themis, Eos, and Koronis) represent the largest catastrophic disruptions in the history of the asteroid belt, consistent with the modest collisional evolution advocated by Davis et al. (1985). There should still have been numerous catastrophic disruptions involving somewhat smaller precursor bodies, due to the steep size-distribution of the asteroidal projectile population. But real, small families seem to be rare, even taking into account the greater difficulty in statistically recognizing them from the background. This unresolved question deserves further analysis; now that nearly twice as many asteroids have known orbits since the time Williams did his study, the time is ripe for a new study. Perhaps the existing families represent only the most recent disruptions and many older families have been dispersed by poorly understood, long-term dynamical "diffusion" processes. In that case, the small number of families need not imply modest collisional evolution but would only set a lower limit to a boundless degree of previous collisional evolution. I have some doubts that families have dispersed in this way: for example, two of the dynamically most well-defined families (Nysa and Eos) have reflectance spectra unlike essentially any other asteroids and would be recognized by spectral type even if they had substantially diffused.

CONCLUSIONS

My remarks in this paper are unsatisfying in an important respect: I have raised a variety of inconsistencies between commonly accepted perspectives on the nature of the asteroids without offering a solution to the difficulties. In short, I have not thought of a mutually consistent scenario of asteroidal evolution that can account for the inconsistencies. It is possible, of course, to selectively discount some of the evidence I have described -- and this is easy to do, because caveats and uncertainties are attached to most of the interpretations and calculations I have summarized. Nevertheless, the interpretations and calculations are the generally accepted ones -- not peculiar or unpopular "strawmen" -- so the mutual incompatibilities require serious consideration by scientists interested in the collisional evolution of asteroids. The existence of Psyche alone (if Ostro is correct that it is a metallic body) would seem at odds with the consensus of the Pisa Workshop concerning the relatively modest collisional evolution of the asteroids.

ACKNOWLEDGEMENTS

I wish to thank J. Bell, D. Davis, M. Drake, M. Gaffey, W. Hartmann, S. Ostro, G. Valsecchi, and S. Weidenschilling for discussions. This is Contribution #214 of the Planetary Science Institute, which is a division of Science Applications International Corporation. This research was supported by NASA Contracts NASW-3718 and NASW-3134.

REFERENCES

Ashwal, L.D., Warner, J.L., and Wood, C.A.: 1982, J. Geophys. Res. (Supplement) **87**, A393.

Carusi, A. and Valsecchi, G.B.: 1982, Astron. Astrophys. **115**, 327.

Chapman, C.R.: 1974, Geophys. Res. Lett. **1**, 341.

Chapman, C.R.: 1976, Geochim. Cosmochim. Acta **40**, 701.

Chapman, C.R.: 1979, The Asteroids: Nature, Interrelations, Origin, and Evolution, in Asteroids, ed. T. Gehrels, Univ. Ariz. Press, 25.

Chapman, C.R. and Gaffey, M.J.: 1979, Reflectance Spectra for 277 Asteroids, in Asteroids, ed. T. Gehrels, Univ. Ariz. Press, 655.

Cruikshank, D.P. and Hartmann, W.K.: 1984, Science **223**, 281.

Cruikshank, D.P., Tholen, D.J., Bell, J.F., Hawke, B.R., Hartmann, W.K., and Storrs, A.D.: 1985, Bull. Amer. Astron. Soc. **17**, 730.

Davis, D.R., Chapman, C.R., Weidenschilling, S.J., and Greenberg, R.: 1985, Icarus **62**, 30.

Drake, M. J.: 1979, Geochemical Evolution of the Eucrite Paren Body: Possible Nature and Evolution of Asteroid 4 Vesta?, in Asteroids, ed. T. Gehrels, Univ. Ariz. Press, 765.

Farinella, P., Paolicchi, P., and Zappala, V.: 1982, Icarus **52**, 434.

Feierberg, M.A., Larson, H.P., and Chapman, C.R.: 1982, Astrophys. J. **257**, 361.

Fernandez, J.A. and Ip, W.-H.: 1983, Icarus **54**, 377.

Gaffey, M.J.: 1984, Icarus **60**, 83.

Gaffey, M.J.: 1985, Lunar and Planet. Sci. XVI, 258.

Gaffey, M.J. and McCord, T.B.: 1979, Mineralogical and Petrological Characterizations of Asteroid Surface Materials, in Asteroids, ed. T. Gehrels, Univ. Ariz. Press, 688.

Gradie, J.C., Chapman, C.R., and Williams, J.G.: 1979, Families of Minor Planets, in Asteroids, ed. T. Gehrels, Univ. Ariz. Press, 359.

Gradie, J. and Tedesco, E.: 1982, Science **216**, 1405.

Greenberg, R. and Chapman, C.R.: 1983, Icarus 55, 455.

Kozai, Y.: 1979, The Dynamical Evolution of the Hirayama Family, in Asteroids, ed. T. Gehrels, Univ. Ariz. Press, 334.

McFadden, L.A., Gaffey, M.J., and McCord, T.B.: 1984, Icarus 59, 25.

Nehru, C.E., Prinz, M., Delaney, J.S., Dreibus, G., Palme, H., Spettel, B., and Wanke, H.: 1983, J. Geophys. Res. (Supplement) **88**, B237.

Ostro, S.J., Campbell, D.B., and Shapiro, I.I.: 1985, Science **229**, 442.

Tholen, D.J.: 1984, Asteroid Taxonomy from Cluster Analysis of Photometry, Ph.D. thesis, Univ. Ariz.

Veeder, G.J., Matson, D.L., and Tedesco, E.F.: 1983, Icarus 55, 177.

Vickery, A.M. and Melosh, H.J.: 1983, Icarus 56, 299.

Wetherill, G.W.: 1985, Meteoritics **20**, 1.

Zellner, B., Leake, M., Morrison, D., and Williams, J.G.: 1977, Geochim. Cosmochim. Acta **41**, 1759.

Zellner, B., Tholen, D.J., and Tedesco, E.F.: 1985, Icarus **61**, 355.