geb. Reihe C 6, 21 (1971); P. Hallock Muller, *Limnol. Oceanogr.* **19**, 802 (1974); J. Erez and D. Gill, *Math. Geol.* **9**, 77 (1977); C. A. Ross, in *Reefs and Related Carbonates: Ecology and Sedimentology*, S. Frost *et al.*, Eds. (Studies in Geology 4, American Association of Petroleum Geologists, Tulsa, Okla., 1977), p. 219.
4. C. A. Ross, *Proc. Int. Coral Reef Symp. 2nd* **1**, 327 (1974).
5. ———, *J. Protozool.* **19**, 181 (1972).
6. G. F. Lutze and G. Wefer, *J. Foraminiferal Res.*, in press.
7. W. H. Berger and J. S. Killingley, *Science* **197**, 563 (1977).
8. S. Epstein, R. Buchsbaum, H. A. Lowenstam, H. C. Urey, *Geol. Soc. Am. Bull.* **64**, 1315 (1953).
9. H. Craig and L. I. Gordon, in *2nd Conference, Stable Isotopes in Oceanographic Studies and Paleotemperatures*, E. Tongiorgi, Ed. (Consiglio Nazionale delle Richerche, Rome, 1965), pp. 9-130.
10. J. C. Duplessy, C. Lalou, A. C. Vinot, *Science* **168**, 250 (1970); A. C. Vinot-Bertouille and J. C. Duplessy, *Earth Planet. Sci. Lett.* **18**, 247 (1973); B. Burchardt and H. J. Hansen, *Bull. Geol. Soc. Den.* **26**, 185 (1977).
11. J. Erez, *Nature (London)* **273**, 199 (1978).
12. P. D. Blackmon and R. Todd, *J. Paleontol.* **33**, 1 (1959).
13. T. Tarutani, R. N. Clayton, T. K. Mayeda, *Geochim. Cosmochim. Acta* **33**, 987 (1969).
14. For the Philippine location, we estimate a salinity range of 0.7 per mil (based on data provided by N. Rau). The corresponding $\delta^{18}O$ range is between 0.2 and 0.3 per mil [based on data in (*9*)]. The salinity range for Bermuda was 0.7 per mil (B. v. Bodungen, personal communication), corresponding to a $\delta^{18}O$ of less than 0.2 per mil.
15. C. A. Ross and J. R. P. Ross, in *Scanning Electron Microscopy/1978*, O. Johari, Ed. (SEM, Inc., AMF O'Hare, Ill., 1978), vol. 2, pp. 53-60.
16. For information on the resorption of the test wall in a reproducing planktonic foraminifera (*Hastigerina*), see C. Hemleben, A. W. H. Bé, M. Spindler, O. R. Anderson, *J. Foraminiferal Res.* **9**, 118 (1979).
17. Data on the seawater composition were taken from the following: P. M. Kroopnick, R. F. Weiss, H. Craig, *Earth Planet. Sci. Lett.* **16**, 103 (1972); P. M. Kroopnick, S. V. Margolis, C. S. Wong, in *The Fate of Fossil Fuel CO_2 in the Oceans*, N. R. Andersen and A. Malahoff, Eds. (Plenum, New York, 1977), pp. 295-321; J.-C. Duplessy, in *Climatic Change*, J. Gribbin, Ed. (Cambridge Univ. Press, London, 1978), pp. 46-67. We calculated the $\delta^{13}C$ of $CaCO_3$ in equilibrium, using the fractionation relationship of K. Emrich, D. H. Ehhalt, and J. C. Vogel [*Earth Planet. Sci. Lett.* **8**, 363 (1970)].
18. L. S. Land, J. C. Lang, D. J. Barnes, *Geochim. Cosmochim. Acta* **41**, 169 (1977); C. Emiliani, J. H. Hudson, E. A. Shinn, R. Y. George, *Science* **202**, 627 (1978).
19. S. A. Mulcahy, J. S. Killingley, C. F. Phleger, W. H. Berger, *Oceanologica Acta* **2**, 423 (1979).
20. C. Vergnaud-Grazzini, *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **20**, 263 (1976); W. H. Berger, J. S. Killingley, E. Vincent, *Oceanologica Acta* **1**, 203 (1978).
21. G. Wefer, J. S. Killingley, G. F. Lutze, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, in press.
22. A. R. Loeblich and H. Tappan, in *Treatise on Invertebrate Paleontology, Part C, Protista 2*, R. C. Moore, Ed. (Geological Society of America and Univ. of Kansas Press, Lawrence, 1964), vols. 1 and 2.
23. R. W. Angell, *J. Foraminiferal Res.* **9**, 341 (1979).
24. H. C. Urey *et al.*, *Geol. Soc. Am. Bull.* **62**, 399 (1951).
25. J. N. Weber, P. Deines, P. H. Weber, P. A. Baker, *Geochim. Cosmochim. Acta* **40**, 31 (1976); T. J. Goreau, *Proc. R. Soc. London Ser. B* **196**, 291 (1977).
26. N. Rau, personal communication.
27. B. von Bodungen, personal communication.
28. Supported by the Deutsche Forschungsgemeinschaft (Sonderforschungsbereich 95 Contribution 260), the Deutscher Akademischer Austauschdienst, and the National Science Foundation (Ocean Sciences Division grant OCE 78-25587). We thank B. von Bodungen and N. Rau for providing unpublished environmental data for the sampling locations at Bermuda and in the Philippines. We are grateful to J. S. Killingley for assistance with the Micromass mass spectrometer and for a critical reading of the manuscript. Contribution Bermuda Biological Station No. 836.

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The Meteorite-Asteroid Connection: The Infrared Spectra of Eucrites, Shergottites, and Vesta

Abstract. *Infrared reflectance spectra have been obtained for the meteorites Shergotty and Allan Hills (ALHA) 77005, a unique achondrite apparently related to the shergottites. Comparisons with the reflectance spectra of eucrites and asteroid 4 Vesta indicate that the surface of Vesta is covered with eucrite-like basalts and that, if shergottite-like basalts are present on the surface of Vesta, they must be a minor rock type. The paradox that both the eucrite and shergottite parent bodies should presently exist is examined. The preferred solution is that both eucrites and shergottites are derived from Vesta, and that this asteroid is compositionally and isotopically heterogeneous; however, other possible solutions cannot be ruled out.*

One of the principal goals of the study of meteorites is the attempt to place the chemical and petrogenetic information obtained in an astronomical context. Thus far this endeavor has met with mixed success. Three meteorites (Pribram, Lost City, and Innisfree) for which orbits may be calculated from photographic records of their atmospheric entry (*1*) appear to have originated in the main asteroid belt, whereas some meteor showers are associated with cometary orbits (for example, the η-Aquarids and Orionids with comet P/Halley). A more direct association has been made by McCord *et al.* (*2*) between asteroid 4 Vesta and the basaltic achondrites. McCord *et al.* and other workers (*3, 4*) have noted that the visible and near-infrared reflectance spectrum of Vesta is unique among main belt asteroids of diameter greater than ~ 50 km and is closely matched by two subclasses of the basaltic achondrites, the eucrites and howardites. This development led Consolmagno and Drake (*5*) to calculate the bulk composition of the parent planet of the eucrites. These investigators concluded that the mantle of the eucrite parent planet should constitute > 90 percent of the planet and should be dominated by olivine with lesser amounts of pyroxene, plagioclase, spinel, and metal. Had the parent planet been completely disrupted, Consolmagno and Drake (*5*) concluded that we would expect to observe at least nine times as many meteorites representative of the mantle as meteorites representative of the basaltic crust (eucrites and howardites). The absence of a single meteorite with the characteristics of this mantle leads to the conclusion that the eucrite parent planet must still be intact and should be covered with basalts. Consolmagno and Drake (*5*) argued on dynamical and geochemical grounds that all major planets and their satellites, together with comets, could be eliminated from candidacy, although Drake (*6*) listed certain caveats. By default, the asteroids remain as the possible location of the eucrite parent body. As Vesta is the only large (diameter, > 50 km) asteroid with an appropriate surface composition, Consolmagno and Drake (*5*) proposed that Vesta is the source of basaltic achondrites. Certain dynamical objections to this proposition have been raised by Wetherill (*7*) and have been discussed by Hostetler and Drake (*8*).

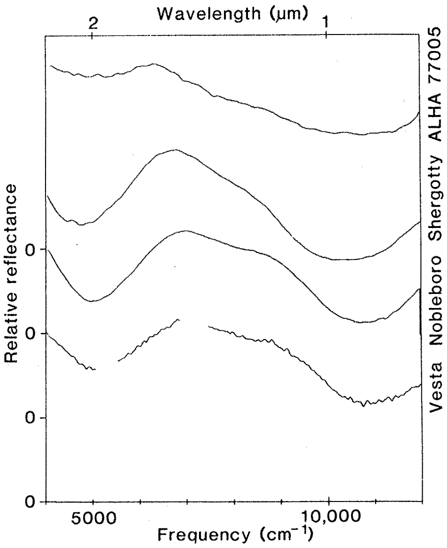

Fig. 1. Spectral reflectance of asteroid 4 Vesta and meteorites Nobleboro (a eucrite), Shergotty (a shergottite), and ALHA 77005 (a shergottite-related achondrite). All spectra were obtained with a Fourier spectrometer in the spectral range 4,000 to 12,000 cm^{-1} (0.8 to 2.5 μm) with a resolution of 25 cm^{-1}.

The eucrites are not the only type of meteoritic basalts, and it has been noted (*6, 9*) that the arguments presented by Consolmagno and Drake (*5*) in favor of Vesta as the eucrite parent body apply equally well to the shergottites. The shergottites are basaltic lavas derived by the melting of a material with different oxygen isotopic composition and volatile content from those of the eucrites (*10*). If the spectral reflectances of shergottites are indistinguishable from those of eucrites, astronomical observations of Vesta could not resolve this ambiguity. In

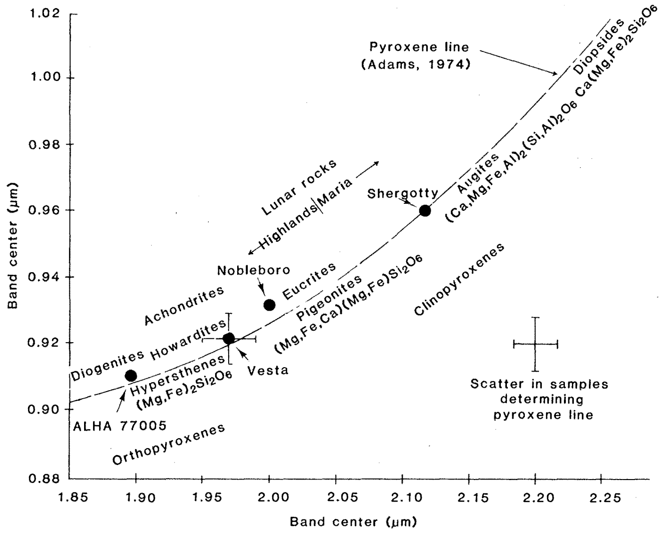

Fig. 2. The relationship of observed infrared band positions to composition for pyroxenes. The dotted line represents the trend toward longer wavelengths with increasing iron and calcium abundance as determined by Adams (*13*). Band positions determined from the spectra in Fig. 1 are closed circles.

order to resolve the candidacy of Vesta as the eucrite parent body from its candidacy as the shergottite parent body, we have carried out infrared reflectance measurements on Shergotty and on Allan Hills (ALHA) 77005, a meteorite apparently related to the shergottites (*11*).

The measurements were made with the Fourier spectrometer used by Feierberg *et al.* (*4*) in an earlier study of Vesta, eucrites, and howardites. Figure 1 presents the infrared reflectance spectrum of Vesta along with those of finely powered samples of Nobleboro (a eucrite), Shergotty, and ALHA 77005. Olivine, pyroxene and feldspar, the major mineral components of achondrites, have Fe^{2+} absorption bands in the infrared which are diagnostic of composition (*12*). All four spectra contain a pair of absorption bands centered near 0.9 and 2.0 μm, due to the presence of pyroxene. In the spectrum of ALHA 77005, the short-wavelength band is blended with an olivine absorption band centered at 1.1 μm. The spectra of Nobleboro and Shergotty each have an inflection from 1.1 to 1.4 μm due to a feldspar absorption band centered at 1.25 μm. The positions of the two pyroxene bands are known to shift to longer wavelengths with increasing iron and calcium abundances (*13*). Figure 2 shows the trend of band positions for ALHA 77005, Vesta, Nobleboro, and Shergotty. The pyroxenes on Vesta fall in the middle of the compositional range of pyroxenes in eucrites and howardites, whereas the pyroxenes in Shergotty and ALHA 77005 fall well outside this range. The band position of Shergotty is consistent with the calcium-rich composition of the Shergotty pyroxenes, and the band position of ALHA 77005 is consistent with the low-iron composition of the pyroxene in ALHA 77005.

The meteorite ALHA 77005 is probably a cumulate rock formed earlier than the shergottites from the same or a similar parent magma, although there is a lesser probability that it is a completely remelted sample of the source region from which the shergottite magmas were derived (*11*). In either case, ALHA 77005 would not be expected to have been a major constituent of the surface of its parent planet. Shergotty has the properties of a surface lava. If shergottites are present on the surface of Vesta, they must constitute a minor rock type, since tight constraints on the upper limits of spectral variation with rotation for Vesta (*4*) rule out major local concentrations of any rock types with spectral reflectances differing from those of eucrites and howardites.

We note the paradox that both the eucrite and shergottite parent planets should be extant, and that we have only one candidate (Vesta) for both at present. Several solutions to this paradox are possible.

1) The shergottite parent body is in elliptical orbit with high eccentricity, and is undetected with modern astronomical instruments because of its present large distance from the sun. Such orbits are characteristic of comets, however, and the igneous differentiation event recorded in the shergottites would be expected to vaporize cometary ices unless the comets were assembled subsequent to differentiation and disruption of the original shergottite parent planet.

2) Asteroid 349 Dembowska is the shergottite parent planet. This large, main-belt asteroid is located near a Kirkwood gap, a dynamically favorable source of meteorites (*7*). McCord and Chapman (*14*) noted that the reflectance spectrum of Dembowska is similar to that of an LL6 ordinary chondrite, but subsequent interpretations (*4*, *15*) have favored an olivine-rich achondritic composition. The reflectance spectrum of ALHA 77005 is indistinguishable from that of an LL6 ordinary chondrite. Thus the surface of Dembowska could plausibly be interpreted as the exposed mantle of the shergottite parent planet. This interpretation contradicts the argument above that the crust of the shergottite planet should still be intact, but the small number of samples and the possibility that ALHA 77005 is derived from the mantle make this argument weaker than in the case of the eucrite parent planet.

3) The shergottite parent planet is a main-belt asteroid with a diameter of less than ~ 50 km. Observations of cumulate eucrites by Walker *et al.* (*16*) indicate that the eucrite parent body was at least 20 to 200 km in diameter. If ALHA 77005 is a cumulate from the shergottite parent body, similar studies may show that it is improbable that the shergottite parent planet is small.

4) The eucrites and shergottites were produced by partial melting in, or impact melting of, a single isotopically and compositionally heterogeneous parent body. Certainly there is theoretical (*17*) and observational (*18*) evidence for the assembly of materials from different locations in the solar system in a single body. Were Vesta this body, the shergottites must comprise a minor fraction of the surface lavas. This requirement is consistent with the small number of shergottites (Shergotty, Zagami, ALHA 77005?) relative to eucrites and howardites present in our museum collections. Other asteroids can be eliminated as candidates because none have reflectance spectra characteristic of basaltic lavas.

5) The shergottites are derived from Mars. Wasson and Wetherill (*19*) and McSween *et al.* (*20*) have suggested that meteorites could be derived from Mars and that, if any meteorite came from Mars, Shergotty is the best candidate (*19*). The mechanism consists of acceleration to escape velocity as a result of the volatilization of martian permafrost. Wasson and Wetherill noted the problem that the cosmic-ray exposure age of 2×10^6 years is short in comparison with the rubidium-strontium and argon ages of $\sim 2 \times 10^8$ years, implying that the ejected mass must have had dimensions of at least 5 m and possibly as large as 100 m. It is unclear if such large masses can be ejected from Mars without being totally melted.

Our preferred solution to the paradox is that Vesta is the parent body of both the eucrites and shergottites, and that it is chemically and isotopically heterogeneous. The dynamical difficulties (7) encountered in delivering meteorites from Vesta to Earth suggest that Vesta has a low probability of being the source of these meteorites. Moreover, the young rubidium-strontium and argon ages of the shergottites are difficult to understand if they come from a small object such as Vesta, because recent internal heating is unlikely and impacts create only a small volume of total melt relative to unmelted material. However, the other solutions examined also have difficulties and appear to be even more improbable, on the basis of our current state of knowledge. At present, no meteorite group has been associated unequivocally with an existing astronomical object. Nevertheless, meteorites are samples from elsewhere in the solar system delivered to Earth at no cost. In view of the chemical similarities between Earth and shergottites, and the moon and eucrites, the plausible identification of these meteorite types with an astronomical object is an important contribution to our knowledge of the distribution of chemical composition in the solar system.

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References and Notes

1. I. Halliday, A. T. Blackwell, A. A. Griffin, *J. R. Astron. Soc. Can.* **72**, 15 (1978).
2. T. B. McCord, J. B. Adams, T. V. Johnson, *Science* **168**, 1445 (1970).
3. H. P. Larson and U. Fink, *Icarus* **26**, 420 (1975).
4. M. Feierberg, H. P. Larson, U. Fink, H. Smith, *Geochim. Cosmochim. Acta* **44**, 513 (1980).
5. G. J. Consolmagno and M. J. Drake, *ibid.* **41**, 1271 (1977).
6. M. J. Drake, in *Asteroids*, T. Gehrels, Ed. (Univ. of Arizona Press, Tucson, 1979), p. 765.
7. G. W. Wetherill, *NASA Contract. Publ. 2053* (1978), p. 17.
8. C. J. Hostetler and M. J. Drake, *Geochim. Cosmochim. Acta* **42**, 517 (1978).
9. E. Stolper, personal communication.
10. ______ and H. Y. McSween, Jr., *Geochim. Cosmochim. Acta* **43**, 1475 (1979).
11. H. Y. McSween, Jr., L. A. Taylor, E. M. Stolper, *Science* **204**, 1201 (1979).
12. M. J. Gaffey, *J. Geophys. Res.* **81**, 905 (1976).
13. J. B. Adams, *ibid.* **79**, 4829 (1974).
14. T. B. McCord and C. R. Chapman, *Astrophys. J.* **197**, 781 (1975).
15. M. J. Gaffey and T. B. McCord, *Space Sci. Rev.* **21**, 555 (1978).
16. D. Walker, E. M. Stolper, J. F. Hays, *J. Geophys. Res.* **83**, 6005 (1978).
17. G. W. Wetherill, *Proc. 7th Lunar Sci. Conf.* (1976), p. 3245.
18. R. N. Clayton and T. K. Mayeda, *Geochim. Cosmochim. Acta* **42**, 325 (1978).
19. J. T. Wasson and G. W. Wetherill, in *Asteroids*, T. Gehrels, Ed. (Univ. of Arizona Press, Tucson, 1979), p. 920.
20. H. Y. McSween, Jr., *et al.*, *Earth Planet. Sci. Lett.* **45**, 275 (1979).
21. We thank R. Clarke of the Smithsonian Institution for the loan of Shergotty, the Antarctic Meteorite Working Group for the loan of ALHA 77005, and M. J. Gaffey of the University of Hawaii for the loan of Nobleboro. Supported by NASA grants NSG 7576 and NSG 7607.

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Human Taste: Response and Taste Bud Number in Fungiform Papillae

Abstract. *The number of basic taste qualities registered by single human fungiform papillae is correlated with the number of taste buds borne on these papillae. Multiple sensitivity was demonstrated both in single fungiform papillae and in single taste buds, with response to all four of the basic taste qualities occurring in a single taste bud.*

Taste depends on an interaction between stimulus ions or molecules and receptors located in taste buds. On the mammalian tongue, taste buds are found on the circumvallate, foliate, and fungiform papillae (*1*). Fungiform papillae, because they are easily located and separated from other structures on the dorsal anterior part of the tongue, have been the most convenient experimental system for both psychophysical and electrophysiological studies of taste. Some psychophysical experiments (*2, 3*) have indicated that single fungiform papillae react to only one of the four basic taste qualities (salt, sweet, sour, and bitter), whereas others have shown that more than one taste can be identified by a single papilla (*4-9*). In addition, not all fungiform papillae can be stimulated (*6-9*). These conflicting reports have raised the questions of whether a single papilla can respond to more than one taste quality and, if so, whether the number of taste qualities recognized is related to the number of taste buds borne by that papilla, especially since taste bud numbers seem to vary more than is usually assumed (*10*).

We compared the number of taste qualities recognized with the number of taste buds present per papilla in a total of 110 fungiform papillae of 31 volunteer subjects (*11*). The volunteers ranged in age from 18 to 35 and were in good general and oral health. Before the tests began, volunteers were familiarized with the techniques involved in stimulating both a small area on the anterior part of the tongue and single papillae (*6, 8, 12*); they were also given preliminary tests for response to all of the taste solutions. Nine other potential volunteers were excluded during these preliminary tests because they reported taste sensations with both distilled and tap water or because they were unable to distinguish among the four taste qualities (or both).

The concentration of taste solutions was adequate to ensure a strong taste sensation without being painful. Analytical reagent 10 percent sodium chloride (1.7*M*), 2 percent citric acid (0.1*M*), 0.01 percent quinine hydrochloride (0.025*M*), and 40 percent sucrose (1.2*M*; commercial grade) solutions made in glass-distilled water and stored frozen were used as test solutions; distilled water was

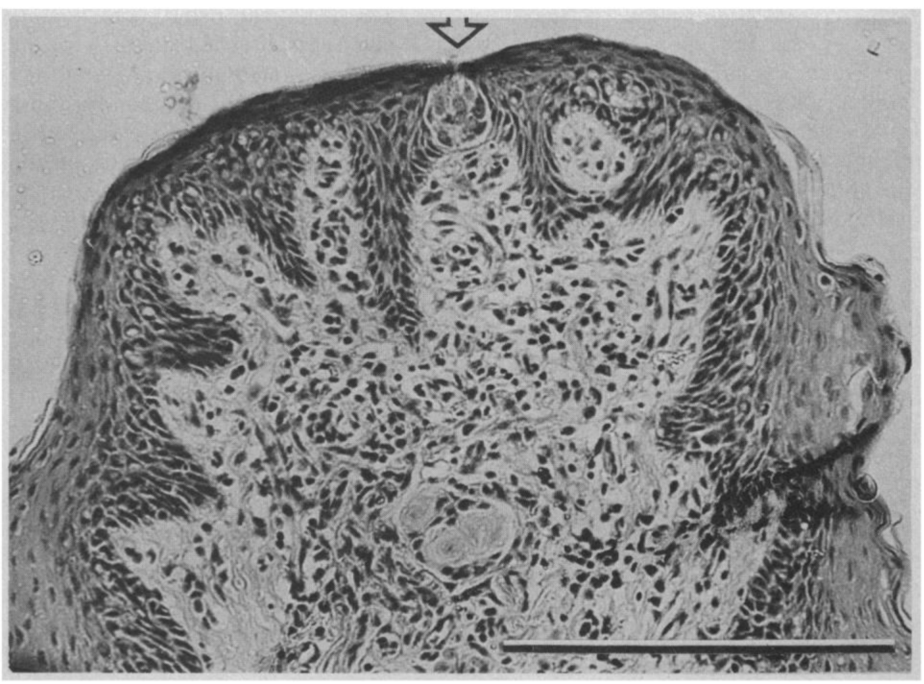

Fig. 1. Upper portion of a fungiform papilla showing a single taste bud (arrow). The bar indicates 0.25 mm.

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