Kirbyville

BASALTIC ACHONDRITES AND A

MINERALOGICAL ANALYSIS OF THE

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by
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Background to meteorite identification and classification

Meteorite identification. Numerous solid objects called meteoroids travel through the solar system. When such an object nears the Earth, gravitation often pulls the meteoroid into the atmosphere where, if it is not too small, friction heats the particle to fusion and incandescence. Glowing meteoroids falling through the atmosphere produce light streaks called meteors. Objects that are sufficiently strong and/or large enough to survive the fall and reach the Earth's surface are meteorites. Meteorites have been of scientific interest since the late 18th century, when E. F. F. Chladni, a German physicist, theorized that meteorites were fragments of interplanetary material that had fallen to the earth. Today, aside from lunar rocks, meteorites are the only concrete evidence readily available to explore the geology of the solar system.

Between 10^2 and 10^3 tons of extraterrestrial material daily reaches the Earth's atmosphere. Most of that material is fine dust, leaving about 1% as recoverable meteorites (Parkin and Tilles, 1968). Sizes range from a few grams to 66 tons. If a meteor is sighted and the meteorite is recovered, then the recovery is called a fall. If no sighting is associated with a recovery, then it is called a find. The potential to retrieve and/or identify a meteorite in the field depends on the type of meteorite.

The two broad classes of meteorites are stony, which consist of silica minerals, and iron, which contain metallic components. Among the falls that have been recovered, 97% have been stony meteorites. A roughly equal number of iron (52%) and stony (48%) meteorites have been recovered as finds (Dodd, 1981, p. 7). This phenomenon reflects differences in preservation and field recognition between stony and iron meteorites. Iron meteorites can be identified easily in the field by their unique density. Stony meteorites may be missed in the field because of their similarity with terrestrial materials. Furthermore since iron meteorites are less likely to break up as they enter the Earth's atmosphere, the larger fragments of metal are more visible in the field. Meteorites in general are most easily recovered where other rocks are rare, exposed, and the meteorites are preserved. Numerous meteorites have been recovered in Antarctica because of such conditions.

Classification of meteorites. There are two general classifications of meteorites: stony and iron. As mentioned, stony meteorites are abundant in silicate minerals and sparse in metals, whereas irons are predominantly metal. A few meteorites have significant amounts of both silicate and metal material and often are called stony-irons, however the petrogenesis and texture of these meteorites resemble either iron or stony meteorites. Most stony meteorites have a characteristic chondritic texture, discussed below. A few stony and all of the iron and stony-iron meteorites lack this texture and are designated differentiated meteorites. More commonly meteorites are classified by their mineral content.

Iron meteorites. Iron meteorites are classified on the basis of chemical content and the texture of the metal phases. Because texture is more easily determined, it is most often used to infer the chemical content. Texture in iron meteorites most reflects the nickel content of the rock (Dodd, 1981, pp. 194-98).

The common mineralogy of iron meteorites consists of kamacite, taenite, troilite, and schreibersite. Both kamacite and taenite are iron-nickel minerals that are distinguished from each other by the amount of iron and nickel present in each mineral. Kamacite is the nickel-poor phase, whereas taenite is the more nickel-rich phase. Troilite, an iron sulfide (FeS), is found commonly as large included nodules; schreibersite is an iron-nickel phosphate $(Fe, Ni)_3P$ usually found as an accessory. All of these minerals are unique to meteorites (Dodd, 1981, 198-201).

Taenite and kamacite form an exsolution phase relationship which is most obvious in the Widmannstätten structures of iron meteorites called octahedrites. Generally, octahedrites contain a nickel weight percent between 6 and 16%. Irons with less than 6% nickel are called hexahedrites, whereas ataxites are nickel-rich iron meteorites with Widmannstätten structures that can be seen only at a microscopic level (Dodd, 1981, p. 198). Pallasites are stony-iron meteorites containing 40 to 60% metal composed of magnesian olivine and nickel-iron minerals. Olivines are typically found as single crystals or crystal aggregates of millimeter to centimeter size in an iron-nickel matrix. Like the octahedrites, pallasites usually show Widmannstätten structures, thus representing an intermediate class between iron meteorites and stony chondrites (Dodd, 1981, p. 213).

Stony meteorites: chondrites. Stony meteorites are the most abundant of the meteorites, and the most common type of stony meteorite is the chondrite. Analysis has revealed that chondrites are chemically similar to the sun without its hydrogen, helium, and volatiles. They have a characteristic texture consisting of an agglomeration of ovoid to spherical silicate masses up to a millimeter in size called chondrules. Stony meteorites that lack these chondrules are called achondrites. The chondrules, set in a fine-grained matrix, have a mineralogy and texture that infer crystallization from a molten droplet state and are composed mostly of olivine, pyroxene, and glass. The origin of chondrules is uncertain, though several hypotheses have been proposed to explain their origin. One suggests that nebular gases condensed through overpressure (Wood, 1963), subcooling (Blander and Katz, 1967), dust enrichment (Wood and McSween, 1977), or H_2 depletion (Herndon and Seuss, 1977). Another hypothesizes fusion of nebular dust particles through lightning (Whipple, 1966), impact (Whipple, 1972), or atmospheric heating (Podolak and Cameron, 1974). A third explains the formation as the impacting of rock fragments with other meteoroids (Dodd and Walter, 1972).

Both chondrites and achondrites often exhibit evidence of brecciation. This is thought to occur from internal disruptive or gravitational mixing within the parent body, or "due to collisions, aggregation together, or shock deformation after the separation of discrete individual meteoroids from the parent body." (McCall, 1973, p. 173) Such brecciation is noted to have an effect on the mineral phases and chemical composition of the meteorite. Stony meteorites that contain fragments of different chemical groups (multiple source liquids) are called polymict, whereas breccias composed of fragments of one chemical type are called monomict.

Achondrites. Stony meteorites containing no evidence of chondrules, called achondrites, typically have igneous textures and mafic mineralogy. Achondrites can be subdivided into associated and unassociated classes. Associated achondrites include eucrites, diogenites, howardites, and mesosiderites, all of which are chemically related and which possibly came from a similar parent body through fractional crystallizaton. The unassociated achondrites, including shergottites, nakhlites, chassignites, and ureilites, cannot be related to other meteorite groups or to each other. One piece of evidence for their unrelatedness is their wide range in ages, ranging from 164 my to 4.55 by. The first three are often found with cumulate textures.

The associated achondrites--eucrites, diogenites, howardites, and mesosiderites--show evidence of similar magmatic origin. This evidence includes serial chemical variations shown in Fig. 1. Eucrites are the more aluminum-rich members, whereas diogenites are aluminum-poor. Howardites fall between these two extremes. Mesosiderites are chemically similar to howardites, though they also contain more metal and thus do not lie on the diagram.

Eucrites are pyroxene-plagioclase achondrites resembling terrestrial basalts. Characteristics that can be found in some of the almost 30 known eucrites (Dodd, 1981, p. 239) are preferred crystal orientations and exsolution textures in the pyroxenes suggesting slow cooling. Achondrites with these features and mineralogy are called <u>cumulate eucrites</u>. <u>Noncumulate eucrites</u> usually show ophitic or subophitic textures. Most noncumulate eucrites are brecciated and monomict in composition.

The mineralogy of eucrites consists of roughly equal amounts of plagioclase (An_{85-95}) and orthopyroxene (inverted pigeonite). In noncumulate eucrites the amount of pyroxene is greater than plagioclase. Eucrites also contain tridymite and accessory phases of troilite, ilmenite, chromite, nickel-poor metal, and phosphates.

Howardites most closely resemble eucrites because of the predominance of plagioclase and pyroxene, but the polymict chemistry of howardites defines the distinction. This polymict chemistry can be seen best in the pyroxene compositions; eucrites contain differentiated, slightly iron-rich pyroxenes, whereas howardites contain clasts of magnesium-rich orthopyroxenes found in diogenites and the more iron-rich variety found in eucrites (Fig. 2). Additionally, howardites, of which roughly 20 are known to exist (Dodd, 1981, p. 249), show a variety of textures caused by reheating and shock metamorphism.

Though a few contain olivine, diogenites are predominantly orthopyroxene

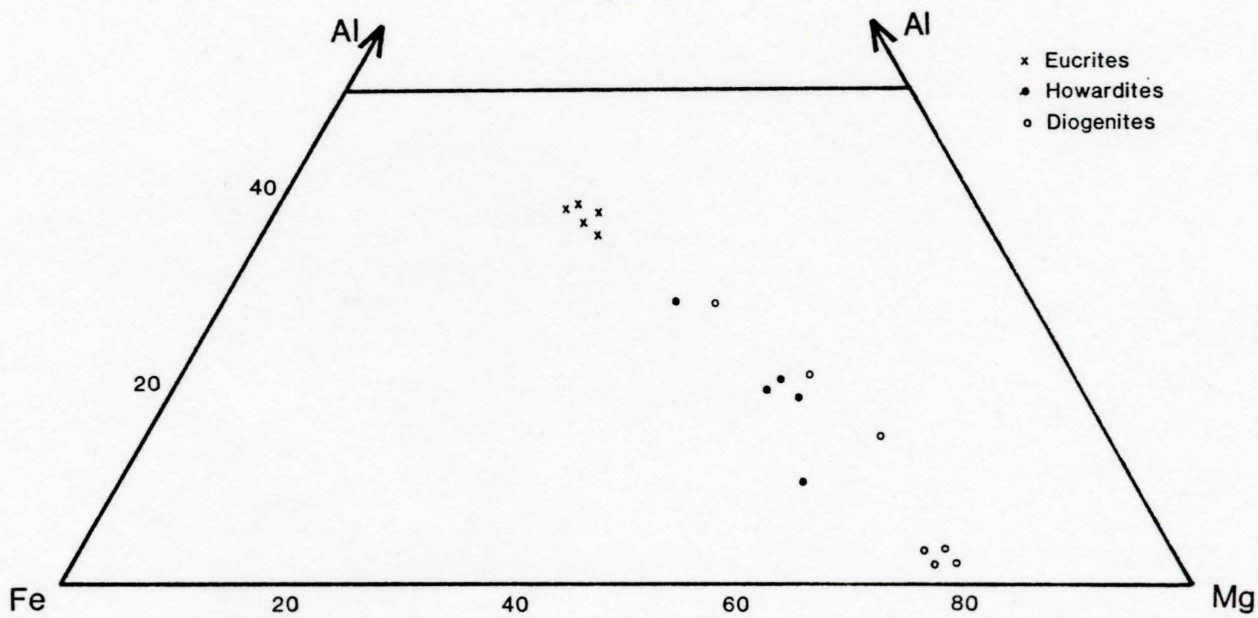

Fig. 1: Distribution of Fe, Mg, and Al components in eucrite-associated achondrites. (modified from Dodd, 1981)

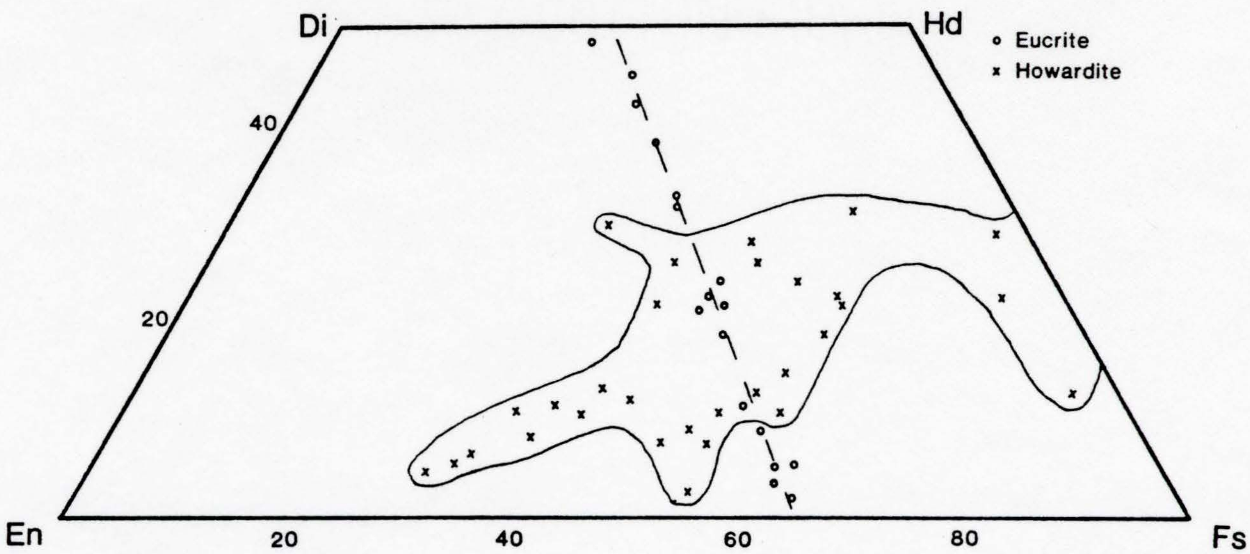

Fig. 2: Pyroxene compositions for the Jonzac eucrite and the Nobleborough howardite. The eucrite pyroxenes trend along a line, indicating a monomict petrogenesis, whereas the howardite pyroxenes fall into a broad field. (modified from Mason et al., 1979)

achondrites with small amounts of plagioclase and chromite as well as trace quantities of ilmenite and phosphate, suggesting that cumulate pyroxenites are the terrestrial analog to these meteorites. About 12 diogenites are known to exist, and, like eucrites, they also show monomict brecciation (Dodd, 1981, pp. 244-245). Mesosiderites contain a mixture of both eucritic and diogenitic material, but with additional clasts of chondritic material and a metal matrix.

The Kirbyville eucrite

Background. The Kirbyville meteorite fell on November 12, 1906 in Jasper County, Texas. The approximate coordinates of the site are 30°48'N, 93°56'W. Mr. Oscar Monnig obtained the only known specimen of the fall in 1934. Originally the specimen weighed 97.7 g, but subsequent chemical analysis and probe work has removed material, making the current weight 94.6 g.

The Kirbyville meteorite has been mentioned as a eucrite in several papers, including Mason et al. (1979), and Heymann et al. (1968). Heymann, et al. dated the Kirbyville, assigning a K/Ar age of 3.2 by. The K/Ar age range among the known eucrites is 2.4 to 4.4 by. The authors also used U/He dating, finding an age of 4.5 by on the Kirbyville. The radiation age of 14.9 my that they calculated is young relative to the average radiation age of 20.6 my for known eucrites. The lithology of the Kirbyville meteorite, however, has never been described.

Specimen description. The single known specimen (Fig. 3) vaguely forms a truncated pyramid about 3.5 cm high with regmaglypts forming a base 4x4 cm. The truncated surface is slightly concave, rectangular in shape measuring about 2.5x2.5 cm., and is marked by small pits. Radial melt lines originate from a small central knob at the base, where the fusion crust is thinnest, and flow over the sides toward the truncated top, where the crust

Fig. 3: The only known specimen of the Kirbyville eucrite. The base of the "pyramid" is toward the bottom of the page, and the truncated top contains the specimen number. The melt lines on the surface are observable on the fusion crust, front side. The scale above the specimen is in centimeters.

is thickest. This suggests that the base was facing forward in flight, with the top toward the rear. Two sides, the truncated top, and the base of the pyramid are roughly perpendicular to each other. The other sides join as a gentle curve, forming an obtuse angle with the truncated top. The fusion crust and some of the meteorite is absent along two edges of the base, perhaps removed during its fall through the atmosphere. Material was removed from one corner of the pyramid for sections used for the electron microprobe analyses.

Under a binocular microscope at 15x magnification, cracking in the fusion crust is visible. This likely resulted from cooling of the crust after atmospheric entry and before impact. Numerous yellowish to brown globules show through the crust, which are probably chemically altered material from fusion melting. The freshly exposed surface at the corner of the pyramid is generally gray in color. That exposure, which was cut flat for thin sections, readily shows distinct clasts and fracture lines.

Inspection of the probe section using a petrographic microscope revealed much evidence for brecciation: fractures, clast outlines, undulatory extinction in the plagioclase, and warping of the polysynthetic twins in the plagioclase and pyroxene. Clast sizes range from 1-8 mm. Subophitic textures of both fine and coarse grains are easily visible as a characteristic of distinct clasts. The coarser-grained subophitic texture has euhedral plagioclase lathes up to 5 microns long, whereas the finer-grained textures have up to one micron lathes (Fig. 4). The interstices are filled with pyroxene crystals that are optically continuous in discrete regions. Clasts with brecciated textures contain subhedral plagioclase and pyroxene up to 4 microns in size in a fine matrix of grains of the same minerals.

Mineralogy, petrography, and chemical composition. Electron microprobe analyses were made on the pyroxenes, plagioclase, and opaque minerals

A

B

C

Fig. 4: Photomicrographs of Kirbyville under cross-polarized light. A) subophitic texture; B) brecciate texture; C) impact fractures crossing the length of the photo. Bottom edge = 3.5 mm on all photos.

in polished thin sections using an ARL EMX-SM set at 15 kev and with a 20 nA sample current. The appendix has a few representative points taken with the microprobe. From the best 20 of 80 readings, the pyroxenes had a compositional range of Wo_{2-41}, Fs_{27-61}, and En_{30-40} with most of the points centered around Wo_{8}, Fs_{56}, and En_{36}. The Wo and Fs tended to vary inversely, but the En was consistant, indicating equilibrium crystallization of inverted pigeonite (Fig. 5). The pyroxene compositions transgressed into the immiscibility field in the center of the diagram. The reason that points are more evenly across the line of compositional trend is probably due to a moderate to rapid cooling rate. This did not allow the parent liquid to fractionate pyroxenes into strictly calcium-rich and calcium-poor end members. The plagioclase composition had a range of An_{86-92} with an average of An_{89}. No significant compositional variations were noted between different grains of the same mineral. Point counts showed that the meteorite consisted of approximately 3.5% opaque minerals with a predominance of ilmenite, some magnetite, and one grain of chromite. A small quantity of tridymite was also found.

Mason et al. (1979) conducted a bulk chemical analysis on a sample of the Kirbyville. Their results by weight percent were: SiO_2 49.8, TiO_2 0.67, Al_2O_3 11.9, Cr_2O_3 0.40, FeO 18.7, MnO 0.54, MgO 6.96, CaO 10.0, Na_2O 0.45. They calculated the weight percentages of the normative minerals plagioclase, 49.1; pyroxene, 44.0; tridymite, 4.0; other, 2.8. Mineralogical and textural evidence indicates that the Kirbyville is a monomict eucrite, which confirms the conclusion of Mason, et al. (1979).

Other eucrites. According to Fig. 6 Kirbyville contains slightly more iron-rich pyroxenes than most other eucrites. The pyroxene compositional trend of Kirbyville is similar to the Jonzac and Juvinas eucrites (Juvinas is virtually identical in composition to Jonzac). Jonzac has a composition-

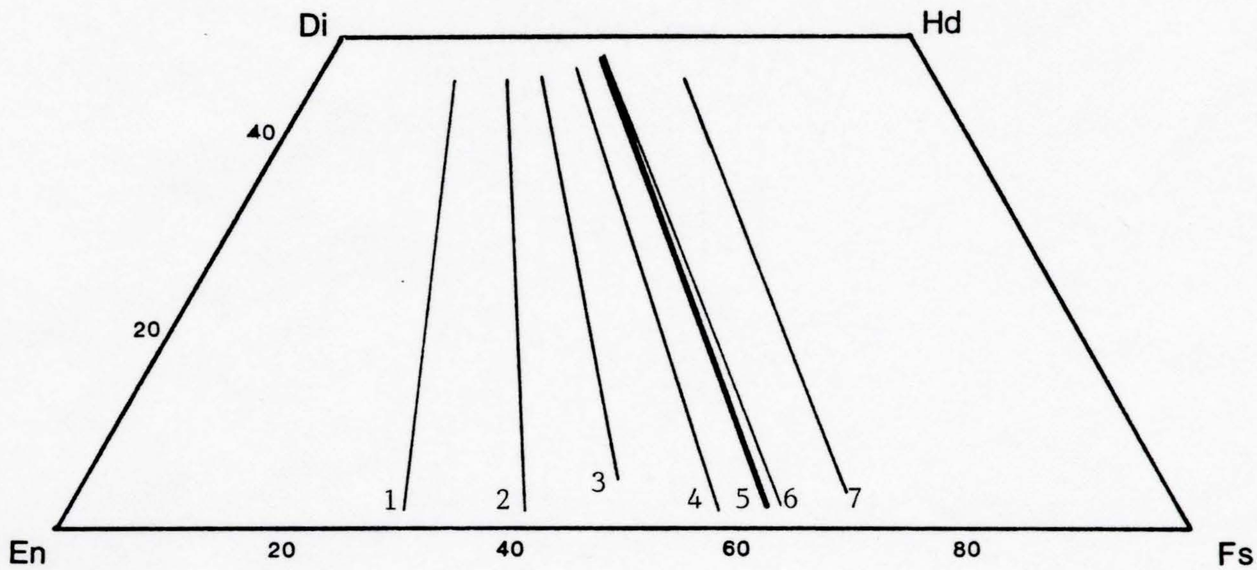

Fig. 6: Composition lines for the pyroxenes in several eucrites: 1) Binda, 2) Moama, 3) Moore County, 4) Ibitira, 5) Kirbyville, 6) Jonzac, 7) Lakangon. (modified from Mason et al., 1979)

al range of Wo_{2-47}, Fs_{24-65}, and En_{29-34} for pyroxenes and An_{83-93} for the plagioclase (Mason et al., 1979). Juvinas has ranges of Wo_{2-38}, Fs_{32-68}, and En_{31-45} for its pyroxenes (Duke & Silver, 1967). The differences in the compositional trends of the eucrites is discussed in the following section on the formation of eucrites. The plagioclase composition of Kirbyville is virtually identical with those found in other eucrites.

Evolution of eucrites

Parent liquid. In an earlier section it was suggested that diogenites, eucrites, howardites, and mesosiderites are related by fractional crystallization. Howardites and mesosiderites are considered mixtures of diogenitic and eucritic material (Jérome and Goles, 1971), whereas diogenites and eucrites are derived from magmatic processes (Dodd, 1981, p. 262). The problem then is to determine the petrogenetic relationships among these achondrites, the origin of the liquid from which these meteorites crystallized, and the nature of the eucrite parent body.

Prior to the availability of lunar rocks, it was thought that these basaltic achondrites had a lunar surface source (Duke and Silver, 1967). Later, differences in oxygen isotope composition, in REE, and in ages between the meteorites and lunar basalts dispelled that theory. Workers have developed two other theories for the formation of the associated achondrites. One depicts a magma more magnesian than eucrites as a primary liquid from which the differentiated meteorites came (Mason, 1962). In this model the magnesian pyroxenes found in diogenites crystallized from this magma. Noncumulate eucrites formed from the remaining residual liquid. This assumes diogenites and eucrites to be differentiated so strongly that their compositions tell little of the source region and the primary magma. The model considers the parent magma to have a composition at P in Fig. 7. As the

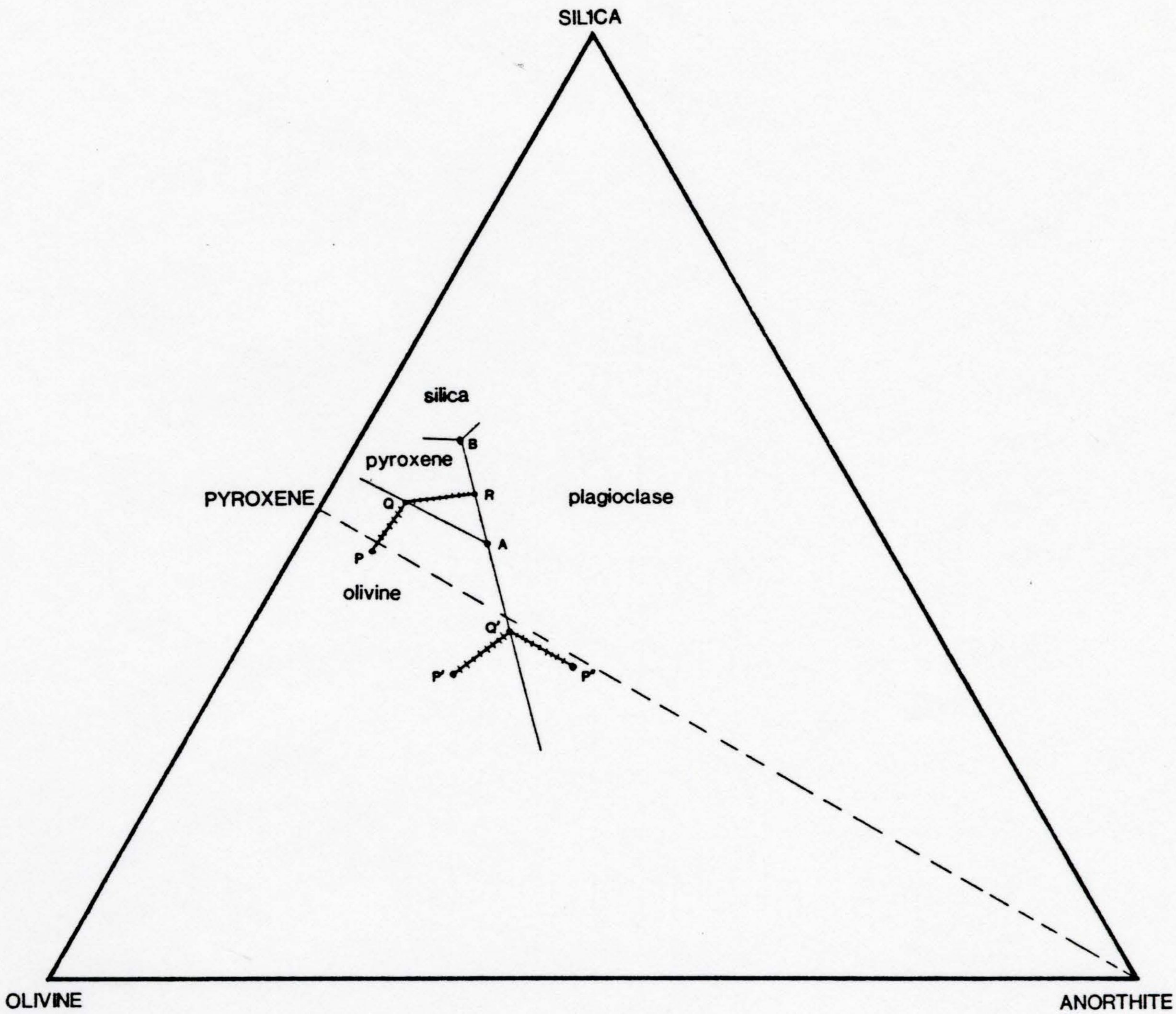

Fig. 7: A part (in molar proportions) of the ternary system silica-olivine-anorthite. (modified from Stolper, 1977)

liquid cools, it moves toward Q and olivine crystallizes. With continued falling temperatures and the removal of crystallized olivine, the magma moves toward R, and pyroxene crystallizes. The magnesian-rich minerals of diogenites form along the P-Q-R path whereas eucritic material forms along the Q-R-B path.

The other theory, explained in detail by Stolper (1977), pictures eucrites as representing the primary magmas. To arrive at his conclusions, Stolper melted and crystallized samples of noncumulate eucrites at low pressures (one atmosphere). At low oxygen fugacities he observed that four or five crystalline phases at temperatures close to their liquidi were at saturation in the noncumulate eucritic liquids: ±olivine-Fo_{65}, pigeonite-Wo_5En_{65}, plagioclase-An_{94}, Cr-rich spinel, and metal. The compositions of the meteorites plotted around point A in Fig. 7. Stolper's analysis showed that fractionating the saturating phases as Mason had done was not a plausible explanation, because most eucrites fall near point A (Fig. 7) which is not on Mason's crystallization path. Stolper's explanation was the crystallization of noncumulate eucrites from liquids generated by the limited partial melting of source material plotting near point Q' on Fig. 7. Variable degrees of partial melting may explain the differences in the abundances of minor- and trace-elements in eucrites. Differing degrees of partial melting also account for the variations in the pyroxene content in the meteorites diagrammed in Fig. 6. This model suggests cumulate eucrites are the compositional complement to noncumulate eucrites rather than diogenites, as is the case with Mason's (1962) model. Stolper demonstrated that magnesian liquids could be produced by exhausting the source material of plagioclase and then melting it further. Such liquids would be able to crystallize pyroxenes found in diogenites. Slow crystallization of the same liquids could also form cumulate eucrites.

Source body. Removal of magnesian liquids would leave concentrations of olivine, spinel, and metal in the source, the three minerals likely to be found in pallasites. Such speculation suggests that pallasites and eucrites come from the same parent body, with pallasites forming the core regions, olivine-metal minerals from the mantle, and associated achondrites from the surface. In such and extended model, olivine-rich eucrites would be expected. Because such meteorites are in very small abundance, Consolmagno and Drake (1977) concluded that the source body for eucrites is still intact. The pallasites that are available are thought to have come from a different body, leaving associated achondrites as the only physical evidence of the parent body.

The fact that eucrites crystallized in a low-volatile environment led Consolmagno and Drake (1977) to eliminate most of the planets, their moons, and comets from consideration, leaving asteroids as the probable parent. Studies of asteroids have narrowed the field of candidates to 4 Vesta which has the adequate density for such a model, is of sufficient size (radius of 25 km) to permit partial melting, and has an adequate composition based on infrared photometric studies.

Conclusions

The Kirbyville meteorite is similar to other known noncumulate, brecciated, monomict eucrites. The pyroxenes had a compositional range of Wo_{2-41}, Fs_{27-61}, and En_{30-40}, and the plagioclase had a range of An_{86-92}. Tridymite was also present, as were accessory ilmenite, magnetite, and chromite. Subophitic and brecciated textures were recognized within distinct clasts. With such a composition it is not anomalous to existing theories on the origin of eucrites.

APPENDIX

	1	2	3	4	5	6	7	8
SiO_2	49.63	49.68	49.54	49.47	48.01	48.56	48.98	49.52
TiO_2	0.05	0.17	0.15	0.30	4.86	0.34	0.24	0.33
Al_2O_3	0.00	0.05	0.07	0.00	0.21	0.22	0.02	0.09
Cr_2O_3	0.16	0.15	0.16	0.11	0.16	1.37	0.41	0.72
FeO	35.81	35.70	34.28	34.12	17.98	35.02	35.79	31.66
MnO	0.93	1.07	0.81	1.00	0.42	0.94	1.09	0.95
MgO	11.93	12.43	12.38	11.71	10.04	11.83	11.43	11.57
CaO	1.13	0.91	2.71	3.42	19.73	0.97	3.79	6.49
Total	101.42	99.26	99.67	101.75	101.35	100.19	100.12	100.13
Wo	41.3	2.2	2.5	8.0	13.7	2.0	5.8	7.4
Fs	29.4	61.1	61.2	58.7	52.2	60.5	57.3	57.5
En	29.3	36.8	36.3	33.4	34.0	37.5	36.9	35.1

Representative compositions of pyroxenes in the Kirbyville eucrite based on points taken from the electron microprobe. The numbers are weight percentages.

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