

# Moore County

Unbrecciated Cumulate Eucrite, 1.88 kg

*Seen to fall*

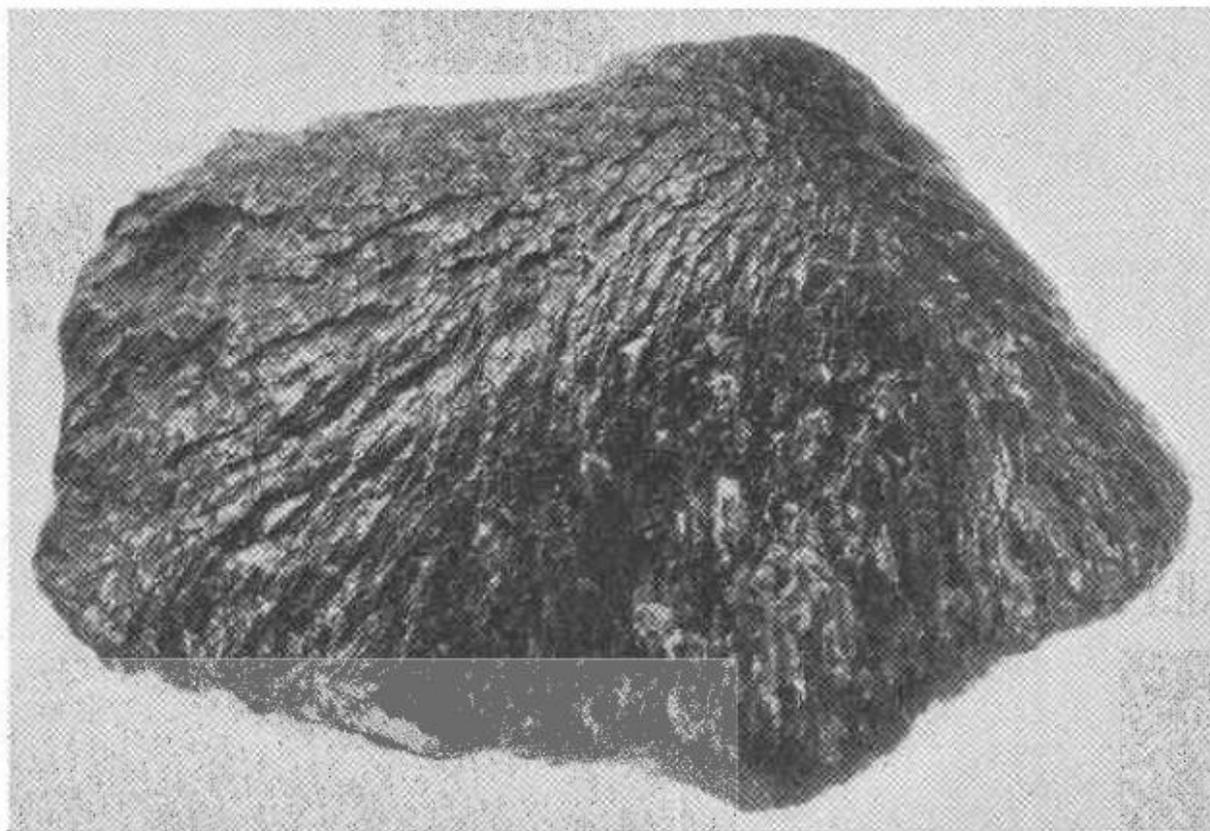


**Figure 1a:** The Moore County eucrite (fusion crust on left), from the collection of the North Carolina Museum of Natural Sciences. Scale from top to bottom of sample is ~ 5 cm. Photo courtesy of Chris Tacker.

**Introduction:** The Moore County meteorite (**Figures 1a,b,c**) fell at 5:00 PM on April 21, 1913, on the farm of George C. Graves, located approximately three miles east of Carthage, Moore County, North Carolina (79°23'W, 35°25'N) (Henderson and Davis, 1936). A loud “rumbling and zooming” noise “with no distinct explosions” was first observed within a five or six mile radius of the fall, followed by a sighting of a red hot ball with a 15-foot trail of blue-black smoke; the meteorite itself landed within a few feet of a farmer, in a nearly-vertical (but slightly SW-sloping) hole in a freshly-plowed field (Henderson and Davis, 1936). Only one stone was recovered (**Figure 1b**), weighing approximately 1.88 kg (4 lbs. 2 oz.), with maximum dimensions approximately 15 cm x 10.5 cm x 8 cm (6 in x 4 3/16 in x 3 3/16 in) (Henderson and Davis, 1936). This stone was divided between the US National Museum (Smithsonian) in Washington, D.C., and the North Carolina State Museum in Raleigh, now the North Carolina Museum of Natural Sciences (Henderson and Davis, 1936), where the main fractions of the stone are still kept (0.9 kg at the USNM and ~0.56 kg at the NC Museum: Grady, 2000; Tacker, pers. comm.).

Moore County is a flattened, conical-shaped (“shield”) meteorite with a dark brown, glossy fusion crust, well-developed flow lines and up to 4-mm deep regmaglypts. The fusion crust is <1 mm on the front face, which is transparent enough to observe the color of component minerals (Henderson and Davis, 1936). The fusion crust on the rear face is opaque, vesicular, and approximately twice as thick, but the crust is thickest near the rim of the rear face, just under the sloped front edges, in a 5 mm thick section about 1.5 cm wide (Henderson and Davis, 1936). An analysis of cosmic-ray track densities in Moore County revealed a likely pre-atmospheric spherical radius of >7 cm and a geocentric velocity of  $\geq 6$  km/sec (Carver and Anders, 1976).

Moore County is an unbrecciated cumulate eucrite, composed mostly of equigranular, uniformly-distributed, coarse-grained plagioclase and pyroxene. It is texturally and chemically similar to terrestrial cumulates, including evidence of crystal accumulation at the bottom of a magma chamber (Hess and Henderson, 1949). Chemically, it is more magnesian than non-cumulate eucrites, but it is the most iron-rich cumulate eucrite.



**Figure 1b:** The Moore County meteorite. This view is of the forward face with clear regmaglypts and flow lines. No scale is given for the photo, but maximum dimensions (at right angles) were reported as 15 cm x 10.5 cm x 8 cm (6 in x 4 3/16 in x 3 3/16 in). From Henderson and Davis (1936).

**General Petrography:** The Moore County eucrite was first described by Henderson and Davis (1936), followed by Hess and Henderson (1949). These sources contain significant and detailed petrographic descriptions, as well as whole-rock and mineral chemistry data, and provide a good basic overview of the meteorite.

Moore County is an unbrecciated, coarse-grained, equigranular to subophitic orthocumulate (Hsu and Crozaz, 1997) eucrite, consisting almost entirely of 0.5-1.5 mm, white to gray, subhedral to euhedral



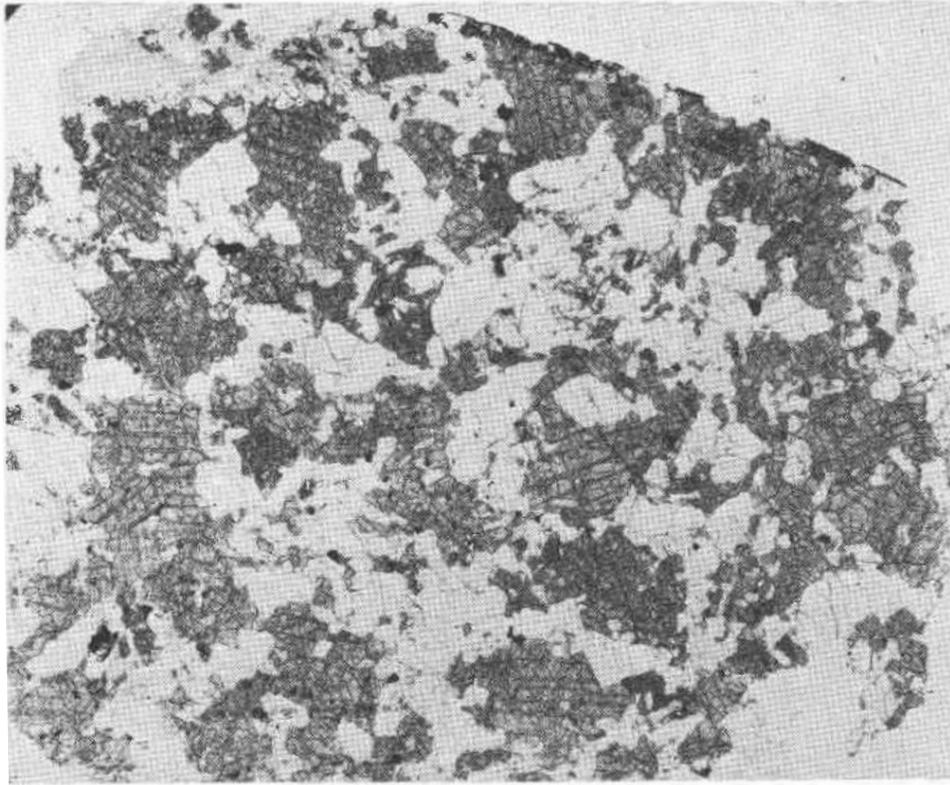
**Figure 1c:** Two different views of the Moore County eucrite (exterior – top, interior – left), from the collection of the North Carolina Museum of Natural Sciences. All photos courtesy of Chris Tacker at the NC Museum.

laths of calcic plagioclase and 0.2-6 mm, brown-yellow, subhedral to euhedral crystals of ortho- and clinopyroxene (which also occur as inclusions and exsolution lamellae) uniformly distributed throughout the rock (Henderson and Davis, 1936; Hess and Henderson, 1949; Nord, 1983). Plagioclase is often included in pyroxene (Nord, 1983; Mittlefehldt, 1990) but pyroxene is never included in plagioclase (Nord, 1983). Henderson and Davis (1936) reported both plagioclase and pyroxene grains with well-developed cleavage faces; however, Hess and Henderson (1949) reported cleavage in pyroxene but not plagioclase.

Tridymite is present as large, anhedral, interstitial grains; primary plagioclase and pyroxene grains abutting these large tridymite crystals have well-formed crystal faces, consistent with late tridymite formation from an intercumulus liquid trapped in pore spaces during crystal settling (Hess and Henderson, 1949; Nord, 1983, Mittlefehldt, 1990).

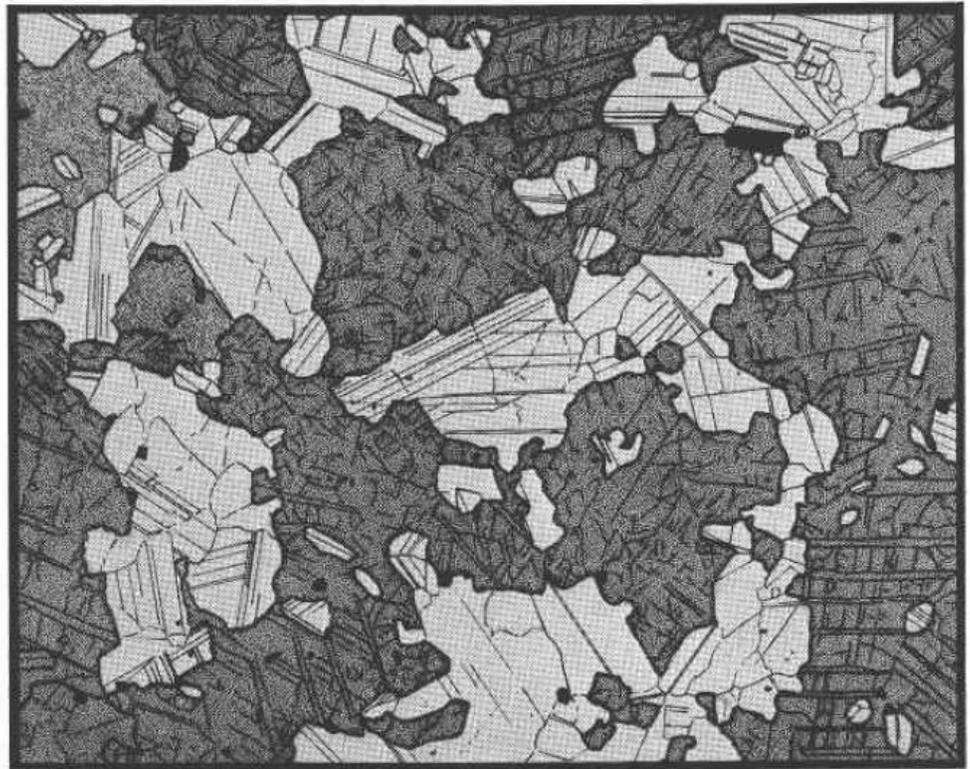
**Figure 2** shows a thin section photograph, and **Figure 3** shows a drawing made from the same photo; both show basic textural and mineralogical relationships.

Other accessory minerals in Moore County include opaques (ilmenite, chromite, troilite), and apatite, with some evidence of free metal; most of these minerals occur as interstitial grains (Hess and Henderson, 1949; Hostetler and Drake, 1978; Nord, 1983) and as inclusions in pyroxene or plagioclase (Henderson and Davis, 1936; Hess and Henderson, 1949; Hostetler and Drake, 1978). All component minerals are only loosely held together (i.e., weak intergranular bonding), and they can be easily separated by lightly rubbing a fresh surface of the rock, which complicated initial attempts to obtain a thin section (Henderson and Davis, 1936).



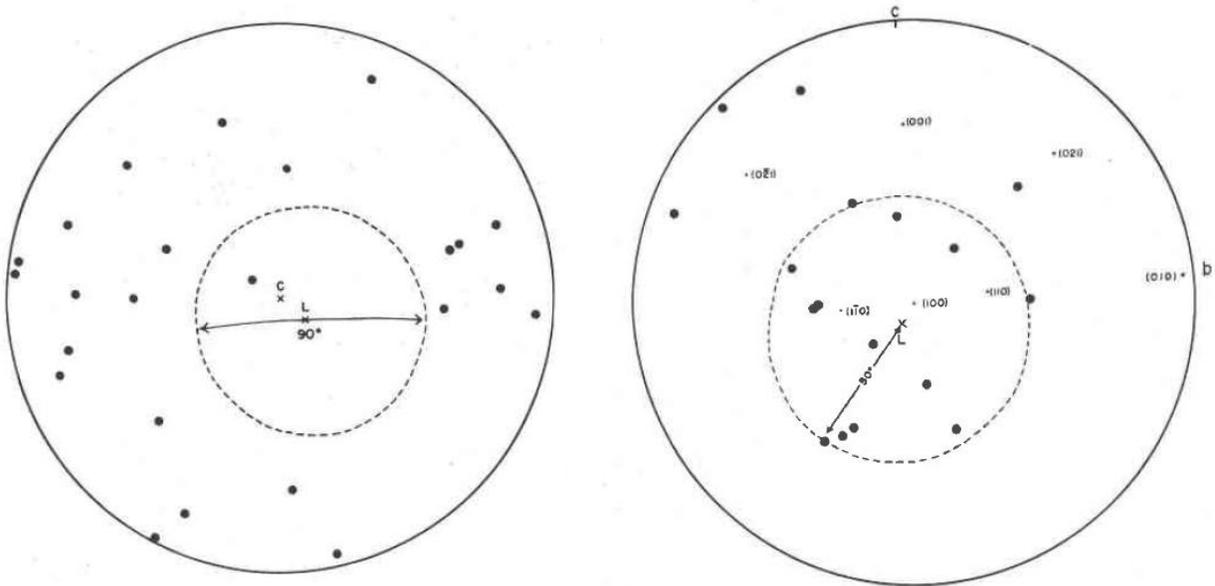
**Figure 2:** Thin section photomicrograph of Moore County, with dark pyroxenes, light plagioclase, and scattered opaques (tridymite is present as a dark gray interstitial phase but very hard to discern from pyroxene). Augite lamellae are parallel to (001) in pyroxenes. A 0.2 mm-thick fusion crust with small bubbles can also be seen in the upper right hand corner. From Hess and Henderson (1949). No scale given.

**Figure 3:** Drawing of a portion of a Moore County thin section, traced from the photograph in Figure 2, above. White = plagioclase, dotted gray = pyroxene (with (001) augite lamellae), black = opaque (mostly along boundaries between plagioclase and pyroxene). The gray areas in the upper left corner are interstitial tridymite. From Hess and Henderson (1949). The long dimension of the drawing is 1.2 centimeters.



Nord (1983) reported a 1-mm thick fine-grained zone of pyroxene and plagioclase traversing their entire thin section, with 0.2-0.5 mm crystals and a more granoblastic texture; this zone was found to be in optical continuity with the rest of the thin section, strongly suggesting its origin as a primary crystallization feature, possibly as a “nucleation burst” similar to those found in terrestrial cumulates.

Moore County has a noticeable and quantifiable fabric, as the c-axes of primary pyroxene grains are in the same plane as the longer axes (b and c) of the plagioclase, resulting in a planar orientation for these crystals (Hess and Henderson, 1949; **Figure 4**). These observations are characteristic of plutonic cumulates, where crystals accumulate in nearly horizontal layers along the floor of the magma chamber, and thus these textures in Moore County indicate magmatic differentiation and crystal settling in an extraterrestrial setting (Hess and Henderson, 1949).



**Figure 4:** Stereographs of pyroxene c-axes with respect to the plane of the thin section (left) and poles of the thin section with respect to plagioclase crystallographic axes (right). In the left diagram, C represents the center of the graph and is perpendicular to the thin section. In both cases, L represents the pole to the supposed plane of layering in Moore County. From Hess and Henderson (1949).

**Table 1** shows normative and modal mineralogy for Moore County. There is significant variability between the amounts of plagioclase and pyroxene in a number of the modes, and this is likely due to local heterogeneities within the meteorite, as well as the small areas counted by different authors for reported modes. Like the other cumulate eucrites, SiO<sub>2</sub> contents in Moore County require an olivine-normative calculation, even though there is no olivine actually present (Mason et al, 1977).

**Pyroxene:** Three different varieties of pyroxene (hypersthene and two pigeonites) were initially reported from mineral separates for Moore County; an exhaustive discussion of these pyroxenes can be found in Henderson and Davis (1936). More recent analyses have clarified at least four types with distinctly

different chemical compositions (Hess and Henderson, 1949; Hostetler and Drake, 1978) and some researchers have reported even more (Mori and Takeda, 1981b).

**Table 1: Modal and normative mineralogy of Moore County.**

Reference	Hess and Henderson 49		Prinz et al 80	Nord 83	Delaney et al 84e	Kitts and Ladders 98		Mayne et al 09
	norm	mode	mode	mode	mode	norm, wt %	norm, vol %	mode
Pyroxene	50.13	56	36.7	37.4	36.7	54.8	49.7	52
Plagioclase	44.54	40	58.5	55	61.1	41.8	48.5	44
Ilmenite	0.61	--	0.2	0.2	0.2	0.7	0.5	--
Chromite	0.67	--	0.5	0.2	0.4	0.6	0.4	--
Tridymite	1.68	1.5	4.1	7.2	1	0.7	0.8	3
Troilite	0.46	--	--	trace	0.6	--	--	--
Apatite	--	trace	--	--	--	0.1	0.1	--
Metal	2.78	--	--	--	--	--	--	--

### Mineral Petrography and Chemistry:

The main pyroxene phase in Moore County is pigeonite (Henderson and Davis, 1936; Hess and Henderson, 1949), with chemical compositions clustered around  $\text{Ca}_6\text{Mg}_{47}\text{Fe}_{47}$  and exhibiting an average Mg# of 51 (Hess and Henderson, 1949; Ishii and Takeda, 1974; Hostetler and Drake, 1978; Mori and Takeda, 1981b; Nord, 1983; Mittlefehldt, 1990; Mayne et al, 2009). These pigeonites have well-developed, coarse (25-100  $\mu\text{m}$ ) augite lamellae, with composition  $\text{Ca}_{41.5}\text{Mg}_{36.8}\text{Fe}_{21.7} - \text{Ca}_{43}\text{Mg}_{36}\text{Fe}_{21}$ , parallel to (001) planes in the host pigeonite (Hess and Henderson, 1949; Ishii and Takeda, 1974; Miyamoto and Takeda, 1977; Takeda, 1979; Takeda et al, 1981; Mori et al, 1981; Mori and Takeda, 1981b; Mayne et al, 2009; **Figure 5**). There are also finer ( $\leq 0.3 \mu\text{m}$ ) lamellae of (001) augite, present between the coarse lamellae, with higher Ca and Mg contents (Takeda, 1973; Takeda, 1979; Takeda et al, 1981; Mori et al, 1981; Mori and Takeda, 1981b); these fine augite lamellae share a common c-axis with the host pigeonite, but the coarser augite lamellae are rotated approximately  $1.5^\circ$  towards the  $a^*$ -axis from  $c^*$  (Takeda, 1973). There is also twinning and cleavage within pigeonite (Takeda et al, 1983; **Figure 5**).

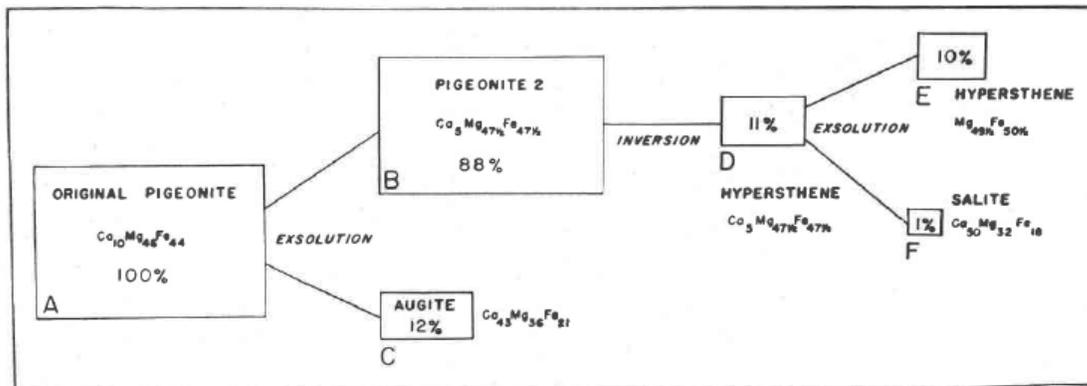
A small amount of the pigeonite (20-30%; Nord, 1983) has inverted to orthopyroxene ( $\text{Mg}_{50}\text{Fe}_{50} - \text{Ca}_6\text{Mg}_{47}\text{Fe}_{47}$ ; Hess and Henderson, 1949; Nord, 1983; Takeda et al, 1983), especially in small quadrilateral areas, bounded by pigeonite cleavages/twins and coarse augite lamellae, that cut through the fine augite lamellae (Hess and Henderson, 1949; Takeda et al, 1981; Mori et al, 1981; Mori and Takeda, 1981; **Figure 5**). This orthopyroxene, in turn, has very fine exsolution lamellae of high-Ca clinopyroxene (salite), with composition  $\text{Ca}_{50}\text{Mg}_{32}\text{Fe}_{18}$ , parallel to (100) planes (Hess and Henderson, 1949); alternatively, these lamellae could be finely chopped pieces of the fine augite lamellae that have elongated and formed short slabs of (100) augite, simulating (100) augite lamellae (Takeda et al, 1981; Mori and Takeda, 1981b). In some grains, pigeonite that has completely inverted to *non*-oriented orthopyroxene, with blebby (100) augites, coexists with partially inverted, oriented orthopyroxene (bounded by coarse (001) augite lamellae) (Mori and Takeda, 1981b; Takeda et al, 1983). Nord (1983) reported orthopyroxene that initially formed by an oriented reaction in one grain has continued across grain boundaries, transforming adjacent pigeonite grains by a *non*-oriented mechanism.

Augite also occurs as 0.2-0.5 mm primary grains in Moore County, as well as epitaxial overgrowths on pigeonite (Nord, 1983). It probably formed later than pigeonite and plagioclase but before tridymite and chromite (Nord, 1983).



**Figure 5:** Photomicrograph of partly inverted pigeonites from Moore County; dark = orthopyroxene, light with small dark horizontal lamellae = pigeonite with twins and exposed cleavages, white = coarse (001) augite lamellae. Notice that the orthopyroxene is in small quadrilaterals bounded by coarse augite lamellae and pigeonite cleavages. From Takeda et al (1983).

Two theories have been presented concerning the formation of different pyroxene phases in Moore County, one by Hess and Henderson (1949) (also cited in Hostetler and Drake, 1978), and the other presented in Mori and Takeda (1981b). The first theory is shown in **Figure 6**. Bulk compositional data for all Moore County pyroxenes indicate that the original pyroxene phase was pigeonite, with composition  $\text{Ca}_{10}\text{Mg}_{46}\text{Fe}_{44}$ ; 12% of this original pigeonite was exsolved into the coarse (001) augite lamellae ( $\text{Ca}_{43}\text{Mg}_{36}\text{Fe}_{21}$ ), whereas the rest of the original pigeonite formed a second, less calcic pigeonite ( $\text{Ca}_6\text{Mg}_{47}\text{Fe}_{47}$ ), now the dominant pyroxene phase in Moore County. Some of this second pigeonite (~10%) inverted to a calcic hypersthene (opx) with similar composition to the host ( $\text{Ca}_6\text{Mg}_{47}\text{Fe}_{47}$ ), which then further exsolved calcium-rich (100) salite lamellae ( $\text{Ca}_{50}\text{Mg}_{32}\text{Fe}_{18}$ ). The rest of the inverted hypersthene formed a new hypersthene composition with little to no calcium ( $\text{Mg}_{50}\text{Fe}_{50}$ ). Pigeonite

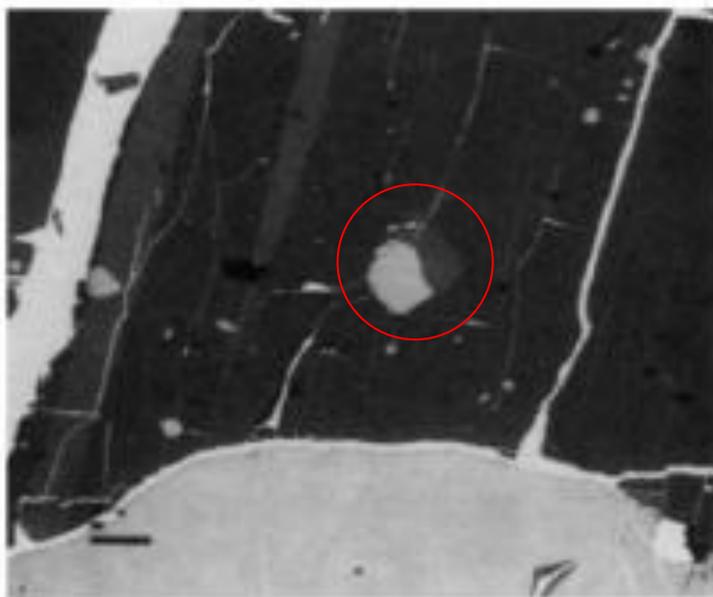


**Figure 6:** The Hess and Henderson (1949) model of pyroxene exsolution and inversion in Moore County; see text for discussion.



There are no other known cumulate or non-cumulate eucrites that display the same “intricate complexity” inherent to Moore County pyroxenes, but similar, partially-inverted pigeonites with augite exsolution lamellae are found in other observed falls and Antarctic meteorites. Hence, any pyroxene clasts with partial to total pigeonite inversion and (001) augite lamellae up to 20  $\mu\text{m}$  wide are described as “Moore County-type” pyroxenes (Delaney et al, 1984e).

Inclusions of euhedral to subhedral plagioclase (Nord, 1983; Mittlefehldt, 1990; **Figure 8**) and euhedral tridymite (Mittlefehldt, 1990) are found in Moore County pyroxenes, usually at the margins of the grains, especially where they abut interstitial tridymite (Mittlefehldt, 1990). The included plagioclase grains are of similar composition to larger plagioclase grains, and thus probably represent plagioclase nuclei that were trapped in growing pyroxenes (Mittlefehldt, 1990). There is some evidence of small metal droplets along fractures in pyroxene (Hess and Henderson, 1949).

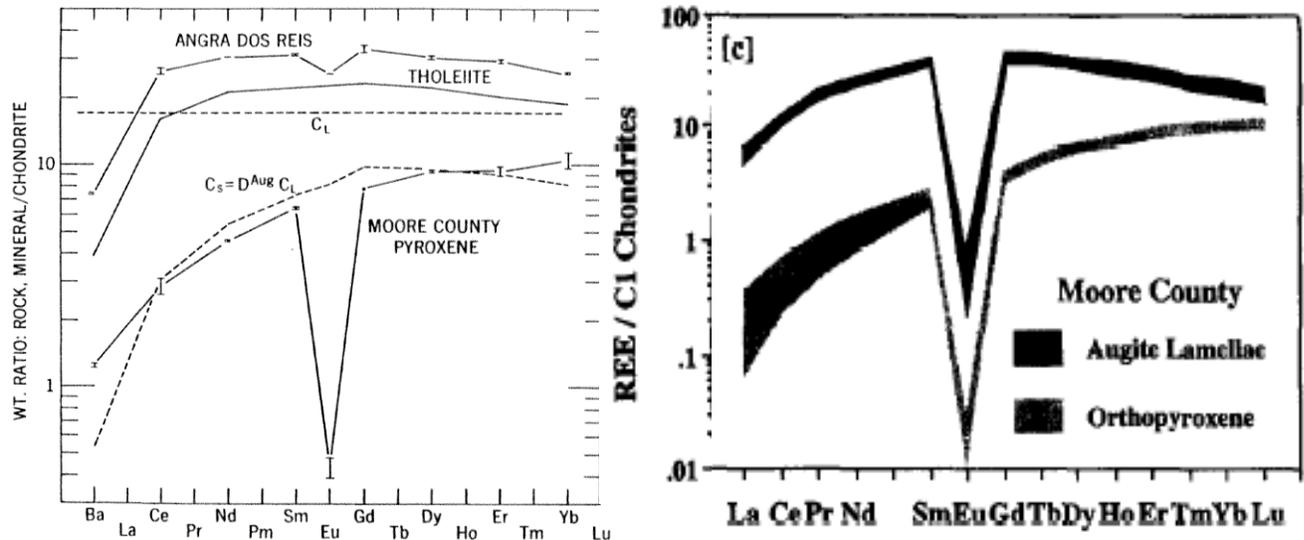


**Figure 8:** Inverted BSE micrograph of Moore County. Plagioclase is light gray, tridymite is white, opaques are black, open cracks are white, and filled cracks are black; the light gray rectangular lines in the dark gray pigeonite host are coarse augite lamellae. Note the subhedral plagioclase inclusion (center, circled) located near where pyroxene abuts interstitial tridymite. From Mittlefehldt (1990).

Pyroxene REE patterns show general increases in chondritic enrichment from LREE to HREE with a very sizeable europium deficiency (Schnetzler and Philpotts, 1969; Hsu and Crozaz, 1997; **Figure 9**), perhaps due to post-accumulation competition between pyroxene and plagioclase for these elements (Schnetzler and Philpotts, 1969). This competition did not greatly affect the pyroxene REE pattern outside of Eu (Schnetzler and Philpotts, 1969), but it may suggest that these crystals are zoned (Allen and Mason, 1973), though this latter contention is unsupported by chemical data.

Additional, more recently published chemical data for Moore County pyroxenes can be found in Mittlefehldt (1990), Miyamoto and Takeda (1992, 1994), Pun and Papike (1995) and Hsu and Crozaz (1997). A discussion of the thermal and metamorphic history that produced the wide array of pyroxene compositions and textures seen in Moore County can be found in the **Metamorphism** section, below.

*Plagioclase*: Moore County plagioclase occurs primarily as large grains dispersed throughout the meteorite (Henderson and Davis, 1936; Hess and Henderson, 1949), but also as minute euhedral inclusions in pyroxene (**Figure 8**), both with similar compositions (Mittlefehldt, 1990). Henderson and



**Figure 9:** Rare-earth element patterns in Moore County pyroxenes; graphs from Schnetzler and Philpotts (1969) (top) and Hsu and Crozaz (1997) (bottom).

Davis (1936) originally reported strongly cleaved plagioclase in their analysis of Moore County mineral separates, but this is contradicted by a lack of plagioclase cleavage found in the first thin section analysis (Hess and Henderson, 1949). These initially-reported cleavages may be curved, conchoidal fracture planes (Hess and Henderson, 1949) that were not immediately obvious from macroscopic observations.

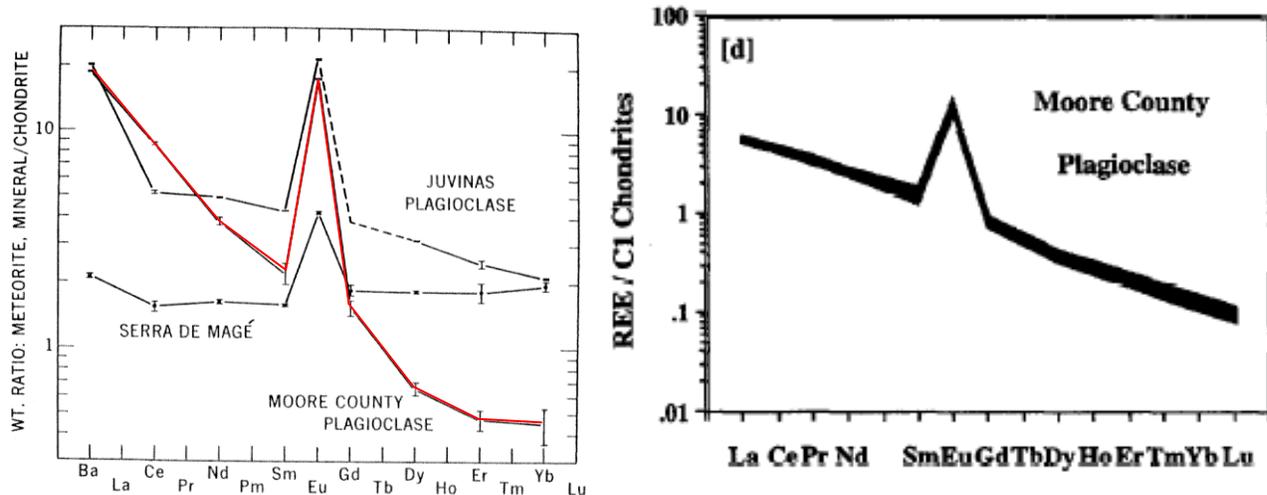
Numerous chemical analyses (e.g., Henderson and Davis, 1936; Duke and Silver, 1967; Hostetler and Drake, 1978; Tagai et al, 1994; Pun et al, 1997; Mayne et al, 2009) give a range of compositions from An<sub>89</sub>-An<sub>93</sub>. Al/Si ordering was attained in the tetrahedral sites ~94% (Tagai et al, 1994). There is no observable zoning (Hess and Henderson, 1949; Hostetler and Drake, 1978) but some crystals show late-stage alteration to less calcic plagioclase (Hess and Henderson, 1949). Plagioclase in Moore County is the least calcic among the cumulate eucrites (Tera et al, 1997).

Plagioclase twins are predominantly of albite, pericline, and manebach varieties, with no reported Carlsbad twinning (Hess and Henderson, 1949).

The larger plagioclase grains contain numerous minute inclusions (Henderson and Davis, 1936). These include (1) minute blebs and spherical particles of metal along fracture planes (Hess and Henderson, 1949), (2) faintly pink, Fe-rich isotropic, translucent crystals with an index of refraction between feldspar and tridymite (Hess and Henderson, 1949; Hostetler and Drake, 1978), (3) elongated, rhombohedral, brownish-red crystals (Henderson and Davis, 1936), (4) spherical reddish crystals (Henderson and Davis, 1936), and (5) slender, uniform, prismatic crystals arranged in rows along cleavage (Henderson and Davis, 1936). None of these inclusions have been analyzed chemically or mineralogically by more recent authors.

REE patterns in Moore County plagioclase indicate a decrease in enrichment from LREE to HREE, with a very large positive europium anomaly (Schnetzer and Philpotts, 1969; Hsu and Crozaz, 1997; **Figure 10**). This pattern indicates that the plagioclase was not in equilibrium with the same melt that crystallized pyroxene, and seems to suggest post-accumulation competition between pyroxene and plagioclase during slow cooling (Schnetzer and Philpotts, 1969; Allen and Mason, 1973). While the pyroxene REE patterns were not seriously affected by this incomplete re-equilibration, subtraction of REEs from plagioclase (especially HREE) affected its REE patterns significantly, as plagioclase initially had about one-third the concentration of these elements compared to pyroxene (Schnetzer and Philpotts, 1969).

Moore County plagioclase has often been used for comparison in Rb-Sr studies of lunar and meteoritic materials (Papanastassiou and Wasserburg, 1972; Wasserburg et al, 1977; Wooden et al, 1981; Nakamura et al, 1985), as the calculated initial  $^{87}\text{Sr}/^{86}\text{Sr}$  total rock (0.69908) and plagioclase values (0.69898) for Moore County (Papanastassiou and Wasserburg, 1972) are very close to the calculated initial  $^{87}\text{Sr}/^{86}\text{Sr}$  for the parent body of basaltic achondrites (0.698990: Papanastassiou and Wasserburg, 1969).



**Figure 10:** Rare-earth element patterns in Moore County plagioclase; graphs from Schnetzer and Philpotts (1969) (top – modified to show Moore County data in red) and Hsu and Crozaz (1997) (bottom).

**Ilmenite:** Ilmenite is found in Moore County in well-developed, 0.15-0.3 mm crystals (1) in association with chromite, usually surrounded by tridymite (Nord, 1983), or (2) on or near plagioclase-pyroxene boundaries (Hess and Henderson, 1949), suggesting a late-phase origin. Ilmenite grains are anisotropic, pleochroic, and likely represent ilmenite-magnetite solid solution (Hess and Henderson, 1949). In cases where it appears with chromite it is separated by sharp, straight boundaries (Hess and Henderson, 1949) which are probably minute fractures (Hostetler and Drake, 1978). Chemical analyses of Moore County ilmenite indicate an Mg# = 5-8 (Bunch and Keil, 1971; Hostetler and Drake, 1978; Mayne et al, 2009) and FeO/MnO = 49-52 (Bunch and Keil, 1971; Mayne et al, 2009). No zoning was observed in Moore County ilmenites (Hostetler and Drake, 1978).

**Chromite:** Chromite occurs in Moore County as well-developed, 0.15-0.3 mm crystals (1) in association with ilmenite surrounded by tridymite (Nord, 1983), (2) on or near plagioclase-pyroxene boundaries

(Hess and Henderson, 1949), or (3) smaller grains included in pyroxene (Nord, 1983). These occurrences indicate chromite as a late-crystallizing phase (Nord, 1983). In cases where it appears with ilmenite it is separated by sharp, straight boundaries (Hess and Henderson, 1949) which are probably minute fractures (Hostetler and Drake, 1978). Chemical analyses of Moore County chromite indicate an Mg# = 5-7 and a Cr# = 80-83 (Bunch and Keil, 1971; Hostetler and Drake, 1978; Mayne et al, 2009). No zoning was observed in Moore County chromites (Hostetler and Drake, 1978).

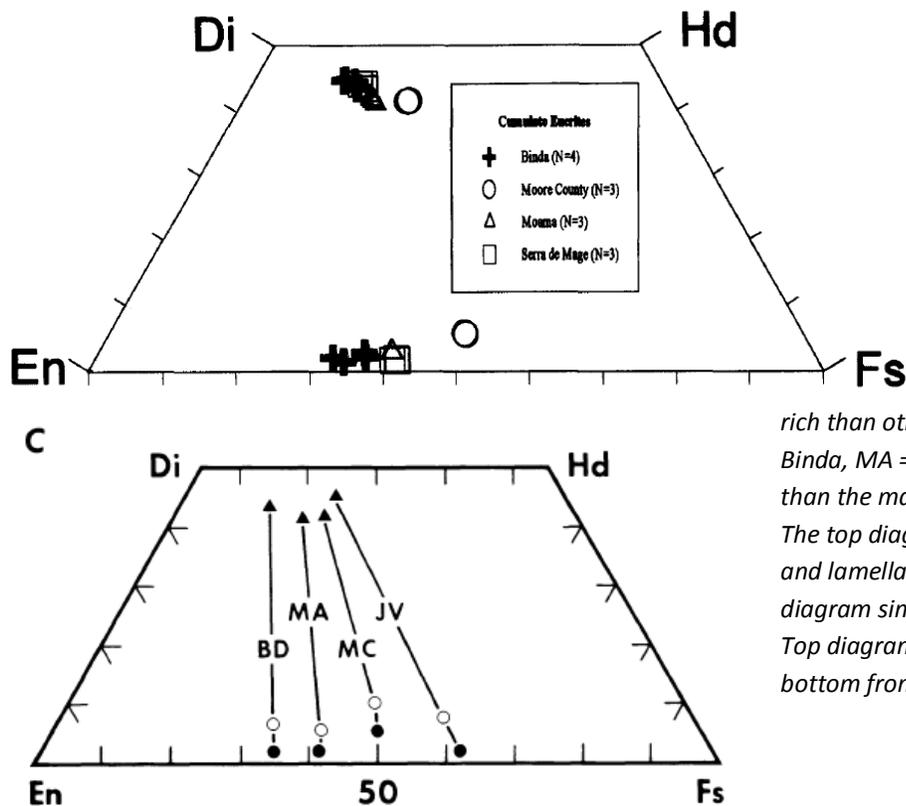
*Tridymite*: Silica in Moore County was originally reported as quartz (Henderson and Davis, 1936), but later workers (e.g., Hess and Henderson, 1949; Duke and Silver, 1967; Hostetler and Drake, 1978; Nord, 1983; Mittlefehldt, 1990) have all reported tridymite. It occurs mainly as large anhedral grains, interstitial to pyroxene and plagioclase (Hess and Henderson, 1949; see **Figure 3** and discussion of petrography, above). Numerous minute, acicular crystals of apatite occur as inclusions, in addition to an unidentified pink isotropic mineral (also found in plagioclase) and minute opaque specks (Hess and Henderson, 1949). Tridymite itself also occurs as euhedral inclusions in the margins of pyroxene and plagioclase, most commonly where these minerals abut interstitial tridymite, further implying its origin as a late phase crystallized from trapped liquid (Mittlefehldt, 1990). Chemically, it is essentially pure SiO<sub>2</sub> with trace amounts of Al and Mg (Hostetler and Drake, 1978).

*Troilite*: Troilite is present in Moore County as small, subhedral grains (Hostetler and Drake, 1978) and occurs similarly to ilmenite and chromite. Unlike many other HED achondrites, troilite occurrences are not associated with metal (Hostetler and Drake, 1978). A recent chemical analysis of Moore County troilite showed mostly Fe and S with a trace amount of Ni (Mayne et al, 2009).

*Apatite*: Apatite occurs in Moore County in two ways, as (1) sharp, well-formed, acicular crystals included in large interstitial tridymite grains (Hess and Henderson, 1949), and as (2) small inclusions in pyroxene grains (Delaney, 1982c). As these apatites make a significant contribution to the REE abundances in Moore County, it is likely that REE analyses of pyroxene are contaminated by included phosphates, as pyroxene/plagioclase REE ratios are much higher than modal ratios (e.g., Ce<sub>pyx</sub>/Ce<sub>plag</sub> ≈ 4, whereas pyx<sub>modal</sub>/plag<sub>modal</sub> ≈ 1) (Delaney, 1982c). However, direct quantitative analysis of apatite in Moore County is inhibited by its small size (Hostetler and Drake, 1978).

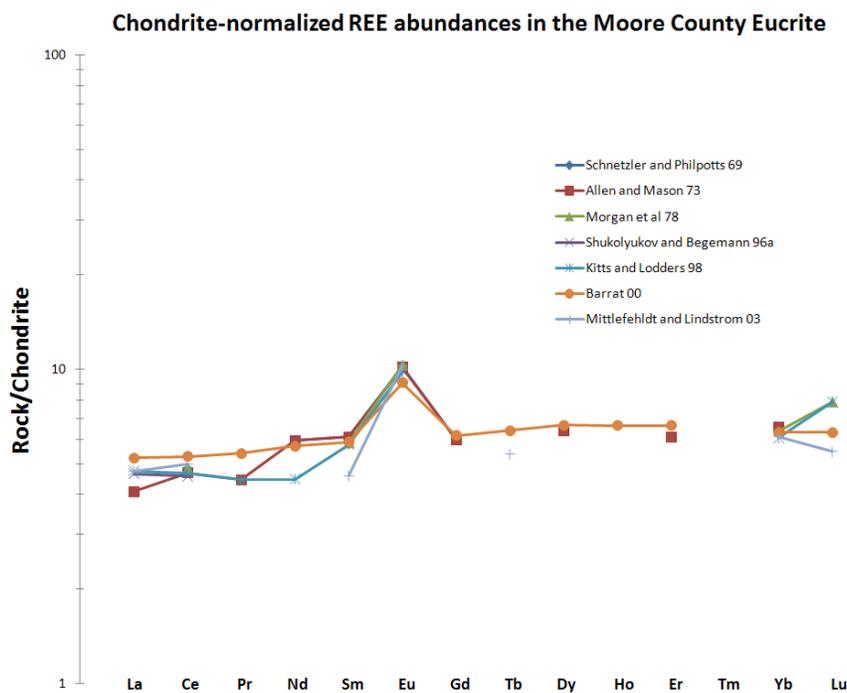
*Metal*: The only occurrences of free metal in Moore County have been reported along curved, conchoidal fractures in plagioclase, and to a lesser extent in pyroxene as well (Hess and Henderson, 1949). They appear as tiny, barely visible blebs or spherical masses that transition to “minute specks”; their appearance as droplets rather than distinct crystals suggests that they are metallic iron, and their presence along fractures implies a younger formation age for the metal inclusions than the crystals they are included in (Hess and Henderson, 1949). A recent chemical analysis of Moore County metal shows that it is >99.5% Fe, with less than 1% Co and trace amounts of Ni and P (Mayne et al, 2009).

**Whole Rock Composition**: The major element chemistry of Moore County is shown in **Table 2**, followed by minor and trace element data in **Table 3**. Mg# (MgO/(MgO+FeO)) is also reported for whole rock values, as Moore County is more iron-rich (and calcium-rich) than most other cumulate eucrites (Mittlefehldt, 1990; Pun and Papike, 1995) but more magnesium-rich than most non-cumulate eucrites (e.g., Stannern, Nuevo Laredo, and Juvinas), as observed especially well in pyroxene chemistry (**Figure 11**).



**Figure 11:** Pyroxene quadrilaterals showing Moore County in relation to other cumulate eucrites (as well as JV = Juvinas on the bottom diagram).

Moore County is more Fe-rich than other cumulate eucrites (BD = Binda, MA = Moama) but more Mg-rich than the main group noncumulate eucrites. The top diagram shows corresponding host and lamellae compositions; the bottom diagram similar data connected by tie lines. Top diagram from Pun and Papike (1995), bottom from BVSP (1981).



**Figure 12:** Chondrite-normalized REE data (whole-rock) for the Moore County eucrite, showing generally flat but enriched REE patterns and a noticeable positive Eu anomaly. Reference chondrite (CI) is from Evensen et al (1978).

Duke and Silver (1967) plotted the bulk composition of Moore County on a normative  $\text{MgSiO}_3\text{-FeSiO}_3\text{-CaAl}_2\text{Si}_2\text{O}_8$  (enstatite-ferrosilite-anorthite) ternary diagram; whereas most eucrite bulk compositions plot near the pyroxene-plagioclase boundary curve (suggestive of coincident crystallization of pyroxene and plagioclase), Moore County falls within the anorthite stability field, and is thus termed a “feldspar-cumulate” eucrite.

Whole-rock REE data from **Table 3** is plotted in **Figure 12**, normalized to chondritic values. REE patterns for Moore County show overall enrichment (4-6x) from chondritic values, with a slight increase from LREE to HREE enrichment and a noticeable positive Eu anomaly. These values are consistent with the cumulate, plagioclase-rich nature of Moore County.

Mittlefehldt (1987) investigated volatile alkali contents in Moore County and other cumulate eucrites, and compared them to an average of normalized cosmic abundances of refractory elements in each sample (referred to as AHIR = average highly incompatible refractory). He found that AHIR increased among the feldspar-cumulate eucrites with increasing Fe content (consistent with fractionation from a single magma), but saw that K/AHIR and Rb/AHIR decreased with similar increases in Fe, suggesting volatile loss and degassing during magma cooling and crystallization. (As Moore County is the most Fe-rich cumulate eucrite, this suggests more volatile loss in Moore County relative to the other cumulates.)

**Radiogenic Isotopes:** The first reported age date for Moore County was a K-Ar age of  $3.23 \pm \sim 0.2$  Ga (Geiss and Hess, 1958), who posited that this age could represent crystallization or the last serious heating event experienced by the rock. This and other variable K-Ar ages (e.g., 3.5 Ga: Heymann et al, 1968) suggest the likelihood of argon loss post-crystallization for Moore County. However, careful correction of argon isotopic character in Moore County can still provide important constraints on the crystallization and cooling history, as the most recently-obtained age (4.460 Ga: Shukolyukov and Begemann, 1996b) is coincident with other Sm-Nd and Lu-Hf age dates (see below).

Other early ages for Moore County include Rb-Sr and Sr-Sr ages for HED achondrites as a whole (4.5 Ga: Gast, 1962;  $4.39 \pm 0.26$  Ga: Papanastassiou and Wasserburg, 1969), as well as a (U,Th)- $^4\text{He}$  age, specific to Moore County, of  $5.0 \pm 0.2$  Ga (Heymann et al, 1968). However, as noted by Carver and Anders (1976), Moore County has a significant  $^4\text{He}$  excess (estimated at  $580 \times 10^{-8}$  STP/g using 4.56 Ga as the crystallization age, or 14% of the total  $^4\text{He}$ ), and thus this (U, Th)- $^4\text{He}$  age does not have any significance to the history of the meteorite.

**Table 2:** Major element data, and literature averages, for the Moore County eucrite.

reference	Hess and Henderson 49	Schmitt et al 72	Allen and Mason 73 recalc. from H&H, 49	McCarthy et al 73	Kitts and Lodders 98	Barrat et al 00	Mittlefehldt and Lindstrom 03	Average Literature Values
weight	--	226 mg	--	--	--	103.32 mg	63.73 mg	--
SiO <sub>2</sub>	48.16	--	48.16	48.32	48.24	--	--	<b>48.22</b>
TiO <sub>2</sub>	0.32	--	0.32	0.438	0.37	0.43	--	<b>0.38</b>
Al <sub>2</sub> O <sub>3</sub>	15.57	15.61	15.57	12.65	14.68	14.77	--	<b>14.81</b>
FeO	13.98	11.45	15.02	17.24	14.82	15.64	13	<b>14.45</b>
Fe <sub>2</sub> O <sub>3</sub>	1.9	--	--	--	--	--	--	<b>1.9 (H&amp;H 49 only)</b>
MnO	0.31	0.45	0.31	0.52	0.46	0.45	--	<b>0.42</b>
MgO	8.41	--	8.41	9.41	9.04	8.54	--	<b>8.76</b>
CaO	11.08	--	11.08	9.37	10.29	9.8	10.9	<b>10.42</b>
Na <sub>2</sub> O	0.45	0.43	0.45	--	0.44	0.45	0.471	<b>0.45</b>
K <sub>2</sub> O	0.09	--	0.09	0.02	0.02	--	0.025	<b>0.05</b>
Cr <sub>2</sub> O <sub>3</sub>	0.44	0.28	0.44	0.44	0.39	0.41	0.301	<b>0.39</b>
P <sub>2</sub> O <sub>5</sub>	--	--	--	0.036	0.036	--	--	<b>0.04</b>
S%	0.3	--	--	--	0.33	--	--	<b>0.32</b>
FeS	--	--	0.82	--	--	--	--	<b>0.82</b>
<b>sum (reported)</b>	<b>101.01</b>	--	<b>100.67</b>	--	--	--	--	--
<b>Mg#</b>	<b>52</b>	--	<b>50</b>	<b>49</b>	<b>52</b>	<b>49</b>	--	<b>52</b>
<i>technique:</i>	<i>wet chemistry</i>	<i>INAA</i>	<i>wet chemistry</i>	<i>X-ray flour. spec.</i>	<i>lit survey</i>	<i>ICP-AES</i>	<i>INAA</i>	--

**Table 3: Minor, trace, and REE data for Moore County.**

reference	Reed and Jovanovic 69	Ahrens 70	Tera et al 70	Schmitt et al 72	Allen and Mason 73	Morgan et al 78	Mittlefehldt 87
weight	--	--	182 mg	226 mg	--	--	--
Ca ppm	--	--	67500 (c)	--	--	--	--
Na ppm	--	--	2750 (e)	--	--	2920 (a)	--
K ppm	--	--	159 (c)	--	--	--	175 (a)
P ppm	--	--	--	--	--	--	160 (a)
Sc ppm	--	24 (a)	--	24 (b)	24 (a)	24 (a)	--
Ti ppm	--	--	--	--	2000 (a)	--	--
V ppm	--	--	--	--	70 (f)	--	--
Cr ppm	--	--	--	--	3000 (a)	1930 (a)	--
Mn ppm	--	--	--	--	2400 (a)	--	--
Co ppm	--	--	--	3 (b)	3 (a)	3 (a)	--
Ni ppm	--	--	--	--	16 (f)	3.5 (g)	--
Cu ppm	--	--	--	7 (b)	3 (a)	--	--
Zn ppm	--	--	--	--	11 (f)	1.2 (g)	--
Ga ppm	--	--	--	--	2 (f)	--	--
Ge ppm	--	--	--	--	--	0.0073 (g)	--
As ppb	--	--	--	--	--	--	--
Se ppm	--	--	--	--	--	0.5 (g)	--
Rb ppm	--	--	0.0497 (c)	--	--	0.03 (g)	0.055 (a)
Sr ppm	--	79.5 (a)	64.1 (c)	--	70 (f)	--	--
Y ppm	--	--	--	--	9 (f)	--	--
Zr ppm	--	--	--	--	22 (f)	--	--
Nb ppm	--	--	--	--	--	--	--
Mo ppb	--	--	--	--	--	--	--
Ru ppm	--	--	--	--	--	--	--
Rh ppm	--	--	--	--	--	--	--
Pd ppb	--	--	--	--	--	0.4 (g)	--
Ag ppb	--	--	--	--	--	3.2 (g)	--
Cd ppb	--	--	--	--	--	7.1 (g)	--
In ppb	--	--	--	--	--	--	--
Sn ppb	--	--	--	--	--	--	--
Sb ppb	--	--	--	--	--	1.1 (g)	--
Te ppb	22.5 ± 7 (d)	--	--	--	--	4.1 (g)	--
Cs ppb	--	--	0.71 (c)	<i>Schnetzer and Philpotts 69</i>	--	0.7 (g)	0.70 (a)
Ba ppm	--	21 (a)	18.6 (c)	22.5 (c)	21 (f)	--	--
La ppm	--	--	--	--	1.0 (f)	--	--
Ce ppm	--	--	--	3.08 (c)	3.0 (b)	3.1 (a)	--
Pr ppm	--	--	--	--	0.43 (f)	--	--
Nd ppm	--	2.81 (a)	--	2.81 (c)	2.81 (a)	--	--
Sm ppm	--	--	--	0.0938 (c)	0.938 (a)	0.9 (a)	--
Eu ppm	--	--	--	0.591 (c)	0.59 (a)	0.6 (a)	--
Gd ppm	--	--	--	1.22 (c)	1.22 (a)	--	--
Tb ppm	--	--	--	--	--	--	--
Dy ppm	--	--	--	1.62 (c)	1.62 (a)	--	--
Ho ppm	--	--	--	--	--	--	--
Er ppm	--	--	--	1.01 (c)	1.01 (a)	--	--
Tm ppm	--	--	--	--	--	--	--
Yb ppm	--	1.08 (a)	--	1.08 (c)	1.08 (a)	1.05 (a)	--
Lu ppm	--	--	--	--	--	0.2 (a)	--
Hf ppb	--	--	--	--	--	610 (a)	--
Ta ppb	--	--	--	--	--	--	--
W ppb	--	--	--	--	--	--	--
Re ppb	--	--	--	--	--	0.060 (a)	--
Os ppb	--	--	--	--	--	0.400 (a)	--
Ir ppb	--	--	--	--	--	--	--
Pt ppb	--	--	--	--	--	--	--
Au ppb	--	--	--	--	--	0.23 (g)	--
Th ppb	--	62 (a)	--	<i>Duke and Silver 67</i>	--	--	--
U ppb	14.4 (d)	30 (a)	--	19.6 (a)	--	48 (g)	--
Li ppm	--	--	2.95 (c)	--	--	--	--
B ppm	--	--	--	--	--	--	<i>Gibson et al 85</i>
S ppm	--	--	--	--	--	--	3375
F ppm	91.5 ± 0.6 (d)	--	--	--	--	--	--
Cl ppm	5.7 ± 1.3 (d)	--	--	--	--	--	--
Br ppm	0.068 ± 0.017 (d)	--	--	<i>Kuroda et al 66</i>	--	0.014 (g)	--
I ppb	--	--	--	81 ± 8 (b)	--	--	--
Pb ppm	--	--	--	--	--	--	--
Hg ppb	--	--	--	--	--	--	--
Tl (ppb)	--	--	--	--	--	0.08 (g)	--
Bi (ppb)	--	--	--	--	--	0.36 (g)	--

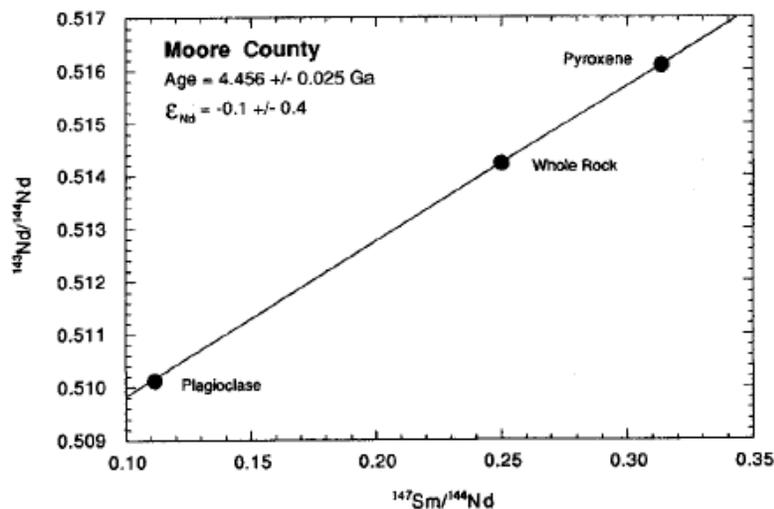
technique: (a) lit survey, (b) INAA, (c) stable isotope dil. MS, (d) photon & neutron activation, (e) atomic absorption, (f) spark source MS, (g) RNAA, (h) ICP-MS

**Table 3 (cont.):** Minor, trace, and REE data for Moore County.

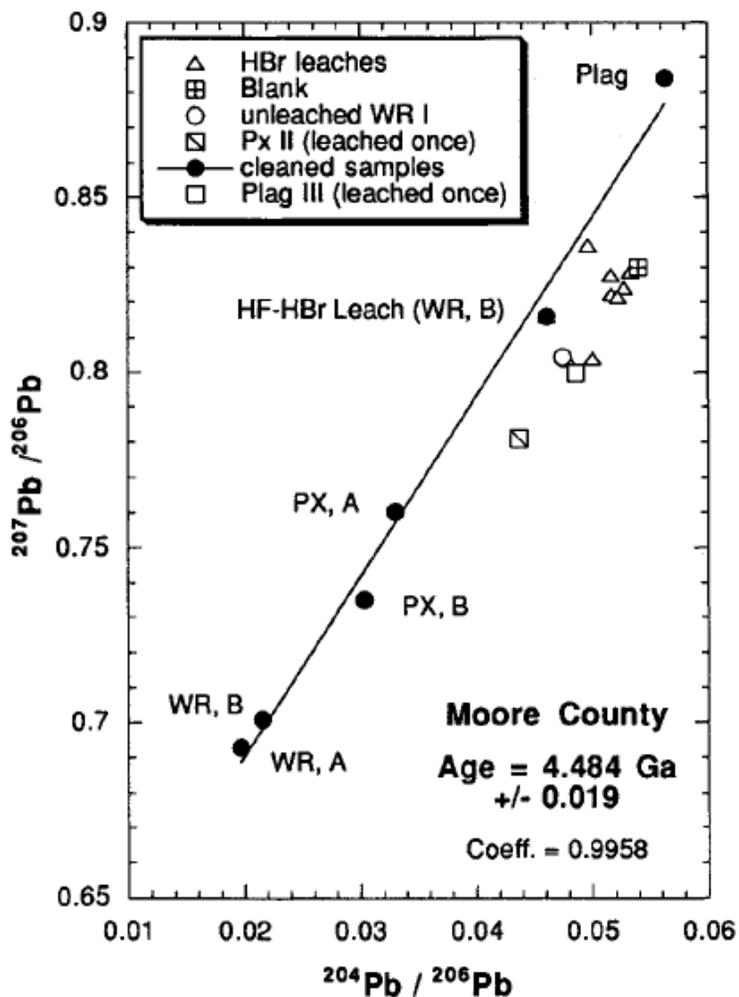
reference weight	Paul and Lipschutz 90	Shukolyukov and Begemann 96a	Kitts and Lodders 98	Barrat et al 00	Mittlefehldt and Lindstrom 03
comments	avg. of 2 samples	no technique given	--	103 mg	63.73 mg
Ca ppm	--	72300	73500 (a)	--	--
Na ppm	--	--	3130 (a)	--	--
K ppm	--	180	191 (a)	--	210 (b)
P ppm	--	--	157 (a)	--	--
Sc ppm	--	--	22.5 (a)	19.8 (h)	19.7 (b)
Ti ppm	--	--	2194 (a)	--	--
V ppm	--	--	92 (a)	--	--
Cr ppm	--	--	2650 (a)	--	--
Mn ppm	--	--	3526 (a)	--	--
Co ppm	5.06 (b)	--	5 (a)	11.3 (h)	6.33 (b)
Ni ppm	--	--	12 (a)	4.2 (h)	--
Cu ppm	--	--	5.5 (a)	6.0 (h)	--
Zn ppm	0.98 (b)	--	1.1 (a)	3.4 (h)	--
Ga ppm	1.65 (b)	--	1.8 (a)	1.60 (h)	--
Ge ppm	--	--	0.007 (a)	--	--
As ppb	--	--	--	--	150 (b)
Se ppm	0.275 (b)	--	0.35 (a)	--	--
Rb ppm	0.046 (b)	--	0.06 (a)	0.06 (h)	--
Sr ppm	--	70.9	71 (a)	70 (h)	91 (b)
Y ppm	--	9.5	9 (a)	10.29 (h)	--
Zr ppm	--	19	22 (a)	15.38 (h)	--
Nb ppm	--	--	--	0.57 (h)	--
Mo ppb	--	--	--	--	--
Ru ppm	--	--	--	--	--
Rh ppm	--	--	--	--	--
Pd ppb	--	--	0.4 (a)	--	--
Ag ppb	2.31 (b)	--	2.6 (a)	--	--
Cd ppb	17.2 (b)	--	12.2 (a)	--	--
In ppb	0.09 (b)	--	0.09 (a)	--	--
Sn ppb	--	--	--	--	--
Sb ppb	4.5 (b)	--	3.3 (a)	--	171 (b)
Te ppb	2.5 (b)	--	3 (a)	--	--
Cs ppb	0.88 (b)	--	0.8 (a)	1 (h)	--
Ba ppm	--	22	26 (a)	20.6 (h)	33 (b)
La ppm	--	1.14	1.160 (a)	1.28 (h)	1.16 (b)
Ce ppm	--	2.93	3 (a)	3.38 (h)	3.2 (b)
Pr ppm	--	--	0.430 (a)	0.521 (h)	--
Nd ppm	--	2.81	2.120 (a)	2.70 (h)	--
Sm ppm	--	--	0.886 (a)	0.906 (h)	0.705 (b)
Eu ppm	--	--	0.570 (a)	0.527 (h)	0.598 (b)
Gd ppm	--	--	--	1.26 (h)	--
Tb ppm	--	--	--	0.239 (h)	0.201 (b)
Dy ppm	--	--	--	1.69 (h)	--
Ho ppm	--	--	--	0.376 (h)	--
Er ppm	--	--	--	1.10 (h)	--
Tm ppm	--	--	--	--	--
Yb ppm	--	--	1 (a)	1.04 (h)	1.01 (b)
Lu ppm	--	--	0.2 (a)	0.160 (h)	0.139 (b)
Hf ppb	--	--	610 (a)	530 (h)	460 (b)
Ta ppb	--	--	--	30 (h)	36 (b)
W ppb	--	--	--	18 (h)	--
Re ppb	--	--	0.041 (a)	--	--
Os ppb	--	--	0.003 (a)	--	--
Pt ppb	--	--	--	--	--
Au ppb	0.41 (b)	--	0.3 (a)	--	10.3 (b)
Th ppb	--	--	62 (a)	125 (h)	51 (b)
U ppb	8.6 (b)	30	27 (a)	64 (h)	--
S ppm	--	--	3300 (a)	--	--
F ppm	--	--	60 (a)	--	--
Cl ppm	--	--	5.65 (a)	--	--
Br ppm	--	--	0.05 (a)	--	0.230 (b)
I ppb	--	--	135 (a)	--	--
Pb ppm	--	--	25 (a)	--	--
Hg ppb	--	--	2740 (a)	--	--
Tl (ppb)	0.070 (b)	--	0.08 (a)	--	--
Bi (ppb)	0.54 (b)	--	0.5 (a)	--	--

technique: (a) lit survey, (b) INAA, (c) stable isotope dil. MS, (d) photon & neutron activation, (e) atomic absorption, (f) spark source MS, (g) RNAA, (h) ICP-MS

More recent Moore County age-dating work (i.e., post-1970) has focused primarily on Sm-Nd and Pb-Pb ages. Nakamura et al (1977) reported an internal isochron Sm-Nd age of  $4.60 \pm 0.04$  Ga, which was later corrected by Nakamura and Tatsumoto (1980) to  $4.54 \pm 0.04$  Ga based on an error in tracer calibration. Younger Sm-Nd ages of  $4.457 \pm 0.025$  Ga and  $4.456 \pm 0.025$  Ga (**Figure 13**) were obtained by Tera et al (1987b) and Tera et al (1997), respectively; a similar bulk eucrite Sm-Nd isochron of  $4.464 \pm 0.075$  Ga and a cumulate eucrite Lu-Hf isochron of  $4.470 \pm 0.022$  Ga were also obtained by Blichert-Toft et al (2002).



**Figure 13:** Sm-Nd isochron for Moore County, revealing a crystallization (or differentiation) age of  $4.456 \pm 0.025$  Ga. From Tera et al (1997).



**Figure 14:** Six-point Pb-Pb isochron for Moore County, revealing a Pb-Pb age of  $4.484 \pm 0.019$  Ga. Samples were taken from  $>10$  mm below the fusion crust to avoid contamination from terrestrial Pb. From Tera et al, 1997.

These Sm-Nd and Lu-Hf ages are in contrast with initial Moore County Pb-Pb ages determined by Tera and other workers in multiple studies. Early results gave Pb-Pb ages of 4.55 Ga (Tera et al, 1987a); these results were affected by severe terrestrial Pb contamination similarly to other cumulate eucrites (Tera et al, 1987a; 1987b; 1997), but progressive leaching experiments suggested that the 4.55 Ga age was valid (Tera et al, 1987b). This age-date was significantly older than reported Moore County Sm-Nd ages (above), suggesting that Pb-Pb isochrons did not actually represent crystallization ages, but may have been related to very early U enrichment relative to Pb (Tera et al, 1987b). However, later research revealed a younger Pb-Pb age of  $4.484 \pm 0.018$  (Tera et al, 1996; 1997; **Figure 14**), which is concordant with Sm-Nd and Lu-Hf ages. This sample was taken from >10 mm below the fusion crust to avoid the effects of terrestrial Pb contamination (Tera et al, 1997).

Coincident 4.45-4.48 Ga Pb-Pb and Sm-Nd ages derived from multiple cumulate eucrites indicate that these Moore County age-dates could possibly represent either true crystallization ages (Tera et al, 1997; Blichert-Toft et al, 2002) or the last time of mantle differentiation on the eucrite parent body (Blichert-Toft et al, 2002). However, an older Pu-Xe age of 4.548 Ga (Shukolyukov and Begemann, 1996b), a Lu-Hf age of 4.550 Ga (Patchett and Tatsumoto, 1980) and a similar Mn-Cr age of 4.549 Ga (Lugmair and Shukolyukov, 1998), suggest that Moore County formed early, contemporaneous with the non-cumulate eucrites, but Sm-Nd and Pb-Pb isotopic systems were held above their closure temperature by deep crustal burial and exposure to elevated temperatures for a significant period of time (~90 Ma) (Shukolyukov and Begemann, 1996b), and thus represent cooling ages. This last theory is complicated by a recently-obtained Moore County Sm-Nd age of 4.547 Ga (Boyet et al, 2009); clearly, more work is needed to clarify Moore County ages.

$^{129}\text{I}$ - $^{129}\text{Xe}$  and  $^{244}\text{Pu}$ - $^{136}\text{Xe}$  formation intervals ( $\Xi_{129}$  and  $\Xi_{244}$ , representing the time between the cessation of solar ( $^{129}\text{I}$ ) and galactic ( $^{244}\text{Pu}$ ) nucleosynthesis and the formation of the meteorite) have been reported for Moore County by Kuroda et al (1966), with  $\Xi_{129} = \sim 300$  m.y. and  $\Xi_{244} = 185$  m.y. These ages are discordant with U- $^{136}\text{Xe}$  and  $^{129}\text{I}$ - $^{129}\text{Xe}$  formation intervals reported by Rowe (1967), with  $\Xi_{136} \approx 75$  Ma and  $\Xi_{129} = 235 \pm 50$  Ma. The discordance in these ages may be related to excess fissiogenic and radiogenic Xe in Moore County as reported by Reynolds (1968).

**Cosmogenic Isotopes and Exposure Ages:** Cosmic-ray exposure ages for Moore County, taken from the literature, are shown in **Table 4**, and each source contains further information on the isotopic character of the noble gases. More information on xenon isotopes (but without cosmic-ray exposure ages) is also available from Kuroda et al (1966) and Rowe (1967).

**Table 4: Cosmic-ray exposure ages for Moore County.**

source	Heymann et al 68	Carver and Anders 76 recalc. from Heymann et al 68	Aylmer et al 88	Eugster and Michel 95	Shukolyukov and Begemann 1996a	Shukolyukov and Begemann 1996b
Ages						
$^3\text{He}$	6.7	5.5				
$^{21}\text{Ne}$				10		
$^{38}\text{Ar}$			8.9			
$^{81}\text{Kr}$					$9.7 \pm 0.3$	
$^{126}\text{Xe}$						$9.7 \pm 0.3$
"Adopted"				7.3		

As a caution to future workers, Shukolyukov and Begemann (1996a, 1996b) found that  $^{126}\text{Xe}$ ,  $^{81}\text{Kr}$ , and other cosmogenic gas production rates for Moore County are ~30% smaller than most other eucrites; coupled with excess (~14%) radiogenic  $^4\text{He}$  (Carver and Anders, 1976) and excess fissionogenic and radiogenic Xe (Reynolds, 1968), research on radiogenic and cosmogenic noble gas contents in Moore County warrants extra care.

**Other Isotopes:** Oxygen isotopes have been analyzed in Moore County by a number of workers. Taylor et al (1965) analyzed  $\delta^{18}\text{O}$  for plagioclase ( $4.8\text{‰} \pm 0.1\text{‰}$ ), pyroxene ( $3.8\text{‰} \pm 0.3\text{‰}$ ), and free silica ( $11.1\text{‰}$ ), from which a whole rock  $\delta^{18}\text{O}$  value of  $4.3\text{‰}$  was calculated; these values are similar to others determined for HED achondrites in the same study. Clayton and Mayeda (1983, 1996) reported a slightly lower  $\delta^{18}\text{O}$  whole rock value for Moore County ( $3.45\text{‰}$ ), as well as a new  $\delta^{17}\text{O}$  whole rock value ( $1.64\text{‰}$ ); Clayton and Mayeda (1983) also analyzed for excess  $^{16}\text{O}$  ( $+0.32\text{‰}$ ) while Clayton and Mayeda (1996) determined  $\Delta^{17}\text{O} = -0.15$ . All values for Moore County determined by Clayton and Mayeda (1983, 1996) are within the ranges determined (in the same studies) for other eucrites and HED achondrites. More recently determined oxygen isotopic values ( $\delta^{18}\text{O} = 3.747\text{‰}$ ,  $\delta^{17}\text{O} = 1.763\text{‰}$ ,  $\Delta^{17}\text{O} = -0.224 \pm 0.016$ ; Wiechert et al, 2004;  $\delta^{18}\text{O} = 3.666\text{‰} \pm 0.163\text{‰}$ ,  $\delta^{17}\text{O} = 1.677\text{‰} \pm 0.078\text{‰}$ ,  $\Delta^{17}\text{O} = -0.224 \pm 0.017$ ; Greenwood et al, 2005) are in general agreement with those from Clayton and Mayeda (1983, 1996).

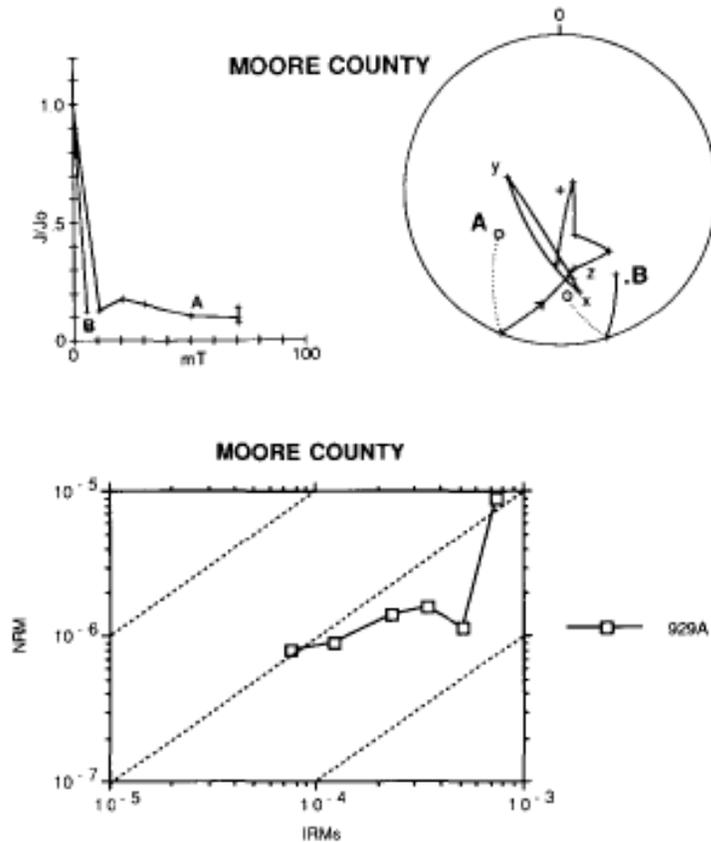
$^{10}\text{Be}$  (measured) and  $^{26}\text{Al}$  (measured and literature values) from Moore County were summarized by Aylmer et al (1988), with  $^{10}\text{Be} = 18.8 \pm 1.3$  dpm/kg and  $^{26}\text{Al}$  values at  $69 \pm 7$ ,  $77.6 \pm 0.7$ , and  $75 \pm 8$  dpm/kg; Lavrukhina and Ustinova (1972) used  $^{26}\text{Al}$  to calculate the aphelion of the meteorite after its separation from the parent body.

Isotopic ratios of silicon ( $\delta^{30}\text{Si} = -0.22\text{‰}$ ,  $\delta^{29}\text{Si} = -0.05\text{‰}$ ; Molini-Velsko et al, 1986) and calcium ( $^{40}\text{Ca}/^{44}\text{Ca} = 47.138 \pm 0.004$ ; Shih et al, 1993) have also been reported for Moore County.

**Experiments:** Many early experiments with Moore County (e.g., Fleischer et al, 1967b) focused on fission track analysis. Bhandari et al (1971a) used selective annealing in Moore County pyroxenes to find evidence of superheavy elements in extraterrestrial samples, while other researchers used similar methods to explain excess  $^4\text{He}$ , and thus anomalous age-dates in Moore County (Carver and Anders, 1976; Wilkening and Parker, 1977), while at the same time questioning the presence of superheavy elements as inferred from Bhandari et al (1971a) (Carver and Anders, 1976).

Natural and isothermal remnant magnetism were investigated in Moore County by Cisowski (1991), the results of which can be found in **Figure 15**. Other investigations of magnetism in Moore County can be found in Gattacceca et al (2005, 2008).

Natural thermoluminescence was investigated in Moore County by Sears et al (1991) and Batchelor and Sears (1991). Moore County showed significantly less TL sensitivity than was found in other cumulate eucrites, but this may be reflective of cooling rates (rather than metamorphism) or sample heterogeneities (Batchelor and Sears, 1991).



**Figure 15:** Top = response of NRM intensity and direction to AF demagnetization, bottom = log-log plot of NRM vs IRM as a function of AF demagnetization. From Cisowski et al (1991).

There is a significant body of work on the petrogenesis of the Moore County meteorite (both calculated and experimental). Though there is disagreement among different workers, some important data, interpretations, and conclusions to consider are as follows:

- (1) Early petrogenetic work suggested Moore County probably formed by fractional crystallization of peritectic plagioclase and pyroxene from a Juvinas-like eucritic liquid; partial melting is unlikely due to its cumulate nature (Schnetzer and Philpotts, 1969; McCarthy et al, 1973; Consolmagno and Drake, 1977; Hamet et al, 1978). REE patterns suggest crystallization after 85% fractional solidification (Consolmagno and Drake, 1977; Hamet et al, 1978) with 55% differential accumulation of plagioclase (Hamet et al, 1978).
- (2) However, pyroxene compositions suggested that the parent liquid for Moore County had to be much more iron-rich than normal eucrites (Stolper, 1977a, 1977b), and plagioclase compositions indicate a parent liquid that is different from any known eucrite (Stolper, 1977a). In addition,

the density of a Juvinas-like (or similarly eucritic) liquid would cause plagioclase to float rather than sink and accumulate (Stolper, 1977b). Experimental evidence suggests that the cumulate eucrites (including Moore County) may have indeed formed by plutonic fractional crystallization, but from a later, more ferroan liquid that first extensively crystallized magnesian diogenites and orthopyroxenites (Stolper, 1977a, 1977b). On the other hand, REE data do not necessarily agree with this contention (Ma and Schmitt, 1979), and a unique source region must be considered for the Stolper (1977a) hypothesis to hold (Ma and Schmitt, 1979).

- (3) Moore County trace element and REE abundances in pyroxene are higher than those observed for other cumulate eucrites (Pun and Papike, 1995; Pun et al, 1997). These may reflect an REE-enriched (especially LREE) or closed-system parental melt (Stolper, 1977a; Ma et al, 1977; Ma and Schmitt, 1979; Pun and Papike, 1995; Pun et al, 1996; Hsu and Crozaz, 1997), but could also be due to increased Ca and Fe contents in pyroxene, allowing for greater REE accommodation (Pun and Papike, 1995). However, these abundance patterns can also be explained by sub-solidus REE re-equilibration (Schnetzler and Philpotts, 1969; Pun and Papike, 1995; Treiman, 1996a) or trapped melt fractions (see below), which would imply a “normal” eucritic source region (Pun and Papike, 1995; Treiman, 1996a, 1996b; Pun et al, 1997).
- (4) The most recent explanation for the variety of chemical anomalies in Moore County suggests the influence of trapped melt fractions in cumulate eucrites, as they can contribute significantly to trace element abundances and eliminate the need for a REE-enriched source region (Treiman, 1996b; Pun and Papike, 1995; Pun et al, 1997; Treiman, 1997; Barrat et al, 2000). Newer models show that Moore County major and trace element abundances could be achieved from 37.5% cumulus pigeonite, 27.5% cumulus plagioclase, and ~35% main group or Nuevo Laredo eucritic melt (Treiman, 1996b; Treiman, 1997; Barrat, 2004).
- (5) The cumulate eucrites (e.g., Moama, Serra de Mage, Moore County, etc.) may have formed by a single fractional crystallization sequence (Hamet et al, 1978; Pun et al, 1996); if so, variable Eu data from these eucrites could indicate variable  $fO_2$  conditions for crystallization (Hamet et al, 1978) or  $Eu^{2+}/Eu^{3+}$  buffering (Pun et al, 1996).
- (6) Partition coefficients for Moore County plagioclase and pyroxene have been determined by Ma et al (1977), Huebner and Nord (1981), Pun and Papike (1995), Hsu and Crozaz (1997), Treiman (1997), Pun et al (1997), Barrat et al (2000), and Barrat (2004).

**Cooling History:** Much of the work on exsolution, decomposition, and inversion textures in Moore County (see discussion in Mineral Chemistry) has been accompanied by investigations into the complex cooling history that produced these textures. Early workers, deriving conclusions from the limited state of igneous petrology at the time, suggested slow cooling followed by reheating to  $>1000^{\circ}C$  (Henderson and Davis, 1936) or a sudden and catastrophic removal of the meteorite from its source at a near-solidus temperature ( $\sim 1135^{\circ}C$ : Hess and Henderson, 1949); both hypotheses were posited to explain the arrested inversion of pigeonite to orthopyroxene (i.e., no more than 30%: Nord, 1983).

More detailed analyses of pyroxene exsolution lamellae suggest that the (001), coarser ( $\leq 100 \mu m$ ) augite lamellae were produced at 8-9 km depth, with a cooling rate of  $0.00016^{\circ}C/year$ , until the crystals cooled from  $990-730^{\circ}C$  (Miyamoto and Takeda, 1977; Mori and Takeda, 1981b; Takeda et al, 1981; Miyamoto and Takeda, 1992; Miyamoto and Takeda, 1994). These crystals then experienced an early catastrophic removal (as in Henderson and Davis, 1936); the finer (001) augite lamellae and partial orthopyroxene inversion were produced by a later, more rapid cooling rate ( $0.3-0.48^{\circ}C/year$ ) during a short reheating ( $\leq 940^{\circ}C$ ) event at a depth of 100-150 meters, possibly in an ejecta blanket (Mori and Takeda, 1981b; Takeda et al, 1981; Miyamoto and Takeda, 1992; Miyamoto and Takeda, 1994). This later reheating

event was likely arrested by an impact event at 770°C (Miyamoto and Takeda, 1992; Miyamoto and Takeda, 1994). Some recent work has called into question the extremely slow cooling rate for the coarse augite lamellae, and suggested that it may be three times as fast (Stimpfl et al, 2003); this does not necessarily call the entire two-stage thermal model into question but exposes the need for model refinement. At the very least, this model implies that the early history of the eucrite parent body was defined by numerous impact events that exposed and displaced deep crustal material.

The above research coincides with the work of Hostetler and Drake (1978), who investigated the quench temperatures for (1) pigeonite with coarse (001) augite lamellae and (2) orthopyroxene with (100) salite lamellae. They found that the original coarse augite lamellae were produced at high but still subsolidus temperatures (710-1070°C: Hostetler and Drake, 1978; 1000-1025°C: Huebner and Nord, 1981), while the salite exsolved at lower temperatures (650-800°C: Hostetler and Drake, 1978; 900-950°C: Nord, 1983); both temperature ranges are subsolidus, and the authors interpreted this as evidence for production of *both* sets of lamellae by slow subsolidus cooling with no intermediate events (Hostetler and Drake, 1978; Nord, 1983). However, this data is also consistent with slow cooling at the site of crystallization, sudden removal, and then near-surface reheating, as in Mori and Takeda (1981b), Takeda et al (1981), Miyamoto and Takeda (1992), and Miyamoto and Takeda (1994).

**Shock Effects:** Shock textures are generally absent in Moore County, though there is evidence of fracturing in plagioclase (Hess and Henderson, 1949) that may be shock-related, in addition to some (100) and (001) twins within augite that suggest a maximum shock pressure of 50 kbars (Nord, 1983).

The lack of major shock features in Moore County is puzzling, considering the cooling history described above and the general cumulate nature of the eucrite; it is almost certain that Moore County experienced at least one catastrophic impact during its history (if not more). A reasonable explanation is that Moore County was initially excavated from depth by the removal of a very large crustal block (Miyamoto and Takeda, 1992, 1994), limiting the shock effects that would be experienced in any given part of the section. The observation of  $\leq 10$  km Vestoid fragments (Binzel and Xu, 1993) confirms that such large pieces of eucritic crust could be transport mechanisms for deep crustal materials; these larger pieces would break up and expose new material over time, thus giving young cosmic-ray exposure ages for meteorites that had a much longer transit time (Hostetler and Drake, 1978). However, as Moore County was likely emplaced in the parent body regolith after the initial excavation of the large block (Hostetler and Drake, 1978; Miyamoto and Takeda, 1992, 1994) and experienced further slow cooling prior to final ejection (Mori and Takeda, 1981b; Takeda et al, 1981; Miyamoto and Takeda, 1992; Miyamoto and Takeda, 1994), it could also be a large lithic fragment of a howardite that was separated prior to atmospheric entry (Duke and Silver, 1967; Hostetler and Drake, 1978).