

Aubrites: Their origin and relationship to enstatite chondrites

Thomas R. Watters

Department of Geology, Bryn Mawr College, Bryn Mawr, Pennsylvania 19010

Martin Prinz

Department of Mineral Sciences, American Museum of Natural History,
New York, New York 11024

Abstract—All ten known aubrites (enstatite achondrites) as well as Happy Canyon and Mt. Egerton, related anomalous meteorites, have been studied in order to understand their origin and relationship to enstatite chondrites. Mineralogically, aubrites contain 75–98% enstatite (En_{98.76-99.54}), 1–16% plagioclase (An_{1.8-8.2}), 0.2–8.1% diopside (Wo_{40.1-46.1}), 0.3–10.0% olivine (Fo_{99.79-99.99}), <0.1–3.7% metallic Fe-Ni (Ni, 3.7–6.8%; Si, 0.1–2.4%), <0.1–7.1% Ti bearing troilite (Ti, 0.6–5.7%), and trace amounts of oldhamite, daubréelite, ferromagnesian alabandite and schreibersite. Generally, the silicate and sulfide portions of Happy Canyon and Mt. Egerton show strong similarities to the aubrites. Based on similarities in bulk chemistry of the silicate portions, major and minor phases and inferred oxygen fugacity, we conclude that the most likely parent material for the aubrites are E6 chondrites. REE data on the aubrites shows negative Eu anomalies. This indicates that the aubrites formed through fractional crystallization. The addition of 10% plagioclase of An₁₅ composition (avg. E6 plagioclase) to the bulk composition of the silicate portion of the aubrites results in good agreement with that of E6 chondrites.

INTRODUCTION

Ten meteorites have been classified as aubrites or enstatite achondrites. Nine of these are falls and one is a find. The classification is based on their unique mineralogy (primarily enstatite) and bulk chemical composition. They are similar to enstatite (E) chondrites, which have chondrules and metallic Fe-Ni.

The idea of a genetic relationship between the aubrites and enstatite chondrites is not new, but it is not clear if aubrites are a different type of nebular condensate or igneous differentiates. Many studies on the individual meteorites of the aubrite group have suggested some sort of relationship, but there has been a lack of complete mineralogical and petrological data for all the members necessary for a proper evaluation. This paper presents the results of such a study and includes mineralogical, modal, and bulk chemical data. Data on major, but especially the minor, phases of all ten known aubrites provide a base from which meaningful

comparisons may be made. In addition, Happy Canyon (Olsen *et al.*, 1977) and Mt. Egerton (McCall, 1965), which are related meteorites classified by Wasson (1974) as being anomalous, have also been studied. The purpose of these comparisons is to present a model for the origin of aubrites and their relationship to E chondrites which best satisfies the observed chemical and mineralogical data.

Aubrites fall into several petrographic groups. Bustee (Maskelyne, 1870; Keil and Brett, 1974), Pesyanoe (Yudin and Smishlaev, 1964), Pena Blanca Springs (Lonsdale, 1947), Bishopville (Shepard, 1848; Derham *et al.*, 1964), Norton Co. (Beck and LaPaz, 1951; Keil and Fredriksson, 1963), Khor Temiki (Hey *et al.*, 1967), Aubres (Gregory, 1867) and Mayo Belwa (Graham *et al.*, 1977) are all monomict breccias. Cumberland Falls (Binns, 1967) is a polymict breccia containing chondritic clasts. Shallowater (Foshag, 1940), is the only aubrite which is not brecciated, consisting of cm-sized grains of intergrown enstatite forming a networklike fabric.

Mt. Egerton (McCall, 1965) also has cm-sized grains of enstatite with small amounts of diopside (Mason, 1974) minor kamacite and sulfides, all included within Fe-Ni. Happy Canyon has a distinctly cumulate texture (Olsen *et al.*, 1977) but the bulk composition of an E6 enstatite chondrite.

ANALYTICAL TECHNIQUES AND MATERIALS

Polished thin sections of all the aubrites and the two related meteorites were used for petrographic studies and microprobe analysis. Microprobe analyses were attained on a 9-channel fully automated ARL-SEMQ instrument. Appropriate standards were selected and correction methods for silicates (Bence and Albee, 1968) and metals (Colby, 1968) were employed. A MAGIC IV program, modified for the ARL-SEMQ, was utilized in reducing metal data. A modal analysis computer program was used to calculate a volume % mode for point counts on thin sections using the probe. This method involves an area defined by 20 points or less and sampled by a desired number of measurements on a point grid. Generally, 500 to 1000 points were counted for each thin section. Nine elements (Si, P, Ti, Al, Cr, Fe, Mg, Ca, Ni) are measured with a 2 second counting time and examined with a "filter" of ratios and abundances to determine the phase at each measured point. The data for all points are printed and then checked for consistency. Modes are then recalculated excluding all unidentified points.

Polished sections and meteoritic material were acquired from the American Museum of Natural History (AMNH), the Smithsonian Institution (NMNH) and the British Museum (BM). The following is a list of the polished sections used in this study; Aubres, BM63552-1, 2 and 3; Bishopville, AMNH386-2, NMNH222; Bustee, AMNH4240-1, NMNH979; Cumberland Falls, AMNH222-1, NMNH604; Khor Temiki, AMNH3973-3, NMNH1551; Mayo Belwa, AMNH4465-1; Norton Co., AMNH3846-2, NMNH1712; Pena Blanca Springs, AMNH4114-1, NMNH1451; Pesyanoe, NMNH1425-2; Shallowater, AMNH4130-1, NMNH1206-1 and 2; Happy Canyon, AMNH4454-1; Mt. Egerton, NMNH.

Bulk analyses were computer calculated using modal data. Volume percentages were converted to weight percentages using appropriate densities, and average phase compositions were used.

MINERALOGY

Enstatite is by far the dominant mineral in the aubrites, but many minor phases have been found. Table 1 is a listing of the minerals we have found in the aubrites

Table 1. Major and minor phases present in Aubrites and related meteorites.

	En	Fo	Diop	Plag	Amph	Fe-Ni	Troil	Old	Abd	Daub	Sch	Per	Os	Cu	Hei	Djf
Aubres	X	X	X	X		X	X	X			f					
Bishopville	X	X	X	X		X	X	X	X		f,g		i			
Bustee	X	X	X	X		X	X	d	X			d			m	
Cumberland																
Falls	X	X	X	X		X	X			X						
Khor Temiki	X	X	X	X		X	X	X			f					
Mayo Belwa	X	X	X	X	b	X	X	e	e	e	e		f			
Norton Co.	X	X	X	X		X	X		X	X	f,h			k		
Pena Blanca																
Springs	X	X	X	X		X	X	X								n
Pesyano	X	X	X	X		X	X	X	l,j	X	h					
Shallowater	X	X	X	X		X	X				X					
Happy Canyon	X	X	X	X		c	c						f			
Mt. Egerton	X		a			X	X	X	X	X	X					

X This work; a, Mason, 1974; b, Bevan *et al.*, 1977; c, Olsen *et al.*, 1977; d, Maskelyne, 1870; e, Graham *et al.*, 1977; f, Wasson and Wai, 1970; g, Shepard, 1848; h, Beck and La Paz, 1951; i, Derham *et al.*, 1964; j, Yudin and Smishlaev, 1964; k, Keil and Fredricksson, 1968; l, Keil, 1968; m, Keil and Brett, 1974; n, Ramdohr, 1963.

En, Enstatite; Fo, Forsterite; Diop, Diopside; Plag, Plagioclase; Amph, Amphibole; Fe-Ni, metallic Fe-Ni; Troil, Troilite; Old, Oldhamite; Abd, Ferromagnesian Alabandite; Daub, Daubreélite; Sch, Schreibersite; Per, Perryite; Osb, Osbornite; Cu, Metallic Cu; Hei, Heideite; Djf, Djerfisherite.

and their occurrences in the various members. It also includes data from the literature on minerals we have not found in our sections. Modal data for all aubrites and Happy Canyon are presented in Table 2. Non-metallic portions of Mt. Egerton are dominantly enstatite.

Enstatite. Orthoenstatite and associated clinoenstatite make up 75 to 98% of the aubrites (Table 2). Enstatite of this composition has no terrestrial equal, having a much lower FeO content. Compositions of the enstatite of aubrites, Mt. Egerton and Happy Canyon are given in Table 3 and Fig. 1. The range in composition is from En 98.76-99.54.

Composition is not the only unique feature of enstatite in aubrites. Metallic Fe-Ni and related sulfides and phosphides are commonly found as inclusions in the enstatite. Most enstatite in aubrites is disordered (Brown and Smith, 1963; Reid and Pollack, 1963; Pollack and Ruble, 1964; Reid and Cohen, 1967). Reid and Cohen (1967) reported that disordered orthopyroxene was found in all aubrites, except for Shallowater, and that some samples contained both ordered and disordered grains. Brown and Smith (1963) and Reid *et al.* (1964) reported disordered orthopyroxene produced in synthetic samples by quenching from high temperatures. However, as Reid and Cohen (1967) pointed out, this is an unlikely mechanism since the presence of large unzoned homogeneous crystals with associated diopside suggests a slow cooling history. Shock-induced disordering of the enstatite seems to be the most likely mechanism (Reid and Cohen, 1967).

Cathodoluminescence is also characteristic of the enstatite in the aubrites (Derham and Geake, 1964; Derham *et al.*, 1964; Reid *et al.*, 1964; Reid and Cohen, 1967; Grögler and Liener, 1968). The characteristic luminescence spectrum consists of a peak of 6700 Å (red) and one at 4000 Å (blue). The 4000 Å luminescence was dominant in most of the enstatite observed in this study. Reid and Cohen (1964) found a correlation between degree of redness of the luminescence and content of Mn in the enstatite.

Plagioclase. Plagioclase in aubrites varies modally from 1 to 16% (Table 2). Compositions range from mainly An 1.8 to 8.2, but Khor Temiki was found to have two distinct compositions, one of An 2.0 and another of An 23.8 (Table 4, Fig. 2). Olsen *et al.* (1977), reported An 26.4 in Happy Canyon but we found compositions of An 15.8. No plagioclase was found in the Mt. Egerton meteorite.

The occurrence of plagioclase is quite variable in the aubrites. Shallowater has small irregularly shaped grains that are included in enstatite (Foshag, 1940). Some grains show polysynthetic twinning. Graham *et al.* (1977) reported large rounded grains and sinuous aggregates of plagioclase, some up to 1 mm across, but we found none of this size in our section. In fact, plagioclase was very difficult to find in most of the sections studied, except for Bustee, Khor Temiki and Pena Blanca Springs, which had some grains large enough to be recognized with a microscope. In brecciated aubrites with visible grains plagioclase is present as angular clasts.

Table 2. Modal compositions (vol. %) of Aubrites and Happy Canyon.

	Aubres	Bishop-ville	Bustee	Cumb. Falls	Khor Temiki	Mayo Belwa	Norton Co.	Pena Bl. Springs	Pesyano	Shallowater	Happy Canyon
Enstatite	96.7	74.8	81.9	94.0	88.5	97.5	84.5	95.4	90.2	81.6	52.8
Plagioclase	1.3	16.2	3.0	0.7	6.6	0.3	1.0	2.1	7.3	2.9	7.6
Diopside	0.2	1.9	0.9	8.1	1.5	0.6	2.7	2.7	1.3	—	5.3
Forsterite	0.8	6.7	5.8	1.5	3.6	1.6	10.0	0.3	1.4	4.7	—
Kamacite	0.1	tr	0.2	0.7	0.1	tr	0.3	tr	0.2	3.7	*
Troilite	0.9	0.5	0.6	1.1	0.1	0.1	1.0	tr	tr	7.1	*

tr, trace; all other phases <0.1%. * Weathered kamacite and troilite.

Table 3. Enstatite compositions in Aubrites and related meteorites.

	Aubres	Bishop-ville	Bustee	Cumb. Falls	Khor Temiki	Mayo Belwa	Norton Co.	Pena Bl. Springs	Pesyano	Shallowater	Happy Canyon	Mt. Egerton
SiO ₂	59.4	59.8	59.4	59.5	60.0	59.9	59.1	59.8	59.5	60.1	59.9	59.9
TiO ₂	0.21	0.02	0.02	0.02	0.05	0.03	<0.02	<0.02	0.03	0.02	<0.02	<0.02
Al ₂ O ₃	<0.02	0.06	0.09	0.09	0.07	0.13	0.07	0.08	0.09	0.13	0.13	0.18
Cr ₂ O ₃	0.02	0.02	0.02	0.05	<0.02	<0.02	<0.02	0.03	0.03	<0.02	<0.02	0.02
FeO	<0.02	0.08	0.05	0.08	<0.02	0.03	0.07	0.07	0.06	0.04	0.13	0.07
MnO	0.07	<0.02	0.11	0.08	0.04	0.02	<0.02	0.06	0.03	<0.02	<0.02	0.05
MgO	39.8	39.6	40.3	40.0	39.9	39.4	39.6	39.8	40.2	40.1	39.7	39.8
CaO	0.44	0.68	0.42	0.33	0.47	0.54	0.64	0.57	0.45	0.15	0.40	0.45
Na ₂ O	<0.02	0.03	0.02	<0.02	0.06	0.05	0.02	0.02	0.02	0.05	<0.02	<0.02
Total	100.0	100.3	100.4	100.2	100.6	100.1	99.5	100.4	100.4	100.6	100.3	100.6
En	99.20	98.67	99.19	99.28	99.15	98.97	98.76	98.90	99.12	99.54	99.07	99.11
Fs	0.02	0.11	0.07	0.12	0.01	0.05	0.10	0.10	0.08	0.06	0.22	0.09
Wo	0.78	1.22	0.74	0.60	0.84	0.98	1.12	1.00	0.80	0.40	0.71	0.80

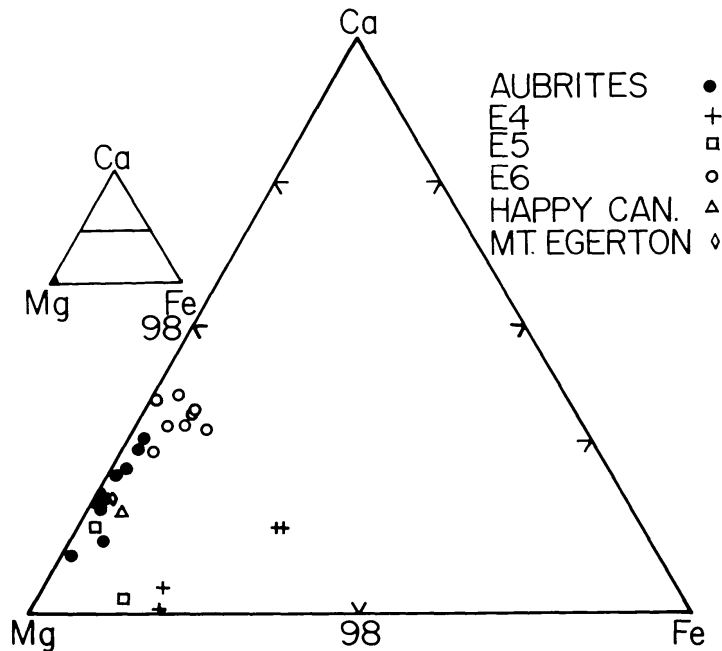


Fig. 1. Enstatite compositions (atomic %) in aubrites and related meteorites compared with enstatite chondrites. Data on E chondrites from Keil (1968).

Diopside. Diopside was found in all aubrites except for Shallowater. Happy Canyon (Olsen *et al.*, 1977), and Mt. Egerton (Mason, 1974), have both been reported to contain diopside, although we found none in our section of Mt. Egerton. Diopside comprises 0.2 and 8.1% of the aubrites (Table 2). Compositions are pure diopside with essentially no Fs component; Wo varies from 40.1–46.1 (Table 5). The composition of diopside in Happy Canyon reported by Olsen *et al.* (1977) agrees with our analysis.

Reid and Cohen (1967) report that diopside occurs as exsolution lamellae in pyroxene. We observe diopside as separate grains and have detected no evidence of its presence as exsolution lamellae.

Boyd and Schairer (1964) determined the solvus temperatures for the iron-free system diopside-enstatite at one atm. This system is very similar to that of pyroxenes in aubrites. Assuming equilibrium crystallization of enstatite and diopside, the distribution of Ca in the pyroxene corresponds to a temperature of about 1050°C. This agrees with the equilibrium temperature determined by Mason (1974) for pyroxene in Mt. Egerton.

Olivine. Forsterite olivine has been found in all aubrites. No olivine was found in Happy Canyon. The modal forsterite content in aubrites varies from 0.3 to 10.0% (Table 2). Forsterites range in composition from 99.79 to 99.99 (Table 6).

Olivine, in contrast with plagioclase and diopside, is relatively easy to identify. In Shallowater, olivine occurs as equant or subhedral grains poikilitically enclosed in enstatite, as also noted in Foshag, 1940. Brecciated aubrites also have olivine poikilitically enclosed in enstatite, but angular grains up to about 0.5 mm are

Table 4. Plagioclase composition in Aubrites and related meteorites.

	Aubres	Bishop-ville	Bustee	Cumb. Falls	Khor Temikti*	Khor Temikti	Mayo Belwa	Norton Co.	Pena Bl. Springs	Pesyanoe	Shallo-water	Happy Canyon
SiO ₂	67.7	67.7	66.3	68.8	61.9	67.6	67.6	65.3	67.2	67.8	65.1	64.5
TiO ₂	<0.02	0.02	<0.02	0.10	0.03	<0.02	<0.02	0.03	0.02	0.02	0.03	0.03
Al ₂ O ₃	20.3	20.2	21.1	19.9	24.2	20.3	19.8	21.8	20.4	19.6	21.2	21.7
FeO	0.04	<0.02	<0.02	0.06	<0.02	<0.02	<0.02	0.02	<0.02	0.03	0.29	0.36
MgO	0.15	0.03	0.04	0.15	0.14	0.08	0.53	0.03	0.02	0.04	0.03	0.05
CaO	0.85	0.41	1.50	0.69	5.1	0.43	0.73	1.77	0.54	0.72	1.63	3.3
Na ₂ O	10.1	11.3	10.9	10.1	9.0	11.2	11.2	10.7	11.7	11.4	10.7	9.6
K ₂ O	0.45	0.59	0.46	0.47	0.23	0.64	0.84	0.53	0.57	0.59	0.77	0.59
BaO	0.02	0.04	<0.02	0.15	<0.02	0.02	0.07	0.03	0.02	0.12	0.07	0.05
Total	99.6	100.3	100.3	100.5	100.6	100.4	100.9	100.1	100.4	100.3	99.9	100.6
An	5.54	1.80	7.00	3.40	23.76	1.98	3.26	8.24	3.06	3.28	7.70	15.81
Ab	91.69	95.09	90.50	93.76	74.98	94.23	92.13	88.64	94.50	93.64	88.50	81.00
Or	2.77	3.12	2.56	2.85	1.27	3.77	4.61	3.10	2.49	3.08	3.85	3.16

* One grain which differed from others. None found in Mt. Egerton.

Table 5. Diopside compositions in Aubrites and related meteorites.

	Aubres	Bishop- ville	Bustee	Cumb. Falls	Khor Temiki	Mayo Belwa	Norton Co.	Pena Bl. Springs	Pesyanoë	Happy Canyon
SiO ₂	55.6	55.3	54.6	54.4	55.1	56.5	54.4	56.9	54.8	56.4
TiO ₂	0.17	0.42	0.28	0.19	0.30	0.33	0.20	0.18	0.17	0.05
Al ₂ O ₃	0.52	0.38	0.39	0.70	0.54	0.75	0.51	0.55	0.14	0.50
Cr ₂ O ₃	0.02	0.04	0.02	0.04	0.02	0.03	<0.02	0.02	0.02	0.03
FeO	0.09	0.02	<0.02	0.12	0.03	0.07	0.03	0.06	0.04	0.64
MnO	0.04	0.03	0.04	0.05	0.04	0.06	0.03	0.05	0.06	0.04
MgO	20.5	20.0	20.2	22.8	20.6	20.9	22.2	20.1	21.4	19.0
CaO	23.0	23.3	24.0	21.3	23.0	21.5	22.9	22.0	23.0	23.6
Na ₂ O	0.25	0.39	0.29	0.33	0.29	0.46	0.30	0.27	0.15	0.20
Total	100.1	99.9	99.8	100.0	99.9	100.5	100.6	100.1	99.8	99.9
En	55.32	56.06	53.86	59.69	55.43	57.47	57.38	55.90	56.35	52.33
Fs	0.15	0.03	0.02	0.22	0.05	0.10	0.04	0.09	0.06	1.01
Wo	44.53	43.91	46.12	40.09	44.52	42.43	42.58	44.01	43.59	46.66

None found in Shallowater. Present in Mt. Egerton, CaO, 22.8% (Mason, 1974).

found. Olivine poikilitically enclosed in enstatite in brecciated aubrites tends to occur as small anhedral grains, compared with those in Shallowater which tend to be larger.

Metallic Fe-Ni. Kamacite was found in all the aubrites and in Mt. Egerton (Table 2). In our samples of Happy Canyon kamacite was altered to limonite and analyses of metal could not be obtained. Olsen *et al.* (1977) did report analyses of partly altered kamacite in Happy Canyon, but it contained no Si. Keil (1969) notes the presence of taenite in Pesyanoë. Kamacite ranges modally from <0.1–3.7% (Table 2). Metallic Fe-Ni analyses are given in Table 7 and shown in Fig. 3. Ni contents range from 3.7 to 6.8% except for several grains in Shallowater

Table 6. Forsterite compositions in Aubrites.

	Aubres	Bishop- ville	Bustee	Cumb. Falls	Khor Temiki	Mayo Belwa	Norton Co.	Pena Bl. Springs	Pesyanoë	Shal- lo- water
SiO ₂	41.7	42.4	42.8	42.3	43.1	43.0	42.3	42.4	43.4	43.0
FeO	0.04	<0.02	<0.02	<0.02	<0.02	0.02	<0.02	<0.02	0.02	0.16
MnO	0.08	<0.02	<0.02	0.02	<0.02	0.07	<0.02	0.02	<0.02	<0.02
MgO	57.5	56.9	56.9	57.4	56.8	56.4	56.9	57.0	56.4	56.7
CaO	0.06	0.05	0.05	0.06	0.05	0.07	0.05	0.10	0.07	<0.02
Total	99.4	99.4	99.8	99.9	99.9	99.8	99.4	99.6	100.0	100.0
Fo	99.99	99.99	99.99	99.99	99.99	99.79	99.99	99.99	99.99	99.86

TiO₂ and NiO <0.02, Al₂O₃ not detected. None found in Happy Canyon and Mt. Egerton.

Table 7. Metallic Fe-Ni compositions in Aubrites and related meteorites.

	Aubres	Bishop-ville	Bustee	Cumb. Falls	Khor Temiki	Mayo Belwa	Norton Co.	Pena Bl. Springs	Pesyanoë	Shallo-water	Shallo-* water	Happy+ Canyon	Mt. Egerton
Fe	92.9	92.6	91.9	95.4	94.0	91.2	93.6	95.4	94.3	91.9	86.0	91.9	90.4
Si	0.23	2.40	1.42	0.12	0.15	2.44	0.91	0.12	0.29	1.96	1.89	-	4.02
Co	0.23	0.32	0.29	0.25	0.36	0.28	0.14	0.25	0.40	0.36	0.19	0.36	0.32
Ni	5.8	4.3	6.3	3.7	5.4	6.8	4.7	3.7	4.9	5.5	11.6	6.4	5.7
P	<0.02	<0.02	<0.02	<0.02	0.02	0.03	0.02	<0.02	<0.02	0.24	0.07	0.45	0.07
Total	99.1	99.6	99.9	99.5	99.7	100.7	99.3	99.5	99.9	99.9	99.8	99.1	100.4

* Several grains which differ from others. † Olsen *et al.*, 1977

Table 8. Ti-bearing troilite compositions in Aubrites and related meteorites.

	Aubres	Bishop-ville	Bishop-ville	Bustee	Cumb. Falls	Khor Temiki	Mayo Belwa	Norton Co.	Pena Bl. Springs	Pesyanoë	Shallo-water	Happy Canyon*	Avg Aubrite	Avg E6	Avg E4-5
Ca	0.13	0.12	0.29	0.16	0.14	0.16	0.15	0.13	0.11	0.17	0.17	-	0.13	-	-
Fe	59.0	57.1	60.6	59.6	61.3	57.8	60.6	58.3	59.2	62.5	55.4	56.6	59.2	61.2	60.6
Ti	3.57	5.70	1.50	2.19	0.55	4.34	0.92	3.95	3.15	0.46	1.24	1.15	2.51	0.65	0.41
Mg	0.08	0.06	0.07	0.17	0.13	<0.02	0.10	0.04	0.05	0.08	0.25	-	0.07	-	-
Mn	0.11	0.25	0.42	0.20	0.18	0.14	0.15	0.11	0.12	0.12	0.49	0.12	0.21	0.09	0.16
Cr	0.91	0.52	0.40	0.87	0.58	1.15	1.49	0.55	0.90	0.21	5.50	5.10	1.20	1.03	1.90
S	36.7	36.5	36.8	37.3	37.4	36.7	36.7	36.8	36.9	37.3	37.2	36.4	36.9	37.0	37.0
Si	<0.02	0.06	<0.02	<0.02	0.09	<0.02	<0.02	0.02	0.03	0.04	<0.02	-	0.03	-	-
Total	100.5	100.3	100.1	100.4	100.4	100.3	100.1	99.9	100.4	100.9	100.3	99.4	-	-	-

* Olsen *et al.*, 1977.

which have an average of 11.6%. Si varies from 0.1–2.4%. Mt. Egerton has the largest amount of Si in the metal at 4.0%.

In brecciated aubrites, kamacite occurs as both separate grains and as inclusions in enstatite. Shallowater, with the highest volume % metal of the aubrites (3.7%), has somewhat larger grains. Foshag (1940) reported some irregular masses of metal which, in rare cases, reach 3 mm in diameter. Shallowater also has kamacite, which occurs interstitially and as inclusions in enstatite. The kamacite analyzed in Mt. Egerton occurs as irregular masses of quite varying size. Unfortunately, no matrix metal was available in our section for analysis. In all these meteorites kamacite is often associated with sulfides and phosphides.

Sulfides and Phosphides. Titanium-rich troilite was found in all the aubrites and in Mt. Egerton. It was reported in Happy Canyon (Olsen *et al.*, 1977), but was not found in this study. Modal troilite varies from <0.1–7.1% in the aubrites (Table 2). Ti content ranges from 0.6–5.7% (Table 8). Bishopville contains troilite with two distinct Ti contents, 1.5 and 5.7% (Table 8) in the same thin section. Mt. Egerton sulfides presented analytical problems which are as yet unresolved. Some of the troilite is highly enriched in Cr. Further studies on Mt. Egerton are in progress and sulfide data will be presented at a later time.

Oldhamite was found in Aubres, Bishopville, Khor Temiki, Pena Blanca Springs and Pesyanoe and has been reported in Bustee (Maskelyne, 1870) and Mayo Belwa (Graham *et al.*, 1977). Compositions are given in Table 9. Oldhamite represents only one or two small grains in most cases. Oldhamites in Pesyanoe and Khor Temiki both gave low sums and the reasons for this are not clear.

Daubréelite was found in Cumberland Falls, Norton Co. and Pesyanoe (Table 10) and has been reported in Mayo Belwa (Graham *et al.*, 1977). Like oldhamite, daubréelite is represented by one or two small grains. Mt. Egerton was also found to have daubréelite.

Ferromagnesian alabandite was found in Bishopville, Bustee and Norton Co. (Table 11) and has been reported in Mayo Belwa (Graham *et al.*, 1977). This phase is also represented by only one or two grains. Ferromagnesian alabandite was found in Mt. Egerton.

Schreibersite was found in Shallowater and Mt. Egerton (Table 12) and has been reported in Aubres, Khor Temiki, Pesyanoe (Wasson and Wai, 1970), Norton Co. (Beck and LaPaz, 1951; Wasson and Wai, 1970), and Mayo Belwa (Graham *et al.*, 1977).

MINERALOGICAL COMPARISON WITH ENSTATITE CHONDRITES

The concept of a genetic relationship between aubrites and enstatite chondrites has intuitive appeal, since both are unique highly enstatite-enriched groups. Indeed, the ideal of a genetic relationship between the various subgroups of the E chondrite family has appeal. Mason (1966) and Van Schmus and Wood (1967) proposed models which relate E4–5 and E6 chondrites to a single parent body.

Mason (1966) suggested that Mt. Egerton and Shallowater might be related to an E chondritic parent body which had undergone partial melting. Van Schmus and Wood suggested that E6 chondrites could be derived by reheating of E4–5 chondrites and that the textural and chemical differences were a result of thermal metamorphism. Keil (1968) and Baedeker and Wasson (1975) concluded that the gap in composition between E4–5 and E6 chondrites was more easily reconciled through independent formation in the same region of the solar nebula. We will treat E4–5 and E6 as distinct groups for purposes of comparison with the aubrites.

Figure 1 is a plot of the composition of enstatite in aubrites (from this study) as compared with that in E chondrites (Keil, 1968). With the exception of one E5 chondrite, enstatite of aubrites is most similar to that of E6 chondrites. Mt. Egerton and Happy Canyon both fall in the aubrite-E6 chondrite grouping. E4–5 chondrites are richer in FeO relative to aubrites and E6 chondrites. This indicates that aubrites and E6 chondrites are slightly more reduced than E4–5 chondrites. The small differences in CaO between enstatite of aubrites and E6 chondrites is probably due to the presence of diopside in the aubrites which has removed some of the Ca (E chondrites have no diopside).

Figure 2 is a plot of the plagioclase compositions in aubrites (this study) and E chondrites (Keil, 1968). Both plagioclase compositions found in Khor Temiki have been plotted. Plagioclase in aubrites is intermediate between those in E4–5 (avg. An 2.2), and E6 chondrites (avg. An 15.0), but closer to E4–5 chondrites. Plagioclase in Happy Canyon falls within the E6 chondrite grouping.

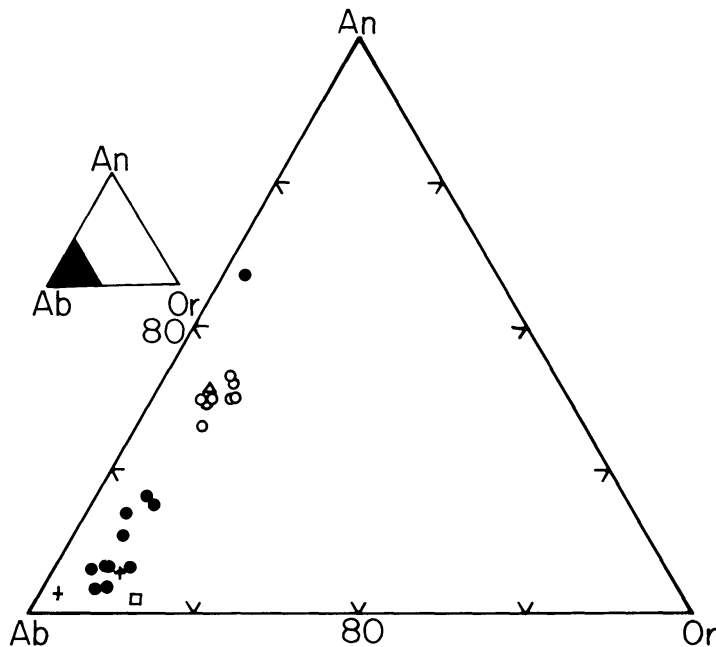


Fig. 2. Plagioclase composition (mol. %) in aubrites and related meteorites compared with enstatite chondrites. Symbols same as in Fig. 1. Data on E chondrites from Keil (1968).

No diopside has been reported in any E chondrite, but forsterite has been reported in two E4 chondrites (Binns, 1967). The compositions are Fo 99.2 and 99.6. Compared with forsterite in aubrites (Table 6), olivine in the two E4 chondrites is slightly enriched in FeO.

Figure 3 is a plot of Fe, Ni and Si in the metallic Fe-Ni of aubrites (this study) and E chondrites (Keil, 1968). In general, aubrites have lower Si (avg. 1.2%) than in E4-5 chondrites (avg. 3.3%), but have similar Si contents to metal in E6 chondrites (avg. 1.3%). Since Si in metallic Fe-Ni, and FeO in enstatite, are both similar to that in E6 chondrites, it indicates that both groups formed under similar oxygen fugacity conditions.

The average compositions of troilite, oldhamite, daubréelite and ferromagnesian alabandite for aubrites, as compared to E chondrites, are given in Tables 8-12. The most notable differences in troilite compositions are in the Ti content. The average Ti in troilite (2.5%) of aubrites is much higher than that in E4-5 (0.41%) and in E6 chondrites (0.65%) (Table 8). However, Keil (1969a) showed that the average Ti contents in E chondrites and aubrites are very similar (0.06% and 0.04% respectively). He also reported that the average troilite modal content in E chondrites is 7.7 wt. % as compared to $\leq 1\%$ wt. % in aubrites.

Oldhamite in the aubrites is generally closest in composition to that in E6 chondrites (Table 9). The largest difference is in Fe content. Both E4-5 and E6 chondrites have slightly higher Fe contents in their oldhamite relative to that in aubrites. Daubréelite in aubrites is also generally closer in composition to that in E6 chondrites, but has higher Fe, Ti and Mg contents than in E chondrites (Table 10). E4-5 chondrites show a strong enrichment in Zn compared to both

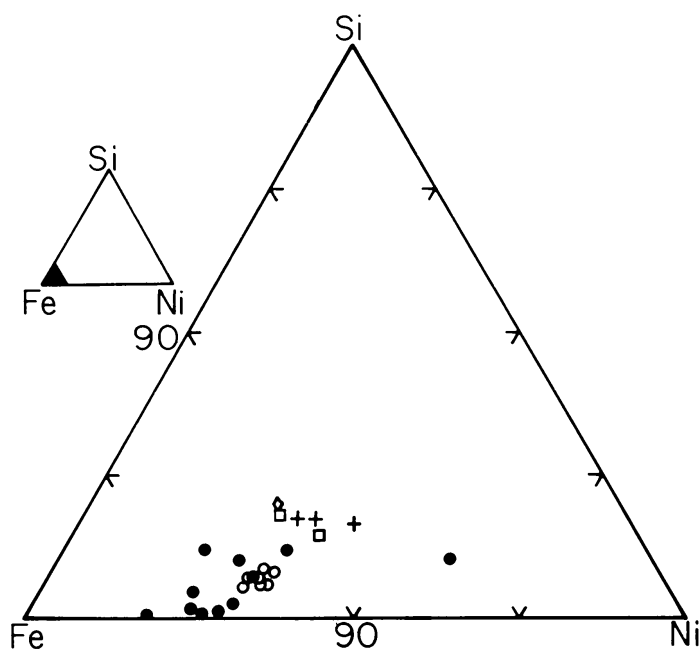


Fig. 3. Kamacite compositions (wt. %) in aubrites and related meteorites compared with enstatite chondrites. Symbols same as in Fig. 1. Data on E chondrites from Keil (1968).

Table 9. Oldhamite compositions in Aubrites.

	Aubres	Bishop- ville	Khor Temiki	Mayo Belwa*	Pena Bl. Springs	Pesyanoë	Avg Aubrite	Avg E6	Avg E4-5
Ca	54.8	54.7	52.0	53.8	54.3	52.7	53.7	53.6	52.8
Fe	<0.02	<0.02	<0.02	0.40	<0.02	<0.02	0.07	0.32	0.81
Ti	<0.02	<0.02	<0.02	<0.02	0.12	<0.02	0.02	-	-
Mg	0.18	0.23	0.19	0.30	0.89	0.14	0.32	0.52	1.26
Mn	0.67	0.84	1.06	1.10	<0.02	0.85	0.75	0.96	0.32
Cr	<0.02	<0.02	<0.02	0.10	<0.02	<0.02	0.02	0.02	0.02
S	44.1	44.4	42.4	43.8	44.5	43.4	43.8	43.8	43.7
Si	<0.02	<0.02	<0.02	-	<0.02	0.04	0.01	-	-
Zn	0.02	<0.02	<0.02	<0.01	<0.02	<0.02	0.01	-	-
Total	99.8	100.2	(95.7)	99.5	99.8	(97.1)			

* Graham *et al.*, 1977.

aubrites and E6 chondrites. Alabandite in aubrites has more Fe but less Mg than alabandite in E6 chondrites (Table 11). Keil (1968) found no alabandite in E4-5 chondrites. Average Ni and P in schreibersite in aubrites is very similar to that in E6 chondrites and Ni is depleted by about a factor of 2 in schreibersite in E4-5 chondrites (Table 12).

MAJOR AND TRACE ELEMENT CHEMISTRY

Bulk analyses for all aubrites have been calculated (Table 13) using the modal data (Table 12). The calculated bulk analysis of Mayo Belwa differs from that given in Graham *et al.* (1977) in having less Al_2O_3 and Na_2O , suggesting a lower plagioclase component in our sample. The high modal plagioclase content of Bishopville results in this aubrite having the highest Al_2O_3 and Na_2O .

Table 10. Daubréelite compositions in Aubrites and related meteorites.

	Cumb. Falls	Mayo Belwa*	Norton Co.	Pesyanoë	Avg Aubrite	Avg E6	Avg E4-5
Ca	<0.02	-	<0.02	<0.02	0.03	-	-
Fe	17.9	19.6	17.0	17.8	18.1	16.7	14.8
Ti	<0.02	0.07	0.96	0.17	0.30	0.07	0.07
Mg	0.74	-	0.71	0.75	0.73	<0.03	0.03
Mn	1.10	-	1.21	1.27	1.20	2.53	0.89
Cr	34.3	35.2	33.5	33.9	34.2	35.5	34.7
S	46.3	44.4	45.6	45.9	45.6	44.5	43.5
Si	0.04	-	<0.02	0.04	0.03	-	-
Zn	0.02	0.22	0.13	<0.02	0.09	0.12	5.2
Total	100.4	99.5	99.2	99.9			

* Graham *et al.*, 1977.

Table 11. Ferromagnesian alabandite compositions in Aubrites.

	Bishop- ville	Bustee	Mayo Belwa ⁽¹⁾	Norton Co.	Pesyano ⁽²⁾	Avg Aubrite	Avg E6
Ca	0.27	0.70	0.72	0.29	0.43	0.48	0.34
Fe	19.9	22.0	23.5	17.1	14.6	19.4	15.4
Ti	0.05	0.04	0.16	<0.02	—	0.06	—
Mg	1.06	1.90	2.10	1.42	2.22	1.74	3.54
Mn	40.2	36.0	33.7	42.9	43.4	39.2	41.3
Cr	0.21	0.56	1.50	0.13	0.44	0.57	0.31
S	38.7	39.1	38.1	38.7	38.3	38.6	38.8
Si	<0.02	0.02	—	<0.02	—	0.01	—
Zn	<0.02	<0.02	<0.02	<0.02	—	<0.01	—
Total	100.4	100.4	99.8	100.6	99.4		

⁽¹⁾ Graham *et al.*, 1977. ⁽²⁾ Keil, 1968.

Table 14 compares the average of the silicate portions of our calculated bulk analyses with the average of wet chemical analyses of aubrites, and with those of E chondrites. The average of the wet chemical analyses of aubrites (Keil, 1969b) is very similar to that of our calculated bulk analyses, except for Na₂O and, to a lesser extent, K₂O. The amount of reported Na₂O (1.32%) (Keil, 1969b) would result in a great excess of Na₂O when combined with the available Al₂O₃ (0.67%). Therefore, the high Na₂O content of the average of wet chemical analyses for the aubrites must be due to analytical error in these measurements. This is supported by INAA data of Schmitt *et al.* (1972) on five aubrites, four E4–5 and three E6 chondrites. Their reported average Na content in aubrites (0.48% Na₂O) is lower by about a factor of three. However, Na data given for E4–5 and E6 chondrites agrees well with those presented by Keil (1969b).

Bulk analyses of aubrites (this study), when compared to average E4–5 and E6 chondrites show that aubrites are closer in bulk composition to E6 chondrites. This generally confirms the mineral data which also show a similar relationship. Although similar, the major difference between aubrites and E6 chondrites is the

Table 12. Schreibersite compositions in Aubrites and related meteorites.

	Aubres*	Bishop- ville*	Khor Temiki*	Mayo Belwa ⁺	Norton Co.*	Pesyano [*]	Shallo- water	Mt. Egerton	Avg Aubrite	Avg E6	Avg E4–5
Fe				69.8			73.3	65.5			
Si				—			1.42	0.23			
Co				0.07			0.11	0.02			
Ni	28.4	51.2	48.0	13.3	26.1	25.0	10.4	18.4	27.6	25.2	12.4
P	15.4	15.0	15.1	15.0	15.4	15.3	15.1	15.2	15.2	15.4	15.5

* Data from Wasson and Wai, 1970. ⁺ Graham *et al.*, 1977.

Table 13. Calculated bulk compositions of Aubrites (wt. %).

	Aubres	Bishop-ville	Bustee	Cumb. Falls	Khor Temiki	Mayo Belwa	Mayo Belwa*	Norton Co.	Pena Bl. Springs	Pesyanoe	Shallowater	Average
SiO ₂	59.5	59.1	57.3	57.2	59.1	59.5	59.3	56.5	59.3	59.1	48.9	57.6
TiO ₂	0.20	0.03	0.04	0.02	0.05	0.03	0.07	0.01	0.01	0.03	0.02	0.05
Al ₂ O ₃	0.23	2.72	0.61	0.21	1.25	0.18	2.30	0.25	0.46	1.27	0.55	0.91
Cr ₂ O ₃	0.02	0.02	0.02	0.05	0.01	0.02	0.06	0.01	0.03	0.03	0.0	0.03
FeO	0.02	0.07	0.05	0.08	0.01	0.03	0.25	0.06	0.07	0.05	0.04	0.07
MnO	0.07	0.01	0.09	0.08	0.04	0.02	0.08	0.0	0.06	0.03	0.0	0.04
MgO	38.9	34.8	37.9	38.5	37.8	39.3	34.2	39.8	38.5	37.5	32.8	37.3
CaO	0.48	1.03	2.29	0.63	0.75	0.64	0.75	1.16	0.83	0.62	0.15	0.85
Na ₂ O	0.13	1.53	0.30	0.08	0.59	0.08	1.19	0.11	0.24	0.61	0.26	0.20
K ₂ O	0.0	0.08	0.01	0.0	0.02	0.0	0.12	0.0	0.01	0.03	0.02	0.03
P ₂ O ₅	0.0	0.0	0.0	0.0	0.0	0.0	0.02	0.0	0.0	0.0	0.0	<0.01
Fe	0.23	0.0	0.45	1.51	0.24	0.0	0.35	0.72	0.0	0.50	7.42	3.20
Ni	0.01	0.0	0.03	0.10	0.01	0.0	0.01	0.04	0.0	0.03	0.44	0.06
Co	0.0	0.0	0.0	0.01	0.0	0.0	-	0.0	0.0	0.0	0.03	<0.01
P	0.0	0.0	0.0	0.0	0.0	0.0	-	0.0	0.0	0.0	0.02	<0.01
FeS	1.19	0.68	0.89	1.54	0.15	0.15	-	1.34	0.0	0.0	9.13	1.34
Schreib.	0.0	0.0	0.00	0.0	0.0	0.0	-	0.0	0.0	0.0	0.18	0.02

* Analysis from Graham *et al.*, 1977.

Table 14. Silicate portions of Aubrites and enstatite chondrites, recalculated to 100 wt.%.

	Aubrites This work	Aubrites Keil, 1969b	E4-5 Keil, 1969b	E6 Keil, 1969b	Aubrites+10% Plag An15
SiO ₂	59.5	58.1	61.6	60.3	60.0
Al ₂ O ₃	0.94	0.72	3.35	2.90	2.8
MgO	38.5	38.7	30.8	33.5	34.9
CaO	0.88	0.98	2.46	1.82	1.10
Na ₂ O	0.21	(1.42)	1.60	1.24	1.10
K ₂ O	0.03	(0.11)	0.22	0.20	0.10

Other oxides generally 0.05% and not included in calculation. Parentheses indicate less reliable older data.

result of plagioclase content. Aubrites have less plagioclase than E6 chondrites as indicated by their lower Al₂O₃, Na₂O, K₂O and CaO.

Rare earth element data for aubrites, as compared to E chondrites, are most critical in an interpretation of their origin. REE data of Schmitt *et al.* (1966) and Boynton (pers. comm., 1978) on seven aubrites show negative Eu anomalies which are not found in E chondrites. REE data for Norton Co. (an aubrite) and Abee (an E4 chondrite) are shown in Fig. 4 in order to compare these two groups. REE data by Wänke (pers. comm., 1979) on Abee and Hvittis (an E6 chondrite) show nearly identical patterns, suggesting that these may be typical of the entire enstatite chondrite group.

The presence of large negative Eu anomalies in aubrites indicates that they probably formed by fractional crystallization of a melt and are not simply nebular condensates. If 10% plagioclase, with a composition of An₁₅ (that of the average for E6 chondrites), is added to the average aubrite (as shown in Table 14) good agreement between the two groups is reached. This is consistent with derivation of aubrites from E6 chondrites by means of differentiation and fractional crystallization.

Identical oxygen isotope ratios have been found in all aubrites, Mt. Egerton and Happy Canyon (R. N. Clayton, pers. comm., 1979). Clayton *et al.* (1976) concluded that aubrites are the only known meteorites that can be related to E chondrites on the basis of oxygen isotopes. This indicates that aubrites and E chondrites must have formed in the same region of the solar nebula, thus sharing a common oxygen reservoir.

Richter *et al.* (1979) determined concentrations of certain siderophile and volatile trace elements in the aubrites, diogenites and E chondrites. They examined the data and determined patterns for each group and found that each group differed. They argue that the observed mismatches between aubrites and diogenites indicates that aubrites could not have formed by planetary differentiation processes and thus, by default, formed by nebular condensation. However, a mismatch also exists between aubrites and E chondrites, making it difficult to argue in favor of an origin by nebular condensation.

COSMIC RAY EXPOSURE AGES

Eberhardt *et al.* (1965) determined ages on nine aubrites. Six have exposure ages of approximately 50 m.y. Aubres and Shallowater have ages of about 20 m.y. and Norton Co. has an age of about 200 m.y. Herzog *et al.* (1977), correcting for shielding effects on Norton Co., reported an exposure age of about 80 m.y. Zähringer (1962, 1968) determined exposure ages of 6 E chondrites. E6 chondrites have an age of about 21 m.y. If the aubrites formed by accretion of E chondritic material, one would like to see older exposure ages for the E chondrites and younger ages for the aubrites. To attempt to reconcile this problem, Wasson and Wai (1970) proposed a model which involved accretion of E4–5 chondritic material followed by accretion of aubritic material, so that aubrites would be on the outside of the parent body and therefore have the longest exposure to cosmic-rays. This would account for the presence of solar-type gases in the aubrites, which were supposedly trapped during recrystallization while in the presence of the solar nebula. However, this theory for the formation of the aubrite parent body is not consistent with REE data. Also, these solar-type gases are found on

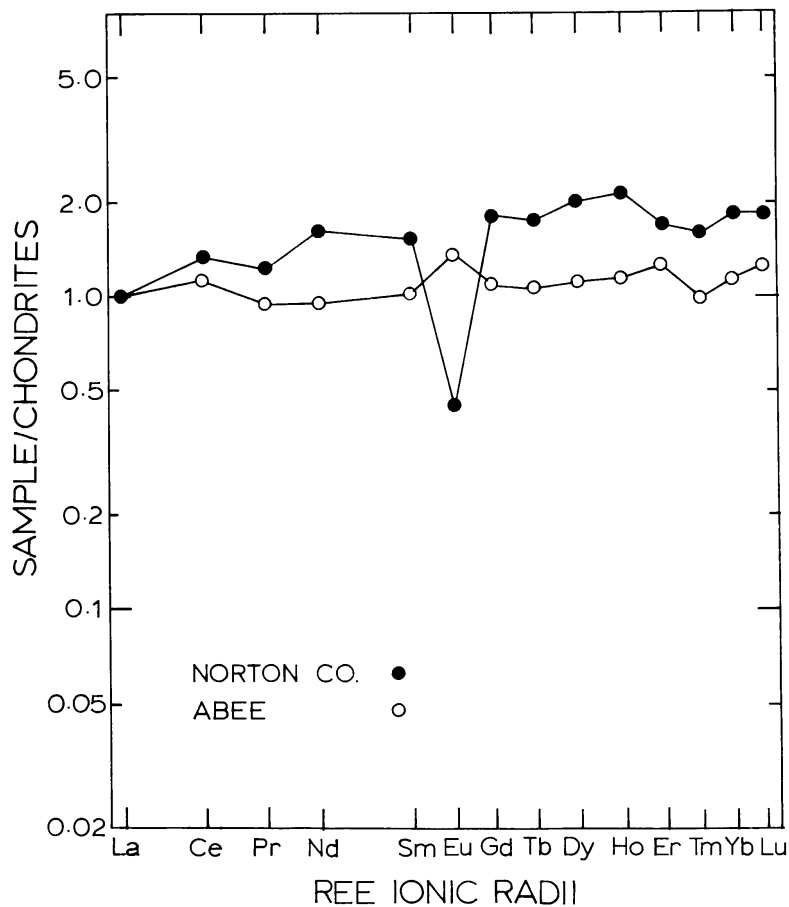


Fig. 4. Rare earth element data for the Norton Co. aubrite compared with the Abee enstatite chondrite. Data from Schmitt *et al.* (1963).

the surface of grains and concentrated in dark portions of the meteorites, suggesting that they are the result of irradiation by cosmic wind and not trapped during recrystallization.

Since the mechanism for moving meteoritic material from the asteroid belt to earth-crossing orbits is poorly understood, it is difficult to interpret the range in exposure ages observed in aubrites and E chondrites. A number of collisional events may successively expose fresh portions of the same meteorite, thus yielding a range in exposure ages for chunks of the same parent.

Zellner *et al.* (1977) have made a study of several asteroids using multispectral photoelectric photometry and polarimetry. They compared this to laboratory photometry and polarimetry data of Norton Co. Based on the similarities in spectral and polarization characteristics, they have identified three asteroids that could be the parent bodies of the aubrites. The three lie at various distances, ranging from about 2 to 2.7 AU, a separation of some 65 million miles. Meteoritic materials from these asteroids will have widely varying path lengths to earth interception. This, coupled with variable collisional histories for the material, may explain the range in exposure ages observed in the aubrites.

CONCLUSIONS AND MODEL

Based on the similarities in bulk chemistry of the silicate portions, individual phases, and inferred oxygen fugacity, we conclude that the parent material for the aubrites may have been E6 chondrites and propose the following model for the formation of aubrites.

Agglomeration of silicates and metal produced by successive nebular fractionation resulted in an asteroid-sized body of E6 chondrite composition (Baedeker and Wasson, 1975). Accretional heating and decay of radionuclides such as ^{26}Al resulted in melting either of the entire body or just the interior. An immiscible liquid of Fe-Ni and sulfides sank to form a core. This process removed most of the refractory, volatile siderophile and calcophile elements. Heat loss through conduction and radiation cooled the body and forsterite and enstatite began crystallizing near the surface and sank. With increased cooling enstatite became the dominant crystallization phase. As more and more enstatite crystallized and sank, the surface became enriched in elements such as CaO, Al_2O_3 , Na_2O and K_2O which do not enter the enstatite lattice. This assumes that little or no mixing of the liquid occurred. Divalent Eu is also incompatible in the enstatite lattice and would also be concentrated with the other incompatibles (Taylor *et al.*, 1969; Schnetzler and Philpotts, 1970; Drake and Weill, 1975). Adcumulate growth of enstatite resulted in the entrapment of olivine, as well as small amounts of metal and sulfides that had not yet sunk to the core. As the body continued to cool, adcumulate crystallization dominated and minor amounts of diopside crystallized from interstitial liquid. Crystallization of diopside is unlikely to have occurred at the surface, due to the strong depletion of MgO and SiO_2 that resulted from the crystallization of enstatite. The interstitial liquid also became enriched in incom-

patible elements but differed in composition from the liquid near the surface in that it was depleted in CaO due to the crystallization of diopside. Plagioclase was the last phase to crystallize in the melt as indicated by its highly albitic composition and the enstatite-rich parent melt. This occurred in the remaining interstitial areas and at the surface. The composition of the feldspar at the surface was approximately An 15, as found in E6 chondrites. Since the crystallization of diopside depleted the interstitial liquid in CaO, the feldspar that crystallized here was of lower An composition. This would explain the difference in plagioclase composition between aubrites and E6 chondrites. Mt. Egerton, which is predominantly enstatite included in metallic Fe-Ni, probably represents the core-mantle boundary of the aubrite parent body. Shallowater, with the highest modal % metal of the aubrites, may represent the transition between the metal-enstatite interface and the more dominantly enstatitic layer higher in the mantle.

If melting were limited to the interior of the body, the inner portion of the crust would have experienced thermal metamorphism through heat loss from the interior of the body. This would account for the equilibrated nature and highly recrystallized textures observed in E6 chondrites. Happy Canyon may represent the product of impact melting of E6 chondritic material (Olsen *et al.* 1977) on this parent body.

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