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First known EL5 chondrite—evidence for dual genetic sequence for enstatite chondrites

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The enstatite chondrites form two compositionally distinct groups—the EH and EL chondrites—and four petrologic types (types 3–6), where each type represents increasing degrees of metamorphic alteration[1,2]. Prior to the recovery of the Antarctic meteorite Reckling Peak A80259, the subject of the present report, all known EL chondrites were petrologic type 6, whereas all known EH chondrites were types 3–5. It has long been appreciated that the variations in bulk composition preclude a simple conversion of EH4 material into EL6 material[3–7]. However, complex models involving simultaneous variations in bulk composition and petrologic type have been discussed[1,5,8,9] and may be implied by other classification schemes in common use; that of Anders-Keil (type I–intermediate–type II) and that of Van Schmus and Wood (E3-E4-E5-E6). We report here the discovery of the first EL5 chondrite. An EL5 breaks the EH3,4-EH5-EL6 sequence, and indicates that the enstatite chondrites constitute two discrete, isochemical metamorphic sequences, EH3–5 and EL5–6.

The enstatite chondrites are a small (25-member) class of meteorites which formed in a uniquely reducing environment. As a consequence, they contain many terrestrially unknown minerals, such as niningerite ((Mg,Fe)S), and Si-bearing metal. They are extremely heterogeneous and show large variations in their bulk composition; sulphur and other chalcophile elements vary by a factor of three and iron and the other siderophiles vary by a factor of approximately two. They also differ from each other in the extent to which they have suffered metamorphism; some are only slightly recrystallized while others are highly recrystallized, possess coarse textures and have experienced complete obliteration of primary structures such as chondrules[3–6]. When these characteristics were first described, it seemed as though there was a single sequence of enstatite chondrites. At one end of the sequence were meteorites which Anders[4] and Keil[6] termed type I, with high siderophile element abundances and with textures displaying small amounts of recrystallization. These graded through two intermediate meteorites (St Sauveur and St Marks) to type II, with low siderophile element abundances and highly recrystallized textures. The situation was apparently very different from the ordinary chondrite case, where textural variations occur in each of the three coherent chemical groups.

Table 1 Modal abundance (wt %) in Reckling Peak A80259

Enstatite	47
Plagioclase	4
Kamacite	10
Limonite	28
Troilite	10
Niningerite	0.5
Schreibersite	<0.1
Total	99.5
Points counted	1,555
Area analysed (mm^2)	143

In 1967 Van Schmus and Wood[1] introduced a highly successful two-dimensional grid scheme for classifying meteorites in which bulk composition constitutes one dimension and extent of metamorphic alteration (petrologic type) constitutes the other. Keil's type I, intermediate type and type II are equivalent to E4, E5 and E6 in this scheme, even though the E class thus defined is not isochemical. Sears *et al.* suggested that the E class actually comprises two isochemical classes, EH and EL, and emphasized that the EH and EL chondrites were not simply related by the sequence EH4-EH5-EL6. The discovery of an EL5 chondrite now provides strong evidence that the enstatite chondrites are not a single genetic sequence.

The Reckling Peak A80259 meteorite is a highly weathered, 20.2 g stone which was found in the Antarctic during the 1980–81 summer season. B. Mason originally classified it as an E5 chondrite[10]. We have carried out a detailed petrologic examination of the meteorite using the library section at the Smithsonian Institution, and we have performed a bulk analysis using neutron activation analysis. Modal analyses (Table 1) were made microscopically, using an automated point counter; mineral vol. % was converted into wt % using estimated mineral densities. Mineral compositions (Table 2) were determined with an electron microprobe using crystal spectrometers and following standard Bence–Albee and ZAF correction procedures. Cobalt was determined in Fe,Ni metal after subtracting the contribution of the Fe K_β peak from Co K_α. Two 150 mg fragments of Reckling Peak A80259 were analysed by instrumental neutron activation analysis, along with two other enstatite chondrites and a variety of primary synthetic and secondary standards. The data reported here were gathered in four irradiations with duplicate chips always being run in

Table 2 Mineral compositions (wt %) in Reckling Peak A80259

	Enstatite		Kamacite	Troilite	Niningerite
No. of grains	16		25	26	12
SiO_2	59.4	Si	2.1		
Al_2O_3	0.19	Ni	6.4		
FeO	0.37	Co	0.43		
MgO	39.9	P	0.64		
CaO	0.69	Fe	89.7	58.1	32.1
MnO	<0.08	Mg		0.07	11.2
Total	100.55	Ca		<0.04	3.0
End member	$Fs_{0.5}Wo_{1.2}$	Mn		0.48	12.8
		Cr		3.1	1.3
		Ti		0.47	<0.08
		Zn		0.10	<0.09
		S		37.8	41.5
		Total	99.27	100.12	101.9

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separate irradiations. Irradiations were performed at the University of Missouri research reactor and samples were counted for various times over a period of 6 weeks.

Reckling Peak A80259 consists predominantly of enstatite, kamacite and troilite, with minor plagioclase and accessory niningerite and schreibersite (Table 1). It contains approximately 12 vol.% radial, barred and porphyritic pyroxene chondrules, 980–1,600 μm in apparent diameter. Chondrule textures are recrystallized but readily delineated. Euhedral enstatite grains exhibit highly undulose extinction and range in size from 15 to 375 μm. They occur in kamacite- and/or troilite-rich areas and in apparently recrystallized areas surrounded by anhedral enstatite and plagioclase. Approximately 90% of the enstatite exhibits parallel extinction under crossed polarizers and, hence, is probably orthorhombic. Because clinoenstatite may also exhibit parallel extinction under certain crystal orientations, the actual abundance of clinoenstatite is somewhat greater than 10%. Plagioclase occurs as very small (≤2 μm) grains, interstitial to euhedral enstatites. Plagioclase volatilized very rapidly under electron bombardment and was impossible to analyse with the microprobe. Kamacite occurs interstitial to silicates and troilite and as round globules, 30–110 μm is apparent diameter. Much of the kamacite has been replaced by limonite, a terrestrial weathering product that constitutes 28 wt% of the meteorite.

The high CaO and low MnO content of enstatite in Reckling Peak A80259 (Table 2) is similar to type 6 enstatite chondrites, although Abee (petrologic type 4) and St Sauveur (type 5) also contain enstatite with low MnO (6). Enstatite FeO content in Reckling A80259 is most similar to the two type 5 chondrites and is intermediate between that of type 4 and type 6 meteorites. The predominance of orthoenstatite and presence of ≥10% clinoenstatite is most similar to that of St Marks (type 5)[6]. (Type 6 chondrites contain almost entirely orthopyroxene and type 4 enstatite chondrites contain abundant clinopyroxene.) The kamacite Si content of Reckling Peak A80259 (2.1 wt%) is greater than that of type 6 chondrites (1.3 wt%) and less than that of type 4 or 5 chondrites (3.2 wt%)[6]. The presence of niningerite and absence of ferroan alabandite in Reckling Peak A80259 is a characteristic shared by the type 4 and 5 chondrites[6]. Some of the mineralogical characteristics of Reckling Peak A80259 are intermediate between type 4–5 and 6, but the absence of any large grains of plagioclase and the recrystallized, but readily delineated texture of the chondrules, unequivocally indicate type 5. Thus, the petrographic, mineralogical and crystallographic characteristics of Reckling Peak A80259 indicate that it is the third known type 5 enstatite chondrite.

The results of our determination of the bulk composition of the meteorite are presented in Fig. 1. In the same irradiation as that of Reckling Peak A80259 we analysed four samples of the Allende meteorite and found excellent agreement with literature values. Also shown in Fig. 1 are the mean compositions of the EH and EL groups, as calculated from the data compilations of Baedecker and Wasson[11] and Sears *et al.*[2], the compositions of the two previously known type 5 enstatite chondrites (St Marks and St Sauveur), and two other enstatite chondrites (Qingzhen and Allan Hills A77295) which were analysed at the same time and with the same standards and techniques as Reckling Peak A80259. Qingzhen and Allan Hills A77295 (paired with Allan Hills A77156) are two EH chondrites[12,13] whose analyses we publish here to demonstrate the absence of systematic errors in our data. The St Marks data are from various sources[2,11] and the St Sauveur data are from ref. 2. Siderophile, chalcophile and alkali elements have been plotted separately from refractory, lithophile and other elements because of their different abundance patterns in these meteorites. Within each division, elements are plotted in order of decreasing nebula condensation temperature. The element to Sc ratio for the sample has been divided by the same ratio for CI meteorites to obtain the value for the vertical axis. Normalization to a refractory element is the standard procedure for removing the effect of variations in major volatiles (for enstatite chondrites it is not normally an important normalization, but in the present case would remove any effects resulting from hydration during weathering; this is discussed below). The CI normalization removes abundance trends resulting from nucleosynthesis.

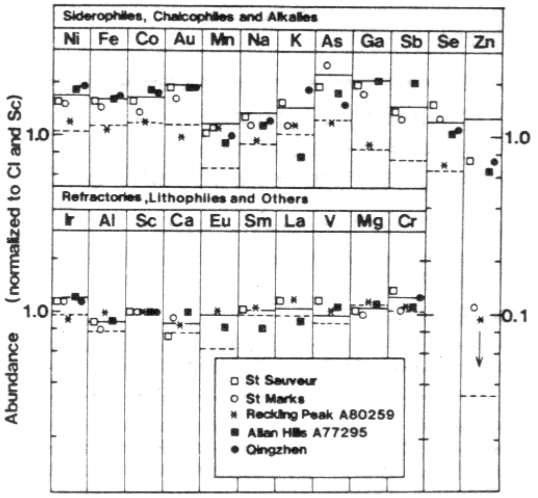

Fig. 1 Abundance pattern for selected elements in enstatite chondrites as determined by neutron activation analysis. The solid horizontal lines indicate mean values for the EH class and the broken horizontal values refer to mean values for the EL class.

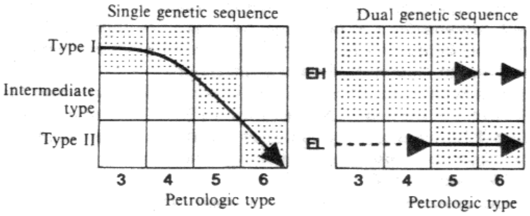

Fig. 2 Schematic diagram illustrating the two ways of viewing enstatite chondrite relationships. The existence of an EL5 is evidence for the dual genetic sequence.

When normalized this way, EH chondrites are approximately 50% enriched in siderophile, chalcophile and alkali elements with respect to EL chondrites (Fig. 1). St Marks, St Sauveur, Qingzhen and Allan Hills A77295 usually plot close to the mean EH value, whereas Reckling Peak A80259 plots significantly below these meteorites, close to the mean EL value. In the one case where this does not happen (Mn), we suspect a problem with the literature value. Zinc is a special case, since it is a particularly volatile element and in ordinary chondrites its abundance varies systematically with petrologic type. This suggests that metamorphism may be involved in determining its abundance, rather than the factors (usually thought to be nebular processes) which result in the bimodal distribution of the other chalcophile elements.

Nickel, Co, Fe, Au and Ir are siderophile elements which lie within experimental error of the mean EL value. Iridium is unusual in that the difference between EH and EL is much less than for the other siderophiles—probably this is associated with its refractory nature—but nevertheless indicates an EL classification for Reckling Peak A80259. The chalcophiles—even Mn and the alkalies behave like chalcophiles in enstatite chondrites—are also consistent with an EL classification, with the exception mentioned above. Overall, the compositional data indicate that Reckling Peak A80259 is an EL chondrite.

A major potential problem in interpreting the present data is associated with the extensive weathering the meteorite has suffered. Biswas *et al.* discussed the effects of weathering on several Antarctic stone meteorites and concluded that any effects were minor[14]. However, their samples were less severely weathered than Reckling Peak A80259 (category 'A' compared with 'B/C' for Reckling Peak A80259 according to ref. 10). On the other hand, Bhandari *et al.*, when analysing the Parsa enstatite chondrite, argued that their data should be multiplied by 1.1 to compensate for weathering which had caused a dilution effect[15]. In fact, the concentrations we determined for Reckling Peak A80259 are 15–20% lower than mean EL for all elements; for example, our values for Fe, Co, Na and Sc are 218 $\mathrm{mg\,g^{-1}}$, 668 $\mu\mathrm{g\,g^{-1}}$, 4.60 $\mathrm{mg\,g^{-1}}$ and 5.93 $\mu\mathrm{g\,g^{-1}}$, respectively, compared with EL group means of 265,780, 5.9 and 7.7, respectively. However, a dilution effect due to weathering will not affect Fig. 1 because of the Sc-normalization. It is possible, in principle, that a factor of 2 dilution could cause the siderophile elements in an EH chondrite to mimic EL values (we question that such extensive weathering would leave the rock recognizably meteoritic), but then the lithophile element concentrations would also be a factor of 2 lower than mean EH which is certainly not the case for Reckling Peak A80259. Interestingly, the mineral in enstatite chondrites that is most vulnerable to weathering is oldhamite (CaS) and, indeed, this mineral is absent from Reckling Peak A80259, yet the elements associated with oldhamite (the rare earth elements and much of the Ca) are present in normal EL abundances. Presumably, although decomposition of the oldhamite occurred, its decomposition products were not transported more than a few millimetres.

Figure 2 summarizes the relationship between enstatite chondrite classification and the question of whether there are one or two genetic sequences. The left-hand panel represents the single sequence model whereby type I → intermediate type → type II; the right-hand panel describes the two sequence models wherein EH3 → EH6 and EL3 → EL6. The occupied locations in the grid are shaded. The important point is that petrologic type 5 enstatite chondrites are now known to exist from both the EH and EL chemical groups. We suggest this is compelling evidence for two genetic sequences, analogous to the three sequences formed by H, L and LL ordinary chondrite cases. The observed tendencies for most EH chondrites to be of low petrologic type, and most EL chondrites to be of high petrologic type is also analogous to the situation for ordinary chondrites; for instance, most L chondrites (69%) are type 6, whereas most H chondrites (49%) are type 5[16].

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