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The Lodran meteorite and its relationship to the ureilites

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SUMMARY. Lodran is a unique meteorite consisting of roughly equal amounts of metal, olivine, and pyroxene with minor amounts of sulphide, chromite, phosphide, chrome-diopside, and a new phase with a composition close to $(K,Na)AlSi_5O_{12}$. Zähringer reported planetary-type rare gases in both the metal and silicates, suggesting a primitive nature. The pyroxene composition is $Fs_{13\cdot8}$ with little variation. Olivine composition averages $Fa_{12\cdot6}$, but varies at least ±20 % both among grains and zoned within single grains; only the Fe-rich olivine is in equilibrium with the pyroxene. The metal probably cooled rapidly (700 K/Myr) at high temperatures and slower (30 K/Myr) at lower temperatures. Two compositional populations of chromite are found.

A model for the formation of Lodran includes three steps: Formation of large olivine, pyroxene, and metal grains, with the trapping of small olivine inclusions in pyroxene and pyroxene in olivine. Equilibration and recrystallization of olivine, pyroxene, and metal, loss of alkalis and Ca; this probably occurred in a parent-body setting. And incorporation of reducing materials and mild reheating sufficient to produce the zoning in the olivine but not enough to re-equilibrate the pyroxene.

Phase compositions and rare-gas concentrations in ureilites are similar to those in Lodran. In some respects Lodran appears to be a metal-rich ureilite, but the higher Fe/(Fe+Mg) ratios in the latter (Fa 21 olivine) suggest origin on separate parent bodies.

The Harvard University meteorite is a mesosiderite and not closely related to Lodran.

THE Lodran meteorite fell in 1868 (Oldham, 1869). Tschermak (1870) reported that the meteorite is granular, friable, and composed of roughly equal amounts of metal, olivine, and pyroxene with minor amounts of troilite, chrome-diopside, and chromite. Many silicate grains are euhedral to subhedral and as large as 1 to 2 mm. Prior (1916) classified Lodran as the only member of his 'lodranite' group of stony-irons and stated that it was closely related to the ureilites.

Tschermak (1870) reported orthopyroxene and olivine compositions Fs 18 and Fa 13, values quite far from equilibrium. Zähringer (1968) reported rare-gas data that showed Lodran to be rich in planetary-type rare gases. This together with the approximately chondritic composition reported for the silicates suggested that Lodran might be rather primitive (i.e. have escaped igneous fractionation) and worthy of further study.

Experimental

Microscopy and sample description. Samples available to us were a microprobe thick section and a petrographic thin section from the British Museum (BM44003, probe section P911) and two microprobe thin sections from the Smithsonian Institution (USNM 481). The main mass listed by Hey (1966) as being in the Geological Survey

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Museum, Calcutta, is apparently lost. Although Coulson's (1940) catalog listed a mass of 707 g at Calcutta, a personal inquiry at the museum by K. Fredriksson (private communication) revealed that its whereabouts are not known.

Figs. 1a-1d and 5 are photomicrographs of the Lodran probe sections. The silicates are typically large (0·5 to 2 mm) equant grains. Metal shows in polished surfaces as mm-sized patches and is probably interconnected throughout the meteorite. The abundant 120° triple junctions and rounded and sutured grain boundaries give evidence of solid-state recrystallization. Stewart (1975) attributes similar textures in some lunar rocks to long (*c.* 10^8 yr) subsolidus annealing at high (1250 K) temperatures. Some olivine and pyroxene grains have euhedral faces extending into metal, indicating either that the faces grew into voids that were later filled with metal or that crystallization energy for these silicates is great enough to overcome stabilization that would be gained by minimizing the area of the metal-silicate interface.

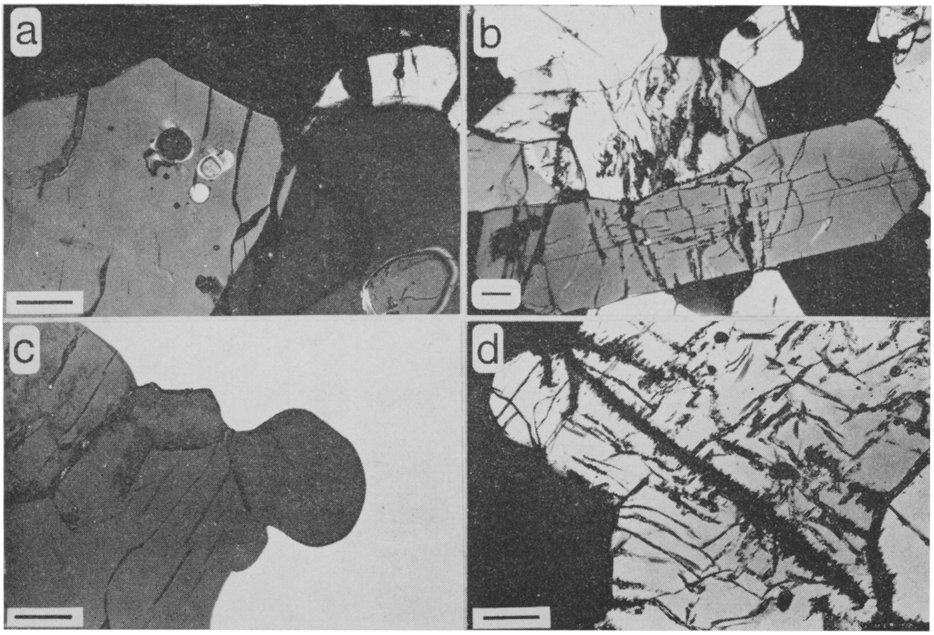


FIG. 1. Photomicrographs of Lodran thin sections: (a) Pyroxene (large grain on left) with three included unzoned olivine grains. (b) Suturing of grain boundaries. Large elongate grain with crystal faces against metal (opaque) is olivine. (c) The rounded grain surrounded on three sides by metal (white) is the olivine grain that was scannned to produce fig. 4. (d) Crack in olivine containing a melange of unresolvable silica-rich material. All scale bars 100 μm. 1 a,b,d—transmitted light, crossed polars; 1 c—reflected light.

Thin sections between crossed polars have two particularly striking features: One is the clean condition of the grains giving uniform, bright interference colours; occasional pyroxene grains show polysynthetic twinning with parallel extinction. The other is the presence of rounded olivine inclusions in many pyroxene grains (fig. 1a) and, somewhat less common, rounded pyroxene inclusions in some olivine grains; because of the rounded shape and lack of uniform crystallographic orientation with respect to the host grain, these inclusions are a result of entrapment rather than exsolution.

Tschermak (1870) reported rounded inclusions in the pyroxene which he suspected to be plagioclase. We scanned our three sections on the microprobe for Al-rich grains, but no plagioclase was found. An optical search was also negative. Tschermak's description and sketches of the 'feldspar' inclusions are similar to the rounded olivine and pyroxene inclusions and these may be what he observed.

Point counting the three probe sections yielded a bulk mineralogy (by volume) of 77 % silicate, 20 % metal, 2·7 % troilite, 0·3 % chromite.

Electron-probe techniques. The ARL-EMX electron microprobe at U.C.L.A. was operated at a potential of 15 kV and a sample current of 0·03 μamp. For alkali-containing phases the sample current was reduced to 0·02 μamp and counting times held to 4 sec. Standards were measured before and after samples and the two sets averaged for data reduction. Drift was calculated from the two standards measurements. Runs with >3 % drift were discarded; in most cases the drift was much less. Backgrounds were measured on representative sample grains. Standards were either analysed minerals and synthetic glasses of similar composition to the samples or elemental oxides. Data corrected for background and deadtime were reduced using the method of Bence and Albee (1968; Albee and Ray, 1970). A typical analysis was made by moving linearly across the grain in five (or more, depending on grain size) subequally spaced steps. Data were averaged to calculate a bulk analysis for the grain.

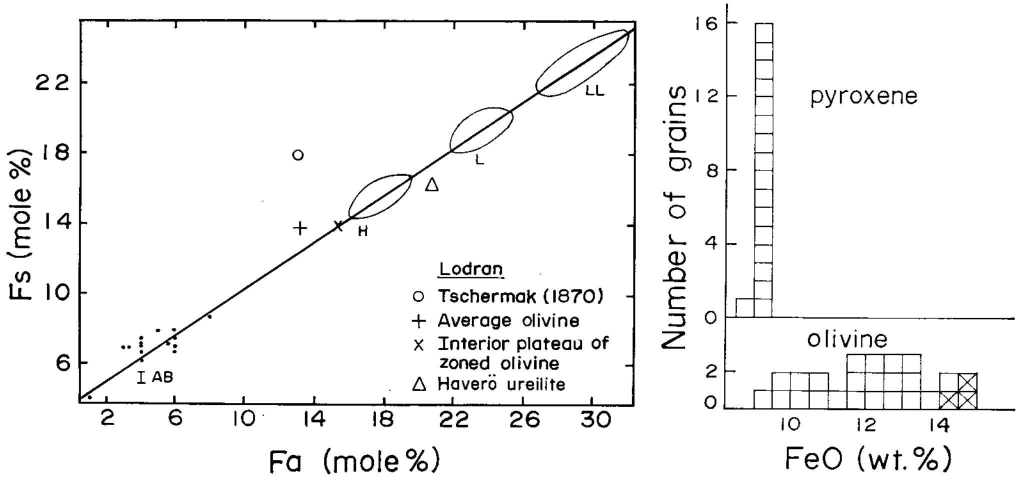
Bence-Albee correction factors and well-analysed standards were not available for V. The V values for chromite (Table IV) were determined by comparing counting rates with those for chromite in the Patwar mesosiderite (0·60 wt. % V_2O_3 by microprobe, Bunch and Keil, 1971). Only background and deadtime corrections were made.

An approximate bulk analysis for the major elements in the silicate minerals of Lodran was obtained by defocusing the electron beam to about 10 μm diameter and taking data for Si, Fe, and Mg at 137 random points and for Ca and Al at 159 random points. These data were also reduced by the Bence-Albee scheme.

An analysis for bulk Ni in the metal was made by counting with a focused beam at 10 points in each of seven metal grains. Similar counts were made on 10 synthetic Fe–Ni alloys previously analysed by atomic absorption. These spanned a range of 3·8 to 41·01 wt. % Ni. A sample of 99·99 wt. % Fe was used to obtain a background value. A working curve of background corrected counting rate *v*. Ni content was prepared from the standards and used to determine Ni concentrations. Using a 20 kV accelerating potential Ni values were determined at the edges and centres of taenite grains and lamellae in order to estimate cooling rates. A step scan was made across the lamellae to establish the Ni profile. The width of the grain was measured using the calibrated stage drive on the probe. Several analyses were made at each edge and in the centre of each grain to improve the precision of these Ni values.

TABLE I. *Average compositions (in wt. %) and molecular components of pyroxene, chromian diopside, and olivine in the Lodran meteorite*

	SiO_2	MgO	FeO	CaO	MnO	Cr_2O_3	Al_2O_3	Na_2O	Sum	En	Fs	Wo
Px	57·6	31·3	9·2	1·36	0·51	0·39	0·49	0·03	100·8	84	13·8	2·6
Cr-Di	55·7	17·2	3·9	20·6	0·32	1·55	1·28	0·77	101·3	50	6·4	43
Ol	40·8	46·8	12·0	0·08	0·47	0·04	0·10	—	100·3	87	12·6	—



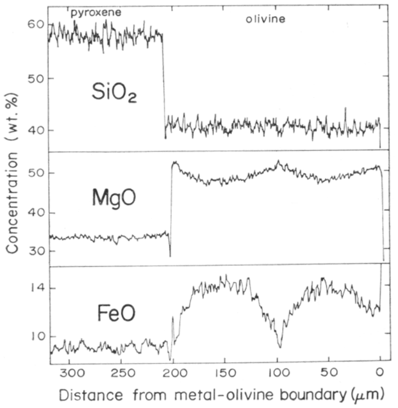
FIGS. 2 and 3: FIG. 2 (left). Plot of Fa content of olivine *v*. Fs content of orthopyroxene for ordinary chondrites, silicate inclusions of group IAB irons, Lodran, and Haverö ureilite. (Chondrite data from Keil and Fredriksson, 1964, and tabulations in Wasson, 1974; IAB data from Bunch *et al.*, 1970, Bunch *et al.*, 1972, Rambaldi *et al.*, 1974, and Scott and Bild, 1974; Haverö data from Wlotzka, 1972). FIG. 3 (right). FeO content (in wt. %) of olivine and pyroxene in Lodran. The three olivine boxes with X's represent grains included in pyroxene illustrated in fig. 1a.

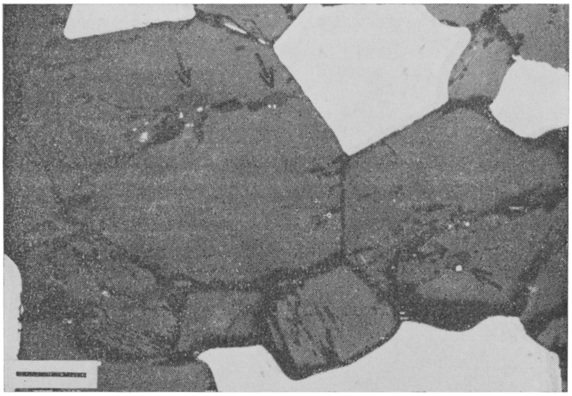
Results and Discussion

Table I shows the average olivine and pyroxene compositions in Lodran. Relative errors on these and other analyses are ±2 % or less for major elements and ±10 % or less for minor elements. The pyroxene values are based on the average composition of the three major elements in 15 grains and the minor elements in 4 grains. The olivine averages represent 21 grains for the major and 6 grains for the minor elements. Only one chrome-diopside grain was found. Compositions are also listed in terms of end-member minerals. The values of Fs 13·8 and Fa 12·6 are much closer to values observed in equilibrated meteorites (fig. 2) than are Tschermak's values of Fs 18, Fa 13.

The grain-to-grain variation in olivine and pyroxene composition is shown as histograms in fig. 3. The pyroxene is essentially constant in composition. The olivine has an FeO content that varies between about 9·2 and about 14·7 wt. %. The three X-marked boxes on the olivine plot are grains included in pyroxene (fig. 1a). Individual olivine grains are zoned with FeO decreasing from centre to edge. This zoning is opposite in sign to that normally observed during igneous fraction or expected for nebular condensation (Lord, 1965). Instead, a distinct decrease in degree of oxidation after grain formation is required.

Fig. 1c shows olivine bordering pyroxene. This olivine is a single grain (it goes to extinction uniformly between crossed polars), but it has a crack running through it. Scans were made for Fe, Mg, and Si from the metal going through the olivine to the pyroxene, crossing the crack in the process (fig. 4); metal is on the right and pyroxene on the left. The FeO content of olivine ranges from about 8·5 wt. % (Fa 8·6) at the edge and near the crack to a plateau of 14·5 wt. % (Fa 15·2) about 35 to 50 μm from the edges of the grain. This same maximum FeO content is found in all large grains. The scan continues across about 100 μm of pyroxene, which shows no zoning. The Mg data mirrors the Fe, and Si, as expected, remains nearly constant. Such zoning at cracks is observed in many grains and indicates that the cracks predate the reducing event that produced the zoning. Data on unequilibrated ordinary chondrites provide evidence regarding the diffusion equilibration of olivine and pyroxene; olivine equilibrates more rapidly than pyroxene (Dodd *et al.*, 1967). The reducing event producing the zoning in the olivine was not strong enough to zone the pyroxene. Much of the scatter of olivine compositions in fig. 3 reflects differences in grain size of the olivine; smaller grains are more reduced.





FIGS. 4 and 5: FIG. 4 (left). Strip chart scans across olivine grain in FIG. 1c. Metal is at right edge of the scan. Olivine is zoned with MgO decreasing towards interior; zoning repeats from the crack in the centre of the grain. FIG. 5 (right). Three grains of the new alkali and Al-rich phase (arrows) found as inclusions in an olivine grain. Formula of the phase is close to (K,Na)$AlSi_5O_{12}$. Scale bar is 100 μm.

The small olivine grains included in pyroxene (fig. 1a) show no zoning and have the same composition as the iron-rich centres of the large grains. The pyroxene apparently insulated this olivine from the change in oxygen fugacity. The maximum Fa values found in the olivine are very near those that would result from equilibrium with the pyroxene (fig. 2).

Four unusual, small (<40 μm) inclusions in three different olivine grains (fig. 5) were discovered; their average composition is given in Table II. The four grains show a constant intergrain composition and no zoning. X-ray scanning photos for Si, Al, Na, and K show no inhomogeneities or exsolution precipitates down to the μm level. Small grains of either troilite or metal are situated at the boundary of each grain with the surrounding olivine. The microprobe data yield the formula:

$$(K,Na)_{0.991}Al_{1.007}Ca_{0.001}Fe_{0.033}Si_{4.980}O_{12}$$

which is close to an ideal formula:

$$(K,Na)AlSi_5O_{12}.$$

The four grains analysed (and several others observed microscopically) were located in the thick section. None has yet been located in the thin sections so the only optical information is that their R.I. is less than that of the surrounding olivine. Chemically the phase has some similarities to the high silica, high K glassy melt inclusions observed by Roedder and Weiblen (1971, 1972, 1975) in lunar and terrestrial basalts. However, they do not find primary inclusions of these compositions in an olivine host, the inclusions do not have a simple stoichiometric formula, and inclusions even in the same sample vary widely in composition (e.g. by as much as 10 % in SiO_2 and 30 % in Al_2O_3 in Apollo 17 rock 70035, 13; Roedder and Weiblen, 1975). It is possible the Lodran phase is a glass that accidentally has a simple stoichiometric formula, but it is statistically unlikely both that a stoichiometric formula would result and that the four grains would be so close to each other in composition. The phase also has some chemical similarities to stuffed tridymite in which Al^{3+} replaces Si^{4+} and charge balance is maintained by trapping alkalis or alkali earths in the open structure (Buerger, 1935; Lukesh and Buerger, 1942; Mason, 1953). This is consistent with the 1 to 1 ratio of alkalis to Al in the Lodran phase. However, the most highly substituted tridymites reported by Mason (1953) are only 5 % oxides other than SiO_2 while in Lodran about 24 % of the phase is oxides other than SiO_2. The 1 to 5 ratios of alkalis and Al to Si in the Lodran phase also suggest a stoichiometric compound rather than a fortuitous level of substitution. If the proposed formula is correct, the phase is a new mineral.

TABLE II. *Composition of new phase found in Lodran, and a molecular formula based on 12 oxygen atoms*

	K	Na	Al	Si	Ca	Fe	Sum
Wt. % (as oxides)	7·50	2·89	13·1	76·2	0·01	0·60	100·3
Cations/(12 O)	0·626	0·366	1·01	4·98	0·001	0·033	7·02

Tschermak (1870) observed and sketched jagged cracks filled with dark material in many olivine grains; he thought the materials might be chromite. Probe analyses of such materials (fig. 1d) showed mainly Si, Fe, Mg, S, and Ni in varying proportions; chromite could not be found. Relatively high concentrations of C of uncertain origin were also present; these are discussed in a later section. Some points approach the composition of the large pyroxene grains, but most points are more silicia rich with 60 to 75 wt. % SiO_2. The Si is not from the glass slide under the section since Na present in the glass-slide material was not observed. This material is possibly a secondary product associated with the reaction or reactions that produced the zoning of the olivine.

Results of the probe bulk analysis of the silicates are given in Table III along with a bulk analysis calculated from Tschermak's data. Abundance ratios normalized to Si relative to CI chondrites were calculated from these data and plotted in fig. 6. Data on diogenites adapted by Wasson (1974) and ranges for unweathered ureilites (Wilk, 1972) are plotted for comparison. The order of the elements from left to right is roughly the order of decreasing tendency to concentrate in the melt during partial melting. The low Ca and Al abundances in Lodran indicate that the meteorite may have undergone some partial melting with loss of a low melting fraction. This shows up mineralogically as the lack of feldspar.

TABLE III. *Bulk analysis of Lodran silicates (in wt. %) and elemental abundances relative to CI chondrites*

	SiO_2	MgO	FeO	CaO	Al_2O_3	Sum
1. This work (microprobe)	50·5	39·0	10·0	0·62	0·31	100·4
2. Calculated from data of Tschermak (1870)	47·6	38·8	12·7	0·30	0·31	99·7

*Abundances relative to CI chondrites**

	Si	Mg	Fe	Ca	Al	Total† Fe
1. This work	1·00	1·09	0·184	0·186	0·0847	1·11
2. Tschermak (1870)	1·00	1·15	0·248	0·093	0·0913	1·59

* CI data from Table VII–1 of Wasson (1974).

† Includes Fe in silicate, metal, and sulphide.

Four chromite grains were analysed (Table IV). Three were oval with major axes ranging from 40 to 150 μm and were included in olivine and pyroxene. The other grain (A) was roughly rectangular, about 90×60 μm, and was associated with the metal. The Fe/(Fe+Mg) ratios vary but all four values are within the range expected from the maximum and minimum olivine Fe/(Fe+Mg) ratios and the plot of chromite *v.* olivine Fe/(Fe+Mg) ratios from Bunch and Keil (1971). Grain A differs from the others in its lack of Al and correspondingly higher Cr content. Bunch *et al.* (1967) observed a similar bimodality in the Al contents of chromites in H-3, L-3, and LL-3 chondrites.

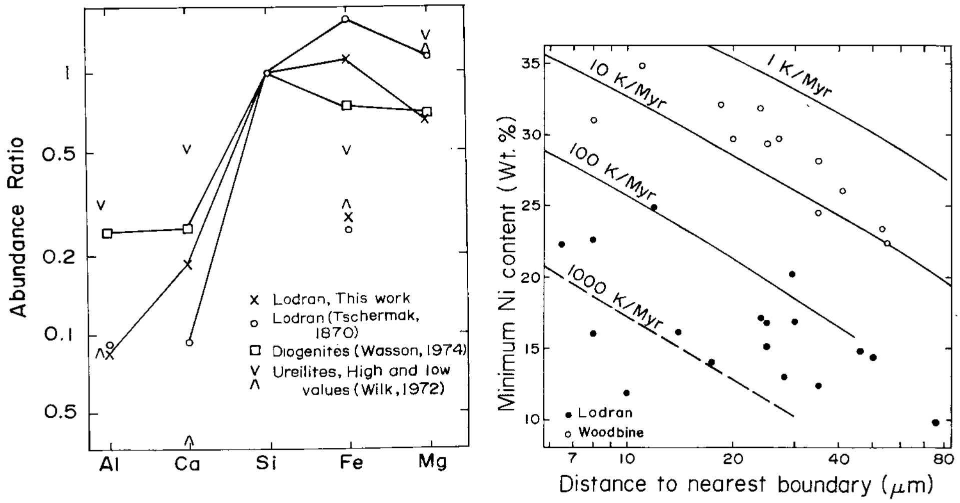
The average Ni content of the metal determined from microprobe data is 9·3 wt. %, much closer to Prior's (1919) value of 7·97 % than to Tschermak's value of 12 %. Most of the metal is kamacite but many of the metallic areas contain taenite either as

TABLE IV. *Chromite in Lodran: composition (in wt. %) and molecular formula based on 32 oxygens*

Grain	FeO	MnO	MgO	ZnO	Cr_2O_3	Al_2O_3	V_2O_3	TiO_2	Sum
A	20·6	1·51	6·00	1·66	69·1	<0·03	0·47	0·17	99·5
B	21·5	0·69	7·94	0·78	60·4	5·77	0·42	1·02	98·5
C	22·4	1·36	6·22	1·68	59·5	6·07	0·49	1·25	99·0
D	24·6	0·84	5·71	0·96	58·3	5·88	0·46	1·21	98·0

Cations (per 32 oxygens)

Grain	Fe	Mn	Mg	Zn	Cr	Al	V	Ti	Sum	Fe/(Fe+Mg)
A	4·98	0·37	2·58	0·35	15·76	—	0·11	0·04	24·19	0·658
B	5·04	0·17	3·31	0·16	13·36	1·90	0·10	0·22	24·26	0·610
C	5·26	0·33	2·62	0·34	13·26	2·02	0·11	0·26	24·20	0·668
D	5·88	0·20	2·43	0·20	13·18	1·98	0·10	0·26	24·23	0·709



FIGS. 6 and 7: FIG. 6 (left). Abundance ratios relative to CI chondrites normalized to Si. Data are from Table III. Lodran is depleted in elements that would be enriched in a low-temperature melt. Diogenites and ureilites are plotted for comparison. The lower Fe point for Lodran represents Fe in the silicate phase only. FIG. 7 (right). Plot showing minimum Ni content at centre of taenite grains as a function of grain size for Lodran and Woodbine (group IB iron). Curves calculated by Wood (in Powell, 1969) are theoretical relationships for the cooling rates shown. The majority of the Lodran points fall well on the fast-cooling side of the 100 K/Myr line. The 1000 K/Myr line was estimated by extrapolating the family of curves shown in Powell (1969) one factor of ten.

veins, polygonal inclusions in kamacite, or entire sections of grains. Schreibersite inclusions are observed in many grains.

Nickel distribution in the taenite showed a typical 'M-shaped' profile—high Ni at the taenite/kamacite interface and low Ni at the centre of the taenite. In the 17 taenite grains examined central Ni contents ranged from 10 to 25 wt. % Ni and maximum Ni contents ranged from 32 to 36 wt. %.

Two different methods of cooling rate estimation for the temperature range 600 to 1000 K were applied. The method developed by Wood (1964, 1967) was applied by him to iron meteorites and metal in chondrites. In this method one determines the relationship between the size of the taenite grain, its central Ni content, and the cooling rate. The central Ni content is that measured by the microprobe and the grain size is the distance from the center of the grain to the nearest kamacite boundary. Wood computed relationships between the measured parameters as a function of cooling rate. His curves of distance to kamacite *v.* minimum central Ni content as shown by Powell (1969) were applied to Lodran (fig. 7). Bulk Ni has no appreciable effect above 7·4 % Ni (Wood quoted in Powell, 1969) so the 8 % bulk Ni curves should be applicable. Fifteen of the 17 Lodran points lie on the fast-cooling side of the 100 K/Myr line. Because the section does not always cross the centre of the three-dimensional taenite fields, measured Ni values may be higher than the true minimum for the grain, and the lower edge of the field of points is believed to yield more accurate estimates. This yields a cooling rate of about 700 K/Myr.

The other method of cooling rate determination used is the 'rapid method 2' of Short and Goldstein (1967). This method is based on the observed empirical relationship between the maximum Ni content ($\mathrm{Ni}_{\mathrm{max}}$) at the edge of taenite to cooling rates (*CR*) calculated by their precise method (Goldstein and Short, 1967), and can be represented by the equation: $\log CR = 4{\cdot}77 - 0{\cdot}104\ \mathrm{Ni}_{\mathrm{max}}$. Since our Lodran Ni determinations were made at similar excitation conditions, this equation should apply. The clustering of Lodran values at 32 to 36 % Ni indicates cooling rates of 10 to 31 K/Myr. Short and Goldstein (1967) claim this method results in cooling rates within ±50 % of their 'precise method'. For comparison reported cooling rate ranges for metal in various types of meteorites are: irons and pallasites 0·4 to 40 K/Myr (Goldstein and Short, 1967), chondrites 2 to 10 K/Myr (Wood, 1967), mesosiderites 0·08 to 0·15 K/Myr (Powell, 1969).

The cooling rates estimated by the two methods differ by a factor greater than 20. Samples of the iron meteorite Woodbine run under the same conditions give values of about 7·6 (fig. 7, Wood method) and 1·5 K/Myr (Short and Goldstein 'rapid method 2'), a factor of 5 different. Cooling rates of 3 iron meteorites determined by Wood (1964) after correction upward by a factor of 4 (Wood, 1967), are 2·5 to 4·5 times higher than the cooling rates calculated for the same meteorites by Goldstein and Short (1967). The Goldstein and Short precise method, their 'rapid method 2' using their Ni data, and their 'rapid method 1' using Wasson's (1971) equation with bulk Ni and band width data from Wasson (1974) gives Woodbine cooling rates of 2·7, 2·0, and 4·0 K/Myr, respectively. The approximate agreement of our two Woodbine values with each other and with the Goldstein and Short values indicates that the large differences observed in Lodran cannot be explained by experimental errors. An explanation for the difference could be that the cooling rate varied with time and the two measured rates should be referred to different periods. The high value (Wood method) is based on Ni diffusion to the centre of taenite grains. The $\mathrm{Ni}_{\mathrm{max}}$ values used in the

Short and Goldstein method depend on Ni diffusion in the outer two or three microns of the taenite and should represent reaction at lower temperatures than those estimated from diffusion over much larger distances (*c.* 100 μm) to the centres of taenite grains. Lodran metal may have cooled rapidly (700 K/Myr) at high temperatures allowing little Ni diffusion to the centres of grains and more slowly (30 K/Myr) at temperatures where appreciable alteration of the taenite Ni content was occurring in the outer margin. Another possible explanation is cooling at a constant, high rate followed by a mild reheating which caused additional reaction at the kamacite-taenite interfaces. Note that late addition of Fe produced by reduction of olivine could only result in a lowering of the Ni content in the taenite margins and lead to spuriously high cooling rates by the Short-Goldstein method.

Schriebersite was not analysed completely, but a check on the Ni content of one 6-μm grain showed a flat-topped profile (like those in Reed, 1965) and a high Ni content (48 ± 3 wt. % Ni). This value is consistent with Ni contents in similar sized grains in iron meteorites (Reed, 1965) and is an equilibrium value below 550 °C (Goldstein and Doan, 1972).

Rare-gas data on separated fractions (Zähringer, 1968) show that the heavier primordial rare gases $^{36}Ar_p$, ^{84}Kr, and ^{132}Xe are more abundant in Lodran metal by roughly a factor of 2, while the lighter gases ^{4}He and ^{20}Ne are about 2 to 10 times more abundant in the silicate. Both fractions yield the planetary-type patterns typical of chondritic meteorites and the concentrations are in the range reported in type 3 and 4 ordinary and CV chondrites. Such high planetary rare-gas contents are normally not found in differentiated meteorites; the ureilites are the exception, and their formational history is poorly understood. In the case of Lodran the large grain size of the olivine, pyroxene, and metal could have been effective in preventing the escape of gases during the partial melting process that is inferred from low abundance of Ca, Al, and alkalis. But, if the large grains were formed by recrystallization of grains as small as those found in unequilibrated chondrites, it is remarkable that such high rare-gas contents were retained during this recrystallization. An alternative explanation is that the rare gas resides in a minor fraction present in both the magnetic and non-magnetic fractions studied by Zähringer (1968). Weber *et al.* (1971) found that the bulk of the rare gas in the Haverö ureilite is present in C-rich vein material. As discussed below, there is some evidence for C-rich vein material in Lodran.

Relationship to ureilites

Prior (1920) suggested that Lodran was closely related to the ureilites on the basis of their similar silicate mineralogies. A recomparison shows many other similarities. Ureilites are a group of about six calcium-poor achondrites. Their composition and properties have been described by several authors (Vdovykin, 1970; Neuvonen *et al.*, 1972; Ramdohr, 1972; Wlotzka, 1972; Wiik, 1972; Marvin and Wood, 1972; Wasson *et al.*, 1976). They consist of olivine aggregates 0·5 to 3 mm in diameter (similar to Lodran grain size) made up of a mosaic texture of olivine grains typically 10 to 100 μm in diameter. Intensely twinned low-Ca clinopyroxene is present but is 8 to 10 times less abundant than olivine, and plagioclase is absent or very minor. Low Ni kamacite

(1·5 to 4·5 wt. % Ni) occurs as veins and in a finely divided net-like distribution in the silicates. Elongate curved voids occur in ureilites as do veins of carbonaceous material. Wiik (1972) reports 1·5 to 4·1 wt. % C in ureilites; Vdovykin (1970) breaks this down as 2 to 5 % of the C in organic compounds with the remainder being graphite and diamond.

Ureilitic olivine aggregates have the same reversed zoning as the Lodran olivine. Marvin and Wood (1972) measured values of Fa 13·7 at the centre of one olivine aggregate in Haverö and Fa 4·8 at the edge. The cause of the zoning is thought to be a late reduction of Fe to the metal by reaction of the aggregates with the surrounding graphite; Ni-poor kamacite is observed in the veins (Wlotzka, 1972; Marvin and Wood, 1972).

No graphite was observed optically in Lodran. A microprobe search for C in the thin sections did detect high C levels in cracks and at some grain boundaries, but the significance of this result is not certain, since the sections had been carbon coated and repolished several times. Epoxy impregnating agent and mounting adhesive could also be the source of the observed C. A search for C in a fresh section should be made.

Published microprobe analyses of pyroxene and centres of olivine aggregates in Haverö result in the following molar Fe/(Fe+Mg) values (in mole %): pyroxene 19, 15 (Neuvonen *et al.*, 1972); pyroxene 16·2, olivine 20·8—both averages of six grains or aggregates (Wlotzka, 1972); pyroxene ~ 16, olivine 13·7 (Marvin and Wood, 1972). Wlotzka's averages are plotted as Fa and Fs for Haverö on fig. 2. The high Ca contents probably cause some of the deviation from the equilibrium line. The ureilitic silicates have distinctly higher Fe/(Fe+Mg) ratios than are found in the Lodran silicates.

The CaO contents of the olivine (0·08 wt. %) and orthopyroxene (1·36 wt. %) are much higher than those found in recrystallized ordinary chondrites of petrologic types 4–6. Dodd (1972) reports 0·03–0·06 wt. % in the olivine of the latter, and Keil and Fredriksson (1964) 0·3–0·97 wt. % in the pyroxene. Ureilitic values are still higher; Wlotzka (1972) found 0·27 and 1·7 wt. % CaO in the olivine and pyroxene of Haverö. Wasson *et al.* (1976) argue that the high ureilitic CaO contents were established at high temperatures, and indicate that these materials experienced rapid quenching resulting from removal by impact of an insulating layer. The lower CaO contents in the Lodran silicates may reflect either rapid quenching from a lower initial temperature, or a lower rate of cooling from a comparable temperature.

Ureilites, like Lodran, are rich in planetary-type rare gases despite highly recrystallized textures. The rare gas in Lodran (Zähringer, 1968) is more similar to that in Goalpara than that in more volatile-rich ureilites such as Dyalpur, Novo Urei (Mazor *et al.*, 1970), or Haverö (Weber *et al.*, 1971). As noted above, Weber *et al.* (1971) found a high enrichment of noble gases in the C-rich vein material of Haverö. Cosmic-ray exposure-ages for Lodran calculated from ^{3}He and ^{21}Ne data of Zähringer (1968) using production rates calculated by the methods described in Herzog and Anders (1971) and bulk composition of Lodran calculated from data of Tschermak (1870) are 7·6 and 8·6 Myr respectively. These values are in the same range as exposure-ages for ureilites (Wilkening *et al.*, 1973) and for ordinary chondrites.

Data on oxygen isotopes are useful for establishing genetic relationships, but none are available for Lodran.

Many of the differences between Lodran and ureilites can be attributed to the severe shock event experienced by the ureilites. Shock effects in ureilites include presence of diamond, highly twinned clinopyroxene, conversion of any orthopyroxene to clinopyroxene, conversion of large olivine grains to polyscrystalline aggregates (Neuvonen *et al.*, 1972, showed these aggregates were once single large olivine grains), injection of metal into cracks in silicates, and void production as a result of volatile evolution (Vdovykin, 1970). Some differences that cannot be explained by shock are the high abundance of metal and troilite in Lodran and the lower Fe/(Fe+Mg) ratios in the silicate minerals.

A model for the formation of Lodran

The formation of Lodran should include the following six events:

Formation of olivine and pyroxene with pyroxene trapping or including smaller olivine grains and to a lesser extent olivine trapping some pyroxene grains. If the rare gases are in the silicates and the metal, this probably occurred during nebula condensation. The high Fe/Si ratio probably reflects preferential incorporation of metal during nebula agglomeration.

The alkalis and Ca were depleted relative to typical chondritic matter, probably as a low-temperature liquid squeezed out of the body during partial melting. Appreciable melting of the body did not occur otherwise separation of the immiscible silicate and metal would have occurred. Most of the retained alkalis were trapped in the olivine as the new phase or incorporated into the pyroxene structure.

The olivine and pyroxene compositions equilibrated.

Recrystallization took place suturing grain boundaries and forming 120° triple boundaries.

Steps 2, 3, and 4 could have occurred together.

The cracks in the olivine were formed.

Conditions became more reducing. Diffusion was rapid enough in olivine to produce 50-μm layers with inverse zoning. Diffusion was slower in the orthopyroxene, and reduction was confined to a much thinner layer. The reduction of the olivine formed metallic Fe and either pyroxene or SiO_2 depending on kinetic factors. The SiO_2-rich residue seen in some cracks in olivine probably resulted from the latter.

Lodran seems to be a partially differentiated meteorite, containing much of its original complement of planetary-type rare gases but having lost most of its low-melting silicates. Trace element and isotopic data on bulk samples and on separated fractions would be very useful for further delineation of its history, and a more thorough understanding of its relationship to the ureilites.

Appendix: Harvard University—A mesosiderite

Ramdohr (1967) described the Harvard University meteorite as being very similar to Lodran in composition though also showing strong similarities to mesosiderites. Zähringer (1968) found much lower rare-gas concentrations in Harvard University than in Lodran, but very similar concentrations in Hainholz and Estherville. Our analyses of some Harvard University silicates are given in Table V together with analyses of the same phases in Lodran and the Vaca Muerta mesosiderite. The phases of Harvard University are much more like the latter than the former. Ramdohr further reported olivine in Harvard University occurring in 'large, partly rounded, euhedral grains'. This sort of occurrence of olivine is typical of mesosiderites (see, e.g., Powell, 1971). On the basis of these observations we conclude that Harvard University is a mesosiderite and not closely related to Lodran. Vaca Muerta is the most widely distributed mesosiderite; every major collection has to 5 to 100 fragments. Our best guess is that this is the mesosiderite that was labelled a tellurium ore when found at Harvard University by Ramdohr (1967).

TABLE V. *Comparison of the major silicates of Harvard University with the Lodran anomalous meteorite and the Vaca Muerta mesosiderite*

	Orthopyroxene	Olivine	Plagioclase	SiO_2
Lodran*	$Fs_{13\cdot8}$	$Fa_{15\cdot2}$	§	‡
Harvard U.*	Fs_{27-35}	§	$An_{89}Ab_{10}Or_{0\cdot6}$	Present
Vaca Muerta†	Fs_{23-44}	Fa_{30-48}	An_{80-89}	Present

* This work, Fa value is from central plateaux of zoned olivine.
† Powell (1971).
‡ Not observed as a resolvable phase; see text regarding a SiO_2 enrichment along cracks.
§ Not observed.

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