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THE LANDES METEORITE

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The Landes silicate-bearing octahedrite is a new find from Grant County, West Virginia. Minerals and their compositions are very similar to those in Odessa-type silicate inclusions. The angular nature of the inclusions, recrystallization textures, and mineral compositions indicate a "xenolithic" origin for the inclusions.

INTRODUCTION

The Landes octahedrite was found by Mr. V. A. Stump about 1930 while plowing a field on his farm located approximately one mile east of the Landes Post Office, lat 38° 54′ N.; long 79° 11′ W., Grant County, West Virginia. The iron was identified as a meteorite by one of us (G.H.) in 1968.

When the meteorite was received at the American Meteorite Laboratory, it weighed 69.8 kg and its dimensions were approximately 40 × 27.5 × 27.2 cm. The surface was covered with a thin "iron shale" coating of iron oxides; only a small portion of the surface resembled fusion crust. After cleaning the surface, it showed little evidence of pitting or ablation features. Field investigations have so far failed to yield additional pieces of the fall.

GENERAL DESCRIPTION

The Landes octahedrite contains abundant angular silicate rock fragments and mineral grains that are randomly scattered throughout the nickel-iron matrix, giving a "brecciated" appearance, Fig. 1. The inclusions vary in size from a few microns to 5 cm. Many appear to be "veined" by the nickel-iron matrix, Fig. 2. On inspection under a reflecting light microscope,

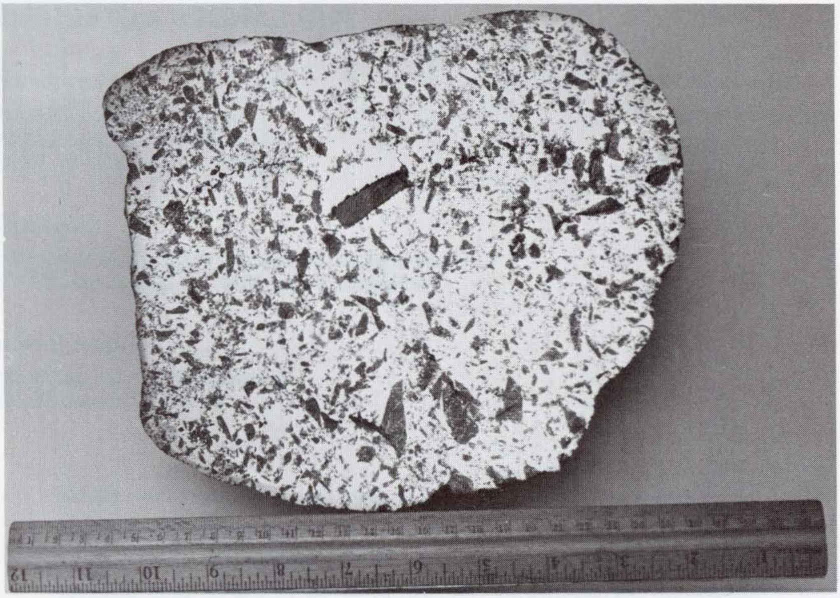

Fig. 1. Polished surface of a slice through the center of the Landes meteorite showing the "brecciated" appearance of the silicate inclusions.

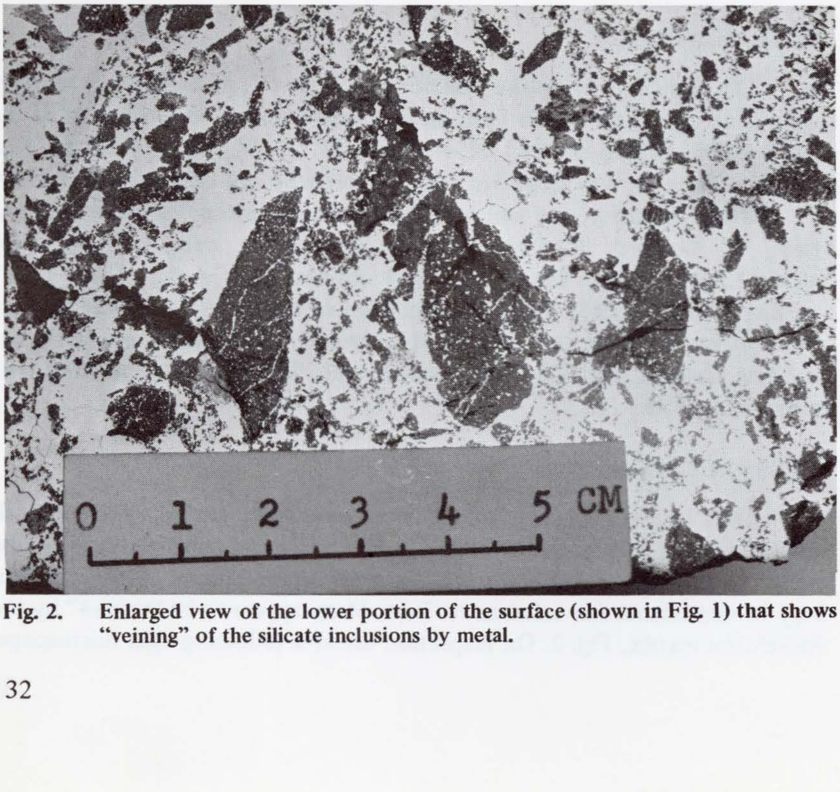

Fig. 2. Enlarged view of the lower portion of the surface (shown in Fig. 1) that shows "veining" of the silicate inclusions by metal.

the inclusion-matrix interface is not as sharp as it appears to be in the hand specimen observations. Instead, subhedral to rounded silicate grains protrude, rather sharply in many cases, into the matrix, the size of these grains being larger on the average than those within the inclusion interior. Constituent minerals within inclusions range from 10 μ to 1 mm, whereas individual grains in the nickel-iron host range in size from 300 μ to 2.0 mm. Single discrete grains or clusters of silicates in the matrix are subhedral and tend to be much larger than those inside the rock fragments. In addition, the nickel-iron veins are actually discontinuous, being interrupted by sulfide and silicate grains.

Textures of inclusions are quite variable, ranging from equal dimensional, granoblastic to irregularly shaped and variable-grained types. Although many types are observed, we can summarize the most abundant types into the following categories: 1, granoblastic, equidimensional plagioclase-poor, with a grain size range of 50-200 μ, 2, variable-sized, subhedral to rounded ferro-magnesian minerals of similar size and variable plagioclase content, with a grain size range of 200-1000 μ, and 3, single grains and clusters of large grains up to 2.0 mm in size.

A large variety of minerals occur in Landes and compare favorably to the mineral assemblages in Odessa-type inclusions described by Bunch, *et al.* (1970). Minerals found to date are forsterite, Cr-diopside, enstatite, oligoclase, magnesiochromite, whitlockite, chlorapatite, sphalerite, troilite, graphite, schreibersite, taenite, kamacite, copper, daubreelite, and ferroan alabandite.

Modal analysis by point-counting technique of the major phases over a 9 cm^2 area (26,710 point counts) gives the following abundances in weight per cent: nickel-iron, 81; silicates, 16; troilite, schreibersite, and graphite, nearly 1% each. In addition, chromite accounts for about 0.2%. The silicate inclusion content is among the highest of known silicate-bearing irons.

MINERAL COMPOSITIONS

Analyses were made with an ARL-EMX electron microprobe using an accelerating voltage of 20 kV and a sample current of 0.04 μA with the exception of plagioclase and phosphate analyses, which were run at 15 kV and 0.03 μA. Additional procedures and corrections follow those employed by Bunch, *et al.* (1970), except that Frazer's (1967) mass absorption coefficient data were used.

Mineral descriptions are given only where they differ from Odessa-type inclusions described by Bunch, *et al.* (1970). Grain-to-grain and within-grain compositional variabilities, regardless of textural type or location of the grain, are remarkably small, mostly within the analytical error; the only notable exception is chromite.

Silicates.

Pyroxenes (Cr-diopside and enstatite) and olivine are nearly identical in composition to pyroxenes and olivine of Odessa-Copiapo-type inclusions, see Table 1. The only exceptions are Na_2O in Cr-diopside, which is about 25% of the amounts found in Odessa-Copiapo Cr-diopside and MnO, which is higher in both Landes Cr-diopside and enstatite. The plagioclase is oligoclase (An_{16}) whose composition is SiO_2, 63.5; Al_2O_3, 22.4; FeO, 0.30; CaO, 3.37; Na_2O, 9.6; and K_2O, 0.39 weight percent, based on an average of 20 grains.

Chromite.

Small grains of chromite are dispersed throughout many of the inclusions, although the relative abundance is quite low. It is more closely associated with troilite where it is present in euhedral form, than with silicates, where it tends to be subhedral. Chromite is the only mineral other than nickel-iron that shows notable compositional differences among grains of different size and mineral associations. A rather large (0.8 mm) grain completely surrounded by the metal matrix is lower in Al_2O_3, TiO_2, MgO, and ZnO contents and higher in MnO and FeO than chromite within inclusions, see Table 2. This discrepancy is attributed to the isolated environment of the larger chromite where it was not allowed to equilibrate with ferro-magnesian silicates. This example lends support to earlier observations by Bunch, *et al.* (1970) that FeO and MgO contents of coexisting chromite, orthopyroxene, and olivine show regular distribution patterns and indicate crystallization or recrystallization under equilibrium conditions.

Phosphates.

Both chlorapatite and whitlockite are present in nearly equal abundance. These minerals are commonly located at or near the inclusion-matrix interface and less commonly occur as large isolated grains within the metal matrix. A large (1.5 mm) whitlockite grain was found in the matrix with an inclusion of fine-grained silicates showing a very definite recrystallized texture. Phosphates show greater within-grain compositional variabilities than any other mineral.

Chlorapatite in Landes is different from most previously analyzed in silicate inclusions: other chlorapatites show significant amounts of F substituting for Cl (Bunch, *et al.*, 1970), whereas no detectable amounts of F were found in Landes chlorapatite, see Table 3.

Sulfides.

Of all the minerals in other meteorite inclusions, troilite is one of the most diagnostic for classification purposes. Troilite in Odessa-type inclusions contains Zn, Mn, and Ti, whereas troilite in Copiapo-type inclusions does not. Landes troilite contains small amounts of these elements, Table 4, and is therefore more similar to Odessa-type inclusions.

Table 1.
Electron Microprobe Analyses of Clinopyroxene, Orthopyroxene, and Olivine from the Landes Meteorite (in weight percent)

	Cpx (25)	Opx (25)	Olivine (25)
SiO_2	54.1	57.5	41.5
Al_2O_3	0.87	0.08	–
Cr_2O_3	1.17	0.27	–
TiO_2	0.69	0.22	–
MgO	18.5	36.1	53.8
FeO	2.07	4.36	4.0
MnO	0.23	0.59	0.46
CaO	22.7	0.92	–
Na_2O	0.30	–	–
Total	100.63	100.04	99.76
Fe	3.2	6.2	4.0
Mg	51.4	92.1	96.0
Ca	45.6	1.7	–

Numbers in parentheses indicate number of grains analyzed.

Table 2.
Electron Microprobe Analyses of Chromite from the Landes Meteorite

	A*	B**
Cr_2O_3	69.0	67.3
Al_2O_3	0.79	2.72
V_2O_3	0.89	0.77
TiO_2	0.24	1.08
FeO	15.2	13.5
MgO	9.1	11.3
MnO	3.85	1.98
ZnO	1.76	2.22
Total	100.83	100.87

*0.8 mm grain in NiFe.
**007-0.12mm grains in inclusions.

Sphalerite and ferroan alabandite are quite rare and are found in intimate contact with troilite. Analyses are given in Table 4.

Copper.

Two small (10-25 μ) grains of copper were found in direct contact with silicates and one with troilite. The unusual aspect of their compositions,

Table 3.
Electron Microprobe Analyses of Chlorapatite and Whitlockite from the Landes Meteorite

	Chlorapatite (5)	Whitlockite (5)
Al_2O_3	0.04	0.10
P_2O_5	41.3	45.8
FeO	0.26	0.38
MgO	0.03	3.75
CaO	53.0	46.7
Na_2O	0.49	3.0
Cl	6.1	<0.05
F	<0.05	<0.05
	101.19	99.73
$O \equiv Cl$	1.4	–
Total	99.79	99.73

Table 4.
Electron Microprobe Analyses of Troilite and Sphalerite from the Landes Meteorite

	Troilite (5)	Sphalerite (5)
S	36.3	36.0
Fe	62.8	27.6
Mn	0.09	4.0
Zn	0.12	32.7
Cr	0.21	<0.02
Ti	0.08	<0.02
V	<0.02	<0.02
Total	99.60	100.30

Table 5, is the amount of Ni (2.4%) and Fe (0.6-1.4%). Duke and Brett (1965) maintain that Fe of this concentration in copper is not real, but the result of an analytical error introduced by fluorescence effects from surrounding nickel-iron. Their suggestion does not apply to our copper analyses since there is no visible nickel-iron in the immediate vicinity of the copper and the lowest Fe value is found in the copper grain surrounded by troilite, a high Fe-bearing mineral. The possibility of nickel-iron contamination during sample preparation does exist, although this seems unlikely in view of the fact that the Fe:Ni ratio in copper is considerably different from either the matrix metal or metal within the inclusions.

Table 5.
Electron Microprobe Analyses of Metallic Copper in the Landes Meteorite

	Copper Associated with Silicates	Copper Associated with Troilite
Cu	96.8	97.4
Fe	1.41	0.57
Ni	2.36	2.31
Total	100.57	100.28

Nickel-iron.

Average composition of the metal matrix and metal veins that transect silicate inclusions is 92.8 weight percent, Fe; 6.2 weight percent, Ni; and 0.52 weight percent, Co. Nickel content of small nickel-iron grains included within the silicate inclusions ranges from 5.8 to 49.0 weight percent. Cobalt content ranges from 0.48 weight percent in low-nickel kamacite grains to less than 0.02 weight percent in highest nickel taenite.

PARTITION OF Fe^{2+} AND Mg BETWEEN PYROXENES

The distribution of Fe^{2+} and Mg between ortho- and clinopyroxenes in Landes is nearly identical to that in Odessa- and Copiapo-type inclusions, thus indicating a close approach to equilibrium (Bunch *et al.*, 1970). By using the distribution coefficient

$$K_D = (Fe/Mg)^{OPX} \; (Fe/Mg)^{CPX}$$

and the temperature-distribution coefficient curve of McCallum (1968), an equilibration temperature of nearly 1000 °C is indicated for coexisting pyroxenes. The Ca/(Ca + Mg) ratio in Cr-diopside also shows an equilibration temperature of nearly 1000 °C, consistent with data obtained for most other silicate inclusions (Bunch, *et al.*, 1970).

DISCUSSION

A tentative classification of silicate inclusions based on mineral compositions, characteristic phases, mineral abundances, textures, and inclusion shape was suggested by Bunch, *et al.* (1970) in a study of 18 silicate-bearing irons. Inclusions in Landes appear to belong to the Odessa class in view of the characteristic phases present and mineral compositions (particularly troilite); other factors are inconclusive. Wasson (personal communications, 1970, 1971) has indicated that the division of Odessa- and Copiapo-type inclusions is probably not valid on the basis of his trace element work on the metal of silicate-bearing iron metals. While this observation may be true for the metal component of these meteorites, it has little to do with the nonmetal portions, which we contend are independent in origin, i.e., Landes is a prime example of broken (brecciated) silicate material incorporated into a nickel-iron melt, which somewhat modified the fragment shapes and allowed for recrystallization and reequilibration under elevated temperatures. While it is true that the partitioning of certain elements, particularly lithophile elements, in the metal would be influenced by the presence of silicates, the overall effect would be negligible when attempting to make a chemical distinction among iron meteorites with included silicates solely on the basis of metal.

Mason (1967) and Bunch, *et al*., (1970) have suggested the possibility that the original nature of the inclusions was chondritic. At least one silicate-bearing meteorite, Netschaëvo, has relict chondrules and an analysis of the silicate material is given by Olsen and Jarosewich, (1971). Since the mineral abundances among silicate inclusions in most meteorites are quite variable, many bulk analyses are required to obtain a meaningful value. Bulk analysis can be accomplished with the electron microprobe using a broad beam. Since inclusions in Landes are variable in texture, but tend to group into four main categories, it may be possible to relate inclusion textures with bulk chemistry. This, along with a study of the inclusions near the center of the Landes meteorite, is now being undertaken.

ACKNOWLEDGMENTS

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