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THE NEW MINERAL SPECIES KEILITE, (Fe,Mg)S, THE IRON-DOMINANT ANALOGUE OF NININGERITE

Masaaki SHIMIZU§

Department of Earth Sciences, Faculty of Science, Toyama University, 3190 Gofuku, Toyama 930-8555, Japan

Hideto YOSHIDA§

Department of Earth and Planetary Science, Graduate School of Science, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan

Joseph A. MANDARINO§

94 Moore Avenue, Toronto, Ontario M4T 1V3, and Earth Sciences Division, Royal Ontario Museum, 100 Queens's Park, Toronto, Ontario M5S 2C6, Canada

Abstract

Keilite, (Fe,Mg)S, is a new mineral species that occurs in several meteorites. The original description of niningerite by Keil & Snetsinger (1967) gave chemical analytical data for "niningerite" in six enstatite chondrites. In three of those six meteorites, namely Abee and Adhi-Kot type EH4 and Saint-Sauveur type EH5, the atomic ratio Fe:Mg has Fe > Mg. Thus this mineral actually represents the iron-dominant analogue of niningerite. By analogy with synthetic MgS and niningerite, keilite is cubic, with space group *Fm*3*m*, *a* 5.20 Å, *V* 140.6 Å^3, *Z* = 4. Keilite and niningerite occur as grains up to several hundred μm across. Because of the small grain-size, most of the usual physical properties could not be determined. Keilite is metallic and opaque; in reflected light, it is isotropic and gray. Point-count analyses of samples of the three meteorites by Keil (1968) gave the following amounts of keilite (in vol.%): Abee 11.2, Adhi-Kot 0.95 and Saint-Sauveur 3.4. Associated minerals are: enstatite, kamacite and troilite. The type material, from the Abee enstatite chondrite, is preserved in the collections of the Hawaii Institute of Geophysics and Planetology, University of Hawaii, Honolulu, Hawaii, U.S.A. (specimen UH 13). New chemical and optical data are presented.

Keywords: keilite, new mineral species, niningerite, enstatite chondrite, meteorite, Abee, Alberta.

Sommaire

La keilite, (Fe,Mg)S, est une nouvelle espèce minérale présente dans plusieurs météorites. Dans la description originale de la niningerite, Keil et Snetsinger (1967) ont publié des données chimique à propos de la "niningerite" dans six chondrites à enstatite. Dans trois de ces six cas, Abee et Adhi-Kot, de type EH4, et Saint-Sauveur, de type EH5, le rapport atomique Fe:Mg montre plus de Fe que de Mg. Ce minéral représente donc l'analogue de la niningerite ayant une dominance de Fe. Par analogie avec le MgS synthétique et la niningerite, la keilite est cubique, groupe spatial *Fm*3*m*, *a* 5.20 Å, *V* 140.6 Å^3, *Z* = 4. La keilite et la niningerite se présentent en grains atteignant quelques centaines de micromètres de diamètre. A cause de cette taille infime, la plupart des propriétés physiques n'ont pas pu être déterminées. La keilite est métallique et opaque; en lumière réfléchie, elle est isotrope et grise. Les analyses modales des trois échantillons de météorite par Keil (1968) indiquent les proportions suivantes de keilite (en % du volume): Abee 11.2, Adhi-Kot 0.95 et Saint-Sauveur 3.4. Les minéraux associés sont: enstatite, kamacite et troilite. L'échantillon type, provenant de la chondrite à enstatite de Abee, est préservé dans les collections de la Hawaii Institute of Geophysics and Planetology, University of Hawaii, Honolulu, Hawaii, U.S.A. (spécimen UH 13). De nouvelles données chimiques et optiques sont présentées ici.

(Traduit par la Rédaction)

Mots-clés: keilite, nouvelle espèce minérale, niningerite, chondrite à enstatite, météorite, Abee, Alberta.

§ *E-mail address*: mshimizu@sci.toyama-u.ac.jp, yoshida@eps.s.u-tokyo.ac.jp, j.a.mandarino@puffin.net

Introduction

In the course of compiling the *International Encyclopedia of Minerals*, preparation of the description of niningerite was assigned to the senior author (MS) of this paper. Editing of that description by the junior author (JAM) revealed that the published data for niningerite (Keil & Snetsinger 1967) really consisted of data for two species: niningerite *sensu stricto*, (Mg,Fe)S, and the unnamed iron-dominant analogue of niningerite. A proposal to define and name the latter was submitted to the Commission on New Minerals and Mineral Names of the International Mineralogical Association, and both mineral and name were approved (IMA 2001–053). The mineral is named after Dr. Klaus Keil (b. 1934), Hawaii Institute of Geophysics and Planetology, University of Hawaii, Honolulu, Hawaii, U.S.A., in recognition of his outstanding research on the mineralogy and petrography of chondritic meteorites. Subsequent to the approval by the CNMMN of IMA, Dr. Keil kindly provided us with new material, which permitted the measurement of additional data. The type locality is the site where the Abee meteorite was found: near Abee, Alberta, Canada, about 80 km north-northeast of Edmonton, approximately at Lat. 53°50'N, 113°15'W).

Occurrence

Initially, the mineral named niningerite was found in three enstatite chondrites: Abee and Adhi-Kot are of type EH4 [the E means "enstatite chondrite", the H means "high-iron group", and the 4 means "petrological (metamorphic) type 4"], and St. Sauveur is of type EH5 [the 5 means "petrological (metamorphic) type 5"]. Point-count analyses of samples of the three meteorites studied by Keil (1968) gave the following amounts of "niningerite" (in vol.%): Abee 11.2, Adhi-Kot 0.95 and Saint-Sauveur 3.4. Associated minerals are: enstatite, kamacite and troilite.

Appearance and Physical Properties

Keilite occurs as small grains up to several hundred micrometers across; in the section designated as the type material, the analyzed grains are up to 80 μm. Because of the small grain-size, most of the usual physical properties could not be determined. The density could not be measured, but calculated values range from 3.59 to 3.67 g/cm^3.

Optical Properties

In reflected light, keilite is isotropic and gray. Reflectance spectra in air and in oil (Nikon nD =1.515) for keilite were measured relative to a SiC standard (Zeiss No. 851). The equipment used was a Nikon photometry system P100 including an Optiphot-2 microscope photometer with photometer-controller P101, monochromator G–70 and two-light flux interference examination. The results are given in Table 1. In Figure 1, curves marked 1 and 2 refer to compositions 2 and 5 in Table 2, respectively. Reflectance values of keilite increase with increasing Fe content.

TABLE 1. REFLECTANCE VALUES FOR KEILITE

	Air		Oil	
	R Fe-rich	R Mg-rich	R Fe-rich	R Mg-rich
470 nm	27.2 %	26 9 %	12 2 %	12.0 %
546	26.7	26.1	11.9	11.7
589	26.4	26.0	11.7	11.4
650	26.0	25.5	11.7	11.4
400	27 0	27.0	11.8	10.9
420	27.1	27.1	12.3	12.3
440	27.6	27.4	12.8	12.8
460	27.2	26 9	12.2	12.2
480	27.1	26.8	12.1	11.8
500	26.6	26.4	12.0	11.8
520	26 6	26 6	11.8	11.6
540	26.6	26.3	11.8	11.7
560	26.5	26.0	11.7	11.5
580	26 7	26.0	11.7	11.5
600	25.9	25.5	11.9	11.6
620	26.2	25.7	11.7	11.6
640	26.1	25.4	11.6	11.3
660	25.9	25.5	11.7	11.4
680	26.0	25.5	11.3	11.1
700	25.9	25.2	11.1	10.9

Fe-rich and Mg-rich compositions refer to compositions 2 and 5 in Table 2.

TABLE 2. REPRESENTATIVE CHEMICAL COMPOSITIONS OF KEILITE AND TROILITE IN THE ABEE METEORITE

	Keilite						Troilite
	1	2	3	4	5	6	7
Fe wt.%	40.14	39.57	39.45	38.66	37.70	36.99	59.7
Mg	10.05	10.36	10.42	10.07	10.95	11.96	0.04
Mn	3.37	3.43	3.42	3.45	3.58	3.95	0.2
Ca	1.98	1.86	2.23	2.91	2.60	1.70	0.2
Cr	1.91	1.98	1.89	1.96	1.84	1.84	2.05
Zn	0.24	0.30	0.23	0.31	0.28	0.13	0.03
Ti	0.06	0.09	0.09	0.09	0.08	0.05	0.33
Ni	0.01	-	-	0.01	0.02	0.02	0.1
Cu	-	0.01	0.29	-	-	0.31	0.11
S	41.39	41.46	41.24	41.60	42.15	42.23	36.94
Total	99.15	99.06	99.26	99.06	99.20	99.17	99.52
Atom proportions based on total atoms = 2							
Fe *apfu*	0.558	0.549	0.547	0.536	0.517	0.504	0.939
Mg	0.321	0.330	0.332	0.321	0.345	0.374	0.001
Mn	0.048	0.048	0.048	0.049	0.050	0.055	0.003
Ca	0.038	0.036	0.043	0.056	0.050	0.032	----
Cr	0.029	0.030	0.028	0.029	0.027	0.027	0.035
Zn	0.003	0.004	0.003	0.004	0.003	0.002	----
Ti	0.001	0.001	0.001	0.001	0.001	0.001	0.006
Ni	----	----	----	----	----	----	0.001
Cu	----	----	0.004	----	----	0.004	0.001
S	1.002	1.002	0.995	1.004	1.007	1.002	1.012
FeS	56.1	55.3	54.8	54.1	52.3	50.8	96.1
MgS	32.3	33.2	33.3	32.4	34.9	37.7	0.0
(Mn,Ca,Cr)S	11 6	11.5	11.9	13.5	12.8	11.5	3.9
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Analyst: Hideto Yoshida. Atom proportions are expressed in atoms per formula unit (*apfu*). The grains that provided the data in columns 2 and 5 also were used to obtain the reflectance values in Table 1 and Figure 1 (curves 1 and 2, respectively).

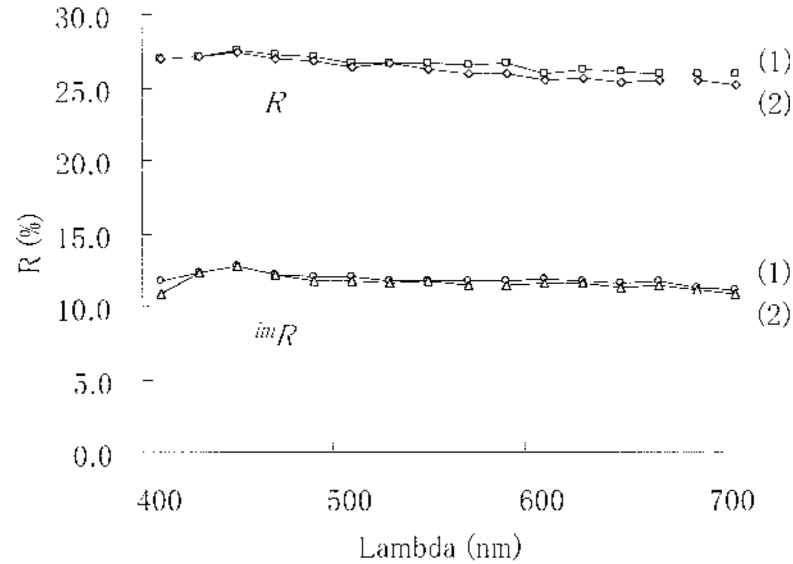

FIG. 1. Reflectance spectra of keilite in air and oil. Curves labeled 1 and 2 are for compositions 2 and 5 in Table 2, respectively.

CHEMICAL DATA

Keil & Snetsinger (1967) analyzed "niningerite" in six meteorites with an electron microprobe; they used the following standards: FeS_2 (Fe, S), ZnS (Zn), $MgSiO_3$ (Mg), andesine (Ca), chromite (Cr) and pure Mn (Mn). The analytical results are given in Table 3.

The analyses carried out in this study were made with a JXA–8900L (JEOL) electron microprobe at an operating voltage of 15 kV and beam currents of 120 nA (for mapping), 20 nA (for keilite) and 12 nA (for silicates) and a beam diameter of 1 μm. The following synthetic standards were used: $CuFeS_2$ (Fe, Cu, S), MgO (Mg), Mn metal (Mn), $CaSiO_3$ (Ca), Cr metal (Cr), Zn metal (Zn), TiO_2 (Ti) and Ni metal (Ni). Corrections were made according to Armstrong (1988). The analytical results are given in Table 2 and are plotted in terms of the diagram FeS – MgS – (Ca,Mn,Cr)S in Figure 2. The ideal formula of keilite is FeS, which requires: Fe 63.53, S 36.47, for a total 100.00 wt.%. It is a cubic polymorph of FeS.

TABLE 3. ANALYTICAL DATA GIVEN FOR "NININGERITE" BY KEIL & SNETSINGER (1967)

Anal. No.	Meteorite (No. of grains)	Fe	Mg	Ca	Mn	Zn	Cr	S	Total	Mineral
1	Abee (20)	37.1	10.1	3.03	4.02	0.31	1.84	41.0	97.40	keilite
2	Saint Sauveur (15)	35.2	13.2	2.55	3.93	n.d.	1.77	42.7	99.53	keilite
3	Adhi-Kot (14)	34.2	11.3	1.96	7.1	n.d.	1.97	42.6	99.13	keilite
4	Indarch (7)	27.0	18.3	1.28	6.5	n.d.	1.66	43.4	98.14	niningerite
5	St. Mark's (10)	16.6	22.7	0.53	11.8	n.d.	0.40	47.4	99.43	niningerite
6	Kota-Kota (10)	15.6	23.5	0.39	11.6	n.d.	0.14	46.9	98.13	niningerite

Empirical formulae (total atoms = 2.00)	*a*	density (calc.)
1. $(Fe_{0.52}Mg_{0.33}Ca_{0.06}Mn_{0.06}Cr_{0.03})_{\Sigma 1.00}S_{1.00}$	5.17 Å	3.67 g/cm³
2. $(Fe_{0.47}Mg_{0.41}Mn_{0.05}Ca_{0.05}Cr_{0.03})_{\Sigma 1.01}S_{1.00}$	5.16	3.59
3. $(Fe_{0.47}Mg_{0.35}Mn_{0.10}Ca_{0.04}Cr_{0.03})_{\Sigma 0.99}S_{1.01}$	n.d.	3.63*
4. $(Mg_{0.54}Fe_{0.35}Mn_{0.09}Ca_{0.02}Cr_{0.02})_{\Sigma 1.02}S_{0.98}$	5.18	3.38
5. $(Mg_{0.63}Fe_{0.20}Mn_{0.15}Ca_{0.01}Cr_{0.01})_{\Sigma 1.00}S_{1.00}$	5.17	3.24
6. $(Mg_{0.66}Fe_{0.19}Mn_{0.14}Ca_{0.01})_{\Sigma 1.00}S_{1.00}$	n.d.	3.22*

* *a* taken as 5.17 Å. n.d.: not detected. Compositions are quoted in wt.%.

CRYSTALLOGRAPHY

Single-crystal X-ray studies could not be carried out because of the small size of the crystals, but the X-ray powder-diffraction pattern is similar to that of alabandite (MnS). The data were indexed by Keil & Snetsinger (1967) by analogy with the data for alabandite, and gave the unit-cell edge reported in Table 3. The strongest two lines for the mineral from the Abee meteorite (analytical data 1) are 2.584 (200) and 1.829 (220). The full data could not be obtained, but probably are very similar to those for synthetic magnesium sulfide given by Swanson *et al.* (1957). Spacings calculated for the same planes and for a = 5.17 Å are compared in Table 4 with the data of Swanson *et al.* (1957).

Skinner & Luce (1971) studied the synthetic system MgS–FeS–MnS–CaS corresponding to niningerite –

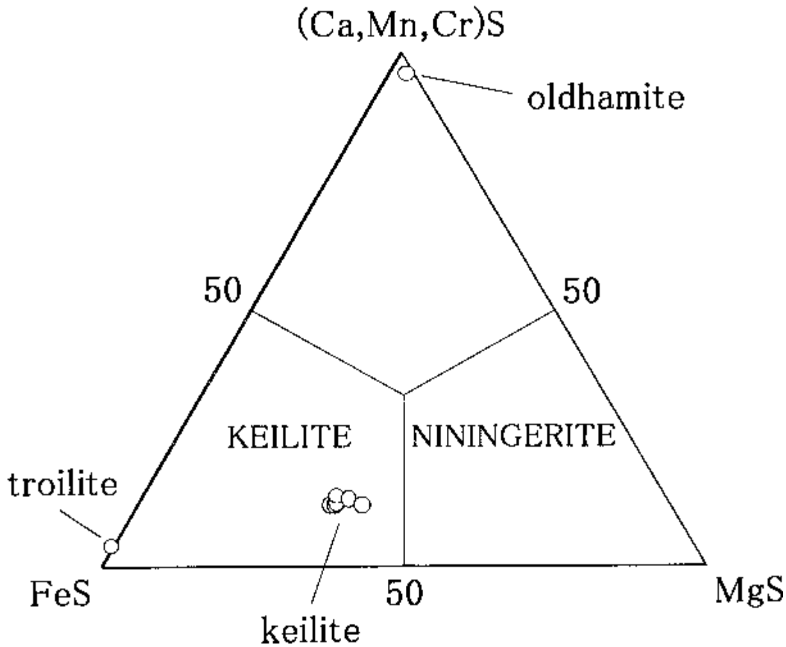

FIG. 2. The composition of the six grains of keilite analyzed in this study in terms of the triangular diagram FeS – MgS – (Ca,Mn,Cr)S. Results for a grain of oldhamite and one of troilite also are indicated.

TABLE 4. X-RAY POWDER-DIFFRACTION DATA FOR KEILITE AND NININGERITE

Keilite (a 5.17 Å)			Synthetic niningerite (a 5.200 Å)			
d(meas.)	*d*(calc.)	*hkl*	*d*(meas.)	(I)	*hkl*	*d*(calc.)
	2.985	111	3.004	8	111	3.0022
2.584	2.585	200	2.601	100	200	2.6000
1.829	1.828	220	1.8388	60	220	1.8385
	1.492	222	1.5010	15	222	1.5011
	1.292	400	1.3001	7	400	1.3000
	1.156	420	1.1630	13	420	1.1628
	1.055	422	1.0617	10	422	1.0614
	0.914	440	0.9194	<1	440	0.9192
	0.862	600	0.8667	6	600	0.8667
	0.817	620	0.8222	6	620	0.8222
	0.779	622	0.7840	5	622	0.7839

Measured values of keilite from Keil & Snetsinger (1967); calculated values of keilite and synthetic niningerite from this study; data for synthetic niningerite from Swanson *et al.* (1957).

keilite – alabandite – oldhamite, and presented the cell edges for cubic MgS, MnS and CaS. They also presented cell-edge data *versus* composition for portions of the binary systems CaS–MnS, MnS–FeS, CaS–MgS, MnS–MgS and MgS–FeS. Also given are data for portions of the ternary systems CaS–MgS–MnS, CaS–MgS–FeS, CaS–MnS–FeS and MgS–MnS–FeS.

When we plotted the binary data, each set showed a linear relationship between composition and cell edge. Linear regression analysis (with R^2 values over 0.99) permitted the derivation of the following equations for each of the binary systems:

System	R^2	cell edge a in Å
CaS–MnS	0.9998785	5.6954 – (mol.% MnS × 0.0048)
MnS–FeS	0.9989155	5.2244 – (mol.% FeS × 0.0017)
CaS–MgS	0.9992183	5.7233 – (mol.% MgS × 0.0053)
MnS–MgS	0.9938159	5.2280 – (mol.% MgS × 0.0002)
MgS–FeS	0.9936741	5.2038 – (mol.% FeS × 0.0013)

According to these data, the cell edge of pure keilite, calculated from the data for the system MgS–FeS, should be 5.0738 Å.

OTHER OCCURRENCES OF NININGERITE AND KEILITE

The preceding data pertain to information published by Keil & Snetsinger (1967) and measurements by the present authors. A search of the literature revealed that numerous studies have been carried out on meteorites that contain "niningerite". This section of our paper summarizes some of those studies.

Ehlers & El Goresy (1988) studied zoning in niningerite in the EH chondrites Abee, Indarch, Kaidun III, South Oman, St. Marks, Y74370, Y691 and Qingzhen. Their data indicate the presence of niningerite in all of these except Abee, which contains keilite. El Goresy (pers. commun., 2002) stated that keilite in Abee displays, in some cases, exsolution platelets of troilite, where (001) of troilite is parallel to (111) of keilite. Ramdohr (1973) first reported this textural development in Abee, and it also was observed by Ehlers (1989).

Zhang *et al.* (1995) presented electron-microprobe data for Mg–Mn–Fe sulfides in thirteen EH and El chondrites; their data show that four of these (LEW 88180, RKP A80259, LEW 87119 and LEW 88714) contain keilite. Kimura & Lin (1999) gave electron-microprobe analytical data for "niningerite" in the paired Antarctic meteorites Y–791790 and Y–791811, as well as in Y–86760 and Abee. All four are Fe-dominant, and are thus keilite. In addition, Drs. Lin and Kimura allowed Prof. Dr. El Goresy to send us the complete set of analytical data for "niningerite" in section Y8404. Of these 132 sets of data, only one is Mg-dominant, and the rest pertain to keilite. The one true niningerite has a magnesium to iron ratio of 0.425:0.421, so it is marginally Mg-dominant. In contrast, Lin & El Goresy (2002) studied the opaque phases in the Qingzhen and MacAlpine Hills meteorites and presented electron-microprobe data for three samples of "niningerite"; two are true niningerite (Mg-dominant), and one is alabandite (Mn-dominant). Similarly, Leitch & Smith (1982) analyzed "niningerite" from four meteorites (Indarch, Kota-Kota, Adhi-Kot and Abee), and all of this material is Mg-dominant, *i.e.*, true niningerite.

Aside from the data of Lin & El Goresy (2002) and of Leitch & Smith (1982), most of the analytical data show clearly that keilite is a widespread constituent of enstatite chondrites. Optically, it would be difficult to differentiate keilite from niningerite.

In summary, according to the data presented here and in the literature, keilite occurs in the following meteorites: Abee, Adhi-Kot, Saint-Sauveur, LEW 88180, RKP A80259, LEW 87119, LEW 88714, Y–791790, Y–791811, Y–86760 and Y8404. Information on these meteorites was given by Grady (2000).

Remarks

Keilite is an example of a mineral whose description has been in the literature for many years (Anthony *et al.* 1990, Gaines *et al.* 1997) "masquerading" as a different species, in this case niningerite. The authors of the original description did not differentiate between the Mg-dominant and Fe-dominant members of the series. In his abstract of the niningerite description, Fleischer (1967) noted that some samples of niningerite have Fe > Mg and others have Mg > Fe. In the Discussion part of the abstract, Fleischer stated: "It has been customary to give separate names to the parts of such a series with Mg > Fe and Fe > Mg. If the composition is found to extend much farther towards Fe, another name may be needed for the cubic phase with Fe > Mg, but for the present it seems desirable to use a single name."

Considering the definition of a mineral by Nickel (1995) and, more specifically, the paper on solid solutions in mineral nomenclature by Nickel (1992), it seems justified to assign separate names to the Fe-dominant and Mg-dominant members of this series.

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