

Article

Trigonal Fe₂Si from the Blackville site, South Carolina, USA: occurrence, composition and determination of the crystal structure

Luca Bindi¹ , James P. Kennett², Malcolm A. LeCompte³, Gunther Kletetschka^{4,5}, Christopher R. Moore^{6,7} and Allen West⁸ 

¹Dipartimento di Scienze della Terra, Università di Firenze, Firenze, Italy; ²Department of Earth Science and Marine Science Institute, University of California Santa Barbara, Santa Barbara, CA, USA; ³Center of Excellence in Remote Sensing Education and Research, Elizabeth City State University, Elizabeth City, NC, USA; ⁴Geophysical Institute, University of Alaska, Fairbanks, AK, USA; ⁵Faculty of Science, Charles University, Prague, Czech Republic; ⁶South Carolina Institute of Archaeology and Anthropology, University of South Carolina, Columbia, SC, USA; ⁷SCDNR Heritage Trust Program; Land, Water, and Conservation Division; South Carolina Department of Natural Resources, Columbia, SC, USA; and ⁸Comet Research Group, Prescott, AZ, USA

Abstract

Iron silicides, including hapkeite (Fe₂Si), are rare minerals found in both terrestrial and extraterrestrial environments. In this study, we present the discovery of trigonal Fe₂Si in glass from the Blackville site, South Carolina, USA, in a discrete, deeply buried layer where it is associated with suessite and other impact-related materials. The site has been previously studied for its rich assemblage of Fe–Si spherules, platinum, iridium and nanodiamonds. Using advanced micro-computed tomography, scanning electron microscopy, electron microprobe analysis, and single-crystal X-ray diffraction, we have characterised the crystal structure of trigonal Fe₂Si, identifying it as a distinct phase from the cubic hapkeite. The high concentrations of V, Ti and P in trigonal Fe₂Si and its co-occurrence with suessite suggest an impact-related origin or a lightning strike. Anthropogenic processes, although unlikely, cannot yet be completely ruled out. While this compound represents a new polymorph of Fe₂Si, we refrain at this time from proposing it as a new mineral species to the International Mineralogical Association (IMA) because of remaining uncertainties about its formation. Further research is needed to determine whether this trigonal Fe₂Si was produced by natural processes or by anthropogenesis.

Keywords: Fe₂Si; hapkeite; suessite; Blackville site; crystal structure; reducing conditions

(Received 22 April 2025; revised 30 July 2025; accepted 30 July 2025; Accepted Manuscript published online: 8 August 2025)

Introduction

Iron silicides are a relatively rare family of minerals with only seven Fe-silicides having been approved as minerals by the IMA: suessite (Fe₃Si), xifengite (Fe₅Si₃), gupeite (Fe₃Si), hapkeite (Fe₂Si), luobusaite (Fe_{0.84}Si₂), linzhiite (FeSi₂) and naquite (FeSi). Among these, hapkeite has been reported to occur in different environments. As terrestrial occurrences, it has been found in three locations. (1) In corundum xenocrysts in Late Cretaceous pyroclastic ejecta from Mount Carmel (northern Israel), associated with alluvial deposits in the Kishon River area (e.g. Xiong *et al.*, 2017; Griffin *et al.*, 2021). At Mt. Carmel, large corundum grains contain several forms of iron silicides, including gupeite, xifengite, naquite, hapkeite, and an unnamed Fe₅Si, either pure

or in combination with Ti and P (Griffin *et al.*, 2019, 2020). (2) In carbonate xenoliths of Neogene basalts at Dalihu, Inner Mongolia, China (Liu *et al.*, 2015; He *et al.*, 2017). At Dalihu Ni-rich hapkeite (empirical formula: Fe_{1.56}Ni_{0.49}Si_{1.00}) coexists with Ni-rich suessite (empirical formula: Fe_{2.92}Ni_{0.02}Cr_{0.01}Si_{1.08}) and an unnamed Fe_{2.86}Ti_{0.19}Ni_{0.16}Al_{0.11}Si_{7.00}. (3) In limestones of the Targhasa reef massif, Eastern Sayan mountains, Krasnoyarsk Krai, Russia (Eremenko *et al.*, 1974), hapkeite is associated with naquite, linzhiite, xifengite, unnamed FeSi₉, unnamed Fe₃Si₂, and unnamed Fe₄Si₉ (Rappenglück, 2022). Natural silicides – including hapkeite – have also been reported in the streambed of a tributary to the Sheshenyak Minor River (Basu *et al.*, 2000) between the Alatau and Kalu ranges, close to the abandoned settlement of Utar-Yurt (Southern Urals, Ishimbayskiy rayon, Russia). Here, hapkeite is associated with gupeite, xifengite, naquite and other exotic phases such as Fe₇Si₂, Fe₃Si₂, (Fe,Ti)₄Si₅, (Fe,Ca,Ti)₅Si₄, and (Fe,Ca,Ti)₄Si₇. Lastly, hapkeite is also known to occur in either natural or anthropogenic fulgurites, along with other unusual compositions such as Fe₈Si₃ and Fe₇Si₃, as well as Fe–Si–Al alloys like FeTi(Al,Si)₂, Fe(Al,Si)₃, Fe(Al,Si)₅ or Fe₅AlSi₁₀ (Ramírez-Cardona

Corresponding author: Luca Bindi; Email: luca.bindi@unifi.it

Associate Editor: Ian Graham

Cite this article: Bindi L., Kennett J.P., LeCompte M.A., Kletetschka G., Moore C.R. and West A. (2026) Trigonal Fe₂Si from the Blackville site, South Carolina, USA: occurrence, composition and determination of the crystal structure. *Mineralogical Magazine* 90, 87–92. <https://doi.org/10.1180/mgm.2025.10130>

et al., 2006; Sheffer, 2007; Pasek *et al.*, 2012; Abbatiello *et al.*, 2025; Morana *et al.*, 2025).

As an extraterrestrial occurrence, hapkeite has been reported in Comet 81P/Wild 2, associated with suessite, unnamed (Fe,Ni,Cr)Si and an unnamed Fe₇Si₂ (Nakamura *et al.*, 2008). These iron silicides are thought to have been produced by a hypervelocity impact of (Fe,Ni)-S particles, leading to a temperature above 1400 K, heating the aerogel substrate (containing Si), melting it and mixing matter from the particle and the aerogel (SiO₂), followed by rapid cooling. Hapkeite has also been reported with naquite, linzhiite, gupeite, P-bearing suessite, and Cr-bearing xifengite in the lunar meteorite Dhofar 280 (Anand *et al.*, 2004 and references therein), and in one of the samples from crater ejecta blanket at the Mare Crisium landing site returned by the Luna-24 mission (Ashikmina *et al.*, 1979). It was also discovered in association with suessite and naquite in the polymict DAG 1066 meteorite (Dar al Gani, Libya; Moggi Cecchi *et al.*, 2015), in the ureilite EET 83,309 (Elephant Moraine, Antarctica; Herrin *et al.*, 2007), and in the FRO 90,228 dimict ureilite (Smith, 2008), all indicating an origin as impact-induced melt phases.

In impact-related material, hapkeite (Fe₂Si) has been reported in magnetic spherules (100–200 µm) from Üveghuta, Lower Carboniferous Mórággy Granite Complex, Tolna County, Hungary, and from the Mesozoic Gemic Granite Complex, and thought to be either extraterrestrial dust or remnants of a meteorite impact (Szöör *et al.*, 2001). Also, together with gupeite and probably naquite, it has been found in a rock from the Koshava gypsum deposit, Moesia region, Northwest Bulgaria (Yanev *et al.*, 2021). This exotic rock was initially identified as a meteorite, but since then, it has been reclassified as an impact ejecta. In addition, previous research into a proposed group of airburst/impact craters in Chiemgau, Germany, identified gupeite, xifengite, hapkeite, naquite and linzhiite in glass (Bauer *et al.*, 2019; Ernstson *et al.*, 2023). Iron silicides were also reported at a proposed 12,800-year-old airburst/impact site within the prehistoric village of Abu Hureyra, Syria (Moore *et al.*, 2020, 2023), but their impact-related origin has been challenged (e.g. Holliday *et al.*, 2023).

Here, we report the results on a study of a glass fragment from a sediment sequence at the Blackville site in South Carolina, USA. The glass was found in a 15 cm interval between 175 to 190 cm with maximum concentrations at ~183 cm below the surface. The glass was accompanied by peak concentrations of platinum and iridium (Kennett *et al.*, 2015), Fe- and Si-rich spherules (Bunch *et al.*, 2012; Wittke *et al.*, 2013), glass containing suessite and native iron (Bunch *et al.*, 2012), soot/aciniform carbon (Wolbach *et al.*, 2018), carbon spherules (Kinzie *et al.*, 2014), and nanodiamonds (Kinzie *et al.*, 2014). The stratum was dated by Optically Stimulated Luminescence to 12,960 ± 1190 calendar years, leading Bunch *et al.* (2012) to conclude that the stratum is too old and too deeply buried to contain anthropogenic contamination.

For our investigation, trigonal Fe₂Si was isolated and studied using micro-computed tomography, scanning electron microscopy, electron microprobe and X-ray single-crystal diffraction. The results are presented here.

Material and methods

Samples

The samples were collected by one of us (AW) at the Blackville site, South Carolina, USA (33.361545°N, 81.304348°W) using hand

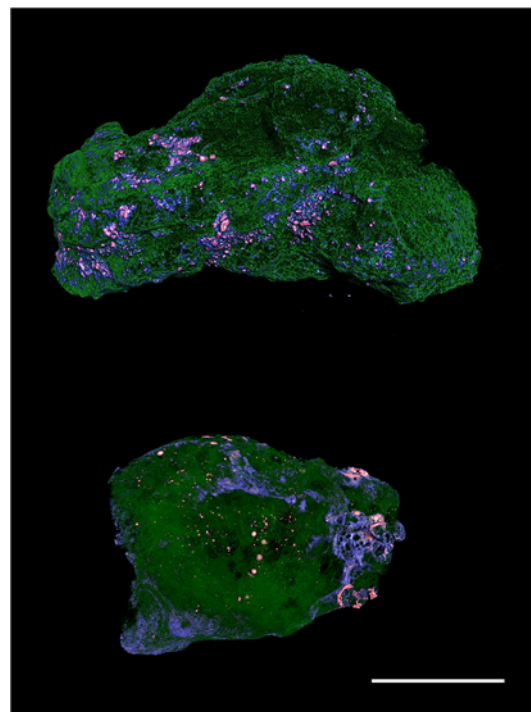


Figure 1. Micro-CT images of the two rock fragments studied from the Blackville site. Silicate glass is in green and silicide droplets in orange. Scale bar is 1 cm.

auger coring. The sediment sequence consists of aeolian and alluvial sediments, specifically variable loamy to silty red clays, extending downwards to an apparent discontinuity at 190 cm below the surface. A 15-cm-thick interval from 175 to 190 cm below the surface displayed an enrichment in glass. Little to no glass was observed above or below this layer.

Micro-computed X-ray tomography

Initially, X-ray imaging was carried out using an Rx Solution NanoCT “EasyTom” with a voxel size of 13.69 µm. A 150 kV X-ray source was used with a current of 200 µA. A total of 1920 absorption radiographs were acquired over a 360° rotation. The raw data were reconstructed into two-dimensional slice images (Fig. 1) using Rx Solution Software. CT datasets were visualised and customised using Bruker’s CTAn and CTVox software.

Scanning electron microscopy

Three samples were embedded in epoxy, polished and then studied with a Zeiss EVO MA15 scanning electron microscope coupled with an Oxford UltimMax 40 energy-dispersive spectrometer (EDS), operating at 15 kV accelerating potential and 700 pA nominal current in focused beam mode for EDS mapping and spectra acquisition (30 s live time). For linescan analyses, the instrument was set up at 10 kV acceleration voltage and 500 pA nominal probe current (20 s dwell time for each point). One sample was randomly selected and sputter-coated with a 30 nm thick carbon film.

Electron microprobe

Quantitative analyses on suessite and hapkeite (initially identified by scanning electron microscope) comprising a 250 µm-diameter

Table 1. Electron microprobe data (wt.% of elements) and chemical formulae for suessite (S – on the basis of 4 atoms) and trigonal Fe₂Si (TH – on the basis of 3 atoms) from the Blackville site

	S1	S2	S3	TH1	TH2	TH3	TH4
Fe	83.18	84.11	83.09	73.25	73.29	73.05	73.01
Si	14.09	14.09	14.07	18.45	18.21	18.45	18.33
V	0.35	0.15	0.25	4.37	4.41	4.39	4.45
P	0.29	0.14	0.20	1.95	2.06	2.06	2.15
Ti	2.25	2.18	2.18	2.04	2.01	2.15	2.05
Total	100.16	100.67	99.79	100.06	99.98	100.10	99.99
Atoms per formula unit							
Fe	2.90	2.92	2.91	1.82	1.83	1.81	1.82
Si	0.98	0.97	0.98	0.91	0.90	0.91	0.90
V	0.01	0.01	0.01	0.12	0.12	0.12	0.12
P	0.02	0.01	0.01	0.09	0.09	0.09	0.10
Ti	0.09	0.09	0.09	0.06	0.06	0.07	0.06

droplet were carried out using a JEOL 8200 electron microprobe (WDS mode, 12 kV and 5 nA, focused beam). The focused electron beam was ~150 nm in diameter. Analyses were processed using the CITZAF correction procedure. Both suessite ($n = 3$) and hapkeite ($n = 4$) were found to be homogeneous within analytical error (Table 1). The standards used were Fe metal, Ni metal, V metal, synthetic FeSi and GaP.

Single-crystal X-ray diffraction

A small fragment (size ~18 × 15 × 10 µm) exhibiting an Fe₂Si composition was extracted from the droplet shown in Fig. 2 under a reflected light microscope and mounted on a 5 µm diameter carbon fibre, which was, in turn, attached to a glass rod. The single-crystal X-ray study was carried out using a Bruker D8 Venture diffractometer equipped with a Photon III detector. Unit-cell parameters (Table 2) and intensity data were collected using graphite-monochromatised MoK α radiation ($\lambda = 0.71073$ Å); the data were then integrated and corrected for Lorentz-polarisation effects and absorption using the APEX5 software suite (Bruker, 2023).

Surprisingly, the unit-cell parameters observed for the selected Fe₂Si crystal indicated a trigonal symmetry, with $a = 3.9782(2)$ and $c = 5.0691(3)$ Å. No systematic absences were observed, in keeping with the space group $P\bar{3}m1$. As trigonal Fe₂Si has been previously described by several authors (e.g. Khalaff and Schubert, 1974; Heinz, 1977; Tang *et al.*, 2016), we decided to begin the refinement using these atom coordinates. The program SHELXL (Sheldrick, 2008) was used for the refinement of the structure. The occupancy of all the sites was left free to vary (Fe vs. vacancy; Si vs. vacancy), but they were found to be fully occupied by the corresponding atomic species and then fixed accordingly. Neutral scattering curves for Fe and Si were taken from the *International Tables for X-ray Crystallography* (Ibers and Hamilton, 1974). At the last stage, with anisotropic atomic displacement parameters for all atoms and no constraints, the residual value settled at $R = 0.0224$ for 60 observed reflections [$2\sigma(I)$ level] and 11 parameters and at $R = 0.0336$ for all 160 independent reflections.

Experimental details and R indices are given in Table 2. Fractional atomic coordinates and equivalent displacement parameters are reported in Table 3 (anisotropic displacement parameters can be found in the accompanying crystallographic information file). Bond distances are given in Table 4. The cif has

Table 2. Crystallographic data and refinement parameters for trigonal Fe₂Si

Crystal data	
Ideal formula	Fe ₂ Si
Crystal system	trigonal
Space group	$P\bar{3}m1$
Unit-cell parameters	
a, c (Å)	3.9782(2), 5.0691(3)
$\alpha/\beta/\gamma$ (°)	90/90/120
Unit-cell volume (Å ³)	69.476(8)
Z	2
Crystal size (mm)	0.018×0.015×0.010
Data collection	
Diffractometer	Bruker D8 Venture
Temperature (K)	293(2)
Radiation, wavelength (Å)	MoK α , 0.71073
2θ max for data collection (°)	75.704
Crystal-detector distance (mm)	50
Total reflections collected	2356
Unique reflections (R_{int})	160 (0.030)
Unique reflections $I > 2\sigma(I)$	60
Data completeness to θ_{max} (%)	99.8
Absorption correction method	Multi-scan
Structure refinement	
Refinement method	Full-matrix least-squares on F^2
Data/restraints/parameters	2356/0/11
$R_1 [I > 2\sigma(I)]$, R_1 [all reflect.]	0.0224, 0.0336
Goodness-of-fit on F^2	0.654
Largest diff. peak and hole (e ⁻ /Å ³)	0.96, -1.18

Notes: $R(n/n-1)^{1/2} [Fo^2 - Fo(\text{mean})^2] / \sum Fo_{int}^2$

$R_1 = \sum ||Fo| - |Fc|| / \sum |Fo|$

Goof = $\{\sum [w(Fo^2 - Fc^2)^2] / (n-p)\}^{1/2}$ where n = no. of reflections, p = no. of refined parameters

Table 3. Atoms, Wyckoff letter, fractional atom coordinates (Å) and equivalent atomic displacement parameters for trigonal Fe₂Si

Atom	Wyckoff	x	y	z	U_{eq}
Fe1	1a	0	0	0	0.0166(3)
Fe2	1b	0	0	½	0.0183(3)
Fe3	2d	⅓	⅓	0.7783(4)	0.0203(3)
Si	2d	⅓	⅓	0.2787(7)	0.0191(4)

been deposited and is available as Supplementary material (see below).

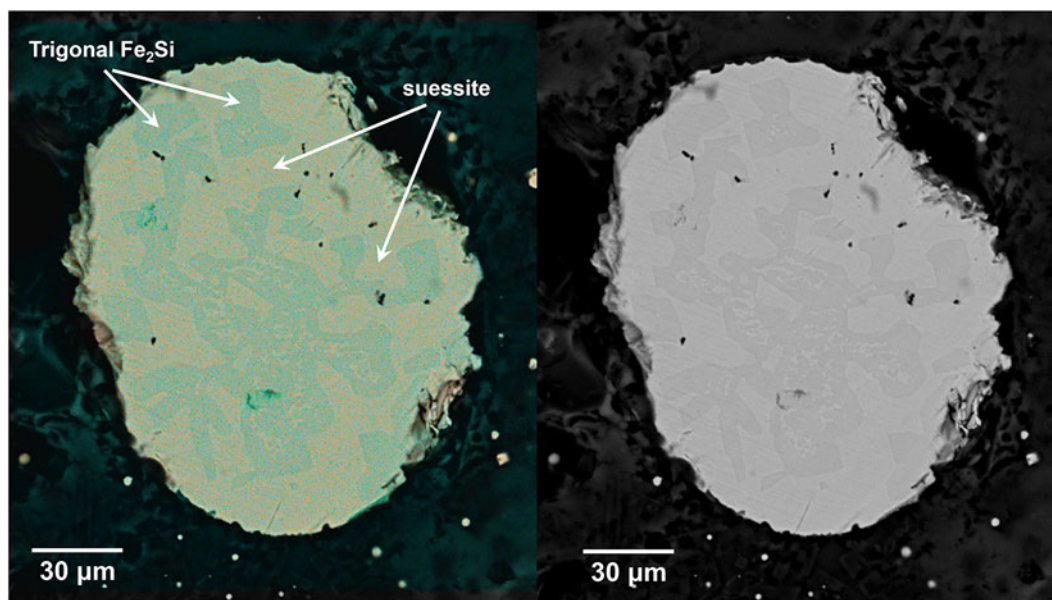


Figure 2. X-ray element-distribution map (left) and scanning electron microscope back-scattered electron image of the investigated droplet composed of Fe-silicides. Trigonal Fe_2Si and suessite are indicated.

Table 4. Selected bond distances (Å) for trigonal Fe_2Si

Fe1–Fe2 (×2)	2.53455(15)	Fe3–Si1 (×3)	2.3149(4)
Fe1–Fe3 (×4)	2.5571(8)	Fe3–Si1	2.532(5)
Fe1–Fe3 (×2)	2.5568(8)	Fe3–Si1	2.537(5)
Fe1–Si1 (×6)	2.6966(18)	Fe3–Fe1 (×2)	2.5571(8)
		Fe3–Fe1	2.5568(8)
Fe2–Fe1 (×2)	2.53455(15)	Fe3–Fe2 (×3)	2.6953(9)
Fe2–Si1 (×6)	2.5560(15)		
Fe2–Fe3 (×6)	2.6953(9)		
Si1–Fe3	2.537(5)		
Si1–Fe3	2.532(5)		
Si1–Fe3 (×3)	2.3149(4)		
Si1–Fe2 (×3)	2.5560(15)		
Si1–Fe1 (×3)	2.6966(18)		

Results and discussion

Crystal structure and nomenclature remarks

Hapkeite was originally defined with the formula Fe_2Si , cubic $Pm\bar{3}m$ structure ($a = 2.831$ Å) and $Z = \frac{2}{3}$ (Anand *et al.*, 2004). In the structure, there are two positions with the same multiplicity: $1a$ (0,0,0) and $1b$ ($\frac{1}{2}, \frac{1}{2}, \frac{1}{2}$). The $1a$ position is occupied by Fe only, whereas the $1b$ position is occupied by $\sim \frac{2}{3}\text{Si}$ and $\sim \frac{1}{3}\text{Fe}$. Given the preference to not give non-integer Z values and taking into account the rule of the dominance of a cation at a structural site, the formula had to be written either as $\text{Fe}(\text{Si},\text{Fe})$ or FeSi with $Z = 1$. Because of this, hapkeite should be revisited and should be considered as a second polymorph of FeSi after naquite (Shi *et al.*, 2012). On the contrary, the trigonal, ordered variant of Fe_2Si described here consists of four positions: $1a$ (0,0,0; fully occupied by Fe), $1b$ (0,0, $\frac{1}{2}$; fully occupied by Fe), $2d$ ($\frac{1}{3}, \frac{2}{3}, z$; fully occupied by Fe), and $2d$ ($\frac{1}{3}, \frac{2}{3}, z$; fully occupied by Si), with $Z = 2$. In this case, the formula must be written as Fe_2Si .

In addition to these nomenclature considerations, hapkeite and the compound described here (both with the Fe_2Si formula) cannot

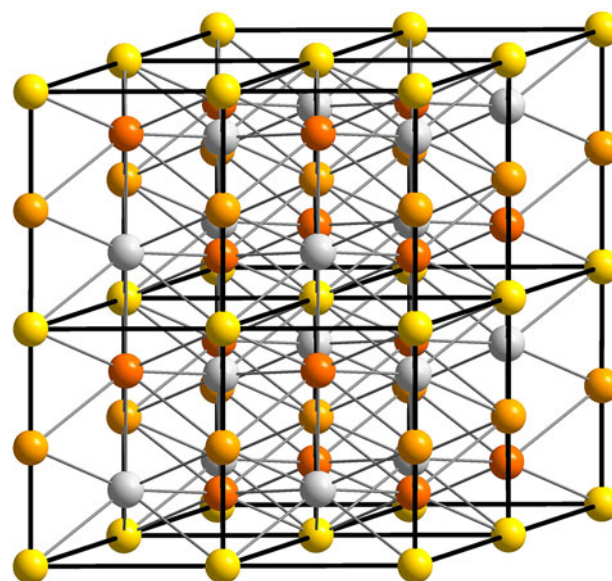


Figure 3. The crystal structure of trigonal Fe_2Si down the $[100]$ (perspective view). Yellow, light orange, orange and white spheres refer to Fe1, Fe2, Fe3 and Si atoms.

be considered polytypes because the crystal-chemical environment of Fe atoms is different in the two phases. In cubic Fe_2Si (hapkeite), Fe is surrounded by 8 (Si,Fe) atoms, whereas in trigonal Fe_2Si (Fig. 3), Fe atoms exhibit different coordination spheres (Fig. 4 and Table 4). In detail, the latter is characterised by three inequivalent Fe sites. In the first Fe site, Fe is bonded in a 14-coordinate geometry to eight equivalent Fe and six equivalent Si atoms. All Fe–Fe bond lengths are in the range 2.53–2.56 Å, and the Fe–Si bond distances are close to 2.70 Å. The second Fe site shows a coordination environment very close to that observed for Fe1 (Table 4). In the third Fe site, Fe is bonded in an 11-coordinate geometry to

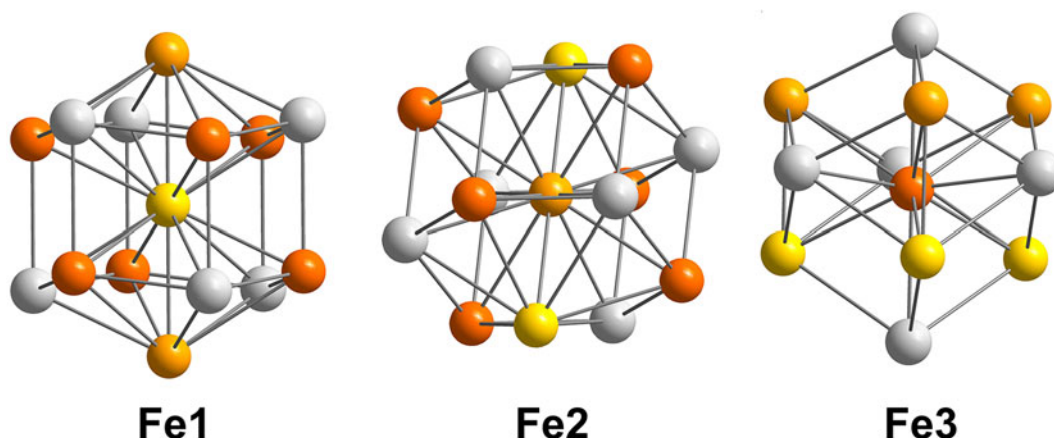


Figure 4. Crystal-chemical environments of Fe atoms in the crystal structure of trigonal Fe_2Si . Colours as in Fig. 3.

six equivalent Fe and five equivalent Si atoms. Notably, Fe3 shows three short bond distances with Si (~ 2.31 Å). Si is bonded in a distorted body-centred cubic geometry to eleven Fe atoms.

Interestingly, Errandonea *et al.* (2008) performed *ab initio* total energy calculations for both polymorphs (cubic and trigonal) of Fe_2Si and found that at zero and low pressure, the most stable variant for Fe_2Si is the trigonal structure because the cubic hapeite structure is higher in energy by more than 200 meV pfu (particle flux unit).

Possible origin for silicides at the Blackville site

The discovery of trigonal Fe_2Si and associated suessite in glass from the Blackville site suggests formation under highly reducing conditions related to unusual terrestrial conditions. Although the precise formation mechanism is unclear, past research suggests an as-yet-unidentified impact or a lightning strike event. Indeed, very similar silicide assemblages have been recently reported in fulgurites (e.g. Bindi *et al.*, 2023; Abbatiello *et al.*, 2025; Morana *et al.*, 2025). It is noteworthy that Essene and Fischer (1986) observed that Fe–Si-bearing glass was associated with charred tree roots, suggesting that carbon may have assisted with the production of the highly reducing environment required for Fe–Si phase formation. However, though the sediment at the Blackville site contains carbon, it is probably insufficient by itself to drive the reduction process but still may have contributed to the formation of silicides. So, the origin of the Blackville silicides remains enigmatic and requires further research.

Conclusions

Given the structural differences with hapeite, trigonal Fe_2Si would normally be considered a new mineral species. However, after thorough analysis and consideration of the circumstances surrounding the formation of this mineral, we have opted not to propose this compound as a new mineral species to the International Mineralogical Association (IMA) at the present time. One of the key factors in this decision is the possibility that anthropogenic activity may have played a role in the formation of this mineral, although that possibility seems unlikely given the depth of burial (183 cm) where the samples were collected. Further investigation is needed to understand the mineral origin better, and any future proposals will depend on a clearer delineation between

natural and anthropogenic contributions to its formation. Until then, this discovery remains a significant observation in the field of Fe-silicides.

Supplementary material. The supplementary material for this article can be found at <https://doi.org/10.1180/mgm.2025.10130>

Acknowledgements. The paper benefited by the official reviews made by Peter Leverett and two anonymous reviewers. Associate Editor Ian Graham is thanked for his efficient handling of the manuscript. SC-XRD and EMPA data were collected, respectively, at CRIST (Centro di Servizi di Cristallografia Strutturale) and LaMA (Laboratorio di MicroAnalisi) of the Università degli Studi di Firenze, Italy.

Funding statement. This study was also conducted within the Space It Up project funded by the Italian Space Agency, ASI, and the Ministry of University and Research, MUR, under contract n. 2024-5-E.O-CUP n. I53D24000060005. GK was supported by the Czech Science Foundation (Grant 23-06075S) and the Ministry of Education, Youth and Sports (Grant LUAUS25082).

Competing interests. The authors declare none.

References

- Abbatiello J., Bindi L. and Pasek M.A. (2025) Constraints on iron silicide formation from a fulgurite from Southwick Massachusetts. *Mineralogical Magazine*, **89**, 476–482, doi: [10.1180/mgm.2024.108](https://doi.org/10.1180/mgm.2024.108)
- Anand M., Taylor L.A., Nazarov M.A., Shu J., Mao H.-K. and Hemley R.J. (2004) Space weathering on airless planetary bodies: Clues from the lunar mineral hapeite. *Proceedings of the National Academy of Sciences USA*, **101**, 6847–6851.
- Ashikmina N.A., Bogatkov O.A. and Gorshkov A. (1979) Aktsesornye minerali steklovatikh fragmentov Luni 24. *Doklady Akademii Nauk SSSR Earth Sciences Section*, **248**, 953–955.
- Basu S., Murty S., Shukla P.N. and Shukla A.D. (2000) Origin of Silicides (Unknown Meteorites). *Meteoritics & Planetary Science*, **35**, A22–A23.
- Bauer F., Hilt M., Rappenglück M.A. and Ernstson K. (2019) Trigonal and cubic Fe_2Si polymorphs (hapeite) in the eight kilograms find of natural iron silicide from Grabenstätt (Chiemgau, Southeast Germany). *50th Lunar and Planetary Science Conference*, abstract #1520.
- Bindi L., Feng T. and Pasek M.A. (2023) Routes to reduction of phosphate by high-energy events. *Communications Earth & Environment*, **4**, 70.
- Bruker (2023) *APEX5 software suite*. Bruker AXS Inc., Madison, Wisconsin, USA.
- Bunch T.E., Hermes R.E., Moore A.M., Kennett D.J., Weaver J.C., Wittke J.H., DeCarli P.S., Bischoff J.L., Hillman G.C., Howard G.A., Kimbel D.R., Kletetschka G., Lipo C.P., Sakai S., Revay Z., West A., Firestone R.B. and

- Kennett J.P. (2012) Very high-temperature impact melt products as evidence for cosmic airbursts and impacts 12,900 years ago. *Proceedings of the National Academy of Sciences USA*, **109**, E1903–E12.
- Eremenko G.K., Polkanov Y.A. and Gevorkyan V.K. (1974) Cosmogenic minerals in the Poltava deposits of the Konka–Yalynsk depression in northern Azov Region. *Mineral. Osadochnih Obrazie*, **1**, 66–75 [in Russian].
- Ernstson K., Bauer F. and Hiltl M. (2023) A prominent iron silicides strewn field and its relation to the Bronze Age/Iron Age Chiemgau meteorite impact event (Germany). *Earth Sciences*, **12**, 26–40.
- Errandonea D., Santamaria-Perez D., Vegas A., Nuss J., Jansen M. and Munoz A. (2008) Structural stability of Fe_5Si_3 and Ni_2Si studied by high-pressure x-ray diffraction and *ab initio* total-energy calculations. *Physical Review*, **B77**, 094113.
- Essene E.J. and Fisher D.C. (1986) Lightning strike fusion: Extreme reduction and metal-silicate liquid immiscibility. *Science*, **234**, 189–193. doi:10.1126/science.234.4773.189
- Griffin W.L., Gain S.E.M., Huang J.-X., Saunders M.J., Shaw J., Toledo V. and O'Reilly S.Y. (2019) A terrestrial magmatic hibonite-grossite-vanadium assemblage: Desilication and extreme reduction in a volcanic plumbing system, Mt Carmel, Israel. *American Mineralogist*, **104**, 207–219.
- Griffin W.L., Gain S.E.M., Saunders M.J., Bindi L., Alard O., Toledo V. and O'Reilly S.Y. (2020) Parageneses of TiB_2 in corundum xenoliths from Mt. Carmel, Israel: Siderophile behavior of boron under reducing conditions. *American Mineralogist*, **105**, 1609–1621. doi: 10.2138/am-2020-7375
- Griffin W.L., Gain S.E.M., Saunders M.J., Huang J.-X., Alard O., Toledo V. and O'Reilly S.Y. (2021) Immiscible metallic melts in the upper mantle beneath Mount Carmel, Israel: Silicides, phosphides and carbides. *American Mineralogist*, **107**, 532–549.
- He D., Gao C., Chen C., Liu Y. and Hu Z. (2017) SiC-dominated ultra-reduced mineral assemblage in carbonatitic xenoliths from the Dalihu basalt, Inner Mongolia, China. *American Mineralogist*, **102**, 312–320.
- Heinz K. (1977) Die Kristallstruktur von Fe_2Si , ihre Verwandtschaft zu den Ordnungsstrukturen des α -(Fe, Si)-Mischkristalls und zur Fe_5Si_3 -Struktur. *Zeitschrift für Kristallographie – Crystalline Materials*, **145**, 177–189.
- Herrin J.S., Mittlefehldt D.W., Downes H. and Humayum M. (2007) Diverse metals and sulfides in polymict ureilites EET 83309 and EET 87720. *Proceedings of the 38th LPSC, League City, TX, USA*, 12–16 March 2007, long abstract.
- Holliday V.T., Daulton T.L., Bartlein P.J., Boslough M.B., Breslawski R.P., Fisher A.E., Jorgeson I.A., Scott A.C., Koeberl C., Marlon J., Severinghaus J., Petaev M.I. and Claeys P. (2023) Comprehensive refutation of the Younger Dryas Impact Hypothesis (YDIH). *Earth-Science Reviews*, **247**, 104502.
- Ibers J.A. and Hamilton W.C. (editors) (1974) *International Tables for X-ray Crystallography*, vol. IV. Kynock, Dordrecht, The Netherlands, 366pp.
- Kennett J.P., Kennett D.J., Culleton B.J., Tortosa J.E.A., Bischoff J.L., Bunch T.E., Daniel I.R. Jr., Erlandson J.M., Ferraro D., Firestone R.B., Goodyear A.C., Israde-Alcántara I., Johnson J.R., Jordá Pardo J.F., Kimbel D.R., LeCompte M.A., Lopinot N.H., Mahaney W.C., Moore A.M.T., Moore C.R., Ray J.H., Stafford T.W.Jr., Tankersley K.B., Wittke J.H., Wolbach W.S. and West A. (2015) Bayesian chronological analyses consistent with synchronous age of 12,835–12,735 Cal B.P. for Younger Dryas boundary on four continents. *Proceedings of the National Academy of Sciences USA*, **112**, E4344–53.
- Kinzle C.R., Que Hee S.S., Stich A., Tague K.A., Mercer C., Razink J.J., Kennett D.J., DeCarli P.S., Bunch T.E., Wittke J.H., Israde-Alcántara I., Bischoff J.L., Goodyear A.C., Tankersley K.B., Kimbel D.R., Culleton B.J., Erlandson J.M., Stafford T.W., Kloosterman J.B., Moore A.M.T., Firestone R.B., Tortosa J.E.A., Jordá Pardo J.F., West A., Kennett J.P. and Wolbach W.S. (2014) Nanodiamond-rich layer across three continents consistent with major cosmic impact at 12,800 cal BP. *The Journal of Geology*, **122**, 475–506.
- Khalaff K. and Schubert K. (1974) Kristallstruktur von Fe_2Si (h). *Journal of Less Common Metals*, **35**, 341–345.
- Liu Y., He D., Gao C., Foley S., Gao S., Hu Z., Zong K. and Chen H. (2015) First direct evidence of sedimentary carbonate recycling in subduction-related xenoliths. *Scientific Reports*, **5**, 11547.
- Moggi Cecchi V., Caporali S. and Pratesi G. (2015) DaG 1066: A newfound anomalous ureilite with chondritic inclusions. *Proceedings of the 78th Annual Meeting of the Meteoritical Society, Berkeley, CA, USA*, 27–31 July 2015, Abstract. #5252.
- Moore A.M.T., Kennett J.P., Napier W.M., Bunch T.E., Weaver J.C., LeCompte M., Adedeji A.V., Hackley P., Kletetschka G., Hermes R.E., Wittke J.H., Razink J.J., Gaultois M.W. and West A. (2020) Evidence of Cosmic Impact at Abu Hureyra, Syria at the Younger Dryas Onset (~12.8 ka): High-temperature melting at >2200 °C. *Scientific Reports*, **10**, 4185.
- Moore A.M.T., Kennett J.P., Napier W.M., Bunch T.E., Weaver J.C., LeCompte M., et al. (2023) Abu Hureyra, Syria, Part 2: Additional evidence supporting the catastrophic destruction of this prehistoric village by a cosmic airburst ~12,800 years ago. *Airbursts and Cratering Impacts*, **1**, 1–36. doi: 10.14293/ACI.2023.0002
- Morana M., Pasek M., Catelani T. and Bindi L. (2025) Mineralogical characterization of the Seffner fulgurite, Florida: Insights into lightning-induced petrogenesis. *American Mineralogist*, **110**, 1149–1157.
- Nakamura T., Tsuchiyama A., Akaki T., Uesugi K., Nakano T., Takeuchi A., Suzuki Y. and Noguchi T. (2008) Bulk mineralogy and three-dimensional structures of individual Stardust particles deduced from synchrotron X-ray diffraction and microtomography analysis. *Meteoritics & Planetary Science*, **43**, 247–259.
- Pasek M.A., Block K. and Pasek V. (2012) Fulgurite morphology: A classification scheme and clues to formation. *Contributions to Mineralogy and Petrology*, **164**, 477–492.
- Ramírez-Cardona M., Castro K.F. and Cortés García P.P. (2006) Mineralogical study of binary iron silicides (Fe-Si system) in a fulgurite from Hidalgo, Mexico. *Boletín de Mineralogía*, **17**, 69–76.
- Rappenglück M.A. (2022) Natural iron silicides: A systematic review. *Minerals*, **12**, 188.
- Sheffer A.A. (2007) *Chemical Reduction of Silicates by Meteorite Impacts and Lightning Strikes*. Ph.D. Thesis, The University of Arizona, Tucson, AZ, USA.
- Sheldrick G.M. (2008) A short history of SHELX. *Acta Crystallographica*, **A64**, 112–122.
- Shi N., Bai W., Li G., Xiong M., Yang J., Ma Z. and Rong H. (2012) Naquite, FeSi , a new mineral species from Luobusha, Tibet, Western China. *Acta Geologica Sinica*, **86**, 533–538.
- Smith C.L. (2008) Metal and sulphide phases in interstitial veins in “dimict” ureilites—Insights into the history and petrogenesis of the ureilite parent body. *Proceedings of the 39th LPSC, League City, TX, USA*, 10–14 March 2008, Abstract #1669.
- Szöör G., Elekes Z., Rózsa P., Uzonyi I., Simulák J. and Kiss Á.Z. (2001) Magnetic spherules: Cosmic dust or markers of a meteoritic impact? *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, **181**, 557–562.
- Tang C.P., Tam K.V., Xiong S.J., Cao J. and Zhang X. (2016) The structure and electronic properties of hexagonal Fe_2Si . *AIP Advances*, **6**, 65317.
- Wittke J.H., Weaver J.C., Bunch T.E., Kennett J.P., Kennett D.J. et al. (2013) Evidence for deposition of 10 million tonnes of impact spherules across four continents 12,800 y ago. *Proceedings of the National Academy of Sciences USA*, **110**, E2088–E97.
- Wolbach W.S., Ballard J.P., Mayewski P.A., Adedeji V. and Bunch T.E. (2018) Extraordinary biomass-burning episode and impact winter triggered by the Younger Dryas cosmic impact ~12,800 years ago. 1. Ice cores and glaciers. *The Journal of Geology*, **126**, 165–184.
- Xiong Q., Griffin W.L., Huang J., Gain S., Toledo V., Pearson N.J. and O'Reilly S.Y. (2017) Super-reduced mineral assemblages in “ophiolitic” chromites and peridotites: The view from Mount Carmel. *European Journal of Mineralogy*, **29**, 557–570.
- Yanev Y., Benderev A., Zotov N., Dubinina E., Iliev T., Georgiev S., Ilieva I. and Sergeeva I. (2021) Exotic rock block from the Koshava gypsum mine, Northwest Bulgaria: Petrography, geochemistry, mineralogy and melting phenomena. *Geologica Balcanica*, **50**, 45–65.