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Impact glasses from Belize represent tektites from the Pleistocene Pantasma impact crater in Nicaragua

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Tektites are terrestrial impact-generated glasses that are ejected long distance (up to 11,000 km), share unique characteristics and have a poorly understood formation process. Only four tektite strewn-fields are known, and three of them are sourced from known impact craters. Here we show that the recently discovered Pantasma impact crater (14 km diameter) in Nicaragua is the source of an impact glass strewn-field documented in Belize 530 km away. Their cogenesis is documented by coincidental ages, at 804 ± 9 ka, as well as consistent elemental compositions and isotopic ratios. The Belize impact glass share many characteristics with known tektites but also present several peculiar features. We propose that these glasses represent a previously unrecognized tektite strewn-field. These discoveries shed new light on the tektite formation process, which may be more common than previously claimed, as most known Pleistocene >10 km diameter cratering events have generated tektites.
Our tektite strewn-fields have been recognized so far, all of them identified since the 1930's\textsuperscript{1-4} australasites, ivorites, moldavites, and North American tektites (also called bediasites and georgiatis). Only the latter three strewn fields have been firmly connected to a known source crater (Bosumtwi, Ries, and the Chesapeake Bay, respectively), which all have diameters >10 km. The identification of the australasite source crater is still controversial despite recent studies, but its diameter is suggested to be >10 km\textsuperscript{4,5}. The specificities of the generation process of tektite versus other known impact glasses are not well understood, despite numerous sample studies and modeling. Tektite generation may be favored by high velocity (>20 km s\textsuperscript{-1}) and low angle impacts in a soft water-rich surface, such as loess or soil\textsuperscript{6,7}. Why only four out of the 78 known impact craters larger than 10 km in diameter\textsuperscript{10} are known to have generated tektites, including the putative crater responsible for the australasites, still remains an unsolved and challenging issue.

The criteria for differentiating between impact and volcanic glasses are their very low water content (compared to obsidians), the presence of high-temperature and/or high-pressure phases, and potential contamination by extra-terrestrial matter derived from the impactor. Tektites are characterized by the size of the strewn-fields (over 300 km wide except the Ivorite case that is about 60 km wide) and the distance from the source crater (over 200 km and up to 5000 km or even 11,000 km including microtektites\textsuperscript{11}). Other criteria include in particular their volatile depletion, the rarity of unmelted inclusions, low vesicularity, chemical homogeneity\textsuperscript{3}, and a reduced character\textsuperscript{12,13} marked by the lack of Fe\textsuperscript{3+}.

**Results**

In archeological excavations of the Mayan city of Tikal (North Guatemala; Fig. 1), tektite-looking glasses were identified\textsuperscript{14,15}. Based on their andesitic composition (i.e., different from obsidian artifacts), low water content (=80 ppm), and low Fe\textsuperscript{3+} concentration (from Mössbauer spectroscopy and magnetic properties) they were proposed to be tektites. J. Cornec (J.C.) engaged in concentration (from Mössbauer spectroscopy and magnetic properties) but a few samples are bubble-rich (one zone with up to 20% porosity). The magnetic susceptibility, measured on circa 4000 samples, is distributed in a very narrow range\textsuperscript{23} with a mean of 125 ± 4 × 10\textsuperscript{−9} m\textsuperscript{3} kg\textsuperscript{−1} excluding 31 more magnetic outliers (>200 × 10\textsuperscript{−9} m\textsuperscript{3} kg\textsuperscript{−1}) that will be discussed later. Such a narrow distribution is typical of tektites\textsuperscript{12,23}, as it indicates both the lack of Fe\textsuperscript{3+} and homogeneous iron content. Negligible Fe\textsuperscript{3+} is
confirmed by synchrotron X-ray absorption near-edge structure (XANES) spectroscopy on two specimens yields values of 53 and 114 ppm, in the low range for tektites. It compares well to previous data from 60–80 ppm. It is lower than the 240–280 ppm range determined in Pantasma glass, in agreement with the fact that tektites are more depleted in volatiles than proximal glass.

Optical and back-scattered electronic microscopic investigations (Fig. 3) reveal fluidal textures typical of pure impact glasses, with no unmelted inclusions and limited content of spherical vesicles. The only common (still <1 vol.%) inclusions are pure SiO$_2$ with smooth edges and often strong elongation, which is typical for the high-temperature silica glass lechatelierite. Lechatelierite was further identified by Raman spectroscopy, along with a few α-cristobalite inclusions (Supplementary Fig. 4 and Note 1). The search for contamination by extra-terrestrial matter using chromium isotopic ratio analyses (e.g., ref. 27) yields clear evidence of contamination by an ordinary chondrite impactor: $^{54}$Cr is $0.26 \pm 0.12$ and $0.39 \pm 0.12$ for a belizite sample and $0.30$. We also tested if these age distributions could result from a single impact event by using a $\chi^2$ test on the entire dataset. Using the present eight $^{40}$Ar/$^{39}$Ar plateau ages returns a $P$-value of 0.081 which is concordant, yielding a weighted mean age of 803.7 ± 8.5 ka ($n = 8$; MSWD = 1.8). The available $^{40}$Ar/$^{39}$Ar data are thus fully compatible with belizites and Pantasma impact glasses being both produced from the same impact event.

Major and trace elements obtained on three 50 g pooled samples of belizites are highly homogeneous (supplementary data 2). Normalized to an average value for the Pantasma target rocks and impact glasses, the belizites data show flat spectra close to 1 for most non-volatile and non-siderophile elements (Fig. 6), especially when compared to Pantasma glass. The clear enrichment in Cr, Ni, Co suggests extra-terrestrial contamination, which is confirmed by the analysis of Cr isotopic ratio (Fig. 4). A rough estimate for the amount of extraterrestrial contamination can be derived from a mixing model comparing average Pantasma rocks, belizite, and ordinary chondrite Ni and Cr contents. Both elements provide the same value of contamination, 0.6%, which is likely an underestimate as Pantasma soils are also enriched in Ni and Cr of likely terrestrial origin. Moderately volatile elements (Na, K, Cu, Zn, Rb, and Pb) are depleted, which is commonly observed in tektites, resulting from the very high temperatures reached during their formation. Some differences occur in other elements (such as Ti, Mn, K, Sr, Th, U, for Pantasma glass), maybe due to the fact that the material that produced tektites may come from a different depth in the target than the analyzed Pantasma glasses and rocks. However, the overall match, particularly between belizites and proximal impact glasses from Pantasma, is consistent with their co-genesis. Isotopic ratios of radiogenic elements Sr and Nd are commonly used to trace the source of tektites. Figure 7 (see Supplementary Table 1) shows that these ratios are similar in both the belizite and Pantasma glass and rocks. Moreover, the trade of this rare material from a Mayan city within the Belize strewn-field. The latter hypothesis is not presently supported by archeological studies as no evidence of reworking or presence in ceremonial deposits has been found. However, this eventuality cannot be discarded without further dedicated study. To test if belizites are present between Tikal and the Belize border, one of us (P.R.) performed a five days systematic search (Fig. 1) without making any new discoveries. Several tektite-lookalike gravels were collected near El Remate, but they were identified as cherts or volcanic rocks in the laboratory. However, the rate of discovery in the established Belize strewn-field is of the order of one sample per day. Belizite-like glass was reportedly found in Maya sites from El Pilar, Topoxte, and Dzibilchaltun (450 km further North in Yucatan, Fig. 1 insert). Therefore, it seems that the strewn-field defined in central Belize is relatively rich in belizites, whereas fewer belizites occur elsewhere, in Guatemala and possibly Yucatan.

Pantasma crater as the source of belizites. Pantasma has been suggested as a candidate source crater for the belizites because of coeval ages with proximal impact glasses. However, this hypothesis remains tied to published ages on belizites that are rather scattered and of low precision. We, therefore, introduce four new high-precision plateau $^{40}$Ar/$^{39}$Ar ages of belizite samples (Fig. 5), compared to the same number of ages for Pantasma glasses (implementing with two new ages). These ages are obtained in two laboratories using the same protocol and samples (see supplementary Fig. 5 and Supplementary Data 1 for spectra, isochrons, and full data). Average ages for belizite and Pantasma glass are 792.1 ± 9.2 ka (2σ; $n = 4$; Mean Squares Weighted Deviation (MSWD) = 0.05; Probability ($P$) = 0.98) and 809.1 ± 6.4 ka ($n = 4$; MSWD = 1.2; $P = 0.30$). We also tested if these age distributions could result from a single impact event by using a $\chi^2$ test on the entire dataset. Using the present eight $^{40}$Ar/$^{39}$Ar plateau ages returns a $P$-value of 0.081 which is concordant, yielding a weighted mean age of 803.7 ± 8.5 ka ($n = 8$; MSWD = 1.8). The available $^{40}$Ar/$^{39}$Ar data are thus fully compatible with belizites and Pantasma impact glasses being both produced from the same impact event.

| Elts | Na$_2$O | MgO | SiO$_2$ | Al$_2$O$_3$ | K$_2$O | CaO | FeO |
|------|---------|-----|---------|-------------|--------|------|-----|
| Mean wt. % | 3.6 | 1.8 | 62.0 | 17.2 | 2.0 | 4.7 | 6.4 |
| Min wt. % | 2.7 | 1.5 | 60.3 | 16.1 | 1.7 | 4.0 | 5.5 |
| Max wt. % | 4.2 | 2.1 | 63.3 | 17.9 | 2.4 | 5.4 | 7.4 |
| Mean % XRF | 3.76 | 1.84 | 61.73 | 16.95 | 1.92 | 3.79 | 7.01 |
| % variability | | | | | | | |

Belizites$^a$ 37.3 25.4 4.6 10.1 28.8 26.6 25.3
Belizites$^b$ 15.6 13.0 1.2 3.4 6.8 5.8 9.6
Belizites$^c$ 23.3 18.1 2.3 6.1 9.1 9.7 20.6
Ivoirites 36.9 32.8 3.3 7.6 17.9 55.9 11.3
Australasites 60.3 83.5 18.7 49.7 52.3 81.1 58.6
Moldavites - 58.8 12.0 47.0 41.5 76.0 69.1
Bediaisites-georgiatis 45.7 - 14.0 46.0 36.3 - 68.2

Average major elements (% wt., i.e., excluding Mn and Ti) analyzed by microprobe (MBA) on 6 belizite samples (3 to 24 individual measurements were first used to produce sample average) with the indication of minimum and maximum values. The next line indicates average values obtained by X-ray fluorescence (XRF; see supplementary data 2). Between samples relative variability in %, (1-min/max) ×100, is indicated for belizites, as well as average or maximum intra sample variability (%, respectively). Between samples variability in other tektite strewn-fields, respectively.
observed Sr and Nd ratios lay within the observed range for the volcanic arc in Nicaragua\(^3\), and are very different from the values for all other tektites\(^1\). Variable \(\varepsilon_{Sr}\) values may tentatively be attributed to variable weathering effects, but we note that observed \(\varepsilon_{Sr}\) variability is lower than for the previously known tektite strewn-fields\(^1\).

Pantasma impact glasses are rich in melted inclusions of Fe–Ti oxides with peculiar granular texture\(^1\). For the 31 belizite samples that are anomalously magnetic, one-third of them have \(\chi > 2000 \times 10^{-9} \text{ m}^3 \text{ kg}^{-1}\). For those samples, hysteresis shape and parameters are typical of magnetite. Saturation magnetization measured allows estimating pure magnetite equivalent content of 0.2 to 1\%. A microscopic search in those samples revealed the observed Sr and Nd ratios lay within the observed range for the volcanic arc in Nicaragua\(^3\), and are very different from the values for all other tektites\(^1\). Variable \(\varepsilon_{Sr}\) values may tentatively be attributed to variable weathering effects, but we note that observed \(\varepsilon_{Sr}\) variability is lower than for the previously known tektite strewn-fields\(^1\).

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Fig. 3 optical transmission images of lechatelierite. optical transmission images of lechatelierite (arrows), vesicles, and fluidity in belizites \(\sim 1 \text{ mm}\) thick sections; (a) full composite image; (b–d) selection of representative lechatelierites.

Fig. 4 Cr isotopic data. \(\varepsilon^{54}\text{Cr}\) data obtained on a belizite sample, the Pantasma breccia bulk (after\(^{19}\)) and magnetic extract, compared to carbonaceous and ordinary chondrites\(^{28}\), as well as terrestrial rocks\(^{29}\). 2σ error bars shown.

Fig. 5 Ar/Ar ages. \(^{40}\text{Ar}/^{39}\text{Ar}\) plateau ages with 2σ boxes obtained from the belizites and Pantasma impact glasses in two different laboratories (Curtin and LSCE Gif), together with the composite average in yellow. The first two Pantasma ages come from\(^{19}\).
Are belizites tektites? The delineation of a specific type of impact glass called tektite was initially based on an empirical definition, i.e., a material alike the first three known tektite strewn-fields\(^1,2\). A more rational definition was proposed\(^3\) with criteria (Table 2 of ref. 3) being the occurrence in a sufficiently large strewn-field, away from source crater if known, the chemical homogeneity, water content <200 ppm, regular "spherically symmetric" shape, rare inclusions (mostly lechatelierite), low extra-terrestrial contamination, low heavy noble gases content and derivation from a continental surface. Our analysis of tektite literature raises further criteria: depletion in volatile elements, lack of Fe\(^{3+}\), regular splash forms with maximum mass >>10 g (allowing to discriminate tektites from "tektite-lookalike" impact glass, named tektoid\(^12\)) such as irghizites and atacamaites, as well as Libyan desert glass). Apart from heavy noble gases content and derivation from a continental surface (discussed below), we have already shown that belizites fulfill all those criteria, with values well within the range of other tektite strewn-fields, and clearly different from other known non-tektite impact glasses.

For young enough impact glasses, derivation from the continental surface can be proved by significant atmospheric \(^{10}\)Be content\(^33\)–\(^35\). Eight belizite samples yield an average \(^{10}\)Be content (corrected to the time of impact) of 9.1 ± 2.1 Mat g\(^{-1}\) (Supplementary Table 2), not significantly different from the mean from 7 samples at 12 ± 5 Mat g\(^{-1}\) reported\(^36\). It is significantly lower compared to the ivoirites and australasites: 35 ± 7 and 143 ± 50 Mat g\(^{-1}\), respectively.

Alternative sources for the \(^{10}\)Be content of belizite may be in situ production, and oceanic sediment recycling in subduction-related volcanics. However, these sources are estimated to correspond to less than 1 Mat g\(^{-1}\) (see discussion in supplementary note 3). The average belizite value lies between the values measured from two Pantasma soil samples (290 ± 8 Mat g\(^{-1}\)) and two Pantasma impact glasses (0.6 ± 0.1 Mat g\(^{-1}\)). This indicates that although the belizites are derived from an upper level of the target rocks compared to the Pantasma impact glasses, they contain a smaller fraction of surface soil (<few %) than the ivoirites and australasites, which is possibly due to the rugged terrain on which the impact occurred\(^19\).

Concerning heavy noble gases, our Ar/Ar experimental protocol does not allow us to compute reliable \(^{36}\)Ar content. However, this criterion seems somehow redundant with water and other volatile elements contents and not able to distinguish Muong Nong tektites from non-tektite impact glasses\(^37\). Belizites thus share most characteristics of tektites. They closely match ivoirites in many aspects: size and shape of specimens, strewn-field size, distance to the crater, crater diameter, presence of minor ordinary chondrite contamination.

**Discussion**

The proposed belizites-Pantasma crater couple is the fourth known tektite-crater couple, and presently the youngest. The suggested synchronism of this event with the australasites\(^18\) is not supported by our composite age for belizite-Pantasma, at 803.7 ± 14 ka, compared to the most recent high-precision age for australasite, at 788.1 ± 2.5 ka\(^38\); both ages were obtained in the same laboratories and are reported with 2\(\sigma\) error bars. Besides the observed common features among the four tektite-crater couples, plus the australasite strewn-field, the Central American couple displays a number of peculiarities. It is the only strewn-field to show a mantle signature due to its derivation from volcanic arc
target rocks (Fig. 7 and ref. 39). The target near-surface origin of the ivorites and australasites, demonstrated by high 10Be content32–34, is less prominent in the belizites. A final peculiarity is the presence of cristobalite, previously described only in layered tektites from Indochina40. These peculiarities, together with the lack of noble gases data, suggest that our interpretation of belizites as tektites requires further confirmation to be wholly accepted.

A common idea about tektites is that they may have formed by unusual processes7–9, based in particular on the low number of known strewn-fields compared to known craters >10 km: presently 4 out of 78 (or 14 if one restricts the list to well-dated post K/T craters: Table 2). One may cite more distal microtektite like ejecta (from Popigai, Chicxulub, and several Precambrian spherule layers4) but the list of tektite strewn-fields47 has been restrained to younger than K/T and presence of macroscopic material8. Considering only young craters is partly motivated by (1) the number of them in the holder, thus explaining that the histogram presented in23 is built from 1000 measurements rather than 40 and in the second cell (17 x 10)

### Table 2 List of well-dated post K/T cratering events >10 km diameter.

| Crater   | Diameter (km) | Age (Ma) | Melt type |
|----------|---------------|----------|-----------|
|          | 1  | 2  | 3  |
| Pantasma | 14 | 0.8 | x  | x  | x  |
| Australasian | ? (>10) | 0.8 | x  | x  | x  |
| Zhamanshin | 147 | 0.9 | x  | x  | x  |
| Bosumtwi | 10.5 | 1.1 | x  | x  | x  |
| El'gygytgyn | 18 | 3.6 | x  | x  | x  |
| Ries | 24 | 15 | x  | x  | x  |
| Haughton | 23 | 23 | x  | x  | x  |
| Logosk | 15 | 30 | x  | x  |
| Chesapeake | 40 | 35 | x  | x  |
| Pogigai | 90 | 36 | x  | x  | x  |
| Mistastin | 28 | 38 | x  | x  |
| Montagnais | 50 | 51 | x  | x  |
| Kamens | 25 | 51 | x  |
| Marquez | 12 | 58 | x  |

Well-dated post K/T cratering events >10 km diameter (postulated for Australasian strewn-field) ordered by age50. Melt type encountered indicated by a cross (x): (1) tektite, (2) proximal glass in the ejecta, (3) in-situ glass, and melt in the crater floor. For glass in suevite, the distinction between 2 and 3 may be problematic. The presence of long-distance ejecta as clinopyroxene spherules7 is means unknown in the first cell (>10) and questionable in the second cell (17 x 10).

Therefore, there is still a majority (4 out of 6) of large tektite-producing craters since the Middle Miocene. The putative tektite strewn-fields from Zhamanshin and El’gygytgyn craters would be located in remote semi-arid areas, and hence may have remained undiscovered. An independent clue for the rather “normal” production of the tektite is the observation that the most common type of impactor, ordinary chondrite, is responsible in the three cases for which it has been identified: belizites, ivorites45, and possibly australasites46. This agrees with the theoretical and experimental arguments that the type of projectile does not influence melt production72.

The evidence from the proposed central American tektite-crater couple can be compared to the previously known couples or strewn-fields, and allows making two predictions: (1) the analogies between the belizites and ivorites strongly suggest that thousands of ivorites may remain to be found in this very poorly explored strewn-field22,24 where only a few hundred tektites are currently reported; (2) microtektites ejected from the Pantasma crater may be found within a few thousands of km distance from the crater, i.e., within oceanic sedimentary cores, as is the case for the ivorites strewn-field47. This may help to confirm our findings that the australasites are slightly younger than belizites, based on the climatostratigraphic positions of the respective microtektite layers in the sedimentary cores. We emphasize that searching for microtektite layers, or other distal impact material (e.g., clinopyroxene and impact glass spherules8) connected to other well-dated large craters may help to overcome the preservation issue for macroscopic tektites and confirm our proposition for a ubiquitous tektite production process for large impacts. As an example, a microtektite layer dated 56 Ma has been proposed recently48.

### Methods

Thin sections of representative rocks were prepared for optical microscopy, while polished thin sections of the glass were examined in CEREGE using a Hitachi S3000-N scanning electronic microscope (SEM), operated at 15 kV, and fitted with a Bruker energy dispersive spectrometry (EDS) microanalysis system. Additional higher-resolution images were obtained at Center Pluridisciplinaire de Microscopie électronique et de Microanalyse (CP2M), Marseille, with a Zeiss Gemini 500 field-emission gun SEM operated at 15 kV and fitted with an EDAX EDS microanalysis. Further microanalyses were obtained by electron microprobe analysis using a Cameca SX-100 at the Center de Microanalyse de Paris VI (CAMPARIS). Double-polished sections were prepared from two belizite samples in order to determine water content through transmission measurements. Samples were polished using SiC disks under ethanol until they were optically thin through the 532 nm laser beam. Water contents were measured using a Micròtobo Dinagmic micromer. Water content was determined using Fourier transform infrared (FTIR) transmission microscopy with a VERTEX V70 spectrometer coupled to a Hyperion 3000 infrared microscope (IPAG, Grenoble; see Supplementary Method 1).

Raman spectra of SiO₂ rich inclusions in several belizite polished sections were obtained using a LabRAM HR800 Evolution spectrometer that has a confocal Czerny-Turner geometry and a laser source of 532 nm in wavelength. Each spectrum was acquired with a power of 10 mW, and 25 accumulations of 5 to 15 s. Gratings with 600 groove/mm were used in order to cover the frequency range 60 to 1300 cm⁻¹.

Magnetic susceptibility (χ) measurements of glass samples of J.C. collection were obtained in Denver using the portable SM150 susceptibility meter (working in a field of 1 kHz frequency and 320 A m⁻¹ intensity) that has a sensitivity better than 10⁻⁵ m² kg⁻¹ for sample mass >5 g. This mass threshold was obtained in the case of small samples by pooling a sufficient number of them in the holder, thus explaining that the histogram presented in23 is built from 1000 measurements made on >4000 samples. Hysteresis measurements were performed on the high susceptibility samples using a Micromag VSM in CEREGE. Specific gravity was determined using a precision scale and volume determination by helium pycnometer with a Quantachrome instrument in CEREGE.

Major and trace element analyses were performed on Pantasma rocks and glasses at the Laboratoire G-Time at the Université Libre de Bruxelles. For each sample, approximately 50 mg of crushed material was dissolved by alkaline fusion using an ultrapure (>99.999%) mixture of 4.1 lithium hydroxide and tetaborate. Major elements were measured using a Thermoscientific ICP inductively coupled plasma atomic emission spectrometry (ICP-AES) instrument (see Supplementary Method 2). For trace elements, the concentrations were measured on an Agilent
7700 quadrupole ICP-mass spectrometer. For belizites, analysis was performed by ALS Minerals inc. (Renon, USA) using for minor elements EPMS after lithium borate fusion and for major elements XRF after fusion. Three batches were analyzed, each circa 3 g made of a pooled cleaned tektites.

For isotope measurements, around 100 mg of samples were digested by digesting subboiled concentrated 1:3 mixture of HF and HNO3 and subboiled concentrated HCl after evaporation. After complete digestion, an aliquot was separated for Sm-Nd spike, another one for Rb/Sr measurements, and the last one for Sr isotopes. Strontium was purified on Sr-Spec resin using HNO3. The rare earth elements from the remaining solutions were purified using first cationic resin AG50X8 in HCl, and then Nd was purified from Ce and Sm using HDEHP resin, also using HCl. The spiked cuts followed the same chemical purification. The Nd and Sr purified cuts were both measured on the Nu-Plasma 2 multi-collection ICP-MS at Laboratoire G-Time (see Supplementary Method 3).

For Cr isotope analysis, 30 mg of belizite sample BLZ3, as well as of the magnetic extract from PSB breccia (bulk and for major elements XRF after fusion. Three batches were analyzed, each circa 3 g made of a pooled cleaned tektites.

 extraction from P5B breccia (bulk and for major elements XRF after fusion. Three batches were analyzed, each circa 3 g made of a pooled cleaned tektites. 

Cutting was both measured on the Nu-Plasma 2 multi-collection ICP-MS at Laboratoire G-Time (see Supplementary Method 3).
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Author contributions
P.R. led the project, collected Pantasma samples, performed a number of measurements, and handled the manuscript; P.B. performed water measurements; M.B. and Frédéric M. performed the Cr isotopic measurements; R.B. performed the $^{10}$Be measurements; J.C. collected the main belzite collection and provided the geological background for Belize; V.D. performed Sr, Nd isotopic measurements; R.D. performed petrographic analyses; J.G. performed microprobe measurements; F.J. and S.N. performed the Ar isotopic measurements; Fabien M. contributed to sample description, preparation, and measurements; B.R. performed Raman spectroscopy. All co-authors contributed to the interpretation of measurements, figure and table preparation, as well as manuscript writing.

Competing interests
The authors declare no competing interests

Additional information

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