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The Musgrave impact diamonds from MAPCIS very probable impact basin, West Central Australia

Diamantes de impacto de Musgrave de la cuenca de impacto muy probable de MAPCIS, Centro Occidental de Australia

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Abstract.- Massive Australian Precambrian-Cambrian Impact Structure (MAPCIS) is a very probable peak ring impact basin with an approximate radius of 300-350 km. The Musgrave Block, located on its southern MAPCIS flank, contains abundant pseudotachylite breccia. This study aimed to identify impact diamonds (lonsdaleite to lonsdaleite diamonds) within this breccia using Raman spectroscopy. All analyzed spectra displayed a D band (diamond), indicating lonsdaleite or Popigai-like impact diamonds with a peak wavelength of 1296-1369 cm^{-1}. The estimated lonsdaleite content varies between 8% and 100% based on the D band's FWHM values (~11-247 cm^{-1}). Maximum temperatures reached during the event were calculated at 1183°-1282°C based on the G band (graphite) peaks in some spectra. The presence of lonsdaleite and the temperature calculations support the hypothesis of an impact origin for MAPCIS. As lonsdaleite formation requires extreme pressures and temperatures only achievable during powerful meteorite impacts, these diamonds serve as crucial indicators of such events.

Key words: *MAPCIS, peak ring impact basin, Popigai-like impact diamonds.*

Resumen.- La Estructura de Impacto Precámbrico-Cámbrico Australiana Masivo (MAPCIS) es una cuenca de impacto de anillo pico muy probable con un radio aproximado de 300-350 km. El Bloque Musgrave, ubicado en el flanco sur MAPCIS, contiene abundante breccia pseudotaquilitica. Este estudio tuvo como objetivo identificar diamantes de impacto (lonsdaleita a diamantes lonsdaleiticos) dentro de esta brecha utilizando espectroscopia Raman. Todos los espectros analizados mostraron una banda D (diamante), indicando lonsdaleita o diamantes de impacto tipo Popigai con una longitud de onda máxima de 1296-1369 cm^{-1}. El contenido estimado de lonsdaleita varía entre 8% y 100% según los valores de FWHM (ancho de línea a media altura) de la banda D (~11-247 cm^{-1}). Las temperaturas máximas alcanzadas durante el evento se calcularon en 1183°-1282°C según los picos de la banda G (grafito) en algunos espectros. La presencia de lonsdaleita y los cálculos de temperatura respaldan la hipótesis de un origen de impacto para MAPCIS. Como la formación de lonsdaleita requiere presiones y temperaturas extremas solo alcanzables durante poderosos impactos de meteoritos, estos diamantes sirven como indicadores cruciales de tales eventos.

Palabras clave*: MAPCIS, cuenca de impacto de anillo en pico, diamantes de impacto tipo Popigai.*

The Massive Australian Precambrian-Cambrian Impact Structure (MAPCIS), proposed by Connelly and colleagues (2009a, 2009b; Connelly & Presser, 2015; Connelly & Sikder, 2017, 2018; Connelly *et al.*, 2019), is a very probable peak-ring impact basin with an estimated minimum radius of 300-350 km, comparable to the Martian mega-crater Lowell. As shown in Figure 1, MAPCIS is located slightly west of central Australia.

Exposed on the southern flank of the MAPCIS megastructure lies the Musgrave Block, where samples of pseudotachylyte breccia, prevalent in this region (Hawemann *et al.*, 2019), were collected for petrographic (Connelly & Sikder, 2018), geochemical (Connelly

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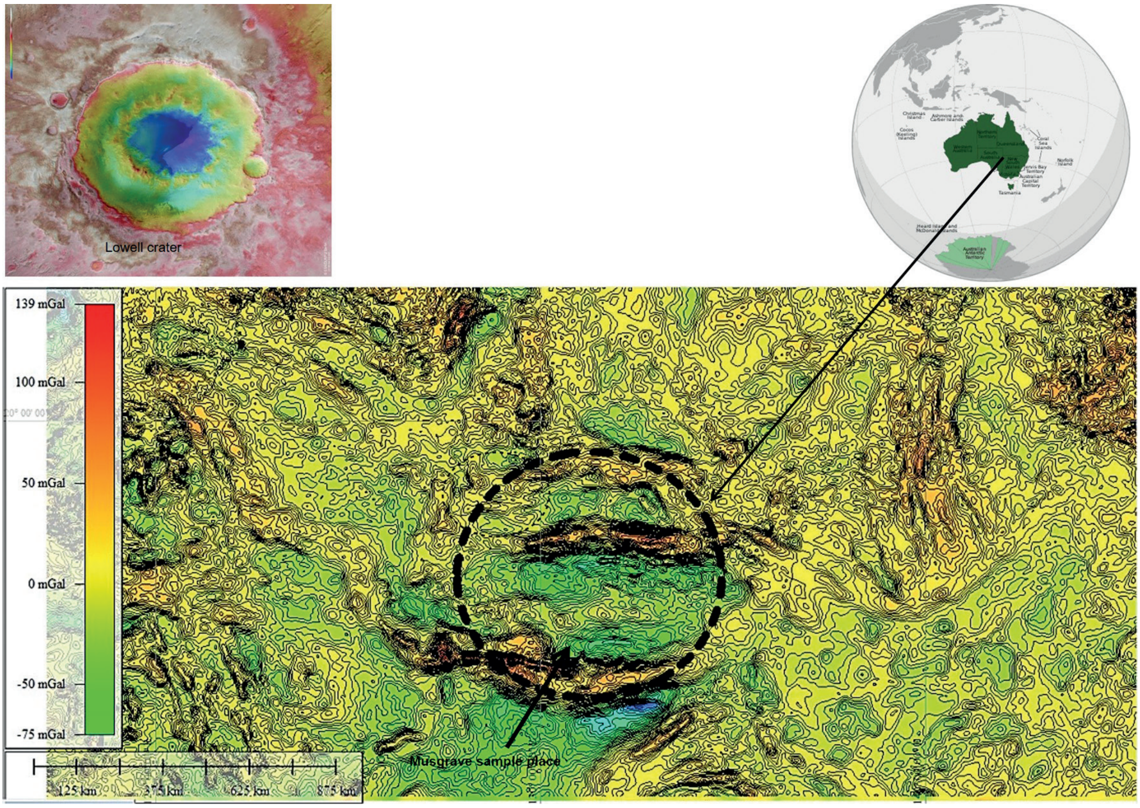

Figure 1. MAPCIS (main image at the bottom) is a highly probable peak ring-type impact basin with a slight east-west elonga-tion, and having similarities with the Martian Mega-Crater Lowell (upper left corner). The minimum reference diameter of MAPCIS is 300-350 km, indicated by the circular dashed line. The Musgrave pseudotachylyte breccia was collected on the SSE flank (arrow). Source: Australia Free Air maps (portion).

et al., 2017), and present studies.

These Musgrave pseudotachylyte breccia deposits reach up to 5 km in width and extend intermittently for 300 km, with an estimated 10% pseudotachylite veining. Individual veins range in width from centimeters to a maximum of 4 meters and can be traced for up to 10 meters. The orientation of the veins appears to be random.

Pseudotachylytes are exclusively found within granulite facies rocks. Rotated blocks of ultra-mylonite occur within some pseudotachylytes, and some veins themselves exhibit plastic deformation, suggesting near-contemporaneous semi-ductile and brittle behavior (Connelly *et al.*, 2019, and references therein).

This study aims to identify impact diamonds (lonsdaleite to lonsdaleite diamonds) using elemental Raman spectroscopy analysis within the Musgrave pseudotachylyte breccia, following the prior suspicion of Connelly *et al.* (2022). The presence of such diamonds could contribute significant evidence supporting the meteorite impact origin hypothesis for MAPCIS.

Materials and methods

Raman Spectroscopy Analysis:

Seventeen (17) selected points within the Musgrave pseudotachylyte breccia were subjected to Raman spectroscopy analysis. The Horiba LabRAM HR Evolution Confocal micro-Raman spectrometer, housed at the Nanomaterial Core Characterization Facility (NCCF) of

Virginia Commonwealth University (VCU), USA, was employed for this purpose.

Instrumentation:

- Laser excitation system: 20 mW, 532 nm He-Ne laser
- Grating: 600 grooves/mm
- Detector: Thermoelectrically cooled CCD array detector
- Magnification: 100x, 50x, or 10x long working distance lenses, enabling analysis depths of up to a few millimeters

Spectral Acquisition:

- Raman spectra were collected at each point within a range of 100 to 1800 cm^{-1}.
- Acquisition time per spectrum: 300 seconds

Data Processing:

Two open-source software programs were employed for data processing:

- Crystal Sleuth (https://rruff.info): utilized for background noise removal, facilitating comparison between multiple spectra.
- Spectragryph: used for obtaining individual peak values, calculating full width at half maximum (FWHM), and performing Gaussian deconvolution of the spectra.

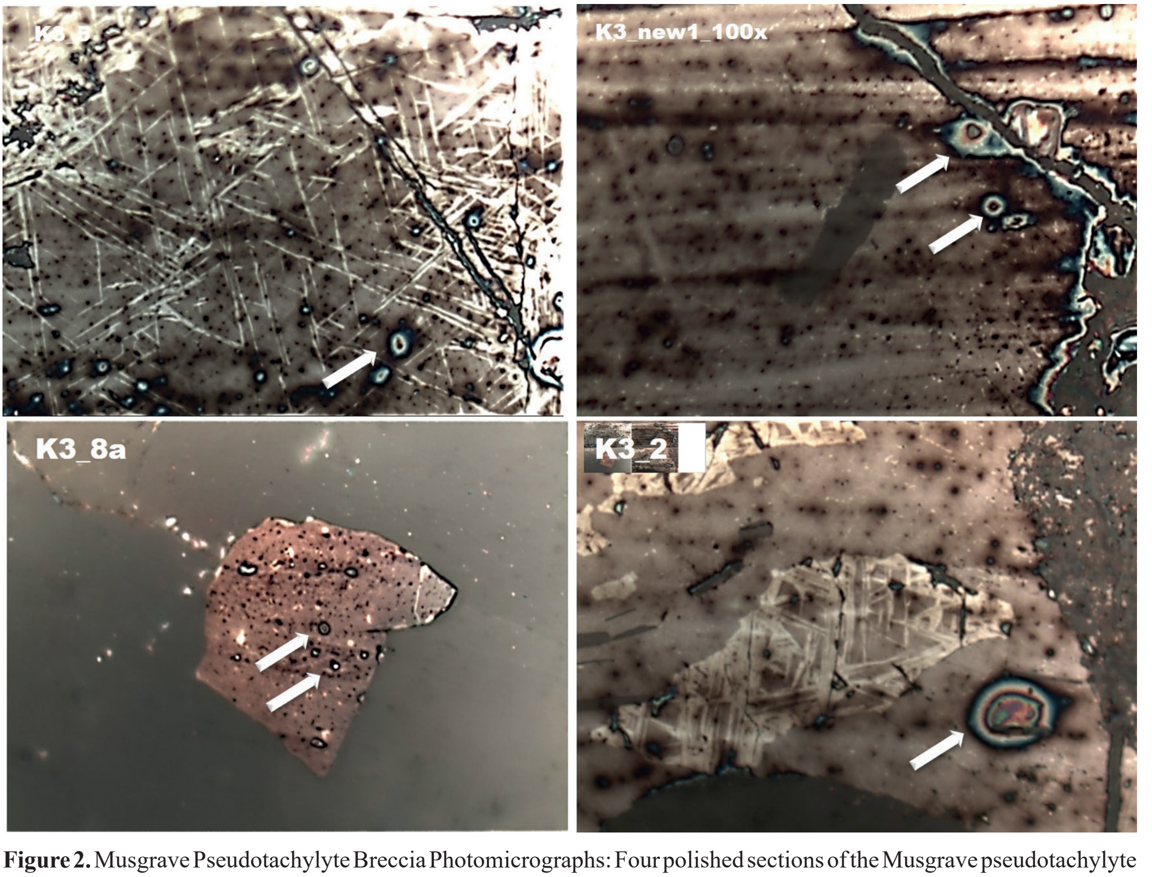

Figure 2. Musgrave Pseudotachylyte Breccia Photomicrographs: Four polished sections of the Musgrave pseudotachylyte breccia are shown. **K3-B)** (100x) Partially transformed metal (meteoritic) into hematite with intergrown magnetite. Arrows indicate shiny, birefringent concentric dots of irregular shape and size (analyzed). **K-3-2)** (50x) Similar to K3-B. **K3-8a)** (50x). **K3 new-1)** (100x).

Results and discussions

Musgrave pseudotachylite breccia fragments were sectioned, polished, and examined microscopically and using Micro Raman spectroscopy. Polished sections revealed irregularly shaped and sized, shiny, concentric, birefringent dots (Figure 2). These dots were mainly associated with remnants of (presumably) meteoritic metal partially altered to hematite and/or magnetite (Figure 2). Raman analysis of this sub-millimeter, shiny, birefringent mineral revealed peaks in both the D and G bands (Figure 3),

Table 1. Selected Musgrave diamond-like materials Raman spectra feature D, and G bands. Maximum graphite formation tem-perature (T-graphite) is calculated according to the Cody et al. (2008) method; however, only positive temperatures and the highest are taken into consideration. Three results modes are presented as: RAW, Baseline, and Smoothed.

ID	Raman shift [1/cm]	intensity	FWHM [1/cm]	Raman shift [1/cm]	intensity	FWHM [1/cm]	T-graphite °C	Mode
k3_PT-5a_100x	1354	310	37					RAW
k3_PT-5a_100x	1323	20	36	1587	4	108	65	Baseline
k3_PT-5a_100x	1327	19	247	1586	42	128	-67	Smooted
k3_PT-6_100x	1316	47	71	1581	54	47	766	RAW
k3_PT-6_100x	1316	4	11	1581	12	22	1183	Baseline
k3_PT-6_100x	1335	3	43	1581	12	22	1183	Smooted
k3_PT-6a_100x	1359	56	43	1576	160	25	1118	RAW
k3_PT-6a_100x	1349	9	36	1576	111	16	1282	Baseline
k3_PT-6a_100x	1349	9	36	1576	15	161	-187	Smooted
K3_5	1315	89	188	1598	77	86	267	RAW
K3_5	1315	19	70	1599	10	71	437	Baseline
K3_5	1333	25	143	1598	17	124	-43	Smooted
K3_5a	1314	66	28	1579	65	22	1181	RAW
K3_5a	1314	9	29	1601	8	19	1228	Baseline
K3_5a	1336	10	161	1600	8			Smooted
K3_new1_100x								RAW
K3_new1_100x	1306	4	19					Baseline
K3_new1_100x	1301	4	58					Smooted
K3_new1a_100x								RAW
K3_new1a_100x	1294	5	27					Baseline
K3_new1a_100x	1296	5	72					Smooted
K3_8a	1346	718		1582	823	154	-171	RAW
K3_8a	1345	191	179	1582	373	103	110	Baseline
K3_8a	1345	208	90	1582	385	105	93	Smooted
k3_PT-2a_100x								RAW
k3_PT-2a_100x	1352	92	66	1592	238	106	80	Baseline
k3_PT-2a_100x	1370	97		1591	242	116	8	Smooted

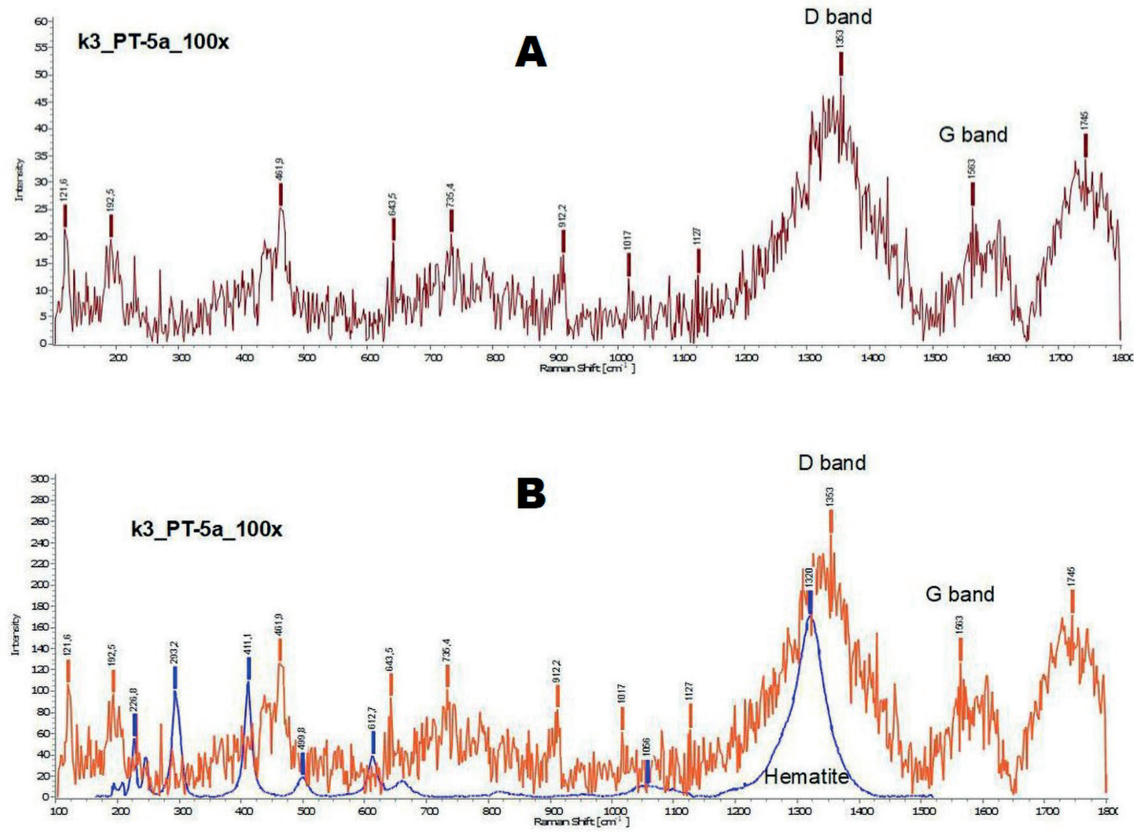

Figure 3. Musgrave Pseudotachylyte Breccia Diamond-like Materials Type 1 Spectra: Raman spectra of the diamond-like materials in the Musgrave pseudotachylyte breccia exhibit Type 1 characteristics, with prominent (wide) D-band peaks and a weaker G-band, resulting in an M-shape characteristic of lonsdaleite diamonds. **A)** Raw spectrum. **B)** Spectrum compared to a reference hematite spectrum. The K3_PT-5a_100X spectrum shows clear differences from the hematite.

characteristic of diamond-like materials. Seventeen Raman spectra were carefully analyzed for confirmation (Table 1).

The examined and selected Musgrave pseudotachylite breccia diamond-like materials spectra exhibit four distinct spectral types, as shown in Figures 3, 4, 5, and 6:

Type 1 (Lonsdaleite/graphite): This type displays a prominent and wide D band peak accompanied by a less intense G band peak. For example, spectrum k3_PT-5a_100x shows a D peak at 1327.2 cm^{-1} with a full width at half maximum (FWHM) of 247.3 cm^{-1} and a G peak at 1586 cm^{-1} with a FWHM of 128.0 cm^{-1}. (Figure 3)

Type 2 (Magnetite/lonsdaleite/graphite): This type features a weak D band alongside a strong G band peak and an additional peak characteristic of magnetite. For instance, spectra k3_PT-6_100x and k3_PT-6a_100x exhibit a D peak at 1316.1–1349.1 cm^{-1} with a FWHM of 11.3–36 cm^{-1} and a G peak at 1576–1581 cm^{-1} with a FWHM of 16–22 cm^{-1}. (Figure 4)

Type 3 (Magnetite/lonsdaleite/graphite): Both D and G bands are weak in this type, while the magnetite peak is dominant. Spectra K3_5, K3_5a, K3_new1_100x, and K3_new1a_100x exemplify this type, with a D peak at 1296–1335.5 cm^{-1} and a FWHM of 57–160 cm^{-1}. The G band is only present in spectra K3_5 and

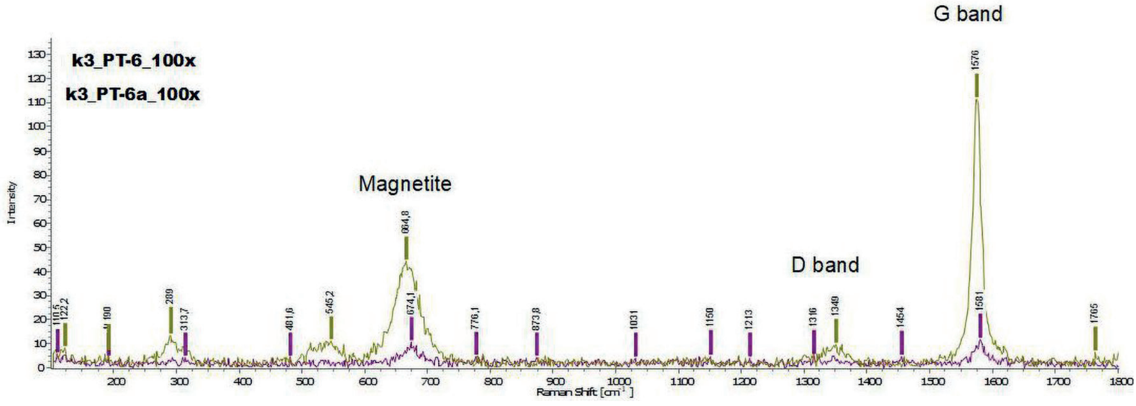

Figure 4. Musgrave Pseudotachylyte Breccia Diamond-like Materials Type 2 Spectra: This figure shows Raman spectra of Type 2 diamond-like materials found in the Musgrave pseudotachylyte breccia. These spectra are characterized by: **Low-intensity D-band peaks,** Indicated by arrows in the spectra. **Strong G-band peak,** suggesting a higher degree of graphitization compared to Type 1 spectra. **Magnetite peak,** indicating the presence of magnetite alongside the diamond-like material.

K3_5a, at 1598–1600 cm^{-1} with a FWHM of 124 cm^{-1} (K3_5). (Figure 5)

Type 4 (Lonsdaleite/graphite): Similar to Type 1, this type displays prominent and wide peaks in both the D and G bands. Spectra K3_8a and k3_PT-2a_100x are representative, showing a D peak at 1345–1369 cm^{-1} with a FWHM of 66–90 cm^{-1} and a G peak at 1582–1591 cm^{-1} with a FWHM of 103–121 cm^{-1}. (Figure 6)

Generally, the D band peaks exhibit low intensity, especially in spectra with wide FWHM values (Table 1). This observation coincides with findings for yakutites (lonsdaleitic impact diamonds) reported by Yelisseyev *et al.* (2018) and for nanodiamonds, as described by Mermoux (2017).

Hematite can also contribute a peak in the D band around 1320 cm^{-1}, potentially overlapping with the D band of impact diamonds. Figure 3b compares the k3_PT-5a_100x spectrum with the hematite spectrum, clearly demonstrating their distinct features. Similarly, the k3_PT-5a_100x

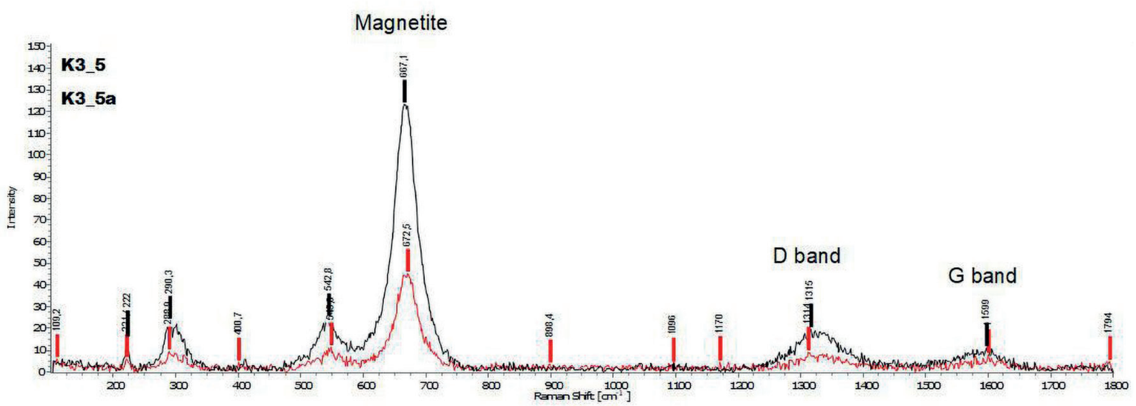

Figure 5. Musgrave Pseudotachylyte Breccia Diamond-like Materials Type 3 Spectra: This figure shows Raman spectra of Type 3 diamond-like materials found in the Musgrave pseudotachylyte breccia. These spectra are characterized by: **Low-intensity D-band and G-band peaks,** indicated by arrows in the spectra. **Pronounced magnetite peak:** meaning a significant presence of magnetite alongside the diamond-like material, suggesting potential contamination or poor crystallinity.

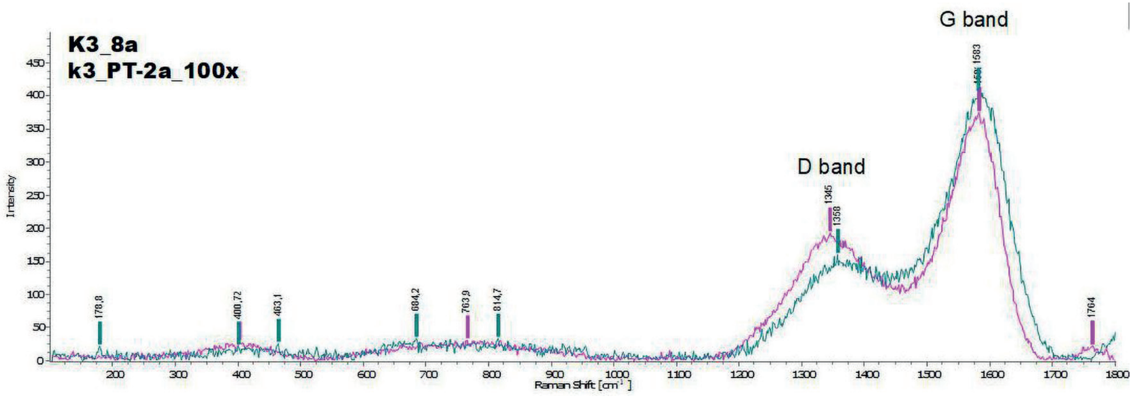

Figure 6. Musgrave Pseudotachylyte Breccia Diamond-like Materials Type 4 Spectra: This figure presents Raman spectra of Type 4 diamond-like materials discovered in the Musgrave pseudotachylyte breccia. These spectra exhibit characteristics resembling lonsdaleite, as documented by Denisov et al. (2011): **Prominent D-band and G-band peaks,** indicated by arrows. **M-shaped peaks,** being this pattern, similar to the reference lonsdaleite spectrum, suggesting a hexagonal diamond structure characteristic of lonsdaleite.

spectrum differs markedly from the Raman spectra of maghemite and goethite.

As Presser & Sikder (2022, 2024) and their cited references point out, the first-order Raman spectrum of undisturbed, defect-free cubic diamonds exhibits a single, narrow Lorentzian peak at 1332.5 cm^{-1} (4×10^{13} Hz, 165 meV), with a Full Width at Half Maximum (FWHM) of ~1.5–3 cm^{-1}. Deviations from this wavenumber hold genetic significance. Notably, the four spectral types observed in the apparent diamonds from the Musgrave pseudotachylite breccia align more closely with the Raman signatures typically associated with lonsdaleitic or Popigai-like impact diamonds (Presser et al., 2020; Presser & Sikder, 2022).

The observed D peak wavenumbers in the Musgrave pseudotachylite diamond-like materials range from 1296 to 1369 cm^{-1}, deviating from the single, narrow peak at 1332.5 cm^{-1} characteristic of undisturbed cubic diamonds. This shift is consistent with the behavior of lonsdaleitic or Popigai-like impact diamonds, as reported in previous studies (Presser & Sikder, 2022, 2024).

Mildren (2013) reported that the first-order Raman peak wavenumber in diamonds exhibits a temperature dependence, with lower values observed at higher temperatures. Following this observation, one could expect lower D peak wavenumbers (<1332.5 cm^{-1}) in the Musgrave pseudotachylite materials formed at lower temperatures, and conversely, higher D peak wavenumbers (>1332.5 cm^{-1}) for materials formed at higher temperatures.

To estimate the formation temperature of the apparent Popigai-like impact diamonds, the calculation formula proposed by Cody *et al.* (2008) based on the G band was applied to selected spectra exhibiting a peak around 1582 cm^{-1}. While the obtained temperatures (1183–1282 °C) are indicative, they should be interpreted with caution as the data were not corrected and serve as reference values only.

Interestingly, despite one spectrum showing a D peak above 1332.5 cm^{-1}, the estimated temperature differences are practically negligible. This suggests that the temperature dependence of the D peak wavenumber may not be a reliable indicator for formation temperature in these highly defective diamond-like materials.

Ovsyuk *et al.* (2019) demonstrated a correlation between the Full Width at Half Maximum (FWHM) of the D band in Raman spectra and the lonsdaleite content of the material. Goryainov *et al.* (2018) and Presser & Sikder

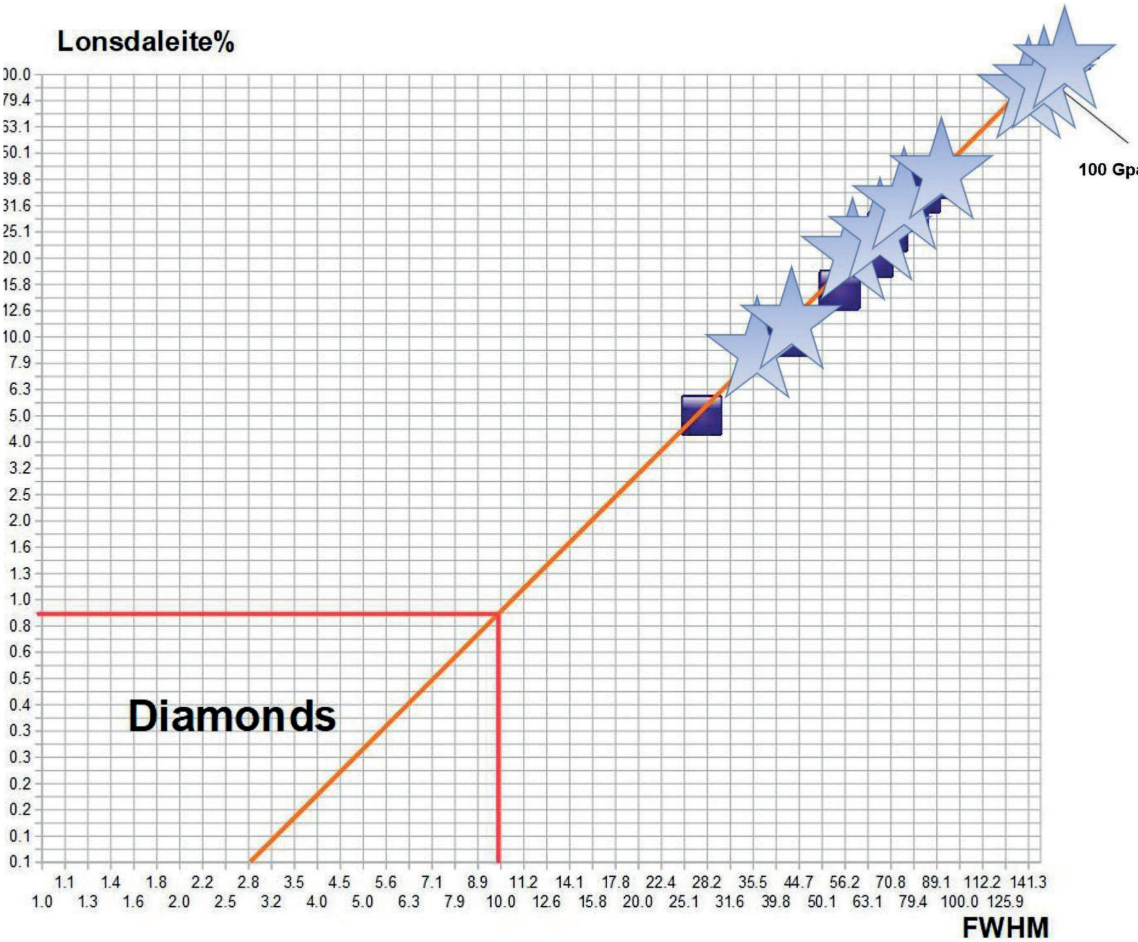

Figure 7. Diamond vs. Lonsdaleite Content in Impact Diamonds: This figure, adapted from Ovsyuk *et al.* (2019), depicts the relationship between lonsdaleite content and full width at half maximum (FWHM) of the D-band in Raman spectra of impact diamonds. **Key features:** ***Y axis:*** percentages of Lonsdaleite. ***X axis:*** cm-^{1}. ***Black boxes:*** Data points for Popigai impact diamonds from Ovsyuk *et al.* (2019). ***Stars:*** FWHM values for Musgrave pseudotachylyte breccia lonsdaleitic diamonds. ***Solid line:*** Best-fit line for Popigai diamonds (Ovsyuk *et al.*, 2019), demarcating the diamond field (FWHM ≤ 10 cm^{-1}) and the lonsdaleite field (FWHM > 10 cm^{-1}). **Implications:** Higher FWHM indicates increasing lonsdaleite content, with values above 10 cm^{-1} suggesting significant lonsdaleite presence in Musgrave diamonds. This has potential thermodynamic implications discussed in the text.

(2024) have further explored this relationship. As illustrated in the bi-logarithmic plot of Figure 7, the data from Ovsyuk *et al.* (2019) suggests that diamonds with FWHM below 10 cm^{-1} are unlikely to contain lonsdaleite, while those with FWHM exceeding 10 cm^{-1} exhibit increasing lonsdaleite content, reaching 100% (equivalent to a formation pressure of 100 GPa) at a FWHM of around 150 cm^{-1}. Natural diamonds typically form at pressures below 23 GPa (Gu *et al.*, 2022), suggesting that lonsdaleite formation requires much higher pressures (Baek *et al.*, 2019; Mittal *et al.*, 2021; Stavrou *et al.*, 2020; Katagiri *et al.*, 2018; Jones *et al.*, 2016).

For the Popigai-like impact diamonds recovered from the Musgrave pseudotachylite breccia, Raman spectra were pre-processed using the "edited" mode to minimize background noise and distortion, particularly for the G band peaks. The exception is the k3_PT-2a_100x spectrum, where the baseline version was retained due to its very low peak intensity. Figure 7 presents the

FWHM data for these diamonds, indicating lonsdaleite content ranging from ~8–90% (FWHM 36–143 cm^{-1}) to 100% (FWHM 161–247 cm^{-1} in k3_PT-5a_100x and K3_5a) (Table 1).

Conclusions

The Raman spectra of all analyzed Musgrave pseudotachylite diamond-like materials exhibit D band characteristics typically observed in lonsdaleitic diamonds or Popigai-like impact diamonds, deviating from the signature of natural cubic diamonds. Analyzing the Full Width at Half Maximum (FWHM) of the D band suggests lonsdaleite content ranging from 8% to 100% in these materials.

Among the analyzed Musgrave Popigai-like impact diamonds, a small subset displayed peaks in the G band, indicating the presence of graphite. For three of these spectra, the maximum formation temperature was estimated to be between 1183°C and 1282°C. These temperatures are similar to those reported for graphite within impact diamonds from meteorites (Christ *et al.*, 2022; Barbaro *et al.*, 2022).

The presence of lonsdaleitic diamonds, requiring extremely high pressures for formation (above 23 GPa), coupled with the observed formation temperatures compatible with meteorite impacts, strongly supports a meteorite impact origin for the Musgrave pseudotachylite breccia (MAPCIS). The impact event would have generated the necessary pressure and heat to form these unique diamond-like materials.

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Contribution of the authors:

Jaime L. B. Presser: developed the idea and structure of the paper, wrote the original manuscript, and designed figures. Arif M. Sikder: Acquired the Raman spectra used in the research. Daniel P. Connelly: Acquired the samples studied.

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