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How to cite:

Gilmour, I.; Franchi, I. A.; Koeberl, C. and French, B. M. (2002). A Raman spectroscopic study of carbon phases in impact melt rocks and breccias from the Gardnos impact structure, Norway. In: 33rd Lunar and Planetary Science Conference, 11-15 Mar 2002, Houston, Texas, USA.

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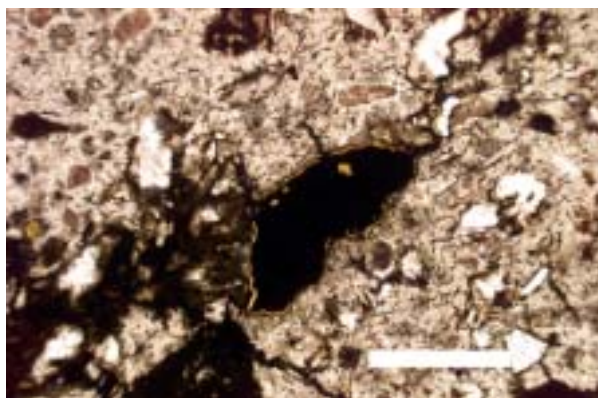
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**A RAMAN SPECTROSCOPIC STUDY OF CARBON PHASES IN IMPACT MELT ROCKS AND BRECCIAS FROM THE GARDNOS IMPACT STRUCTURE, NORWAY.** I. Gilmour<sup>1</sup>, I.A. Franchi<sup>1</sup>, C. Koeberl<sup>2</sup> and B.M. French<sup>3</sup>, <sup>1</sup> Planetary and Space Sciences Research Institute, The Open University, Milton Keynes MK7 6AA, U.K., <sup>2</sup> Institute for Geochemistry, University of Vienna, Althanstrasse 14, A-1090 Vienna, Austria, <sup>3</sup> Smithsonian Institution, Washington, DC 20560, U.S.A (I.Gilmour@open.ac.uk)

**Introduction:** The Gardnos impact structure [1] is located in southern Norway (60°40'N; 9°00'E), approximately 125 km northwest of Oslo, Norway. The structure, originally about 5 km in diameter, has been deeply eroded. It lacks any distinctive circular form and is now represented by outcrops of impact-produced breccias, both lithic and melt-bearing. Its impact origin has been convincingly established from three lines of evidence [1]: (1) the presence of melt-bearing breccias containing granitic rock fragments with definite Planar Deformation Features (PDFs) in quartz and feldspar; (2) the demonstration, using chemical mixing models, that the breccia compositions could be produced by mixing the exposed target rocks; (3) an extraterrestrial signature from the projectile in the breccias, established using osmium-isotope analyses.



**Figure 1.** Photomicrograph of a carbonaceous clast in a suevite from the Gardnos impact structure. Scale bar is 100 $\mu$ m.

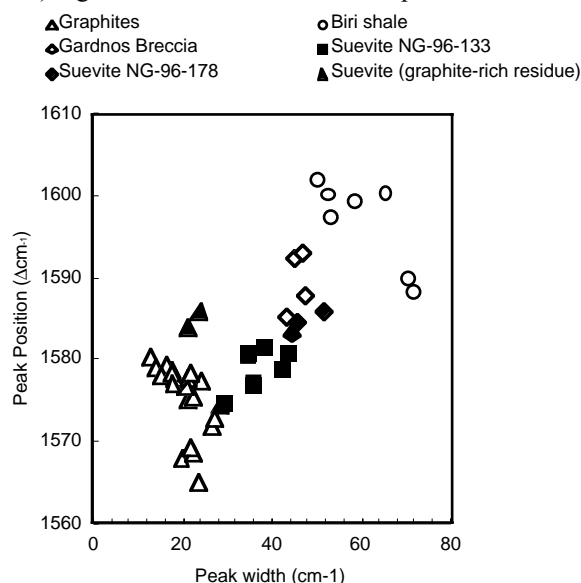
A major unresolved problem about the Gardnos structure is the unusually high content of carbon in its impact-produced rocks (Fig. 1). Gardnos is one of only two known impact structures (among approximately 175) whose impactites contain significant amounts (typically 0.2-1.0 wt%) of carbon, or 5-10 times the amount present in the target rocks; Sudbury, Canada is the other [2]. Values of  $\delta^{13}\text{C}$  for the Gardnos carbon range from -28 to -32 ‰ [1], strongly suggesting an origin from biogenically derived carbon. We have previously suggested the carbonaceous Proterozoic Biri Shale, which could have been present overlying the basement rocks at the impact site, as a possible carbon source [1].

**Experimental:** Powdered samples (ca. 4g) were demineralized using procedures described previously [2] with the exception that microwave assisted dissolution was used for the initial removal of silicates. The demineralized residues were also sub-sampled and treated with chromic acid (6 M at 70°C) to remove amorphous and organic carbon. Aliquots of this residue were then treated with fuming perchloric acid at 110°C to remove crystalline graphite. The sequence of residues so produced were studied using (1) a transmission electron microscope which was also to obtain selected-area electron diffraction (SAED) patterns to confirm the identity of carbon components. (2) High sensitivity stable isotope mass spectrometry and (3) Raman Spectroscopy. Here, we report the results of the Raman investigation.

**Raman Spectroscopy:** For all measurements a Jobin-Yvon Labram HR laser Raman microprobe system was used. Excitation was with a 40 mW 514 nm Ar-ion laser (amount of power on sample <8mW). Spectra were obtained using a 50 X objective and a 600 grids/mm grating from 600  $\text{cm}^{-1}$  to 2300  $\text{cm}^{-1}$  with a spectral resolution of 2  $\text{cm}^{-1}$ . The detection time was varied from 1 to 50 s, but most of the samples were analyzed with a detection time of 30 s. Peak areas, widths, positions and ratios were determined using Jobin-Yvon Labspec software.

**Results:** First order spectra were analyzed from 600 to 2300  $\text{cm}^{-1}$  for carbonaceous residues from 5 samples together with spectra from a suite of crystalline graphite standards. Between 3 and 7 spectra were measured for carbonaceous material from each sample. The spectra from the Gardnos samples all contained the first-order single band at around 1582  $\text{cm}^{-1}$  (O-peak) that is characteristic of well-crystallized graphite. Disorder in graphite appears as a broadening of the 1582  $\text{cm}^{-1}$  band together with a shift toward higher wavenumbers as a result of the development of an additional band near 1360  $\text{cm}^{-1}$  (D-peak) [3]. With the exception of a chemically isolated graphite sample from the suevite NGF-96-137 carbon from all of the Gardnos impactite samples studied show two large peaks, at about 1582  $\text{cm}^{-1}$  and 1360  $\text{cm}^{-1}$ . Carbonaceous material from suevite NGF-96-178 also showed a shoulder developed on the high wavenumber side of the 1582  $\text{cm}^{-1}$  peak indicating disorder in the graphite. Carbonaceous material from the Biri shale gave much broader 1582

cm<sup>-1</sup> peaks (shifted to high wavenumbers around 1597 cm<sup>-1</sup>) together with a broad 1360 cm<sup>-1</sup> peak.



**Figure 2.** Position of the O-Raman peak (corresponding to ordered carbon) vs. O-peak width for isolated C grains from Gardnos impactites and potential C-rich target rocks. Shown for comparison are a series of crystalline graphite standards (open triangles).

A range of ordering can be identified for the carbon present in Gardnos impactites from poorly ordered C in the Biri shale to crystalline graphite in the isolated residues from suevite NG-96-137. The range in ordering of the C is shown in Figure 2 which plots the position of the 1582 cm<sup>-1</sup> O-peak against its width. Graphitic material in the Gardnos Breccia and Suevites is more ordered than in the Biri shale with some samples approaching the crystallinity of well-ordered crystalline graphite.

**Origin of carbon:** The variations in graphite ordering in Gardnos impactites, which range from well-crystallized graphite to more poorly-ordered C, may reflect more than one episode of C-emplacment. The Raman spectra of graphite formed in-situ from the metamorphism of organic matter can be used to estimate the rock's peak metamorphic temperature [3]. Graphitic material produced by the progressive metamorphism of organic matter shows an increase in crystallinity with metamorphic grade. In contrast, graphite deposited due to nucleation and crystal growth from fluids generally does not show the same degree of

ordering as metamorphic graphite subjected to the same temperatures. Metamorphic temperatures at Gardnos reached 350-400°C during the Caledonian orogeny, consistent with the degree of ordering observed in Raman spectra of carbonaceous material from the Biri shale. The higher degree of ordering in much of the graphitic material in Gardnos suevites and Breccias suggests that this C was either derived from more crystalline graphite incorporated into these rocks during the impact event or that it has experienced temperatures higher than those due to the regional metamorphism of the Caledonian orogeny. The more crystalline nature of graphite in the suevites and breccias also apparently precludes a fluid-deposited origin during regional metamorphism. Andersen and Burke [4] measured Raman spectra for carbonaceous material in Gardnos quartzite that were very similar to the spectra obtained in this study for the Biri shale, i.e., C with a lower degree of ordering than the C present in the suevites and breccias but consistent with the temperatures reached during the Caledonian orogeny. This suggests that the degree of ordering of C in Gardnos impactites may be related to post-impact temperatures with C in suevites having the greatest degree of ordering, breccias less ordered, and shocked quartzites the least ordered. Andersen and Burke [4] also concluded that hydrocarbon fluid inclusions present in the quartzite were trapped at temperatures of around 320 °C and pressures of around 2.5 kBar, trapping conditions consistent with conditions during the Caledonian orogeny but not with the higher temperatures and lower pressures associated with post-impact cooling.

**Conclusions:** The variations observed in the ordering of C in Gardnos impactites suggest that there were at least two episodes of C emplacement in Gardnos impactites. An initial impact-related incorporation and shock transformation of graphitic material from target rocks followed by later mobilization of C.

**References:** [1] French B. M., Koeberl C., Gilmour I., Shirey S. B., Dons J. A., and Naterstad J. (1997) *Geochim. Cosmochim. Acta* **61**, 873-904. [2] Gilmour I., Russell S. S., Arden J. W., Lee M. R., Franchi I. A., and Pillinger C. T. (1992) *Science* **258**, 1624-1626. [3] Wopenka B. and Pasteris J. D. (1993) *Am. Mineral.* **78**, 533-557. [4] Andersen T. and Burke E. A. J. (1996) *European J. Min.* **8**, 927-936