A TRIPLE COMPLEX OF LOW-ANGLE OBLIQUE IMPACT STRUCTURES IN THE MIDLAND VALLEY OF SCOTLAND. B. J. Hamill, Wester Tillyrie House, Milnathort, Kinross, Scotland KY13 0RW. b.hamill@zoo.co.uk

Synopsis: A linear chain of three elliptical impact structures has been identified in the Midland Valley of Scotland. These structures appear to have been produced by fragments of a large asteroid which disintegrated on impact. The primary impact site was the Loch Leven basin (56° 12' N, 3° 23' W), which is an elongated structure (18 x 8 km) with a central ridge and lateral terraces. Field evidence suggests an end-Carboniferous date for this impact, similar to that of several known North American craters and suggesting that this was a global event which may have been implicated in the disappearance of the forests of Laurentia and Laurussia.

Field evidence: The Loch Leven basin of Kinrossshire, east-central Scotland lies 30 km N of Edinburgh and 40 km SW of St. Andrews. It is an elliptical low-lying area surrounded on three sides by quartz-dolerite hills of the Midland Valley Sill (290 Ma), which appears to have been intruded around the edges of the debris infill of the crater, thereby preserving its shape. The sill is known to have been intruded at depth (1.8 km), and the present-day structure therefore represents only the eroded base of the crater. Vestigial outcrops of impactites are preserved close to the quartz-dolerite and include impact melts, suevites, lithic breccias and friction-melt rocks. The structure also has a central ridge composed of basalts and basaltic breccias, which hosts the most altered rocks, including highly vesiculated "frothed" clasts in breccias. A series of lateral terraces runs parallel to this ridge. These features are also seen in the lunar crater Schiller, which is believed to be a low-angle oblique impact structure [1]. Such structures are formed under rare circumstances in which the impactor is not effectively buried but instead disintegrates into multiple fragments which ricochet downrange and form secondary impacts elsewhere [2].

A second structure downrange of Loch Leven is indicated by a semi-circular arrangement of rock outcrops centered near Bannockburn, Stirlingshire, 30 km WSW of Loch Leven. This structure is composed of coarse breccias and melt rocks, and a natural cross-section through what is believed to be the north wall of the crater is exposed along the line of the Ochil fault. As at Loch Leven, the shape of the structure is partially preserved by peripheral quartz-dolerite intrusions of the Midland Valley Sill.

A third downrange structure is represented by the plateau of the Gargunnock Hills W of Stirling, an elliptical area (14 x 6 km) of basalts previously interpreted as of volcanic origin. Field evidence demonstrates the existence of two separate series of basalts in which the upper series is overprinted on the lower series and also forms low-angle intrusions into both the volcanic rocks and sedimentary rocks of known stratigraphic position. A distinctive lithology in these rocks (the Kirkwood formation), previously interpreted as a detrital sedimentary rock because of its intense stratification, probably represents a transitional "buffer zone" facies between the static country rocks and a high-velocity body of intrusive melt-rock. It shows laminar flow properties, demonstrating the existence of a velocity gradient across the interface between sub-horizontally intruded impact melts and the target rocks. The Gargunnock structure is believed to represent the eroded base of a crater floored by impact melts. The crater walls have been removed by erosion and the floor survives as a pedestal crater. The Kirkwood formation is widespread in western Scotland and there may therefore be several further impact structures in the area.

Petrologic data:

Loch Leven structure. A variety of impact effects are observed in the Loch Leven structure, in which the country rocks are mostly sandstones. At the eastern (proximal) end of the structure, thermal effects dominate, with formation of indurated quartzitic rocks containing tridymite and devitrified glasses but no Planar deformation features (PDFs). At the western (distal) end of the structure, target rocks do contain PDFs (Fig 1, PPL) and planar fractures (Fig 2, XPL) and the presence of residual glass in these features is confirmed by SEM of HF-etched grains from these sandstones (Fig 3).

The most altered lithologies are found in the central ridge of the structure which contains many vesiculated rocks. One highly "frothed" clast is largely composed of grains of vesicular lechatelierite (Fig 4, SEM) and the unvesiculated quartz cores of these grains are revealed by HF treatment (Fig 5). Unaltered grains of quartz in this rock commonly have a tabular habit produced by a set of basal planar fractures and also contain PDFs (Fig 6, oil mount).

The structure also contains a distinctive suite of pale flow-banded glassy rocks which are interpreted as friction melts.

Bannockburn structure. A coarse immature sandstone from the central part of the structure contains PDFs in quartz and feldspar and is believed to be a "wash-back" impact breccia. PDFs are also found in clasts of coarse breccias on the north wall of the structure and in the underlying country rocks.

Gargunnock structure. This structure adjoins the Bannockburn structure and PDFs found in the underlying country rocks are therefore ambiguous. No PDFs have yet been found in rocks uniquely associated with the

Gargunnock structure. However, basalts from the structure include composite rocks in which a macroporphyritic and microporphyritic component are present simultaneously and behave as immiscible liquids. This phenomenon has been reported in "Tagamites" of the Popigai structure [3]. Similar rocks are present at Loch Leven.

Global implications: An end-Carboniferous date for the impact event is suggested by the field relationships with the Midland Valley Sill and supported by anomalous K-Ar dates obtained for some of the Gargunnock hills basalts [4]. The sudden disappearance of the forests of Laurentia and Laurussia at the end of the Carboniferous has been attributed to climate change. However, coal-producing forests thrived throughout the Permian in China and Siberia, which were separated from the main Pangean continent at the time [5].

Analysis of known impact structures [6] shows that three small North American craters (Decaturville, Des Plaines and Ile Rouleau) of approximately end-Carboniferous date lie (within 1.3 km) on a great circle, suggesting a common provenance. A further 8 North American craters have similar ages. These could be further secondary impact craters produced by fragments of the Loch Leven asteroid, and the impacts may have contributed to the destruction of the forests.

References: [1] Melosh, H. J. (1989), *Impact Cratering*, 25 (OUP). [2] Schultz, P.H. & Gault, D.E. (1990), *GSA Spec. Pap. 247*, 239-261. [3] Masaitis, V.L. (1994), *GSA Spec. Pap. 293*, 153-162. [4] De Souza, H. (1979) Ph.D. thesis, Edinburgh. [5] Ziegler, A.M. et al., *in* Martini, I.P. (ed) *Late Glacial and Post-Glacial Environmental Changes* (1996), 111-146 (OUP). [6] Grieve, R.A.F. et al. (1995), *GSA Today 5*, 189-196.

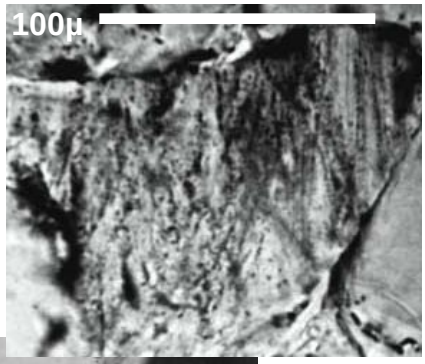

Fig 1
PDFs in
sandstone

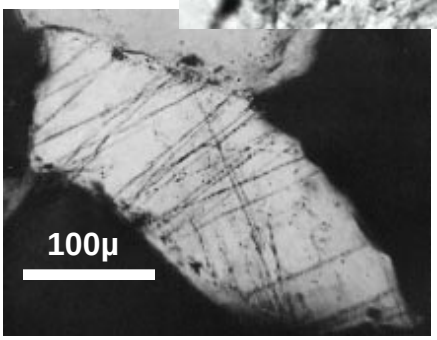

Fig 2
PDFs and
PFs in
sandstone

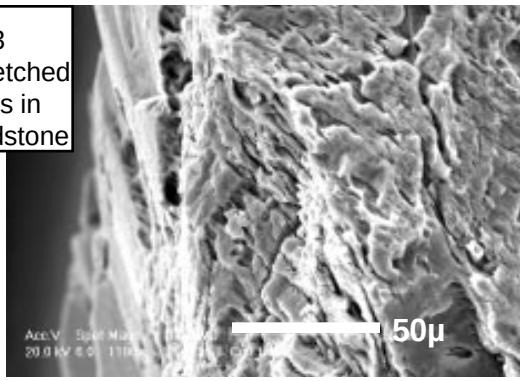

Fig 3
HF-etched
PDFs in
sandstone

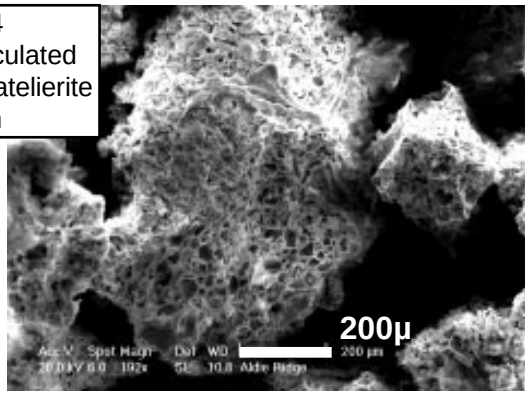

Fig 4
vesiculated
lechatelierite
grain

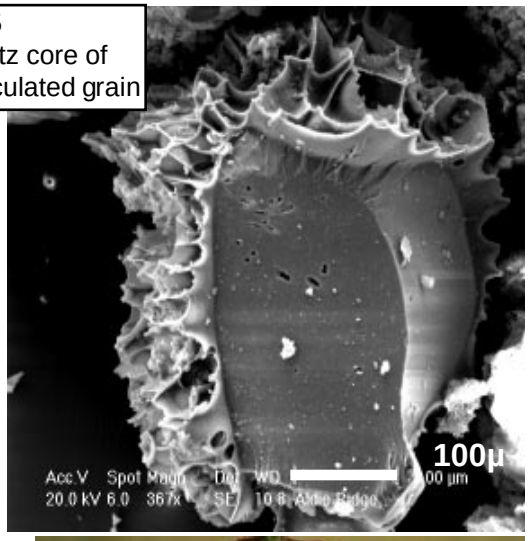

Fig 5
quartz core of
vesiculated grain

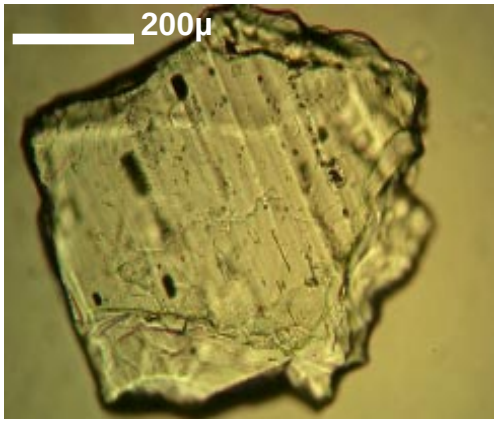

Fig 6
quartz
grain
with
PDFs