THE GARDNOS CRATER, NORWAY: AN OBLIQUE IMPACT?

A. K. Matysiak[1], R. Winkler[1] and T. Kenkmann[1], [1]Albert Ludwigs Universität, Freiburg, Germany, Institut für Geo- und Umweltnaturwissenschaften – Geologie; agnes.matysiak@geologie.uni-freiburg.de.

Geological setting: The Gardnos impact crater is located on the western slope of the Hallingdal valley approximately 150 km NW of Oslo, Norway. The present rim-to-rim diameter of this complex crater is approximately 5 km and it is characterized by a circular area comprising numerous outcrops of autochthonous lithic breccias, allochthonous melt-bearing (suevite) impactites as well as post-impact sediments [1, 2]. The impact event of a non-magmatic iron meteorite [3, 4] occurred ~546 Ma ago into a crystalline target covered by a thin sedimentary layer in a shallow marine environment [1, 5, 6]. The crystalline target consisted of different target lithologies including quarzites, quarzitic and granitic banded gneisses and some amphibolites [7]. It was fractured in place [8] leading to monomict brecciation at outcrop scale. The breccia is mostly clast-supported near the crater rim. Matrix-supported breccia becomes more prominent towards the crater center. Sealed fractures that contain a dense black matrix (up to x cm wide) and breccia filled dikes (up to >1m) occur. Their amount increases towards the crater center. The matrix of the breccia consists of finely comminuted minerals and bed rock. Its dark color is due to enriched amounts of carbon in the impactites [5, 6].

Caledonian overthrusting and burial preserved the crater for a long time. Erosion since the Tertiary have exposed different levels of the crater subsurface and crater fill and thus gives us an excellent opportunity to study impact-induced deformation.

Field work: During a field campaign in 2014 a detailed study of the autochthonous breccia has been performed in order to contribute to a better understanding of the fracturing and fragmentation processes during crater formation. The structural analysis of the crater included ~1000 systematic measurements of orientations of planar macro-features including faults, cleavage planes, fractures, breccia-filled dikes and foliations of gneissic clasts. Best outcrops of the Gardnos Breccia are found along the Dokkelvi river bed which crosses the crater from west to east and passes the center of the crater. Thus it was possible to make measurements along of two profiles which are oriented roughly radial towards the crater center (Fig. 1, locations of measurements are indicated). Further measurements were also performed outside of the crater in order to compare the structural record of the crater interior with the regional pattern.

Results: *Foliation orientation.* Outside of the crater the foliation is gently dipping towards W / NW with a dip angle of 30-45° (Fig. 2a). In contrast inside of the crater the foliation dips either towards NE or SW and generally shows steep dip angles between 70 and 90° (Fig. 2b-c). Interestingly this foliation orientation is present in both the eastern and the western part of the crater.

Fracture orientations. Outside of the crater there are two dominant fracture orientations namely N-S and E-W (Fig. 3a). The eastern part of the crater shows one dominant orientation of sealed fractures which strikes NE-SW (Fig. 3b). In the western part there are two strike orientations present, NE-SW and less pronounced NW-SE (Fig. 3c).

Matrix-filled fractures and breccia-filled dikes are predominantly oriented NE-SW (with some scatter; Fig. 4a-c). Interestingly wide breccia-filled dikes show on orientation maximum which is oriented N-S (Fig. 4b) similar to one fracture orientation outside of the crater.

Interpretation: The observation of the same foliation orientations in the western and eastern part of the crater indicates complex rotation directions of foliated blocks during the excavation and/or modification phase. On the first sight it contradicts a flow field which is supposed to be oriented towards the crater center at every point of the transient cavity. Previous studies of terrestrial and martian craters have shown that obliquely impacting projectiles can cause non-radial deformation by transferring a remnant horizontal momentum from the projectile to the target. This can result in strata which preferentially strike perpendicular to the impact trajectory and dip uprange in the central uplift and faults trending parallel to the trajectory [e.g., 9, 10, 11, 12].

According to these findings it is suggested that the uniform rotation direction of the foliated blocks (irrespective of their location in the crater) is a result of an oblique impact and the related horizontal momentum. The rotation operation necessary for tilting the foliation from its gentle dip to its present sub-vertical orientation would indicate an impact from SW. This trajectory is supported by two observations: 1) There is a dominant fracture orientation trending parallel SW-NE in both the western and eastern part of the crater. This might be a similar structural feature like the faults which were preferentially oriented parallel to the trajectory [12]. 2) The central uplift is offset from the geometric crater center to ENE by ~300-400m [13, 14].

References: [1] Kalleson, E. (2009). *Dissertation university of Oslo*. ISSN 1501-7710. [2] Kalleson, E. et al (2008a) *GSA Special Paper 437*, 19-41. [3] French B.M. et al. (1997) *GCA 61*, 873–904. [4] Goderis, S. et al (2009), *Chem. Geol. 258*, 145–156. [5] Dons, J.A. and Naterstad, J. (1992) *Meteoritics 27*, 215. [6] Kalleson, E. et al (2008b) Excursion guide to Gardnos Meteorite Crater, Issue 102 of 33 ICG excursion. [7] Gilmour, I. et al. (2003), *GCA 67*, 3889–3903. [8] Jaret, S.J. et al (2010) 41st LPSC conf. [9] Kenkmann, T. et (2005) *GSA Special Paper 384*, 85-115. [10] Scherler, D. et al (2006) *EPSL 248*, 43-53. [11] Kenkmann, T. and Poelchau, M.H. (2009) *Geology 37*, 459-462. [12] Wulf, G. et al (2012) *Icarus 220*, 194-204. [13] Shuvalov, V.V. and Dypvik, H. (2004) *Met.Planet.Sci. 39*, 467-479. [14] Elbeshausen, D. et al (2007), LPSC 38, no. 1952.

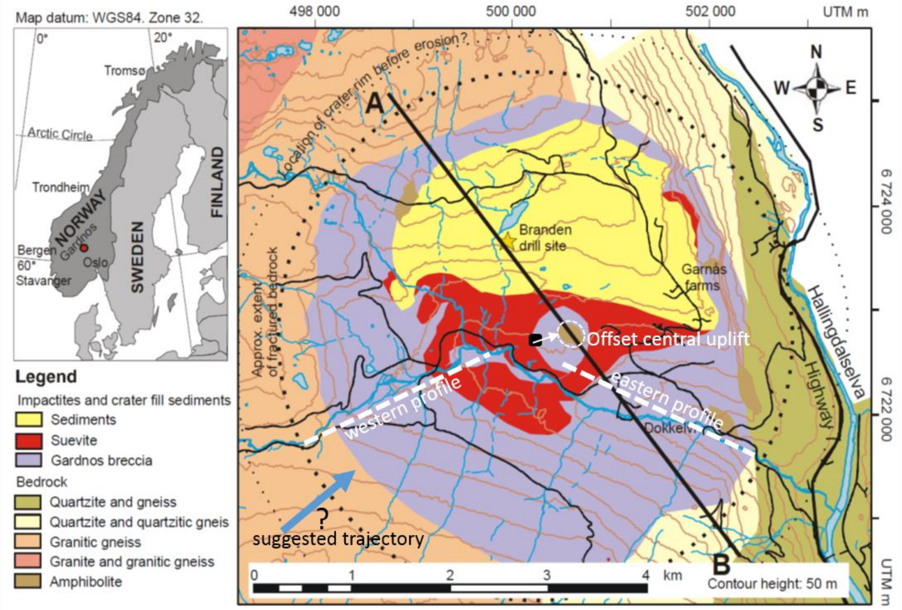

Fig. 1) Geological map of the ~5 km wide Gardnos impact structure (measurement profile lines, central uplift offset and the suggested trajectory are indicated) [6]. Black square indicates geometric center of the crater.

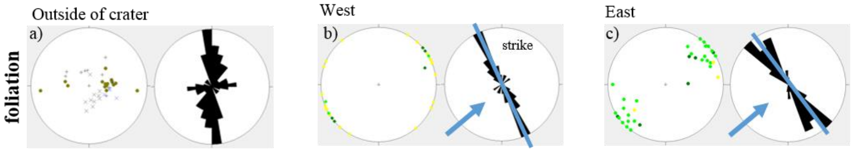

Fig. 2) Pole figures (equal angle projection, lower hemisphere) and correspondent rose diagrams (strike directions; 10° classes) of the foliation orientation (a) outside of the crater, (b) in the western crater part and (c) the eastern part.

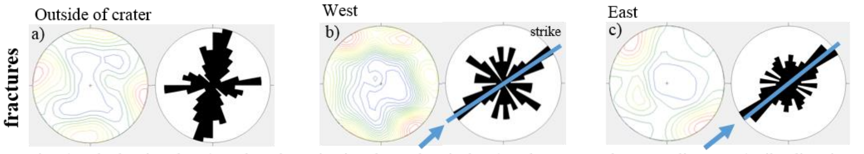

Fig. 3) Pole density plots (equal angle projection, lower hemisphere) and correspondent rose diagrams (strike directions; 10° classes) of the fracture orientations (a) outside of the crater, (b) in the western crater part and (c) the eastern part.

Fig. 4) Pole density plots (equal angle projection, lower hemisphere) and correspondent rose diagrams (strike directions; 10° classes) of the orientations of a) matrix-filled fractures, b) breccia-filled dikes and c) both plotted in one diagram.