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A rock magnetic profile through the ejecta flap of the Lockne impact crater (central Sweden) and implications for the impact excavation process

Irene Melero-Asensio [a,*], Fátima Martín-Hernández [b,c], Jens Ormö [a]

[a] Centro de Astrobiología (INTA-CSIC), Carretera de Ajalvir km 4, Torrejón de Ardoz, Madrid 28850, Spain
[b] Department of Geophysics, Faculty of Physics, Universidad Complutense de Madrid, Madrid 28040, Spain
[c] Instituto de Geociencias (UCM-CSIC), Faculty of Physics, Madrid 28040, Spain

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ABSTRACT

The well-documented, well-preserved, and well-exposed Lockne crater is a reference crater for marine-target impacts on Earth. The large amount of data allows detailed analysis of the cratering and modification processes. A unique feature of Lockne as compared with other similar craters is its pristine ejecta layer. Here, we provide the first complete lithological description coupled with an analysis of the rock magnetic properties of the Lockne-9 core drilled through the ejecta flap. Low-field bulk magnetic susceptibility, magnetic hysteresis, isothermal remanent magnetization curves (IRM), and the corresponding model of the coercivity spectra, backfield IRM, and thermomagnetic curves are used to fully characterize the magnetic mineralogy (i.e., pseudo-single domain (PSD) magnetite and pyrite). Variation of the magnetic properties with depth reveals a characteristic maximum in the magnetic susceptibility and magnetization within the crystalline ejecta. The magnetic properties of rocks affected by the impact show a slight weakening in the coercivity of magnetic minerals in comparison with rocks not affected by the impact. Altogether, this suggests to us that the high magnetization zone already existed before the impact event took place. Therefore, it can be inferred that during the cratering process, the Lockne ejecta was repositioned *en masse* from the central part of the crater in the form of an ejecta flap. This stands in contrast to the standard ballistic emplacement model wherein individual particles move in an ejecta curtain.

1. Introduction

The 458 million years old Lockne crater in central Sweden (Fig. 1) is today one of the best accessible, well-preserved marine-target craters on Earth because of the fact that—immediately after its formation—the crater was covered by post-impact marine sediments and, subsequently, by over-thrusted Caledonian nappes (Lindström et al., 2005a). It was thus protected from erosion until Cenozoic isostatic uplift and Pleistocene glaciations event exposed the crater. This fortunate set of circumstances has triggered many geological and geophysical studies during the last few decades, spanning the pre-impact sedimentary record, impact process, and post-impact sedimentation (e.g., Sturkell, 1998; Lindström et al., 2005a; Ormö et al., 2010b; Sturkell et al., 2013, and references therein). This impact structure has been explored by 11 short core drillings (Fig. 1), and over 5000 outcrop descriptions, which is the basis for a detailed geological map (i.e., Lindström et al., 2005a). In addition, this impact crater has been the site of several geophysical surveys (e.g., Sturkell and Ormö, 1998; Sturkell et al., 1998b). Cores 1–6 were drilled in order to constrain the crater dimensions and to determine the stratigraphy of the crater infill and the biostratigraphic age of the crater (Lindström et al., 1996). Drill cores 7, 8, and 9 (the latter being the subject of this study) were obtained during 2004 with the main objective to study the depositional environment within the crater as well as the ejecta dynamics (Ormö and Lindström, 2005). A brief description of the Lockne-9 core is given by Ormö and Lindström (2005), and a study on biomineralization at certain core levels was carried out by Lindgren et al. (2007). Drill cores 10 and 11 are subject for an ongoing geological and geophysical study (Sturkell et al., work in progress). Previous geophysical studies include modeling of the gravimetric and magnetic anomalies generated by the crater (Sturkell and Ormö, 1998; Sturkell et al., 1998b). The magnetic modelling was restricted to the use of aeromagnetic anomalies and measured values of the induced magnetization (i.e., magnetic susceptibility) for the geological bodies in consideration. The magnetic signature of the crater is very weak due to the low contrast between the main lithologies (Sturkell and Ormö, 1998) and for simplicity, remanent magnetization as a contribution to the total signal was not considered.

Rock magnetism and paleomagnetism analysis related with impact cratering are commonly used for two main purposes: magnetic modelling and studies of shock effects. Rock magnetic characterization allows the magnetic susceptibility as initial input in the modelling of magnetic

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* Corresponding author. Tel.: +34 915872982.
E-mail address: meleroai@cab.inta-csic.es (I. Melero-Asensio).

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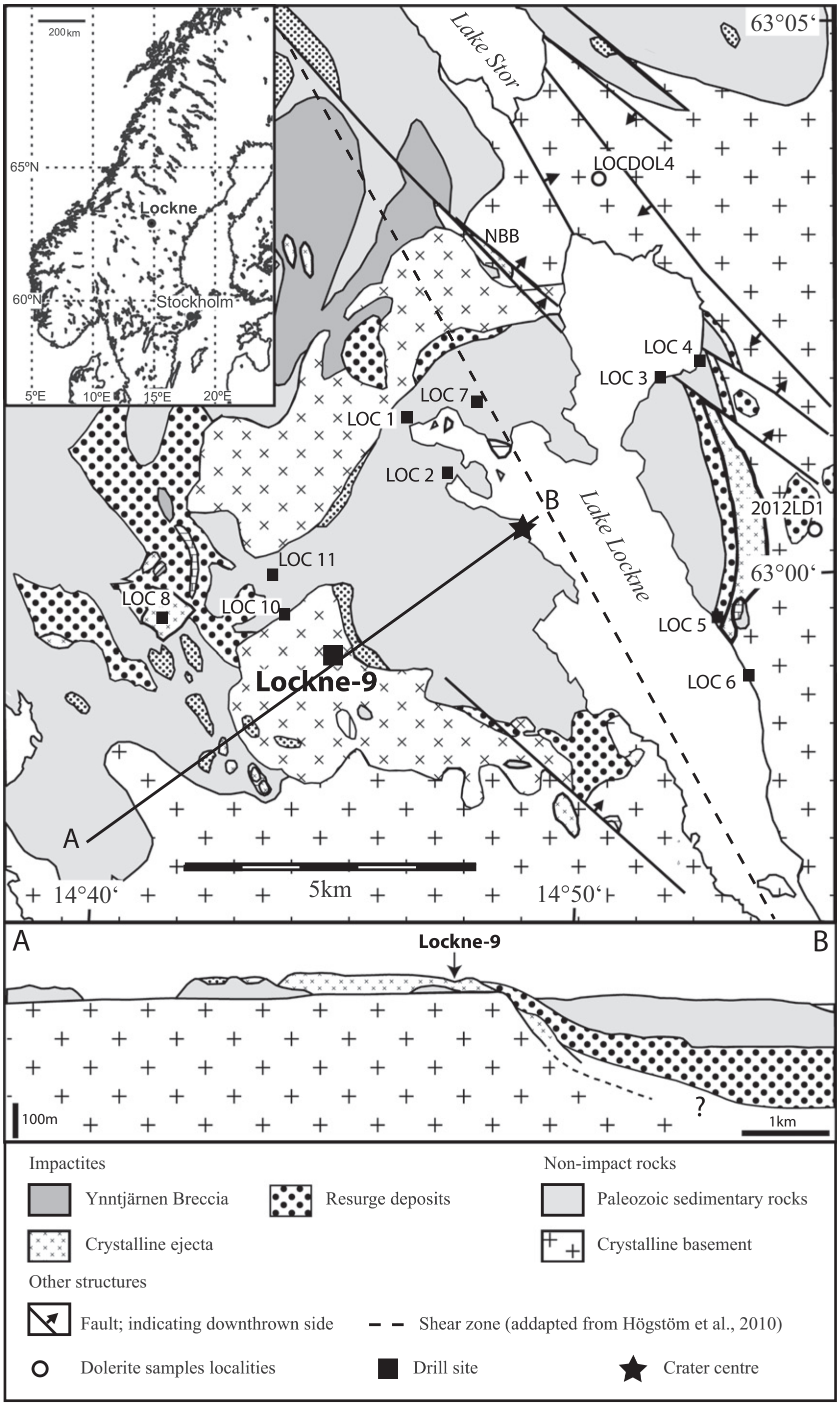

Fig. 1. Geological map and location of Lockne-9 drill core with respect to the crater centre (modified from Lindström et al., 2005a and Frisk and Ormö, 2007). The lower panel displays a simplified geological section through the Lockne crater passing by the Lockne-9 core (modified from Lindström et al., 2005a).

anomalies (e.g., Henkel and Reimold, 2002; Henkel et al., 2002; Ormö et al., 2010a; Scott et al., 1997). Paleomagnetic studies constrain the amount of remanent magnetization that contributes to the magnetic anomaly model (e.g., Elbra et al., 2009). Combined analysis in pyrrhotite-bearing rocks has been applied to understand shock demagnetization by impacts on Earth and other planetary bodies (e.g., Kontny et al., 2007; Louzada et al., 2010).

1.1. Setting of the Lockne-9 drilling

The formation of the Lockne crater in an epicontinental sea of about 500 m water depth is of interest as the layer of seawater is known to affect the excavation process and the ejecta emplacement (e.g., Lindström et al., 2005b; Ormö and Lindström, 2000; Shuvalov et al., 2005). So far, there is not much known about the ejection process at marine impacts with such a relatively deep target water depth as Lockne (i.e., a water depth equal or more than the projectile diameter). Especially enigmatic is the apparent absence of a structural uplift (Fig. 1) below the ejecta of the rim area (e.g., Sturkell and Lindström, 2004), which is common at the land-target craters more frequently used as standards for crater morphologies (e.g., Melosh, 1989 and references therein). Instead, the formation of exceptionally wide, relatively coherent ejecta flaps is realized in this setting (e.g., Lindström et al., 2005a). It is possible that these features are a consequence of the low position of the basement crater below a