THE MÅLINGEN STRUCTURE: A PROBABLE DOUBLET TO THE LOCKNE MARINE-TARGET IMPACT CRATER, CENTRAL SWEDEN.

J. Ormö[1], E. Sturkell[2], I. Melero Asensio[1], Å. Frisk[3], A. Lepinette[1] and A. Moro Martin[1] [1]Centro de Astrobiologia (INTA-CSIC), Spain, ormo@inta.es, [2]Department of Earth Sciences, University of Gothenburg, Sweden, [3]Department of Earth Sciences, Uppsala University, Sweden.

Introduction: Målingen is a 1km wide, circular structure located 16km down-range of the 7.5km wide, Upper Ordovician Lockne crater. The circular shape in the Precambrian crystalline basement and exposed sedimentary breccias resembling the resurge deposits at Lockne of the same age [1] have led to suggestions for an impact origin in relation to Lockne [2], but it has so far been generally considered that the breccias are Caledonian allochthonous deposits of distal Lockne resurge materials and that the circular feature is merely a coincidence [3]. An impact origin appeared problematic as it was assumed that the structure extended only a few meters into the basement .

Objectives: Here we are investigating the geology and geomorphology of the Målingen structure to evaluate a potential formation in relation with the Lockne impact. If an impact origin is established then the Lockne/ Målingen is the first known doublet marine impact. This gives a unique possibility of studying the consequences of a thick target water layer on the cratering process (i.e., identical target setting, different magnitude of the two individual events). In addition, estimates of impact angle and direction of the Lockne/ Målingen asteroid may be used to calculate the orbital parameters of the asteroid.

Methods: We have carried out geological mapping of the area during several field seasons. The latest edition of the map is shown in Fig. 1. We have also performed core drilling in two stages at the apparent center of the circular structure: A drilling during 2009 produced a 45 m core (Målingen-1A) aimed mainly to investigate the stratigraphic relationships of the sedimentary infill as well as the depth of the structure. As the core ended in the sedimentary infill without reaching the crystalline basement the drilling was resumed in the same hole during 2010. The new drilling (Målingen-1B) ended in the crystalline basement at 149m depth and, thus, provides information on the depth of the sediment-filled structure. The core location near the center of the structure is ultimate for the recovery of potentially shocked materials considering the small size of the crater and the relatively deep target water depth. It is known from other marine impact sites that shocked minerals are most frequent in the arenitic parts of the resurge deposits [4]. In addition, even small craters may have shocked material near the true crater floor at the crater center. Thin sections are currently being prepared from both these locations in the core. However, due to the proximity to Lockne ejecta, the existence of shock metamophism in the Målingen resurge deposits may not unequivocally support an impact origin. Therefore, the search is focused on the true crater floor material.

The geological investigation is complemented by 2-D numerical simulation of vertical (15km/s) impacts into the presumed target configuration (i.e., 500m of water, 80m of sediments, granitic basement). This will aid the interpretation of the geological data and test the impact hypothesis. We are also carrying out a geophysical survey of Målingen [5], in order to provide a geophysical model that better constrains the numerical simulations (i.e., depth and width of the basement crater).

Results and discussion: The mapping shows a ring-shaped topographic high (i.e., topographic rim) of crystalline basement rocks of about 1km in diameter. In the SW section of the rim crystalline rocks overlay Cambrian alum shale. This may be due to either outwards upthrusting or an overturned ejecta flap as seen at Lockne [3].

The Målingen-1A&B cores reveal a sequence expected for a marine-target impact crater (i.e. Lockne): Post-impact deposits (3m) of the same unit (Dalby Age) as at Lockne are coarsening gradually downwards into calcareous siltstone, arenite, and sedimentary breccia (3m). The breccia is mainly made up of fragments from the 50 m thick orthoceratite limestone of the upper target sequence. It rests with sharp contact on dark mudstone (97m) originating from the 30m thick Cambrian alum shale of the lower sedimentary target, which was unconsolidated mud at the time of the Lockne/Målingen event. At 105m depth the dark mudstone passes into a polymict, matrix-supported breccia (3m). It contains dm-size blocks of basement rocks, and some smaller clasts of limestone and alum shale, but gets increasingly clast supported and monomictic crystalline downwards. In the interval 105-119m the rock is partially brecciated granite, which passes downwards into relatively intact basement rocks.

Visual inspection of the resurge deposits reveal a relatively low content of crystalline material compared with the equivalent deposits at the Lockne crater. This indicates a different mode of excavation of the basement crater at Målingen than at Lockne.

The first stages of numerical simulation aimed to establish the projectile diameter required to crater both the water and the seafloor so that a 1km wide depression is formed in the basement. We conclude that a 250m projectile provides the best fit (Fig. 2), notwithstanding the simplifications causing an underestimation compared to a more likely oblique impact. Nevertheless, the projectile diameter in relation to the great distance to the Lockne crater favors a formation by a primary impact rather than a secondary from the Lockne event. The second stage of the simulations aimed to explain the relatively high amount of dark mudstone in the sedimentary infill compared to the amount of limestone fragments. For this we used sediment tracers in the simulation (Fig. 3). Unfortunately, we are limited to the use of only one layer of sediments (limestone). Nevertheless, it is clear that a large portion of the target sediments would remain inside the crater during the excavation stage. At first glance, the dark mudstone infill does not show any indication for being heated to high temperatures. The numerical simulation shows that although sediments remain inside the crater some of the material is subject to rather high temperatures (Fig. 4). Thus the sediments must originate from near the crater rim, which is very poorly developed in the models.

The interpretation is that the consolidated orthoceratite limestone is more easily ejected than the sticky, dark mud of the lower target, which to a greater extent then remain inside and in close proximity to the transient cavity. Later stages in the simulation show at least two oscillations of water resurge each accompanied by the strong formation of a central water plume. The collapses of these central water plumes cause strong erosion and reworking of the crater infill. This may explain the relatively thin resurge deposit at the crater of the center, where instead reworked crater ejecta is spread this over a large area of the seafloor. At Lockne, the anti-resurge from the collapsing central water plume did not overcome the force of the resurge proper, which lead to the accumulation of much of the reworked material within the basement crater [6].

Conclusions: The shape and depth of the Målingen structure together with the cored sequence support an impact origin. The stratigraphic and geographic relationship to Lockne indicates that it most likely occurred in conjunction with the Lockne impact. The thick infill of dark mudstone (relocated lower target alum shale) and relatively thinner deposits from the limestone target, as well as the lower crystalline content in the resurge deposits than at the nearby Lockne crater, are likely consequences of the relatively deep target water (500 m) causing most of the basement crater to develop due to displacement.

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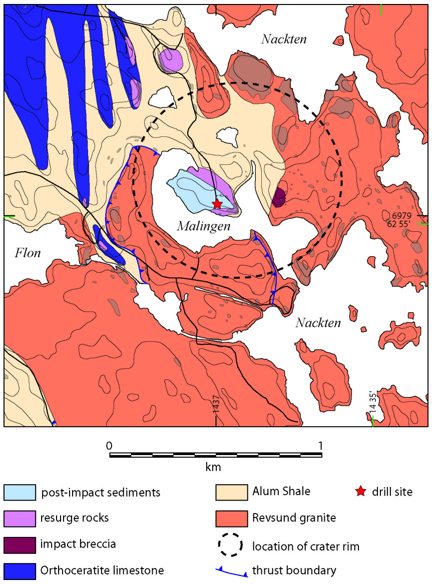

Fig.1. Geological map of the Målingen structure.

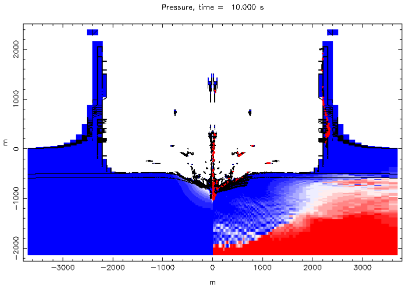

Fig. 2. 2-D simulation of 250m projectile impact into 500 m deep water.

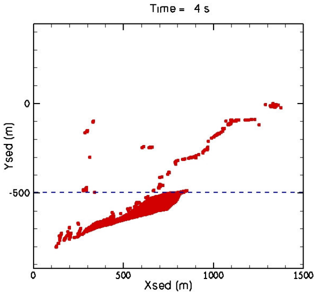

Fig. 3. Sediment tracers (red).

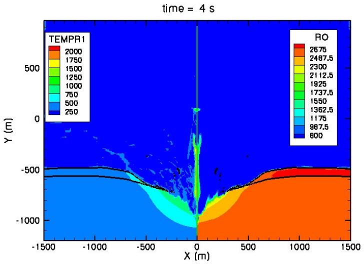

Fig. 4. Temperature and density at the same time frame as in Fig. 3.