LOCKNE CRATER AS A RESULT OF OBLIQUE IMPACT. M. Lindstrőm[1], V. Shuvalov[2], B. Ivanov[2], [1]Department of Geology and Geochemistry, Stockholm University, 106 91, Stockholm, Sveden (maurits.lindstrom@geo.su.se), [2]Institute for Dynamics of Geospheres RAS, Leninsky pr. 38-1, 119334 Moscow, Russia, (shuvalov@idg.chph.ras.ru, ivanov@lpl.arizona.edu)

Introduction. The asymmetry of ejecta distribution around the Lockne crater suggests that the crater was formed due to an oblique impact directed approximately from East to West. In this paper we present the results of 3D numerical modeling conducted to give more theoretical constraints for the geologic data interpretation, and conversely, to control the numerical model assumption with the field observation. Based on previous results [1] we consider a 45 degree oblique impact of a 600-m-diameter asteroid (with density 2.63 g/cm^3) into a 500 m deep sea. The impact velocity is 15 km/s. A 3D version of the SOVA multi-material hydrocode [2] has been used to model the shock wave propagation in a double layer (water and basement rocks) target, transient crater growth, material ejection, and ejecta expansion. Our mechanical model for rocks includes dry friction behavior of disrupted rocks, thermal softening close to the melting point (zero strength for melt), and acoustic fluidization [3].

Special efforts are undertaken to describe ejecta flight and deposition taking into account their interaction with air and water. When any part of a solid target material rises 200 m above the sea floor it is considered as ejecta and transforms into discrete particles. The size distribution of ejected material is defined from the data available for land craters. We consider 4 groups of particles with sizes: <0.1 m, 0.1÷1 m, 1÷10 m, and 10÷100 m. The motion of particles is calculated taking into account ejection velocity, drag force (depends on water/air density and relative velocity), and gravity. This procedure is described in more detail in [1,4].

Results of numerical simulations. The stage of penetration is strongly asymmetric. The projectile first strikes water. During the passage through water the projectile is strongly deformed and partially fragmented (see Fig.1).The motion of the projectile generates a strong shock wave in water. The wave reaches the basement and generates cratering flow in the basement. The projectile itself only slightly touches the left (downrange) lip of the growing basement crater and being reflected moves downrange. The initial cavities in both water and basement are asymmetrical. The horizontal size of the water cavity exceeds that of the basement crater.

At the initial stage of the excavation stage the basement crater has different diameters in the direction along the projectile trajectory and in transverse direction (see Fig.2). The crater is elongated along the trajectory by 10-15%. The difference vanishes at the end of excavation (approximately at 20 s). 8 s after the impact the transient cavity reaches its maximum depth (about 1.4 km in relation to the sea floor level), however, its diameter continues to grow (initially due to excavation and later due to crater collapse).

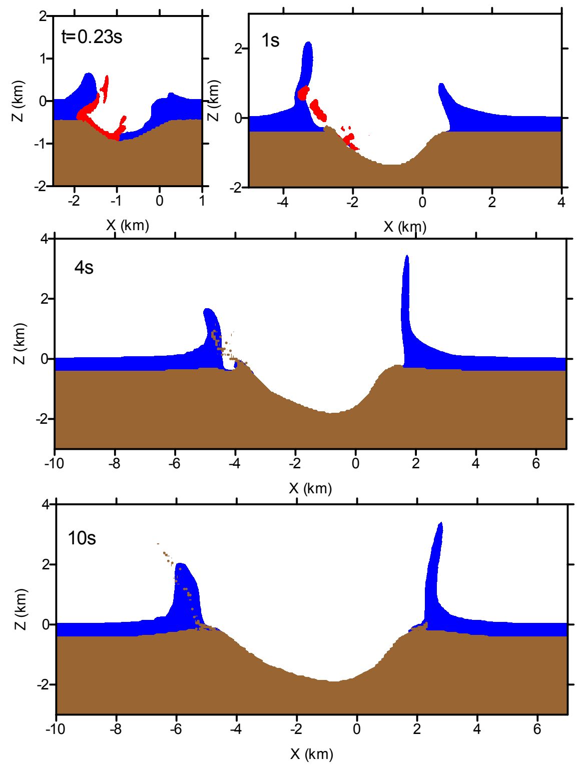

Fig.1 Initial stage of a 45^0 oblique impact of a 600-m-diameter asteroid into the sea 500 m deep.

The volume of ejected material (all particles ever uplifted 200 m above the pre-impact basement level) grows till the end of excavation (about 20 s) and reaches the value of 6.5 km^3. The initial position of ejected rocks (excavation crater) is shown in Fig.3. The shape of the excavation crater considerably differs from typical excavation craters for vertical continental impacts. The maximum excavation depth is about 250 m under the sea floor level. About 50% of the ejecta consist of sediments, the remaining 50% are basement rocks.

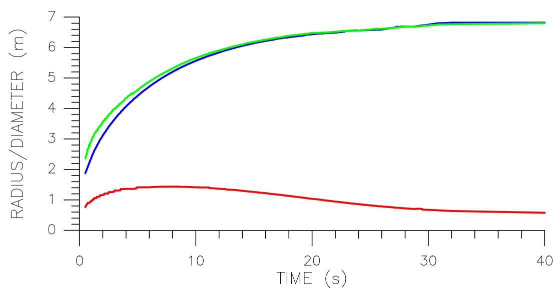

Fig.2. Basement crater depth (red) and diameters versus time.

Fig.4 shows the calculated distribution of ejected rocks in respect to the maximum shock pressure. The "average" shock loading level for the ejected material is about 1 GPa. About 70% of the ejected rocks have experienced shock compression below 4 Gpa (a level of main microscopic shock metamorphism features like PDFs). Only about 10% of the ejected rocks have been compressed above 10 GPa. A volume of ejected impact melt (approximately 4×10^7 m^3) is less than 1% of the total ejecta and about 8% of the total melt volume (0.5 km^3).

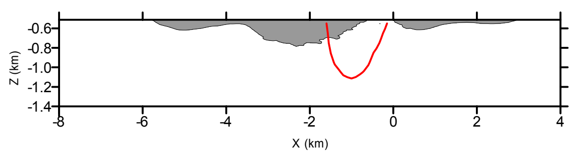

Fig.3. Excavated crater. The red line is the boundary of impact melt volume.

Due to the presence of water the main mass of ejecta can not fly out far from the crater center: the expansion of solid ejecta is restricted by the curtain of ejected water. However, some separated large fragments have a chance to pass through the water curtain and create local areas of distal ejecta, which are observed around the Lockne crater.

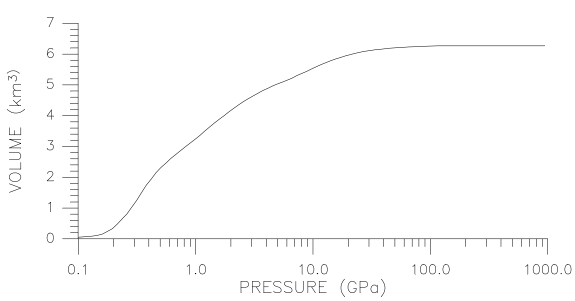

Fig.4. Volume of ejecta that experiences pressure below given value.

The velocity *U* of particle sedimentation can be estimated from equality between gravity and drag forces. This gives *U*<4 m/s for the first group of particles (<0.1 m), *U*=4-12 m/s for the second group (0.1-1 m), *U*=12-40 m/s for the third group (1-10 m), and *U*=40-120 m/s for the forth group (>10 m). Consequently, fragments from the third and fourth groups (from 1 to 100 m) reach the sea floor for 5-50 s. These fragments (57% of the total ejecta mass) are very slightly affected by resurge flow (the time scale of which is just a few minutes) and form the main ejecta blanket. The time of sedimentation for the first group of fragments (<10 cm) is comparable to or greater than the resurge time. These fragments (21% of the total ejecta mass) travel with water for a long time and form resurge deposits. The fragments from the second group (0.1-1 m, 22% of the total ejecta mass) can be displaced by resurge flow for a distance of about 1 km.

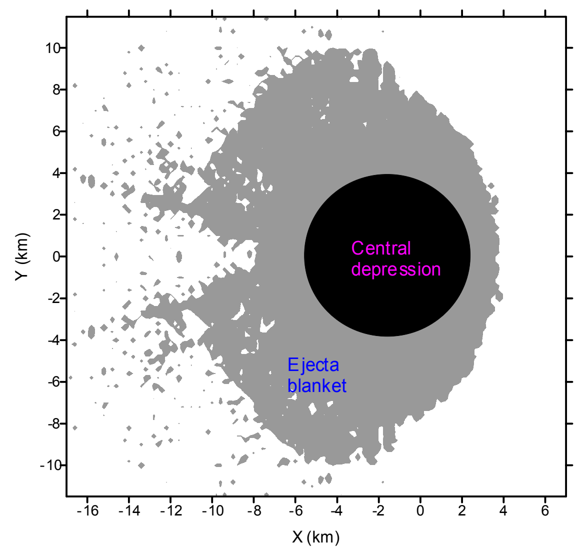

Fig.5. Ejecta blanket and central depression.

The final distribution of ejecta deposits (Fig.5) clearly demonstrates two main features well known from the field observations: a strong asymmetry of the ejecta blanket with considerably higher extension in downrange direction and a possibility of formation of local areas of crystalline ejecta outside the main distribution (also in down range direction). Numerical simulations show that several fragments with a size of about 10 m fly for a distance of 30-40 km from the crater and form distal ejecta.

References: [1] Ormö J. et al. (2002) *JGR, 107*, 3-1–3-9. [2] Shuvalov V.V. (1999) *Shock Waves, 9*(6), 381-390. [3] Melosh H. J. and Ivanov B. A. (1999) *Annu. Rev. of Earth and Planet. Sci., 27*, 385-425. [4] Shuvalov V.V. (2003) In *Impact markers in the stratigraphic record* (ed. C. Koeberl and F.C.Martinez-Ruiz (Eds.) pp. 121–135. Springer Verlag Berlin, Germany.