EFFECTS OF TARGET LAYERING ON SUBSURFACE DEFORMATION. A. Agarwal¹, A. Kontny², M. H. Poelchau³ and T. Kenkmann¹. ¹Institute of Earth and Environmental Sciences – Geology, Albert-Ludwigs-Universität Freiburg, Germany, Albertstrasse 23-B, 79104 Freiburg im Breisgau. amar@daad-alumni.de. ²Institute of Applied Geosciences, Karlsruhe Institute of Technology, Karlsruhe, Germany.

Introduction: Target layering is common on most bodies in the solar system [1]. Layers formed by lithological variation display mechanical anisotropies and heterogeneities. These variations can significantly influence crater formation [2], [3]. Differences in thickness of the stratigraphic layering also yield significant structural differences between terrestrial craters formed under similar conditions [4], [5].

Target layering is thus expected to affect subsurface deformation. The only established techniques to investigate subsurface deformation over a large range of depths are either drilling into real craters or numerical modelling. While the former is very expensive, the later does not consider the mechanical heterogeneity of the target rocks.

Therefore, in the present study, we conducted cratering experiments with layered targets and their subsurface deformation was quantified through detailed strain and magnetic fabric analysis.

Methods: Two cubical blocks of Maggia gneiss were used for impact cratering experiments. The foliation was vertical, i.e., perpendicular to the target surface, in experiment A38, and horizontal, i.e., parallel to the target surface, in experiment A37. Aluminium sphere projectiles, 5 mm in diameter (dp) and 0.177 g in weight, impacted the targets at 7 km/s. The two cratered blocks were sawn in half and thin sections were made perpendicular to the foliation and to the target surface.

For anisotropy of magnetic susceptibility (AMS), a non-magnetic diamond bit, 14 mm in diameter, was used to drill oriented cylindrical cores from an unshocked and the two shocked blocks. Specimens were drilled parallel and perpendicular to the metamorphic foliation in the unshocked block. From samples A38 and A37, specimens were drilled into the target surface and into the sawed surface. The specimens are 14 mm in diameter and 11.2 mm long. Thermomagnetic behavior was analyzed and AMS was measured at low-temperature (LT) and room-temperature (RT).

For strain analysis in the subsurface, high resolution BSE image maps of the thin sections were made. Based on these maps, the amount of kinking in individual biotite grains was quantified. The length of kinked biotite c-axis planes \( l_0 \) was measured as well as the length of the shortened biotite \( l_i \), giving a strain value \( \varepsilon = (l_0 - l_i) / l_0 \). A total of 1337 values were measured. Furthermore, the orientation of the kink plane, which is a hypothetical plane lying within the fold hinges of a kink, was measured relative to the foliation and relative to the impact point source. The interlimb angle, which is the opening angle of the two limbs of a kink, was also measured.

Results: The target rocks in the subsurface of the two craters experienced low shock pressures (< 3 GPa).

Magnetic fabric analysis: A Curie temperature of \( \sim 576^\circ \) C indicates almost pure magnetite, which often occurs within biotite. The LT-K3 and the LT-magnetic foliation planes coincide with RT-K3 and the RT-magnetic foliation planes, respectively. This, indicates no difference in the orientation of AMS at room and low temperature. The ferrimagnetic fabric is, thus, co-axial with the paramagnetic biotite fabric.

Impact cratering has increased the average susceptibility from 0.61 x 10⁻⁵ SI (in unshocked specimens) to 1.47 x 10⁻⁵ SI (in A38) and 1.49 x 10⁻⁵ SI (in A37). Moreover, \( P^\prime \) has increased from 1.49 to 1.72.

The deviation in K3 is more significant (up to 22°) when the shock waves propagate along the magnetic foliation. Whereas, K3 deviates < 4° for an oblique incidence of the shock wave. As a consequence, in A38 the maximum deformation is concentrated beneath the crater centre, while in A37 it is along the sides (yellow zones in figure 1). In A37, the deviation in K3 near the surface is less than in the vertical sections.

Strain analysis: The crater of experiment A37 (horizontal foliation) shows a fundamentally different pattern of strain with respect to the crater of A38 (Fig. 2). First, the principal strain axes are flipped so that in A38 the elongation axis \( e_1 \) is oriented radially whereas the shortening direction \( e_2 \) is trending concentric with respect to the source point. In A37 \( e_1 \) is concentric and \( e_2 \) is radial. This is because in A37 horizontal layering of biotite grains allows compression in horizontal direction, and low kinking corresponds with weak damping of the shock wave, thus allowing strong reflections. The reflections cause tensile fracturing, which lead to extension in vertical direction.

In general, the strain decreases with depth below the crater floor. In the strain anisotropy map, below the crater floor of A37, the strain is highest in the left part as compared to the central and right part (Fig. 2). The strain is higher below the crater centre, than adjacent to the crater below the target surface.
The distribution of strain was also analysed within single grains of twenty biotite flakes of A38. ~70% of biotite reported here are more strained at the top and bottom compared to the middle.

**Discussions:** Folding and kinking of biotite due to shock deformation may cause a significant re-orientation of magnetic fabrics by passively changing the position of magnetite grains with respect to each other. Re-orientation of magnetic fabrics is conspicuous down to 20 dp (10 cm) below the point source.

Higher strain at the top of a single grain is owed to the stronger shock wave at the top, which loses part of its energy as it travels down the grain. Higher strain at the lower part of the grain may be explained by the superimposing of the deformation by the incident shock wave and its reflected part. Thus the strain distribution is heterogeneous at the grain scale.

Comparison of strain anisotropy maps of A38 and A37 reveal two important pieces of evidence which clearly demonstrate the control of the foliation on strain. First, the strain below the crater floor in A38 is an order of magnitude higher than in A37. Second, near the crater floor in A38, the highest strain is recorded vertically below the point source and is lower in the grains near the crater floor in the left and right oblique profiles. On the other hand, in A37 the vertical profile has lower strain than the left oblique profile even though the grains in the former are nearer to the point source. These two stark contrasts are owed to the ability of biotite to deform easily along its basal plane [6].

AMS and strain analysis show comparable results. Both AMS and strain analysis reveal the effect of interaction of free surface with the shock wave. This interaction decreases the deformation near the target surface adjacent to the crater wall.

**Conclusions:** The cratering experiments into gneiss have shown that deformation is higher below the crater floor than adjacent to the crater wall. Furthermore, the intensity and distribution of deformation (represented by strain and dispersion of K3) depends upon the orientation of the layering. This anisotropy of deformation underlines the critical effect of the orientation of mechanical heterogeneities such as stratigraphic layering or foliation.


![Figure 1: The maps show the position of the specimens (black dots) and the deviation in K3 with distance from the point source in A38 and A37. The impact crater is represented with red arc and the point source is marked by a red dot.](image1)

![Figure 2: Strain anisotropy map of A37 (left) and A38 (right). The data points are shown with the black dots. The projectile and the point source are shown at the estimated burial depth.](image2)