STRUCTURAL INDICATORS FOR OBLIQUE IMPACT TRAJECTORIES FOUND IN MARTIAN AND TERRESTRIAL IMPACT CRATERS. T. Kenkmann[1], G. Wulf[1] and M. H. Poelchau[1], [1] Institut für Geowissenschaften, Albert-Ludwigs-Universität Freiburg, Albertstrasse 23 B, 79104 Freiburg, Germany Thomas.kenkmann@geologie.uni-freiburg.de

Introduction: The majority of impacts on planetary bodies occur at an oblique impact angle to the target surface, where the incidence angle follows a Gaussian probability distribution with a mean value of 45° [1, 2]. Although oblique impacts are prevalent occurrences, the crater shape remains circular for impact angles above 10-15° from the target surface [3] and thus can rarely give implications for the impact direction or angle. The distribution of the ejecta blanket, on the other hand, is a distinctive indicator for oblique impacts. It loses its radial symmetry at angles below 45-35° and at lower angles forms “forbidden” zones and “butterfly” patterns [3, 4]. Unfortunately, on Earth most ejecta blankets are eroded and cannot be used to determine the impact direction for terrestrial craters. Hence, other potential indicators for an oblique impact are needed if the impact trajectory is to be determined in terrestrial craters.

An offset position of the central uplift relative to the crater center observed in several terrestrial and lunar impact structures was proposed to be caused by oblique impacts [5-7]. However, statistical analyses of central uplifts and ejecta blankets in Venusian craters were not able to confirm this [8, 9] and it has been suggested that an offset can be caused by heterogeneous target structures [10].

Mapped impact craters: Over the past years the subsurface structures of eroded central uplifts of several terrestrial impact craters have been investigated. Results show that the internal structure of central uplifts (as opposed to the morphological offset) is influenced by an oblique impact angle. Preferential, non-radial orientation of tilted, folded, and faulted layered bedrock implicates a preferred transport direction during the crater formation process (Table 1). Recent high resolution remote sensing studies of Martian impact craters could complete and validate the findings of the terrestrial studies. The survey is based on the structural analysis of the following impact craters: Upheaval Dome, Utah, USA (5-6 km Ø) [11], Spider, WA, Australia (13 km Ø) [12], Gosses Bluff, WA, Australia, [13, 14], Matt Wilson, NT, Australia, (6.3 x 7.5 km Ø) [15], Jebel Waqf as Suwwan, Jordan, (6 km Ø) [16], Martin crater, Thaumasia Planum, Mars (21.4°S 290.8°E) (60 km Ø) [17-19], Unnamed central peak crater, Noachis Terra, Mars, (28.40°S 304.9°E) (18 km Ø) [17, 20], and an Unnamed central pit crater, Thaumasia Planum, (15.8°S 296.3°E) (55 km Ø) [17]. An independent determination of the impact trajectory that does not rely on the internal asymmetric structure of the crater was possible in four cases: in one terrestrial crater (Matt Wilson) the elliptical crater morphology constrains the trajectory, in three further cases (the Martian craters) it is the asymmetric ejecta blanket and the existence of an uprange forbidden zone that provide an independent indicator for impact trajectory (Table 1).

New structural criteria: The structural criteria to determine the impact direction are:

(i) **Strata strike:** All investigated oblique impact craters show a preferred orientation of layered bedrock in the central uplift. The dominant strike orientation is perpendicular to the impact direction. Some statistical noise and bias can occur due to strata folding. In most cases strata dip steeply or vertically and result in the formation of morphological ridges that follow the strata strike. The usefulness of strike orientation as an indicator for defining impact trajectories is validated and confirmed by the presence of asymmetric ejecta blankets [17-19] and crater ellipticity [15]. It is the most important structural criterion.

(ii) **Strata dip:** An uprange dip of strata is predominant if layers are not in an upright position. This uprange dip is a consequence of stacking of tilted bedrock that experienced a top-downrange shearing. However, as Martin crater shows the opposite dip [17-19] this criterion has to be considered with caution.

(iii) **Fault orientation:** The main faults in central uplifts of oblique impact craters trend both parallel to the impact trajectory and perpendicular to it. Faults parallel to the trajectory are predominantly strike-slip faults, whereas those perpendicular to the trajectory are reverse or normal faults. Faulting parallel to the trajectory seems to be caused by differences in the magnitude of horizontal transport of rock units in downrange direction during uplift formation. The downrange movement is expected to be strongest along the trajectory axis that runs through the crater center and decrease further outwards in the crossrange regions of the uplift. Thus, the shear sense of strike slip faults changes its direction on the opposing side of the symmetry axis of the crater’s central uplift. Faults that strike perpendicular to the trajectory axis accommodate the propagation of the central uplift center from uprange in downrange direction by imbricated stacking of inclined layers.

(iv) **Fold orientation:** Radial folding is a typical structural feature for central uplifts and particularly

Structural criteria to infer the impact trajectory in complex impact craters		Martian craters			Terrestrial craters			
		Martin	Unnamed central peak	Unnamed central pit	Matt Wilson	Upheaval Dome	Spider	Gosses Bluff
Ejecta pattern	Asymmetry of the ejecta blanket	x	x	x				
Crater shape	Elliptical crater shape				x			
Central uplift	Strata strike preferentially perpendicular to trajectory	x	x	x	x	x	x	x
Central uplift	Dip preferentially up range	-		x	x	x	x	x
Central uplift	Faults parallel to trajectory	x	x	x	x	x	x	?
Central uplift	Faults perpendicular to trajectory	x			x	x	x	?
Central uplift	Fold axes dominantly parallel to trajectory	x			x	x	x	

Table 1. Summary of structural criteria to infer the impact trajectory in complex craters. In the blue rows established obliquity criteria are listed that provide an independent proof of the inferred trajectory and confirm the new criteria.

(v) occurs in their periphery, where radial, crater-inward directed compression is dominant. Radial folds usualy
plunge outward. In craters that result from highly oblique impacts folding is often more strongly concentrated uprange and downrange along the trajectory axis [15]. At Waqf as Suwwan it was observed that strata and fold axes are overturned downrange while they are in normal position in the uprange sector.

Discussion and Conclusion: Formation of central uplifts during the modification stage of impact cratering is the result of the inward and upward movement of rock towards the crater center and may result in a concentric strike of tilted uplifted bedrock and a radial symmetry of faults and folds. Tin Bider, Libya or the BP structure, Libya may be examples of such high angle impact craters, where a horizontal impact component does not play a role.

The preferred orientation of strata and faults is the result of shortening in the direction of the impact trajectory, and is statistically significant, as documented in [17-20]. With regard to experimental and numerical studies of oblique impact cratering, we infer that this lateral displacement component reflects a shift in the onset of crater collapse and the migration of the uplifting crater floor downrange, i.e. in the impact direction. The presented structural arrangements are regarded as tools to derive impact trajectories in eroded craters. The validation of the structural criteria by independent methods was possible in four craters. Target heterogeneities such as joint sets may weaken or even obliterate the structural signature of oblique impacts.

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