IMPACTOR TRACES ON A SHATTER CONE SURFACE FROM THE AGOUDAL IMPACT SITE, HIGH ATLAS MOUNTAINS, MOROCCO. M. Schmieder[1], H. Chennaoui Aoudjehane[2], E. Buchner[3,4], E. Tohver[5], [1]Philamlife Village, Cagayan de Oro, 9000 Philippines, martin@suevite.com, [2]Hassan II University Casablanca, Faculty of Sciences Ain Chock, GAIA Laboratory, BP 5366 Maârif 20000, Casablanca, Morocco, [3]HNU – Neu-Ulm University of Applied Sciences, Wileystrasse 1, 89231 Neu-Ulm, Germany, [4]Institut für Mineralogie und Kristallchemie, Universität Stuttgart, Azenbergstraße 18, 70174 Stuttgart, Germany, [5]University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Australia.

Introduction: The newly discovered Agoudal impact site (31°59'N, 5°31'W) ~3 km SW of the village of Agoudal in the High Atlas Mountains of Morocco [1] is the latest addition to the list of impact structures recognized on Earth. Well-developed auto- and allochthonous shatter cones in fine-grained lime- and marlstones (Fig. 1) provide evidence for an eroded small impact structure. The exact original crater size is unknown [1] but probably on the order of some hundreds of meters [2]. The age of the impact is stratigraphically bracketed by the Middle Jurassic shocked target rocks and Upper Pleistocene alluvial-fluvial sediments in which shatter cones occur as reworked clasts [1]. Estimates for the age of the Agoudal impact based on erosion rates are on the order of ~100 ka [1; 3].

Prior to the discovery of shatter cones, an iron meteorite with an estimated total known weight of more than 500 kg, classified as a IIAB iron and named 'Agoudal', was discovered in a ca. 6 x 2 km strewn field in the same area [4]. The meteorite contains abundant coarse-grained kamacite and schreibersite, as well as rhabdite (prismatic schreibersite) and troilite, and has an average Ni content of ~5.5 wt% [5–6]. It has been speculated whether the Agoudal iron meteorite was the projectile that created the Agoudal impact structure; however, a firm genetic link between the two phenomena is currently still missing [1–4].

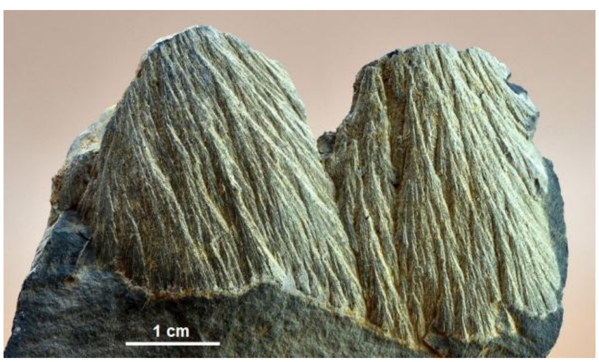

Fig. 1: Well-developed shatter cones in limestone from the Agoudal impact site. Image courtesy: Marco Frigerio.

Scanning Electron Microscopic Observations: A preliminary scanning electron microscopic (SEM–EDS) investigation of a randomly selected Agoudal shatter cone fragment was carried out in search of possible meteorite-derived contaminants. One limestone shatter cone specimen ~3 cm in length was carbon-coated and its convex side was studied using a VEGA3 TESCAN scanning electron microscope (SEM) equipped with an X-Max 50 silicon drift detector and energy-dispersive X-ray spectroscopy (EDS) system at the Centre for Microscopy & Characterisation (CMCA) at the University of Western Australia.

Petrographic SEM-EDS analysis revealed a number of exotic particles adherent to the shatter cone surface. A striking feature is the occurrence of schreibersite with its characteristic brittle fracturing pattern (e.g., [7]). Over an area of ~2 cm^2, three schreibersite aggregates ~10–20 µm in size were encountered. The schreibersite locally occurs together with with P- and Ca-rich Fe-oxides, and Bi-rich microparticles of uncertain origin. Brecciated and 'microtectonized' schreibersite aggregates are in places elongated in the direction of the shatter cone striation, locally at angles of up to 45° relative to the main cone striation (Fig. 2A).

In addition to schreibersite, several flakes of P- and Si-bearing Fe-Ni-oxides typically 10–20 µm across (Fig. 2B) were found. The platy mineral shape suggests that these oxide phases could be an impure (Ni-and P-rich) variety of hematite or maghemite. A smooth coating of 'glassy' appearance in SEM images marks the surface of the shatter cone and seems to serve as an adhesive for the exotic mineral grains. Locally, the shatter cone surface exhibits distinct grooves and striae. Spheroidal and rod-shaped microcrystalline iron oxide framboids may be primary constituents of the limestone.

EDS analysis of mineral fragments in two schreibersite aggregates yielded the following major element composition: Ni ~12–15 wt%, P ~10–17 wt%, and Fe ~60–71 wt%. The average atomic ratio (Fe+Ni)/P is ~3, consistent with the schreibersite formula $(Fe,Ni)_3P$. The analysis of Fe-Ni-oxides yielded Ni contents of ~1.5–7 wt%, at O concentrations of ~30 wt% and P concentrations of ~0.1–0.5 wt%.

Discussion and Conclusions: The Agoudal impact structure might be among the smallest known impact structures on Earth that have shatter cones, and is thus an interesting candidate for the study of the meteorite–

target rock interaction during shatter cone formation. With some rare exceptions in the terrestrial impact cratering record, most of the impacting projectile is vaporized during a larger impact event, and meteorite-derived elements are in many cases redistributed in impact melt lithologies; thus, impactor traces in terrestrial impact structures are usually investigated by means of geochemical analyses [8].

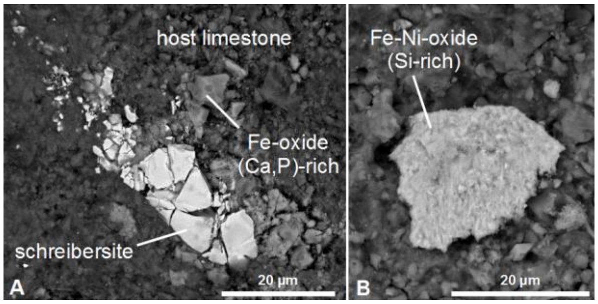

Fig. 2: Exotic minerals adherent to the shatter cone surface. **A**: Aggregate of brecciated and sheared schreibersite. **B**: Fe-Ni oxide flake. Backscattered electron images (15 kV).

The discovery of schreibersite represents the rare finding of primary impactor material preserved in direct association with terrestrial shatter cones. Only under strongly reducing conditions is schreibersite formed on Earth, e.g., in fulgurites [9] or in very rare crustal rocks that also contain native iron (e.g., [10]). In contrast, schreibersite is common in iron and stony-iron meteorites [11] but comparatively rare in stone meteorites, although schreibersite and/or its Ni analog, nickel-phosphide: $(Ni,Fe)_3P$, have been found in lunar rocks, enstatite chondrites, aubrites, and carbonaceous chondrites [12–14]. We, thus, propose that the Agoudal impact structure was most likely formed by the impact of an iron meteorite – possibly the Agoudal IIAB iron given its geographical position within the corresponding meteorite strewn field. The formation of Fe-Ni-oxides, with Ni and P concentrations that are consistent with those of the Agoudal IIAB iron meteorite and most other IIAB irons [5; 15], is best explained by terrestrial oxidation and alteration of kamacite particles, one of the main constituents of the Agoudal meteorite [5]. Similar Ni-rich Fe-oxides are also known from a number of other small terrestrial impact structures produced by iron meteorites [16–20].

Earlier SEM studies had revealed spherules and other melting features on shatter cones from the Sudbury, Canada [21] and Vredefort, South Africa [22] impact structures. The formation of spherules was suggested to be related to frictional melting after impact-induced fracturing of the target rock, i.e., the localized production of melts and vapors followed by condensation processes within the shocked host rock. The discovery of schreibersite and Fe-Ni-oxides on the Agoudal shatter cone surface seems to be in conflict with melting processes and requires a formation mechanism for shatter cones that allows for the rapid injection of solid, particulate meteorite matter into transient open fractures; this is compatible with the prevalent models [23; 24], suggesting shatter cones are rapidly produced tensile fractures. The brecciated and sheared texture of the schreibersite aggregates suggests the influence of rather mild shock metamorphism in combination with 'cataclastic' microdeformation after the closure of open shatter cone fractures.

The discovery of impactor matter associated with the shatter cones at Agoudal also poses the question whether similar exotic particles could occur on shatter cones from other similar-sized and larger terrestrial impact structures. For deeply eroded structures, where evidence for impact is restricted to the field occurrence of shatter cones, fresh shatter cone surfaces might hold valuable information towards the nature of the impacting body.

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