AGOUDAL (HIGH ATLAS MOUNTAINS): CONFIRMATION OF REMNANTS OF A POST MID-JURASSIC IMPACT STRUCTURE IN MOROCCO. H. Chennaoui Aoudjehane[1], W. U. Reimold[2,3], C. Koeberl[4], S. Bouley[5], M. Aoudjehane[6], M. Aboulahris[1,7], H. El Kerni[1,7], A. Hutzler[7], D. Bourles[7] , P. Rochette[7]. [1]Hassan II University Casablanca, Faculty of Sciences Ain Chock, GAIA Laboratory, BP 5366 Maârif 20000 Casablanca, Morocco. Email: chennaoui_h@yahoo.fr. [2]Museum für Naturkunde Berlin, Invalidenstrasse 43, 10115 Berlin, Germany. [3]Humboldt-Universität zu Berlin, Unter den Linden 6, 10099 Berlin, Germany. [4] Natural History Museum, Burgring 7, 1010 Vienna, Austria, and Department of Lithospheric Research, University of Vienna, Althanstrasse 14, 1090 Vienna, Austria. [5] IDES - Interactions et Dynamique des Environnementsde Surface Université Paris Sud - Bât. 509 - 91405 Orsay Cedex France. [6] 302 Boulevard Panoramique, 20150 Casablanca, Morocco. [7] CEREGE, CNRS Aix-Marseille University, BP80 13545 Aix en Provence, Cedex 4, France.

Introduction: In spring 2013, a Russian team searching for the Agoudal meteorite [1,2] found a large outcrop of marly limestone with shatter cones and breccia in the area of meteorite occurrence [3,4]. Since that time, shatter cones from this area have obtained much attention by scientists, dealers, and collectors. We carried out a field mission to the site in early October 2013 to investigate the exact shatter cone provenance and distribution, and to try to constrain their relevance for a likely Agoudal impact structure, as well as its possible relationship with the Agoudal iron meteorite fall, which was suggested by Sadilenko et al. [3] and Lorenz et al, [4].

Geology of the site: Agoudal is located in the High Atlas Mountains in Morocco, about 20 km to the southeast of the town of Imilchil, and about 25 km southeast of lakes Isli and Tislit. A previous claim that these lakes represented two impact structures had been refuted by Chaabout et al. [5] .

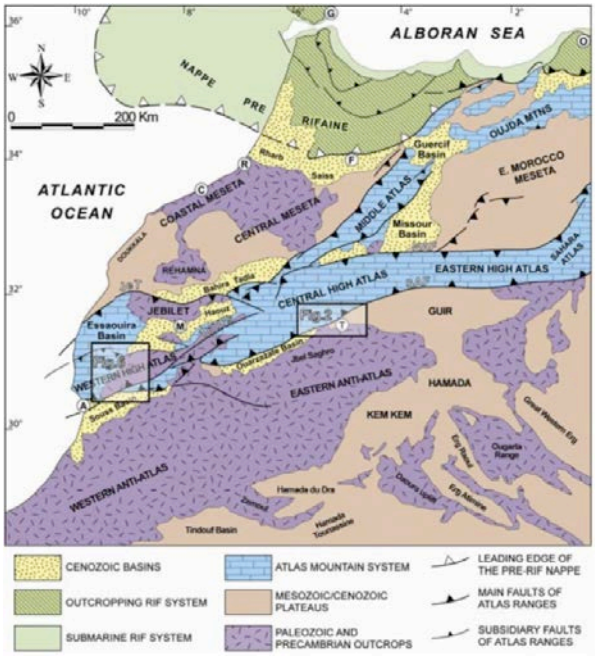

Fig. 1. Schematic structural map of the northern part of Morocco [7]. SAF: South Atlas Fault; NAF: North Atlas Front; TnTFs: Tizi n'Test Fault system; JeT: Jebilet Thrust; A: Agadir; C: Casablanca; F: Fes; G: Gibraltar; M: Marrakech; O: Oujda; R: Rabat; T: Tinerhir.

The shatter cones are found in the Binelouidane Marly Limestone Formation that was deposited during the Bajocian period (Middle Dogger). The location is in the central part of a highly eroded syncline trapped between the Amagmag and Ikerzi northeast-southwest trending anticlines, to the South of the Principal High Atlas Fault [6,7] (Fig. 1). Very close to the shatter cones, breccias have been found, some of which incorporate shatter cone fragments.

Agoudal meteorite: Agoudal is the most recently approved iron meteorite from Morocco [1]; it has been classified as a IIAB iron. Hundreds of small pieces (1-100 g), many of 100-1000 g mass, and a few pieces >1 kg, have been recovered. The majority of the material occurs as 2-5 cm-sized, irregularly-shaped shrapnel pieces. Most fragments have a thin weathering rind. Some smaller bullet-shaped (~cm-sized) fragments are rounded, showing apparently possible well-developed fusion crust (Fig. 2).

Fig. 2. Two Agoudal II AB iron meteorite slide and etched pieces, showing a possible fusion crust and a heated rims. Photos courtesy Mirko Graul.

Initially, the total mass was estimated at more than 100 kg, but because many large fragments have been recovered (e.g., 196 kg, 78 kg, 31 kg, 23 kg, 17 kg, 12 kg, 7.8 kg, 5.7 kg), the total mass was revised to > 500 kg. Small fragments are found between 5 and 10 cm depth and large pieces between 40 and 90 cm depth. The extent of the estimated strewn field is about 4x1 km, trending approximately E-W.

Distribution of meteorites and shatter cones: Shatter cones have been located in situ in a limited area of some 500x500 m in the eastern part of the meteorite strewn field, where a number of small outcrops of generally < 1x1 m extent was detected within a mostly gravel-debris covered terrain. Floats of small, generally <4–cm-sized shatter cone fragments occur scattered over a much larger area of ca. 1x1 km extent. No meteorites have been found directly in the shatter cone area but have been collected in the surroundings. All larger meteorite pieces were collected at least 500 m from the shatter cone discovery site (Fig. 3).
No circular structure is evident from remote sensing or field observations around the shatter cone location; no upturned strata that might be related to a rim segment of an impact structure have been noted. This indicates that the original crater structure has been eroded, the only remaining remnants being shatter cones that were previously in the floor of the original impact structure.

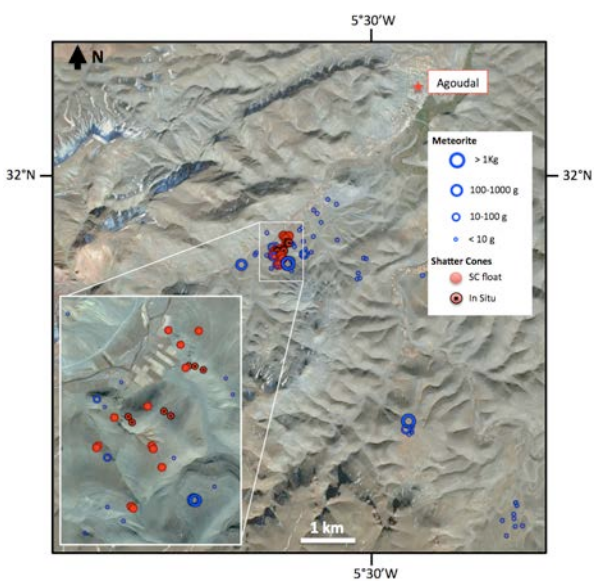

Fig. 3. Locations of finds of shatter cones and Agoudal meteorite specimens of this area.

Shatter cones and breccia:
The shatter cones occur in marly limestone from the Middle Jurassic (Upper Bajocian). The breccias found in the shatter cone area represent carbonaceous shale with slightly magnesian calcite and relatively low but somewhat variable amounts of quartz microclasts, besides some potassic phyllosilicate (montmorillonite, illite) and traces of Fe-oxide. There are two generations of carbonates: the carbonate groundmass of the breccia that cements the shale fragments and some carbonate clasts, some of which contain shatter cones. The clast population did not yield any evidence for significant deformation – in particular shock deformation was completely absent. It is thought that this breccia represents a secondary deposit akin to calcrete.

Dating the Agoudal meteorite: Preliminary results of cosmogenic nuclides measured at ASTER (CEREGE, Aix en Provence) with two different small size samples indicate a low content of ^{36}Cl, from 0.1 to 0.6 dpm/kg, indicative of a large impactor and/or an old terrestrial age. Such low values are found in, e.g., Campo del Cielo and Cape York, while Gebel Kamil (ASTER data: 1.7 to 6 dpm/kg) or Canon Diablo give nearly an order of magnitude higher values. Ongoing measurements of other cosmonuclides will help constrain the depth versus terrestrial age and exposure history model.

Discussion: The Agoudal shatter cone occurrence provides unambiguous evidence for an impact event in Morocco. The fact that no impact structure is preserved anymore implies that the age of the impact is high. The first cosmogenic nuclide results indicate that the meteorite could have a relatively old terrestrial age. However, compared to the relative apparent freshness of the meteorites found on or near surface, this does not yet resolve whether there could be a genetic relationship between the meteorite strewnfield and the shatter cone occurrence. In the field, we did not observe any evidence supporting such a relationship.

References: [1] Chennaoui Aoudjehane H. et al. (2013) *Meteoritics & Planet. Sci., 48,* #5025. [2] Garvie L. et al. (2013), The Meteoritical Bulletin N°102, *Meteoritics & Planet. Sci.,47.* [3] Sadilenko D. A. et al. (2013) *Meteoritics & Planet. Sci., 48,* #5215. [4] Lorenz C. A. et al. (2014) submitted to *Meteoritics & Planet. Sci.,* [5] Chaabout S. et al. (2013) *Meteoritics & Planet. Sci., 48,* #3074. [6] Michard A. et al. (2011) *Terra Nova*, 23, 314–323. Ellero A. et al. (2012) "Tectonics - Recent Advances", ISBN 978-953-51-0675-3.