KESS KESS carbonate mounds, Hamar Laghdad, Anti-Atlas, SE Morocco – A FIELD GUIDE

01-05 December 2006

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This field guide was prepare for the UNESCO Field Action - Morocco 2006 for an excursion conducted in Hamar Laghdad, Eastern Anti-Atlas, Morocco on 01-05 Dicember 2006

Cover image by B. Cavalazzi

Outcrop image of the Devonian mounds in the central area of Hamar Laghdad Ridge (31° 23' N, 4° 4' W), eastern Anti-Atlas, Morocco

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CONTENTS

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1. *Carbonate mounds, Hydrothermal Vent and hydrocarbon (cold) seep systems* - AN INTRODUCTION

CARBONATE MUD MOUNDS span from Proterozoic to Recent times, in shallow- and deep-water settings, and are an Earth's history expression of microbial life (Riding, 2002). Carbonate mounds occur as localized clusters with different size and shape and show typical features such as stromatactis and zebra cavity structures, fenestral fabrics, fractures, and veins in which some microbial mediation can take place during construction and early lithification of the mounds (Monty et al., 1995). Common features in Paleozoic ramps and steep platform-basin slope settings (Monty et al., 1995), the carbonate mounds are poorly known in modern environments, especially in deep-water conditions (Henriet et al., 2001). The origin of carbonate mud-mounds has long been debated and the discovery from different geotectonic settings of seep- and vent-related ecosystems, associated to authigenic carbonate deposits and mounds, has allowed the re-interpretation of some of them as the product of chemosynthetic microbial mediation fueled by fluid fluxes (Campbell, 2006). Few seep carbonate deposits, however, are known to form large mounds or fields of conical/pinnacle-shaped structures, and some models explain the upward growth (following the fluid flow direction) of these seep buildups (Teichert et al., 2005).

Seafloor HYDROTHERMAL VENTS and HYDROCARBON COLD SEEPS were first discovered more than two decades ago (Lonsdale, 1977; Paull et al., 1984). Since then exploration of the deep-sea has revealed numerous modern vent-seep sites in different geo-settings from the tropics to the poles (for review see Campbell, 2006) (fig. 1). One of the main features of vent-seep sites is that their hydrothermal-/hydrocarbon-rich fluids directly support exceptionally productive biological communities, especially metazoans and microbes, in the deep sea (fig. 2). Hydrothermal vent deposits include the igneous rocks and massive sulfide deposits, whereas hydrocarbon seep deposits are characterized by authigenic carbonates with ^{13}C-depleted values, commonly cementing shelled biota (fig. 2).

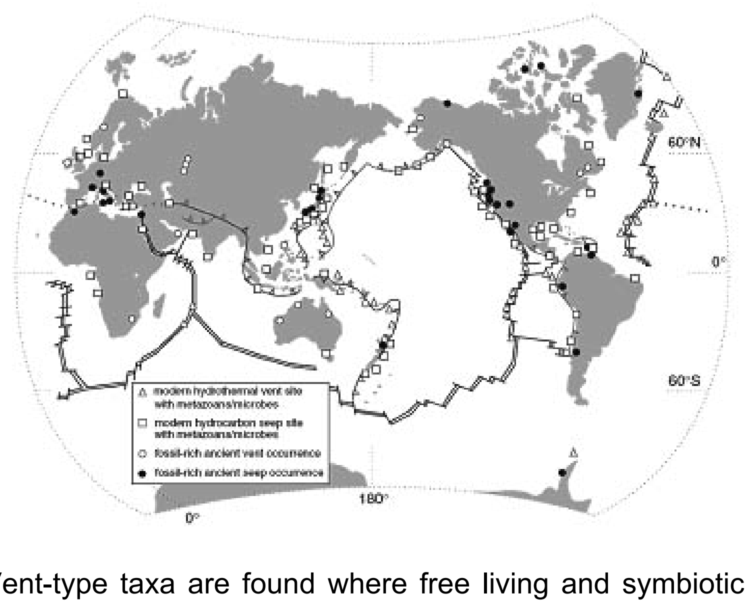

Fig. 1. Distribution map of chemosynthesis-based settings, illustrating those Archean to Recent hydrothermal vents and hydrocarbon seeps with associated metazoan and/or microbial signatures. From Campbell (2006).

Vent-type taxa are found where free living and symbiotic prokaryotes oxidize the methane and/or sulfide-rich fluids of vents and seeps to produce biomass utilized by mega-invertebrates, many of which are chemosymbiotic (Van Dover et al., 2002).

Recent developments in modern vent-seep research have outlined:
- the importance of sulfate-dependent, anaerobic oxidation of methane (AOM) in authigenic carbonate formation
- the significant role of microorganisms in global biogeochemical process
- the relationship between periodic, catastrophic release of methane stored in gas hydrates, and their implication in the global climate change. Today, the release of hydrothermal vents and hydrocarbon seeps are included in the climate models
- the ocean floor instability
- astrobiological implications
- and more (see Henriet & Mienert, 1988; Zhang & Lanoil, 2004; Campbell, 2006).

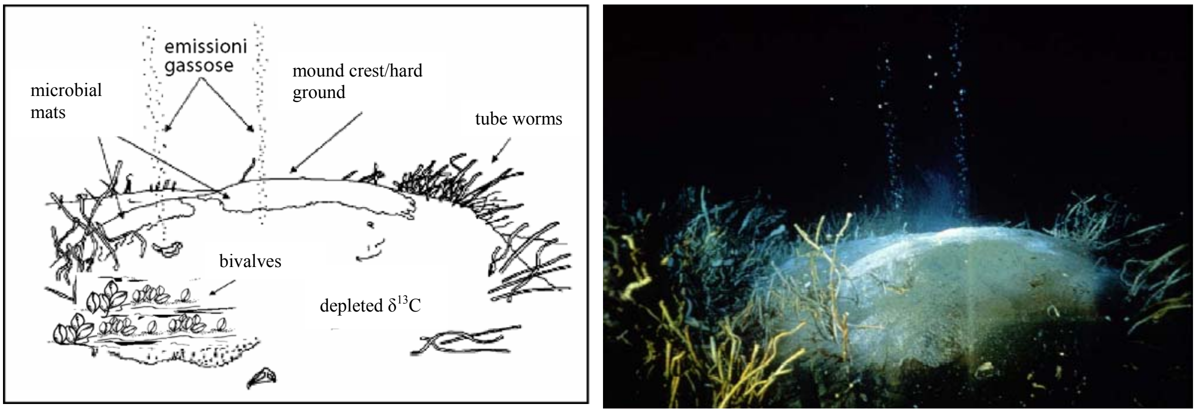

Fig 2. Features of a typical gas hydrate mound (diameter of mound: ~2 m) at Bush Hill with gas vents and associated chemosynthetic community. Modified from Sassen et al., 2004. Photograph by I.R. MacDonald.

Intensive studies of vent-seep deposits from Early Archean to Pleistocene age in different settings, show that they are characterized by metazoan and/or microbial fabrics (Campbell, 2006). Microbes were the dominant organisms in the oldest purported hydrothermal and hydrocarbon deposits, such as from Archaen Pilbara craton deposit, Australia (Rasmussen, 2000), and Silurian El Borj deposit, Morocco, which is the oldest known seep carbonate accumulation (Barbieri et al., 2004). The existence of this vast, partially unexplored microbial biosphere might have a high potential in an astrobiological perspective (Shapiro, 2004; Barbieri & Cavalazzi, submitted).

The characteristic and evolution of recent and fossil vent-seep settings are well defined, as well as the criteria for their recognition in the geologic record. The evolution and (paleo)biogeography of vent-seep biota through time have also been evaluated (Little & Vrijenhoek, 2003). Some controversy, however, surrounds some A number of deposits interpreted to be formed in vent-seep paleoenvironments in the geologic record are still debated. The hydrothermal origin of the Early Devonian Kess Kess mounds, is disputed owing to different interpretation of the measured low $\delta^{18}O$ values (hydrothermal carbonates versus meteoric alteration; Bełka, 1998; Mounji et al., 1998; Joachimski et al., 1999).

2. EXCURSION LOCALITIES

Large carbonate mounds, informally called *Kess-Kess*, are exposed in the Hamar Laghdad Ridge, Tafilalt region, eastern Anti-Atlas, SE Morocco (Plates 1-3). Compared to other recent and fossil carbonate mound occurrences, these Early Devonian mounds are unique and since the study by Meckinkof (in Roch, 1934) their origin and growth are disputed (Massa et al., 1965; Brachert et al., 1992; Bełka, 1998; Mounji et al., 1998; Joachimski et al., 1999;

Peckmann et al., 1999, 2005; Aitken et al., 2002) (Fig. 3). Whereas the Early Devonian mounds have been controversially related to submarine hydrothermal vents (Bełka, 1998; Mounji et al., 1998, 1999; Joachimski & Buggish, 1999) (Plate 6), for the Middle Devonian mound, known as Hollard Mound (Walliser, 1991), located in the eastern part of Hamar Laghdad Ridge (Plates 2, 7), an origin by hydrocarbon seepage has been proposed (Peckmann et al., 1999).
Despite the detailed studies of the *Kess Kess* mounds (Plates 4, 5), several aspects of their setting, composition and geometry are still poorly understood. Due to negligible tectonic complications and the lack of vegetation, a spectacular ancient underwater scenary of mud mounds and associated deposits is exposed in the eastern Anti-Atlas (Plate 7).

Different interpretartions	Authors
reefs; coral reef; reef formation; reef mound; pinnacle reef; bioherm; mud mound	Mekinkoff (in Roch), 1934; Termier e Termier, 1950, 1980; Choubert et al., 1952; Le Maitre, 1952, 1956; Pareyn, 1962; Hollard, 1963, 1967, 1968, 1974a, 1974b, 1981; Massa, 1965; Rabate, 1968; Alberti, 1981; Gendrot, 1973; Michard, 1976; Bultinck and Hollard, 1980; Flajs et al., 1981; Wend et al., 1984; Potthast e Oekentorp, 1987; Töneböhn, 1991; Turneur, 1991; Wallisser, 1991; Brachert et al., 1992; Hüsser, 1994; Kaufmann, 1995, 1997, 1998; Montenat et al., 1996; Hilali et al., 1998
hydrothermal/hydrocarbon venting	Belka, 1998; Mounji et al., 1998; Peckmann et al., 1999, 2005; Aitken et al., 2002; Belka et al., 2003; Berkowski, 2004; Belka and Berkowski, 2005; Berkowski, 2006; Cavalazzi and Barbieri, 2006; Cavalazzi, in press; Cavalazzi et al., submitted

Fig 3. Most important papers on questioned origin of Devonian *kess kess* mounds, Hamar Laghdad Ridge, Morocco.

2.1 Regional Geology

The eastern Anti-Atlas of Morocco (Plate 1) consists of a Precambrian crystalline basement and a thick deformed deposit (upper Precambrian-Namurian), which are covered to the north, east, and south by undeformed Cretaceous and Tertiary sedimentary rocks. The Palaeozoic sediments have been deposited on a epicontinental shelf at the northern rim of the West African Craton. The Lower to Middle Cambrian succession of the eastern Anti-Atlas mostly consists of sandstones with intercalations of conglomerates, shales, and volcanic rocks (Destombes et al., 1985). Upper Cambrian deposits were not found so far. Ordovician strata are dominated by argillaceous rocks, which alternate with several hundred metres thick sandstones. The transgression, related to Early Silurian deglaciation, induced graptolitic shales sedimentation. In the upper Silurian two prominent marker horizons, the *Orthoceras* limestone and *Scyphocrinites* limestone, were deposited (Destombes et al., 1985), which mark the onset of carbonate sedimentation in the Palaeozoic succession of the eastern Anti-Atlas.
Deposits of Early Devonian age show a more or less homogeneous facies distribution in the eastern Anti-Atlas. The shale deposits are dominant in the Lochkovian, whereas limestones and marls predominate in the Pragian and Emsian (Hollard, 1981). Thickness of Emsian deposits ranges from 50 m to about 200 m (Kaufmann, 1997). Uniform facies patterns make up the Lower Emsian limestones, and consist of massive to nodular carbonates, with abundant nautiloids and tentaculitids, interrupted by a thick shale interval. This association can be found throughout the eastern Anti-Atlas and may therefore serve as a marker horizon. In the Middle and Late Devonian carbonate deposition was predominant.
A differential subsidence, probably related to early Variscan block faulting, generated a platform and basin topography, with lateral changes in thickness and facies pattern (Wendt, 1984), evolving in four domains established in the eastern Anti-Atlas (from W to E): the Mader Platform, Mader Basin, Tafilalt Platform, and Tafilalt Basin (Plate 1). Depending on the paleogeographical position, the Middle Devonian deposits are composed of biostromal shallow water float- and boundstones, shales and mudstones as basin fills, and condensed cephalopod-rich nodular limestones on pelagic ridges. According to Scotese (2002), the palaeolatitude of northwest Africa shifted during the Devonian from 50° S to 30° S, but the drift history of Gondwana is still a matter of debate. Carbonate production in the Anti-Atlas

ceased in the upper Famennian. In the southern Tafilalt, the Lower Carboniferous consists of silt- and sandstones. The transition of this shallow-water sequence into slope and basinal settings is possibly located in the northern Tafilalt region, as indicated by debris flow and turbidite deposits (Wendt et al., 1984). Major Variscan deformation occurred during the Late Carboniferous in the eastern Anti-Atlas. Deformation was rather mild, since this region belongs to the stable cratonic domain, which represents the southern limit of the Variscan chains (Piqué et al., 1993).
Palaeozoic strata are weakly folded, but no metamorphism occurred. Flat lying Cretaceous and Tertiary sediments of the Hamada du Guir cap Palaeozoic sediments unconformably.

2.2 Hamar Laghdad's carbonate mounds

The *Kess Kess* mounds are exposed in the Hamar Laghdad Ridge, a small mountain range about 18 km southeast of Erfoud in the Tafilalt region, eastern Anti-Atlas, Morocco (Plates 1, 2, 3).
The predominantly carbonate Devonian succession exposed in the eastern Anti-Atlas was deposited in a wide continental shelf of the NE Gondwana margin. Its depositional history reflects the tectonic evolution of the northward drifting of Gondwana margin, which originated the Tafilalt and Ma'der platform-basin systems.
In the lowest Devonian Early Devonian (middle to late Lochkovian), a submarine eruption produced the topographic high of the Hamar Laghdad Ridge (Belka, 1998). Volcanoclastic (mostly pyroclastic) deposits, derived from calcalkaline basalt (Belka, 1998; Mounji et al., 1998), were subsequently buried by a thick interval (more of 140 m) of crinoidal limestone (Pragian and Early Emsian age), the Kess-Kess Formation (Brachert et al., 1992) (Plate 7). Most of the *Kess Kess* mounds represent the topmost part of this formation, and are Lower Devonian in age (Brachert et al., 1992) (Plate 7). These mounds probably developed in aphotic environment (Belka, 1998) from relatively shallow water conditions (Massa et al., 1965; Brachert et al., 1992). During the Middle Devonian, the continental shelf was differentiated into fault-bounded platform-basin systems, and the Hamar Laghdad deposits of the Tafilalt area were completely buried by Middle Devonian shales, nodular limestones and marls (Belka, 1998; Aitken et al., 2002) (Plates 4, 7).

The circular to sub-elliptical exposed base of the any *kess kess* mound ranges from few meters to about 100 m in diameter. Their elevation does not exceed 55 meters and averages 20-30 meters with generally steep (20° to 65°) asymmetrical flanks (Plate 7). Erosion does not seem to have overprinted the original morphology of the mounds, rather, the complete removal of the surrounding intermound facies and the overlying deposits seem to have emphasized their original conical shape. The mounds locally exhibit a crude stratification.
The Middle Devonian Hollard Mound, located in the eastern margin of the Hamar Laghdad Ridge (south of *Kess Kess* mound no. 45 in Brachert et al., 1992) (Plates 2, 3), is the largest one. Conodont biostratigraphy indicates that the Hollard Mound started to develop in the earliest Eifelian (Brachert et al., 1992; Peckmann et al., 1999, Aitken et al., 2002) (Plates 4, 5).
Comprehensive biostratigraphical, sedimentological, and paleontological studies of the *Kess Kess* mounds have been performed by Gendrot (1975), Alberti (1981), Brachert at al. (1992), Peckmann et al. (1999, 2005), Aitken et al. (2002).

Carbonate mound deposits are poorly differentiated and mostly consist of microsparitic limestone with skeletal components and local concentrations of monospecific megafaunal remains (Plate 6) (for faunal inventory see Brachert et al., 1992; Peckmann et al., 1999, 2005; Aitken et al., 2002; Bełka and Berkowski, 2005). A large number of veins cut the *kess kess* mound and intermound deposits, as well as the underlying crinoidal limestones. In the Hollard Mound, the core facies consists of prevailing fine fossiliferous micrite densely crosscut by veins.

An important feature of the Hamar Laghdad mounds and intermound deposits is the complex system of sediment-filled veins and fissures (Plate 5), referred in the literature to as *neptunian dykes*. Most of these veins are filled by marine carbonates having the same age, or younger age, of their host rocks. Most of veins follow the orientation of tangential and radial faults (Brachert, 1986; Belka, 1998), and also indicate several re-fracturing events. Generally, the veins have black-grey and yellowish-red laminated infill mostly consisting of microcrystalline calcium carbonate. These laminated deposits have negative carbon and oxygen stable isotope values (as -19.5‰ PDB). The vein deposits contain bio-sedimentary fabrics related to microbial activities, multiple paragenetic and diagenetic phases of submarine carbonate cements, and bioclasts (Cavalazzi & Barbieri, 2006; Cavalazzi in press; Cavalazzi et al., submitted).

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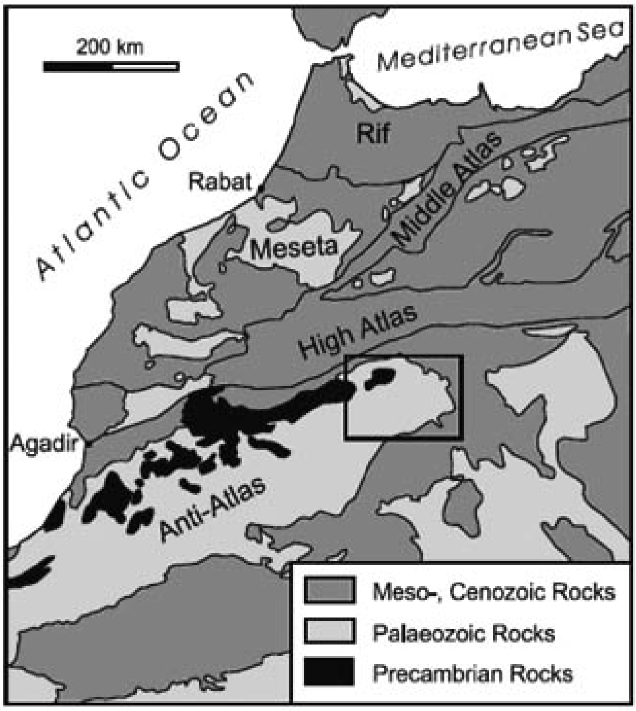
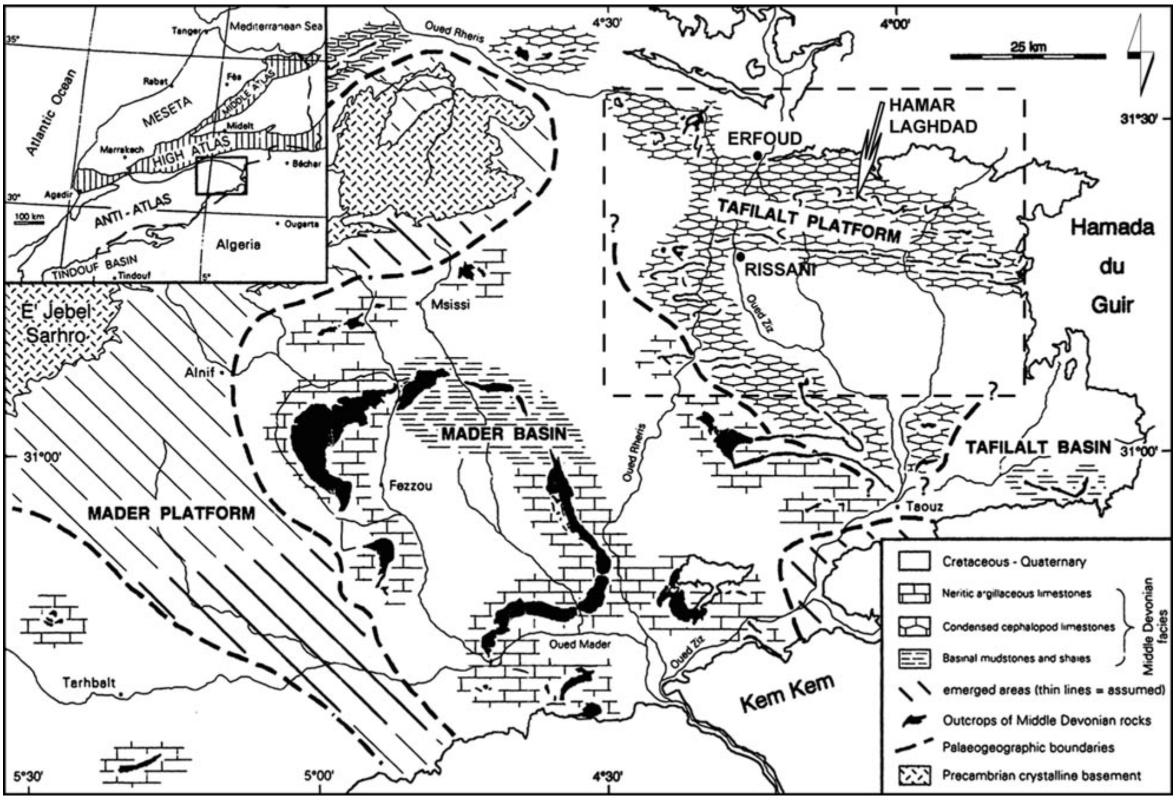
4. PLATE 1 – Simplified geological map of NW-Africa and eastern Anti-Atlas

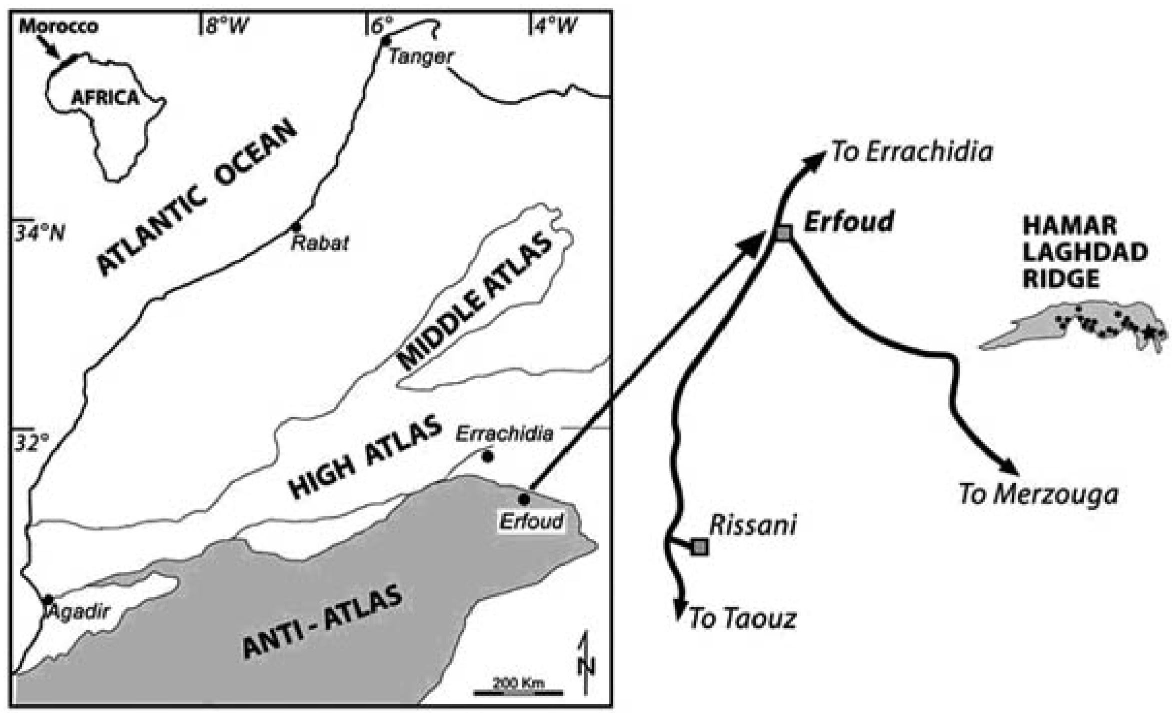


Simplified geological map of NW-Africa. After Piqué & Michard (1989). Boxed area detailed in the next picture.

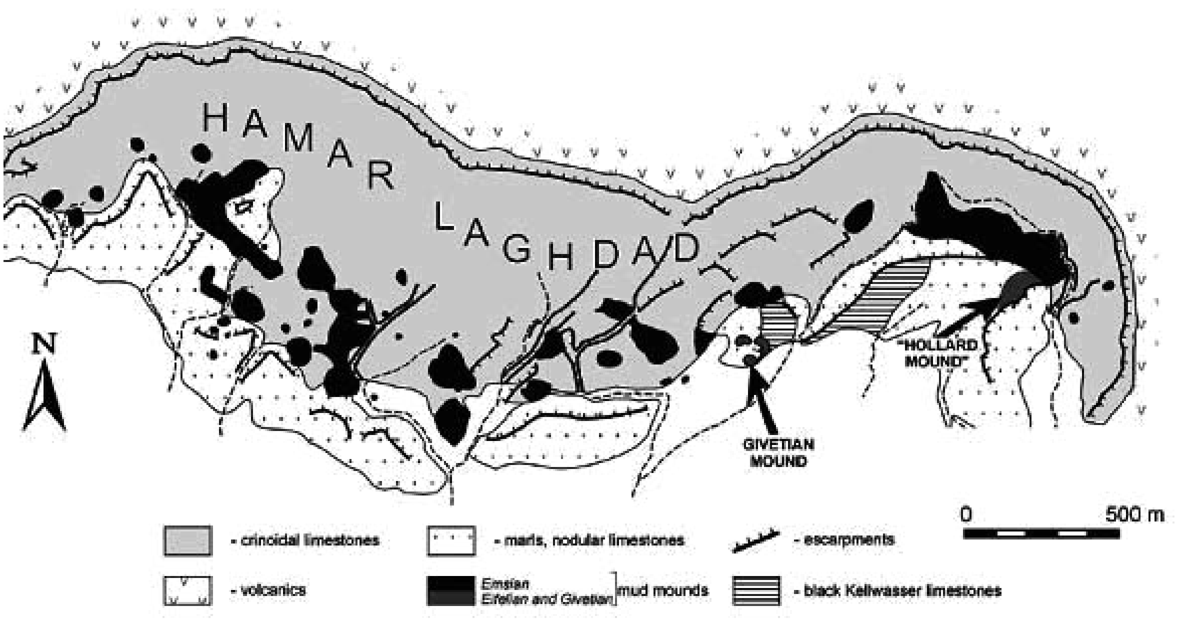


Simplified geological map of the eastern Anti-Atlas showing the Middle Devonian palaeogeographic units of the Tafilalt Region. Boxed area shown in detail in Plate 2. Modified after Kaufmann, 1988.

4. PLATE 2 – Location and geological maps of kess kess mounds, Hamar Laghdad Ridge

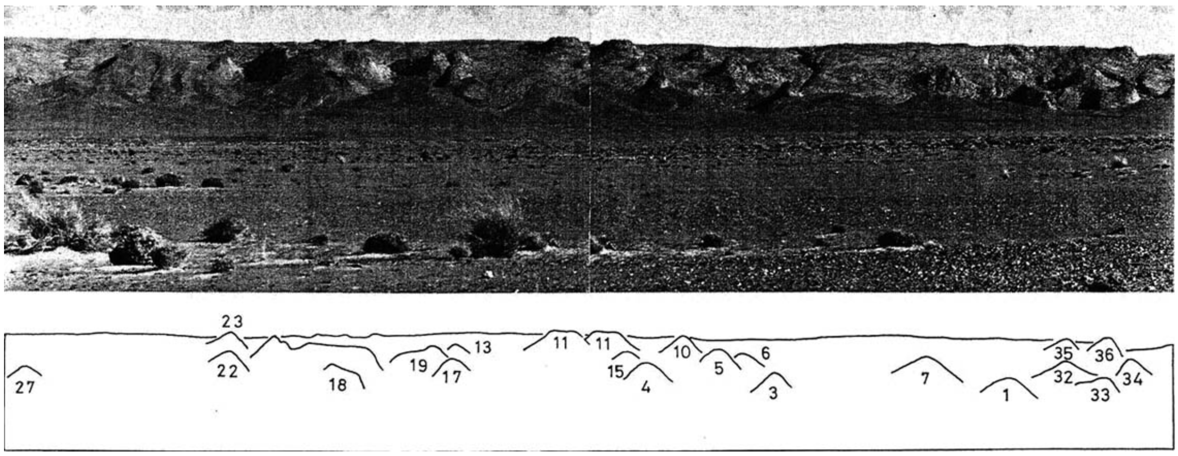


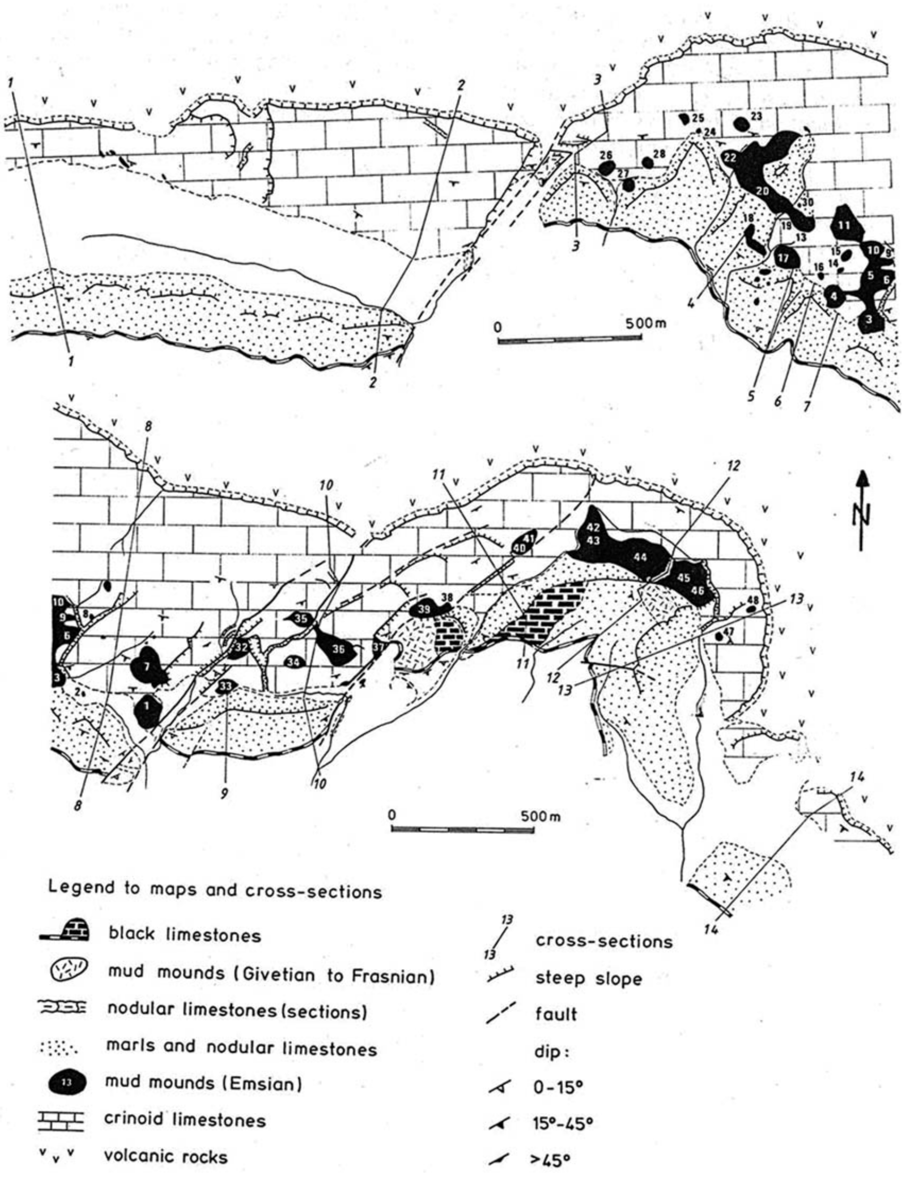
Location map of the Hamar Laghdad Ridge, eastern Anti-Atlas, Morocco, showing excursion locality. Hamar Laghdad Ridge is located 18 km ESE Erfoud (details on the right of the map are not in scale). The carbonate mounds (dots) are concentrated in the central and eastern portion of the Hamar Laghdad Ridge. The Hollard Mound (star) outcrops in eastern part of the ridge. From Cavalazzi et al. (submitted).



Detailed geological map of the Hamar Laghdad Ridge, showing distribution of Devonian rocks. Early (Emsian) and Middle (Givetian) Devonian mounds, including Hollard Mound. From Belka (1998).

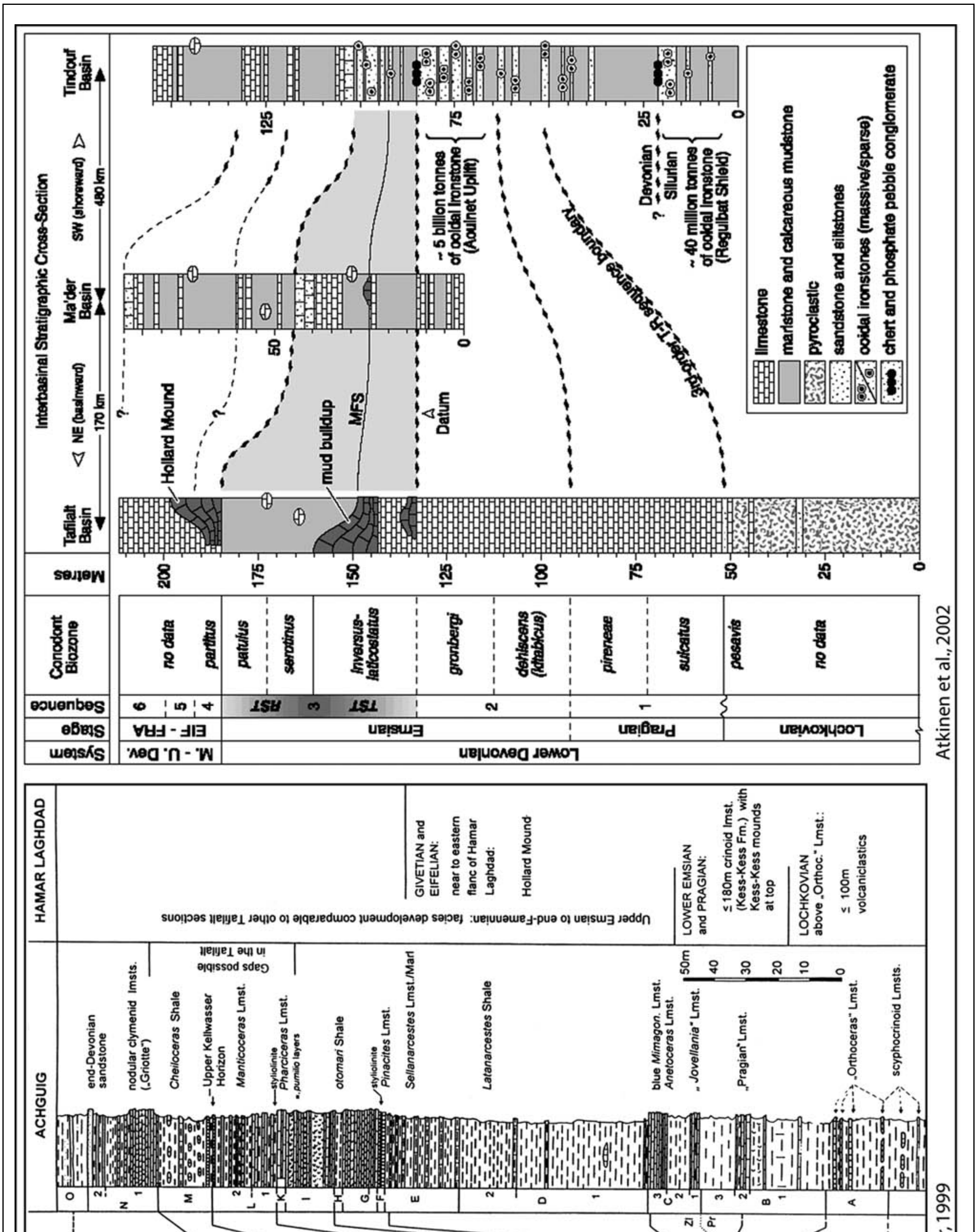
4. PLATE 3 – Simplified geological map of Hamar Laghdad Ridge with an inventory of mounds



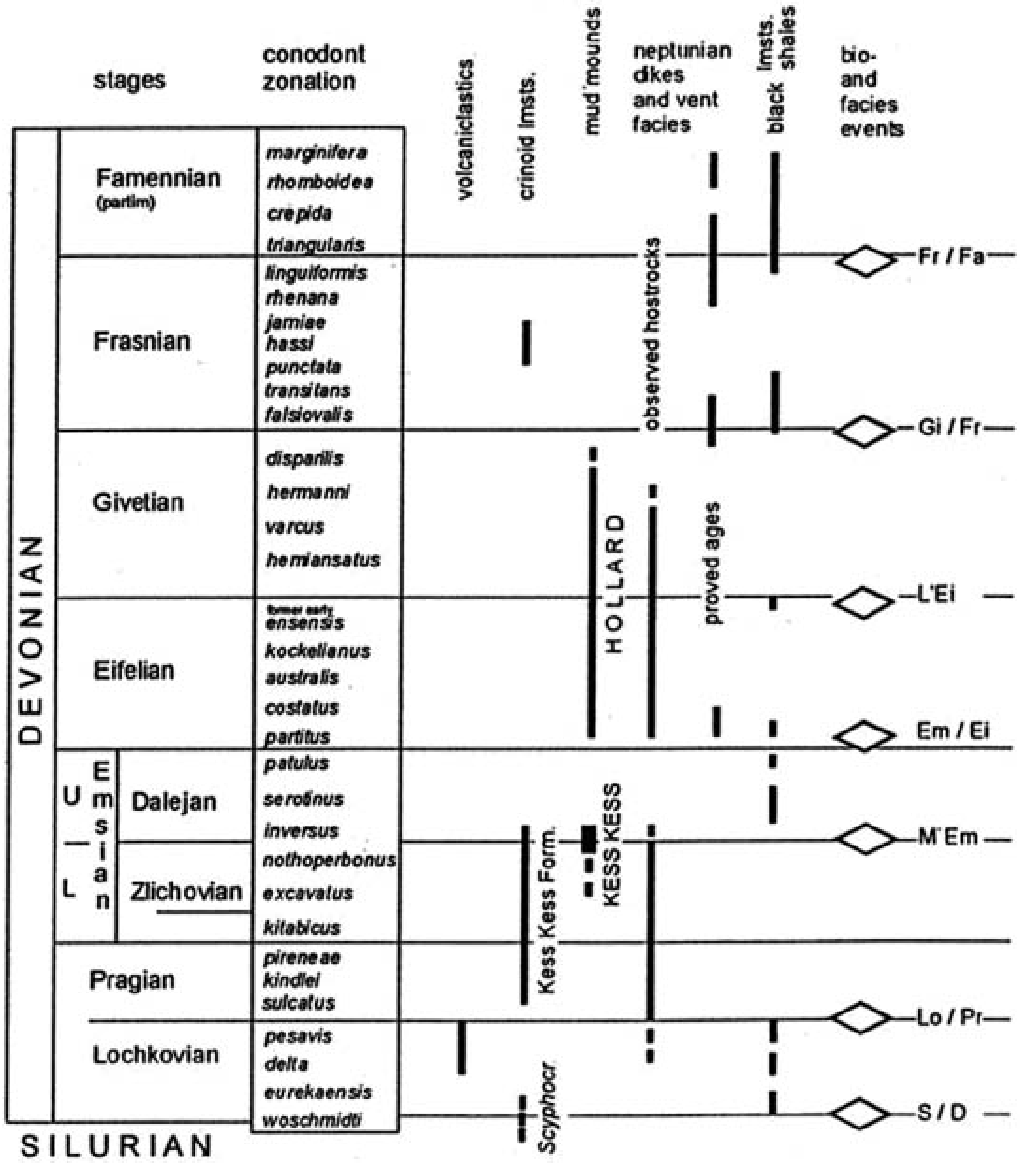


from Brachert et al., 1992

4. PLATE 4 – Correlation of the conodont zonation and the stratigraphic units of the Hamar Laghdad area

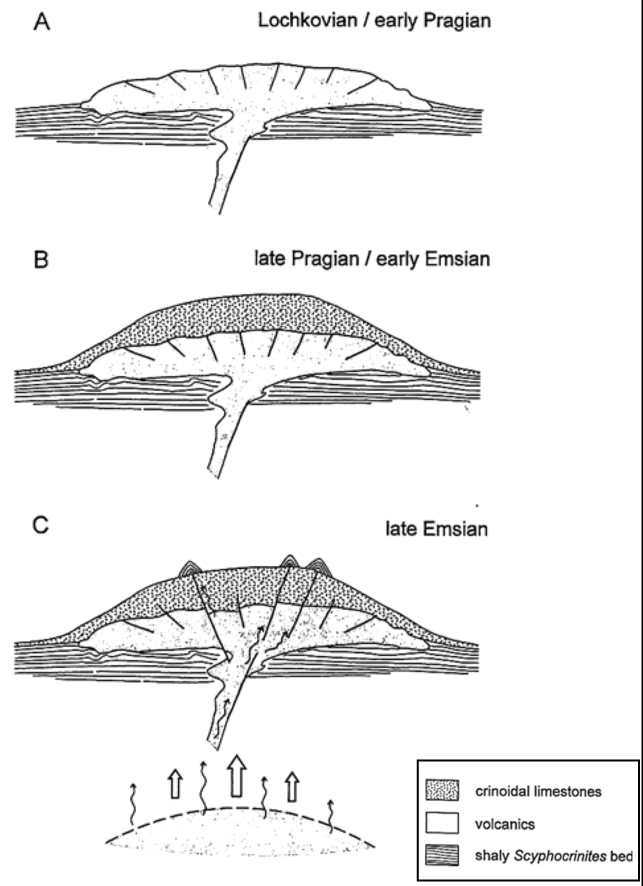


4. PLATE 5 – Stratigraphic distribution of different facies in the Hamar Laghdad area



from Peckmann et al., 1999

4. PLATE 6 – Models of kess kess mound's formation related to hydrothermal venting

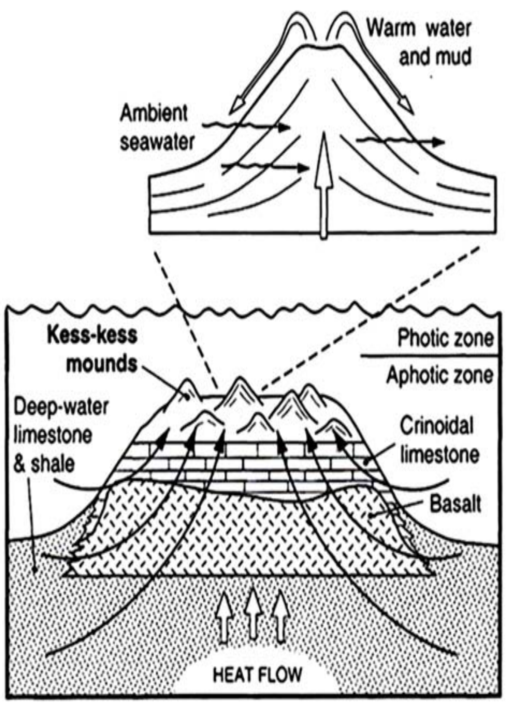


Early Devonian Kess-Kess carbonate mud mounds of the eastern Anti-Atlas (Morocco), and their relation to submarine hydrothermal venting

Z. Belka

ABSTRACT
Spectacular conical Early Devonian carbonate buildups up to 55 m high that crop out in the eastern Anti-Atlas of southern Morocco are microbially mediated carbonate mud mounds that were surfaced by soft-bottom communities dominated by small tabulate corals. They developed on the Hamar Laghdad elevation, which was created by a submarine volcanic activity, and were associated with a network of synsedimentary radial and tangential faults that originated by uplift of the intrusive laccolithic body underlying the Kess-Kess Formation. These faults served as conduits for the migration of hydrothermal fluids to the sea floor. Most mounds developed over cross-points of radial and tangential faults. Vents were episodically active until the Famennian, however extensive vent carbonate production occurred only during the Emsian. Preliminary geochemical results document that mud-mound carbonates and calcite cements in neptunian dikes precipitated from brines comprising a mixture of hydrothermal fluids and seawater. In addition, carbon isotope compositions (delta ^{13} C as low as -18 per mil PDB) suggest a contribution from thermogenic methane presumably derived from underlying basaltic intrusives. Aerobic bacterial oxidation of methane is likely the main process driving carbonate precipitation and rapid lithification of the mounds.

Journal of Sedimentary Research 68 (1998), 368-377



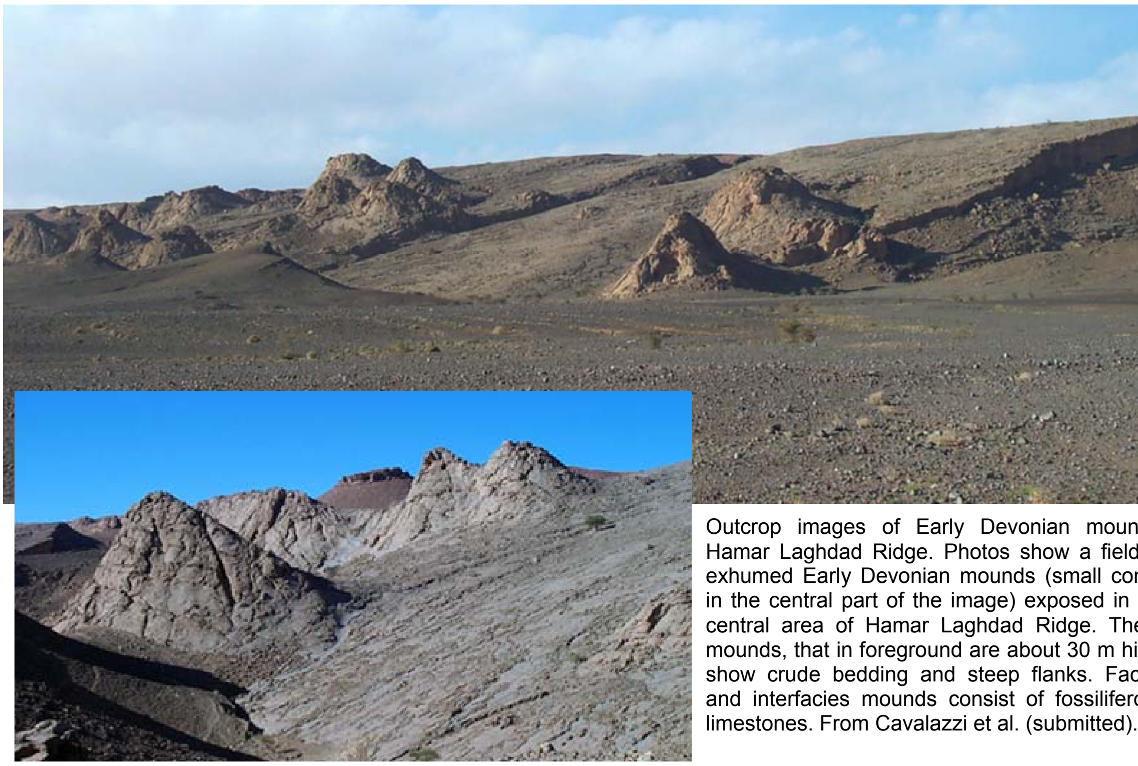
Hydrothermal origin of Devonian conical mounds (kess-kess) of Hamar Lakhdad Ridge, Anti-Atlas, Morocco

D. Mounji, P.A. Bourque, M.M. Savard

ABSTRACT
Various interpretations have been proposed for the origin of these cone-shaped, finely crystalline, Devonian carbonate mounds, ranging from shallow-water reefs to deep-water mud mounds, formed by biogenic and/or hydrodynamic processes. This study is the first integrated sedimentological and geochemical analysis of these structures. The mounds are cone shaped, steep sided, circular to subelliptical in plan view, and exhibit internal crude bedding parallel to the mound's outer surface. They occur in a cluster of 48 mounds on top of a volcanic massif. Stable isotope analyses of first-stage isopachous nonluminescent cement have yielded marine values. In contrast, the finely crystalline carbonate that makes up the bulk of the mound and the internally sedimented mud between crusts of early marine cements have significantly lower delta ^{18} O values, whereas values of delta ^{13}C are similar to those of the early marine cement. Strontium isotope ratios also clearly distinguish the nonluminescent early marine cements from the finely crystalline material. The ^{87}Sr/ ^{86}Sr values for the former (0.707 934-0.709 392) are in or near the Devonian marine range, whereas the ratios for the latter (0.708 515-0.709 656) indicate a more radiogenic Sr source. On the basis of their lithology, architecture, isotope geochemistry, and clustered occurrence on top of a volcanic pile, we propose that the finely crystalline material that forms the mounds and the intermound beds was precipitated from hydrothermal fluids, and that accretion of the material was driven by hydrothermal venting.

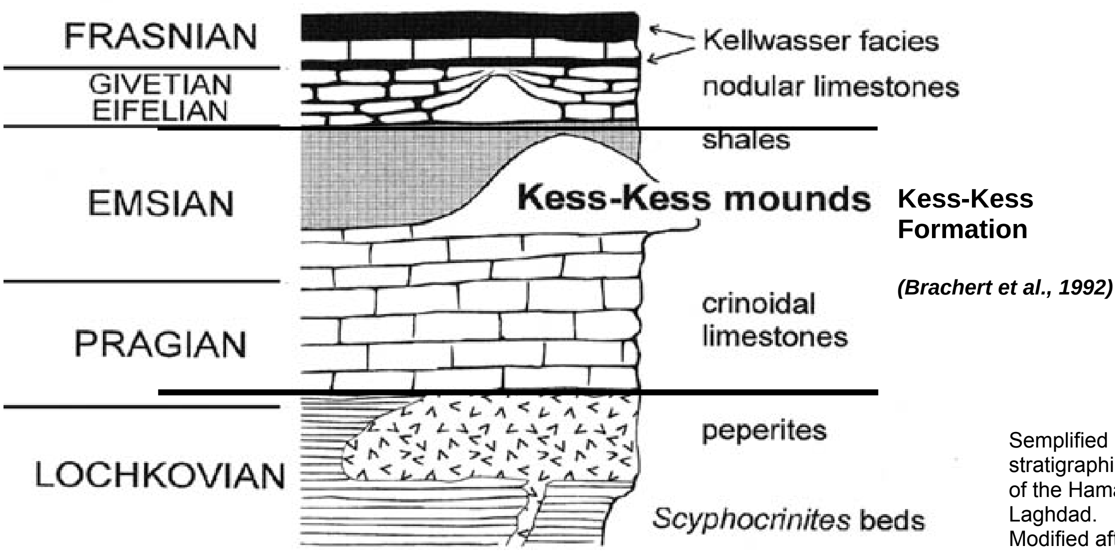
Geology 26 (1998), 1123-1126

4. PLATE 7 – Outcrops and stratigraphic log of kess kess mounds



Outcrop images of Early Devonian mounds, Hamar Laghdad Ridge. Photos show a field of exhumed Early Devonian mounds (small cones in the central part of the image) exposed in the central area of Hamar Laghdad Ridge. These mounds, that in foreground are about 30 m high, show crude bedding and steep flanks. Facies and interfacies mounds consist of fossiliferous limestones. From Cavalazzi et al. (submitted).

Outcrop image of the Middle Devonian Hollard Mound, eastern part of Hamar Laghdad. It is interpreted as hydrocarbon-seep mound with a recognizable core facies. From Cavalazzi (in press).

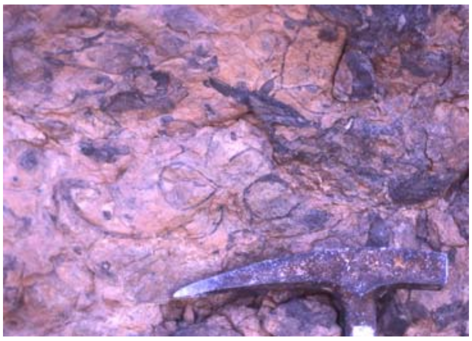


Semplified stratigraphic log of the Hamar Laghdad. Modified after Belka (1998).

4. PLATE 8 – Macrofaunas, Devonian mounds, Hamar Laghdad Ridge

Dense accumulation of trilobite's pygidia, *Scutellum* sp. *Scabriscutellum* sp., closed to veins cutting side of Early Devonian mounds.

Dense accumulation of brachiopods and corals, locally associated with veins cutting the Early Devonian mounds.



Dense accumulation of articulated bivalves and trilobites, Hollard Mound hydrocarbon seep, Middle Devonian.

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