COCARDE Workshop and Field Seminar
Sicily, 23-27 September 2013

Bridging off-shore and on-land research on carbonate mounds: common concepts and techniques

Buildups from Sicily: Triassic to Quaternary examples

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Abstract book

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SCIENTIFIC SUMMARY

The itinerant COCARDE Workshop 2013 aims to gather scientists from different cultural backgrounds (geophysicists, sedimentologists, marine geologists, palaeontologists, oceanographers etc.), from academy and industry, in order to drive an active discussion on the foremost insights gained from recent off-shore and on-land research on carbonate mounds. One of the main goals of the workshop is to promote and facilitate the collaboration between the scientific communities working on ancient and on modern carbonate buildups. For this purpose the meeting will host key presentations which will encompass a range of topics related to Geosphere-Biosphere coupling in fossil and recent carbonate factories.

After a short introductive set of presentations, held at the Botanical Garden (Department of Biological, Geological and Environmental Sciences) of the University of Catania on the 23rd of September, junior and senior scientists will participate in a two-and-a-half-day field seminar, during which they will visit a number of representative carbonate outcrops from Sicily. The field trip will include stops at well exposed buildups formed in different paleoenvironmental settings and ranging in age from Triassic to Pleistocene. On September 26-27th, an intensive workshop will host presentations on ancient-to-modern mound typologies aimed at crossing cultural borders between off-shore and on-land carbonate research. The first workshop day will take place in the countryside, in an agritourism close to Siracusa (Carlentini), the second and last workshop day will be held at the University of Catania and will include an open-access tutorial session with overview presentations. Roundtable discussions are scheduled for both workshop days to plan a common strategy for future research and international collaborations. Special emphasis will be given to (i) the compilation of a protocol for the description of modern and ancient mounds and (ii) further development of a mound database which includes both on-land and off-shore information.

The workshop and field seminar in Sicily is co-organized by two supporting institutions of the ESF COCARDE Research Networking Programme: the University of Milano-Bicocca (*Daniela Basso, Agostina Vertino*) and the University of Catania (*Antonietta Rosso*). The field seminar will be led by the workshop conveners in collaboration with *Rosanna Maniscalco, Rossana Sanfilippo, Francesco Sciuto, Giovanni Sturiale* (University of Catania), *Pietro Di Stefano, Angelo Tripodo* (University of Palermo), *Marco Taviani* (CNR – ISMAR, Bologna), and *Barbara Cavalazzi* (University of Bologna).

Among the participants, belonging to academy and industry, six young researchers have been awarded by the European Science Foundation to participate in the workshop and field seminar. For more information, please visit the COCARDE website (www.cocarde.eu).

DAILY PLAN

MONDAY SEPTEMBER 23rd, 2013

Workshop Session 1 - Introductory Presentations
(Meeting venue: Botanical Garden, University of Catania)

08:40 Welcome and Introduction
08:45 The COCARDE Workshop and Field Seminar 2013 (Vertino A., Basso D., Rosso A.)
09:00 COCARDE -ICA and –ERN A global network to study the "rocks of life" (Spezzaferri S., Rüggeberg A., Vertino A., Henriet J.-P., Foubert A., Van Rooij D., and the COCARDE–ERN steering committee)
09:20 Pioneer carbonate systems: bridging off-shore and on-land research on carbonate mounds (Henriet J.-P., Spezzaferri S., Foubert A., Rüggeberg A., Van Rooij D., Vertino A.)
09:40 The Afar system and carbonates (Varet J.)

Workshop Session 2 - Young Researcher Presentations (ESF-COCARDE Grantees)
(Meeting venue: Botanical Garden, University of Catania)

10:00 Coletti G.: Nutrients influence on Miocene carbonate factories
10:10 Feenstra E.: Stable isotope chemistry of fluid inclusions in CWC
10:20 Jakubowicz M.: Venting- and seepage-derived mud mounds and related authigenic buildups
10:30 Jaramillo-Vogel D.: From warm shallow-marine carbonate platforms towards carbonate build-ups in extreme environments
10:40 Lim A.: Current work on the Moira mounds, Porcupine seabight, offshore Ireland
10:50 Schrøder A.E.: Comparative palaeoecology of brachiopod faunas from Late Cretaceous and Danian coral mound and soft bottom environments
11:00 Brunch at the Botanical Garden
12:30 Transfer to Messina

14:00 Field Seminar, Stop 1: Messina, Pleistocene cold-water coral deposits

16:30 Transfer to Piano Battaglia (Madonie Mountains)
20:00 Dinner at "Baita del Faggio" (Madonie Mountains)
Post-dinner discussion animated by a team of junior scientists
Overnight stay at "Baita del Faggio" (Madonie Mountains)

TUESDAY SEPTEMBER 24th, 2013

09:00 Field Seminar, Stop 2: Madonie Mountains, Upper Triassic and Jurassic Reefs

12:00 Short visit at the "Museo Civico A. Collisani" and lunch in the town of Petralia Sottana
14:30 Transfer to Roccapalumba

16:00 Field Seminar, Stop 3: Roccapalumba, Miocene methane-seep carbonates

20:00 Dinner at "Villa Dafne" (Alia)
Post-dinner discussion animated by a team of junior scientists
Overnight stay at "Villa Dafne" (Alia)

WEDNESDAY SEPTEMBER 25th, 2013

08:30 Transfer to "Contrada Landro" (Resuttano)

10:00 Field Seminar, Stop 4: Caltanissetta Basin, Upper Miocene reefs

13:00 Packed lunch and coffee ("espresso"!) in the surrounding of S. Caterina Villarmosa
14:30 Transfer to Augusta (Costa Saracena – Castelluccio)

16:30 Field Seminar - Stop 5: Augusta, Early Pleistocene algal-bryozoan carbonates

20:00 Dinner at "Tenuta Roccadia" (Carlentini)
Post-dinner discussion animated by a team of junior scientists
Overnight stay at "Tenuta Roccadia" (Carlentini)

THURSDAY SEPTEMBER 26th, 2013

Workshop Session 3 – Ancient to modern carbonate mounds: crossing cultural borders
(Meeting venue: Agriturismo Tenuta Roccadia, Carlentini)

08:45 Hydrocarbons, carbonates & corals: conflict and friendship (Taviani M.)
09:00 The challenge of Devonian-Mississippian carbonate mud mounds (Riding R.)
09:15 The role of hydrothermal vent fluids in carbonate dissolution and precipitation in mud mounds: an example from the Devonian of Morocco (Belka J., Dopieralska S., Skompski S.)
09:30 Rare Earth Element patterns in ancient mound limestone: beyond the classical view of the Kess Kess carbonate mounds (Anti-Atlas, Morocco) (Franchi F., Cavalazzi B., Barbieri R., Hofmann A.)
09:45 Glendonites from the glaciomarine Dwyka Group (Late Carboniferous) in South Africa: evidence for methane seepage? (Cavalazzi B., McLachlan I.R., Beukes N.J., Gasparotto G., Cady S.L., Di Carlo I., Barbieri R.)
10:00 Distribution of microbial boundstones, agal and coral buildups on a Bashkirian carbonate platform, Cantabrian Mountains, Northern Spain (Chesnel V., Samankassou E., Merino-Tomé O., Fernandez L.-P., Villa E.)
10:15 Coffee break
10:45 Upper Triassic atoll-type carbonates from Sambosan Accretionary Complex, Southwestern Japan: sedimentology, conodonts biostratigraphy and paleoecology (Peybernes C., Martini R., Chablais J.)
11:00 Tropical and cold-water reef systems through time (Kiessling W.)
11:15 Temporary development of Early Paleogene bryozoan and coral mounds in Scandinavia – emphasis on sedimentological and ecological methologies (Bjerager M., Lauridsen B.)
11:30 Sedimentation patterns in cold-water coral mounds (Lopez-Correa M.)
11:45 Reasons why "build-up is better" (Basso D., Rosso A., Vertino A., Sanfilippo R.)
12:00 Carbonate build-ups in extreme settings: insights from recent and ancient systems (Foubert A., Fouke B., De Boever E., Dong Y., Jaramillo-Vogel D., Henriet J.-P.)

Workshop Session 4 - Afar geology: prospective research in frontier carbonate systems
(Meeting venue: Agriturismo Tenuta Roccadia, Carlentini)

12:15 Block rotation linked to southward right-stepping propagation and overlap of the Red Sea rift segments, Afar Depression: insight from paleomagnetism (Kidane T.)
12:30 Carbonate sedimentation prior to the formation of the Afar Depression (Atnafu B.)

13:00 Lunch

14:30 Round table discussion

16:00 Transfer to Siracusa

17:00 Field Seminar, Stop 6: The Archeological Park of Siracusa, Geology and culture.

19:30 Dinner in Siracusa
22:00 Transfer to Catania
Overnight stay in Catania

FRIDAY SEPTEMBER 27th, 2013

Workshop Session 5 (open-access) – Carbonate mounds: classification, evolution, reservoir properties
(Meeting venue: Botanical Garden, University of Catania)

08:50 Welcome and Introduction
09:00 Organic reefs and carbonate mud mounds: the broad view (Riding R.)
09:40 Phanerozoic Reef Trends Based on the Paleoreef Database (Kiessling W.)

10:20 Coffee break and Poster Session

11:00 Some reflections on mounds and water masses: a tentative typology of the North Atlantic Carbonate Mound Basin (Henriet J.-P., Rüggeberg A., Foubert A., Vandorpe T., Van Rooij D., Vitorino J.)
11:40 Carboniferous hydrocarbon-bearing mounds: hydrocarbon producing fields, coeval analogue and recent mounds as keys for understanding reservoir characteristics (Lapointe P.)
12:20 The Mila Member of Noto Formation: an example of Triassic microbial reservoir rock (SE Sicily, Italy) (Frixa A., Maragliulo C., Cirilli S., Felici E.)

13:00 Short guided visit to the Botanical Garden of the University of Catania
13:30 Lunch at the Botanical Garden

Workshop Session 6 – Carbonate mound database
(Meeting venue: Botanical Garden, University of Catania)

15:00 The Cocarde Carbonate Mound Database – example for time-slice 33 (Plio-Pleistocene) (Rüggeberg A., Foubert A., Vertino A., Jaramillo-Vogel D., and the participants of the COCARDE Research Network)
15:15 Round Table Discussion
17:30 Meeting Closure

POSTERS

Rugose Corals in Seepage- and Venting-Affected Environments: the Palaeoecology of the *'Amplexus'* in the Devonian of Hamar Laghdad Vent System (Eastern Anti-Atlas, Morocco) (Jakubowicz M.)

A Lower Miocene cold seep system at Roccapalumba (Sicily): geology, paleobiology and isotope geochemistry (Tripodo A., Cavalazzi B., Gasparotto G.)

Nutrient "cooling" effect on carbonates: evidence from a Miocene limestone (Coletti G., Basso D., Frixa A.)

Temporal, spatial patterns and controls on cold-water coral reef development - the Moira Mounds, Belgica Mound Provinces, offshore Ireland (Lim A., Vertino A., Wheeler A., Spezzaferri S., Dorschel B., Arnaubec A.)

Travertines as miniature depositional systems: geometry and evolutionary trends (Anzalone E., Ferreri V., D'Argenio B.)

Microbial carbonate build-ups in a Presalt environment, the Afar Rift Lake System (Held A.E., Camoin G., Virgone A., Rouchy J.M., Caminiti A.M.)

Algal-bryozoans carbonate factories: an example from the Pleistocene of Castelluccio, Hyblean Plateau (Sciuto F., Rosso A., Basso D., Sanfilippo R., Monaco P., Baldanza A.)

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Travertines as miniature depositional systems: geometry and evolutionary trends

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Carbonate rocks are mostly biogenic in origin. They form in a large variety of depositional environments, from continental (springs, rivers, lakes) to shallow and deeper marine settings (above the carbonate compensation depth, if any); moreover, not only they are a biotic product but, to some extent, also an integral part of the organisms themselves.

As for any type of sediment and sedimentary rock, the carbonate bodies (marine and non marine) may be analyzed and interpreted by means of facies analysis. Important elements of this analysis concern both the different types of organisms and related carbonate material (like skeletal grains or frame- builder derived structures) and the textures and sedimentary structures.

In the last decade many studies were addressed, in Italy and abroad, to the description and interpretation of the travertines, freshwater limestones forming at springs as well as in rivers or lakes.

Travertines form miniature depositional systems and display some characteristics which are typical also of the carbonate platforms: ability to (a) modify the morphology of the substrate, (b) develop in differentiated environments where climatic variability directly influences the interaction between physico-chemical processes (like outgassing of CO_2, pH variation, steaming, boiling, water temperature, hydrodynamics) and biological activity, mostly microbial and/or algal (c) pass to "basinal" areas, to build a frontal rim and (e) increase the steepness of the frontal scarp.

Parent water temperature is a key factor in these deposits: high values bring on elevated carbonate precipitation rates and a decrease of abundance, size and diversity of the eukaryotic organisms colonizing the depositional sites, while the decrease of temperature has an opposite outcome. This allows to distinguish between thermal- and ambient-water travertines (the latter often referred to as calcareous tufa). The transition between these two end-members being sometimes gradual, they show, among them, many analogies in their sedimentary organization and environmental evolution.

The internal architecture of travertine terraces is very often characterized by mound-like structures (buildups) occurring at different scale. These travertine buildups may be described as downhill elongated dome-shaped bodies (in Southern Italy studied occurrences spanning from less than 1 to 6 meters high, and from less than 1 to 8 meters wide), with variable steepness of flanks and forehead. Buildups can either be separated from one another by small depressions or coalesce by juxtaposition.

Quaternary travertines cropping out in central and southern Italy, regardless from parent water temperature, are also good paleoclimatic proxies: they developed mostly during interglacial periods. In particular, they appear strictly related to specific warm-wet climatic intervals, characterized by increasing volumes of spring-water in the mountain foothills and by areal forest expansion.

Finally, according the radiometric datation of the main studied travertine bodies, there is often a close correlation between their formation and: a) the unpaired marine isotope stages ($\delta^{18}O$ record); b) the atmospheric CO_2 content of the time of their formation (as recorded in the Vostok core) and c) high sea level stages, in turn ruled by climate.

Carbonate sedimentation prior to the formation of the Afar depression

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The Afar Depression, which is a relatively recent tectonic reality, occurs in between the Red Sea and the Arabian Plateau, the NW Ethiopian and the SE Ethiopian Plateau.

On the Ethiopian side, adjacent to the Plateau, there are two major Mesozoic successions on the two respective plateaus to the west and south of the Afar depression. To the west of the Afar the Mesozoic sequence unconformably overlies older siliciclastic sequences of probably Late Permian to Triassic age.

The stratigraphic succession consists of a lower sandstone unit, the well-known Adigrat Sandstone (Triassic-Middle Jurassic), an intermediate carbonate dominated unit with marls, shale and gypsum (Oxfordian-Kimmeridgian Antalo Limestone and Agula Shale) and an upper sandstone unit, the Amba Aradam Formation (Early Cretaceous).

Regionally, comparison with the Jurassic sequences in Yemen and Afar indicate a possible strongly subsiding trough in the Early Jurassic time.

To the south of the Afar, the marginal parts of the SE Ethiopian Plateau shows a similar Mesozoic sequence with a carbonate unit correlable with the Antalo Limestone in Northern Ethiopia between two sandstone-dominated units. In this case the Mesozoic sequence was deposited in a NW-SE trending trough that extended to the Central Ethiopian Plateau or the Blue Nile Basin.

Reasons why "build-up is better"

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Build-ups encompass a suite of very different structures, ranging from variously composed organic reefs to carbonate mud mounds and biogenically induced constructions, possibly including calcareous tufa and travertines (Riding, 2002). Thus, build-ups occur worldwide, from present-day marine and fresh water environments back to the Archean, showing a long and successful history.

Despite their different origins, most build-ups share some basic features: 1) 3D relief; 2) inhomogeneous internal structure and possible primary cavities; 3) higher biodiversity and 4) higher organic matter than the surrounding bi-dimensional substrate. Interestingly, these are key factors that explain the economic interest of oil companies in build-ups exploration.

Build-ups formation can be summarized by this sequence: a) favorable biotic-physic-chemical interactions haphazardously occur, according to the climatic and edaphic factors controlling the habitat; b) inception of the carbonate deposition; c) pioneer carbonate deposition enhances the possibility of further carbonate deposition (growth).

Within this broad scheme, many sessile organisms have developed their original strategies to cope with the changing environment, and the increasingly complex biotic interactions through geologic time. Yet some common features can be identified across several taxonomic groups of various ages, aimed at attain an advantage over other space/food/light competitors. Among these, the capacity to modify the substrate (following the concept of ecosystem engineers, Jones et al., 1994), the gregarious or colonial mode of life, the vertical or lateral extension/growth of the skeleton, and the modular structure are present in the most important present-day and fossil marine builders (Wood, 1995; Montaggioni, 2000).

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The role of hydrothermal vent fluids in carbonate dissolution and precipitation in mud mounds: an example from the Devonian of Morocco

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Spectacular Early Devonian carbonate buildups exposed in the eastern Anti-Atlas of southern Morocco and widely known as the Kess-Kess mounds constitute a classical example of deep-water mud mounds related to hydrothermal venting. They developed on the Hamar Laghdad elevation, located near Erfoud, which was created by a submarine volcanic eruption, composed by of peperites and tuffs which display geochemical characteristics of typical intra-plate basalts. After the eruption the elevation became a site of extensive crinoid colonization and carbonate production (Aitken et al., 2002). During late Emsian time, reactivation of magmatic processes caused doming of the volcanic complex and the overlying sedimentary strata, and in consequence, a network composed of radial and tangential faults originated (Belka, 1998). The faults served subsequently as conduits for hot fluids migrating to the sea floor (Cavalazzi et al., 2007). Most mounds developed over cross-points of radial and tangential faults. Geochemical data suggest that mud mound carbonates precipitated from brines comprising a mixture of hydrothermal fluids and seawater (Belka, 1998; Mounji et al., 1998). First vent communities and vent chimney conduits were discovered in 1999. Subsequently, detailed studies of the whole Devonian sequence of Hamar Laghdad, provided geological, geochemical, and palaeontological evidences that hydrothermal seepage persisted for a long period of time, from the late Pragian to the early Frasnian (Belka and Berkowski, 2005; Berkowski, 2004; Berkowski, 2006; Jakubowicz et al., 2013). However, individual vent sites were active only for a relatively short time and mostly during one phase. The vent fauna is restricted to chimneys and zones surrounding the vent outlets Fluid inclusion measurements indicate a wide temperature range of hydrothermal fluids, between 75 °C and 295 °C (Eisenmann, unpublished data). Metalliferous and sulphide phases are absent, but vent carbonates exhibit locally very high Ba, Zn, and Cu contents.

One of the characteristic features of the Kess-Kess mud mounds is the presence of irregular small caves (Fig. 1A). Systematic observations revealed that these cavities are fragments of larger open spaces, which largely are still filled with micritic and fine-grained laminated sediments and calcite cements (Fig. 1B). Originally, the cavities formed a complex system of fissures, chimneys and open spaces, connected to the sea-floor (vent outlets). Conodont fauna recovered from the internal sediments indicates the late Emsian age of the infill. Thus, the cavities must have formed almost simultaneously with the formation of mud mounds or immediately after. Their irregular shapes point to chemical corrosion rather than to tectonic control as a mechanism of their origin. Another strong evidence for carbonate dissolution episodes provides also the vent fauna. Its skeletal remains bear very frequently traces of extensive corrosion (Belka and Berkowski, 2005; Olempska and Belka, 2010).

The presence of both the dissolution of the carbonate host rock (hydrothermal karstification) and the precipitation of mud mound carbonates appears to be in conflict, but in fact, it can simply be explained by mixing of two different carbonate solutions (e.g., Corbella et al., 2004; Wigley and Plummer, 1976).

This is because mixing of two carbonate waters (hydrothermal water and seawater, for instance) which are both saturated with respect to calcite can lead to undersaturated or supersaturated conditions if the original solutions have either different CO_2 partial pressures, different temperatures or different ion intensity and pH values. Depending on the proportion of the end members, the mixture dissolves and precipitates carbonates even though the two mixing solutions are both independently saturated in carbonates. Fluid inclusion study (Eisenmann, unpubl. data) showed that hydrothermal vent fluids at Hamar Laghdad exhibited slightly higher salinities than that of modern seawater. These fluids were certainly more acidic than seawater. Numerical models have shown (e.g., Corbella et al., 2004) that mixing of an acidic brine with more dilute water, where both fluids are saturated with respect to calcite, triggers dissolution and precipitation of calcite in separate but adjacent zones. Hence, it can be assumed that during the formation of the Kess-Kess mounds dissolution took place in zones dominated by hydrothermal fluid-rich mixtures, and precipitation occurred where seawater predominated.

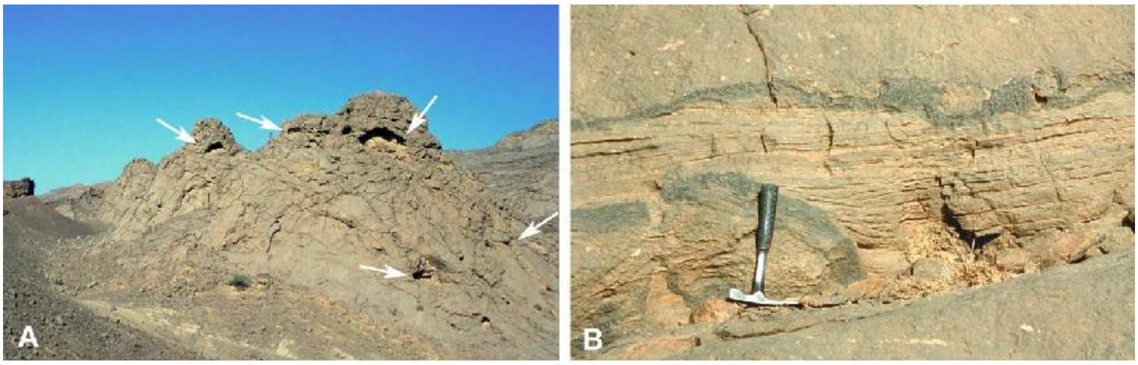

Fig. 1. A - The Kess-Kess mud mounds. Note the presence of numerous caves and cavities (the largest ones are arrowed); mound in the front is ca. 45 m high. **B.** Close-up photo of large cavity within the Kess-Kess mound filled with laminated micritic sediment. The contact with the host rock is lined with black hydrothermal cements.

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Temporary development of Early Paleogene bryozoan and coral mounds in Scandinavia – emphasis on sedimentological and ecological methologies

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Two types of biogenic carbonate mounds characterize the Early Paleogene Boreal Danish Basin in NW Europe. The mounds are well exposed in the coastal cliff Stevns Klint and in the Faxe Quarry in SE Denmark. The bryozoan skeletal mounds developed in a cool water outer shelf setting following a marked transgression in the early Danian. Contour parallel bottom currents rich in particulate nutrients governed a prolific growth of bryozoans into trains of mounds up to about 10 m high and 50–250 meters wide. The mounds experienced a highly complex interaction of biogenic growth, biogenic mottling and degradation in concert with physical winnowing, fragmentation and reworking (Bjerager and Surlyk, 2007). In middle Danian deep water coral mounds initiated and formed mounded complexes up to 40 m high and a few km wide along submarine highs (Bernecker and Weidlich, 1990, Bjerager et al., 2010, Lauridsen et al., 2012). The coral mounds co-existed with bryozoan mounds, and the temporary development of two different biogenic factories reflects a highly dynamic interplay during growth.

Detailed palaeoecological and sedimentary facies analysis and measurements of three-dimensional mound-architecture at successive growth stages are fundamental tools for the reconstruction of the depositional evolution of the mound complexes. The sedimentological analysis includes microfacies descriptions and designation within the expanded and revised Dunham classifications of Embry and Kovan (1971) and Wright (1992). The palaeoecological analysis involves taxonomical descriptions, density and diversity changes compared to facies variations over time and morphological variations of certain fauna groups.

Aspects on the sedimentary and palaeoecological analyses in combination with taphonomic biogenic and diagenetic overprinting in the two Danian mound systems will be discussed and compared to analogues subrecent and modern mounds in e.g. the North Atlantic and Great Australian Bight.

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Glendonites from the glaciomarine Dwyka Group (Late Carboniferous) in South Africa: evidence for methane seepage?

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Ikaite (Ca-carbonate hexahydrate) is a metastable mineral that only forms under specific marine and freshwater environmental conditions of near-freezing temperatures, high alkalinity, and elevated concentration of organic matter and orthophosphate. Due to its instability, evidence of its former presence is only preserved in the sedimentary record by glendonite, a calcite stable pseudomorph after ikaite. Thus, the presence of glendonite is commonly considered to be a good paleoclimatic and paleoceanographic phosphate-rich paleoenvironments indicator.

Moreover, in the marine environment ikaite crystals have been shown to grow close to the sediment-water interface (Kapland, 1979) probably in association with microbial methanotrophic sulfate reduction at hydrocarbon seeps (Greinert et al., 2004). This conclusion has recently been endorsed by Teichert and Luppold (2013) using stable isotope analysis.

In this presentation, we will also outline the mineralogy of ikaite and the glendonite pseudomorph, and then illustrate the use of glendonite as a paleoenvironmental indicator with a special emphasis on its potential role in identifying and elucidating methane paleoseeps.

Preliminary results of a combined mineralogical, petrographical, and geochemical study (optical microscopy, XRD, SEM-EDX, NanoRAMAN, EMPA, C-O stable isotopes) of glendonites recovered in the Late Carboniferous, glaciomarine deposits of Dwyka Group will be also presented. Glendonites from South Africa were firstly reported by McLachlan et al. (2001). The texture and composition, presence of pyrite in the pore space, and the geochemical signatures of these glendonites suggest an early diagenetic phase related to microbially-mediated methane oxidation via sulphate reduction processes possibly associated with paleo-hydrocarbon seepage.

The ability to recognize and characterize peculiar calcite pseudomorphs after *ikaite* (Fig. 1) in terrestrial methane-related carbonate deposits may significantly contribute to their interpretation and paleo-seep reconstruction, to better understand of the significance of terrestrial glendonite formation and the potential role of microorganisms in its formation.

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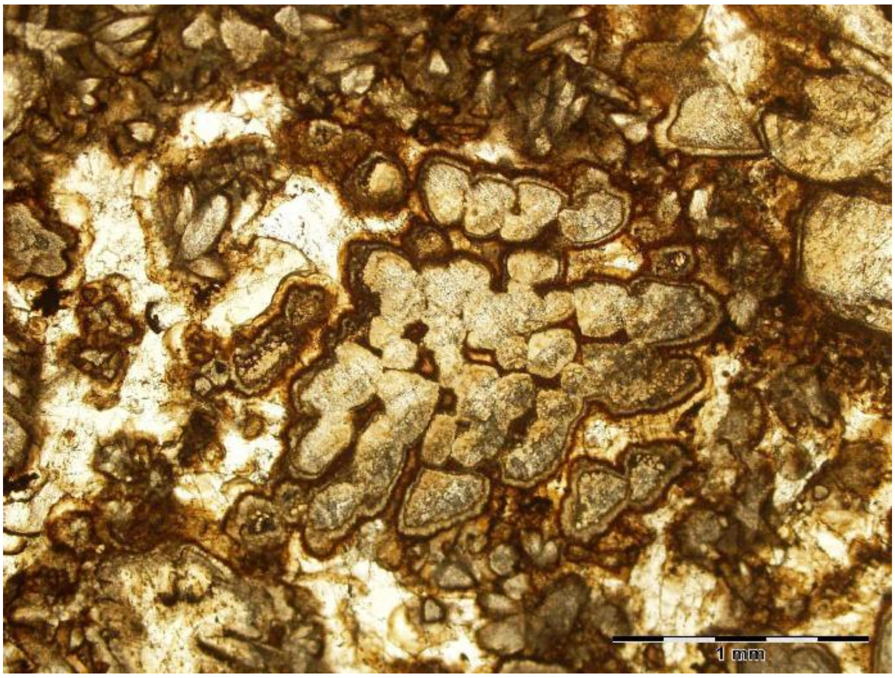

Fig. 1 - Transmitted light optical microphotograph of a thin section of a glendonite sample from Late Carboniferous glaciomarine deposits of the Dwyka Group, Great Karoo Basin, South Africa. The center part of the image shows a common habitus of the calcite crystals from glendonites.

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Distribution of microbial boundstones, algal and coral buildups on a Bashkirian carbonate platform, Cantabrian Mountains, Northern Spain

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Carboniferous carbonate platforms from Northern Spain are of particular interest because they serve as analogs for contemporaneous systems yielding hydrocarbon reservoirs, e.g., in Kazakhstan and the Pricaspian Basin (Karachaganak, Kashagan and Tengiz fields) (Ulmishek, 2001, 2007; Verwer *et al*., 2004; Kenter *et al*., 2005, 2008; Collins *et al*., 2006). Bashkirian platforms were therefore described in details in previous studies (Della Porta *et al*., 2002, 2005; Bahamonde *et al*., 2008; Merino-Tomé *et al*., 2009). Here we report on the Valdorria platform, located northeast of León, Northern Spain, which shows a complete sequence from platform nucleation to demise.

The good preservation of the Valdorria outcrop together with a complete reconstruction of its geometry allowed to constrain the distribution of microbial boundstones, algal and corals buildups. The entire carbonate system developed during Bashkirian, which lasted during 7.9-8.2 My., according to the current time scales (Menning et *al*., 2006; Davydov *et al*., 2010; Schmitz and Davydov, 2011; Davydov *et al*., 2012). Phase II and III have been dated of the Bashkirian substage Asatauian (1.5-1.6 m.y.). With a total thickness of approximately 660-690 m, a high aggradation rate of 412-460 m/My is calculated. This fast rate enabled a rapid evolution of the environment and permitted to perfectly register both lateral and vertical flora and fauna distributions. Nineteen different facies/microfacies have been described (Fig. 1) and correspond to six main depositional environments; (I) inner platform, (II) outer platform, (III) platform break and upper slope, (IV) slope, (V) toe-of-slope, (VI) basin.

Phase II consists of more than 3 km extended packages that prograde and aggrade. It shows cycles of different orders. The depositional environments range laterally from inner platform to deep basin. Corals, algae and microbial boundstones developed mainly in the inner platform area to the slope (Fig. 1). The microproblematicum *Donezella* is the most extended organism (up to 80% of some samples), ranging from area (I) to area (IV), and forming patches, centimeters lenses, meters or kilometers buildups and binding the slope. *Masloviporidium*? is only found as binder/baffler in area (IV). Dasycladaceae (*Anthracoporella*) are mainly constrained in area (I), forming rare centimeters scale lenses. The presence of *Ungdarella* increases to the top of phase II. They do not form buildups, but accumulated continuously as boundstones (hundreds of meters) in area (II). *Stacheoides* and *Archaeolithoporella* appear sparsely in the sediment record of area (I) and (II). *Archaeolithoporella* occur principally as encrusters (on *Donezella, Anthracoporella*, *Stacheia,* Auloporidae). Rugosa corals form biostromes and small decimetre to meter buildups that occur in areas (I) and (II). Buildups are mainly found close to *Anthracoporella* bioconstructions, thus in a low energy environment. Inversely Auloporidae are mainly present in area (II) as sparse decimetres patches. Their lighten structure leaves space for many other organisms (brachiopods, gastropods, Echinoidae, rare trilobite fragments, benthic foraminifera, *Stacheoides* and the encrusting *Archaeolithoporella*), indicating a more agitated environment.

Phase III aggrades upon the platform break of phase II. The sedimentary record is 2 km long, about 520 m thick, and consists of a massive, mound-shape structure. About 80% of the rock volume in phase III is microbially bounded. The eastward flank shows external platform facies that have been eroded and exported on the east slope as major rock avalanches. The westward flank mainly consists of microbial boundstones that show minor flat progradations inclined at about 43-48°. Phylloid algae occur in growth position in a zone equivalent of area (II), on the East flank, forming small bioconstructions, where they constitute about 20% of the rock volume. The residual space is filled by early marine botryoidal cement or peloidal micritic matrix. Sediment-filled cavities are volumetrically important. Except for coprolites and benthic foraminifera, especially Lasiodiscidae, other components are rare. Extraclasts composed of phylloid algal boundstone are common in breccias of area (V).

The Valdorria platform yields a high potential to contribute to our current knowledge of Carboniferous carbonate platforms, since the seismic-scale tilted platform is entirely preserved and accessible. Specifically the preservation in the original platform-slope-basin configuration through time allows a reliable reconstruction of the facies distribution and variations.

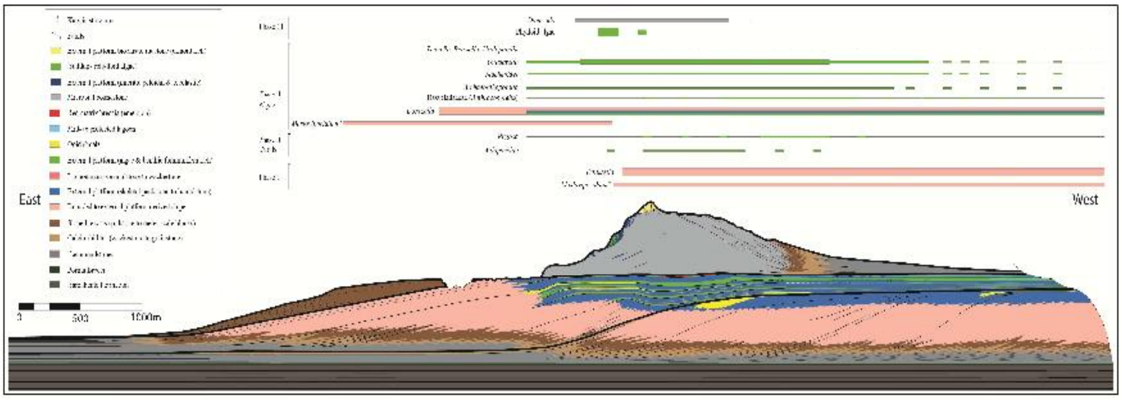

Fig. 1 - Schematic facies distribution (true scale) of the distal eastern part of Valdorria platform; and distribution patterns of algae, microbial boundstones and corals. The distribution is shown with colours corresponding to their facies affiliations.

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Nutrient "cooling" effect on carbonates: evidence from a Miocene limestone

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Carbonates factories grain association is related to environmental temperature. Tropical platforms are dominated by hermatipic corals and calcareous green algae as main sediment producers, while at higher latitudes bryozoans, mollusks and benthic foraminifers dominate. Calcareous red algae may occur or even be locally dominant on the shelf across all latitudes. Temperature and light control carbonate production from the chemical and biological point of view acting on both equilibrium of calcium carbonate minerals and metabolic rate of organisms.

A third parameter controlling the biogenic carbonate production is nutrients availability. Growth of photosynthesizing organisms depends on nutrient concentration in water. Increase in plankton biomass, boosted by phosphorus, nitrogen and iron abundance, enhances the particulate organic carbon (POC) which in turn reduces water transparency and light availability to the benthic community (Hallock and Schlager, 1986). For example, in the present-day Gulf of California, where eutrophic condition prevails, cool-water carbonate assemblages are present on the shelf, while, according to temperature, a warm-water association would be expected (Halfar et al., 2006). In recent sediments this kind of situation is easily detected since low percentages of warm-water carbonate bioclasts (like hermatipic corals) are mixed up with cool water ones. On the contrary, preferential dissolution of aragonite and high-Mg calcite skeletal particles during fossil diagenesis affect the grain association with the consequent loss of ecological information.

The bioclastic limestone of the Pietra da Cantoni Group (Monferrato, Piedmont Tertiary Basin) developed during the lower Miocene in a warm climate. The carbonate assemblage is largely dominated by calcareous red algae and large benthic foraminifera, however, prominent variations locally occur. In Castello di Uviglie and Villa San Bartolomeo quarries, levels of rhodolithic rudstone are composed of barnacle plates (40%), calcareous red algae thalli (35%), bryozoan colonies (35%) and by lesser amount of mollusks, benthic foraminfers, serpulid worms and echinoids. Melobesioids dominate (>80%) the algal assemblage of rhodoliths, as frequently observed in cool water or in deep warm-water associations (Adey, 1979).

The tropical origin of the limestone has been assessed by a detailed paleontological analysis of both fossil flora and fauna. In the algal assemblage few thalli of the warm-water genera *Sporolithon* and *Lithoporella* have been identified, along with the foraminifers of the genus *Amphistegina* and the species *Operculina complanata* and *Stomatorbina torrei*.

Barnacles plate accumulation is the most outstanding feature of these rocks. In the fossil record extensive deposits of barnacle plates are known and widespread in the Pliocene limestone of New Zealand, and have been interpreted as formed in a current-swept temperate to cool benthic environment (Kamp et al., 1988). In the present-day ocean, similar sediments accumulate on isolated and current-dominated banks in the Barents Sea (Henrich and Freiwald, 1995). However, the barnacles of Pietra da Cantoni Group belong to the *Balanus trigonus* "group" which is composed by sub-tidal warm-waters species.

Amongst bryozoans, *Bifissurinella lindenbergi*, belonging to the problematic Bicorniferidae family, is the most abundant element.

This uncommon fossil species is exclusive of Neogene warm-water associations, and its distribution in the Pietra da Cantoni limestone seems to be linked to the barnacle abundance. Such a peculiar carbonate assemblage, mainly composed of warm-water suspension-feeders, with the noteworthy absence of symbiont-bearing organisms, probably formed in POC-rich and high-energy tropical waters. The organic carbon provided plenty of food to suspension feeders, like barnacles and bryozoans, and reduced light availability at the seafloor, thus explaining the red algal assemblage. Currents possibly delivered food to the suspension feeders and at the same time prevented fine sediment settling, also contributing to the increase of primary production by mixing up the water column. The interplay of these environmental factors resulted in high primary porosity, which is preserved in the studied limestone (Fig. 1).

The barnacle-dominated facies of the Miocene Pietra da Cantoni Fm. represents a fossil example of prevailing non-oligotrophic conditions which largely exclude hermatypic corals and allow the deposition of cool-water assemblages in warm water. This effect could solely be identified through a paleontological analysis taking into account the complete array of biotic components along with chemistry and mineralogy of the limestone.

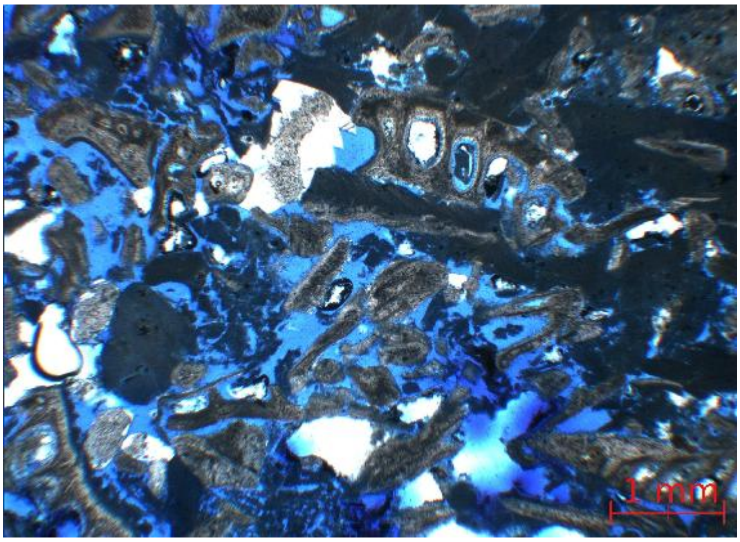

Fig 1 – Thin section of Castello di Uviglie limestone. Effective porosity is marked by methylen blue

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Carbonate build-ups in extreme settings: insights from recent and ancient systems

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Carbonate mound systems represent a recurrent strategy of Life and an exemplary mode of Geosphere-Biosphere coupling throughout Phanerozoic times. The primary building bricks of carbonate mound systems do vary through space and time as a consequence of subtle environmental changes, turning such systems into a challenging but interesting palaeo-environmental archive. Scrutinizing parallelisms and contrasts between mound systems in the present ocean and the geological record deepens our insights in the basic drivers. It should be noted that microbes play a particular role in the evolution of such mound settings.

Microbial carbonate systems seem to be the key to understand the tipping points in mound evolution. Microbial-influenced mound systems especially thrives under extreme conditions, whereby 'extreme environment' refers to any setting that exhibits life conditions detrimental or fatal to higher organisms with respect to its physicochemical properties (Thiel et al., 2012). New views on microbial processes, actors and products emerge through new insights in extreme carbonate environments (encompassing acidic, alkaline, hypersaline, pressurized, hot, cold and dry environments). So, the study of 'extreme' or - better rephrased as 'frontier' - carbonate systems forms the true cornerstone to understand the processes in carbonate mound factories through space and time. Starting from recent observations of cold-water coral carbonate mounds in the cool-water realms as 'frontier carbonate systems', other mound systems in stressed environments are further explored.

Generalizing the marine carbonate precipitation modes conform Schlager (2003), one can talk about three different primary 'carbonate mound' factories (Foubert et al., in prep.): (1) the *biotically-controlled mound factory* dominated by biotically-controlled skeletal production resulting in typical *bioclastic mounds*, (2) the *biotically-mediated mound factory* dominated by (mostly) microbial-induced carbonate precipitation such as often recognized in *mud mounds* and, (3) the *abiotic mound factory* characterized by abiotic (physico-chemical) precipitation modes, for example *travertine mounds* and *spring mounds*. However, most of the observed mounds thriving under 'extreme' conditions are a product of the tight coupling between biotically-controlled, biotically-mediated and abiotic precipitation. For example, travertine build-ups witness a tight interaction between abiotic and microbial-induced precipitation, recording at a high time-resolution (due to high precipitation rates) the response of microbial communities to environmental change. Moreover, travertine deposits and microbial build-ups have played a crucial role in the initial phases of ocean spreading.

The renaissance in the study of the substantial role of microbes in syn-rift carbonates might hold clues to understand microbe-mineral relations and the tight coupling between microbial-induced and physico-chemical precipitation.

It should be noted that carbonate mounds are highly sensitive to the early diagenetic filter and act on their turn as biogeochemical micro-reactors catalyzing dissolution and (microbial-induced) precipitation of carbonate phases (Foubert and Henriet, 2009). Last is often obscuring the primary precipitation modes.

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Rare Earth Element patterns in ancient mound limestone: beyond the classical view of the Kess Kess carbonate mounds (Anti-Atlas, Morocco)

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Rare earth element (REE) chemistry is a valuable tool for investigating marine sedimentary palaeoenvironments, because the relative abundances of REE in marine sediments vary systematically depending on the influence of hydrothermal, terrestrial or marine inputs upon fluids in the basin.

The aim of this work is the study of REE as tracers for fluid composition during early diagenesis of the Devonian Kess Kess mounds (Fig. 1, Anti-Atlas, Morocco). REE analysis has the potential to elucidate the oxidation state (*via* the Ce anomaly) of Early Devonian oceans when the Kess Kess developed and to test claims for a supposed hydrothermal input (Franchi et al., submitted) into the sea-water (*via* the Eu anomaly). Therefore a complete REE dataset complemented by Yttrium (REE+Y) and trace element data were produced for different carbonatic facies: stromatactis-filling cements, trilobite-bearing limestone, vein-filling, red pisolitic limestone, and dark layered micrite.

The contents of REE+Y were determined by solution ICP-MS (at University of Witwatersrand, South Africa) on bulk sample of each carbonate facies. All investigated samples are depleted in light REE (La–Eu) compared to medium and heavy REE (Gd–Lu), relative to average shale (PAAS, McLennan, 1979). Analyses revealed that the REE+Y abundance patterns for the Early Devonian limestone samples are commonly characterized by an unusually high Y/Ho ratio (up to ~ 87, super-chondritic values) and distinct, but variable Ce-anomaly, suggesting deposition under particular chemo-physical conditions.

Fig. 1 - Kess Kess conical mounds

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The Mila Member of Noto Formation: an example of Triassic microbial reservoir rock (SE Sicily, Italy)

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The upper Triassic petroleum system of the Hyblean foreland (SE Sicily island, Italy) represents a proven efficient one also in the Mila and Irminio light oil Fields, located West of the considered area, drilled by Bimmisca 1, Vallazza 1, Cozzo Scalia 1 and Carrubo 1 wells (Fig. 1).

According to Frixa et al. (1998, 2000, 2010) during Norian-Rhaetian, the thick dolomitic peritidal platform (Sciacca Fm.; the main Sicily reservoir rock) underwent an extensional phase that produced two main areas, characterized by mixed carbonate-terrigenous sedimentation: a persistent anoxic lagoons/shallow basins to the North (Noto Fm.; average thickness: 200 m) and a deep anoxic-disoxic intraplatform basin, ascribed to part of "Middle" Members of Streppenosa Fm. (thickness: >2500 m), to the South.

The argillaceous intercalations of Noto Fm. are the main source rock of Sicily (TOC: up to 13%), while Streppenosa Fm. is the second Sicily source rock, having TOC < 1% and a great thickness (Brosse *et al.,* 1988; Cirilli *et al*. 2009).

During Rhaetian, on the tectonically controlled Sciacca platform margin, a complex sedimentary association, drilled by explorative and production wells, set up. Seismic interpretation and well data indicate that microbial mounds (Mila Member of Noto Fm.; thickness: 100->400 m) grew on a NE-SW oriented ridges, between the above-mentioned restricted lagoon/shallow basin and the turbiditic basin (Frixa *et al.,* 1998, 2000, 2010; fig. 1).

The Mila Member coalescent mounds, discovered by Edison Oil in the Mila Field, are made of laminar and small columnar stromatolites, microbialitic and thrombolitic laminae, mudstones with ostracods, peloidal packstones and associated carbonate breccias (Frixa *et al.* 1998, 2000, 2010; Lindsey *et al.* 2002; Felici, 2013). In the examined area the depth of the top of this reservoir range from 2650 m and 3280 m.

This unit seems to be organized in two superimposed backstepped (northwards) bodies, characterized by different log response. The lower one directly grew on the higher portions of the Sciacca tilted blocks, while the upper one overlies the lower Mila body (basinwards) or the Noto Fm. lagoons (landwards) (Frixa *et al.* 1998, 2000, 2010).

Thin pelagic interbeddings, in both Mila Member and Noto lagoon domain indicate transgressive episodes. During the Upper Rhaetian-Hettangian, the transgression of the Streppenosa Fm. basinal deposits ("Upper" lithozone; thickness: 100-600 m) over the entire Hyblean area occurred (Frixa *et al.*, 1998, 2000, 2010).

The poor reservoir properties of the Mila Member, due to the micritic nature of the rock, are improved by hydrothermal dolomitization close to the major faults (Frixa *et al.* 2010; Felici, 2013). On the examined bottom cores, the average porosity is 3% (max: 8%), while the average permeability, due to hydrothermal dolomitization, is 4 mD (max.: 1D on vuggy and fractured samples). Brecciation, zebra structures, saddle dolomite cements and intercrystalline porosities characterize the dolomite reservoir.

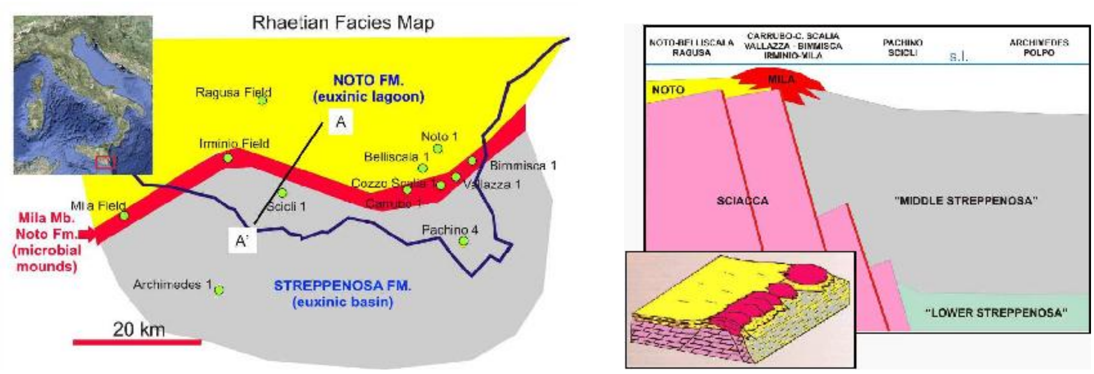

Fig. 1 - Rhaetian facies map and section, with the location of the Mila microbialites (Frixa *et al.,* 1998, 2000, 2010)

Stable isotopes indicate the influence of organic carbon during diagenesis and dolomitization ($\delta^{13}C$ PDB in microbialites around -10‰, in dolomites around -7‰). The fluid inclusion microthermometry of the dolomite cements points out homogenization temperatures of about 70-90 °C and two populations of salinity ranges, which suggest a mixing of two main fluids: the low salinity fluids (from sea water to 7%) are probably the formation fluids, while the saline brine (up to 20% wt NaCl) were probably expelled from the Streppenosa shales. The Raman analysis detected the presence of hydrocarbons entrapped during the growth of the dolomite crystals.

The study demonstrates that the hydrothermal dolomitization and karst considerably improve the reservoir characteristics of microbial mounds and that the structural control on the reservoir body is fundamental during this diagenetic history.

Acknowledgements

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Microbial carbonate build-ups in a Presalt environment, the Afar Rift Lake System

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The recent discovery of vast hydrocarbon reservoirs in Cretaceous marginal lacustrine deposits dominated by composite algal/microbial features in the South Atlantic has reopened the interest of the scientific community and oil companies for the study of recent and past continental carbonate systems.

Recent and past continental carbonate analogs which developed in a wide range of depositional settings, from aerial to subaqueous environments, provide some key elements to depict the sedimentological and sequential patterns observed at the core scale and to better understand the impact of climate change, fluid flow and water chemistry on the carbonate factories.

The Quaternary carbonate systems from the Afar Rift area (Djibouti) are considered as a potential analog of the South Atlantic Cretaceous systems and will be the subject of a multidisciplinary study starting in September 2013.

The Afar area is located at the junction of three magmatically active rifts, the Main Ethiopian Rift, the Red Sea and the Gulf of Aden. This rift-in-rift system is responsible for the occurrence of a wide volcanic basement and a specific topography hosting several perched lakes. To the East, the Abhé Lake represents the topographically higher lake and is hydrologically linked to the western and lower part of the system, the Gulf of Ghoubbat al Kharad.

Changes in hydrological circulation are related to climatic conditions and therefore control the base level and the salinity of the lakes.

Carbonates, mainly comprised of coquinas and algal/microbial build-ups (Caminiti, 2000), developed during wet periods typified by lake level highstands, while evaporites were deposited in lake depocenters during periods characterized by drier conditions and lake level lowstands (Gasse et Fontes, 1989).

The interpretation of fossil systems will rely on the detailed reconstruction of stratigraphic relationships between carbonate build-ups, volcanic basement and salt deposits, the analysis of facies distribution and associated geometries, and the chemical characterization of the fluids which initiated and sustained the development of algal/microbial carbonate build-ups.

This multidisciplinary project will enlighten the relationships between volcanic activity and the development of carbonate systems, especially through the role of hydrothermalism in diagenetic processes in carbonate build-ups. The end-products of the project will also include a 3D geological map displaying the facies distribution, the geometrical characters of the potential reservoirs, and the structural pattern.

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Some reflections on mounds and water masses: a tentative typology of the North Atlantic Mound Basin

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The Atlantic Ocean, and in particular the North Atlantic, features a unique concentration of provinces of giant cold-water coral mounds. On the North American margin, where surface waters reach depths, greater than on the European margin, the mounds of the Florida-Hatteras slope and Blake Plateau occur in depth from 440 m to 1300 m and are fully bathed by the Florida current. The larger mounds occur in the lower interval of this surface water layer, between 1000 and 1300 m. On the north-west European margin, west of Ireland, the mound provinces in Porcupine Seabight range in depth from 750 to 1050 m and are bathed by Mediterranean Outflow Water (MOW), which grades upward into Eastern North Atlantic Water (ENAW) at a depth between 800 to 700 m. Strong internal waves guided by the permanent thermocline have been reported and modelled in the depth interval of the mounds, which also coincides with an oxygen minimum zone. In Rockall Trough, cold-water coral mounds occur in a depth range of 600 to 1000 m, within the lower interval of warm and saline ENAW, overlaying the cooler Labrador Sea Water (LSW) at some 1200 m. Rockall Channel and the Faeroe-Shetland Channel are sites of intense mid-slope resuspension by internal waves. On the north-west African margin, the carbonate mounds on the Pen Duick Escarpment off Larache occur in water depths of 530 to 580 m, in North Atlantic Central Water (NACW) containing several nepheloid layers, and overlying Antarctic Intermediate Water (AAIW) found at a depth of 600 m. Further south, an elongated carbonate mound range occurs in Mauritanian waters at depths of 450 to 550 m, over a linear extent of at least 190 km. Warm and saline Tropical Surface Water (TSW) overlays low salinity South Atlantic Central Water (SACW) down to 600 m, where a sharp halocline marks the boundary with fresher AAIW. The SACW forms an oxygen minimum layer and is the nutrient-rich source of upwelling water in the region.

In the South Atlantic, cold-water coral ecosystems and elongated patches of deep-water coral mounds have been reported on the slopes of the Campos Basin, off Brasil, clustering between 570 m and 800 to 850 m within the upper horizons of the AAIW, right below the South Atlantic Central Water (SACW). On the Patagonian slope off Argentina, cold-water coral mounds occur mainly between 400 and 1000 m depth, in the basal horizons of the AAIW which flows in northward direction over the Upper Circumpolar Deep Water (UCDW).

The intensive charting of continental margins worldwide makes it unlikely that major recent, outcropping cold-water coral mound provinces would have remained unspotted today in other oceans. The virtual absence of large cold-water coral mound provinces in the Pacific and other parts of the global ocean can be primarily explained by a (negative) chemical control on the mound-builders. Most scleractinian corals build their skeletons of aragonite, a metastable form of calcium carbonate that dissolves at shallower depths than calcite. The base of the saturated

water mass in which scleractinian mound building corals (*Lophelia pertusa*, *Madrepora oculata*, etc.) can thrive is given by the aragonite saturation horizon (ASH). So, the majority of large-scaled cold-water coral mound provinces plots in the seabed areas characterized by a deep aragonite saturation horizon (1000-2000 m or more). Such deep aragonite saturation horizons are especially present in the (North) Atlantic.

The building of large provinces of giant mounds however implies an exceptional (positive) control, capable of enhancing the flux of nutrients.

In the absence of photosynthesis, substantial fluxes of nutrients are simply crucial for feeding deep-water carbonate factories. What makes the Atlantic unique is a highly dynamic stratified structure. The mound provinces in the North Atlantic Mound Basin (NAMB) literally girdle subtropical gyres and cluster either right above the present-day base of the warm upper water masses, or just below. The already dynamically stratified Atlantic basin is further stirred by oscillations at various frequencies. At the pace of the glacial-interglacial rhythm, shifts of polar fronts force north-south displacements of cold nutrient-rich intermediate waters and surface productivity. These shifts stimulate coral growth on the European margins in interglacial times, and on the African margins in the arid times that coincide with glacial conditions further north. Furthermore, at the pace of the North Atlantic Oscillations, the upwelling on the north-west African margin can be significantly enhanced (NAO+ phases).

Summarizing, and keeping in mind that large deep-water carbonate mounds in the Atlantic may well have been born over 2.5 My ago, as evidenced by IODP Exp. 307, in a water mass architecture differing from the present one, a general observation today is that the deep carbonate mound provinces seem to closely fringe the roof of the intermediate to deep water masses of the present, dynamically stratified ocean. On the east Atlantic margin, they thrive in the nutrient-rich, low-oxygen horizons either just above or just below the base of the surface circulation layer, in the beat zone of internal waves guided along an interface with significant density contrast (Porcupine-Rockall basins) or in zones of upwelling: the vast and heterogeneous Eastern Boundary Upwelling System stretches along the Atlantic margin from the northern tip of Iberia at 43°N to south of Dakar at about 10°N.

Seen from an energy sourcing and energy processing perspective, the Recent ocean's carbonate world hence essentially splits in two boundary layers, one at the top and one at the interface of ocean water masses. The upper carbonate world directly thrives on light as a main source of energy: it is the domain of the Photozoan carbonates, confined by water depth and the penetration of light. However, heterozoan mound-builder guilds in intermediate water masses directly forage on fluxes of nutrients, which percolate from the photic zone as pelagic rain, and/or get generated by in situ benthic processes, and/or raise from the lower compartment through deep-sourced upwelling. While the occurrence of cold-water coral mounds appears to be frequently coupled to a major interface between water masses, it is not confined in accommodation space: deep water mounds can grow in a virtually unconstrained way, to the dimension of giants. Yet, the subtle functioning of the working parts that underpins the performance of the mound engine remains to be elucidated'.

Pioneer carbonate systems: bridging offshore and on-land research on carbonate mounds

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The COCARDE network roots in the unique momentum of collaborative PhD and postdoctoral research on mostly recent, largely 'live' deep-water coral mounds, a momentum that developed in the past fifteen years within European research projects supported by the EC and ESF, and through coordinated national initiatives. The involved marine research built upon an exploratory strategy of integrated seabed and sub-seafloor imaging (from kilometric to sub-micron scale) and comprehensive 3D sampling including continuous drilling and logging. This was completed with a full environmental assessment (oceanic and sub-seafloor) and analytical characterization of key ecosystem components – from metazoan to microbial – as well as of their functional relationships and products.

This momentum logically led to a curiosity-driven march into the world of "the mounds of the past", and a most stimulating and productive meeting with the investigators of the fossil carbonate record. Evident win-win opportunities soon showed up. Furthermore and in all logic, the study of a frontier domain of carbonate building processes in deep and cold waters progressively sharpened interest for other extreme carbonate environments, such as high-T and hypersaline environments: not truly out of a sense of collection of extreme experiences, but for the likeliness that stresses induced by extreme conditions may have played a crucial role at critical moments in the evolution of Life – if not in the genesis of Life itself. The comparative study – on recent and past systems – of the adaptation of pioneer carbonate-building ecosystems to extreme conditions, and of their development of strategies to tailor these environments to their needs, can deepen our insight in the processes involved at key moments of Biosphere-Geosphere interaction in the history of our planet – not the least in a context of Global Change.

Fostering the creation of multiple projects along those research lines, with a strong capacity-building dimension, is the ambition of COCARDE. In its present functioning COCARDE acts as a network for "Collaborative Frontier Carbonate Systems Research and Project Development" that promotes collaborative research on both live and fossil carbonate systems, in academic and industrial context. COCARDE is an independent, bottom-up and open network with distributed management, pragmatically operating with modest but efficient institutional (ESF, IOC-UNESCO, FWO-Flanders) and industrial support. The effective bridging of domains and communities featuring a proper history and culture will most likely benefit of a convergence of protocols – where applicable. This is a central challenge taken by the conveners of this 5th COCARDE workshop.

In this workshop, continued progress on cold-water coral mounds research will furthermore be reported, while a possible new collaborative project tack is being explored, related to the interaction and the intertwining of carbonate and evaporitic systems, in particular at the crucial transition between continental/lacustrine and oceanic conditions. In the Ries meteor crater, during the 4th COCARDE workshop, COCARDE teams got confronted with amazing carbonate build-ups shaped in an alkaline lake, under apparently vigorous thermally-driven groundwater circulation conditions. It is tempting to extend observations in such a thermally stirred semi-enclosed basin towards an active rift basin, on the verge to oceanization – the Afar – and to compare products and sequences with those, for instance drilled in the deep Atlantic subsalt carbonate world. Opportunities towards continental scientific drilling, actively promoted by COCARDE, obviously hereby keep in the back of our mind. It was tantalizing to potentially discuss these processes and products while effectively walking on carbonate/evaporite sequences – regardless the differing context – and today, the dream comes true.

The 5th COCARDE workshop and field seminar in Catania takes a pivotal position, midway the ESF-supported COCARDE-ERN network lifetime. The two collaborative frontier research strings in which COCARDE thus hitherto has engaged in an exploratory way – "Cool Carbonates" and "Hot Carbonates" – will further give shape to two major sessions at the "First COCARDE Research Conference" planned to be organized late 2015 by the Fribourg University teams, and for which the mythic location of Monte Verità (Switzerland) is targeted. The third planned session – "Rocks of Life"' – aims to bring together project architects and key scientists who achieved the recognition of world-class carbonate sites as UNESCO World Heritage, or who are working at it – from the Jurassic Coast in the West to the Dolomites in the East, and from Stevn's Klint in the North to a planned Moroccan "Route Royale" of Carbonate Mounds in the South. This aiming again to explore win-win collaborative opportunities in the development of for instance common protocols in documentation and promotion, to maximize the outreach and the impact of carbonate research on a wider public and in education.

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http://www.cocarde.eu/

Rugose Corals in Seepage- and Venting-Affected Environments: the Palaeoecology of the *'Amplexus'* in the Devonian of Hamar Laghdad Vent System (Eastern Anti-Atlas, Morocco)

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Hydrothermal vents and hydrocarbons seeps are the environments hostile for modern corals (e.g., Foubert et al., 2008; Becker et al., 2009). Nevertheless, a high environmental tolerance of some Palaeozoic deep-water rugose corals made them capable of colonizing vent- and seep-related settings. In the present study occurrences of solitary rugosans *'Amplexus' florescens* from the famous mud mound locality, the Hamar Laghdad ridge (eastern Anti-Atlas, Morocco; Fig. 1A), have been investigated.

The carbonate buildups occur within the sedimentary cover of the Devonian submarine volcanic intrusion, and their formation has been related to submarine hydrothermal activity based on structural, sedimentological and geochemical data (Belka, 1998; Mounji et al., 1998; Cavalazzi et al., 2007). The coral skeletons are densely packed within several rich, isolated, largely monospecific assemblages, which occur in the Pragian to the Givetian rocks (Fig. 1B-D). The assemblages are always spatially associated with authigenic carbonate bodies, emplaced within bedded, hemipelagic deposits.

Despite their high biomass, the *'Amplexus'* assemblages are very low-diverse, which, together with their spot distribution and petrological and geochemical features of the host carbonates, indicates the involvement of active fluid seepage during the coral growth. Most of the assemblages developed probably in close relation to hydrothermal vents, but in a single occurrence hydrocarbon seepage is evidenced by palaeontological and petrological proxies, as well as $\delta^{13}C$ values of carbonates as low as -17.5‰ PDB.

This seep-related assemblage is also the only one, in which the *'Amplexus'* corals reveal a bizarre, 'calice-in-calice' (*sensu* Berkowski, 2004, 2006) growth pattern (Fig. 1E-F). The 'calice in calice' growth is interpreted as a consequence of increased toxicity, temperature or oxygen-depletion in a near-bottom water layer, resulting in selective survival of larvae settled in shelters of elevated calices.

It can be suspected that unusual, extremely simplified morphology of the *'Amplexus'* corals made them well adapted to living in harsh, unstable environments related to submarine fluid emissions. Thus, although often perceived as typically deep-water species, the *'Amplexus'* corals constituted most likely ecological opportunists, thriving at Hamar Laghdad in the nutrient-rich, venting- and seepage-affected areas that were hostile for other benthic organisms.

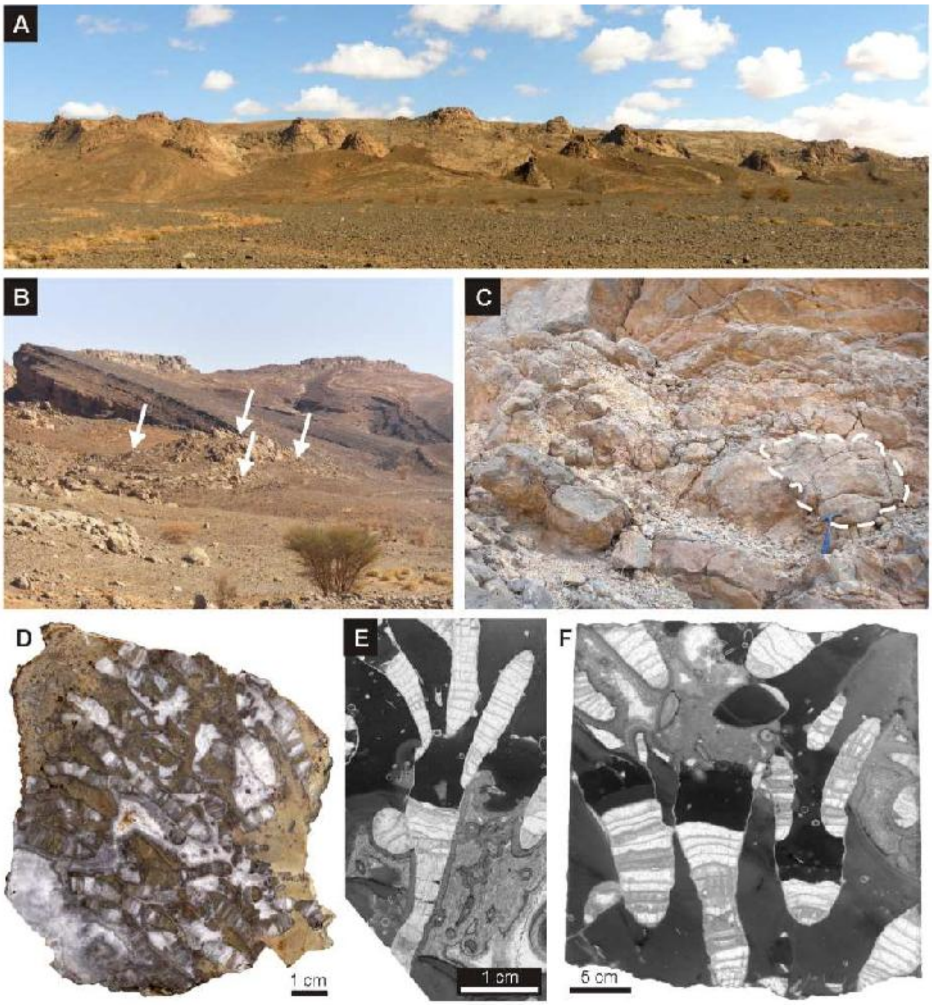

Fig. 1. A - The Hamar Laghdad ridge seen from the south. The carbonate mounds are ca. 40 m high. **B.** '*Amplexus*' occurrences distributed irregularly within the small (ca. 30 x 50 m in outline), Givetian mud mound. **C.** '*Amplexus*'-bearing carbonate lens (bordered) within the Pragian limestones. Hammer for scale. **D.** Densely packed '*Amplexus*' specimens from the Pragian assemblage. **E-F.** 'Calice-in-calice' growing '*Amplexus*' corals from the Eifelian hydrocarbon seep deposits ('Hollard Mound').

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Tropical and cold-water reef systems through time

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Cold-and-deep water reef systems exhibit a larger geographic distribution than tropical, shallow water reefs in the modern oceans. However, their geological record is sparse before the late Pliocene-Pleistocene. There are three potential reasons for the apparent scarcity of ancient cold water reefs: (1) Cold-water reef growth occurs largely in deeper water and, due to plate tectonics, deep water sediments are recycled at higher rates than shallow water sediments; (2) cold-water reefs are much more common in the geological record than currently recognized but geoscientists have overlooked them owing to their biased interpretation towards tropical systems; (3) cold-water reefs develop only under specific oceanographic conditions, which have been rare in the past.

While the scarcity of deep-water carbonates in older settings is often noted (Walker et al., 2002) and certainly not all ancient cold-water systems have been recognized as such, I argue that cold-water reefs were indeed relatively rare through the Phanerozoic.

On a global scale, ancient cold-water reef systems can be distinguished if they differ from tropical reef systems in significant attributes such as taxonomic composition and structure and if the differences agree with systematic changes in environmental settings or geographic distributions indicating colder and/or deeper water for the cold-water systems.

Applying these criteria, I have previously recognized that distinct high-latitude reef provinces (and by inference cold-water reefs) are only common when the earth was in an icehouse mode, that is, in the Late Ordovician, the Late Carboniferous to Early Permian, the earliest Paleogene and the Neogene/Quaternary (Kiessling, 2001).

Although the key builders of cold-water reefs have changed substantially over time, high-nutrient requirements seem to be a universal attribute. Steep latitudinal temperature gradients and well-oxygenated deep waters (rare during greenhouse episodes) appear to be the major precondition of cold-water reef formation at global scales, whereas tropical reef systems were always present, although with highly variable quantity and composition.

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PaleoReefs Database: Insights into the long-term evolution of carbonate mound systems

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The PaleoReefs Database (PARED) has been developed over the last 15 years to compile information on ancient (Pleistocene and older) reef systems. The database currently yields information on more than 4000 reef sites. A broad reef concept is applied such that data on true reefs and mounds as well as on tropical and cold-water reefs are available.

Data on each reef site is coded numerically on reef age, environmental setting, size, geometry, and composition such that reef development over time can be evaluated in a straightforward way. All reefs are linked to paleogeographic maps such that their distribution can be assessed in relationship with inferred paleooceanographic parameters (http://www.paleo-reefs.pal.uni-erlangen.de/).

The detailed taxonomic composition of most reefs is freely available in the Paleobiology Database such that biodiversity patterns can be explored in full detail (http://paleodb.org).

The lecture will highlight major features of PARED and demonstrate how the database may be useful for the scientific goals of COCARDE.

Carboniferous hydrocarbon bearing mounds. Hydrocarbon producing fields, coeval analogue and recent mounds as keys for understanding reservoir characteristics

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Carbonate mounds, Paleozoic in age, are known as hydrocarbon producing reservoirs. They are developed on continental margins, in water depths ranging 1000 to 10's m. The understanding and the evaluation of these reservoirs are not straightforward; the search for coeval analogues is always on. Hopefully outcrop analogues, time and environment equivalent, as well as pro-parte recent carbonate mounds systems, represent a tool to better appraise ancient mound carbonates.

This paper focuses on Carboniferous hydrocarbon bearing mounds. The Mississippian Period (Early Carboniferous) is well known for widespread development of carbonate mud mounds in various regions in Western and Eastern Europe, Kazakhstan and North America. Carboniferous time was a period of extensive mound and reef building on a global scale by a wide variety of organisms playing a role in the colonization, binding, trapping and sediment stabilization. Waulsortian-type mounds are abundant with a characteristic assemblage of bryozoans and crinoids. They are shallow to deep-water deposits often located on a positive topographical bump and formed by the conjunction of algal or microbial binding and baffling caused by bryozoans (Bridges et al, 1995). These carbonate mounds develop under favorable hydrodynamics and water depth along the platform, sometimes, some mounds may be associated with structures or vents, these seep mounds exhibit a distinctive chemoautotrophic biota (Ahr and Stanton, 1997).

Conventional oil is currently produced through several North American oil fields (Bowar, Bindley, Dickinson and other fields), as well as Kazakhstan (Tengiz, Kashagan slopes).

Heavy oil bearing mounds have been drilled in Alberta in the Pekisko formation of the Peace River Embayment (Davies et al, 1990). Heavy oil is trapped within core mound, muddy off-mound facies remaining tight. Late hydrothermal dissolution/karstification processes have enhanced as often their reservoir characteristics (e.g. in Kashagan or Tengiz fields). In opposite hand, Upper Harrodsburg oil reservoirs (Mississippian, Illinois) occur in bryozoan mound aprons (Jobe and Saller, 1995).

Outcrop analogues are abundant, amongst them, the Upper Paleozoic carbonate outcrops of the Bolchoi Karatau of southern Kazakhstan expose bryozoans mounds. Their mapping revealed complex bodies made of superimposed carbonate lenses. They appear located as cluster, commonly disposed on paleobathymetric lines. They show significant facies change, both laterally and vertically. The carbonate build-ups mostly of microbial origin consist of mudstone to wackestone, with locally packstone limestone. They are not framework supported but mud-supported, frequently cemented (cementstone). A few are partly dolomitized. Their bioclastic content consists of crinoids, sponges, bryozoans and brachiopods (Lapointe et al, 1999).

The impact of early diagenesis on carbonates induced dissolution, precipitation, dolomitization, that modifies the porosity and permeability distribution. It is appraised from cored wells and both the modern mounds and ancient outcrops.

The late diagenesis, which is responsible for the present day reservoir characteristics, is identified from cored wells, ancient outcrops and the knowledge of the modifying processes (dissolution and cementing) ubiquitous in the carbonates.

For the exploration, the knowledge of the basin settings as well as the type of sole where the mounds develop is a first step, and then the palaeo-environmental parameters that control mounds growth and their demise.

The cyclic record observed in recent carbonate mounds may be a primary template to understand the reservoir compartmentalization particularly for Icehouse period.

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Spatial and Temporal Patterns and Controls on Cold Water Coral Reef development: The Moira Mounds, Porcupine Seabight, Offshore Ireland

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The initiation and development of Cold-Water Coral (CWC) bioconstructions, from the colony through to the mound stage, are still poorly understood. Our research focuses on small-sized mounds (Moira Mounds, Porcupine Seabight, West of Ireland), considered by Wheeler et al. (2011) as an example of the early stage growth phase of nearby giant coral carbonate mounds. The goal of the project is to combine detailed surface and core features of representative Moira Mounds in order to understand their evolution through time.

We utilise a broad range of data including: high resolution Multibeam data, high definition ROV video data and grab-samples collected during the VENTuRe survey (2011) along with box cores collected during the Eurofleets cruise E-CWC Moira (2012). With this information, we are constructing a 3D video mosaic of a particular Moira Mound, that will aid us to develop the first total-reef scale habitat zonation model of this kind. In addition, a combination of particle-size, percentage carbonate and palaeontological analyses of the box core samples will be used to help determine the recent evolution of this mound.

Thus far, preliminary results of the Eurofleets cruise (Spezzaferri et al., 2012) have allowed to outline and classify a series of facies in the western chain of Moira Mounds. In order to better understand the factors which trigger mound initiation and development, the project seeks access to ship-time, longer core equipment and a lander system in 2014. The longer core material will allow accurate determination of reef initiation and development and could confirm that the Moira Mounds are first generation "Scleractinian spaced cluster macro-reefs" (Wheeler et al. 2011) . In addition, the lander system equipped with current metres and sediment traps will be used to determine how these reefs are currently baffling sediment and the rate at which it occurs.

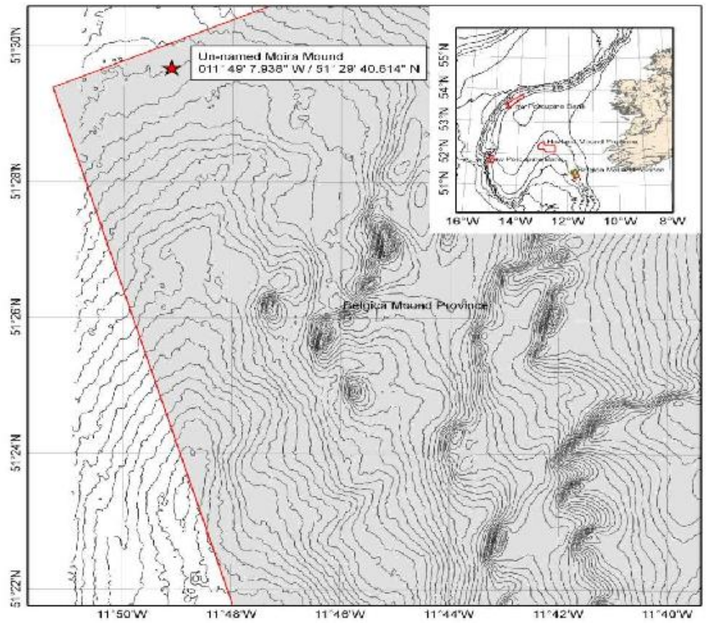

Fig. 1 - Location map showing the position of the Moira Mound study site relative to Ireland

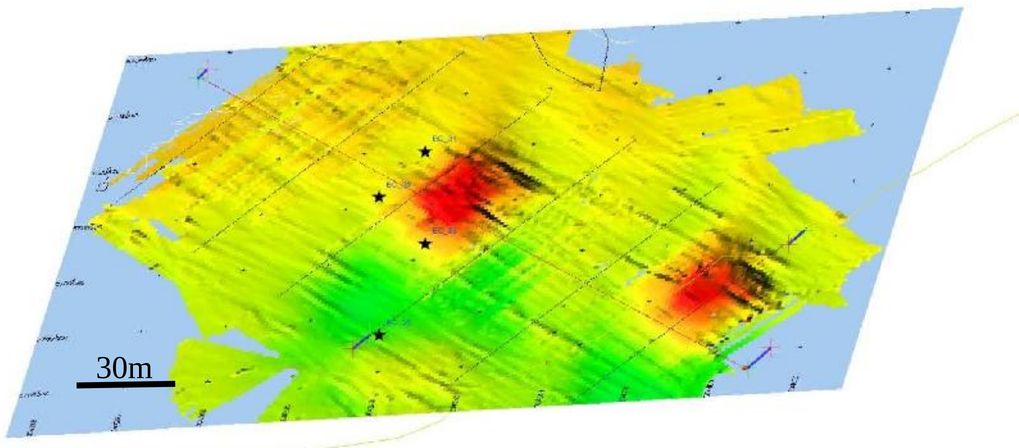

Fig. 2 - Unprocessed microbathymetry of two Moira Mounds, one of which is being used to make a 3D video mosaic. Black stars indicate the location of box core samples around this mound. Mound diameter is approx. 33m.

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Sedimentation patterns in Atlantic and Mediterranean cold-water coral mounds

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Carbonate mounds occurred throughout the Phanerozoic and provide valuable paleoceanographic archives stored in their sedimentological patterns, through their changing biological players involved in their build-up, as well as through geochemical signatures. From the investigation of recent mounds we can gain insight into driving mechanisms, which are valuable for the understanding of past mound accretion.

Among the recent build-ups in intermediate and deep-water settings cold-water coral mounds do play a major role. Cold-water corals are widely distributed in the North Atlantic and the Mediterranean. Some of the most prominent mounds are found on the Irish Margin in the Porcupine Seabight (−650 m) attain heights of over 150 m with a documented sedimentary record spanning ~3 Ma within a single mound (IODP-core U1317E). Their fossil record onshore extends back at least to Early Tertiary with spectacular outcrops in Italy, for instance around the Strait of Messina (Plio-Pleistocene) or in the Northern Apennine (Miocene).

Intense geochronological investigations in the North Atlantic (*e.g.* Frank et al. 2011, *Geology*) and the Mediterranean Sea (*e.g.* McCulloch et al. 2010, *EPSL*) have unveiled a strong climatic and oceanographic coupling of cold-water coral mound accretion phases. North of ~55°N all cold-water coral mounds turned out to be exclusively interglacial. South of ~55°N corals grew additionally also during interstadial and glacial conditions, while in the Mediterranean an predominance of coral ages was found during the Younger Dryas (~12.8 to ~11.7 ka BP).

The sedimentation patterns of the interglacial cold-water coral mounds in Stjernsund (northern Norway, 72°N, −300 m) are the focal point here to illustrate mound accretion patterns. Based on U-series dating, these cold-water coral mounds show a Holocene growth which commenced just after the cold Younger Dryas, during the onset of the warmer Preboreal ~11 ka BP (López Correa et al. 2012). The mound deposits in Stjernsund are constructed by frameworks of *Lophelia pertusa*, while the matrix is generated from a mixture of siliciclastic background sediments and from biogenic carbonate components and carbonate mud. In Stjernsund the background is entirely free of carbonate and hence all carbonate mud is derived from *in situ* production on the mounds. Across the Holocene bulk carbonate concentrations show a typical increase from ~20 to ~30 %, with peaks of >50 % coincident with hiatuses (Fig. 1). The latter horizons are characterized by fragmented corals and reflect either periods of non-deposition or of slow coral growth and concomitant erosion. These hiatuses are particularly conspicuous in computed-tomography scans through the absence of intact coral frameworks, increased fragmented corals and shell hash, as well as through an increased X-ray density of the matrix sediment. These hiatuses appear to be frequent and constitute the rule rather than the exception and occur in most Atlantic and Mediterranean mounds.

Densely spaced U-series ages provide an account of astoundingly fast vertical mound accretion rates of up to ~615 cm/ka (Fig. 1), but also of frequent hiatuses, which span several centuries to several millennia (Fig. 1).

Douarin et al. (2013) have also documented frequent hiatuses in the Scottish Mingulay Mounds. Their well constrained U-series and ^{14}C ages showed a similar coral growth timing as in Stjernsund and as in coral mounds on the Irish Rockall Bank (Frank et al. 2009, Marine Geology). It is indeed tempting to interpret these phases of lacking sediment records in terms of overarching paleoceanographic patterns. For the Irish and Scottish mounds the cyclic changes of the Subpolar and Subtropical Gyre may be responsible for the observed patterns. For Northern Norway we know from independent off-mound records in Stjernsund that the hiatuses are though not accompanied by paleoceanographic changes. Here, auto-cyclic growth patterns of the coral frameworks appear to be the guiding mechanism. Based on grain-size patterns of carbonate components of the encasing matrix, an increase in current speed can be deduced for each cycle topped by an hiatus. This implies that coral colonies reach maximum sizes based on the local bottom current speed, until a maximum threshold level for the polyp feeding-efficiency is reached.

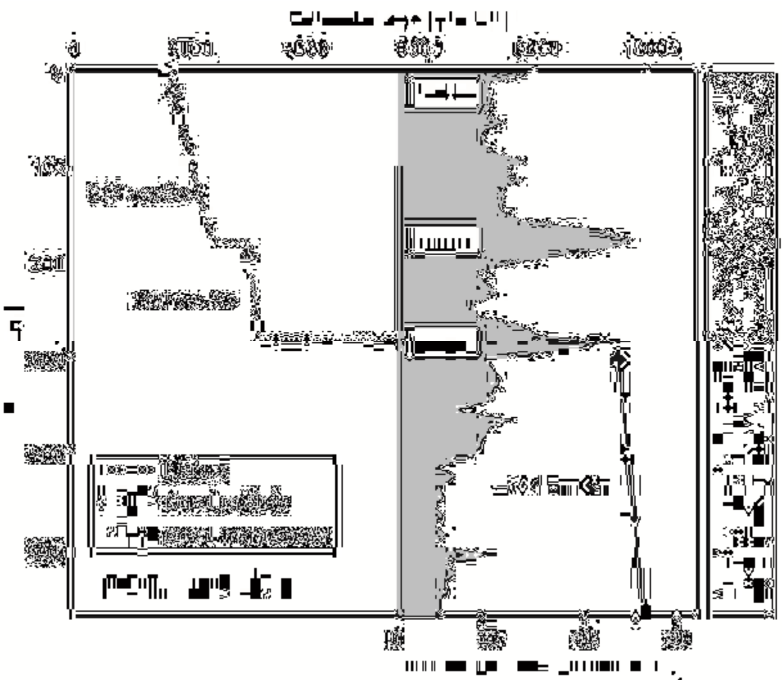

Fig. 1 - Sedimentation and chronological pattern in a Holocene cold-water coral mound in Stjernsund, northern Norway (adopted from López Correa et al. 2012). Note the rapid vertical mound accretion rates as well as the up to ~6 ka spanning hiatuses - evident from U-series ages. Peaks in the bulk carbonate concentrations are centered over the hiatuses and document coral fragmentation and winnowing of the siliciclastic matrix

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Upper Triassic atoll-type carbonates from Sambosan Accretionary Complex, Southwestern Japan: sedimentology, conodonts biostratigraphy and paleoecology

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Upper Triassic shallow water carbonates have been extensively studied in the Tethys. Conversely, mid oceanic shallow water carbonates of the Panthalassa remain poorly understood.
In this contribution, we aim to improve our understanding of mid oceanic shallow water carbonates of the panthalassic domain.

In order to achieve this objective, microfacies analysis, conodont biostratigraphy and paleoecological studies are performed on the Upper Triassic limestone of the Sambosan Accretionary Complex (SAC), Southwestern Japan.
Indeed, several limestone slabs crop out in this subduction-generated accretionary complex, associated with basalts, breccias, cherts and mudstones. These units are interpreted as atoll-type limestone, intra oceanic seamount basalts, seamount flank deposits, pelagic siliceous sediments and trench-fill sediments respectively. According to the Ocean Plate Stratigraphy concept, most of these units represent accreted remains of panthalassic seamounts capped by Upper Triassic atoll-type carbonates.

The ongoing analyses show that most of the characteristic Tethyan Upper Triassic microfacies (e.g. Involutinid dasycladacean wackestone) are present in the SAC. Thus, a depositional setting reconstruction could be proposed, based on comparisons with the Tethyan carbonates. However, for limestones crop out as discrete units in a tectonic mélange, this reconstruction needs better constrains. Therefore, a conodonts biostratigraphy is being performed in order to allow accurate correlation of distant limestone units. Furthermore, quantitative analyses will also improve our understanding of the role of the different organisms and especially the microbial activity, in structuring the build-up frame.

This integrated study would lead to a better constrained depositional model, which can be compared with similar settings in the Panthalassa domain and in the Tethys as well.

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Organic reefs and carbonate mud mounds: the broad view

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Organic Reefs are in place calcareous deposits created by sessile organisms (Riding, 2002). During the Archean and Proterozoic microbes formed stromatolite and then thrombolite reefs by the calcification of biofilm and mats. During the Phanerozoic algal and invertebrate calcification created more complex structures, often together with microbial carbonates. Carbonate mud mounds have remained difficult to interpret due to the difficulties of discriminating between a variety of possible origins for their principal component: fine-grained carbonate sediment. Thus, the organisms and processes involved in organic reef formation are sometimes obvious, as in skeletal reefs. In other cases they can be obscure, as in many microbial carbonates and carbonate mud mounds. Nonetheless, organic reefs have three principal components: matrix (M), in place skeletons (S) and cavity/cement (C), whose proportions can be represented on MSC triangular plots. Separately or together, these components provide the structural support for the reef and can be used to distinguish (1) Matrix-supported reefs (Agglutinated Microbial Reefs, Cluster Reefs, Segment Reefs), (2) Skeleton-supported reefs (Frame Reefs), (3) Crust ('cement')-supported reefs (Crust 'Cement' Reefs).

AGGLUTINATED MICROBIAL REEFS: possess laminated, clotted, or aphanitic fabrics created by microbial trapping of particulate sediment; in place skeletons and large primary cavities are rare; early cementation may provide added support; topographic relief is limited by the need for currents to provide sediment to accreting surfaces.

CLUSTER REEFS: skeletal reefs in which essentially in place skeletons are adjacent, but not in contact, resulting in matrix support; characterized by relatively high matrix/skeleton ratios and low volumes of extra-skeletal early cement. Sediment trapping is an important corollary of skeletal growth and Cluster Reef organisms are tolerant of loose sediment. Absence of framework limits the topographic relief that Cluster Reefs can attain relative to spatial extent, and may permit bedding to develop within the reef. Close Cluster Reefs have skeletons up to 1 unit-distance apart. Spaced Cluster Reefs have skeletons more than 1, and up to 2 unit-distances apart; with increasing separation of skeletons they grade to level-bottom communities.

SEGMENT REEFS: matrix-supported reefs in which skeletons are adjacent, and may be in contact, but are mostly disarticulated and mainly parauthochtonous. Matrix abundance is high, and early cement relatively low. Moderate relief can develop in response to intense on-reef sediment production.

FRAME REEFS: skeletal reefs in which essentially in place skeletons (including calcified microbes) are in contact; characterized by relatively high skeleton/matrix ratio. Skeletal support enables them to raise themselves above the substrate independently of cementation and particulate sedimentation. Simultaneously, by creating partly open shelter cavities, skeletal support may facilitate early cementation.

Both relief and early lithification promote marginal talus formation. Skeletal shape and orientation distinguish: conical/stick-like, dendritic, domical, and laminar frames. Each of these may be open or filled. Open Frame Reefs: cavities remain open during the early stages of reef growth and are occupied by cryptic encrusters, early cements and internal sediment; exposed skeleton encourages endoliths. Filled Frame Reefs: inter-skeletal spaces penecontemporaneously occluded by surficial sediment during reef-growth.

CRUST ('CEMENT') REEFS: reefs created by cementation of essentially in place organisms. Precipitated crust provides strength and volume, mimicking skeletal growth, and can form on non-skeletal as well as skeletonized organisms.

NON-SKELETAL CRUST REEFS: created by synsedimentary lithification of essentially in place non-skeletal organisms. This converts a soft deposit with relatively poor preservation potential into a rigid lithified mass: e.g., Tufa Reefs (phytoherms) in rivers and lakes, cold seep carbonates, and possibly Travertine Reefs associated with hot springs.

If the organisms are skeletal, synsedimentary cementation imparts extra strength and stability to what otherwise would be a Cluster or Frame Reef, and results in Skeleton–Crust/Cement Reefs. Crust/Cement Reefs exhibit complex relationships between cement, matrix and skeletons.

Agglutinated Microbial, Cluster and Segment reefs tend to be structurally simple, have low primary relief, and may show bedding. Frame (including microbial Microframe) and Crust/Cement Reefs tend to be unbedded, structurally complex, and can have high relief.

CARBONATE MUD MOUNDS: carbonate mud-dominated deposits with topographic relief and few or no stromatolites, thrombolites or in place skeletons. Low Relief Carbonate Mud Mounds are typically thin. High Relief Carbonate Mud Mounds are thick, and internal bedding, slumping, stromatactis cavity systems, and steep marginal slopes may be common. Whereas Organic Reefs are biogenic, calcareous, and are created by essentially in place organisms, Carbonate Mud Mounds can be organic and/or inorganic in origin and it can be difficult to distinguish their origins.

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The challenge of Devonian-Mississippian carbonate mud mounds

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Carbonate mud mounds are unusually abundant in the Late Devonian-Early Mississippian. A sediment baffling origin has been suggested, but a suitable source of off-mound carbonate mud has been difficult to identify. Late Devonian changes in atmospheric composition, particularly p_{CO2} reduction and p_{O2} increase, may have been sufficiently large to induce CO_2 concentrating mechanisms (CCM) in phytoplankton. CCM act to maintain photosynthesis, and include active transport of HCO_3^- into the cells that can lead to extracellular pH rise and precipitation of fine-grained carbonate ('whitings') in the water column when carbonate saturation state is sufficiently elevated. It is proposed that Late Devonian-Early Mississippian whitings promoted mound development by generating mud off-mound whose import substantially augmented any on-mound carbonate production. Coeval increase in benthic calcified cyanobacteria supports elevated carbonate saturation state and CCM induction, and potential increase in primary productivity stimulated by CCM induction is consistent with organic carbon rich anoxic sediments and large positive $\delta^{13}C_{PDB}$ excursions at this time.

A number of sedimentary features commonly associated with Late Devonian-Early Mississippian mud mounds are consistent with current-driven accumulation of fine-grained carbonate. These include: (i) formation in a wide range of water depths; (ii) orientation, asymmetry, lateral progradation and amalgamation, (iii) grainstone haloes; (iv) presence of current-reliant filter feeders (bryozoans, crinoids, sponges); (v) layered structure; (vi) collapse structures (stromatactis and slumps). Carbonate mud derived from phytoplanktic whitings can be rich in organic matter. This could have promoted microbial lithification (e.g., by bacterial sulfate reduction) that contributed to the formation of clotted-peloidal microfabric. Thus, whiting processes could have been the primary mud source and also have created conditions favouring syndepositional on-mound early lithification. In this view, on- and off-mound microbial processes were mutually related, with off-mound mud production being mediated by cyanobacterial oxygenic photosynthesis and on-mound lithification mediated by heterotrophic mineralization of whiting organic matter.

The COCARDE Carbonate Mound Database – example for time-slice 33 (Pleistocene–Holocene)

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In the milestone publication of Kiessling and Flügel (2002) an extensive database is presented on pre-Quaternary Phanerozoic reefs including standardized information on (paleo)position, age, reef type, dimensions, environmental setting, paleontological and petrographical features, as well as reservoir quality. This database differentiates between 32 time slices (Golonka and Kiessling, 2002) comprising the occurrence of different carbonate build-ups (shallow and deep marine) during the earliest Cambrian to the late Miocene-Pliocene. The focus is on reefs, defined as laterally confined carbonate bodies built by sessile benthic aquatic organisms differing between 1) true reefs, 2) reef mounds, 3) mud mounds, and 4) biostromes (Kiessling et al., 2003).

Within the COCARDE network the setup of a carbonate mound related database has been initiated and will be further developed and discussed during and after the COCARDE workshop and field seminar in Sicily, Italy (23-27.09.2013). The aim is to focus on carbonate mounds and/or build-ups in general, not limited to the marine realm but including lacustrine, fluvial, spring- or seep-related carbonate precipitates that create a 3D structure – the whole variety of carbonate mounds.

"New views on old mounds" is the principal scientific objective of the European Research Network COCARDE. Throughout Phanerozoic times, mounds have represented recurrent strategies of Life, and an exemplary mode of Geosphere-Biosphere coupling. Partly, these mounds are considered within the Paleoreef Database of Kiessling et al. (2003). However, with the *new view* we would like to focus on carbonate mounds through time starting from the Recent Ocean. We present an example of the Pleistocene-Holocene time slice 33 summarizing the known occurrences of cold-water coral mounds but also integrating other carbonate mound systems differing between mounds in the marine vs. continental realm, pure biogenic deposits vs. spring and seep-related authigenic carbonates, and microbial build-ups vs. bioclastic mounds. Comparable to the Paleoreef Database, we aim to link equivalent metadata of each identified occurrence to existing publications and other information of the mound and/or province.

This presentation is meant to be a basis for discussions and improvement of the envisaged database with the input of all workshop and field seminar participants.

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Rhodolith-bryozoan carbonate factories: the Pleistocene Castelluccio example (NE Hyblean Plateau)

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Rhodalgal and Bryomol facies are widespread in the Pleistocene sediments bordering the Hyblean Plateau where layers, referred to the Emilian, have been documented, particularly from north-western sectors.

An exceptional exposure of these facies is present on the north-eastern margin of the Plateau, along the present-day coastline incised by the S. Calogero River, near Castelluccio, North of Augusta. These carbonate sediments, whose Pleistocene age attribution requires further definition, lay on an irregular and partly erosive surface cut in alcalibasalts and volcanoclastics, and are marked by a basal discontinuous gravelly layer.

Rhodolith-rich layers, a few decimetres to about 1 metre thick, are rudstones to grainstones, with basal sharp contacts on flat to undulating surfaces. Rhodoliths range from few to 12 cm in diameter, are spheroidal to ellipsoidal and commonly protuberant. They are monospecific to oligospecific, dominated by *Lithothamnion* spp. in association with rare fragments of unidentified *Mesophyllum*, *Lithophyllum* and *Peyssonnelia*.

Bryozoans represent a subordinate fraction, as encrusting minor contributors to rhodolith formation, or as delicate erect branching or celleporiform dispersed in the sediment. Bryozoan-rich packstone layers, 30 to 50 decimetres thick, have sharp-to-transitional basal surfaces and a gravelly fraction almost entirely composed of erect delicate branching bryozoans, mostly oligo-to-monospecific (*Smittina cervicornis*). Bryozoan branches are lightly fragmented, although mostly sub-horizontally placed and a selection of different branch thickness can be observed in certain layers. Some decimetre-up to more than 1 metre-thick wackestone layers are interposed in between, including some nearly entire, decimetre-sized, erect delicate branching bryozoan colonies (particularly, *Hornera frondiculata*). Very thin to some centimetres thick pectinid lags, as well as layers enriched in volcanic pebbles, are present at different heights along the section.

Bioturbation is a common feature, becoming pervasive in wackestone layers. Vertical, branched *Ophiomorpha nodosa*-like trace fossils have been found, forming three-dimensional structures, which cut thin storm deposits. Many holes of shafts are visible in plane view. These trace fossils document an intense activity of crustacean decapods, probably referred to Fam. Callianassidae. Other cone-shaped, vertical trace fossils have been found but need a further, accurate investigation of shape and distribution.

These sediments presumably formed during the development of a carbonate ramp system, as proposed by Pedley & Grasso (2002), and particularly, at or near the middle-outer ramp transition, some layers in the inner ramp. The succession, showing a certain rhythmicity, documents repeated slight changes in relative water depth alternatively fostering the development of rhodolith pavements or erect branching bryozoan carpets.

The onset of the different benthic communities was probably driven by small scale climatic oscillations (and the possible concomitant variations in ecological conditions among which mostly, water temperature/salinity, light penetration, hydrodynamic energy, nutrient/food availability, sediment input and sedimentation rate) in the framework of the tectonic uplift of the entire area. Sharp basal surfaces of coarser (rhodolith-bearing) layers could point to rapid shallowing episodes including partial erosion of sediments, possibly within the storm weather wave base.

The comparison of these Pleistocene facies with modern analogues from the Mediterranean will be of great interest, in order to investigate the role of the taphonomic filter and to attain a more precise paleoecological reconstruction.

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COCARDE -ICA and -ERN
A global network to study the "rocks of life"

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Carbonates are important contributors of life in different environmental settings, from warm-water to cold-water, shallow to deep and throughout the geological history. They are the key-players in the biosphere-geosphere coupling to deserve the appellation of *"rocks of life".*

The initial network COCARDE (Cold-Water Carbonate Reservoir Systems in Deep Environment) was conceived in Ghent in 2008. Its two off-springs COCARDE-ICA supported since 2009 by the FWO and COCARDE-ERN launched in 2011 and funded by ESF aim at investigating carbonate mounds in space and time and in the various geological settings where they are formed. These complementary networks represent an ideal platform to apply a flexible and modular Industry-Academia Partnership to consolidate sustainable carbonate mound research and capacity building. Their synergy has the potential to shape the COCARDE Network to a global dimension; COCARDE-Canada and COCARDE-USA are taking shape and will get on tracks in the near future.

Milestones of COCARDE-ICA and -ERN are:

- The ESF Magellan COCARDE Workshop in Fribourg, Switzerland, January 21-24, 2009.
- The ESF MiCROSYSTEMS – FWO COCARDE Flanders – ESF CHECREEF Workshop and Field Seminar, Oviedo, Spain, September 16–20, 2009.
- The COCARDE Workshop and Field Seminar in Rabat and the Moroccan Sahara in October 2011.
- The COCARDE Fluid flow-related carbonate build-ups: from lacustrine to (early) marine environments – *The Ries Impact Crater as a Natural Laboratory*, Nördlingen, Germany, 15-19 October 2012.
- The COCARDE Eurofleets CWC Moira cruise, on the RV Belgica in June 2012, along the Irish off-shore.
- The COCARDE Eurofleets Mediterranean Gateway cruise on the RV Marion Dufresne, June 2013, along Cadiz-Alboran Gateway.

The Workshop "Bridging off-shore and on-land research on carbonate mounds: common concepts and techniques", Catania 23-27 September 2013 is the logical and successful continuation of synergy among the carbonate mound scientific community.

Hydrocarbons, carbonates & corals: conflict and friendship

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As seen in both fossil and recent situations, hydrocarbon-derived limestones and cold-water corals may occasionally occur in strict adjacency. This observation lent some support to the hypothesis of a direct causative link between the seeping of hydrocarbon-rich fluids and the onset of complex megabenthic communities dominated by corals that gain advantage of an enhanced, albeit unconventional, trophic web in the deep-sea (e.g. Hovland & Risk 2003).

One interesting case-study is offered by a Pliocene-age outcrop in the Piedmont Apennines of northern Italy where methane-imprinted limestones and marlstones with chemosymbiotic bivalves embed deep-water coral scleractinians and other non-chemosymbiotic macrobenthos. Fossil examples of this intimacy are scarce and somewhat difficult to decipher since all ingredients are no longer active, resulting inconclusive on this is issue.

Recently, a field of carbonate chimneys unquestionably representing former expulsion of methane-enriched fluids through the sediments onto the seafloor, has been identified in the southern Adriatic at bathyal depths (440 m) on the Montenegrin margin (Taviani et al 2013, and work in progress). This chimney palisade is an unburied relic of a defluidisation process ended in the late Pleistocene. Once exhumed, these carbonate chimneys may serve as a substrate to the settlement of a variety of live sessile megabenthic organisms including serpulids, sponges, cnidarians such as skeletonised scleractinians (e.g. *Madrepora oculata*) that contribute to the general seascape (Fig. 1). This case-study provides an important actualistic example giving an important hint to interpret fossil situations where precise age assessments cannot be ensured but only derived. In fact, while these two worlds (hydrocarbon-imprinted limestones and corals) are definitely topographically mixed, they are nevertheless distant in time.

In summary, as available evidence seems to suggest, the co-occurrence of two contrasting situations in the same place could be only apparent and the role of hydrocarbon fluid expulsion could be rather passive and limited to authigenic carbonate precipitation driving to the formation of hard substrates exploitable by standard deep-sea marine life without invoking a straightforward trophic link.

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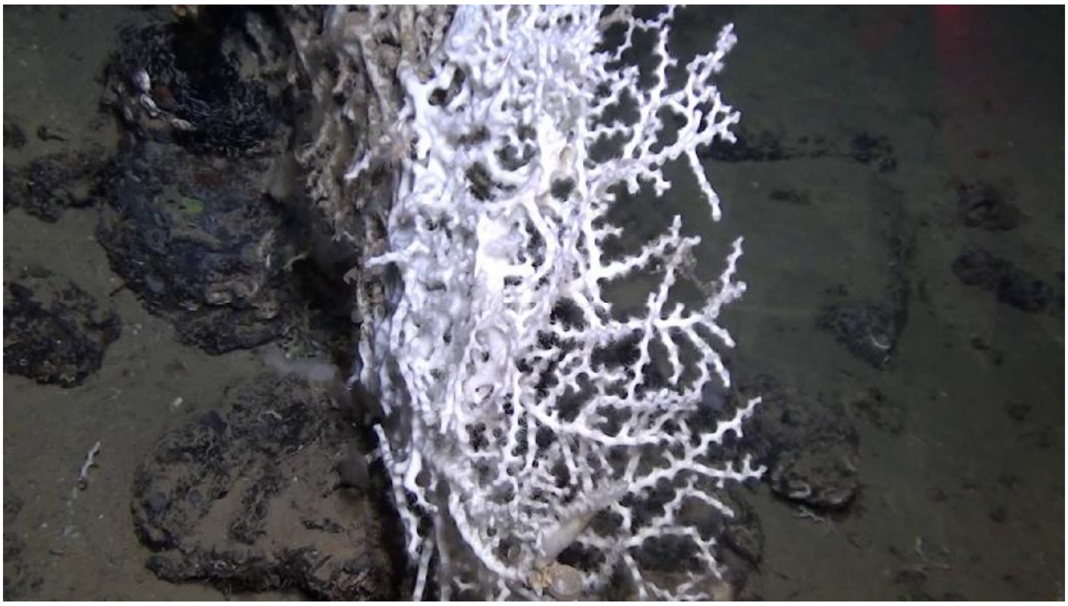

Fig. 1 – Exhumed carbonate chimneys colonized by live *Madrepora oculata* at 440 m in the southern Adriatic off Montenegro (ROV picture taken in January 2013 during RV *Urania* cruise ALTRO (EU project COCONET)

Block Rotation Linked to Southward Right-Stepping Propagation and Overlap of the Red Sea Rift Segments, Afar Depression; Insight from Paleomagnetism

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In September 2005 hundreds of teleseismic events occurred in the Manda Harraro segment of the Red Sea Rift with a volcanic eruption at Dabbahu and a 60 km long crack opening. As part of long term geodetic and seismic monitoring a paleomagnetic investigation was carried out in this region.

Thirty-four cooling units from the Pleistocene extrusive volcanic rocks in the northwestern central Afar depression were sampled for paleomagnetic study. Seven to twelve samples were collected from each cooling unit and on average 5 samples per unit were treated with Alternating Field (AF) demagnetizations while one sample was treated by Thermal (TH) demagnetization technique for a check, all at the department of Earth Sciences of Addis Ababa University.

The Natural Remanent Magnetization (NRM) direction reveals two simple and straightforward components of magnetizations. Generally, the first and low stability component is isolated by heating to 100ºC-300ºC or by AF of 10-20mT. The magnetization directions after these steps have defined straight lines that are directed towards the origin, which are then interpreted as primary NRM or ChRM (Characteristic Remanent Magnetization).

Results of the magnetization decay curve plots and rock magnetic analyses using Variable Field Translation Balance (VFTB) analysis at the paleomagnetic laboratory of LMU, Germany indicate magnetic mineralogy is Ti-poor titano-magnetite, with minor goethite and maghemite with magnetic grain sizes within the pseudo single domain range. The paleomagnetic site mean directional analyses reveal, 3 reversed, 30 normal and 1 transitional direction.

An overall mean direction calculated for 26 sites located within the overlap region (excluding the transitional direction and 6 sites outside the overlap) resulted in Dec=354.4^0, Inc=13.2^0 (N=26, K=43.5, α_{95}=4.3^0). When this value is compared with expected Geomagnetic Axial Dipole (GAD) Field from Apparent Polar Wander Path (APWP) Curve (Besse and Courtillot, 1991, 2002), a difference in declination ΔD=-6.5^0±4.0^0 is obtained. This negative declination difference is interpreted as counterclockwise rotation about a vertical axis, in agreement with rift propagation and right stepping overlap geometry of the Alayta–Dabbahu magmatic segments.

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A Lower Miocene cold seep system at Roccapalumba (Sicily): geology, paleobiology and isotope geochemistry

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Hydrocarbon-related carbonate deposits are common in the Neogene of Apennines and Sicily. They are traditionally named "Calcare a *Lucina*" (*Lucina* Limestone), and mainly consist of isolated carbonate masses embedded in deep-water siliciclastic deposits (Clari et al., 1988; Taviani, 1994).

Here we outline the geological and sedimentological context, as well as the paleobiology and geochemistry of an exceptionally large, Lower Miocene *Lucina* limestone that crops out near the town of Roccapalumba, western Sicily (Tripodo, 2000; Cavalazzi, 2007; Fig. 1).

The *Lucina* limestones are embedded in the Numidian Flysch that in the Roccapalumba area shows a very complex geological context because of the local regional thrust.

The Roccapalumba carbonate deposit mostly consists of foraminiferal-bearing authigenic micrite with a detrital siliciclastic component and abundant macro-invertebrate assemblages including densely packed lucinid-like shells. Methane-induced microbial fabrics and textures, and carbon stable isotopic evidences have also been discussed.

The complex network of veins and cavities and related biosedimentological features (e.g., peloidal and spheroidal cements, biominerals, biofilm remain) strongly suggest that these veins were acting as conduits for fluid migration or escape structures.

Fig. 1 - "Calcari a *Lucina*" of Roccapalumba, Sicily

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The AFAR system and carbonates

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The Afar systems offers a rather wide view of all geological processes operating during the various stages of implementation of an ocean, from the initial continental rifting up to the initial stages of oceanic crust construction. This implies the interference of various geological phenomena, including notably mantle upwelling, extension tectonics, basaltic magmatic production and differentiation, as well as erosion and sedimentation. This include mainly detrital but also carbonate sediments, of both continental (lacustrine) and marine origin.

Initiated in the mid-Miocene (25My), the Afar rifting process was preceded by the up-doming of the whole Afro-Arabian continent, with the resulting development of high altitude plateaus of Nubia, Somalia (both in Ethiopia) and Yemen (Tazieff et al. 1969; Barberi et al., 1973). Important basaltic emissions characterize that early phase, accompanied with acidic magmatic activity both as surface emissions (mainly tufs) and intrusion (alkali granites). The few sediments related to this sequence are dominantly detrital with a few lacustrine intercalations. One must note that this magmatic phase is posterior to the dominantly sedimentary sequence of Mesozoic age including Triassic sandstone, Jurassic limestone and Cretaceous sandstone (Adigrat series). If they characterize the plateaus, these sedimentary units are also observed in Afar, notably along both the western scarp (in Eritrea and Tigre) and the Danakil "alps" (a rotating crustal stretched block located between the northern Afar rift and the southern Red sea) as well as in the "Aisha horst" to the south-east (outcropping in Ali Sabieh region of Djibouti Republic as well as in eastern Ethiopia and N-W Somalia). Here the pre-rift carbonate sequences are intensively faulted (normal faults of dominantly Red sea direction) and eventually intruded by volcanic dikes (Black et al. 1972).

The next stage which lasted nearly 20My, was characterized by continental rifting, the products of which can be observed at present in the Easternmost extremity of Afar (north of Tadjurah in Djibouti Republic) as well as in central western Afar (Mille river area). These are essentially volcanic emissions, with both basaltic and alkali-rhyolite traps (Marinelli and Varet, 1973). In northern Afar, important sequences of detrital sediments are observed in the same period all along the foot of the escarpment,(the "red series") with both evaporitic and volcanic intercalations se sequences (CNR-CNRS Afar team).

A change occurred in around 3My ago, with the development of important basaltic activity constituting the "Afar stratoid series". These continuous eruptions of fissure flows all over the Afar floor, is interpreted as the first phase of oceanization of Afar (Barberi et al., 1973). No evidence of marine sedimentation was observed in this sequence up to now, but intercalated lacustrine carbonate layers are observed, notably in central and eastern Afar, in the upper part of this unit (Varet and Gasse, 1978).

Marine carbonate sediments only occur in Pleistocene, in Northern Afar, surrounding the Erta Ale range, from the Eritrean cost (gulf of Zula) to the north to the lake Afrera to the south, where they are recovered by more recent lacustrine deposits.

A several kilometers thick saline sequence of marine evaporitic origin characterize the axial part of northern Afar (Tazieff et al., 1969, CNR-CNRS Afar team, 1973) and extends underneath the Erta Ale range which, with other axial ranges, represent the first evidence of oceanic rifting in Afar (Barberi and Varet, 1977). This quaternary unit is presently the seat of intense mining exploration (potash, previously mined by Italian and US entreprises). The remnants of the shores of the former Danakil sea are observed all around the northern Afar depression (-120m) at the 0 level altitude. These include coral reefs, flat urchins as well as human occupation remnants.

Similarly, marine sediments also occur in south-eastern Afar, around the gulf of Tadjourah, which started opening with oceanic crust development and marine invasions since 3My (Varet and Richard, 1979). They are found on both sides of the gulf, in faulted and eventually tilted blocks where they cover the basalts emitted at the initial stage of the Afar oceanic rift opening. The outcrops are well developped on the shore of Obock, north of the gulf, where they constitute a wide coral-reef plateau lifted up to +120m (Varet, 1975) along both the Tadjourah gulf and Bab-el-Mandeb straight.

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NUTRIENTS INFLUENCE ON MIOCENE CARBONATE FACTORIES

My PhD studies are concerned with the interaction between nutrient availability in marine waters and benthic community on the shelf, in the fossil record.
Essential nutrients determine primary production and the amount of particulate organic carbon present in water has in turn effects on water transparency; oceanic circulation, upwelling currents and river runoff controls nutrients concentrations on global, regional and local scale.
With accurate paleontological analysis on both benthic and planktonic assemblages it's possible to extract information over nutrients, from the geological record, thus improving the knowledge of past environment and draw a more precise picture of the long term effects of eutrophisation caused by human pollution. The Miocene limestone of the Pietra da Cantoni Group (Northern Italy) and of the Calcareous Molasse Unit of the Sommières Basin (Southern France), which I'm currently studying, represent interesting examples of carbonate factories developed in nutrient-rich waters and hopefully will provide useful information on the subject.

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STABLE ISOTOPE CHEMISTRY OF FLUID INCLUSIONS IN CWC

I am currently conducting an MSc research project at the VU University in Amsterdam to study isotope fractionation effects in cold water corals, in specific the stable isotope chemistry, i.e. $\delta^2 H$ and $\delta^{18}O$, of fluid inclusions in these corals. Samples were collected during several cruises of the Royal Netherlands Institute for Sea Research (NIOZ) at the Rockall Trough in the North Atlantic Ocean. A unique continuous-flow crushing device and coupled mass spectrometry is used for on-line $\delta^2 H$ and $\delta^{18}O$, analyses of fluid inclusions present in the coral skeleton. Data show isotopic fractionation effects and the aim of this study is to gain further insight in these effects to support the use of cold-water coral skeletons as proxy database when reconstructing deep-water paleo-environments. The COCARDE workshop-field seminar would allow me to gain interdisciplinary knowledge and actively discuss topics in line with this study. The field excursion will provide a first-time field experience as well actively contribute to my understanding of cold water carbonate systems.

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VENTING- AND SEEPAGE-DERIVED MUD MOUNDS AND RELATED AUTHIGENIC BUILDUPS

My scientific interests focus on geology and palaeoecology of ancient and modern deep-water carbonate buildups, with special regard to the environments affected by hydrothermal venting and hydrocarbon seepage. My PhD studies concern venting- and seepage-derived mud mounds and related authigenic buildups found in the Hamar Laghdad ridge (southeastern Morocco). The investigations are aimed at interpretation of sedimentary environments and faunas of two Middle Devonian buildups located in the eastern part of the ridge. Both buildups host peculiar fossil assemblages, which are being systematically described in the course of my PhD studies and have been the subjects of my first publications. Except for the palaeontological and standard petrological and structural investigations, currently undertaken research comprises multidirectional geochemical analyses, which will aid in constraining the origin and migration pathways of fluids that contributed to the formation of the unusual palaeoecosystems under study.

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FROM WARM SHALLOW-MARINE CARBONATE PLATFORMS TOWARDS CARBONATE BUILD-UPS IN EXTREME ENVIRONMENTS

After working on warm shallow-marine carbonates for several years, I am highly interested in broadening my knowledge on other equally important carbonate systems, especially deeper-marine cold-water coral mounds and carbonates deposited in extreme environments. As I have mainly worked on fossil carbonates, one of my main interests is to understand the transition from recent sediments to rocks, and thus, the main mechanisms and drivers leading to lithification. The following questions concerning early carbonate diagenesis are in particular attracting my interest: Which compositional changes (facies, fabric and texture) occur during early diagenetic processes? What is the influence of a shallow sulfate-methane transition zone in the early lithification of carbonate mounds? Which is the specific role of microbes in carbonate precipitation and dissolution? How to better understand the processes associated to rock-fluid interaction playing a crucial role during early diagenesis in extreme environments? Participating in this workshop represents a great opportunity for me to meet the scientific community working on such questions, and thus, have the possibility to exchange ideas with other scientists.

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CURRENT WORK ON THE MOIRA MOUNDS, PORCUPINE SEABIGHT, OFFSHORE IRELAND

I have recently started a PhD at University College Cork, Ireland examining spatial and temporal patterns and controls on Cold Water Coral Reef development. The project has a particular emphasis on the Moira Mounds, Porcupine Seabight, offshore Ireland. A variation in reef vitality has been noted between the Eastern and the, lesser-studied, Western chain of Moira Mounds. Further gradation in reef vitality has been noted from North to South of the Western chain. We aim to examine the nature of this variation and make a more detailed examination of one mound. Data specifically available to this project include box-cores, microbathymetry and ROV video data. We will collect longer core material and lander data. We aim to develop a total-reef scale habitat zonation model of a Moira Mound with this high resolution dataset, examine contemporary sediment deposition patterns, and comment on their initiation and development.

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COMPARATIVE PALAEOECOLOGY OF BRACHIOPOD FAUNAS FROM LATE CRETACEOUS AND DANIAN CORAL MOUND AND SOFT BOTTOM ENVIRONMENTS

This study presents a comparison of brachiopod morphology, adaptations and ecology from two different environments: A Late Cretaceous (Maastrichtian) deep-water soft chalk sea bottom, and a middle Danian cool-water coral mound complex. The two different environments share several of the same brachiopod species and eight genera are present in both environments. The most abundant brachiopod species in the Faxe Quarry exhibit asymmetric folding of the frontal commissure. This form of asymmetry is not observed in brachiopods from the Maastrichtian. Cool-water coral mounds were established by the azooxanthellate scleractinian genera *Dendrophyllia, Oculina* and *Faksephyllia* in middle Danian time, shortly after the mass extinction at the Cretaceous–Palaeogene boundary and during a rise in sea level. Two myr after the boundary the coral mounds started to grow in deep water below the photic zone over the easternmost part of the Ringkøbing-Fyn High, limiting the Danish Basin to the south. The main focus of the study is on the shift from the Maastrichtian ecosystem to a new ecosystem in middle Danian, and how this shift is reflected in composition, morphology and adaptations in the brachiopod faunas.