COCARDE Workshop and Field Seminar 2012

Fluid flow-related carbonate build-ups: from lacustrine to (early) marine environments

– The Ries Impact Crater as a Natural Laboratory –

October 15-19, Nördlingen, Germany

Conveners: Anneleen Foubert[1], Gernot Arp[2], Bruce W. Fouke[3] & Stefan Schroeder[4]

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The European Science Foundation (ESF, Cocarde-ERN)

REPORT

Participants COCARDE Workshop and Fieldseminar 2012, Wallerstein Mound (©Arp)

1. Summary

The COCARDE Workshop and Field Seminar 2012 'Fluid flow-related carbonate build-ups: from lacustrine to (early) marine environments: *The Ries Impact Crater as a Natural Laboratory*' did bring together 23 junior and senior scientists from academia and industry working on fluid-flow related carbonate build-ups in lacustrine and (early) marine environments. The workshop has been built upon the outcome from COCARDE's second Workshop and Field Seminar in Morocco (fall 2011, Rabat, Morocco) stressing the need to multiply the studies of small mounds (typically 15 to 30m high) in settings where fluid fluxes play a crucial role, both *marine* and *continental*.

To stimulate open discussions and fuel the workshop with new ideas based on field observations, the workshop was preceded by an intensive field seminar of three days. During the field seminar a wide variety of outcrops has been visited within the Ries crater. The Ries crater was formed 15 Million years ago by the impact of an asteroid. Apart from its impact nature, the Nördlinger Ries Basin offers a great opportunity to study post-impact Miocene lacustrine microbialites and algal build-ups in the light of changing hydrochemical conditions in the crater lake. The second part of the field seminar focussed on the Jurassic limestone plateau's of the Swabian and Franconian Alb. The latter is indeed famous for its vast coral reefs, sponge reefs, microbialites and the lagoonal "lithographic" limestone of Solnhofen, with its legendary fauna and did offer the opportunity for participating scientists to collect some typical specimens of the studied formations.

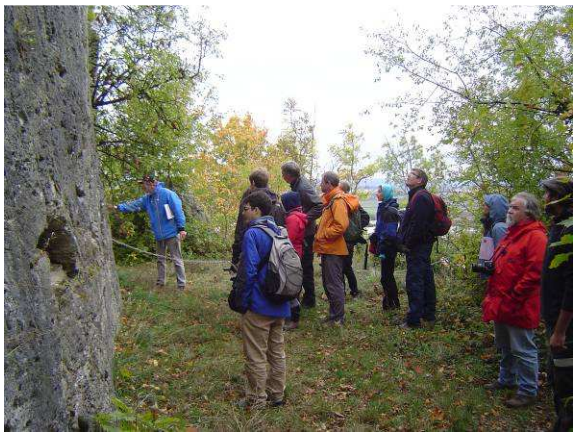
Discussions on the role of fluid geochemistry and microbial biomass on the formation of the observed post-impact Miocene lacustrine microbialites were a central theme throughout the field seminar and formed the base for stimulating presentations during the first session of the workshop. Different case-studies on fluid-flow related non-marine carbonates, with a specific focus on travertines and tufa in present and past times, were presented. Seepage-related carbonate deposits in open marine settings with case studies on the Paleozoic carbonate mounds in Morocco and mounds in the Appenines, were discussed in a second session. The session did conclude with an overview presentation on reservoir compartmentalization in carbonate deposits. The poster session was introduced by flash presentations of the presenting authors, followed by stimulating discussions at the poster panels. The interest of industry on fluid-flow related carbonate deposits was discussed during a third session. Facies, diagenesis and pore-scale architecture of fluid-flow related carbonate deposits carbonates are strongly controlled by specific hydrological conditions in terms of catchment geology and its effect on water chemistry and the nature of solute supply. The COCARDE Ries Workshop and Field Seminar did offer a forum for reflecting on such questions and a training platform to expose young scientists and industrial trainees to new exploration concepts. The need for drilling and new projects were discussed in a final session and resulted in some concrete actions.

2. Scientific content and discussions - COCARDE Workshop and Field Seminar 2012 (Nördlingen, Germany)

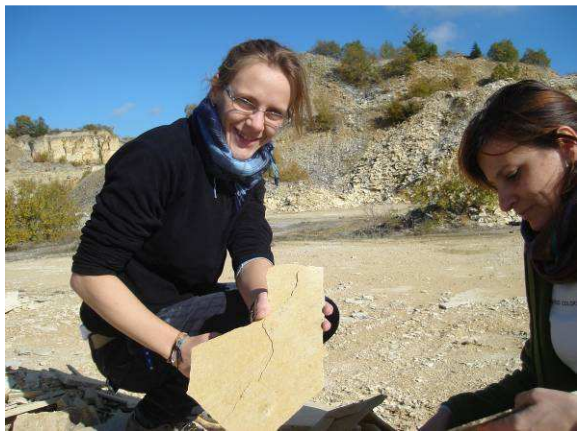
2.1 Field Seminar

Starting from the real natural world and scientific observations, the organizers have decided to begin the COCARDE Workshop and Field Seminar with a three-day field trip towards the carbonate mounds and microbialites in the Ries impact crater lake (Miocene) and the Southern Franconian Alb (Jurassic, Recent). The Field seminar was thoroughly prepared and led by Dr. Gernot Arp who has been working on the Ries crater carbonates for several decades (see Annex 3 – Field Guide). The work shop and field seminar was well attended by 23 senior and junior scientists representing in total 9 countries (see Annex 2 - List of Participants). South-Germany with its Franconian-Swabian Alb and the Ries impact crater are world-class areas in terms of geology and palaeontology. This is especially true for the fossiliferous Jurassic, which is also well-known for its Oxfordian-Tithonian carbonate build-ups and reefs. Moreover, the occurrence of microbial and algal mounds in post-impact sediments of the Ries asteroid crater basin are a true example of how changing hydrochemical conditions of lacustrine systems do play a crucial role in the formation (carbonate precipitation) and early diagenesis of spring carbonates. The latter topic was an important point of discussion through the whole workshop and field seminar.

The field seminar started in the **Ries crater museum** in Nördlingen where a short introduction was given on the general geology of the area and especially on the origin and development of the Ries crater lake. Participants had the time to discover the museum before driving to the first excursion stop, the **suevite quarry 'Aumühle'**. The quarry exposes the contact between the 'Bunte Breccia' and a classical ejecta deposit largely composed of clasts and blocks of the Triassic-Jurassic sedimentary sequence of the area and the typical 'suevite', an impact-melt-bearing breccia with microscopic inclusions of high-pressure mineral phases (Hough et al., 1995; Stöffler et al., accepted). A major point of discussion was the origin of the observed carbonate-inclusions within the suevite, in particular whether they are of hydrothermal or post-depositional origin.



Observing and discussing facies of Wallerstein mound (©Rüggeberg)



Fossil hunting in the Solnhofen limestones (©Rüggeberg)

Once the stage was set to understand the impact nature of the Ries crater, the main focus were the post-impact Miocene carbonates. The largest and most instructive outcrop of lake shore sediments was observed at the **Hainsfarth quarry** at Büschelberg. **Dolomitic algal bioherms** and **cyanobacterial stromatolites** were embedded in carbonate sands composed of ostracods, mesogastropods, ooids, peloids and intraclasts (Arp, 1995). The total bioherm succession extends over an elevation of 80 m. The major bioherm constituent is a fossil green alga closely resembling the modern *Cladophora* (Reis, 1926; Riding, 1979*)*. An important observation is the transition from dolomitized green-algal bioherms (*Cladophorites* –bafflestone and framestone) at the base and in the middle of the succession towards more skeletal stromatolites at the top of the succession. This illustrates the

importance of the changing geochemistry of the lake waters, evolving from an initial playa lake to a permanent soda lake, which successively turned into a halite lake (Arp et al., accepted). The outcrop observations were the base for major discussions on (1) the role of microbes in carbonate precipitation, (2) the biogenic/abiogenic origin of the observed micrite and (3) how diagenetic processes (dolomitization) may impact the primary fabric. Special concerns were stated on the mechanisms, processes and timing responsible for the dolomitization of the Hainsfarth algal and cyanobacterial microbialites.

Spring mound carbonates, also known as 'travertines' in the Ries basin, form localized mounds and pinnacles with steep sides (meters to several decameters in size). **Wallerstein** castle rock is interpreted as such a typical **'travertine' or 'spring carbonate mound'** and is located on the basement blocks of the crystalline rocks (Bolten, 1977; Pache et al. 2001). The facies is characterized by sickle-cell limestone cones veneered by thrombolitic crusts of clotted fabric. Non-skeletal stromatolites and thrombolites are rich in faecal pellets and locally curtains of thin stalactites do occur, reflecting subaerial exposure in Miocene times. Discussions were triggered on the (1) formation mechanisms of the observed spring mound (and the potential fluid pathways crucial for the formation of such spring mounds) and (2) the formation of the typical sickle cell fabric (explained by Arp. et al. (1998) as bacterial exopolymer degradation, mucus shrinkage and secondary Ca^{2+} release from the exoplymers).

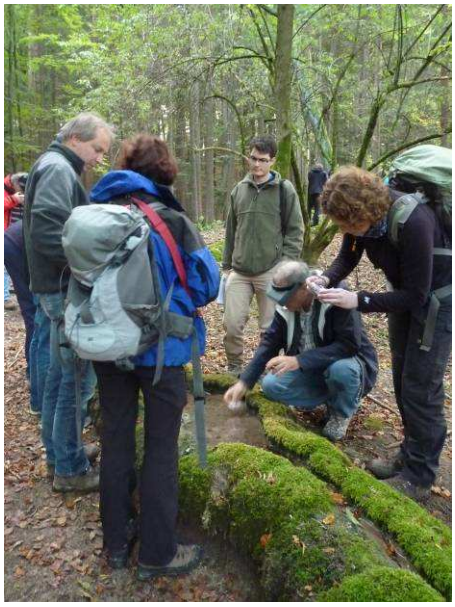
To complete the observation of spring carbonates and as **calcareous tufa deposits** of **springs and creeks** are common in karst regions such as the Franconian and Swabian Alb, recent tufa deposits were visited. '**Steinerne Rinne**' at Erasbach is one of the most striking and amazing tufa deposits where carbonate-precipitation-in-action can be observed (Baier, 2002; Arp et al., 2010). In contrast to other creeks, tufa deposition along the edge of the water course leads to vertical growth and formation of a self-built channel. Discussions on the geochemistry of the waters and CO_2 degassing, the occurrence and role of biofilms composed of cyanobacteria, diatoms and non-phototrophic bacteria, and the typical carbonate fabrics were heavily discussed by the participating scientists in the field.

To understand more profoundly the formation mechanisms of spring mound carbonates, the Geological Survey of the Bavarian Environment Agency drilled in 2006, 18 m of mound carbonates, 1 m of lacustrine carbonates and shales and 2 m of green algal bioherms, known as the '**Erbisberg mound drilling'**. The participants did visit the drilling site, which initiated discussions on the need to drill such pristine records of carbonate mounds in order to obtain high-resolution and high-precise geochemical records to understand the formation mechanisms of spring carbonates.

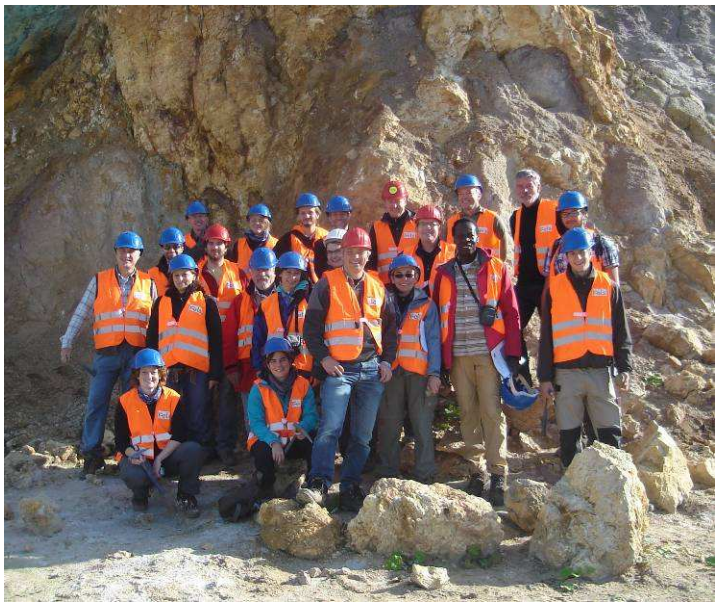
While the first part of the excursion focused mainly on **lacustrine carbonates**, especially green-algal build-ups, microbialites and spring mounds, the second part of the excursion concentrated mainly on carbonates in **open-marine environments**. Interesting were the occurrence and observation of microbial imprints in the Solnhofen lithographic limestones and Upper Jurassic sponge-microbialite mounds in the Sengenthal Quarry.

The second part of the Field seminar started in the **Bürgermeister-Müller-Museum** in Solnhofen (Franconian Alb), representing an excellent exhibition on the fossils occurring in the **lithographic limestones ('Plattenkalke')** of the **Solnhofen Formation**, one of the most famous 'Fossillagerstätten' worldwide. The Solnhofen formation has been deposited in subbasins between declining sponge-microbialite mounds and coral-sponge reefs. The genesis and palaeoenvironment setting of the lithographic limestones have been discussed controversially for many decades (Keupp et al., 2007) and initiated also several discussions among the participants. Keupp (1977) suggested the hypothesis that blooms of coccoid cyanobacteria at the lagoon bottom veneer the carcasses and induces microcrystalline precipitation which would lead to an enhanced preservation of the carcasses and causes the formation of the micritic layers. Within this perspective, Solnhofen could be interpreted

as one large stromatolite. This hypothesis was the base for further discussions. The fact that fossils are – despite the interpreted high preservation index – generally rare in the Solnhofen lithographic limestones could be experienced by the participating scientists by digging by themselves in the lithographic limestones of the Haardt Quarry.



Discussions at the calcareous tufa deposits of 'Steinerne Rinne' (©Gariboldi)



Group picture in front of the reef debris limestones in the Quarry Saal a.d. Donou (©Arp)

The **Upper Jurassic sponge-microbialite mounds** observed in the Sengenthal Quarry, evoked a lot of controversial discussions on the microorganisms and mechanisms involved in the formation of the microbial crusts of these 'sponge-algal' mounds and consequently their bathymetric position (e.g., Leinfelder et al., 1996).

During the last day some more classical examples of reef debris limestones were visited in the Quarry Saal a.d. Donau. Mainly the upper quarry level has been studied by the participants, evidencing of highly diverse coral facies and chaetitid sponges. Typical carbonate mounds and pinnacles (largely composed of sponges, microbial peloids, microbial crusts and echinoderm debris) occur in the basal parts of the quarries. A boat trip along the Danube river allowed to observe in 3D the incised Jurassic reef carbonates, followed by a closer look to the respective facies at the Weltenburg Abbey. The massive limestones are described as being mainly composed of algal crusts, poor in microfossils with only a few scattered reef-building organisms. However, the participants could observe at the access road to the Weltenburg abbey abundant branchy and platy corals between reef debris.

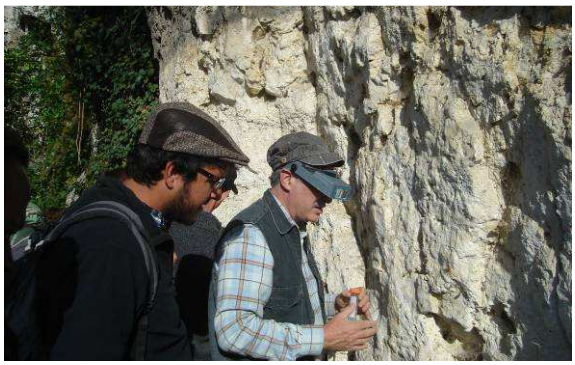
2.2 Workshop

The major items discussed and evoked during the field seminar were filtrated in the discussions and presentations during the workshop, illustrating the advantage of going first on the field before starting intensive workshop discussions. The workshop took place in the historic town hall of Nördlingen and the workshop participants were personally welcomed by the Oberbürgermeister from Nördlingen Herr H. Faul. Because one of the major aims of the workshop was to stimulate open discussions and to confront ideas observed in the field with recent research efforts on fluid-flow related non-marine and marine carbonates, the conveners decided to have extended discussions up to 10 minutes after each presentation.

In total, 17 presentations and 8 posters were presented (see Annex 1 – Programme and Abstract Book). The workshop was organized in five major sessions, respectively (1) Non-marine carbonates: present and past, (2) Seepage-related carbonate systems in marine settings, (3) From lacustrine to

marine fluid-flow related carbonates: lessons from industry, (4) Scientific drilling in frontier carbonate systems: lessons from the past and outlook for the future and (5) Poster session with flash presentations covering the different workshop topics from a multidisciplinary viewpoint.

Gernot Arp opened the first session with a summary of the field observations and an extensive overview of the Ries lacustrine carbonate system. A comprehensive overview and a new view on the classification of non-marine carbonates was given by Giovanna Della Porta. During the discussions ideas were confronted about how to distinguish microbially mediated vs. abiotic fabrics in different environments. It has been provoked that at micro-scale microbial mediated carbonate facies does look similar despite the fact that at macro-scale different morphologies can be observed. Alex Brasier focused in his presentation on the occurrence of tufas and travertines during the Palaeoproterozoic, illustrating the need for the modification of the facies models on modern non-marine carbonates for their application in deep time. The importance of hydrogeology and hydrochemistry was again pointed out by Andreas Reimer to explain the formation of tufa mounds in lake Van (Turkey). Duncan Keenan-Jones, presented how ancient roman aqueducts can function as geo-archeaological laboratories to understand travertine formation under well-constrained flow pathways. Anneleen Foubert (substitute Bruce Fouke) focused on the tight interaction between biotic and abiotic processes in recent and ancient travertines at Mammoth Hot Springs (Yellowstone National Park, US) and Gardiner (Montana, US). Large-scale multiple tufa lobes in Pliocene cascading lake basins were discussed by Natalia Amezcua. Gernot Arp did finish the first session by explaining in the detail potential formation mechanisms of microbialites in hypersaline lakes on Kiritimati in the Central Pacific.



Detailed observation and sampling of the studied outcrops (©Arp)

Opening of the workshop historic town hall of Nördlingen (©Arp)

Seepage-related carbonate deposits in open marine settings with case studies on the Paleozoic carbonate mounds in the Moroccan Meseta and anti-atlas (Roberto Barbieri) and mounds in the Appenines (Marco Taviani), were discussed in a second session. Moreover, the hydrothermal and seep-related Paleozoic carbonate mounds from the Moroccan Meseta have been proposed as potential drilling targets (see paragraph 3.1). The session did conclude with an overview presentation on reservoir compartmentalization in carbonate deposits (Adrian Immenhauser). To broaden towards an industrial perspective and taking into account the numerous discussions on microbial carbonates, Stefan Schroeder presented a review of hydrocarbon reservoirs in microbial carbonates and did evoke some challenges for future exploration. Anneleen Foubert followed this presentation, by evidencing the need for high-resolution visualization tools to understand the 3D architecture of complex carbonate build-ups.

To summarize, Jean-Pierre Henriet gave a nice reflection on migration and fluid dynamics – an important issue when talking about spring and seep carbonates. Elias Samankassou presented an update on the running ICDP proposal LIMODRILL (see paragraph 3.1). Agostina Vertino concluded the workshop presentations giving an overview of the opportunities within the COCARDE network and paving the way for new challenges within COCARDE (see paragraph 3).

3. Scientific outlook

3.1 Mound Drilling

Recent COCARDE research efforts focused on the drilling of recent small cold-water coral mounds in seepage associated settings off Morocco (Pen Duick Escarpment mounds on the Atlantic margin, Melilla mounds in the Alboran Sea). Both sites will be surveyed in 2013 by a COCARDE *EUROFLEETS* cruise with R/V Marion Dufresne: "GATEWAYS". However, the strength of continental drilling lies in the combination of 3D outcrop studies and targeted drilling, which allows to study pristine core sections of carbonate build-ups in their surrounding setting.

The ICDP LIMODRILL proposal 'Drilling Carbonate Mounds in Shallow and Deep Time: Pueblo de Lillo Carbonate Mound Drilling' (presented at the workshop by Elias Samankassou) is moving forward. The pre-proposal was positively evaluated. Upon providing complementary data (database on Palaeozoic mounds, need for such a drilling by the industry), the ICDP Committee has recommended submission of a workshop proposal. Most of the current tasks to be achieved are related to the permission for drilling, considering that the site is located in a protected area. Among the main issues are:

- the provisional path to the site, which needs to be built (Junta Vecinal, City Council)
- the environmental impact evaluation (Environmental office of the Junta de Catilla y León)
- the approval of safety, drilling technique, company licenses (Servicio Territorial de Industria – Seccion Minas of the Junta de Castilla y León), and
- the post-drilling outreach.

Negotiations with the local authorities are currently in good progress. The City Council has already approved the drilling project, an important step for negotiations with the other authorities.

Discussions during the second COCARDE workshop and field seminar already identified the need of further investigation and potential carbonate mound drilling initiatives in Morocco. During this workshop Roberto Barbiero did present an outline to drill respectively (1) Late Silurian and Late Devonian carbonate deposits of the Western Meseta and (2) Devonian carbonate mounds of the Eastern Anti-Atlas domain located in the Tafilalt Platform and the Maider Basin. Both areas have been visited last year and currently these sites are extensively screened as drilling targets. During this workhop both drilling sites have been discussed and soon concrete actions will be taken on-site.

3.2 Towards Frontier Carbonate Systems

Following the numerous discussions on the formation mechanisms of spring carbonates, and especially the role of microbial biomass in carbonate precipitation, Stefan Schroeder presented a potential new target within COCARDE, i.e. the study of frontier lacustrine carbonate systems in extreme environments such as the East African Rift System (EARS). In its eastern branch the EARS contains several saline and alkaline lake systems. Aridity, active faulting and fluid flow along faults, volcanic catchment areas, and access to seawater at the northeastern end of the rift influence hydrochemistry, biomass, precipitation and diagenesis of authigenic minerals in these lakes. Bioconstructions include fluvial travertines, shoreline bioherms and subaqueous spring mounds. Studies of the interaction between lake hydrochemistry, biological activity/biofilms, and mineral paragenesis will shed light on fluid-microbe interactions and mineralization processes in extreme environments, including processes on early Earth. They could also have a bearing on understanding hydrocarbon reservoirs in rifts like the South Atlantic, where similar processes of mineralization and diagenesis have been postulated.

As this is a new research direction, and access and security in the study area need to be evaluated, it is recommended to initiate small or reconnaissance studies based on ideas discussed during the workshop. Local contacts are essential for the success of any such study, and initial contacts already exist between Leuven University and Meleke University in Ethiopia. Further contacts with local

universities in Kenya and Tanzania, as well as with established researchers who know the area, should be sought. Larger, collaborative studies can be developed at a later stage.

3.3 Mound Database

Within the framework of the ESF COCARDE-ERN, it has been planned to set-up an extensive Mound Database reporting on mound occurrences and mound types (skeletal mounds, microbial (mud) mounds, spring and seep mounds) at different time slices. This idea has been further discussed during the workshop and an update on the current status of the database has been given. The database will appear as an open-source online web-database whereby scientists (after the assignment of a username and password) could upload potentially new mound occurrences. Having presented the concept of the Mound Database at the workshop, participating scientists started to contribute already actively to the further development of the respective database.

Additionally, this workshop and field seminar contributed to the long-term objective of the ESF COCARDE-ERN network to evaluate, compile and document in a collective effort "mound reference routes", which eventually may serve both academic and industrial communities as training routes. It has been discussed that the Ries-Franconian Alb region is well-qualified for such a goal, and adds to the already surveyed Asturias-León route (Oviedo field seminar) and the Moroccan mound heritage route (Morocco field seminar).

3.4 Links with Industry

The active participation of scientists from industry, did allow to discuss further projects in collaboration with industry. Carbonate mounds represent important subsurface reservoirs around the world including the Western Alberta, the Paradox Basin, the Karachaganak Field, Kazakhstan, the Norwegian Barents Sea, and the Smackover field, Alabama, USA. Although the overall geometry of carbonate platforms and mounds is well understood, constraining and modeling of reservoirs require qualitative and quantitative details on mound growth dynamics (vertical and horizontal), internal structures, diagenetic pathways and fluid flow (dynamic, extent and timing of cementation), and fracturation. To understand these details, and most important the 3D internal architecture of mounds, those structures need to be drilled and studied in 3D through time, allowing reconstruction of their development. Active collaboration projects – with an active contribution to the proposed continental mound drilling projects (see paragraph 3.1) - have been set-up between industrial partners and the COCARDE scientists. Another urgent request from industrial partners is what controls the potential occurrence of carbonate mounds, i.e. where (basin type, continental margin), when (stratigraphic zones prone for their development), and accessory conditions (structural environment, oceanic characteristics). Within this perspective, a new academia-industry collaboration project has been set up in the wake of the COCARDE workshop in Nördlingen focusing on the understanding of the control of palaeo-water masses on carbonate mound distribution. Of additional interest are the impact of potentially exotic fluids on diagenesis and pore structure, as well as the types of source rocks that can be expected in alkaline and isolated basins.

3.5 Publications

Respecting the publication-pace within the COCARDE ERN network it has been suggested to go next year for a special dedicated volume on carbonate mounds – this representing the online Mound Database and contributions resulting from the 2nd (2011, Morocco) and 3rd (2012, Nördlingen) COCARDE Workshop and Field Seminar. Whereas the focus of the last COCARDE special volume was rather on recent mound structures (Special Issue Marine Geology 282 (2011), pp. 1-160), this special publication should emphasize publications on ancient carbonate mound structures covering the wide variety of carbonate mounds at different time slices. In parallel, efforts are bundled to submit soon a first review paper 'Carbonate Mounds: from Paradox to World Heritage' (Henriet et al., in prep.).

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Annexes

Annex 1

Programme and Abstract Book of the COCARDE Workshop and Field Seminar 2012, 15-19th October 2012 – Nördlingen, Germany

Annex 2

Field Guide of the COCARDE Workshop and Field Seminar 2012, 15-19th October 2012 – Nördlingen, Germany

Annex 3

Participants list of the COCARDE Workshop and Field Seminar 2012, 15-19th October 2012 – Nördlingen, Germany

Annex 4

Reports ESF COCARDE grantees