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14. Traces of life on planet Earth: A tribute to the late Professor Lukas Hottinger

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14. Traces of life on planet Earth: A tribute to the late Professor Lukas Hottinger

Lionel Cavin, Michael Hautmann

“Schweizerische Paläontologische Gesellschaft” (SPG/SPS)

“Kommission der Schweizerischen Paläontologischen Abhandlungen” (KSPA)

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14.1

Giant rodents from the northern Neotropics - taxonomic, phylogenetic and developmental aspects of their evolution within the caviomorph radiation

Geiger Madeleine¹, Wilson Laura¹, Costeur Loïc, Scheyer Torsten¹, Aguilera Orange³, Sánchez-Villagra Marcelo¹

¹ Paläontologisches Institut und Museum der Universität Zürich, Karl Schmid-Strasse 4, CH-8006 Zürich, Switzerland, (madeleine.geiger@uzh.ch, tscheyer@pim.uzh.ch, m.sanchez@pim.uzh.ch)

² Naturhistorisches Museum Basel, Konservator Geowissenschaften, Augustinergasse 2, CH-4001 Basel, Switzerland, (Loic.Costeur@bs.ch)

³ Museu Paraense Emílio Goeldi, Coordenação de Ciências da Terra e Ecologia, CCTE, Departamento de Geociências, Av. Perimetral, 1901, Terra Firme, CEP: 66077-830, Belém, PA, Brasil, (orange.aguilera@gmail.com)

In the last decade, several fossils from giant caviomorph rodents from the Miocene of Venezuela were collected by teams from Zurich and Coro. These materials make possible the first examination of ontogenetic and taxonomic variation in these animals, in the context of the caviomorph evolutionary radiation. We examined continuous and discrete features in a sample of seven fossil specimens (cf. *Phoberomys*) and 149 recent ones representing 46 species. We investigated the order of maturation and fusion of the epiphyses of long bones (humeri and femora) and the pattern of evolution of nine discrete characters of the femur, the postcranial element most commonly preserved among the studied fossils. We found that the epiphyseal closure series of femora is conserved within the rodent clade. The ossification of the humeral epiphyses is similar in rodents and other mammalian clades (e.g. Carnivora, Eulipotyphla). The pattern of evolution of femoral features is largely homoplastic and there are no obvious correlations with ecology or phylogeny. Some but not all peculiarities of the fossils are most likely coupled with their gigantic size. The re-examination of a Miocene femur of giant rodent from Trinidad in the collections of the Naturhistorisches Museum in Basel lead to its identification as cf. *Phoberomys*, a taxon principally known from the Urumaco section in northwestern Venezuela. Current studies of its palaeohistology are revealing features on the growth pattern and functional architecture of the bone microstructure of these giants.

14.2

Palaeoenvironmental reconstruction of the Swiss Molasse Basin (Oligocene and Early Miocene) on the basis of postcranial remains of ruminants (Artiodactyla, Mammalia)

Hiard Florent¹, Mennecart Bastien¹, Berger Jean-Pierre¹

¹*Department of Geosciences_Earth Sciences, Chemin du muse 6, 1700 Fribourg, Switzerland (florent_hiard@unifr.ch)*

Some morphological features of the postcranial skeleton of ruminants are correlated to ecological features such as locomotion, body mass and habitat preferences. Here we propose to use these correlations to define terrestrial paleoenvironments of several Oligocene to Early Miocene Swiss Molasse Basin localities: La Beuchille (MP23), Grenchen 1 (MP24), Moutier-Gare (MP25), Mümliswil-Hardberg (MP26), Rickenbach (MP29), Küttigen (MP30), Engehalde (MN2), Wallenried (MN2), Tavannes (MN2), Benken and Wildensbuch (MN3/4).

Two different methods were used. The first is based on the morpho-functional study of Köhler (1993) and is applied on metapods and phalanges (53 specimens). The second one uses the morphology of astragalus to define habitat preferences of ruminants. It uses a PCA combined with a Support Vector Machine (SVM) calibrated with 209 astragalus of extant ruminants and is applied on 17 fossil specimens.

Between MP23 and MP26, the Swiss Molasse Basin presented essentially heavy forested environments. From MP29 to MP30, the environments seem to have been more open with wooded savannah or sparse forests (Mennecart et al. submitted). In MN2, the environments were more diversified with lightly wooded plains and more wooded environments (Becker et al. 2010). Finally, in MN4, the environments were more open with, however, some wooded area.

This succession of palaeoenvironments shows three different phases, which tend towards a general opening of the environments in the Swiss Molasse Basin. This evolution is consistent with the global evolution of environments in the Western part of Europe (Legendre 1989; Costeur 2005).

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14.3

Ecological structure and taxa distribution in near shore habitats of the Virgin Formation (south-western Utah): Implications for the Early Triassic recovery

Hofmann Richard¹, Hautmann Michael¹ & Bucher Hugo¹

¹ Paläontologisches Institut und Museum, Universität Zürich, Karl Schmid Strasse 4, CH-8006 Zürich (richard.hofmann@pim.uzh.ch)

The recovery from the end-Permian biotic crisis is traditionally perceived to have been significantly delayed as a result of persistent deleterious environmental conditions and/or the extreme intensity of the extinction itself with an estimated species loss of 95% in the marine realm.

Previous studies on the Virgin Formation of the Western U.S. put forward the view that harsh environmental conditions still persisted during the Spathian, at least 2 ma after the main extinction. However, palaeoecological analyses on the basis of species-level abundance data have hitherto not been carried out. Thus, very little is known on the actual ecological structure of the Virgin palaeocommunities and their spatial distribution.

We present a quantitative palaeoecological data-set, which is analysed with respect to the identified sedimentary environments. This integrated approach helps to discriminate between possible effects of the end-Permian mass extinction event and local environmental factors on alpha-diversity and ecological structure of the Virgin Fauna. Shallow subtidal environments (see figure 1 for overview) yield the highest species richness and lowest dominance values as recorded in two benthic associations: the *Eumorphotis ericius*-association and the *Protogusarella smithi*-association, both of which contain 20 benthic species (bivalves, gastropods, brachiopods, echinoderms, and porifers). Tidal inlet deposits yield a low diverse fauna (*Piarorhynchella triassica*-association) with a very high dominance of filter feeders adapted to high energy conditions. Another comparably low diverse fauna is recorded by the *Bakevella exporrecta*-association, which occurs in deposits of the offshore transition zone encompassing unconsolidated, mostly silicilastic substrates with a low preservation potential for calcareous body fossils. A single sample containing five bivalve species (*Bakevella costata*-assemblage) is recorded from a marginal marine setting. The Virgin fauna yields a bulk diversity of 30 species (22 genera) of body fossils and 14 ichnogenera and, thus, represents the most diverse benthic fauna known so far from the Early Triassic.

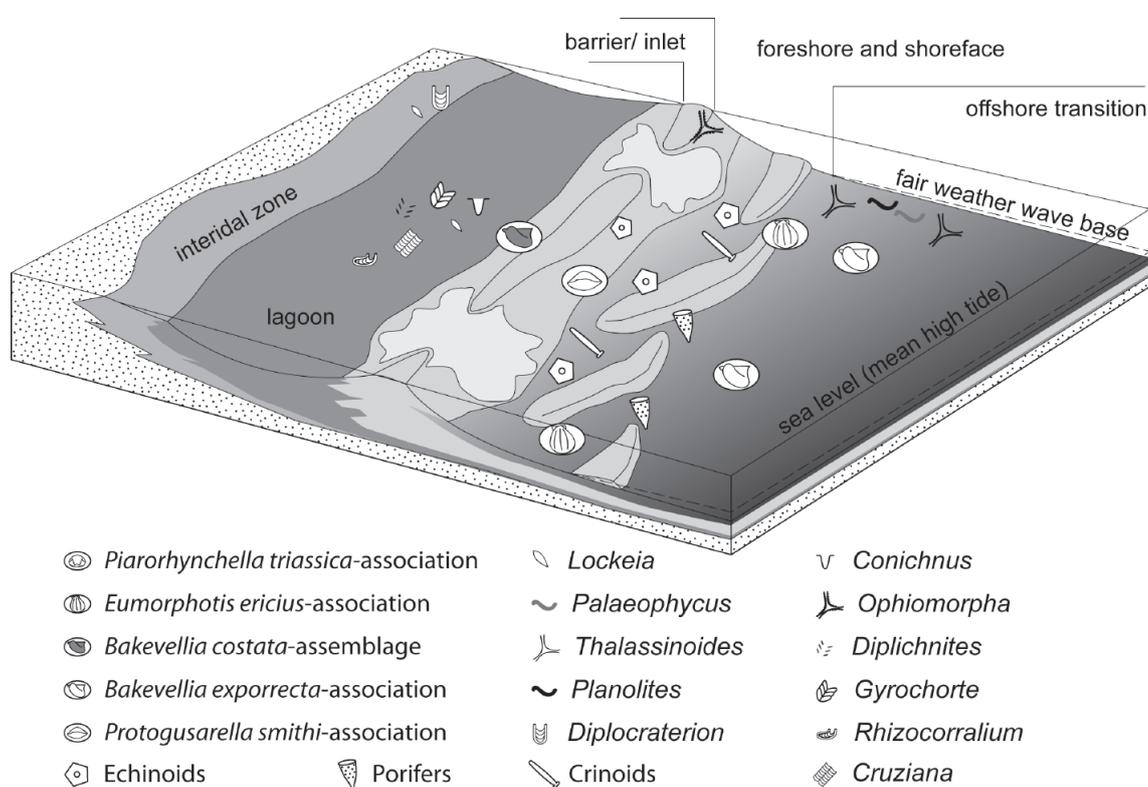


Figure 1. Sedimentological and palaeoecological model of the Virgin Formation as recorded in south-western Utah.

Our results suggest that oceanographic conditions during the Early Spathian enabled ecosystems to rediversify without major abiotic limitations. However, taxonomical differentiation between habitats was still low, indicating a time lag between increasing within-habitat diversity (alpha-diversity) and the onset of taxonomical differentiation between habitats (beta-diversity). We suggest that taxonomical habitat differentiation after mass extinction events starts only after competition within habitats exceeded a certain threshold, which was not yet reached in the Spathian of the investigated area. This interpretation is an alternative to previous suggestions that the prevalence of generalistic taxa in the aftermath of mass extinction events reflects ongoing environmental stress. The onset of increasing beta diversity is a potential criterion for distinguishing two major recovery phases: the first ending with habitat saturation and the second ending with completion of ecosystem differentiation.

14.4

Growth patterns deduced from bone histology of the dwarfed island deer *Candiacervus* from the Late Pleistocene of Crete

Christian Kolb¹

¹ Paläontologisches Institut und Museum der Universität Zürich, Karl Schmid-Strasse 4, CH-8006 Zürich (christian.kolb@pim.uzh.ch)

The Mediterranean island of Crete was connected to the mainland of Asia Minor since the Vallesian age of the Late Miocene, becoming later submerged. After re-emergence of the region at the end of the Pliocene, Crete gained its present shape and became colonized by overseas sweepstakes dispersal (van der Geer et al. 2010). Isolation and colonization led to natural experiments in geological time, as several lineages of mammals experienced rapid evolutionary increases or decreases in body size and life history. The Pleistocene endemic fauna of Crete included dwarfed forms of deer, hippopotamuses, proboscideans, and giant mice. In an analogous case, Köhler & Moyà-Solà (2009) investigated a dwarfed island bovid from the Late Pleistocene of Majorca, *Myotragus balearicus*, and based on palaeohistological studies found flexible synchronization of growth rates and metabolic needs within the bone tissue. This strategy is similar to that of ectothermic reptiles encountering resource limited environments. Whether this pattern is universal for extinct islands, mammals remain unexamined, and this study aims at testing this by deciphering growth and adaptive patterns of bone tissue types in the dwarfed Cretan deer *Candiacervus* as a case study.

The two smallest morphotypes of *Candiacervus* are represented by different ontogenetic stages in specimens from Liko and Gerani cave. Both morphotypes are characterized by a shortening of limb bones already present at birth (van der Geer et al. 2006) and a higher degree of bone fusions, typical evolutionary specializations of island ruminants (van der Geer et al. 2010).

Various long bones of newborn, juvenile, and adult specimens, housed in the Museum Naturalis Leiden, were sampled histologically. For the first time a bone histological examination of an ontogenetic series of *Candiacervus* is conducted.

Throughout limb bone development, ontogenetic changes of bone tissue patterns are observable including lines of arrested growth (LAGs). The number of LAGs indicates an age of about 2 years for juveniles and minimum 5 years for adults sampled.

Nevertheless, large parts of the growth record in the primary cortex were erased as a result of remodeling and resorption. Humeri and femora of newborn *Candiacervus* start with fibro-lamellar bone and show a plexiform arrangement of vascular canals. Layers of secondary deposited endosteal lamellar bone occur in the inner part of the cortex in juvenile and adult specimens as well as areas of Haversian bone or pockets of secondary osteons. Large areas of Haversian bone in adult specimens indicate strong bone remodeling during ontogeny. Metapodials of newborn specimens show woven-fibred bone. In the outer parts, woven-fibred bone is substituted by laminar or plexiform fibro-lamellar bone throughout ontogeny. Secondary deposition of lamellar bone is found in the anterior region of the inner cortex in juvenile and adult specimens as well.

The closely related continental deer *Megaloceros*, the giant Irish elk, shows a similar arrangement of bone tissue types in the metatarsals compared to *Candiacervus*. Both genera show a high amount of bone remodeling, i.e. the presence of Haversian bone is highest in the posterior cortical regions of the fused metatarsals.

Placing the fossil data into a larger phylogenetic context including also living species reveal common patterns of growth as well as life history changes in fossil forms which evolved in isolation or attained extreme sizes on the continent during Pleistocene times.

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14.5

Biogeographic morphological investigations of menardiform globorotalids in a time slice at 3.2 (Mid-Pliocene)

Mary Yannick¹ & Knappertsbusch Michael¹

¹ Naturhistorisches Museum Basel, Augustinergasse 2, CH-4001 Basel (yannick.mary@unibas.ch).

Planktonic foraminifera are one of the most important tools for palaeoceanographic reconstructions and biostratigraphy. Recent outcomes of combined morphometrics and molecular studies have brought forward critical aspects of their classification: within traditionally defined morpho-species there exists genotypic variation that defines biogeographically and ecologically distinct cryptic species (Darling & Wade 2008). Morphological variability within these morphospecies is now considered as the result of genetic diversity, opening a wide field for biometrical investigations. Although fossil record of planktonic foraminifera contains several good candidates for studying morphological diversity, investigation of species-level composition remains difficult. The number of specimens to analyse is very high in order to reliably describe the differences cryptic forms and the morphological overlap of the cryptic forms is important.

The present work documents a new approach trying to tackle the above-mentioned problems. It combines size frequency analysis and morphological measurements with the use of a new automat, the robot AMOR, which orients and images microfossils under a binocular microscope (Knappertsbusch *et al.*, 2009). AMOR significantly increases the number of specimens to be analysed, while the construction of contoured frequency distributions allows to explore subgroups within morphologically convergent populations. Populations of up to 500 specimens are investigated in several locations. Size frequency distribution (SFD) is first calculated and described by superposition of several distinct Gaussian distributions.

Differences between SFDs are used in order to filter out specific frequency trends per locality. Morphological measurements including spiral height (δX), maximum diameter (δY), concavity (δS and δU), keel angles ($\Phi 1$ and $\Phi 2$), and profile view area (GA) employed as a proxy for shell volume, and therefore size estimator. These parameters are then used to characterise morphological variability within the previously defined subgroup.

As an experiment we studied the biogeographic variation of shell morphology of middle Pliocene Atlantic menardellids planktonic foraminifera. The *Menadella* group shows a high diversification during its timespan, as a consequence of the establishment of new ecological niches in the tropical Atlantic during the gradual closure of the ancient American Seaway (Chaisson, 2003). Two lineages which can be defined by their end members *Globorotalia (Menardella) multicamerata* and *Globorotalia (Menardella) pertenuis* evolved from the common ancestor *Globorotalia (Menardella) menardii*. These species strongly intergrade in a time-transgressive morphocline, a large proportion of the morphological overlap being caused by allometric growth of the shell (Cifelli & Scott 1986).

The combination of size frequency distributions with spiral height versus maximum diameter diagrams leads to the recognition of seven different *Menardellid* morphotypes in Mid-Pliocene tropical Atlantic populations: morphotype MA, MB, MC1, MC2, MC3, SH1 and SH2. Each morphotype covers a distinct range of size and is characterised by a distinct morphology, which suggests a distribution in different ecological niches (Al-Sabouni *et al.*, 2007).

Automatisation, morphological analysis and size frequency distribution solves the intergradation problems (without being too much time consuming), accounts for ontogenetic effects and opens prospects into population ecology in microfossils that are otherwise difficult to differentiate.

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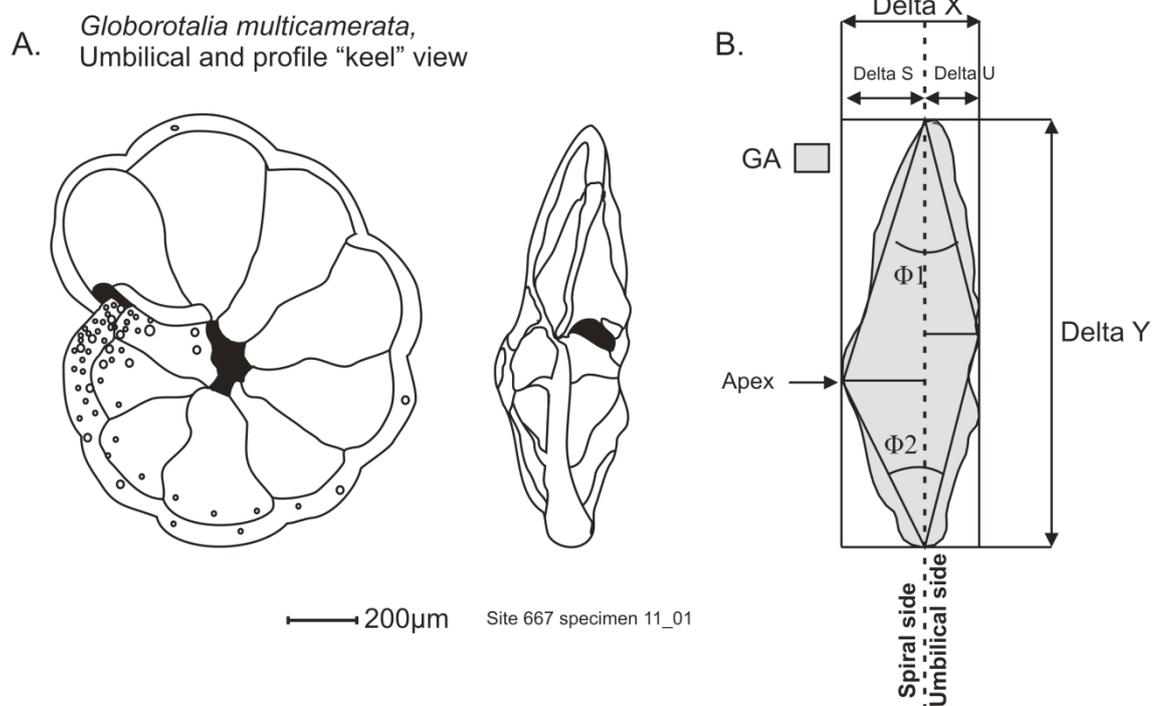


Figure 1: Morphological description of a globorotalid menardiform. A: detailed drawing of the test in umbilical and keel view. B: Outline of this specimen with associated measurements.

14.6

Was the Triassic a plumeworld?

Patrick H. Meister¹

¹ Max Planck Institute for Marine Microbiology, Celsiusstrasse 1, 28359 Bremen (pmeister@mpi-bremen.de)

The onset of pelagic biogenic carbonate production during the Cretaceous has strongly changed the mode of how carbonate is drawn down from ocean water. Before the “invention” of an elaborate mechanism of efficient carbonate precipitation by marine nannoplankton, this task was essentially carried out by benthic organisms and was mostly limited to the photic zone at ocean margins. Nevertheless, several intervals exist in the geological record that are rich in carbonates, and these carbonates often show a homogenous micritic texture draping considerable parts of the seafloor worldwide. According to the plumeworld hypothesis (Shields, 2005), such intervals may result from spontaneous precipitation of carbonate in the water column during times of high ocean water alkalinity. This mode of carbonate precipitation may explain abundant carbonates homogeneously draping the seafloor in the aftermaths of low latitude glaciations during the Neoproterozoic when atmospheric CO₂ levels were supposedly high compared to present levels.

Sedimentation style reminiscent of such cap carbonates is also abundant in the Triassic units of the Alps, even though these carbonates were mostly deposited in shallow seas surrounding the western end of the Palaeotethys embayment. Most of the Triassic carbonates show a predominantly micritic matrix, show features of soft sediment deformation and sometimes bioturbation indicating carbonate mud entirely unlithified at the time of deposition. The enormous quantity of micrite dwarfs the contribution of skeletal material and was unlikely produced by erosive mechanisms. At the same time, nannoplankton had not been produced in large amounts during the Triassic yet. Hence, spontaneous precipitation from the water column may provide an efficient mechanism to produce such carbonates.

Considerable amounts of the platform carbonates are dolomitic, and dolomitic units coincide with the most shallow water conditions as indicated by the sedimentary structures. The distribution of dolomite corresponds to particular conditions conducive to dolomite formation observed in a few modern environments, such as intertidal restricted lagoons or hypersaline sabkhas. Although most Triassic dolostones suffered considerable recrystallization during burial diagenesis, distribution of dolomites is often concordant with particular sedimentary units, and, in some cases, oxygen isotope signatures are preserved that indicate early precipitation at surface temperatures. Carbon isotope signatures of Triassic dolostones generally show marine values indicative of very early precipitation. If dolostones were formed in restricted environments, such values can also be the result of equilibration with atmospheric CO₂.

As a modern analogue we may consider Deep Springs Lake, an alkaline lake in eastern California. This lake also shows the formation of entirely unlithified clay-fraction dolomite ooze. A geochemical study (Meister et al., 2011) suggested dolomite in the water column because dolomite is not supersaturated in the porewater as a result of Ca limitation. Also, microbial sulphate reduction is insufficient to influence supersaturation by increasing the inorganic C pool and alkalinity. Even if the conditions in the lake are probably far more alkaline than in past seawater, the mode of precipitation in the lake may serve as a potential modern analogue for a plumeworld mode of carbonate formation in the past ocean.

The abundance of carbonate in the Alpine Triassic may be explained by high pCO₂ level, tropical and at times humid climate causing strong weathering of the continents and high alkalinity in the ocean. Additionally, uptake of bicarbonate by calcifying organisms was limited to sponges and microbialites in shallow environments while corals played a minor role during most of the Triassic. Hence the ocean was more supersaturated with respect to carbonate, most likely facilitating the spontaneous precipitation of carbonates under warm evaporative conditions. Based on these observations a plumeworld mode of carbonate precipitation may be locally suggested for the shallow platforms of the Triassic Palaeotethys. These platforms resemble ongoing carbonate precipitation in a few modern restricted environments but may have been the main pathway of carbonate formation during Proterozoic times. More research is necessary to understand the fundamental mechanisms of carbonate precipitation during the Triassic and earlier times in earth history.



Figure 1. Deep Springs Lake, California, showing ongoing authigenic formation of clay-fraction dolomite ooze. This mode of carbonate precipitation may have similarly occurred in Triassic marginal seas. (left: after rain; right dry season).

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14.7

Was Europe an evolutionary DEAD END? Case of the Oligocene-Early Miocene ruminants.

Bastien Mennecart

Department of Geosciences – Earth Sciences, ch. du Musée 6, Pérolles, CH-1700 Fribourg, Switzerland, bastien.mennecart@unifr.ch

Nowadays, the ruminants are the most diverse, ecologically dominant, group of the hoofed mammals. Including nearly 210 species, they occur in deserts to tropical forests, have a body weight from 3 kg to 2 tones, and cover feeding habits from selective browser to grazer (Mennecart et al. *subm.1*). The diversification of the current families in Europe seems to have occurred during the late Early to Middle Miocene with the Tragulidae (MN4), the sabertoothed Moschidae (MN5), the antlered Cervidae (MN3), and the horned Bovidae (MN4). The primitive Oligocene ruminants are mainly enigmatic and belong to extinct families or are uncertainly assigned to extant families (Mennecart et al. *subm.1*). Many authors suggest an early appearance of the ruminants in Europe during the Late Eocene. However, the latter are represented by isolated, poorly located, and lost specimens. Additionally, most of the time, the European Oligocene ruminant diversity is mainly related to a regional evolution with few migrations. Based on the review of specimens from 95 localities, this study aims to discuss a new insight into the diverse evolutionary pattern of European ruminants during the Oligocene and the Early Miocene.

The earliest undeniable European ruminants occurred only after the “Grande Coupure” event (MP20/21), at the same age of the Oi1 glaciation event (ca. 33.5 My; *Migr.1*, see Fig.), whereas the first true ruminants appeared earlier in the Middle Eocene in North America and Asia. Following this extinction/origination event, the earliest European families Lophiomerycidae and Gelocidae diversified rapidly and few later, at MP23, the new families Bachitheriidae and Tragulidae migrated from Asia (ca. 30.5 My). Swamps and forests dominated the European landscape, but at the beginning of MP24, a global change coinciding with the Oi2 glaciation event, occurred. In Switzerland, it was marked by the regression of the UMM and the Renish Sea, and drastic changes of the sedimentological context (Berger 2011), that generated a drier climate and a faunal renewal. Within the European ruminant community, we note the disappearance of the Gelocidae and the Tragulidae, and only the larger species of Bachitheriidae and Lophiomerycidae survived (*Ext.1*; Mennecart et al. *in press* and *subm.1*). At MP24/25 (ca. 29.2 My), the Bachitheriidae diversified and the nov. Family appeared in Europe (*Spec.1*). The European mammal evolution was relatively quiet and steady until MP27. In Switzerland, the environment was a wooded floodplain (Berger 2011).

Around MP28, large changes occurred in the faunal communities. First, a specific renewal resulted in more open habitat specialized ruminants (*Ext.2* and *Migr.2*). Then a rapid extinction occurred, during the emergence of new migrants, the Pecora (*Ext.3* and *Migr.3*; Mennecart et al. *subm.2*). In Switzerland, this short time interval coincided with sedimentological changes related to a drier environment (Berger 2011).

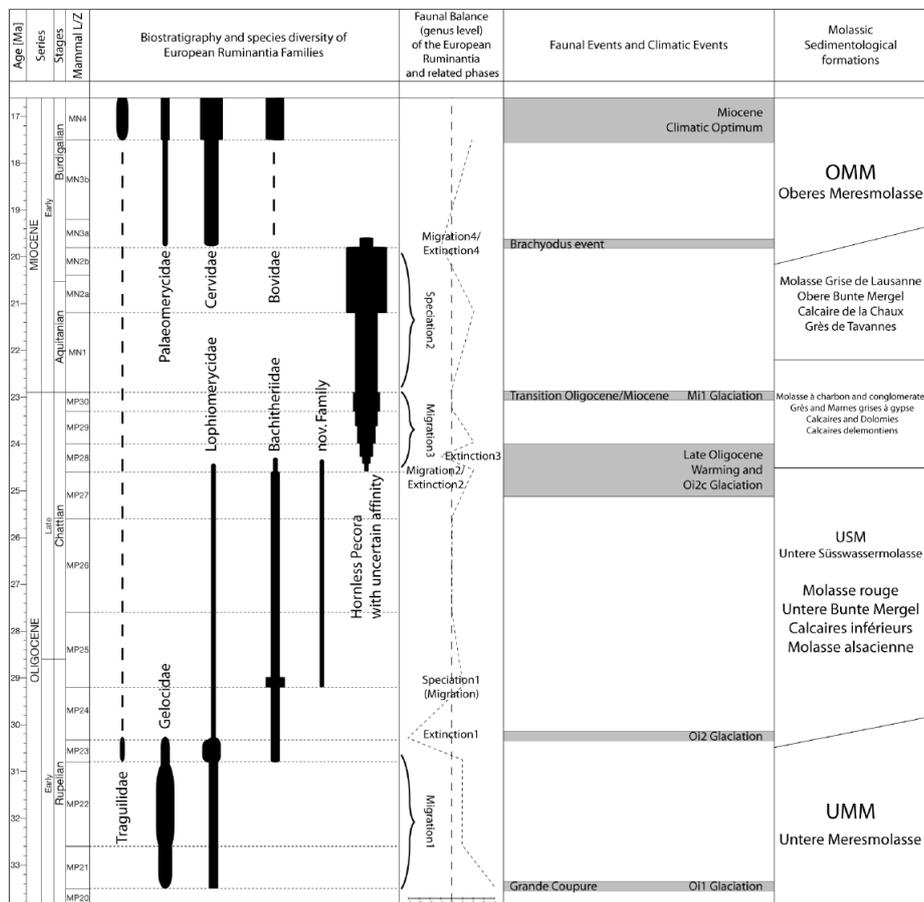
The Oligo-Miocene transition (ca. 22.9 My) was marked by the Mi1 glaciation event, which coincided with a general fragmentation of the environment. In spite of this, the ruminant community was not strongly affected. However, a general trend highlights size changes; the small species derived into smaller species and the medium size species into larger ones. At the end of MN2, a huge diversity of hornless sabertoothed ruminants belonging to uncertain families is recorded (*Spec.2*). The *Brachyodus* event, at the beginning of the Proboscidean datum (MN3a, ca. 19.8 My), coincided with the closing of the Tethys Ocean and, in Switzerland, to the transgression of the OMM. This major climate and faunal change led to the disappearance of old taxa and the emergence of the extant families (*Ext.4* and *Migr.4*).

As opposed to the regional evolution, proposed by older publications, which suggests few migrations, this study highlights an evolutionary pattern marked by several huge Asiatic migrations, strongly related with global and environmental changes and punctuated by some speciation phases. Europe should be considered more as a Dead End (Migration/Extinction) than an area with a normal evolutionary diversification (Speciation).

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14.8

Recovery Patterns of Chondrichthyan and Osteichthyan Fishes after the end-Permian Mass Extinction

Romano Carlo¹, Brinkmann Winand¹, Goudemand Nicolas¹, Vennemann Torsten², Ware David¹, Hermann Elke³, Brühwiler Thomas¹, Bucher Hugo¹

¹ Paleontological Institute and Museum, University of Zurich, Karl Schmid-Strasse 4, 8006 Zürich (carlo.romano@pim.uzh.ch)

² Institute of Mineralogy and Geochemistry, University of Lausanne, Anthropole, 1015 Lausanne

³ Institute of Earth Sciences, University of Utrecht, Budapestlaan 4, 3584 CD, Utrecht

The Permian-Triassic boundary (PTB) extinction event is the largest known crisis of the Phanerozoic, with more than 90% of marine species having been wiped out. The subsequent Early Triassic biotic recovery is traditionally considered delayed. However, although some groups apparently did not reach their pre-extinction diversity before Middle Triassic times (>6 million years after the PTB), others (e.g. ammonoids, conodonts, foraminifers, brachiopods) did recover in less than 1.4 million years after the PTB. Yet, soon after, near the Smithian-Spathian boundary, some clades like ammonoids and conodonts suffered an additional extinction.

Early Triassic recovery studies have mainly focused on marine invertebrates and, with the exception of the conodonts, only little is known about the timing and pattern of recovery of vertebrates. The relatively scarce fossil record and the often poor stratigraphic control of many vertebrate groups make it difficult to assess their diversity dynamics. Nonetheless, higher gnathostomian fishes (Osteichthyes and Chondrichthyes), which are the largest vertebrate group today, are relatively well-represented in the fossil record and, thus, useful for such studies.

Here we present an updated analysis of the diversity dynamics of Chondrichthyes (sharks and their relatives) and Osteichthyes (bony fishes) between the Lopingian (Late Permian) and Anisian (Middle Triassic). Our data reveal different trends in turnovers and generic richness of chondrichthyan and osteichthyan fishes across the PTB and during the Early Triassic. In general, the diversity of chondrichthyans seems to be more stable within the studied interval than that of the bony fishes. The results are discussed in the context of emerging evidence for profound environmental changes during the Early Triassic (e.g. ocean's chemistry, climate).

14.9

Paleobiogeographic and paleoecological considerations on European Anthracotheriidae (Cetartiodactyla, Mammalia)

Scherler Laureline¹

¹ OCC-SAP, PAL-A16, Hôtel des Halles, CP64, CH-2900 Porrentruy (laureline.scherler@net2000.ch)

This study 1) proposes a new vision on the paleobiogeographic repartition of European anthracotheres; 2) highlights surprising facts concerning their paleoecology and evolution; 3) brings new information for the understanding of the ecological dichotomy between the two modern species of hippopotamuses.

Anthracotheres lived almost worldwide from the Late Eocene to the Early Pliocene, migrating early from Southeast Asia towards North America, Europe, and Africa (e.g., Lihoreau & Ducrocq, 2007). The members of this family adapted to many different ecologies and colonized successfully various habitats throughout their evolutionary history.

The first anthracotheres arrived in Europe in the latest Eocene (FAD of *Elomeryx crispus* in MP18, Lutetian). A second migration wave in the “Grande Coupure” allowed an increase in diversity during the Oligocene, and at least five genera and eleven species coexisted until the latest Oligocene. One species survived shortly to this local extinction, until the earliest Miocene (LAD of *Elomeryx minor* in MN1, early Aquitanian). After the complete disappearance of anthracotheres on this continent, the bothriodontine *Brachyodus onoideus* temporarily occurred in Western Europe in the Burdigalian (MN3-4, late Early Miocene). This African genus, along with the proboscidean *Deinotherium*, migrated towards Eurasia when the continents reconnected. This marked the first dispersal episode linked to the Proboscidean Datum Event (e.g., van der Made, 1999).

During the Miocene, in Africa, an evolved subfamily of anthracotheres probably led to the modern hippopotamuses (e.g., Boisserie & Lihoreau, 2006). The latter are, today, only represented by two species, *Hippopotamus amphibius* and *Choeropsis liberiensis*, which display different adaptations to two very different ecological niches. The first one lives as a semi-aquatic mammal, whereas the dwarf hippo prefers forested habitats. The cranial morphology of this latter species is additionally not adapted to the amphibious mode.

The recent systematic review of European anthracotheres (Scherler, 2011) brought new data regarding their paleobiogeography and paleoecology. Firstly, the dispersal routes of this family highlight endemism during the Early Oligocene of Western Europe. Secondly, the description of the first complete skull of “*Anthracotherium*” pinpoints the fact that this very large representative was not amphibious, contrary to earlier thoughts expressed by many authors (e.g., Cuvier, 1822). Indeed, none of the sensitive organs (nasals, orbits, ears) are disposed in a periscopic position. Finally, the surprisingly high $\delta^{13}\text{C}$ values and the low standard deviation in $\delta^{18}\text{O}$ values measured for the tooth enamel of the small *Microbunodon* suggest either an amphibious mode of life, or a strong relation to an aquatic habitat (Scherler, in prep. a, b). Oligocene European anthracotheres may therefore be a key taxon to understand the ecological dichotomy between the two species of modern hippopotamuses.

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14.10

Terrestrial ecosystems during and following the end-Permian mass extinction – or from spore spike to spore spike

Schneebeili-Hermann Elke¹, Hochuli Peter A.², Kürschner Wolfram M.¹, & Bucher Hugo²

¹ *Palaeoecology, Institute of Environmental Biology, Faculty of Science, Utrecht University, Laboratory of Palaeobotany and Palynology, Budapestlaan 4, 3584 CD Utrecht, The Netherlands (ElkeSchneebeili@gmx.net)*

² *Paläontologisches Institut und Museum, Karl Schmid-Strasse 4, CH-8006 Zürich*

The impact of the end-Permian mass extinction on terrestrial ecosystems is still debated. It has been suggested that the destruction of forests left a low-diversity vegetation behind, which was dominated by pioneering plants unvaried for a time interval of 4-5 Ma (Looy et al., 1999).

Here we present an alternative view of the Early Triassic vegetation history based on the palynofloral records of the Permian-Triassic boundary succession in Norway, and the well-dated Upper Permian to Middle Triassic successions of Pakistan and South Tibet.

In Norway, the end-Permian floral succession is marked by a distinct spore spike, which is associated with the end-Permian mass extinction and coincides with the negative carbon isotope shift that has been reported from numerous other Permian-Triassic boundary sections. Its contemporaneous equivalent in Greenland has been interpreted as signal for terrestrial ecosystem destabilisation and the onset of a long recovery time dominated by pioneering lycopods (Looy et al., 1999; 2001). In contrast, the high resolution record from Norway shows that the end-Permian spore spike is immediately followed by the recovery of gymnosperms. Correlation with the Permian-Triassic stratotype section in Meishan (South China) suggests a recovery time of some 10 ka (Hochuli et al., 2010).

Preliminary results from a new Permian-Triassic boundary section in Pakistan (Amb, Salt Range) do not indicate an end-Permian spore spike so far, however, higher spore abundances close to the Permian-Triassic boundary have been observed from single occurrences at Narmia and Chitta-Landu (Surghar Range). The new results from Amb suggest a gradual floral change reflected in the increasing dominance of lycopod spores towards the Dienerian. In Pakistan palynofloras dominated by lycopod spores and low numbers of pteridosperm and conifer pollen prevail from the Dienerian until the early Smithian and are also known from the early Smithian of South Tibet. In Pakistan these assemblages are followed by a pronounced spore spike in the middle Smithian. Similar to the patterns of the end-Permian record, the middle Smithian spore spike coincides with a negative carbon isotope excursion and is followed by the late Smithian marine extinction event. The recurrent Early Triassic negative carbon isotope excursions have been interpreted to reflect volcanically induced CO₂ pulses (Payne and Kump, 2007), thus environmental perturbations in phases of volcanic degassing might be the common cause for both of these events.

In Pakistan and South Tibet palynofloras of early Spathian age (~2 Ma after the end-Permian extinction event) are characterised by increasing abundance of gymnosperm pollen (conifers and pteridosperms) associated with reduced numbers of lycopod spores indicating the onset of terrestrial ecosystems stabilisation.

The described palynofloral patterns are complex and closely related to the changes in the carbon isotope record, which suggests that the floral recovery dynamics were linked to the environmental conditions.

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14.11

Nammal Nala (Salt Range, Pakistan), a potential GSSP candidate for the Induan/Olenekian Boundary (Early Triassic): detailed biostratigraphy and comparison with other GSSP candidates

David Ware*, Hugo Bucher*, Nicolas Goudemand*, Michael Orchard², Elke Hermann³, Peter A. Hochuli*, Thomas Brühwiler*, Leopold Krystyn⁴, Ghazala Roohi⁵

¹ Paläontologisches Institut und Museum, Universität Zürich, Karl Schmid-Strasse 4, CH-8006 Zürich, Switzerland

² Geological Survey of Canada, 625 Robson Street, Vancouver, BC, Canada V6B 5J3

³ Palaeoecology, Institute of Environmental Biology, Faculty of Science, Utrecht University, Laboratory of Palaeobotany and Palynology, Budapestlaan 4, 3584 CD Utrecht, The Netherlands

⁴ Department of Palaeontology – Geozentrum, Althanstrasse 14, A-1090 WIEN, Austria

⁵ Pakistan Museum of Natural History, Garden Avenue, Islamabad 44000, Pakistan

To improve our understanding of the biotic recovery in the aftermath of the Permian/Triassic mass extinction, a reliable high resolution biochronological frame of the Early Triassic period is crucial. This period is currently divided in two stages, the Induan and the Olenekian, but the boundary between the two is still not clearly defined and lacks a stratotype.

Here we present detailed biostratigraphical results based on new collections of ammonoids and conodonts from Nammal Nala (Salt Range, Pakistan), a classical locality for Early Triassic ammonoids, which had never been studied in detail. Our results show that this section provides by far the most complete profile for the definition of the Induan-Olenekian boundary (IOB). The GSSP's golden spike for the base of the Olenekian could be located at the first occurrence of Flemingitidae (a typical Smithian ammonoid family) and of the conodont genus *Novispathodus*. It also coincides with a positive shift of $\delta^{13}\text{C}_{\text{org}}$ of ca. 6‰, with a sequence boundary and with a palynofacies change (Hermann et al., 2011). In this expanded stratigraphical series the IOB falls within the Ceratite Marls without any significant facies change, an ideal configuration for the definition of a boundary.

The same sequence of faunal associations had previously been recognized in Mud (Spiti Valley, India; Brühwiler et al. 2010), another GSSP candidate for this boundary proposed by Krystyn et al. (2007a, b). Here, the faunal turnover occurs 1 m below the previously proposed IOB (in bed 10 instead of bed 13 of Krystyn et al. 2007a, b; Brühwiler et al. 2010), and is associated with a facies change (from dark shales with early diagenetic calcareous concretions to massive, bioturbated limestone beds) in a much more condensed section. Moreover, it has undergone strong diagenetic alteration, so no palynological record is available. Conodonts also allow detailed correlation with the section of Chaohu (SE China), another GSSP candidate for the IOB (Chinese Triassic Working Group 2007). The latter section is however condensed and lacks ammonoid and palynological record.

The use of multiple proxies to define the IOB allows its correlation with other sections throughout the world. However, pending similarly detailed analyses of other IOB localities (e. g. British Columbia, Arctic Canada, Siberia, Madagascar, etc.), detailed correlations with previous biostratigraphic schemes remain challenging.

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P 14.1

A Cretaceous fish takes a fast start: insights from a recent analogue

Loïc Costeur¹, Paolo Domenici², Rubén Ezquerra³, Mathieu Rousseau⁴, Fabio Antognarelli², Andrea Satta², Simone Simeone² & Félix Pérez-Lorente⁵

¹ Naturhistorisches Museum Basel, Augustinergasse 2, CH-4001 Basel (loic.costeur@bs.ch)

² Istituto per l'Ambiente Marino Costiero, CNR, Località Sa Mardini, IT-09072 Torregrande-Oristano

³ Instituto de Estudios Riojanos, Portales 2, SP-26001 Logroño

⁴ CFTJF, Total S.A., F-64000 Pau

⁵ Universidad de La Rioja, C/Madre de Dios, 51, SP-26006 Logroño

We describe here a fish trail found in the Early Cretaceous sediments of the Oliván Group (late Aptian-Albian in age), La Rioja, Spain in the light of a modern analogue. We hypothesize that the trail was caused by a specific fish behaviour commonly observed in modern fish, i.e. a fast-start escape response, which was followed by a 2-meters long irregular swimming sequence. Fast-start behaviors are commonly used in predator-prey encounters either to attack or to escape (Domenici & Blake 1997). Such movements are achieved by most modern fish and are mediated by Mauthner cells in the hindbrain, albeit differences in swimming performance exist among species (Domenici & Blake 1997).

The finding occurred on a micaceous fine to medium sandstone slab taking place at the end of a fluvial channel infill. The whole sedimentary succession indicates continental deposits in fluvial environments (flood plains, channels and point bars). As far as we are aware the fish trail is one of the only traces of a specific behavior (other than routine swimming) ever recorded for fish. Indeed only abrupt turns (Martin & Pyenson, 2005) and a feeding trace (Martin et al., 2010) are known so far. Traces of specific behaviors are very informative since they unravel the range of possibilities allowed by body morphology. They also have an evolutionary significance since specific behaviors evolve in response to specific constraints.

As far as the trail maker is concerned, it should have been a fish with a rather strong anal and/or caudal fin and flexible enough to be able to produce a fast-start; such fishes can be found in the Teleostei or Amiiformes that occur in the Early Cretaceous of Spain although no fish remains is known from the Oliván group itself.

A modern-day species was used to back up the fast-start hypothesis. We built up an experiment using a grey mullet (*Liza aurata*) swimming in shallow water above a sandy sediment with a composition close to that of the fossil site. The fish, when threatened, responded with a fast start and produced a C-shaped trace on the sediment that grossly matches the fossil trail, albeit being not that strongly imprinted and slightly different in shape (Fig. 1). The environmental conditions and the fish species used (most probably not the same family than that of the fossil trail) may account for the differences. Nevertheless, the experiment allowed us to strengthen our hypothesis that the fossil trace refers to a specific swimming behaviour related to predator-prey interactions.

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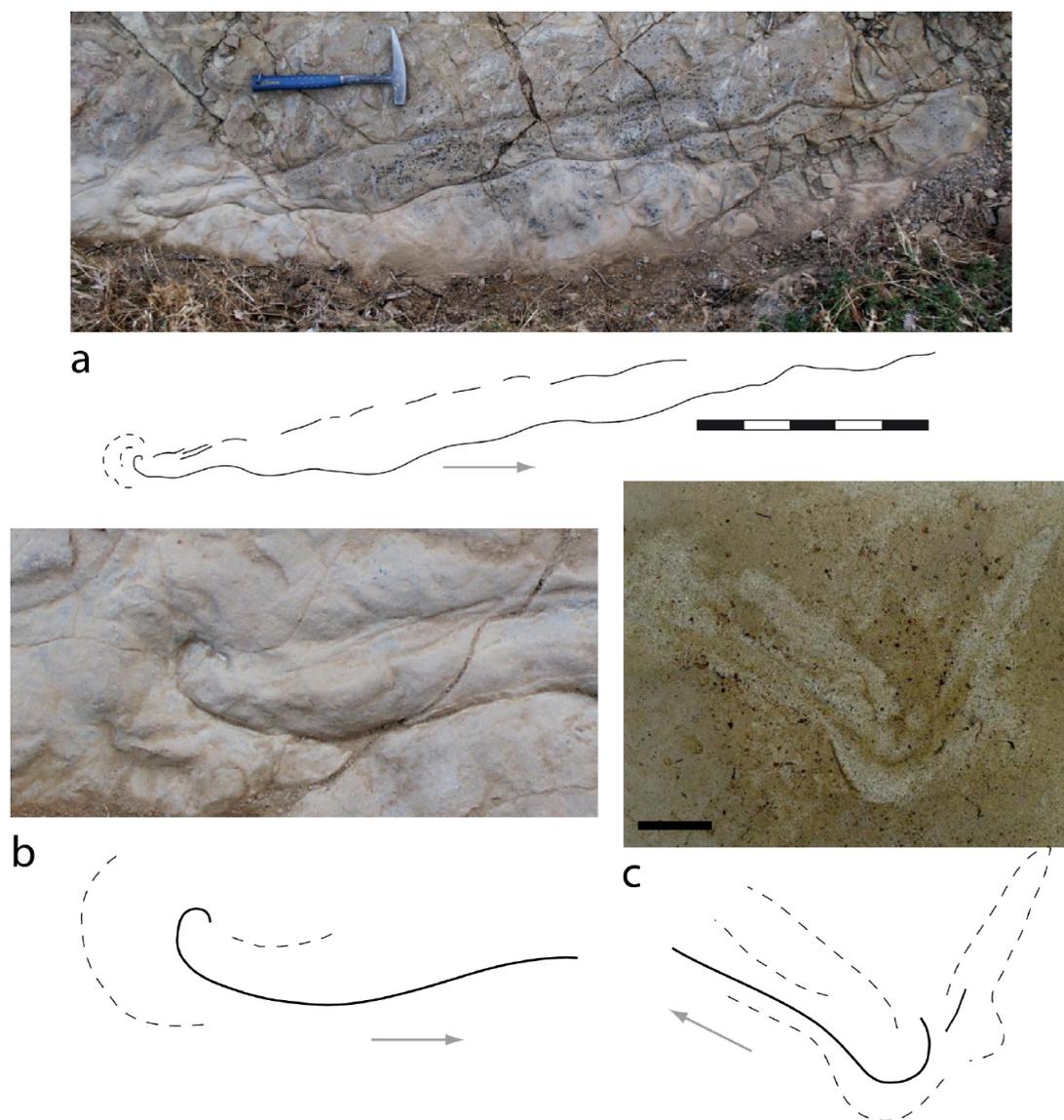


Figure 1. a, overall view of the Valtrujal fossil fish trail with explanatory drawing, scale bar: 50 cm; b, close-up of the C-shape starting point of the fossil trail with explanatory drawing; c, close-up of a fast-start C-shape trace left by a living grey mullet with explanatory drawing, scale bar: 5 cm. Dashed lines indicate mud rims or displaced sediment. Grey arrows indicate swimming direction.

P 14.2

A new skull of *Tapirus* from the Late Eocene of France

Loïc Costeur¹ & Didier Berthet²

¹ Naturhistorisches Museum Basel, Augustinergasse 2, CH-4001 Basel (loic.costeur@bs.ch)

² Centre de Conservation et d'Etude des Collections, 13 rue Bancel, F-69007 Lyon

Tapirus GÉRAIS, 1850 is an enigmatic small artiodactyl from the Late Eocene and Early Oligocene of Europe (Erfurt & Métais, 2007). The genus contains 5 species all characterised by a tapiroid bilophodont dentition which makes them quite different from the other European artiodactyls. The genus is endemic to Western Europe and is known from a relatively low amount of material (but with a rather good geographic distribution), albeit a very nice skull (Fig. 1) was recovered from the Quercy Phosphorites. It is one of the few genera to cross the Eocene-Oligocene famous “Grande Coupure”. The fossil we describe here is an almost complete skull with most of the dentition coming from a Late Eocene site in Central-Eastern France.

The site “Les Plantées” is situated in the vicinity of the city of Saint-Etienne not far from the shores of the Loire River. Geologically the sediments are fluvial in origin and the skull presented here was found in greenish coarse and not strongly consolidated sands. It's dated to MP18-20 (Huguency, 1997), thus Late Eocene. The site yielded few fossils and a preliminary faunal list was published in Huguency (1997).

The new skull is ascribed to *Tapirulus* cf. *hyracinus* STEHLIN, 1910. Preliminary comparisons to Eocene *Tapirulus* from the Middle to Late Eocene was carried out, and especially with skull NMB Q.B.185 (Fig. 1), one of the best preserved specimens from the Quercy Phosphorites and ascribed by Stehlin (1910) to *Tapirulus hyracinus*. Based on size alone, the four other species *T. majori*, STEHLIN, 1910, *T. depereti* STEHLIN, 1910, *T. schlosseri* STEHLIN, 1910, and *T. perrierensis* SUDRE, 1978 can be excluded as they are much smaller. Skull MHNL 20164554 is well preserved except in its basal part; the left tooththrow with I3-M3 together with the right tooththrow with P1-M3 are preserved; it is slightly smaller than that from Quercy, but overall proportions are similar. It is flat and has an elongated snout and thus a longer facial than posterior part. There seems to be two lacrimal orifices, or maybe a splitted orifice inside the orbit, while the skull from Quercy shows a clear situation of two separated orifices on its right virtually uncrushed orbit, one inside the orbit above a second one situated on the rim, both orifices being separated by a small projection of the lacrimal bone. A strong infraorbital foramen lies above the anterior part of the P3 just like on skull NMB Q.B.185. Teeth are worn so that few characteristics can be described in detail. However on molars, paraconules are absent and parastyles are rather strong; pre- and post-cinguli are strong especially on M3, much like on skull NMB Q.B.185 from the Quercy. The M1 and M3, although being larger than longer, do not reach the antero-posterior compression of the M2. P4 is triangular with strong labial styles and pre- and post-cinguli. Sudre (1978) mentions smaller sized *Tapirulus* (than *T. hyracinus*) from the Early Oligocene of Belgium and France and proposes to investigate this material in more details since he suggests that another Early Oligocene species might exist.

Comparisons to this material will be necessary to see if an intermediate sized species between the small *Tapirulus* and *T. hyracinus* did indeed exist. The locality “Les Plantées” is tentatively dated to MP18-20 (Huguency, 1997) and a Late Eocene age would fit well with *T. hyracinus* as this species is only known from the Late Eocene and Early Oligocene, the other species described so far being found in older localities.

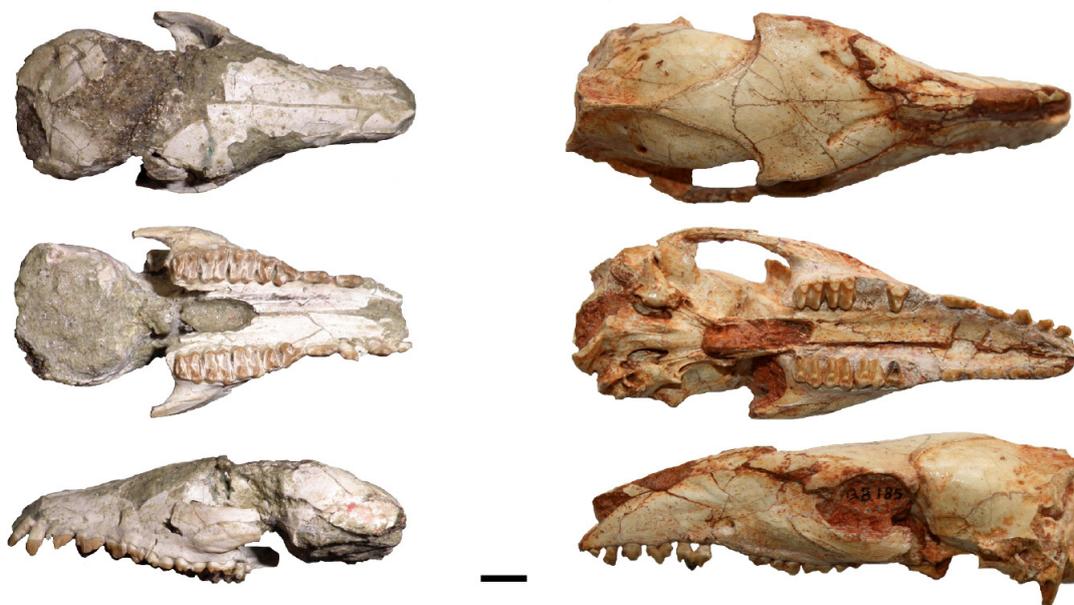


Figure 1: Left, skull MHNL 20164554 and right, skull NMB Q.B.185 from the Quercy Phosphorites in dorsal, palatal and lateral view from top to bottom, respectively. Scale bar 10 mm

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P 14.3

Endolithic microorganisms in Piora Dolomite

Horath Thomas D.¹, Bachofen Reinhard¹, Neu Thomas R.², Strasser Reto J.³

¹Institute of Plant Biology, University of Zürich, Zollikerstr. 107, 8008 Zürich, Switzerland

²Department of River Ecology, UFZ Centre for Environmental Research, Leipzig-Halle, Brueckstrasse 3A, 39114 Magdeburg, Germany

³Laboratory of Bioenergetics, University of Geneva, Chemin des Embrouchis 10, Jussy Lullier, 1254 Geneva, Switzerland

Endolithic microorganisms form a distinct band a few mm below the surface in dolomite rock in the Swiss Alps have been characterized using spectroscopical, optical and molecular methods. The light intensity in the band amounts for 1 to 5 % of the surface illumination. Reflection spectroscopy reveals pigments with *in vivo* absorption maxima around 715 nm, 680 nm, 625 nm and 500 nm, indicating the presence of eukaryotic algae, cyanobacteria and green phototrophic bacteria. Electron microscopy and confocal laser scanning microscopy display cyanobacteria of coccoid and filamentous morphotypes. Colonies of coccoid forms often are surrounded by pigmented sheaths and thick layers of exopolysaccharides protecting them against stress factors such as light, UV, or lack of water and nutrients. Cloning the small subunit ribosomal RNA gene resulted in 53 different clones, while the sequence of most of them was not present in data libraries. Besides *Bacteria* also *Crenarcheota*, eukaryotic *Amoebae* and a *Bryophytum* (moss) were found.

The fluorescence transients of chlorophyll a indicate that the photosynthetic activity of the cyanobacteria is strongly dependent on water availability.

We conclude that the small zone of endolithic microorganisms underneath the rock surface is a nearly closed micro-ecosystem harboring a broad variety of physiologically active species.



Figure 1. Opened dolomite rock from the Piora Valley with endolithic green phototrophs. The scale bar is in centimetres.

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P 14.4

Mining morphological evolution in microfossils using volume density diagrams

Michael W. Knappertsbusch¹ & Yannick Mary^{1,2}

¹Naturhistorisches Museum Basel, Augustinergasse 2, CH-4001 Basel (michael.knappertsbusch@unibas.ch)

²Geologisch-Paläontologisches Institut, Bernoullistrasse 32, CH-4056 Base

Morphometry is an important technique for the quantitative description of variations and differences between closely related extant and extinct species and their phylogenetic relationships. Morphotypes include a group of specimens, that most typically describe the morphological appearance in a fossil assemblage. They are characterized by a combination of meaningful, independent morphological characters. In the ideal case morphotypes are recognizable as well separated data clusters in a multivariate set of morphometric measurements. In reality however, there exists often overlap between such clusters and then statistical and/or graphical methods must be applied to best separate these clusters in a reliable way. Whether a morphotype also represents a biological species must further be clarified using independent evidence from biological, (paleo-) ecological, biogeographic, geochemical or molecular investigations. If the history of morphotype variation is studied in a sequence of successive samples in the geological record moments of evolutionary splitting and divergence may be uncovered, which eventually witness speciation of an ancestral species into a descendent one. Such analysis, however, requires a very large number of measurements through time, from several locations (Knappertsbusch 2011). Understandably, that these data are often difficult to analyse and interpret, even with the help of sophisticated statistical methods. Graphical analysis of the results is thus irreplaceable to reveal the morpho-phylogenetic relationships from one morphotype to another.

In the present contribution a graphical analysis and display software called Voxler from Golden Software is exploited, which allows to communicate complicate morphological evolutionary trends through geological time to researchers and to laymen. Two pre-existing and published data sets for the study of evolution in these organisms are used for the present exercise: The first example is taken from Knappertsbusch (2000), which describes the plexus of *Calcidiscus leptoporus* – *Calcidiscus macintyreii*, a group of Neogene marine calcareous planktonic algae including morphologically closely related extinct and extant morphotypes. These algae produce minute calcite platelets – coccoliths – that surround the cell and which after death accumulate to thick piles of calcareous deep sea oozes at the bottom of the oceans. The second example is taken from Knappertsbusch (2007), where *Globorotalia menardii* was studied, a representative of Neogene planktonic foraminifera, and which belongs to marine calcareous shell secreting planktonic protists. Also these shells - after settlement to the bottom of the ocean - are major contributors to worldwide deep-sea sediments.

In both cases, the original observations consisted of simple bivariate measurements of the hardparts along a number of deep-sea cores, i.e., coccolith size versus its number of sinusoidal ornamentations on the distal side for *C. leptoporus*, and the length versus width of shells in profile view in the case of *G. menardii*. The time-series of bivariate measurements were transformed into discrete time-series of bivariate frequency distributions, which themselves were interpolated to obtain continuous density diagrams of specimens throughout the bivariate morphospace and through geological time. These density variations could then be displayed in three dimensions and animated using Voxler.

The advantage of this graphical representation is, that morphotype evolution could be analyzed and visualized more comprehensively than with any of the previously applied methods (i.e., stacked series of scatter- or contoured frequency plots from one time-level to the next, or stacks of transversal sections of specimen frequencies parallel to the time axis, which were all quite difficult to present to the general audience). Using the animated density diagrams the authors are convinced, that they portray measured evolutionary patterns such as splitting and divergence more intuitively than without such tools.

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Please follow also the links under "Research" from <http://pages.unibas.ch/museum/microfossils/index.html>

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AMOR does it for us

Michael W. Knappertsbusch¹, Yannick Mary^{1,2} & Richard Schorpp^{3,1}

¹Naturhistorisches Museum Basel, Augustinerstrasse 2, CH-4001 Basel (michael.knappertsbusch@unibas.ch)

²Geologisch-Paläontologisches Institut, Bernoullistrasse 32, CH-4056 Basel

³Fachhochschule Nordwestschweiz, Institut für Automation, Steinackerstrasse 5, CH-5210 Windisch

AMOR (Automated Measurement system for shell mORphology) is a robot, which automatically positions, orientates and images isolate planktonic foraminifera, that are mounted in a standard micropaleontological slide under a binocular microscope (Knappertsbusch et al. 2009). It consists of a motorized four-axis tilting and gliding stage, that fits under a binocular and the latter being equipped with a digital video camera. The microscope is driven by a motorized zoom and has an autofocus. All components are controlled via custom developed software AMOR written in LabView 8.5 for a PC. The AMOR software was developed in several successive collaboration projects with students and engineers from the University of Applied Sciences of Northwestern Switzerland (FHNW). Since 2009 it was further improved to its present version 3.17. Using AutoIt v3 (a freeware automate and script language for windows tasks) individual functions from AMOR can be combined as needed and even allows for overnight-processing.

We use AMOR to collect images of shells of the planktonic foraminiferal group *Globorotalia menardii* in upside (keel) or spiral/umbilical view. AMOR first moves to the center of a field in the multicellular faunal slide, focuses, tilts the slide in x- and y direction until the specimen stands perfectly upright in keel position or is perfectly horizontal when spiral or umbilical position is selected. After re-calculation of the vertical position of the microscope and re-focussing and after image rotation for perfect “north-to-south” orientation of the shell on the computer monitor the optimum magnification for final imaging is sought. After auto-zooming and final refocussing a tiff image is saved to disc and the stage moves on to the next specimen repeating the cycle until the last field is completed. The magnification for every image is recorded for conversion of peripheral pixels to micrometers. A slide-calibration routine is implemented for usage of different types of faunal slides. Optionally, a character recognition can be activated in order to differentiate between the foraminiferal shell and white numerals, that are imprinted in the bottom of the slide. Next to operation in automated mode the user can choose a “single-specimen” mode to orientate and image individuals.

While AMOR orientates and collects digital images of isolated microfossils, additional software (MorphCol) developed by ourselves helps to automatically extract morphometric descriptors from the thousands of images, that we have collected so far. The following measurements are used to characterize shell variability: spiral height, axial length, keel angles, osculating circles of the keel region and surface area of the silhouette. For every specimen outline coordinates are extracted for fourier- and/or eigenshape analyses.

Our goal is to quantify inter- and intraspecific morphological shell variation in planktonic foraminifera like *Globorotalia menardii* and to better understand the biogeography of its morphological evolution and speciation (Knappertsbusch 2011). Menardiform globorotalids, our study objects, were selected because of their interesting radiation during the Pliocene. We use core materials from Holocene and ODP samples from a Late Pliocene (3.2 Ma) time-slice, and from from several DSDP and ODP cores considered to be interesting for testing speciation patterns through time. So far we have investigated cores from the Caribbean Sea (DSDP Site 502) and the Eastern Equatorial Pacific (503), and morphometric measurements from menardiform globorotalids are currently collected for the past 8 million years at ODP Site 925 (Ceara Rise).

Practical work with AMOR has proven its advantage for the routine collection of large data sets. However, as the system was especially developed for menardiform morphologies it is not always applicable to strongly different shell morphologies. Systematic shape changes, that other genera than flat globorotalids may have attained during their evolution may cause AMOR to fail for automatic positioning of shells (in such a case the operator has the possibility to escape to the “manual mode” of AMOR). For example, the umbilico-convex and asymmetric shells of *Globorotalia miocenica*, an extinct but related form within the *G. menardii* radiation, requires a slightly modified algorithm for auto-positioning than the bi-convex and almost symmetric shells of a typical *G. menardii*. Such difficulties were not inevitable during our studies and still need adaptation of the software, which is the next task in our effort to automate microfossil shell measurements.

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Please follow also the links under «Research» from <http://pages.unibas.ch/museum/microfossils/index.html>

P 14.6

The Neoproterozoic Oxygenation Event: environmental perturbations and biogeochemical cycling

Och Lawrence¹, Shields-Zhou Graham A.²

¹ Department of Earth Sciences, University College London, Gower Street, London WC1E 6BT, UK
Current address: Eawag, Seestrasse 79, CH-6047 Kastanienbaum

² Department of Earth Sciences, University College London, Gower Street, London WC1E 6BT, UK

The oxygen content of the Earth's surface environment is thought to have increased in two broad steps: the Great Oxygenation Event (GOE) around the Archean-Proterozoic boundary and the Neoproterozoic Oxygenation Event (NOE), during which oxygen possibly accumulated to the levels required to support animal life and ventilate the deep oceans. Although the concept of the GOE is widely accepted, the NOE is less well constrained and its timing and extent remains the subject of debate. We review available evidence for the NOE against the background of major climatic perturbations, tectonic upheaval related to the break-up of the supercontinent Rodinia and reassembly into Gondwana, and, most importantly, major biological innovations exemplified by the Ediacarian Biota and the Cambrian 'Explosion' (see Figure 1).

Geochemical lines of evidence for the NOE include perturbations to the biogeochemical cycling of carbon. Generally high $\delta^{13}\text{C}$ values are possibly indicative of increased organic carbon burial and the release of oxidative power to the Earth surface environment after c. 800 Ma. A demonstrably global and primary record of extremely negative $\delta^{13}\text{C}$ values after about 580 Ma strongly suggests the oxidation of a large dissolved organic carbon pool (DOC), the culmination of which around c. 550 Ma coincided with an abrupt diversification of Ediacaran macrobiota. Increasing $^{87}\text{Sr}/^{86}\text{Sr}$ ratios towards the Neoproterozoic - Cambrian transition indicate enhanced continental weathering which may have fuelled higher organic production and burial during the later Neoproterozoic.

Evidence for enhanced oxidative recycling is given by the increase in sulphur isotope fractionation between sulphide and sulphate, exceeding the range usually attained by sulphate reduction alone, reflecting an increasing importance of the oxidative part in the sulphur cycle. S/C ratios attained a maximum during the Precambrian – Cambrian transition, further indicating higher sulphate concentrations in the ocean and a transition from dominantly pyrite burial to sulphate burial after the Neoproterozoic. Strong evidence for the oxygenation of the deep marine environment has emerged through elemental approaches over the past few years which were able to show significant increases in redox-sensitive trace-metal (notably Mo) enrichment in marine sediments not only during the GOE but even more pronounced during the inferred NOE. In addition to past studies involving Mo enrichment, which has been extended and further substantiated in the current review, we present new compilations of V and U concentrations in black shales throughout Earth history that confirm such a rise and further support the NOE. With regard to ocean ventilation, we also review other sedimentary redox indicators, such as iron speciation, molybdenum isotopes and the more ambiguous REE patterns. Although the timing and extent of the NOE remains the subject of debate and speculation, we consider the record of redox-sensitive trace-metals and C and S contents in black shales to indicate delayed ocean ventilation later in the Cambrian on a global scale with regard to rising oxygen levels in the atmosphere which likely rose during the Late Neoproterozoic.

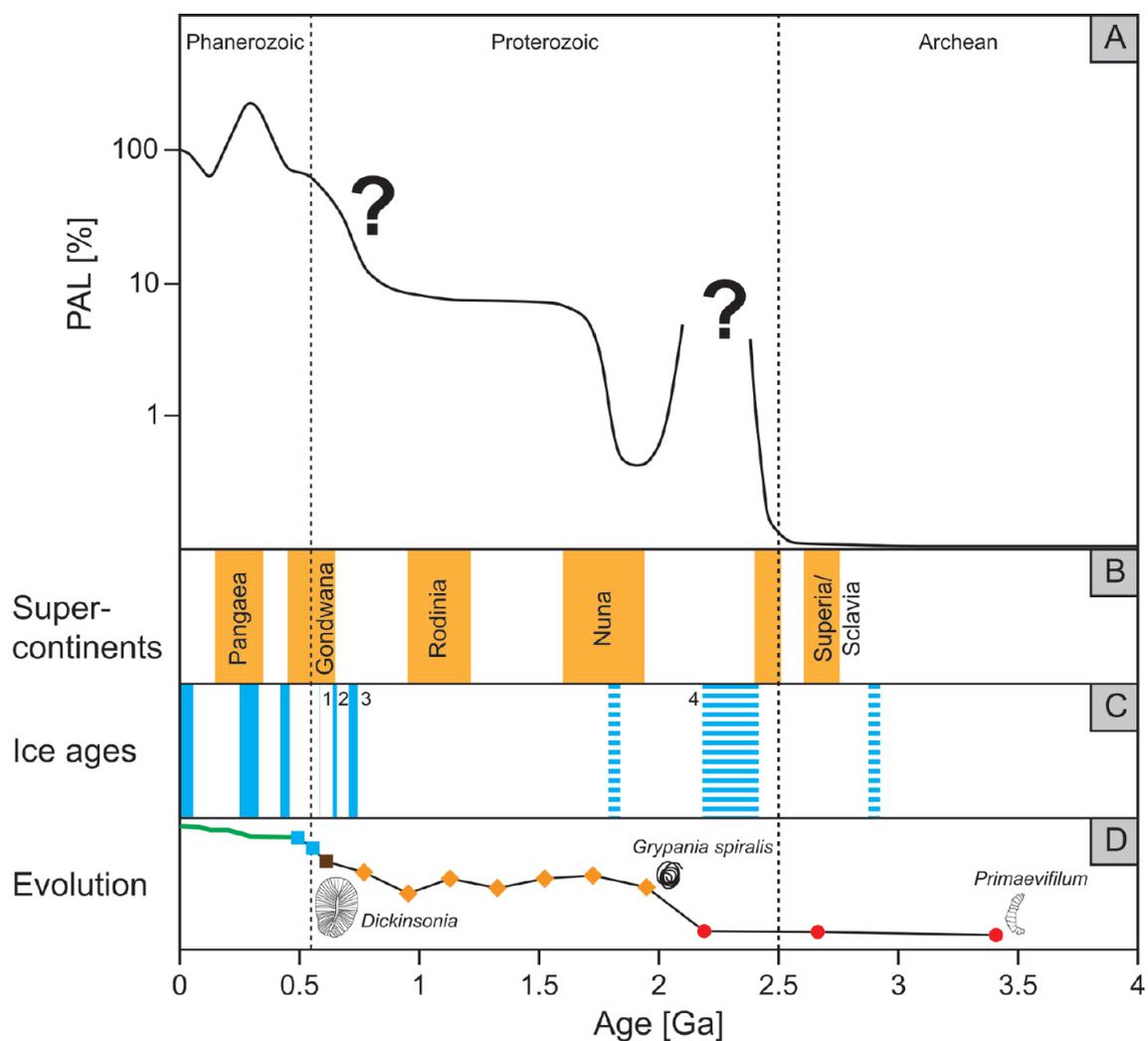


Figure 1: A) Proposed reconstruction of the atmospheric O_2 content through time expressed as the percentage of present atmospheric level of oxygen. B) Periods of supercontinent formation. C) Precambrian glaciations whereby the numbered blue bars are of presumably global extent: 1) Gaskiers glaciation, 2) Marinoan glaciation, 3) Sturtian glaciation, 4) Makganyene/Huronian glaciation. D) Biological innovations exemplified through increase of maximum size of organisms throughout Earth history. Red dots: prokaryotes, orange diamonds: protists, brown square: vendobiont (probable multicellular eukaryote, e.g. *Dickinsonia*), blue squares: animals, green line: vascular plants.

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The *Exogyra aquila* Marls (Lower Aptian) on the Vivarais platform (Ardèche, France) : Sedimentology, stratigraphy, and biostratigraphy.

Pictet Antoine

Géology and Paléontology Institut, University of Lausanne, Anthropole – CH- 1015 Lausanne (sk8chmullen@hotmail.com)

The end of the Urganian carbonate platform is marked by the sudden disappearance of an entire oligotrophic ecosystem dominated by rudist, coral and stromatoporoids. On the Ardèche platform (SE France), this crisis is characterized by a regional discontinuity, polyphased, called DFU or DRBeS according to diverse authors. Petrographic and sedimentologic analyses carried out on this boundary and overlying “*Exogyra aquila* Marls” (Upper *Orbitolina* beds, Lower Aptian) have permitted to distinguish a karstified surface, whose cavities are commonly filled with continental sediments. Over this surface, is directly superimposed a deep-subtidal hardground, characterized by microbial mats (Stromatolites) that developed on internal platform, whose formation is probably linked to the Aptian transgression. Biostratigraphy by ammonites and orbitolinids allows to date this surface to the Forbesi Zone pro parte. This latter formed during a very short period, and indicates that brief eustatic variations of great amplitude must have occurred early in the Aptian, probably related to large-scaled climatic changes that significantly modified sediment and nutrient inputs.

The overlying “*Exogyra aquila* Marls” Formation, extremely well preserved on the Ardèche platform, can be structured into four members that constitute a shallowing-upwards sequence mainly comprised of hemipelagic, shaly limestones and echinoderm-rich limestones. During their deposition, an extensive tectonic activity took place, modifying the local depositional pattern and creating fluctuations within the shaly-calcareous sediments. Thanks to the abundance of ammonites, these sediments were easily dated from Forbesi and Deshayesi Zones.

The “Black Marls” Formation follows the *E. aquila* Marls, with a new transgression brutally interrupted by the highly erosive regional discontinuity DRBeT. The result of this erosion is a basal phosphatic breccia named Pélican Horizon, marking the base of this formation. The DRBeT discontinuity, as well as the “Horizon du Pélican”, were dated to be of the late Dufrenoyi subzone. This limit shows a significant erosion in the inner platform, along with large dissolved and recrystallized areas whose origin remains unclear.

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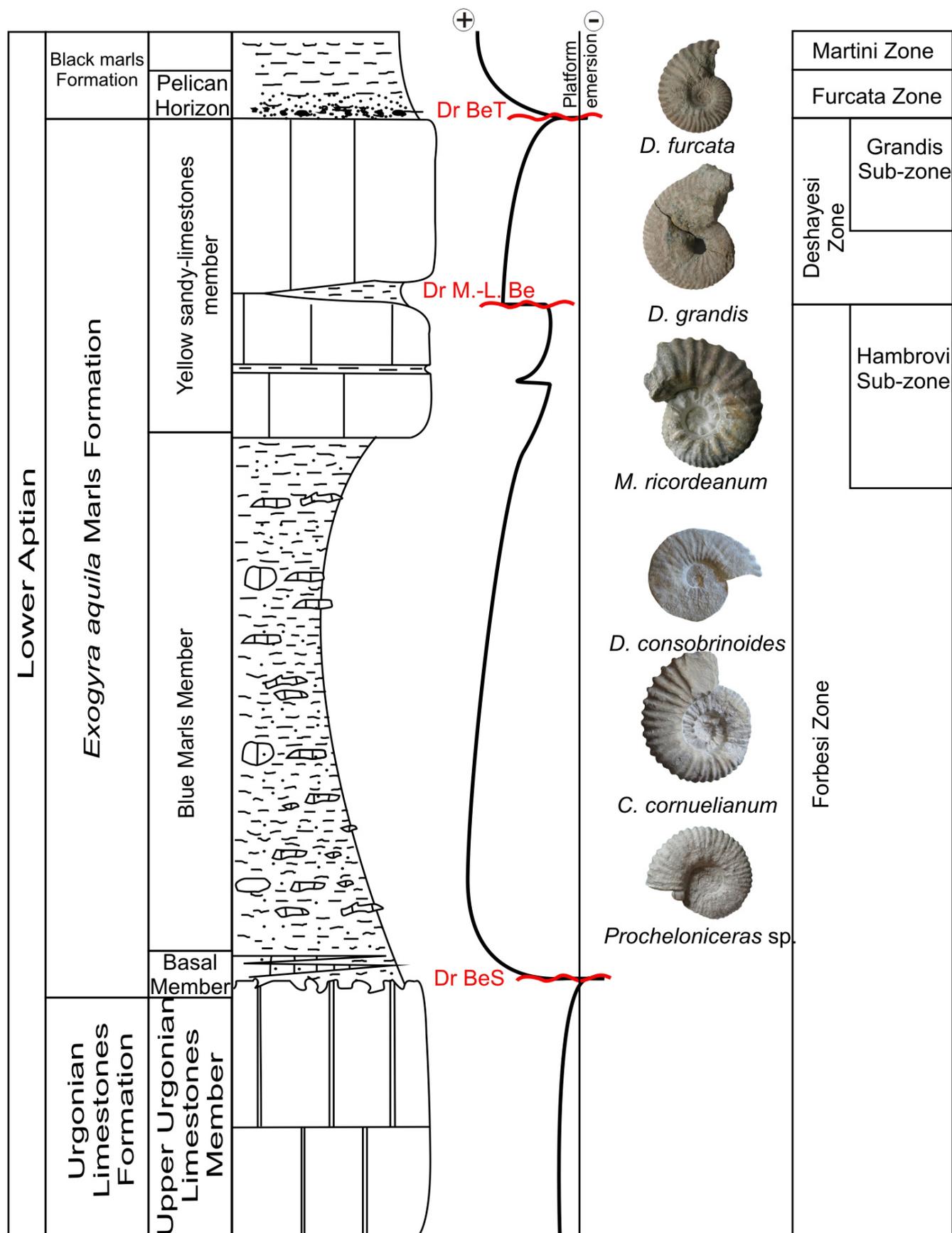


Figure 1. Simplified log of *Exogyra aquila* Marls on the Vivarais platform in regard with lithostratigraphy nomenclature, major discontinuities and eustatic curve, useful ammonites and corresponding biozonation.

P 14.8

Pushing life to the extreme: Investigating the subsurface biosphere in the Dead Sea Basin

Camille Thomas¹, Aurèle Vuillemin¹, Muriel Pacton², Nicolas Waldmann³, Daniel Ariztegui¹ and the DSDDP Scientific Team[°]

¹ University of Geneva, Department of Earth Sciences and Paleontology, CH-1205 Geneva, Switzerland (camille.thomas@unige.ch)

² ETH Zürich, Geologisches Institut, CH-8092 Zürich, Switzerland

³ University of Haifa, Department of Marine Geosciences, 31905 Mt. Carmel, Israel

[°] Complete list of DSDDP scientists at www.icdp-online.org

The Dead Sea Deep Drilling Project (DSDDP) is an internationally funded multidisciplinary initiative aiming to reconstruct the paleoenvironmental and paleoseismicity history of the Dead Sea Basin (DSB). Within this framework an ongoing geomicrobiological study in the recovered sediments aims to characterize the subsurface biosphere. The foci of this study are to identify the microbes surviving in this chemically peculiar environment and their participation in authigenic mineral precipitation.

A 450m long core consisting mainly of detrital mud, salt and primary aragonite has been recovered from the center of the present Dead Sea. DAPI-stained epifluorescence microscopy has allowed the observation and quantification of living bacteria in the uppermost 130m sediments. Several lithological intervals are dominated by needle and star-shaped aragonite interpreted as direct authigenic precipitation from the water column (Stein et al., 1997). SEM imaging and EDX spectroscopy have allowed the identification of precursors of Fe-S minerals within these intervals, pointing towards a microbially-related mineralization.

Similarly, in the superficial sediments of the core, where DAPI counting reaches a maximum, well preserved exopolysaccharide substances (EPS) are closely related to precursors of aragonite stars. We hypothesize that these EPS may act as a template for aragonite nucleation under the chemical conditions prevailing today. This is also supported by observations of dead microbial mats forming thin dark laminae interbedded with white laminae of aragonite in the modern western Dead Sea shore.

These observations have allowed the identification for a first time of a living subsurface biosphere in the Dead Sea sediments. Further investigations using a modern geomicrobiological approach will bring new light on the prevailing conditions behind its survival and its influence on the formation of the Dead Sea sediments throughout time.

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