Report on the activities of the Carboniferous – Permian –Triassic Nonmarine-Marine Correlation Working Group for 2020 and 2021

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The years 2020 and 2021 were marked worldwide by the corona pandemic with restrictions on fieldwork at home and abroad, with limited personal communication and restricted access to fossil and rock collections. Still, remarkable progress has been made by the international team of our working group as shown below by a number of publications, the participation in several online meetings and by the organization of future cooperative research work. Moving up through the geological timescale, we report the following.

Carboniferous

The Geological Society, London, is in the process of publishing a comprehensive volume on the Carboniferous timescale as part of its Special Publications Series, co-edited by Spencer G. Lucas, Joerg W. Schneider, Xiangdong Wang and Svetlana Nikolaeva. Many of the articles are already published online, and the volume will likely be finished in September. The papers already published online on nonmarine biostratigraphy are those of Opluštil et al. (2021) on macrofossil plant biostratigraphy, Lucas (2021a) on tetrapod biostratigraphy (Fig. 1) and Lucas et al. (2021b) on tetrapod footprint biostratigraphy. Papers by Chen et al. (2021) on Carboniferous isotope stratigraphy and by Hounslow (2021) on Carboniferous magnetostratigraphy are also relevant to Carboniferous nonmarine-marine correlations. Additional papers in this volume not yet published concern nonmarine bivalve biostratigraphy (Amler and Silantiev, in review), combined insect-conchostracan biostratigraphy (Schneider et al., in review), palynostratigraphy (Eble) as well as cyclostratigraphy (Montañez, in review) and the Carboniferous numerical timescale (Ramezani).

In early 2021, years of research were culminated by publication of New Mexico Museum of Natural History and Science Bulletin 84, "The Kinney Brick Quarry Lagerstätte, Late Pennsylvanian of New Mexico," a 466-page volume of 20 articles edited by Spencer G. Lucas, William A. DiMichele and Bruce D. Allen (free download here: The Kinney Brick Quarry Lagerstätte, Late Pennsylvanian of New Mexico - Google Books). Kinney has been known as an important Lagerstätte since the 1960s, where a mixture of nonmarine fossils (especially plants, insects and amphibians) are found together with marine fossils (notably brachiopods, bivalves and conodonts) and with an extensive fish assemblage of mixed nonmarine and marine origin (also see Stack et al., 2020). A 2014 controlled excavation at Kinney (the first such excavation) overseen by Spencer G. Lucas and Joerg W. Schneider provided much of the impetus (and new data) for the volume (Schneider at al., 2021a,b) (Fig.2). The conodonts at Kinney and fusulinids found stratigraphically just below the quarry indicate it is of early Missourian (Kasimovian) age, so Kinney provides an important tie point between nonmarine and marine biostratigraphy (see discussion by Schneider et al., 2020).

On May 23-27, 2021, an online meeting on a zoom platform provided by the Smithsonian Institution titled "The Kasimovian Workshop" was sponsored by the Carboniferous Subcommission, and it was co-organized by William A. DiMichele, Spencer G. Lucas, Stanislav Opluštil and Xiangdong Wang. The meeting brought together about 40 scientists from across the globe to present research on diverse aspects of the Late Pennsylvanian world. Many presentations focused on nonmarine depositional systems, paleontology, biostratigraphy and correlation. Smithsonian technical staff are now working to put almost all of the presentations (they were recorded) up on a YouTube channel. Stay tuned!

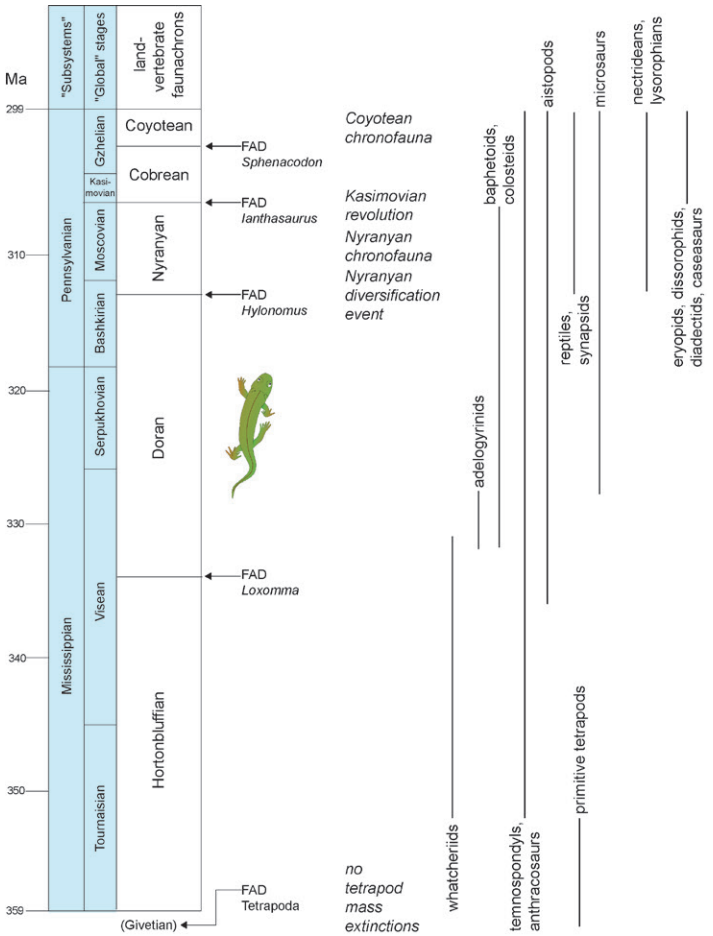

Fig.1. Carboniferous tetrapod biochronology (from Lucas, 2021).

A related article by DiMichele et al. (2020) discussed taphonomic biases in the late Paleozoic plant record, particularly with regard to the problems of so-called "upland" floras. It provides another cautionary note in the use of macrofossil plants in late Paleozoic correlations. In a related paper, Bashforth et al. (2021) have just published an extensive discussion of "mixed" upper Paleozoic floras, those with both wet and dry elements. They argue that the idea that the dryland floral elements grew in uplands and were transported into the mixed floral settings has little support, another example of the problems of facies control of macrofloral assemblages. Nelson and Lucas (2021) published a critique of the ill-defined Cantabrian substage (stage), a chronostratigraphic unit based on macroplant biostratigraphy. Lucas and Tanner (2021) documented calcareous paleosols ("calcretes") from Kasimovian strata in far western Pangea (New Mexico, USA), one of the few well-studied paleosol records of this age. Lucas et al. (2021a) published a monographic study of the Pennsylvanian strata in the Sacramento Mountains of New Mexico that include important Missourian paleofloras and a nonmarine animal fossil record (conchostracans, ostracods, bivalves, insects, fish bits) that merits further development and study.

Luthardt et al. (2020) report on sedimentation and magmatism in one of the most extensive Carboniferous/Permian vulcanite areas, the Flechtingen Volcanic Complex (FVC), at the southern border of the younger Southern Permian basin. Supported by radioisotopic ages, this study contributes to the clarification of stratigraphic constraints on upper Carboniferous to Lower Permian continental deposits and sheds new light on the stratigraphy of significant upper Palaeozoic volcanic deposits. The Mammendorf quarry, situated in the FVC, exposes the above mentioned volcanites as well as upper middle to lowermost upper Permian sediments, and is gaining growing importance as one of the youngest (Capitanian) locations of Permian tetrapod tracks in Europe (Buchwitz et al., 2019).

Trümper et al. (2020a) described fluvial red beds containing anatomically preserved large woody debris in the Kyffhäuser area of the Saale basin (Central Germany), which shed new light on seasonally dry biomes of the Pennsylvanian–Permian transition. The radioisotopic U-Pb age of 299 + 3.2 Ma of this beds improve the calibration of Upper Pennsylvanian (Gzhelian) insect and conchostracan zones.

The age of the world-famous upper Palaeozoic insect locality Xiaheyan in Northwest China has been corrected from an assumed late Namurian age by conodont and ammonoid biostratigraphy as well as by radioisotope ages to latest Bashkirian (latest Duckmantian) to middle Moscovian (Bolsovian) by a Chinese/French/German team (Trümper et al., 2020b). The insect fauna of this locality is of importance for the palaeobiogeographic and biostratigraphic relations of the Cathaysian to the Angaran and Euramerican biotic provinces.

Permian

Spencer G. Lucas, in collaboration with Charles Henderson (University of Calgary, Canada), have been sampling Permian limestones intercalated with nonmarine red beds in Texas, New Mexico and Arizona. The sampling has yielded extensive

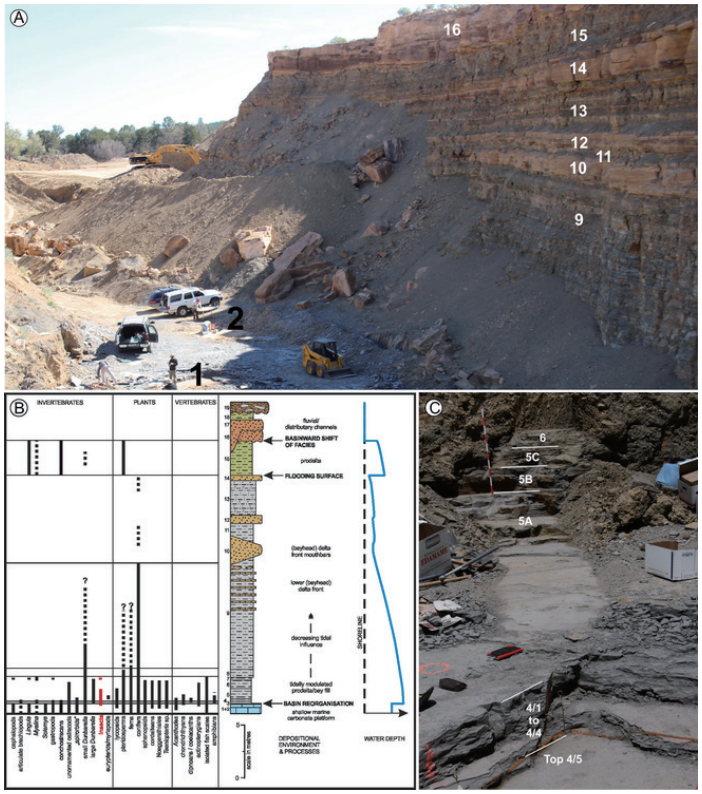

Fig. 2. Kinney Brick Quarry. A, Locations of controlled excavation of beds 2 to 5 (1) and the unit 3 fish bed (2); 9 to 16 are bed numbers in the quarry wall. B, Lithology and fossil content of beds 1 to 19 (modified after Williams and Lucas, 2013) and inferred depositional environments/processes. C, Trench from bed 4/5 into bed 6, which connects the excavation site with the quarry wall section; bed 4 and 5 bear the highest content of fossil insects. Scale near beds 5-6 is 1 m. From Schneider et al. (2021b).

Kungurian conodont assemblages from the Blaine Formation (Texas), Yeso Group (New Mexico) and Fort Apache Limestone (Arizona). In this issue of *Permophiles*, Lucas and Henderson present an initial report on the Arizona conodonts. The Texas (Blaine) conodonts confirm that Olson's gap is longer than previously expected, as earlier concluded by Lucas and Golubev (2019). This work will be published in the near future, as it provides important tiepoints between nonmarine Permian tetrapod and tetrapod footprint assemblages and the marine Permian timescale.

A German-French team has completed the study of a new huge caseid synapsid of estimated 3.6 m length from the Guadalupian La Lieude Formation of the Lodève basin in Southern France, which will appear in press at the end of 2021 (Werneburg et al., 2021, in review). In Germany has started this year after a break of about 10 years a new research project on the world-famous early Permian tetrapod track and skeleton locality Bromacker near Tambach-Dietharz town in the Thuringian Forest basin (Fig. 3). "Opening science: new ways of knowledge transfer using the example of the research project Bromacker" is the title of an interdisciplinary cooperative research project, which started in August 2020 and is funded by the Federal Ministry of Research and Education. Participating institutions are the

Fig. 3. Start of the new 5-years excavation period at the world-famous Lower Permian tetrapod lagerstätte Bromacker in the Thuringian Forest basin, July 2021. J.W. Schneider.

Museum für Naturkunde Berlin – Leibniz-Institute for Evolution and Biodiversity Research, the Stiftung Schloss Friedenstein Gotha, the Friedrich-Schiller-Universität Jena and the recently declared UNESCO Global GeoPark Thüringen Inselsberg-Drei Gleichen, as well as other national and international partners. The focus is not only on investigating the world-famous tetrapod locality Bromacker near Tambach-Dietharz, but essentially the entire Lower Permian Tambach Formation in the Thuringian Forest. The combined record of tracks and body fossils from the Bromacker site, their excellent preservation and extraordinary species richness provide a unique window into the paleobiology and ecology of early tetrapods and their ecosystems. Special focus is being placed on geology, climate, biodiversity, ecology, biomechanics, and physiology. One of the main goals of this project, in addition to the scientific progress, is to enable the participation of the general public in this integrative research project by applying novel science transfer approaches. The first results have been published by Marchetti et al. (2021a) and Buchwitz et al. (2021).

The excavations of the museum Geoskop in southwest Germany in the active Remigiusberg quarry (Fig. 4) will make this site one of the most complex fossil Lagerstätten in Europe with a diverse tetrapod fauna (Voigt et al., 2019). The so far know tetrapod fauna includes fully aquatic (dvinosaurian temnospondyl), semiaquatic (eryopid) and terrestrial (sphenacodontid and edaphosaurid synapsid) animals. First high-precision U-Pb CA-ID-TIMS age from near the base of the overlying Altenglan Formation supports the biostratigraphic data that indicate the Remigiusberg Formation is of latest Gzhelian to earliest Asselian age (Voigt et al., 2021; in review).

Rößler (2021) published a comprehensive report on "the most entirely known Permian terrestrial ecosystem on Earth…," the Chemnitz Fossil Forest in Germany, preserved by explosive volcanism during the late Sakmarian/early Artinskian (291+ 2 Ma). Two excavations at Chemnitz, ongoing since 2008, have opened a unique window into a low-latitude "wet spot" ecosystem, characterized by a dense hygrophilous arborescent vegetation and a diverse fauna of vertebrates and invertebrates.

The team from Kazan University, Tatarstan, other Russian institutions, and Boise State University, Idaho, USA, have delivered very interesting new results of a multidisciplinary study of the Permian-Triassic transition in the continental deposits of the Kuznetsk Basin, Russia (Davydov et al., 2021). These data are important in two aspects. First, the region is proximal to the Siberian Large Igneous Province, and the effects of the flood basalt volcanism in the Kuznetsk Basin may have been of similar scale to the main area of the Siberian Traps distribution, e.g. the Tunguska and Taymyr regions. Second, it provides new insights in the latitudinal effects of the Permian/Triassic crisis, which seems to have been much stronger in low latitudes then in the higher latitudes of Siberia. A climate shift poleward during the Permian-Triassic transition caused the replacement (turnover) of the humid-related biotas by the dry climate-related communities, which continued to expand throughout the Triassic in terrestrial habitats. Additionally, high precision CA-IDTIMS U-Pb zircon ages combined with conchostracan biostratigraphy of the PT-transition are a valuable contribution to nonmarine-marine correlations of the Angaran to the Euramerican biotic region.

Cathaysia correlations

Shuzhong Shen reports that great progress has been made on the Carboniferous and Permian in the North China Block. A series of high-precision CA-ID-TIMS dates from the upper Carboniferous Taiyuan Formation and Permian strata have been published (Wu et al., 2021). The new dates indicate that the lower part of the Taiyuan Formation is of Late Carboniferous age, and the upper part of the Taiyuan, the Shansi and the Lower and Upper Shihhotse formations, all belong to the Cisuralian. A considerable unconformity of ca. 20 m.y. is present that encompasses the late Cisuralian to Guadalupian at the top of the Upper Shihhotse Formation in the northern North China block. The overlying Sunjiagou Formation is of Lopingian age. An analogous unconformity was reported from correlative Permian successions in eastern Xinjiang (Yang et al., 2010). The

Fig. 4. Remigiusberg Quarry, near Kusel, southwest Germany. Exposed are the quarried subvolcanite and above fluvio-lacustrine sediments of the Remigiusberg Formation of latest Gzhelian to earliest Asselian age. Excavations of the Museum Geoscope, Burg Lichtenberg (Pfalz) deliver the so far most diverse tetrapod fauna in this time frame of Europe.

unconformity has been suggested to be related to subduction of the Paleo-Asian Ocean generating arc-continent and retro-arc fold-thrust deformation or to its final closure leading to continental collision during the late Cisuralian to Guadalupian. Another review paper on the Permian stratigraphy in the North China Block has been completed and will be submitted to a journal shortly. In addition, a 10 km-thick Carboniferous-Permian section in the northeastern part of Xinjiang Province has been measured by our group. The succession consists of the Batamayineishan, Shiqiantan, Jingou, Jiangjunmiao, Pingdiquan and Wutonggou formations, in ascending order. More than 100 ash beds were collected, and numerous brachiopods and plant fossils were collected. These samples are the priority for our group to analyze in the near future. They are critical to determining the ages of those formations in the Carbonifeorus and Permian.

Scholze et al. (2020) have added new infomation on conchostracan biostratigraphy of the Permian/Triassic transition in Southwest China compared with P/T sections in Russia and Europe.

North-South correlations

Despite the disruption of fieldwork presented by the Coronavirus pandemic, the last year has seen a particularly large number of papers concerning the biostratigraphy of the main Karoo Basin. Most of these form part of broad review of the tetrapod assemblage zones of the Beaufort Group, published in a special issue of the *South African Journal of Geology* (Botha and Smith, 2020; Day and Rubidge, 2020; Day and Smith, 2020; Hancox et al., 2020; Rubidge and Day, 2020; Smith, 2020; Smith et al., 2020; Viglietti, 2020; Viglietti et al., 2020a, 2020b). Though based mainly on the previous assemblage zones (AZ), these papers considerably revised the ranges of known taxa in light of collecting efforts over the past 25 years. Notable changes included: the partitioning of the former *Pristerognathus* AZ between the *Tapinocephalus* AZ and a resurrected *Endothiodon* AZ, the reduction of the *Tropidostoma* AZ to subzone status, the qualification of the *Lystrosaurus* AZ to *Lystrosaurus* declivis AZ, and the replacement of the defunct and informal name *Euskelosaurus* AZ with the new *Scalenodontoides* AZ. They also provided formal recognition of subzones within the *Tapinocephalus*, *Endothiodon*, *Daptocephalus*, and *Cynognathus* assemblage zones.

There has also been continued attention to the mass extinctions of vertebrates recorded in the main Karoo Basin, and especially their chronology. Day and Rubidge (2021) provided a review of the Capitanian mass extinction in South Africa and included a large primary dataset that allowed them to identify a phased extinction, similar to that described for the End-Permian mass extinction (Fig. 5). This latter was the subject of two papers that presented CA-ID-TIMS ages from a site at Nooitgedacht, although they did not agree; Botha et al. (2020) argued for the synchronicity of vertebrate extinction horizon in the Palingkloof Member with the marine Permian-Triassic extinctions based on geochemical and a detrital zircon age, whereas Gastaldo et al. (2020) used an in situ zircon U-Pb age combined with palaeomagnetism and palynology and found that the extinction horizon occurs several hundred thousand years prior to the marine extinction. In the Triassic, the first comprehensive

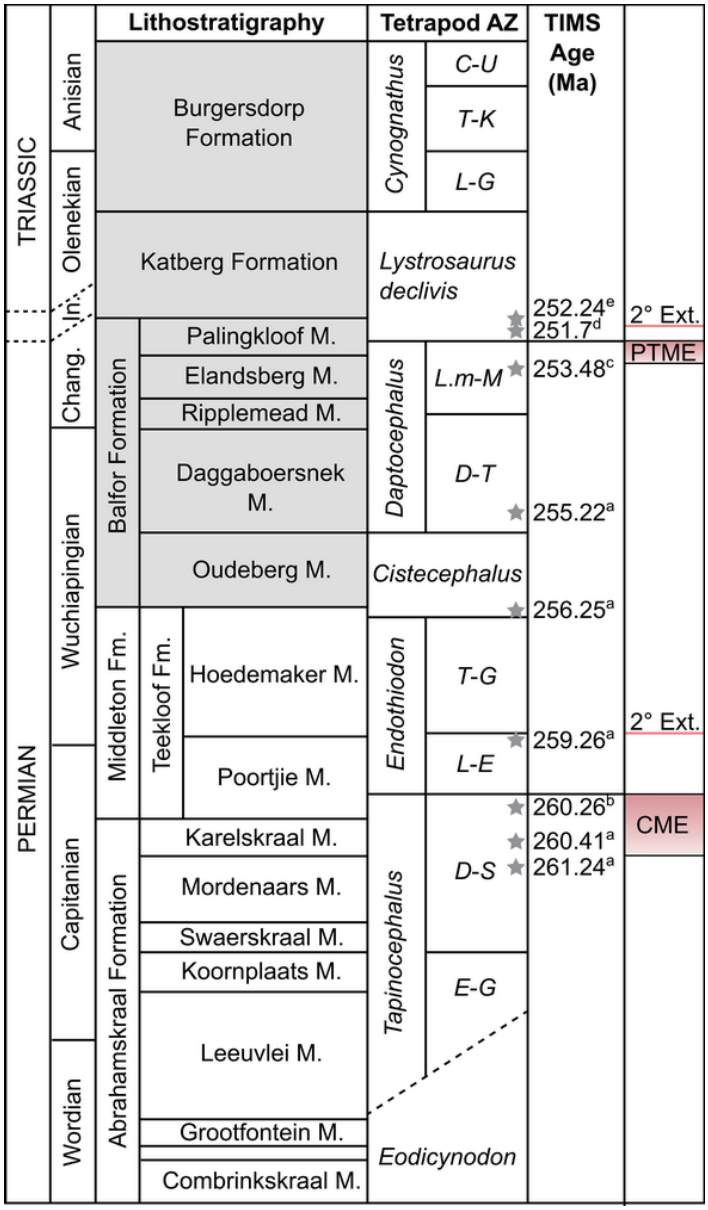

Fig. 5. Stratigraphy of the Beaufort Group showing position of mass extinction intervals. Subzone abbreviations: C-U, *Cricodon- Ufudocyclops*; D-S, *Diictodon-Styracocephalus*; D-T, *Dicynodon-Theriognathus*; E-G, *Eosimops-Glanosuchus*; L-E, *Lycosuchus-Eunotosaurus*; L-G, *Langbergia-Garjainia*; L.m-M, *Lystrosaurus maccaigi-Moschorhinus*; T-G, *Tropidostoma-Gorgonops*; T-K, *Trirachodon-Kannemeyeria*. Other abbreviations: CME, Capitanian mass extinction; Changh, Changhsingian; Fm., Formation; In, Induan; M, member; EPME, end-Permian mass extinction. Lithostratigraphic units in grey found only in the Eastern Cape. Stratigraphy and biozonation modified after Smith et al. (2020) and position of end-Permian mass extinction after Botha et al. (2020). U-Pb ages after: a, Rubidge et al., 2013; b, Day et al., 2015a; c, Gastaldo et al., 2015; d, Botha et al., 2020; e, Gastaldo et al., 2020. Actual position of the Permian-Triassic boundary is disputed. M. Day.

geochronological constraints on the Elliot Formation were presented by Bordy et al. (2020), suggesting that the lower part of this formation is mid-Norian to Rhaetian in age and indicates that sauropodomorph dinosaurs were well-established in the Karoo by 220 Ma.

Carboniferous to Triassic tetrapod footprint and tetrapod biostratigraphy

During 2020 and 2021, a significant number of new papers further investigated the ichnotaxonomy and the tetrapod footprint biostratigraphy in the framework of the activities of the working group on upper Palaeozoic-lower Mesozoic continental chronostratigraphy. The earliest reptile ichnotaxon, *Notalacerta missouriensis*, was comprehensively revised in Marchetti et al. (2020a), significantly extending its biostratigraphic range (middle Bashkirian-Artinskian). A review of the Italian Carboniferous tetrapod footprint ichnotaxonomy and biostratigraphy was provided by Marchetti et al. (2020b), and a review of the Italian Cisuralian tetrapod footprint ichnotaxonomy and biostratigraphy was provided by Santi et al. (2020). In the same volume, devoted to the state of the art of Italian tetrapod ichnology and edited by M. Romano and P. Citton, an updated list of references on Italian tetrapod ichnology was also provided (Antonelli et al., 2020).

A synthesis of Carboniferous tetrapod footprint biostratigraphy was provided by Lucas et al. (2021b). In this work, the base of the *Dromopus* tetrapod footprint biochron has been lowered to the Kasimovian base. A further paper investigated the ichnotaxonomy, biostratigraphy and producers of the Carboniferous material assigned to *Hylopus hardingi*, *Notalacerta missouriensis*, *Varanopus microdactylus* and *Dromopus lacertoides* (Marchetti et al., 2021a). With regard to the Permian, a new study analyzed the Cisuralian-Guadalupian ichnotaxon *Pachypes ollieri* (Marchetti et al., 2020c). Mujal and Marchetti (2020) documented the occurrence of *Ichniotherium cottae* from the lower Cisuralian units of the Lodeve Basin. Another study revised the tetrapod footprint ichnotaxonomy and biostratigraphy of the Carboniferous-Permian units from the Grand Canyon of Arizona (Marchetti et al., 2020d).

Reviews of the Cisuralian and Lopingian Italian tetrapod footprint ichnotaxonomy and biostratigraphy were provided by Santi et al. (2020) and Marchetti et al. (2020e), respectively. A new upper Cisuralian-Guadalupian tetrapod ichnoassociation has been described from the continental basins of Morocco (Zouicha et al., 2021). The tetrapod ichnoassociation from the Capitanian Hornburg Formation of Germany has been revised by Buchwitz et al. (2020), with the addition of new material assigned to *Capitosauroides* isp. This corroborates the Capitanian age of the unit. Voigt and Fischer (2020) described Pachypes from the Zechstein of W Germany. Klein and Lucas (2021) provided an extensive revision of the ichnotaxonomy and biostratigraphy of Triassic tetrapod footprints, which did not change the Triassic tetrapod footprint biochron boundaries given by Schneider et al. (2020). Marchetti et al. (2020f) described some new *Synaptichnium* material from the Muschelkalk of Germany. Marchetti et al. (2021b) revised the tetrapod footprint ichnofauna from the Monti Pisani of Italy, and assigned to it a Ladinian age. They also proposed to move the base of the *Ateipus-Grallator* footprint biochron to the base of the Ladinian. Citton et al. (2020) report on the first tetrapod tracks from the Triassic of the Nurra region (north-western Sardinia, Italy). Lithologic and petrographic features allowed an assignment of the track-bearing blocks to the middle-upper portion of the Anisian (Middle Triassic) Arenarie di Cala Viola ("*Buntsandstein*"). Footprints are attributed to the ichnotaxa *Rhynchosauroides* and *Rotodactylus*, two common ichnotaxa of late Early Triassic and Middle Triassic of Europe and the United States, commonly referred in the literature to neodiapsid and archosaur producers, respectively.

During 2020, a Spanish-Italian team (Lloret et al., 2020) focused on the Olenekian-Anisian continental record of the Central-Eastern Pyrenean basin (NE Spain). This multidisciplinary study, embracing sedimentology, mineralogy, palaeontology, palaeopedology and palaeogeography, of 10 complete and well dated Lower-Middle Triassic field sections has allowed: (1) the location and characterization of the oldest Mesozoic sedimentary record in the basin, which is of late Smithian age and overlies the upper-middle Permian continental rocks and of (2) the Smithian-Spathian transition (SST), (3) the timing of biotic recovery during the late Spathian-Anisian, (4) the characterization of the first incursion of the Tethys sea into the basin, and (5) the comparison of the evolution of this basin with other basins of the same age in SW Europe. The same group (Lloret et al., 2021) used paleosols as stratigraphic tools in the study of Permian and Triassic continental basins in the Central-eastern Pyrenees and offers information on the complex interplay between the factors that control the filling of basins, such as accommodation, deposition, erosion, and climate, which exerts a great influence on the supply rate of sediment and water from the sources to the basin. Grouped into palaeocatenas, the lateral variation of pedotypes across the landscape is used to interpret topography and water table variations, which was explained by variations in climate, available accommodation space, and sedimentary supply. The study of hydrological and climatic conditions was complemented by the identification of the mineralogical composition of the parent material and δ13C and δ18O isotopic signatures from the inorganic pedogenic carbonate of paleosols and lacustrine limestones.

A Moroccan-German team is preparing a publication on Middle to Upper Triassic invertebrate ichnia of the continental Argana basin in continuation of the report of tetrapod tracks from there (Zouheir et al., 2020). A section of approximately 760 m thickness, covering the Anisian to Carnian, was measured sedimentologically and palaeontologically with high resolution. It exhibits remarkable changes of the sedimentary and palaeobiological environments, which may be related to the Carnian pluvial episode (Zouheir et al., in prep.).

As noted above, in early 2021, Hendrik Klein and Spencer G. Lucas published a comprehensive, 194-page-long review of the global Triassic tetrapod footprint record: "The Triassic tetrapod footprint record:" New Mexico Museum of Natural History and Science Bulletin 83 (free download at: THE TRIASSIC TETRAPOD FOOTPRINT RECORD - HENDRIK KLEIN, SPENCER G. LUCAS - Google Books)

Other published work on Triassic biostratigraphy included a review of Upper Triassic metoposaurid biostratigraphy (Lucas,

2020), which demonstrates that the Carnian pluvial episode created a cosmopolitan distribution of metoposaurids followed by their provincialization, largely by the drier climates of the Norian (Fig. 6). Also, Rigo et al. (2020) identified Pangea-wide carbon isotope excursions (chaotic carbon) across the Norian-Rhaetian boundary that correspond to the largest of the stepwise extinctions across the Triassic-Jurassic boundary. The cause of this carbon isotope behavior, however, remains enigmatic, perhaps a little known large igneous province in what is now Alaska and vicinity.

Concluding remarks

On 13 November, 2020, the SPS Chair Lucia Angiolini and ViceChair Mike Stephenson, with the help of Jeanine Newham (BGS), organized a zoom webinar for the the corresponding members. Point three of the summary given by our nonmarine-marine working group was: *The most challenging future task for nonmarine-marine correlations in the Late Carboniferous–Middle Triassic are global north-south correlations. Biostratigraphic correlations among the biotic provinces of Euramerica, Angara, Cathaysia, and Gondwana are still in a very unsatisfactory state. Sections of the East European Platform and Siberia in Russia, those of the Karoo basin in South Africa, sections in North China, in Jordan and North Africa as well as in the Paraná basin of South America should be in the focus of further research of the SPS.*

As summarized above, the working group has completed extensive work. And, the above indicates, we could change the name and field of research of our group to encompass the entire Carboniferous and the entire Triassic.

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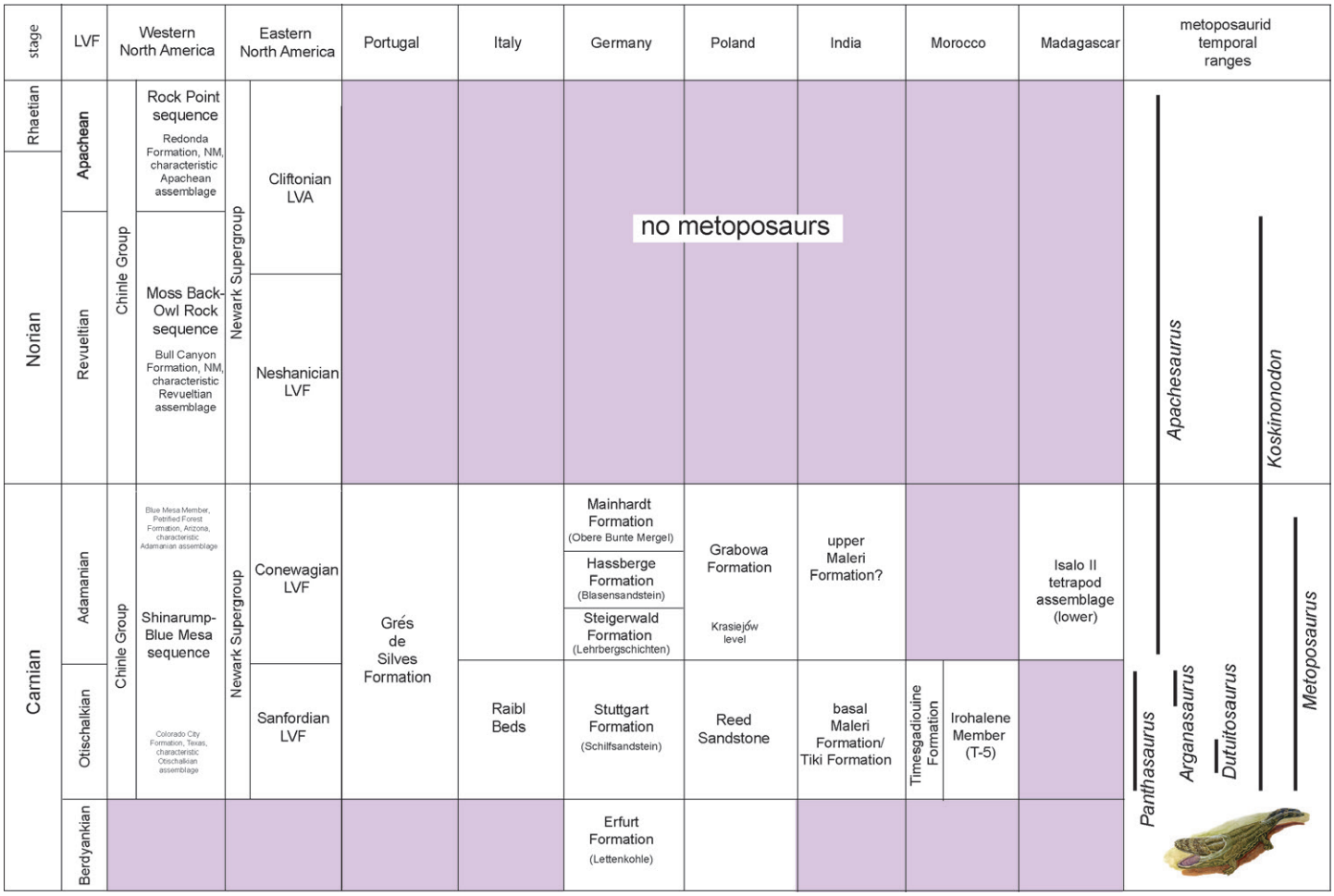

Fig. 6. Upper Triassic metoposaurid amphibian biostratigraphy (from Lucas, 2020).

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