THE PERMIAN–TRIASSIC BOUNDARY AND THE END-PERMIAN MASS EXTINCTION IN THE SOUTHERN AND EASTERN ALPS

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At the end of the Permian (ca. 252 Ma), the most severe mass extinction of the Phanerozoic occurred (e.g., Algeo et al., 2015 and references therein). The end-Permian extinction event had a profound effect on terrestrial and marine ecosystems, but affected the various plant and animal groups and ecosystems differently (Chen & Benton, 2012). Still not much is known about the exact effect and timing of the end-Permian mass extinction in terrestrial ecosystems and about the possible influence of preservational/taphonomic bias on the apparent extinction patterns. The Southern Alps are one of the most important regions for the study of the end-Permian mass extinction since the boundary interval succession is continuous, fossiliferous, crops out in numerous places, and represents terrestrial, as well as coastal and marine settings. While many studies have been conducted in this region, they all had a limited scope. Furthermore, outcrops with successions of the same age in the neighbouring Eastern Alps are barely studied. A three-year research project has now been conducted to examine the PTB interval in various outcrops across the Southern and Eastern Alps and across different palaeoenvironmental settings with a multidisciplinary approach.

The study area (Fig. 1) of the Euregio-Project "The end-Permian mass extinction in the Southern and Eastern Alps: extinction rates vs taphonomic biases in different depositional environments" includes the Dolomites and Carnic Alps of Northern Italy (Southern Alps) and the Lienz Dolomites and Gailtal Alps of Austria (Drau Range, Eastern Alps). The fossil-rich late Permian sequences of the Dolomites represent terrestrial environments (Gröden/Val Gardena Formation) followed by marine strata (Bellerophon Formation; Fig. 2M),

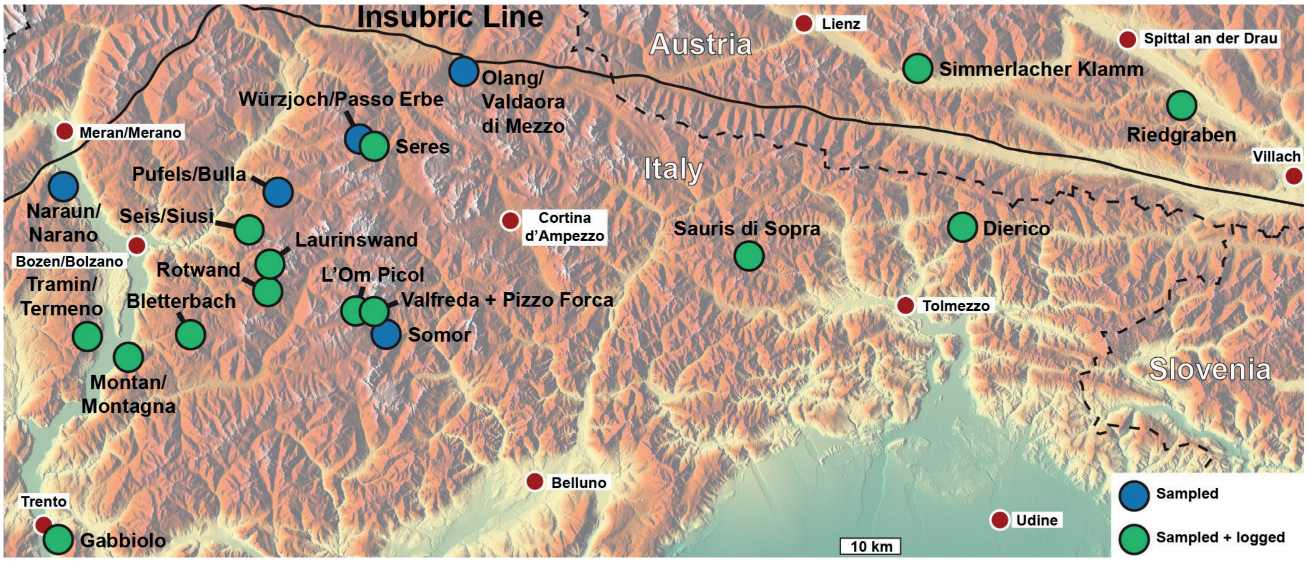

FIG. 1: Map of the study area with marked sections visited during field work campaigns in 2016–2018. Topographic base map © OpenStreetMap contributors, SRTM.

while the Early Triassic deposits are of marginal marine origin (southalpine Werfen Formation). The basal part of the Werfen Formation in the western Dolomites consists of oolite which constitute the Tesero Member (Fig. 2N). The Tesero Member is overlain and laterally interfingering with the Mazzin Member, which consists mostly of marly mudstones. In the Eastern Alps, the late Permian terrestrial continental sediments (Gröden/Val Gardena Formation) are overlain by Early Triassic terrestrial sediments (Alpine Buntsandstein) and marginal marine deposits (northalpine Werfen Formation).

During field work campaigns in 2016, 2017 and 2018, we logged and sampled ten sections in the Dolomites (Bletterbach, Tramin/Termeno, Montan/Montagna, Gabbiolo, Seres, Göma, Laurinswand, Rotwand, L'Om Picol, Valfreda, Pizzo Forca), two in the Carnic Alps (Felempecle near Sauris di Sopra, Dierico) and two in the Drau Range (Simmerlacher Klamm, Riedgraben). Several more localities were sampled, but not logged (Seis, Würzjoch/Passo delle Erbe, Pufels/Bulla, Naraun, Olang, Somor, Passo San Pellegrino). Samples were collected for isotope geochemistry (organic and inorganic), palynology, conodonts, microfacies and magnetostratigraphy. Macrofossils (invertebrates, tetrapod ichnofossils, plants, fishes) were collected where possible.

The Gröden/Val Gardena Fm. in the Bletterbach Gorge (Wuchiapingian, late Permian) yielded diverse fossil assemblages of plants and tetrapod footprints. Some of the plants show damage caused by insects (Fig. 2G). The footprints can be attributed to pareiasaurs (Fig. 2J), youginiformes, herbivorous and faunivorous therapsids (Fig. 2I), captorhinids, and archosauriforms. The most common plants are conifers (Fig. 2F) and ginkgophytes (Fig. 2E). Also present are seed ferns, rare taeniopterids and very rare sphenophytes (Kustatscher et al., 2017). Taken together, the fossils provide an unusually complete picture of a late Permian ecosystem with multiple trophic levels (Bernardi et al., 2017). The distribution of the fossils follows sea-level changes, as footprints are mostly found closely below and above the so-called "Cephalopod Bank", which represents a marine transgression (Kustatscher et al., 2017). The composition of the palaeofloras also changes, with ginkgophytes being the most common elements below the cephalopod bed, but rare above. The cephalopod bank itself contains a fossil assemblage of coiled and orthoconic nautiloids, bivalves and *Skolithos* burrows (Prinoth, 2017).

At the Seres section, the exposed Bellerophon Fm. can be divided into Interval I, Interval II and (above a sharp lithologic boundary) the Bulla Member. The overlying (lower) Werfen Fm. is represented by the Tesero Mb. and lower part of the Mazzin Mb.. In Interval I, bioclastic wackestone and packstone containing abundant foraminifers (Fig. 2K) and calcareous algae (Fig. 2L) are the most common microfacies. In Interval II, limestone of the lower part is less diverse (ostracod and bioclastic mudstone). In the upper part, individual limestone beds contain abundant calcareous algae and foraminifers. The basal bed of the Bulla Mb. is composed of algal and foraminiferal wackestone to packstone, overlain by bioclastic wackestone containing abundant algal fragments and foraminifers. The most common microfacies of the upper part of the Bulla Member is packstone. The topmost grainstone of the Bulla Mb. is sharply overlain by oolitic grainstone of the Tesero Mb. The boundary shows stylolitic overprinting and probably represents an erosional surface. The dominant microfacies of the lower part of the Mazzin Mb. is mudstone containing ostracods. Less common is bioclastic mudstone, ostracod-bivalve wackestone and grainstone.

Previously, no plant fossil assemblages apart from root traces had been described from the Bellerophon or Werfen formations, although the presence of plant fossils in the Bellerophon Fm. at Tramin/Termeno (Brandner et al., 2012) and Seis/Siusi (Siegert et al., 2011) was mentioned. Several plant fossils were now collected in these localities, which are awaiting description. At Seis, the same beds partly yielded fish remains as well. In addition, we found root body fossils in the Bletterbach Gorge, in the uppermost part of the Bellerophon Formation, just below the Tesero Mb., and at Seres, within the Tesero Mb. (Fig. 2H). Additional plant remains were found in the upper part of the Werfen Fm. at the Weisshorn and in the Alpine Buntsandstein in the Gailtal Alps.

Spore/pollen assemblages from the Bellerophon Fm. are diverse and dominated by bisaccate pollen (Fig. 2A). The assemblages indicate a flora of primarily conifers and seed ferns, with more rare lycophytes, sphenophytes, cycadophytes and/or ginkgophytes, as well as possible gnetophytes.

Palynological assemblages from near the PTB are marked by three conspicuous signals that have been found in many places across the world, including the Dolomites: The so-called "fungal spike", a "spore spike" and the frequent occurrence of spore tetrads (Fig. 2B). The "fungal spike" refers to the mass occurrence of *Reduviasporonites* Wilson 1962 (Fig. 2C), a problematic organic-walled microfossil type that has been interpreted on morphological and biogeochemical grounds as both fungal and algal remains (Eshet et al., 1995; Visscher et al., 1996). One of the classical examples is the almost exclusive presence of this taxon (ca. 98 % of organic particles) in assemblages from the Tesero Mb. at Tesero. However, we found mass occurrences (> 50 % of organic particles) of *Reduviasporonites* in the Bellerophon Formation at Pizzo Forca, as well as in the Mazzin Mb. at the Laurinswand section. Conversely, a mass occurrence in the Tesero Mb. could so far only be found at Tesero (Spina et al., 2015). This seems to indicate that there were multiple, possibly local events.

The "spore spike" relates to an increase in the spore/pollen ratio close to the PTB. This is usually taken as an indication for the demise of the Permian floras and their replacement with a disaster flora dominated by herbaceous lycophytes (Looy et al., 1999). In the Werfen Formation, this increase in spores is pervasive, but various pollen types are still present, indicating the continued presence of gymnosperms. Due to a very low overall yield of samples from the Werfen Formation, it is not yet clear if the assemblages reflect an extinction among plants, but a drastic change is indicated.

The higher relative abundance of spores is also related to the frequent occurrence of spore tetrads (Fig. 2B). Permanent tetrads can be found significantly more often near the PTB, e.g. in the Dolomites within the Tesero Mb. (Visscher et al., 2004; Looy et al., 2005). This has been interpreted as a disturbance of plant reproduction due to increased UV-B radiation, which in turn can be related to the destruction of the ozone layer caused by the Siberian Traps volcanism (Visscher et al., 2004; Benca et al., 2018).

Vertebrate remains are scarce around the PTB. Some sections, notably Seis, yielded fairly common fish remains in the uppermost Bellerophon Fm., and a couple of fish teeth were discovered in the Werfen Fm. (possibly Siusi Mb.) of Passo Rolle. Fish ichnofossils were also documented in both the Gröden/Val

Gardena Fm. and the Campil Mb. of the Werfen Fm. (Olenekian) (Ronchi et al., 2018).

More results are to be expected as the work is ongoing. Ultimately, the goal is to compare findings from different sections in order to identify taphonomic constraints.

REFERENCES

Algeo, T.J., Chen, Z.-Q., Bottjer, D.J. (2015): Global review of the Permian–Triassic mass extinction and subsequent recovery: Part II. – Earth-Science Reviews, 149: 1–4.

Benca, J.P., Duijnstee, I.A.P., Looy, C.V. (2018): UV-B–induced forest sterility: Implications of ozone shield failure in Earth's largest extinction. – Science Advances, 4: e1700618.

Bernardi, M., Petti, F.M., Kustatscher, E., Franz, M., Hartkopf-Fröder, C., Labandeira, C.C., Wappler, T., van Konijnenburg-van Cittert, J.H.A., Peecook, B.R., Angielczyk, K.D. (2017): Late Permian (Lopingian) terrestrial ecosystems: A global comparison with new data from the low-latitude Bletterbach Biota. – Earth-Science Reviews, 175: 18–43.

Brandner, R., Horacek, M., Keim, L. (2012): Permian-Triassic-Boundary and Lower Triassic in the Dolomites, Southern Alps (Italy). – Journal of Alpine Geology, 55: 375–400.

Chen, Z.-Q., Benton, M.J. (2012): The timing and pattern of biotic recovery following the end-Permian mass extinction. – Nature Geoscience, 5: 375–383.

Eshet, Y., Rampino, M.R., Visscher, H. (1995): Fungal event and palynological record of ecological crisis and recovery across the Permian-Triassic boundary. – Geology 23: 967–970.

Kustatscher, E., Bernardi, M., Petti, F.M., Franz, M., Van Konijnenburg-van Cittert, J.H.A., Kerp, H. (2017): Sea-level changes in the Lopingian (late Permian) of the northwestern Tethys and their effects on the terrestrial palaeoenvironments, biota and fossil preservation. – Global and Planetary Change, 148: 166 –180.

Looy, C.V., Brugman, W.A., Dilcher, D.L., Visscher, H. (1999): The delayed resurgence of equatorial forests after the Permian–Triassic ecologic crisis. – Proceedings of the National Academy of Sciences, 96: 13857–13862.

Looy, C.V., Collinson, M.E., Van Konijnenburg-van Cittert, J.H.A., Visscher, H., Brain, A.P.R. (2005): The ultrastructure and botanical affinity of end-Permian spore tetrads. – International Journal of Plant Sciences, 166: 875–887.

Prinoth, H. (2017): The Cephalopod Bank in the Gröden/Val Gardena Sandstone of the Bletterbach. – Geo.Alp, 14: 85–91.

Ronchi, A., Santi, G., Marchetti, L., Bernardi, M., Gianolla, P. (2018): First report of swimming trace fossils of fish from the Upper Permian and Lower Triassic of the Dolomites (Italy). – Annales Societatis Geologorum Poloniae, 88: 111–125.

Siegert, S., Kraus, S.H., Mette, W., Struck, U., Korte, C. (2011): Organic carbon isotope values from the Late Permian Seis/Siusi succession (Dolomites, Italy): Implications for palaeoenvironmental changes. – Fossil Record, 14: 207–217.

Spina, A., Cirilli, S., Utting, J., Jansonius, J. (2015): Palynology of the Permian and Triassic of the Tesero and Bulla sections (Western Dolomites, Italy) and consideration about the enigmatic species *Reduviasporonites chalastus*. – Review of Palaeobotany and Palynology, 218: 3–14.

Visscher, H., Brinkhuis, H., Dilcher, D.L., Elsik, W.C., Eshet, Y., Looy, C.V., Rampino, M.R., Traverse, A. (1996): The terminal Paleozoic fungal event: evidence of terrestrial ecosystem destabilization and collapse. – Proceedings of the National Academy of Sciences, 93: 2155–2158.

Visscher, H., Looy, C.V., Collinson, M.E., Brinkhuis, H., Van Konijnenburg-van Cittert, J.H.A., Kürschner, W.M., Sephton, M.A. (2004): Environmental mutagenesis during the end-Permian ecological crisis. – Proceedings of the National Academy of Sciences, 101: 12952–12956.

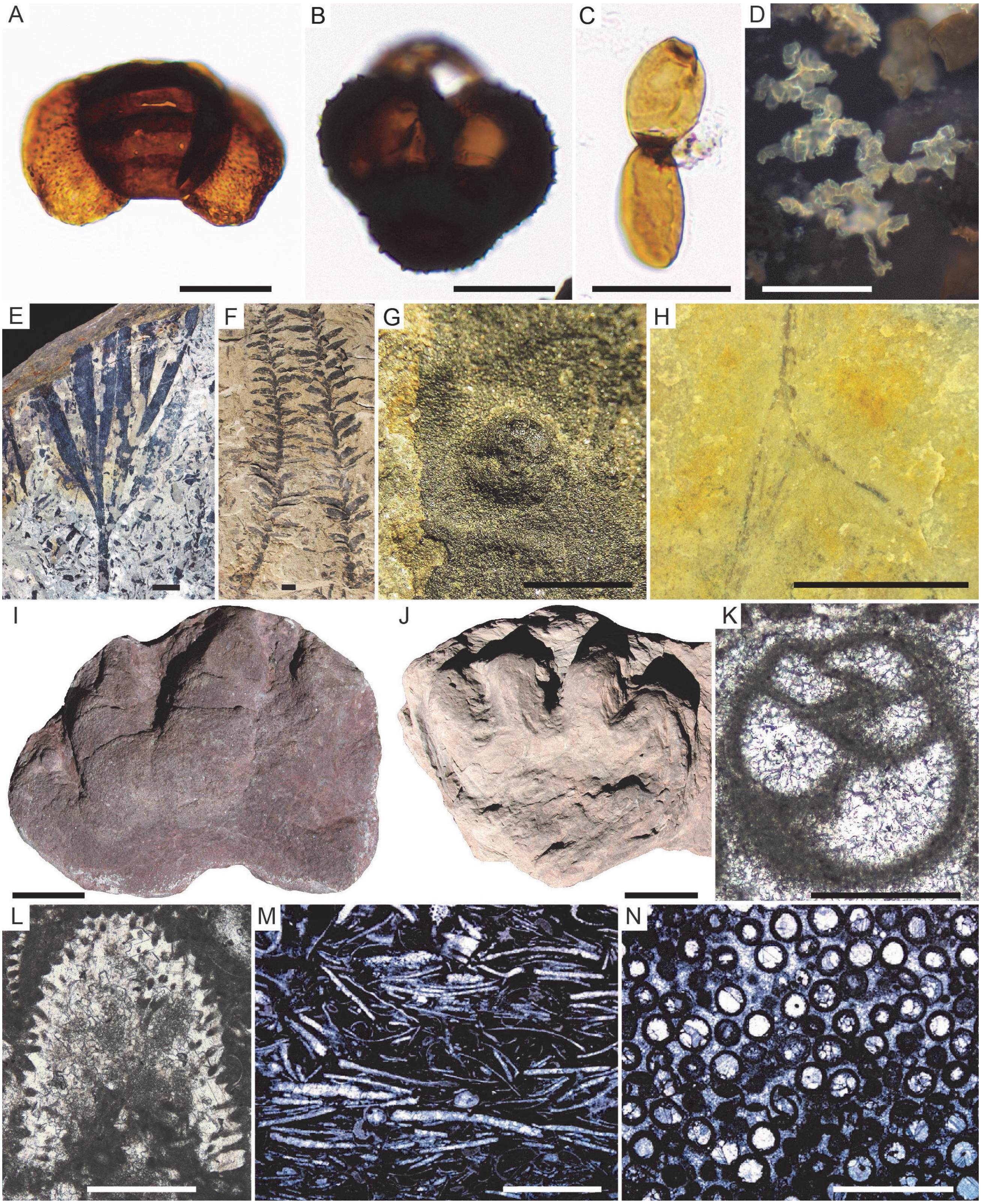

FIG. 2: Examples of fossils from the Permian–Triassic boundary interval in the Eastern and Southern Alps. Scale bars = 50 µm for A–D; 1 cm for E–I; 10 cm for J; 200 µm for K–L; 2 mm for M–N. **A**, *Lunatisporites labdacus* (Klaus, 1963) Visscher, 1971, Bellerophon Fm., Tramin/Termeno. **B**, Spore tetrad, Tesero Mb., Tramin/Termeno. **C**, *Reduviasporonites chalastus* (Foster 1979) Elsik 1999, Bellerophon Fm., Tramin/Termeno. **D**, Unidentified algal or fungal remains (fluorescence), Bellerophon Fm., Laurinswand. **E**, *Baiera digitata* (Brongniart) Heer 1876, Gröden/Val Gardena Fm., Bletterbach. **F**, *Ortiseia leonardii* (Florin) Clement-Westerhof 1984, Gröden/Val Gardena Fm., Bletterbach. **G**, Insect gall, Gröden/Val Gardena Fm., Bletterbach. **H**, Root body fossil in marine sediment, Tesero Mb., Seres. **I**, Therapsid footprint indet., Gröden/Val Gardena Fm., Bletterbach. **J**, *Pachypes dolomiticus* Leonardi et al. 1975, Gröden/Val Gardena Fm., Bletterbach. **K**, Foraminifer, Bellerophon Fm., Seres. **L**, Calcareous Alga, Bellerophon Fm., Seres. **M**, Packstone with ostracods and mollusc shells, Bellerophon Fm., Laurinswand. **N**, Oolithic grainstone, Tesero Mb., Laurinswand.