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The history of palaeontological research and excavations at Monte San Giorgio

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Abstract

There is a long history of palaeontological excavations at Monte San Giorgio (Switzerland) and the adjoining Monte Pravello—Monte Orsa (Italy), aimed at finding well-preserved skeletons of Middle Triassic vertebrates. The first fossils were discovered in the mid-Nineteenth Century during mining of black shales (*scisti bituminosi*) near Besano, Italy, with further finds in the early Twentieth Century through industrial-scale mining. Studies of the material generated international interest and prompted formal palaeontological excavations on both sides of the border. The earliest excavations took place in 1863 and 1878, with the most extensive between 1924 and 1968. Systematic excavations have continued up to the present day, focusing on six distinct fossiliferous horizons: the Besano Formation and the overlying Meride Limestone with the Cava inferiore, Cava superiore, Cassina, Sceltrich and Kalkschieferzone beds. All these have provided material for study and display, with Monte San Giorgio itself recently designated a UNESCO World Heritage Site. The workers and organisations involved, locations excavated and material recovered are described herein.

Keywords Palaeontological excavations, Reptiles, Fish, Middle Triassic, Besano Formation, Meride Limestone, Konservat Lagerstaetten, Monte San Giorgio

Introduction

Exposures of Triassic rocks comprising 1300 m of dolomites, limestones and bituminous shales occur across the flanks of Monte San Giorgio (Canton Ticino, southern Switzerland) and the adjoining north-western flank of Monte Pravello—Monte Orsa (Province of Varese, northern Italy). The Middle Triassic sediments in particular are world-famous as a source of vertebrate fossils, noted for their excellent preservation and diversity (Rieppel, 2019). The most productive layer was known historically as the *Grenzbitumenzone* on the Swiss side and later became known as the Besano Formation (Bernoulli et al., 2018) on both sides of the Switzerland–Italy border, and described as exceptional Konservat Lagerstaette (Etter, 2002; Furrer, 2003; Rieppel, 2019). Today, five additional fossiliferous layers are known in the overlying Meride Limestone, also with excellent fossil preservation (Furrer & Vandelli, 2014).

Mining of black shales (called *scisti bituminosi*) near Besano, Italy, led to the discovery of the first fossils in the mid-Nineteenth Century with more material recovered in the early Twentieth Century through industrial-scale mining of the *scisti bituminosi* on either side of the Switzerland–Italy border (at Besano and Meride, respectively). Further excavation and recovery of fossil material in turn led to establishment and development of various institutions, such as the laboratory at the University of Zurich and newly founded Palaeontological Institute and Museum, University of Zurich (PIMUZ) to store and study fossils. Excavations over the last 50 years have continued through the PIMUZ (Rieber & Lanz, 1999), Museo Civico di Storia Naturale di Milano (Nosotti & Teruzzi, 2008), Università di Milano and, more locally, the Museo

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Cantonale di Storia Naturale di Lugano, with work today seeing collaboration of researchers from these and many other organisations.

All of the fossils recovered from Middle Triassic sediments at Monte San Giorgio (Felber, 2005; Felber et al., 2000; Furrer, 2016) greatly extend our knowledge of the evolution of life in a restricted marine basin, in the neighbouring shallow water areas and on adjacent islands of the north-western Tethys, through an interval of time approximately 242.5–239.5 million years ago (Furrer, 2003; Furrer & Vandelli, 2014).

This review of the historic palaeontological excavations at Monte San Giorgio near Meride, and at Monte Pravello—Monte Orsa near Besano, during the last 160 years documents the immense fieldwork that delivered the rich and high-quality fossils now housed in many museums, locally, nationally and internationally, and that continue to provide material for successful research.

Oil shale mining at Monte San Giorgio

The discovery of the world-famous vertebrate fossils from Besano and Monte San Giorgio is connected to the history of *Saurolo*, a type of oil used mainly for pharmaceutical purposes (Fig. 1). It was extracted through distillation of bituminous mudstones or black shales (*scisti bituminosi*), recovered in open mines and tunnels in the Middle Triassic sediments of the Southern Alps above Besano (Province of Varese, Italy) and Serpiano (Canton Ticino, Switzerland). Due to a high content of combustible oil, the *scisti bituminosi* had been extracted from open mines at «Vallone» above Besano since the mid-18th Century (Felber et al. 2000; Nosotti & Teruzzi, 2008; Pinna & Teruzzi, 1991).

In 1861, the Ticinese government gave permission to mine on the territories of the municipalities Meride and Brusino (Switzerland), but the various mining projects were short-lived. It was only after the commercial success of *Ichthyol* from Seefeld near Innsbruck (Austria), extracted from similar oil shales rich in fossil fish from the Late Triassic, that mining restarted in 1902 at «Cava Ratti» above Besano and in 1907 in an old mine at «Cava Tre Fontane» near Serpiano (Repossi, 1909). In 1910, the newly founded Società Anonima Miniere Scisti Bituminosi di Meride e Besano opened an oil factory at Spinirolo near Meride. Here, the oil was extracted through dry distillation and refined to *Saurolo*, an *Ichthyol*-like product for the pharmaceutical industry of Milano and Basel (Felber et al., 2000; Lanz & Felber, 2020). In 1916, five tunnels with a total length of 900 m were in use at Cava Tre Fontane and had by then supplied an estimated 2100 tons of useful material (Schmidt, 1918) (Figs. 2, 3). By 1940, these tunnels had been expanded to about 1770 m (Rickenbach, 1947; see also Fig. 4). Prior to the First World War and from 1917 to 1928, *scisti bituminosi* at another site at «Val Porina» on the northern side of Monte San Giorgio were also exploited in tunnels. In 1922 mining resumed in the «Selva Bella» mine above Besano. By the end of 1927 the oil factory at «Novella» in Besano started processing the raw material from the Italian locality, before the crude oil produced was transported to Spinirolo (Furrer, 2023; Lanz & Felber, 2020; Mariani, 1933).

The *scisti bituminosi* were mined from a 4–6 m thick sequence of black bituminous mudstones and grey laminated dolomites. Their content of organic carbon lies between 20 and 44 weight percent and their yield at 74–85 L of crude oil per ton of raw material. Through dry distillation at low temperatures, what was produced contained 8% crude oil with a sulphur content of 7%, but also 8–9% of gas and 2–3% of ammonia. The average annual production of oil shales was between 300 and 400 tons, of which 22–30 tons of crude oil were extracted (Rickenbach, 1947). Because of export difficulties, production slowed down during the Second World War, followed by a small resurge that lasted only for a few years. At that time, 30 people (miners and other workers from both sides of the border) were employed in the mining company. The mining of *scisti bituminosi* stopped in 1947, and in 1951, production and distribution of *Saurolo* ceased entirely (Lanz & Felber, 2020).

The first fossil discoveries from Besano

Fossils from the Middle Triassic of Monte San Giorgio and Monte Pravello—Monte Orsa have been documented in numerous publications. The earliest mention was by the geologist Giulio Curioni from Milan. He described, but did not figure, the first vertebrate fossils (ichthyosaurs and fishes) from Besano and named the sauropterygian reptile *Lariosaurus balsami* from Perledo on the eastern side of Lake Como (Curioni, 1847). It was Cornalia (1854) who provided the first figure, showing fossils of the small pachypleurosaurid reptile *Pachypleura Edwardsii* (later changed to *Pachypleurosaurus edwardsii* by Broili, 1927) from Triassic sediments on the north-western flank of Monte Orsa near «Cà del Frate» (Besano, Italy) (Figs. 5, 6).

Other reptile and some fish fossils mentioned by Stoppani (1857), Bellotti (1857) and Curioni (1863) were found at Vallone, where bituminous mudstones known as the *scisti bituminosi* had been mined since the eighteenth century. Sordelli (1879) described the first plant fossils. At the time, these sediments were believed to have a Late Triassic age, but have since been placed in the middle part of the Besano Formation (latest Anisian/earliest Ladinian, Middle Triassic; reviews in Nosotti & Teruzzi, 2008; Pinna, 1991; Pinna & Teruzzi, 1991).

Fig. 1 Packaging of the ointment *Saurolo* from the company Adroka (Basel) with a stylized ichthyosaur. © Adroka/archive PIMUZ

In 1863, the Società Italiana di Scienze Naturali organized the first scientific excavation for fossils in the *scisti ittiolotici di Besano* at Vallone, directed by the abbot Antonio Stoppani (Stoppani, 1863). A second excavation was conducted in 1878 by the Museo di Storia Naturale di Milano, directed by Emilio Cornalia. Bassani (1886) published a list of the recovered fossils. Mojsisovics (1882) and Airaghi (1911, 1912) gave the first descriptions of the ammonoids, Repossi (1902, 1909) figured the first specimen of *Mixosaurus cornalianus* and De Alessandri (1910) described several fishes. Nopcsa (1923, 1925, 1930), Aldinger (1931) and Brough (1939) published more studies, partly based on that material. Unfortunately, many of the fossils found and described up until then were destroyed in 1943 during the Anglo-American bombing of the Museum of Milan in the Second World War.

Fig. 2 Miner at work in a tunnel of the mine Cava Tre Fontane near Serpiano at around 1916. © FMSG/archive Sommaruga

Palaeontological excavations at Cava Tre Fontane and Val Porina

Since 1907, the mining at Cava Tre Fontane near Serpiano and Meride (Canton Ticino, southern Switzerland) revealed many fossils, subsequently mentioned or figured by Repossi (1909), De Alessandri (1910), Airaghi (1912) and Wiman (1912). In 1916, the Swedish palaeontologist Erik H. O. Andersson (better known as Stensiö) described new fossil fishes from the site (Andersson, 1916). In the same year, the first 12 fossils came into the collection of the Zoological Museum of the University of Zurich (Furrer, 2023). Some of these were collected by the geologist Albert Frauenfelder, who published his PhD thesis on the geology of the Southern Alps in Ticino (Frauenfelder, 1916). He introduced the name *Grenzbitumenzone* (Fig. 7) for the 4–6 m thick *scisti bituminosi*, based on dating of ammonoid and bivalve fossils, suggesting the position of the Anisian/Ladinian boundary just on top of the exploited sequence in the mines. It was only after the largest excavation at Point 902/Mirigioli, that the lithostratigraphic unit *Grenzbitumenzone* was expanded by Rieber (1973) with an over- und underlying part to a total thickness of 15.8 m, today named Besano Formation (Fig. 8; see below).

In 1919, the zoologist Bernhard Peyer from the University of Zurich found the paddle-like limb of an ichthyosaur (*Mixosaurus*) in the piles of *scisti bituminosi* extracted but not yet processed at the small oil factory Spinirolo and collected other fragmentary fossils from spoil heaps at the Cava Tre Fontane mine (Fig. 9). Peyer was very excited by his discoveries and returned in the summer of 1924 to look systematically for fossils in the tunnels with the help of miners employed there. However, the first attempts in the narrow mining tunnels at Cava Tre Fontane were not very successful. In the autumn of the same year, he instead began excavations on the surface, outside the entrance of the abandoned mine at Val Porina, where his efforts paid off and he found articulated skeletons of the ichthyosaur *Mixosaurus*, the placodont reptile *Cyamodus,* and some actinopterygian fish (Peyer, 1931a, 1944). The excavation at Val Porina went on into the summer of 1925, across a surface measuring 100 m^2, with the help of two miners and the young zoologist Emil Kuhn, working for the first time as an assistant of Peyer.

In 1927 and 1929, Peyer and his team tried again to collect fossils at Cava Tre Fontane, working mainly at the entrance of the uppermost tunnel named *Arnaldo superiore*. They systematically numbered the black bituminous layers from 1 (top) to 15 (base) (Fig. 10), each already named by the miners as individual *Minerale* beds, occurring alternately with dolomitic beds called *Sasso*. Also in

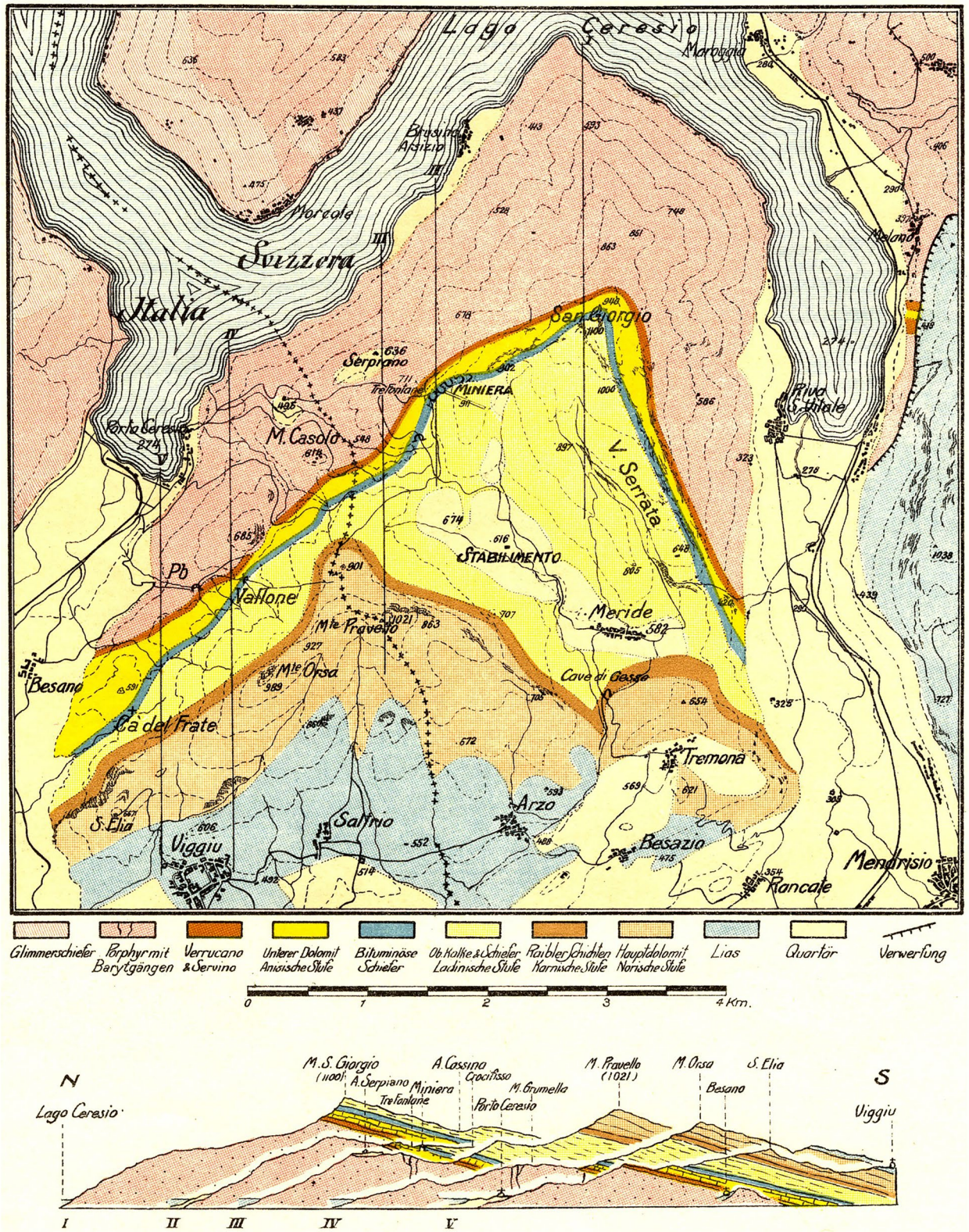

Fig. 3 Historic geological map and sections through the area of Monte San Giorgio, Monte Pravello and Monte Orsa. Note the signs for tunnels beside the name «MINIERA» at the locality of Tre Fontane near Serpiano on Swiss territory and the sites Vallone and Cà del Frate near Besano in Italy. Unpublished report by C. Schmidt, 1918. © archive swisstopo

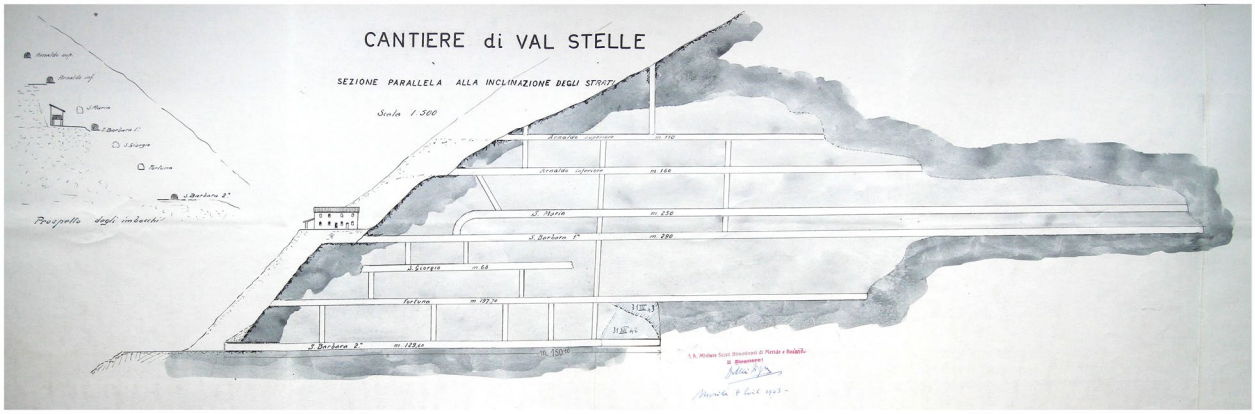

Fig. 4 Map of the Cava Tre Fontane mine, named *Cantiere di Val Stelle* in an application for exploitation by the Società Anonima Miniere Scisti Bituminosi di Meride e Besano from 1943. © archive swisstopo

1929, Peyer and his team opened their largest excavation just above the abandoned mine at Val Porina, where they not only investigated the bituminous layers of the *Grenzbitumenzone* exposed in the tunnels (today the middle Besano Formation), but also carefully studied the overlying laminated dolomitic beds with thin bituminous interlayers (today part of the upper Besano Formation). This continued until 1933 (see overview in Peyer, 1941, 1944; Kuhn-Schnyder, 1974) (Fig. 11).

During their systematic excavation at Val Porina, Peyer and his team found some unique and exciting fossils, mainly the first complete skeletons of the reptiles *Cyamodus hildegardis* in 1924 (Peyer, 1931c), *Tanystropheus longobardicus* in 1929 (Peyer, 1931b), *Paraplacodus broilii* in 1930 (Peyer, 1931e), *Ticinosuchus ferox* in 1933 (Krebs, 1965), *Helveticosaurus zollingeri* in 1935 (Peyer, 1955), *Clarazia schinzi* (Peyer, 1936a), *Hescheleria ruebeli* (Peyer, 1936b), *Macrocnemus bassanii* (Peyer, 1937) and *Askeptosaurus italicus* in 1935 (Kuhn-Schnyder, 1952). Rieppel (2019) published an extensive review of these initial studies. It is noted some reptiles and many fishes were not studied until much later (Bürgin, this volume; Schwarz, 1970). For example, Peyer collected a large number of highly diverse fishes, but left these to focus on the more spectacular reptiles. Descriptions at the time were limited to only a few sharks (Kuhn, 1946).

Discovery of the fossiliferous beds in the Meride Limestone

In 1924, Bernhard Peyer purchased a fragmentary skeleton of a small pachypleurosaur from the local teacher Gaetano Fossati in Meride and became interested in its provenance. In autumn 1927, he and Emil Kuhn discovered two fossiliferous beds in the lower Meride Limestone of the Val Serrata north of Meride, and at the abandoned tunnel at «Acqua del Ghiffo», 400 m north-west of Crocifisso, between Meride and Serpiano (Peyer, 1944; Fig. 12). The layers became known as the *Cava inferiore* and *Cava superiore* and were systematically excavated in autumn 1927 and summer 1928, providing four specimens of the large sauropterygian *Ceresiosaurus calcagnii* (Peyer, 1931d) and numerous specimens of *Pachypleurosaurus edwardsii* (see Peyer, 1932; Zangerl, 1935). Sander (1989b) restudied these skeletons and determined there were two species: *Neusticosaurus pusillus* from the Cava inferiore beds and *Neusticosaurus peyeri* from the Cava superiore beds. Among the rich material from the *Cava superiore*, Sander (1988) described a very small skeleton as an embryo of *Neusticosaurus* sp., the first fossil reptile foetus discovered, despite the diverse reptile fauna at Monte San Giorgio or extensive history of reptiles as a group and well known embryos of ichthyosaurs from the Lower Jurassic elsewhere. Only a few actinopterygian fishes were found, and one echinoid, assigned to *Serpianotiaris hescheleri* (Jeannet, 1933).

Besides the excavations in the *Grenzbitumenzone* at Cava Tre Fontane and Val Porina, Bernhard Peyer continued in the following years to look for fossils in the Meride Limestone, focusing on the Cava inferiore beds (early Ladinian). He directed several bed-by-bed excavations in the 1.50 m thick marker bed with its underlying and overlying volcaniclastic deposits at sites in the Val Serrata in 1930, «Acqua Ferruginosa» in 1937, «Cassinello» in 1938 and «lower Val Porina» in 1941 (Table 1). The numerous pachypleurosaurs were described by Zangerl (1935) and Sander (1989b), the new specimens of *Ceresiosaurus calcagnii* by Hänni (2004). Hugi (2011) and Hugi and Scheyer (2012) analyzed the histology of these reptiles.

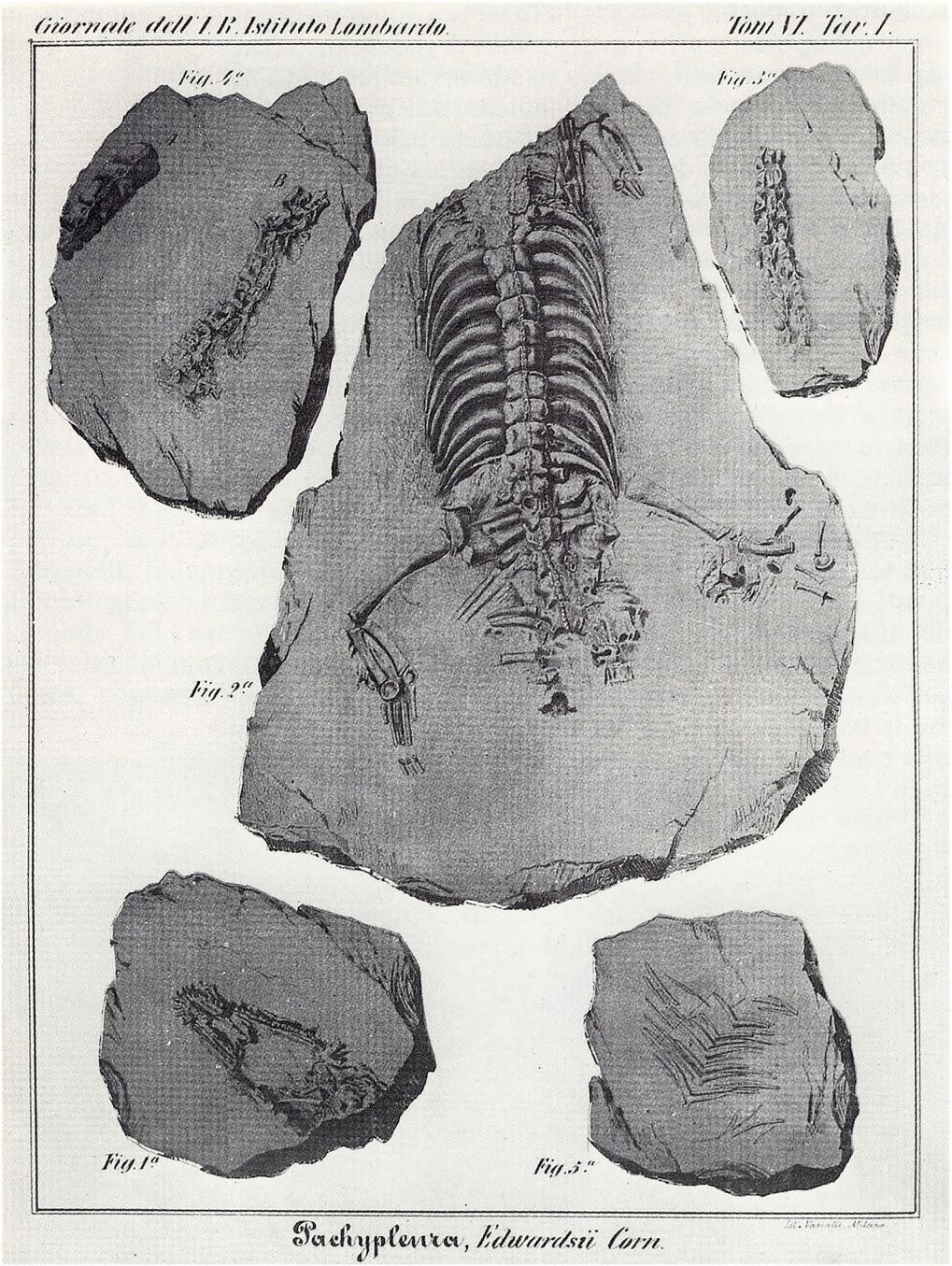

Fig. 5 In 1854, the Milanese palaeontologist Emilio Cornalia described the first fossil reptile from the locality Cà del Frate above Besano under the name of *Pachypleura Edwardsii*. © Museo Civico di Storia Naturale di Milano

A third fossiliferous horizon rich in larger pachypleurosaurid reptiles and actinopterygian fish, 40 m higher up in the section of the lower Meride Limestone, was discovered in 1931 by the local technical assistant Fritz Buchser from Meride at the «Cassina» locality. First excavated in 1933, the so-called Cassina beds were further studied in 1935, 1937, and 1938 (Fig. 13). Several complete specimens of the reptile *Pachypleurosaurus edwardsii* were studied by Zangerl (1935). Further highlights include two examples of a large sauropterygian (see below) and the only find of *Macrocnemus bassanii* from the Meride Limestone, described by Peyer (1937).

Fig. 6 Portrait of the Milanese palaeontologist Emilio Cornalia (1824–1882). © Museo Civico di Storia Naturale di Milano

Around 1940, the team of the University of Zurich also discovered the first fossil fishes and invertebrates in the Kalkschieferzone (uppermost part of the Meride Limestone, named by Senn, 1924) in the Gaggiolo Valley, west of Meride (or «Val Mara»), documented in the stratigraphic study by Wirz (1945).

Bernhard Peyer as an outstanding scientist

Bernhard Peyer (1885–1963) had a great humanistic education and wide interests (see Schlatter, 2007; Rieppel, 2019; Sues, this volume). Born in Schaffhausen, he studied in Tübingen, München, and eventually Zürich, where he later started the research on the vertebrates of Monte San Giorgio. The first excavation in 1924 was financed

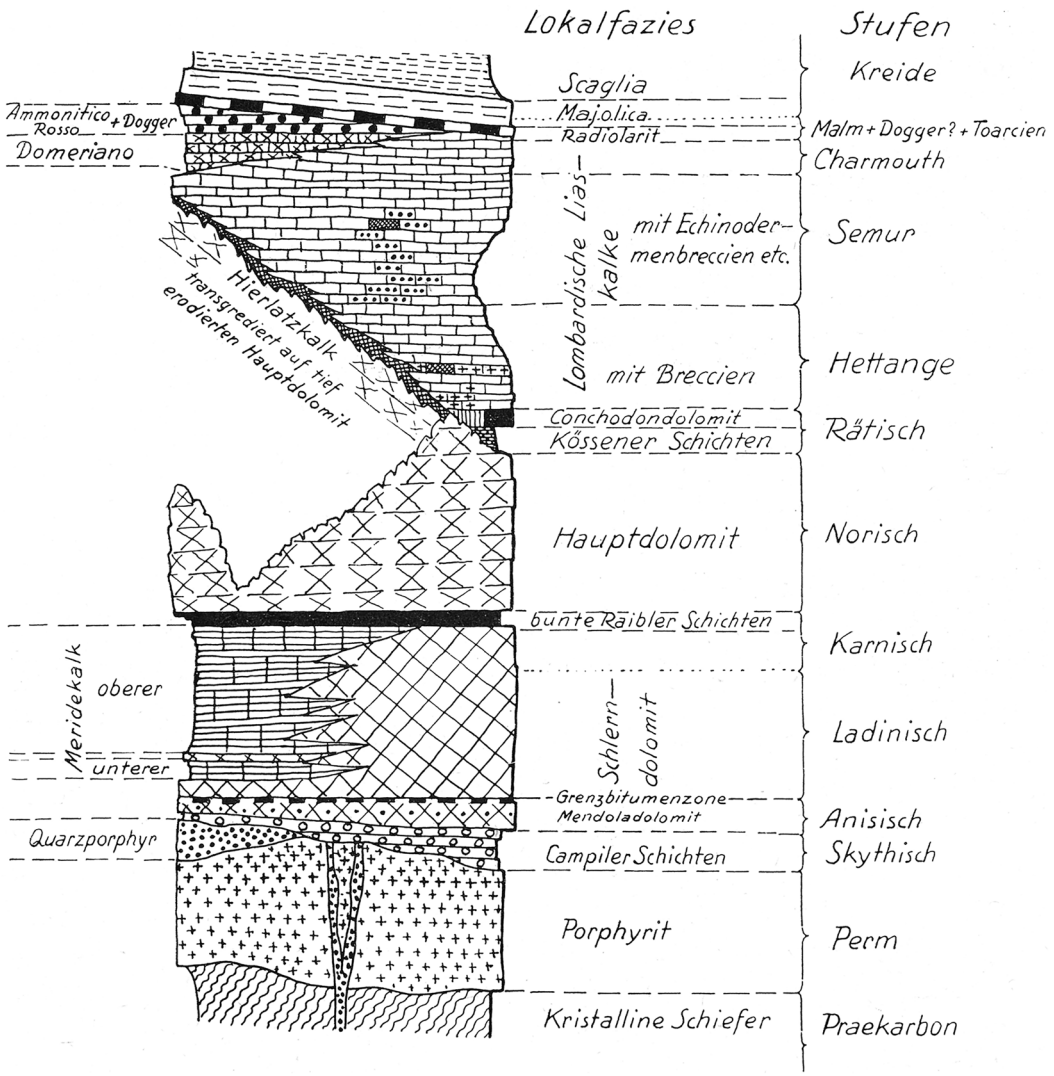

Fig. 7 Historic stratigraphical column of Monte San Giorgio by the Swiss geologist Albert Frauenfelder, introducing the name *Grenzbitumenzone* at the Anisian/Ladinian boundary (Middle Triassic). © Frauenfelder (1916)

by the *Georges und Antoine Claraz-Schenkung* at the University of Zurich. Peyer was a zoologist who became professor of palaeontology from 1930 and director of the Zoological Museum at the University of Zurich from 1940 to 1955. His well-known publications (e.g., in the series *Die Triasfauna der Tessiner Kalkalpen* in the Schweizerische Paläontologische Abhandlungen, today Swiss Journal of Palaeontology) gave much attention to Monte San Giorgio as an important fossil site in southern Switzerland, popularly called «Mountain of fossil reptiles» (Fig. 14).

Bernhard Peyer had good contacts to the local population in Meride, and to Pietro Neri Sizzo de Noris, the director of the Società Anonima Miniere Scisti Bituminosi di Meride e Besano, to whom he paid an annual fee to investigate the mining area and the salary of the miners he hired for his excavations during the summer time. By instructing the miners in recovering fossils during the industrial exploitation of the *scisti bituminosi,* additional interesting fossils were collected from the Cava Tre Fontane mine from 1927 to 1947. Most notable are the ichthyosaurs including examples of the small *Mixosaurus cornalianus* and the big shastasaurid *Cymbospondylus buchseri* (Sander, 1989a), fragmentary skeletons of *Tanystropheus longobardicus* and the big sauropterygian *Paranothosaurus amsleri* (Peyer, 1939 =*Nothosaurus giganteus* in Rieppel, 2000). The final purchase of fossils from the Cava Tre Fontane mine was at a price of CHF

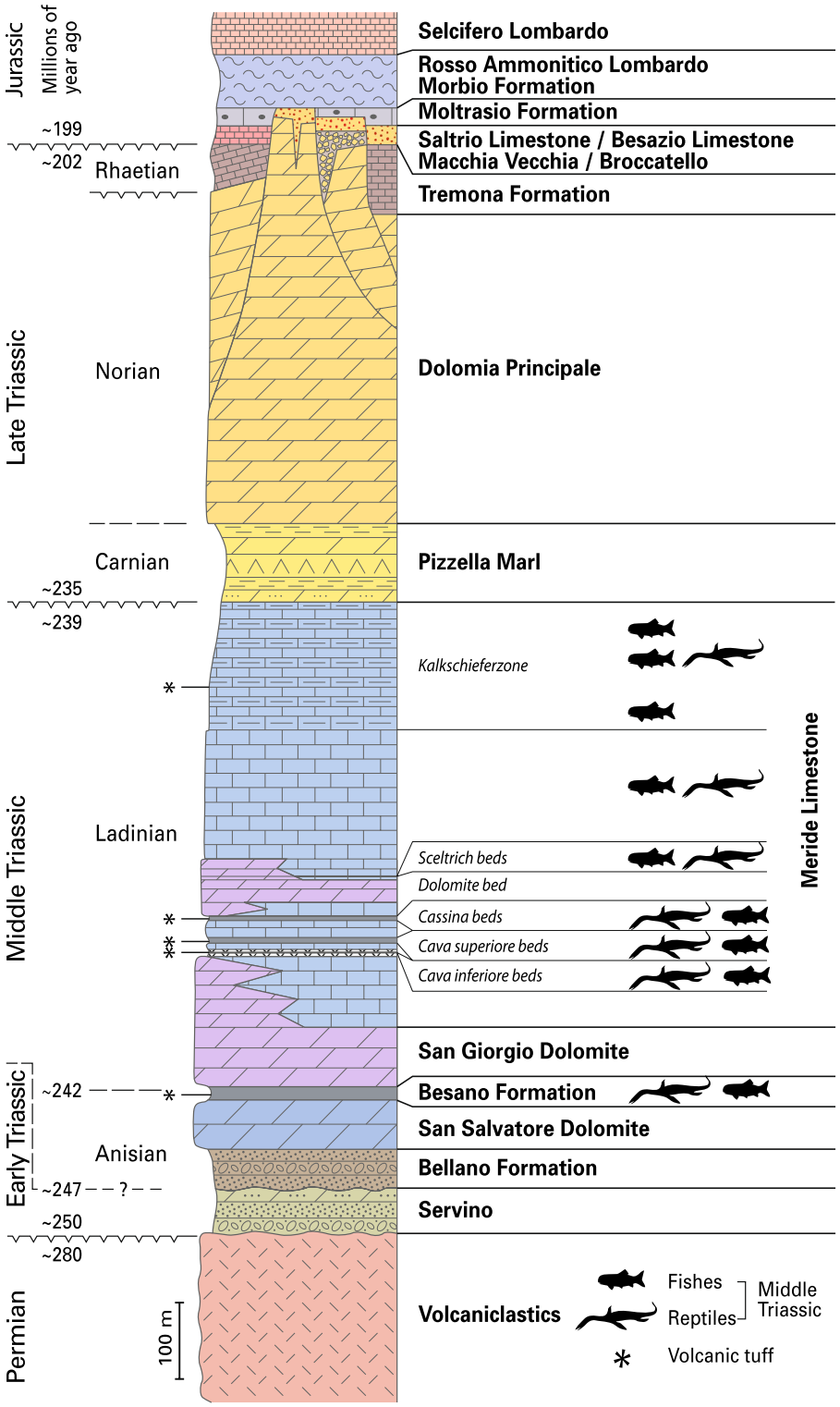

Fig. 8 Stratigraphical column of Monte San Giorgio showing the fossiliferous horizons, and the litho-, bio- and chronostratigraphy used today. © Commissione Scientifico Transnazionale Monte San Giorgio, 2014

Fig. 9 The entrance of the tunnel *Santa Barbara 1* of the Cava Tre Fontane mine, with the miner's house at around 1915 to the left. © FMSG/ Archivio Sommaruga

50.00, and documented in a letter from Emil Kuhn to Bernhard Peyer, dated 30.07.1947 (Furrer, 2023).

The scientific excavations were conducted in agreement with the Canton Ticino and the Museo Cantonale di Storia Naturale in Lugano. The *Risoluzione n. 4467 del 13 ottobre 1944* of the *Consiglio di Stato della Repubblica e Cantone del Ticino* is a convention with the *Zoologisches Museum der Universität Zürich* (Bernhard Peyer, then director) regarding delivery of annual reports and publications, together with donation of some prepared fossils.

In agreement with the Museo Civico di Storia Naturale di Milano, Bernhard Peyer was also allowed to collect fossils on Italian territory, mainly from the *scisti bituminosi* in the «Cave di Besano» (also called «Selva Bella») mine and the younger fossiliferous beds of the Lower Meride Limestone at «Val Piodissa», «Rio dei Poncini», «Prà degli Spiriti» and «Cà del Frate». The best finds were donated after preparation and publication to the museum in Milan (e.g., *Askeptosaurus italicus* and *Macrocnemus bassanii*; see Peyer, 1944).

The largest excavation at Monte San Giorgio from 1950 to 1968

In 1950, Emil Kuhn, the collaborator of Bernhard Peyer, started a project with Louis Vonderschmitt from the University of Basel for a large excavation in the *Grenzbitumenzone* at «Point 902/Mirigioli», a locality between Cava Tre Fontane and the summit of Monte San Giorgio. Work published on this extensive excavation was under the name of Kuhn-Schnyder following his marriage in 1952 (Kuhn-Schnyder & Vonderschmitt, 1954). They documented for the first time not only the distribution and frequency of the fossil fauna and flora, but also the sedimentology in a standard section (Müller, 1969). This project started with an excavation surface of 240 m^2 at the top and continued until 1968 when the active surface was deeper in the ground and a reduced area of 90 m^2 (Kuhn-Schnyder, 1964, 1974) (Fig. 15). The rich material collected became the basis of many subsequent studies on vertebrates, including important fossils from previous excavations by Peyer's team (see also Rieppel, 2019; Bürgin, this volume):

- Reptiles: *Tanystropheus longobardicus* and *T. hydroides* (Wild, 1973; Spiekman & Scheyer, 2019), *Macrocnemus bassanii* and *Macrocnemus* aff. *M. fuyuanensis* (Jaquier et al., 2017; Rieppel, 1989b), *Serpianosaurus mirigiolensis* (Rieppel, 1989a), *Lariosaurus buzzii* (Tschanz, 1989), *Mixosaurus cornalianus* and *M. kuhnschnyderi* (Brinkmann, 1996, 2004; Houssaye et al., 2014; Miedema et al., 2023), *Askeptosaurus italicus* (Müller, 2005), *Cyamodus hildegardis* (Scheyer, 2010)
- Chondrichthyan fish: *Hybodus, Acrodus, Asteracanthus, Paleobates* (Rieppel, 1981), *Acronemus* (Rieppel, 1982), *Acrodus georgii* (Mutter, 1998)
- Actinopterygian fish: *Saurichthys* (Argyriou et al., 2016; Maxwell et al., 2015; Rieppel, 1985b, 1992), small basal ray-finned fishes (Bürgin, 1992, 2004), *Colobodus bassanii* (Mutter, 2002, 2004), *Birgeria stensioei* (Romano & Brinkmann, 2009), *Ticinolepis* and *Eosemionotus* (Bürgin, 2004; López-Arbarello et al., 2016, 2019), *Marcopoloichthys* (Arratia et al. this volume)
- Sarcopterygian fish: *Ticinepomis peyeri* (Rieppel, 1980, 1985a), *T. ducanensis, Rieppelia heinzfurreri* (Ferrante & Cavin, 2023; Ferrante et al., 2023)

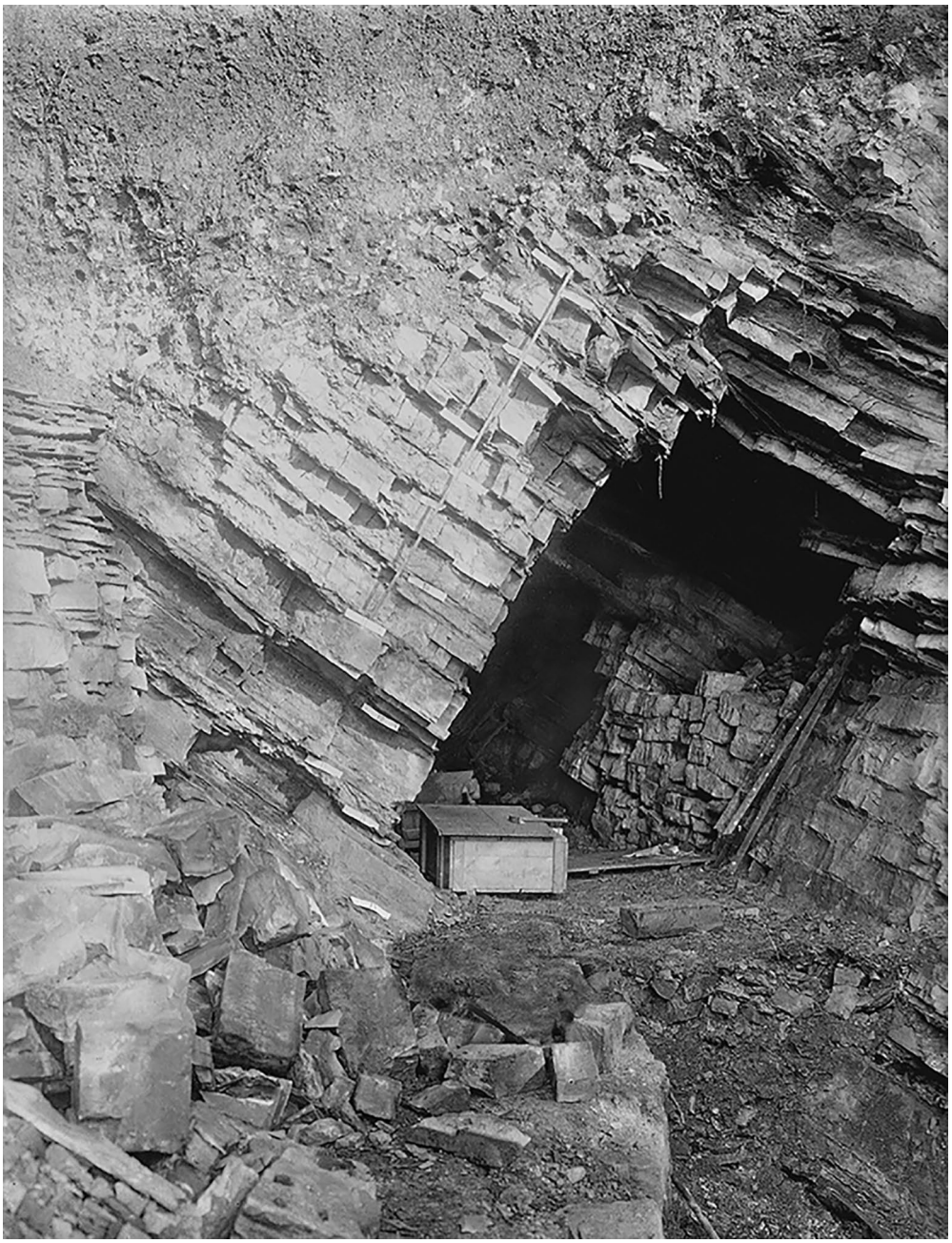

Fig. 10 Entrance of the uppermost tunnel *Arnaldo superiore* of the Cava Tre Fontane mine, with the black bituminous layers numbered from 1 (top) to 15 (base). Foto M. P. Linck, 1929 © archive PIMUZ

- Conodonts (Goudemand et al. 2011; Müller, 1964; Rieber, 1980)
- Bivalves (Rieber, 1968, 1969)
- Gastropods (Pieroni & Furrer, 2020)
- Cephalopods (Pieroni, 2022; Rieber, 1970, 1973, 1974)
- Arthropods (Etter, 1994)
- Palaeoecology (Röhl et al., 2001)
- Taphonomy (Beardmore et al., 2012; Beardmore & Furrer, 2015; Etter, 2002)

Based on the results of this excavation, Rieber (1973) subdivided the total 15.8 m thickness of the *Grenzbitumenzone* (today Besano Formation; Bernoulli et al., 2018) into a lower (beds 3–53, ~ 5.80 m),

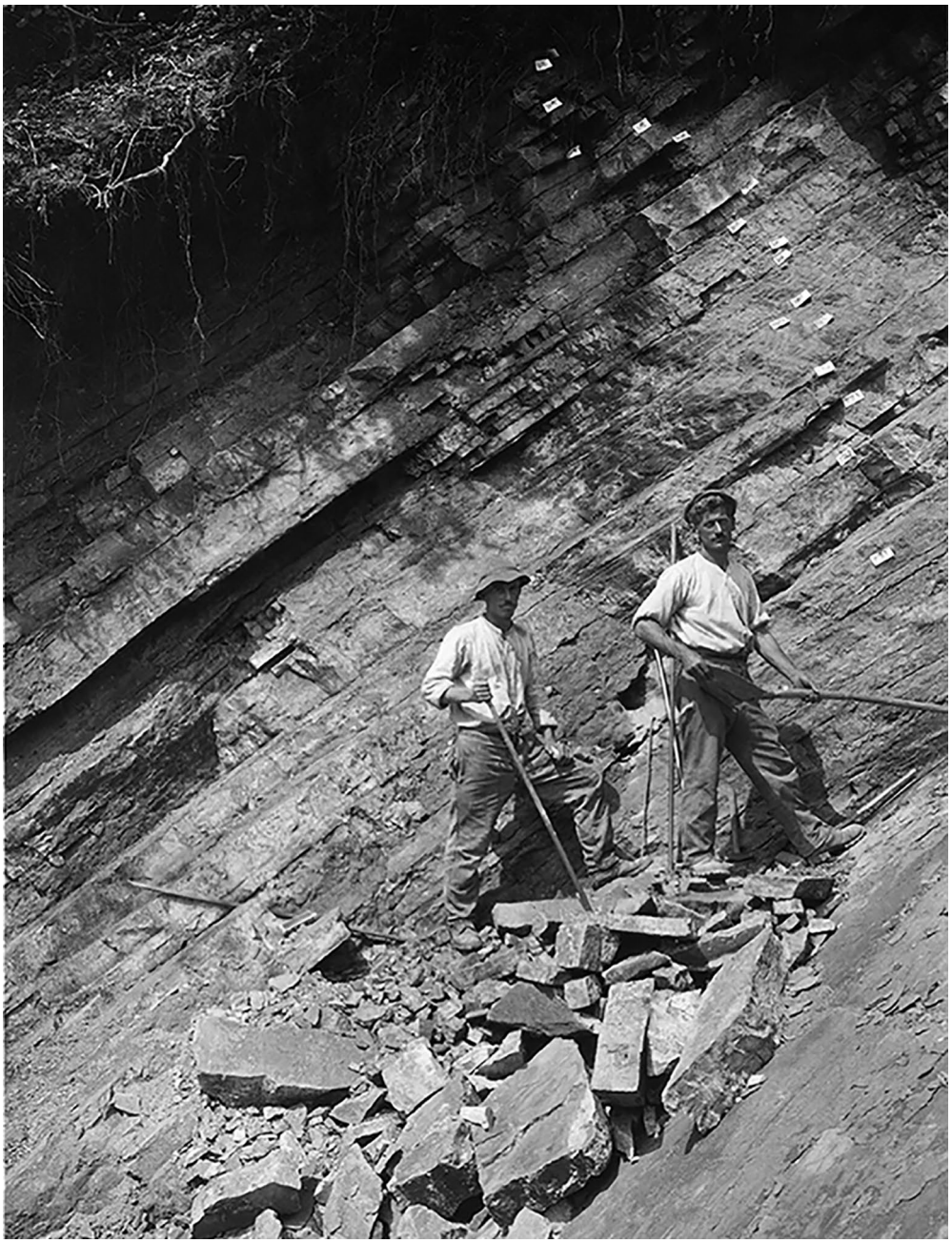

Fig. 11 Start of Peyer's largest excavation in the laminated dolomitic beds with thin bituminous interlayers (today part of the upper Besano Formation), above the abandoned mine at Val Porina. Note the numbering of the bituminous layers, called *Tetto nuovo min 1* (base) to *Tetto nuovo min 17* (top). Foto M. P. Linck, 1929 © archive PIMUZ

middle (beds 54–132, ~ 6.60 m) and upper part (beds 133–186, ~ 4.30 m), suggesting the Anisian/Ladinian boundary was located between beds 97/98 (based on ammonoids and daonellid bivalves) (Brack & Rieber, 1993; Röhl et al., 2001). However, the International Commission on Stratigraphy designated the base of the Ladinian in a section near Bagolino (Province Brescia, northern Italy) (Brack et al., 2005), meaning the Anisian/Ladinian boundary at Monte San Giorgio is between beds 149/150, inside the upper *Grenzbitumenzone* or upper Besano Formation. Radiometric dating (U–Pb) of zircon crystals in a volcanic ash layer 6.30 m below this boundary (bentonite bed 71, inside the middle Besano Formation), indicate an age of 242.1 ± 0.6 Ma (Mundil et al., 2010) (see also

Fig. 12 View of the palaeontological excavation in the Cava superiore beds at the site of an abandoned tunnel at Acqua del Ghiffo in 1928. The young assistant Emil Kuhn (to the left, in white shirt) is sitting next to the miners hired by Bernhard Peyer. Foto B. Peyer © archive PIMUZ

Fig. 8). The Anisian/Ladinian boundary is actually suggested to have an age of ~ 242 Ma (International Chronostratigraphic Chart v2023/09, www.stratigraphy.org).

When Bernhard Peyer retired in 1955, Emil Kuhn-Schnyder became the new professor of Palaeontology at the University of Zurich. In 1956, the Palaeontological Institute and in 1965, the Palaeontological Museum were separated from the Zoological Museum, taking on the care of the largest fossil collection from Monte San Giorgio. It includes about 5000 vertebrate and thousands of

Table 1 More than 30 small and large excavations have been carried out under scientific direction at over 20 different localities in the area of Monte San Giorgio—Monte Pravello—Monte Orsa

Year	Locality, Community, Province/Canton	Fossil bed	Institution	Direction of excavation
1863	Vallone, Besano, Varese	Besano Formation *Scisti ittiolitici di Besano*	Società Italiana di Scienze Naturali	A. Stoppani
1878	Vallone, Besano, Varese	Besano Formation *Scisti ittiolitici di Besano*	Museo di Storia Naturale di Milano	E. Cornalia
1924	Cava Tre Fontane, Meride, Ticino	Besano Formation *Grenzbitumenzone*	Universität Zürich	B. Peyer
1924	Val Porina, Meride, Ticino	Besano Formation *Grenzbitumenzone*	Universität Zürich	B. Peyer
1925	Val Porina, Meride, Ticino	Besano Formation *Grenzbitumenzone*	Universität Zürich	B. Peyer
1927	Cava Tre Fontane, Meride, Ticino	Besano Formation *Grenzbitumenzone*	Universität Zürich	B. Peyer
1927	Acqua del Ghiffo, Meride, Ticino	Cava inferiore beds, Lower Meride Limestone	Universität Zürich	B. Peyer
1928	Acqua del Ghiffo, Meride, Ticino	Cava superiore beds, Lower Meride Limestone	Universität Zürich	B. Peyer
1929	Val Porina, Meride, Ticino	Besano Formation *Grenzbitumenzone*	Universität Zürich	B. Peyer
1930	Val Serrata, Meride, Ticino	Cava inferiore beds, Lower Meride Limestone	Universität Zürich	B. Peyer
1931–1933	Val Porina, Meride, Ticino	Besano Formation *Grenzbitumenzone*	Universität Zürich	B. Peyer
1933, 1935, 1937	Cassina, Meride, Ticino	Cassina beds, Lower Meride Limestone	Universität Zürich	B. Peyer
1937	Acqua Ferruginosa, Meride, Ticino	Cava inferiore beds, Lower Meride Limestone	Universität Zürich	B. Peyer
1938	Cassinello, Meride, Ticino	Cava inferiore beds, Lower Meride Limestone	Universität Zürich	B. Peyer
1941	lower Val Porina, Meride, Ticino	Cava inferiore beds, Lower Meride Limestone	Universität Zürich	B. Peyer
1950–1968	Mirigioli/P. 902, Meride, Ticino	Besano Formation *Grenzbitumenzone*	Universität Zürich	E. Kuhn-Schnyder
1970–1975	Cassina, Meride, Ticino	Cassina beds, Lower Meride Limestone	Universität Zürich	E. Kuhn-Schnyder
1975–1984	Rio Ponticelli, Besano, Varese	Besano Formation *Scisti bituminosi*	Museo di Storia Naturale di Milano	G. Pinna
1983, 1984	Valle Stelle, Meride, Ticino	Besano Formation *Grenzbitumenzone*	Universität Zürich	H. Rieber
1985–2003	Sasso Caldo, Besano, Varese	Besano Formation *Scisti bituminosi*	Museo di Storia Naturale di Milano	G. Teruzzi
1983–1999	Besnasca, Viggiù, Varese	Kalkschieferzone, Upper Meride Limestone	Università Milano	A. Tintori
1994	Val Mara, Meride, Ticino	Kalkschieferzone, Upper Meride Limestone	Universität Zürich	H. Furrer
1995/96	Acqua del Ghiffo, Meride, Ticino	Cava inferiore beds, Lower Meride Limestone	Universität Zürich	H. Furrer
1996–2003	Vecchi Mulini, Meride, Ticino	Kalkschieferzone, Upper Meride Limestone	Università Milano	A. Tintori
1997–2004	Acqua del Ghiffo, Meride, Ticino	Cava superiore beds, Lower Meride Limestone	Universität Zürich	H. Furrer
2006–2012, 2017, 2022	Cassina, Meride, Ticino	Cassina beds, Lower Meride Limestone	Museo cantonale di storia naturale, Lugano	R. Stockar
2008	Costa, Meride, Ticino	Cava superiore beds, Lower Meride Limestone	Museo cantonale di storia naturale, Lugano	R. Stockar

Table 1 (continued)

Year	Locality, Community, Province/Canton	Fossil bed	Institution	Direction of excavation
2010, 2020	Val Mara, Meride, Ticino	Kalkschieferzone, Upper Meride Limestone	Museo cantonale di storia naturale, Lugano	R. Stockar
2010–2014, 2018–2021	Val Sceltrich, Meride, Ticino	Sceltrich beds, Upper Meride Limestone	Museo cantonale di storia naturale, Lugano	R. Stockar
2023	Val Mara, Meride, Ticino	Kalkschieferzone, Upper Meride Limestone	Museo cantonale di storia naturale, Lugano	F. Magnani

Fig. 13 The studied section in the Lower Meride Limestone at the locality Cassina. Fritz Buchser (left), the technical assistant from Meride, discovered these fossiliferous beds in 1931. Foto M. P. Linck, 1933 © archive PIMUZ

invertebrate fossils, alongside many fossils of green algae and terrestrial plants, not yet studied (see https://www.pim.uzh.ch/sammlung/).

Emil Kuhn-Schnyder directed his last excavation from 1970 to 1975 at Cassina, near the site excavated by Peyer's team in 1933. Carroll and Gaskill (1985) studied the recovered pachypleurosaurs, together with Peyer's material from 1933 (described by Zangerl, 1935), and compared it to the original material of *Pachypleurosaurus edwardsii* from Cà del Frate (Cornalia, 1854). However, Sander (1989b) referred this species to the genus *Neusticosaurus* (for details and discussion see Rieppel, 2019). A new specimen of a large sauropterygian together with the two former specimens from 1933 were described by Hänni (2004) as a new species *Ceresiosaurus lanzi*, its holotype deformed by a spectacular synsedimentary slump. Wild (1980) published a unique find of *Tanystropheus*, consisting of only a small skull with associated neck vertebrae (presumably bitten off by a large predator) as a new species *Tanystropheus meridensis*. This was later regarded by Spiekman and Mujal (2023) as the remains of a young individual of *T. longobardicus*. Exceptionally preserved juvenile to adult skeletons of the actinopterygian fish *Saurichthys* from the old and new excavations were analysed by Rieppel (1985b), who divided them into two species: *S. curionii* and *S. costasquamosus*. Bürgin (1992) documented a number of smaller actinopterygians. The

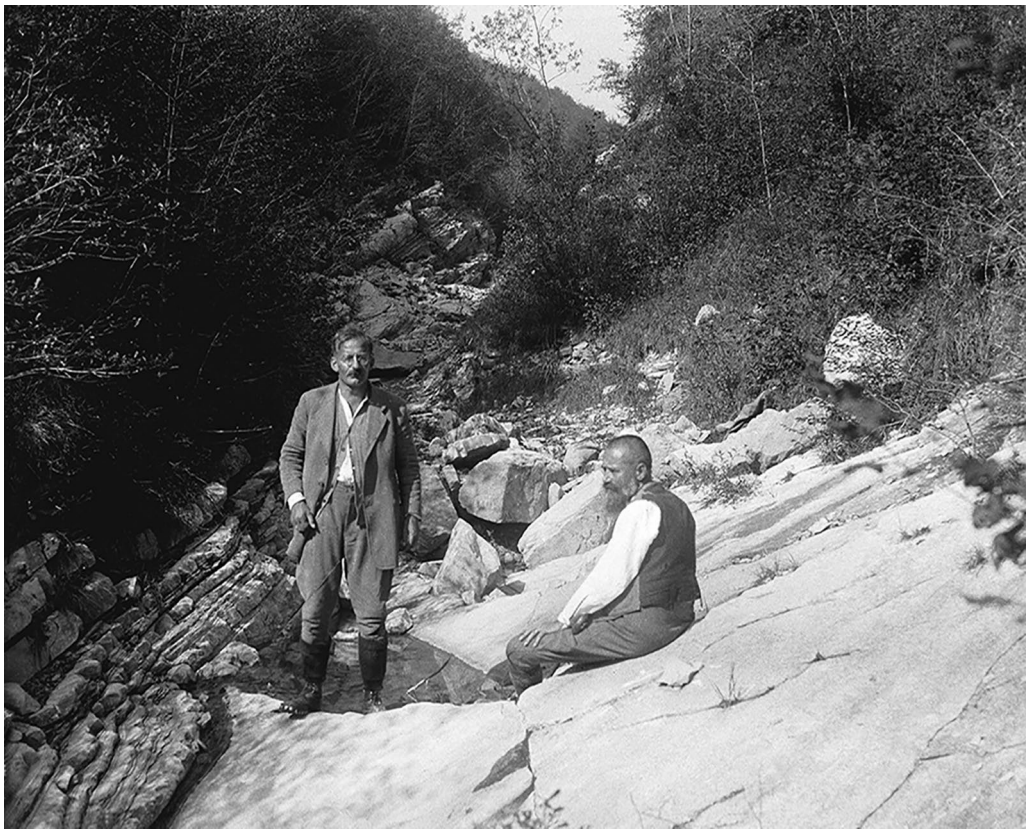

Fig. 14 Bernhard Peyer (University of Zurich) standing to the left of his guest Ferdinand Broili (University of Munich), seen sitting on beds of the Lower Meride Limestone in Val Serrata. Foto 1929 © archive PIMUZ

rich *Saurichthys* material was also the subject of taphonomic studies (Beardmore & Furrer, 2016b, 2019).

The important scientific work of the palaeontologists from the University of Zurich has always been appreciated by the local people. In recognition of their significant contribution, the community of Meride appointed Bernhard Peyer (posthumously), his wife Hildegard, and Emil Kuhn-Schnyder and his wife Hanni as honorary citizens on September 24th 1967. As a further show of gratitude, Emil Kuhn-Schnyder helped the municipality of Meride to install the first museum in the heart of the village in 1973. The new *Museo dei Fossili del Monte San Giorgio*, opened on October 12th 2012, which profited from the help and loan of fossils from the Palaeontological Institute and Museum, University of Zurich (Furrer & Vandelli, 2014).

Excavation near Besano and at Monte San Giorgio from 1974 to 2003

On the Italian side of the border, the Museo Civico di Storia Naturale di Milano restarted excavations directed by Giovanni Pinna and Giorgio Teruzzi in the *Scisti ittiolotici di Besano* (=Besano Formation). These occurred from 1974 to 1984 at «Rio Ponticelli» and from 1985 to 2003 at «Sasso Caldo» above Besano (Nosotti & Teruzzi, 2008; Pinna & Teruzzi, 1991). Highlights were the discovery of the longest complete skeleton of a shastasaurid ichthyosaur with embryos, described as *Besanosaurus leptorhynchus* by Dal Sasso and Pinna (1996), revised by Bindellini et al. (2021), a complete juvenile specimen of *Macrocnemus bassanii* (Renesto & Avanzini, 2002), a new reptile *Eusaurosphargis dalsassoi* (Nosotti & Rieppel, 2003), two nearly complete skeletons of *Tanystropheus longobardicus* (Nosotti, 2007), and two excellently preserved specimens of *Mixosaurus cornalianus* with soft parts (Renesto et al., 2020). The fish fossils have not yet been studied in detail, and there is an equally rich collection of invertebrate material also not yet described. Exceptions are some thylacocephalan crustaceans mentioned by Affer and Teruzzi (1999) and the first fossil scorpion, published by Viaretti et al. (2023) as a new species *Protobuthus ziliolii.*

The last excavation in the middle and upper *Grenzbitumenzone* (Besano Formation) on Swiss territory was carried out in 1983–1984 at «Valle Stelle», about 400 m north-east of Cava Tre Fontane on the path from

Fig. 15 Emil Kuhn-Schnyder during the largest fossil excavation in the *Grenzbitumenzone* at Point 902/Mirigioli. The wall on the left shows the studied section of the upper and middle part of the *Grenzbitumenzone*. Foto H. Rieber, 1963 © archive PIMUZ

Serpiano to Monte San Giorgio. The small excavation under the direction of Kuhn-Schnyder's successor, Hans Rieber, focused on the stratigraphy of ammonoids and daonellids. Bernasconi (1994) performed a sedimentological and geochemical study in the *Grenzbitumenzone* and suggested a model of microbial controls on dolomite formation in the anoxic environments.

From 1983 to 1999, another Italian group, led by Andrea Tintori from the Dipartimento di Scienze della Terra dell'Università di Milano, studied the Kalkschieferzone of the uppermost Meride Limestone (late Ladinian) at the locality of «Besnasca/Cà del Frate», north of Viggiù (Tintori & Renesto, 1983; Tintori et al. 1985). The team discovered the new sauropterygian *Lariosaurus valceresii*, including adult, juvenile and embryonic specimens (Renesto, 1993; Renesto et al., 2003; Tintori & Renesto, 1990), mass mortalities of the small fish *Prohalecites porroi* (Tintori, 1990a), many other actinopterygian fishes (Lombardo, 1999; Tintori & Renesto, 1983; Tintori, 1990c, 1992) and estherid crustaceans (Tintori, 1990b).

Excavations in collaboration with the Museo Cantonale di Storia Naturale di Lugano from 1994 to 2004

In 1994, the author restarted palaeoecological and taphonomic studies in the Meride Limestone at Monte San Giorgio as leader of a team from the University of Zurich in collaboration with the Museo Cantonale di Storia Naturale di Lugano (curator Markus Felber and director Filippo Rampazzi). The first small-scale systematic excavations were done in fossiliferous beds of the middle Kalkschieferzone (uppermost Meride Limestone, late Ladinian) in the Gaggiolo Valley at Val Mara west of Meride. This section, described by Senn (1924), Wirz (1945) and Scheuring (1978), was the source of several actinopterygian fishes and a small reptile found by Urs Oberli in 1971, first described by Kuhn-Schnyder (1987) as a new species *Lariosaurus lavizzarii*, but afterwards regarded as a juvenile specimen of *Lariosaurus* sp. (Renesto, 1993). An interesting fish fauna was also found, described by Bürgin (1995), alongside many estheriid and mysidiid crustaceans, terrestrial plants and several interesting sedimentological structures (Furrer, 1995).

Fig. 16 The new palaeontological excavation in the Cava superiore beds at the Acqua del Ghiffo site. Note the thin orange volcanic ash layer just below the recovered slabs of laminated limestone. Foto H. Furrer, 2000 © archive PIMUZ

From 1997 to 2003, the lower Kalkschieferzone in the same section was excavated bed by bed at «Vecchi Mulini» near Meride by the University of Milano, also in collaboration with the Museo Cantonale di Storia Naturale di Lugano (Tintori et al. 1998). They discovered many well-preserved actinopterygian fishes, described by Lombardo (2001, 2002, 2013), Lombardo and Tintori (2004), Tintori and Lombardo (2007) and Lombardo et al. (2012), together with mysidiid crustaceans and insects, e.g., *Tintorina meridensis* (Krzeminski & Lombardo, 2001; Montagna et al., 2017).

In 1995, the Zurich team restarted an excavation campaign at Peyer's old locality Acqua del Ghiffo, reopened with the help of a small excavator. From 1995 to 1996, the 1.50 m thick section of the Cava inferiore beds was studied carefully across a bedding surface of approximately 10 m^2. This brought to light the first fossil crustaceans, assigned to *Halicyne agnota* (Furrer, 1999), a few actinoptergians (e.g., *Saurichthys curionii*), many skeletons of *Neusticosaurus pusillus* and a juvenile *Ceresiosaurus calcagnii* (Hänni, 2004). A spectacular slab with 12 skeletons of *Neusticosaurus pusillus* was recovered and prepared for the exhibition in the Museo Cantonale di Storia Naturale in Lugano.

From 1997 to 2004, the 10 m thick section of the Cava superiore beds was studied bed-by-bed across a surface of about 10 m^2 (Fig. 16). The pachypleurosaurid *Neusticosaurus peyeri* was dominant, with recovery of more than 50 adult, juvenile and embryonic skeletons. In addition to the usually well-preserved and articulated specimens, some partly disarticulated skeletons and isolated bones were recovered. A complete skeleton of *Ceresiosaurus calcagnii* was the highlight (Furrer & Vandelli, 2014). Actinopterygian fish were present but rare (*Saurichthys, Ticinolepis, Besania;* see Bürgin, 1999), occurring together with dasycladaceen green algae, terrestrial plants (*Equisetites*) and two insect fossils (Felber et al., 2000). One ammonoid (*Arpadites* cf. *arpadis*) from the section confirmed an early Ladinian age (Furrer, 1999; Furrer & Vandelli, 2014). A large slab with 20 skeletons of *Neusticosaurus peyeri* and six small fishes was recovered and prepared for the exhibition in the *Museo dei Fossili del Monte San Giorgio* in Meride, opened in 2012. When the Acqua del Ghiffo site was cleaned and made ready for the public in 2021, a complete fossil scorpion was found by Fabio Magnani (Museo Cantonale di Storia Naturale in Lugano) and described as *Protochactas furreri* (Magnani et al., 2022).

Excavations by the Museo Cantonale di Storia Naturale di Lugano since 2006

Since 2006, Rudolf Stockar (curator at the Museo Cantonale di Storia Naturale in Lugano) has led new detailed excavations in the fossiliferous beds of the Meride Limestone. From 2006 to 2022, the team studied the Cassina

Fig. 17 Palaeontological work in the new fossiliferous level (with a thickness of only 30 cm) at the base of the Upper Meride Limestone at Val Sceltrich. Foto R. Stockar, 2018 © archive MCSN

beds near Peyer's type locality at Cassina (Stockar, 2010; Stockar & Renesto, 2011). Stockar and Kustatscher (2010) published the first plant fossils, Renesto and Stockar (2009) highlighted interesting specimens of the actinopterygian fish *Saurichthys curionii* with preserved embryos, and López-Arbarello et al. (2016, 2019) described the new species *Ticinolepis longaeva* and *Eosemionotus diskosomus*.

During this time, the team from the Museo di Lugano also studied other sites, notably the Cava superiore beds at «Costa» (southwest of Monte San Giorgio's peak) in 2008, and the upper Kalkschieferzone at the lower end of Val Mara in 2010 and 2020, from where the youngest coelacanth fossil from Monte San Giorgio (*Heptanema* cf. *H. paradoxum* in Renesto et al., 2021) and new insects have been reported (e.g., *Dasyleptus triassicus* in Bechly & Stockar, 2011). Rudolf Stockar also studied in detail the stratigraphy, sedimentology and geochemistry of the whole Meride Limestone (Stockar et al., 2012b, 2013) and initiated radiometric dating (U–Pb) of zircon crystals. A volcanic ash layer in the Cava superiore beds was dated to 241.07 ± 0.13 Ma, another one in the Cassina beds to 240.63 ± 0.13 Ma and the youngest one at the boundary of the lower/middle Kalkschieferzone to 239.51 ± 0.15 Ma (Stockar et al., 2012a).

An important new fossiliferous level, with a thickness of only 30 cm, located at the base of the Upper Meride Limestone was discovered and studied from 2010 to 2021 at «Val Sceltrich» (Fig. 17). The new Sceltrich beds yielded a rich vertebrate fossil fauna, mostly articulated fishes, such as *Ticinolepis longaeva* and *Eosemionotus sceltrichensis*, together with rare sauropterygian reptile bones and teeth, invertebrate fossils and terrestrial plant remains (López-Arbarello et al., 2016, 2019). A highlight was the discovery of the first coelacanth fish in the Meride Limestone, *Heptanema* cf. *H. paradoxum* (Renesto & Stockar, 2018). Invertebrate fossils include crustaceans (mysidaceans, decapods, rare cycloids; Stockar & Garassino, 2013), the posidonioid bivalve *Peribositra* and gastropods (Pieroni & Stockar, 2023).

Summary and UNESCO world heritage status

More than 30 palaeontological excavations on various scales have been carried out at over 20 localities in the Monte San Giorgio to Monte Orsa area over the last 160 years, with the fossils recovered still offering enormous potential for palaeontological research.

The sequence of six fossiliferous beds rich in vertebrate fossils and present on both sides of the Switzerland–Italy border has a unique value for various studies. Most notably, the evolution of these vertebrate animals can be observed over a timespan of about three million years, from the base of the Besano Formation about 242.5 million years ago, through the Lower Meride Limestone with the Cava inferiore, Cava superiore and Cassina beds

around 241 million years ago, up to the Kalkschieferzone about 239.5 million years ago. These deposits, representing a subtropical marine basin, are famous not only for their marine reptiles, but also for their high diversity of fishes with excellent preservation. Numerous invertebrates have also been found, together with a few terrestrial reptiles, insects and plants, washed into the sea from islands or the mainland relatively nearby.

Building on previous studies of the fossil material, modern research techniques can be applied to specimens in the rich collections in Switzerland and Italy to learn more about them and the ancient environment they came to rest in. The success of the more recent excavations is highlighted by the many new finds, proving the importance of new systematic field studies on both sides of the border in the future.

The international importance of this classic fossil locality, situated at the southern border of the Alps, is highlighted by its designation as a World Heritage Site by UNESCO (United Nations Educational, Scientific and Cultural Organization) in 2003 for the Swiss part and in 2010 for the neighbouring Italian territory. Following the «Convention Concerning the Protection of the World Cultural and Natural Heritage» of 1972, the countries (Switzerland and Italy) are responsible for protecting this unique natural site and passing it on to future generations.

Abbreviations

FMSG	Fondazione del Monte San Giorgio
MCSN	Museo Cantonale di Storia Naturale, Lugano
PIMUZ	Palaeontological Institute and Museum, University of Zurich

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