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PART V, SECOND REVISION, CHAPTER 9: GEOLOGICAL APPLICATIONS

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INTRODUCTION

Graptolites are probably best known for their role in biostratigraphic dating of rock sequences and by paleontologists for the fascinating complexity of their colonies. However, they have much more to offer, and a look back into the history of graptolite research shows their importance for a variety of geological applications. The distribution of Middle Ordovician isograptids, for instance, has been used to infer the presence of oceanic basins and to outline the rims of ancient continents (Fortey & Cocks, 1986). Plus, the paleogeographical information graptolites provide make them valuable for tracing natural resources such as petrochemicals and mineral deposits, thus adding an economic dimension to the study and usefulness of this fossil group.

The early understanding of the distribution of graptolites was not without controversies, as illustrated by the debate between Joachim Barrande and Charles Lapworth. Barrande's concept of graptolite colonies show him as a staunch supporter of Cuvier's theory of catastrophism, which interprets faunas from tectonic blocks as originating through a number of extinctions and creations (Barrande, 1859, 1861, 1862, 1865, 1870, 1881). Barrande's views stood in direct contradiction with Lapworth's understanding of graptolite faunas as successions of species through time. At the end, the interpretation of Lapworth (1878) was proven correct, and his graptolite research provided the nucleus of modern graptolite biostratigraphy (see Chapter 7, Maletz, 2021) and the basis for many modern applications of graptolite research.

DATING OF ROCK SEQUENCES

The study of Earth history was initially concerned with dating sedimentary sequences; and very early on, graptolites were used for just that purpose. Already James Hall (1850) realized the importance of graptolites for dating certain geological periods, laying the groundwork for the biostratigraphic application of graptolite faunas. Henry Alleyne Nicholson (1868) provided the first workable chart showing the distribution of graptolite species through time, leading to modern graptolite biostratigraphy. These scientists made the first steps toward the wider application of graptolites in the geological sciences.

Modern stratigraphy is unthinkable without the use of paleontology, even though this was not always acknowledged after radiometric dating became one of the key methods of chronostratigraphic dating. Modern understanding of deep time employs numerous additional methods (e.g., Gradstein & others, 2020) that are not discussed here. Nevertheless, the use of fossils and the recognition of a precise and highly reliable succession of fossil faunas that have developed during the last two centuries is key to understanding the geological evolution of our planet and the living organisms on its surface. For graptolites, this means that internationally recognized chronostratigraphic units in the early Paleozoic, GSSPs

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(Global Stratotype Sections and Points) are largely defined by the First Appearance Datum (FAD) of graptolite species (Fig. 1). Thus, graptolites are one of the exemplary groups of fossils for dating rock sequences and correlating them across the planet (Maletz, 2017a). As a group of macrofossils, they are also easily used in the field and do not require extensive work in the laboratory, as is typical for the investigation of microfossils (e.g., acritarchs, chitinozoans, conodonts, spores, foraminifera).

Numerous local, regional, and worldwide biozonations for graptolites have been established, as detailed in Chapter 7.

STRUCTURAL GEOLOGY AND BASIN RECONSTRUCTION

Lapworth (1878), in his important paper on the Moffat Series of the UK, established graptolite biostratigraphy as an important geological mapping tool for unraveling complexly folded and faulted lithological sequences based on the distribution of graptolite faunas. However, he had already indicated earlier (Lapworth, 1872) that he used graptolites for biostratigraphic purposes (Hamilton, 2001). Because it used graptolites for the first time to solve a geological problem, Lapworth's (1878) work on the Moffat Series was a milestone in graptolite research. It is noteworthy that Lapworth's graptolite biostratigraphy for the region is still valid and useful with little revision after nearly 150 years (Fortey, 1993).

The Lachlan Orogen of eastern Australia is another prime example of the use of graptolite faunas and dating to understand the geological history of the region. The geological structure of the area is complex, but age control on the turbidite-dominated Ordovician rocks is made through the presence of rich graptolite faunas (VandenBerg, 1989; VandenBerg & Cooper, 1992). The work began with publication of a pioneering study of the Castlemaine goldfield by Thomas Sergeant Hall (1895). Hall developed this work during the next 25 years, and additional work by William John Harris and David Evan Thomas in the 1930s achieved the subdivision of the Early and Middle Ordovician rocks into 21 graptolite zones (Harris & Thomas, 1938). This work made it possible to subdivide the monotonous turbidite–black shale sequence of the Castlemaine Group, which extends over the westernmost Lachlan Orogen, and unravel its structure, which consisted of tight, closely spaced concertina-like folds interrupted by numerous faults that follow strike. This made it possible to map the Bendigo goldfield, with more than 3,000 graptolite localities, at 1:10,000 scale (Wilkinson, Willman, & Garratt, 1988; Willman, 1992, 1994).

Problems in solving the structural complexity of the eastern Lachlan Orogen, however, could not be tackled until a workable zonation of the Late Ordovician was achieved in the 1980s (VandenBerg, 1981, 1989; VandenBerg & Cooper, 1992). With an extent of more than ten million km^2—much of it in mountainous terrain with granites making up about half of the region—the Ordovician rocks seemingly consisted of turbidites with rare intervals of black shale. Mappable lithological units seemed to be absent and, fossils were few over the widely scattered localities. This picture changed when the region was mapped, initially at a regional scale and subsequently in more detail. This demonstrated the Ordovician sequence could be subdivided into two main units, the Adaminaby Group and the overlying Bendoc Group (VandenBerg & Stewart, 1992). The Adaminaby Group consists of turbidites with rare cherts containing conodonts and very rare graptolites that represented an age ranging from at least the early Floian (Be1) *Paratetragraptus approximatus* plus *Tshallograptus fruticosus* biozones to the late Darriwilian (Da3) *Archiclimacograptus decoratus* Biozone (VandenBerg & Stewart, 1992). The overlying black shale-dominated Bendoc Group contains an almost complete Late Ordovician graptolite sequence ranging from the early Sandbian *Nemagraptus gracilis* Biozone

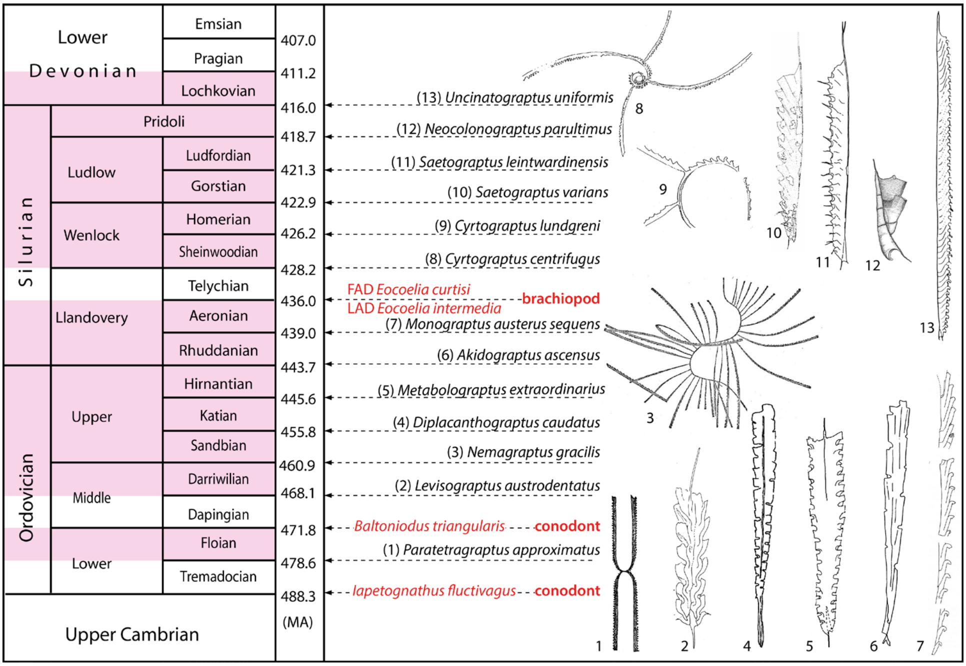

Fig. 1. Index species of graptolites for Global Stratotype Sections and Points (GSSP) in the Paleozoic. Stratigraphic intervals defined by graptolite FADs (First Appearance Datum), highlighted in *color*. Non-graptolitic fossils defining intervals in *red* (adapted from Maletz, 2017b, fig. 8).

to the late Katian *Paraorthograptus pacificus* Biozone. Careful mapping showed that the peculiar ribbon-like outcrop pattern of the Bendoc Group was due to thin-skinned deformation, with the slippery black shale providing a preferred horizon for sliding of multiple stacked thrust sheets (Glen & VandenBerg, 1987; Glen, Stewart, & VandenBerg, 1990; Fergusson & VandenBerg, 1990; VandenBerg & others, 1990; VandenBerg, Nott, & Glen,1992).

The importance of graptolites to understanding basin evolution can also be demonstrated through the investigation of the Ordovician graywackes of the southern Baltic Sea. A number of drill cores made during the 1960s demonstrated the presence of a thick succession of early Paleozoic strata in the subsurface of the German island of Rügen (Jaeger, 1967). Maletz (1997) discussed the succession of the G-14 drill core north of Rügen and demonstrated a close litho- and biostratigraphical connection to the platform succession of Baltica. Whereas the Middle Ordovician Tøyen Shale Formation is strongly condensed, a thick Telychian (Llandovery, Silurian) graptolite succession was documented, similar to that on the Danish island of Bornholm (Bjerreskov, 1975) and of Scania, southern Sweden (Tullberg, 1882). On the island of Rügen, off the southern coast of the Baltic Sea, a number of deep drill cores encountered Middle to Late Ordovician (Darriwilian to Sandbian) graptolite successions, showing tectonic repetition (Maletz, 1998, 2001). Maletz and others (1998) and Beier, Maletz, and Böhnke (2000) interpreted the strata as the remains of a peripheral foreland basin, formed when the microplate East Avalonia collided with Baltica during the Middle Ordovician to late Silurian times. The authors interpreted the stacked succession of Ordovician shales, graywackes, and sandstones (Wittow Group; see Beier & others, 2001) through the effect of thrusting northward onto the shelf region of Baltica. The whole succession was investigated during the unsuccessful exploration for oil and gas in northeastern Germany—a great success, however, for the scientific community because no surface exposures exist of these strata (Franke & others, 1994; Hoffmann & others, 1998).

The Ordovician succession of southern Bolivia provides another example of the use of graptolite faunas for interpreting the basin evolution of an extremely thick monotonous lithological succession (Müller, Kley, & Jacobshagen, 2002; Egenhoff, Maletz, & Erdtmann, 2004). The Eastern Cordillera of Argentina includes an extremely thick succession of early Paleozoic sediments that only fairly recently have been investigated in more detail. Maletz and Egenhoff (2001, 2003) described the diverse Early to Middle Ordovician graptolite faunas of southern Bolivia and recognized a fairly complete biostratigraphic succession from the Tremadocian to the late Floian that Egenhoff (2000) used to interpret the basin evolution of the region.

Graptolites have also proven useful in other geological applications, based on the style of their occurrence on shale surfaces. Schleiger (1968) and others have demonstrated that graptolite tubaria may be aligned, to a variable degree and depending on their shape, with palaeocurrent directions in the turbidites in which they occur. (Maletz, 2019; Cooper & others, 2017) (Fig. 2). From this, paleoslope directions can be determined, and these can be used in basin reconstruction.

In deformed rocks, graptolites with symmetrical tubaria can be used as strain markers (Jenkins, 1987; Maletz, 2020). Cooper (1990) offered a mathematical method of restoring symmetrical fossils from which strain ellipses could be calculated, thus giving the amount and direction of maximum compression of the host rock. Some 27 years later, VandenBerg (2017, fig. 27–28) demonstrated an easier method that gave similar results using modern image processing software.

ECONOMIC GEOLOGY

The value of graptolites for exploration of economic resources cannot be underestimated. Apart from the modern use of graptolite biostratigraphy in the exploration of oil and gas resources worldwide, a number of further important aspects are worth noting here. These have shaped and even initiated the scientific paleontological research of graptolite faunas in many regions of the world.

URANIUM EXPLORATION

Veski and Palu (2003) discussed the Cambrian–Ordovician Alum Shale Formation, including the early Tremadocian former *Dictyonema* oil shale and the Middle Ordovician kukersite deposits of Estonia that were the focus of intensive exploration (see also Bauert & Kattai, 1997; Dyni, 2005; Soesoo, Vind, & Hade, 2020). In Estonia, kukersite beds can reach an organic content of 40–45 wt% (Bauert, 1994). The exploration for uranium in the *Dictyonema* Shales of Estonia after World War II was of the highest priority (Althausen, 1992). Uranium prospecting also took place in the graptolitic Silurian successions of Thuringia, Germany by SAG/SDAG Wismut, producing 220,000 tonnes of uranium ore between 1947 and 1990. The uranium ore was concentrated in lower Paleozoic lithological units, especially in the Unterer Graptolithenschiefer (e.g., Gatzweiler & others, 1997; Wismut, 2010) but also in other units of the succession like the Ockerkalk and the Devonian and Carboniferous intrusions. At the time, the then German Democratic Republic (DDR) in eastern Germany was one of the largest producers of uranium in the world (Kämpf & others, 1995; Czega & others, 2006), and the Ronneburg mining area was the largest uranium mine in Europe, covering an area of 60 km^2 and extending to a depth of 940 m (Paul & others, 2002). Graptolite specialists are familiar with the invaluable monograph on the Silurian graptolite fauna of Thuringia by Schauer (1971), based in part on graptolites collected from sections of the Unterer

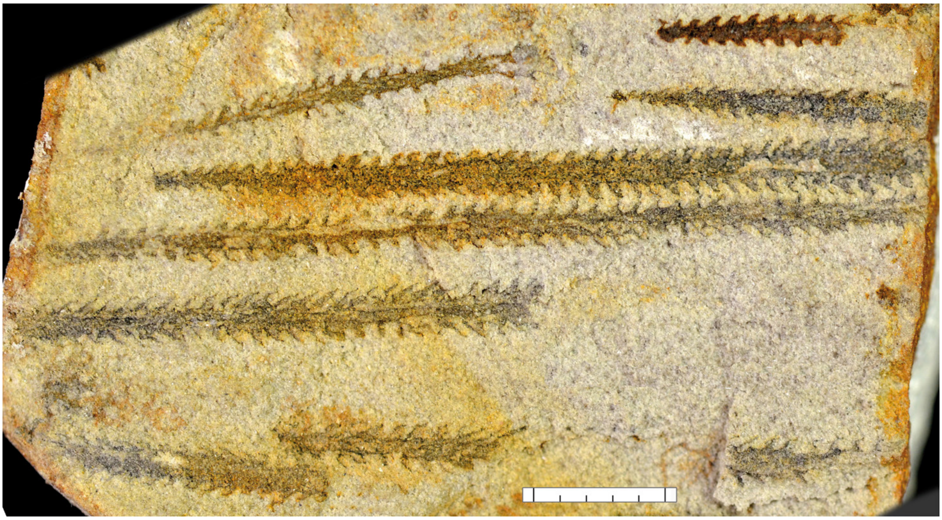

FIG. 2. Current-aligned biserial graptolites from Tb (planar laminated) portion of a turbidite bed from Late Ordovician Sunbury Group, central Victoria, Australia, scale bar, 5 mm (new; A.H.M. VandenBerg).

Graptolithenschiefer (Lower Graptolite Shale) in the Ronneburg area. Most of the paleontological data attained by the uranium industry in central Europe were not officially available for several decades as the discussion of DUFKA, KŘÍŽ, and ŠTORCH (1995) showed. All information on the uranium production from the Silurian strata by Wismut in eastern Germany (DDR) was under strict confidentiality (WISMUT, 2010), indicating the particular strategic importance of the uranium industry. Thus, very little has been published about the results.

MATURITY STUDIES AND PETROLEUM GEOLOGY

Graptolite shales can be important for the exploration of oil and gas source rocks. KONYUKHOV and AGAPITOV (2014) provided a recent overview of the distribution of Paleozoic graptolite shales around the world and their potential as hydrocarbon resources. They noted that Silurian graptolite shales may have been the source of 80–90% of the hydrocarbons stored in the giant oil fields of North Africa and also may have played the main role in the formation of the gas field of the Persian Gulf, the largest natural gas field in the world. Graptolites are made from organic material and thus provide a useful tool for identifying unconventional hydrocarbon deposits, including shale gas, without the need of complicated and expensive analytical studies. Graptolites are equally important for estimating the TOC (Total Organic Carbon) contents. There are many examples of investigations of hydrocarbon potential in graptolite-bearing Paleozoic successions around the world (e.g., FELLO & others, 2006; GRUNDMAN & others, 2012; PODHALAŃSKA, 2013; COLȚOI & others, 2016; ŞEN, 2017; LUO & others, 2016, 2018, 2020; BORJIGIN & others, 2017; WANG & others, 2019; GONG & others, 2020).

Numerous authors have used the reflectance of the graptolite fusellum to determine the organic maturity of lower Paleozoic sediments (Fig. 3), because its behavior is similar to that of other organic materials like plants, chitinozoans, and scolecodonts (TEICHMÜLLER, 1982; BERTRAND & HEROUX, 1978; BERTRAND, 1990; GOODARZI, 1990; PETERSEN, SCHOVSBO, & NIELSEN, 2013; HARTKOPF-FRÖDER & others, 2015; ZHENG & others, 2021). Graptolite reflectance can

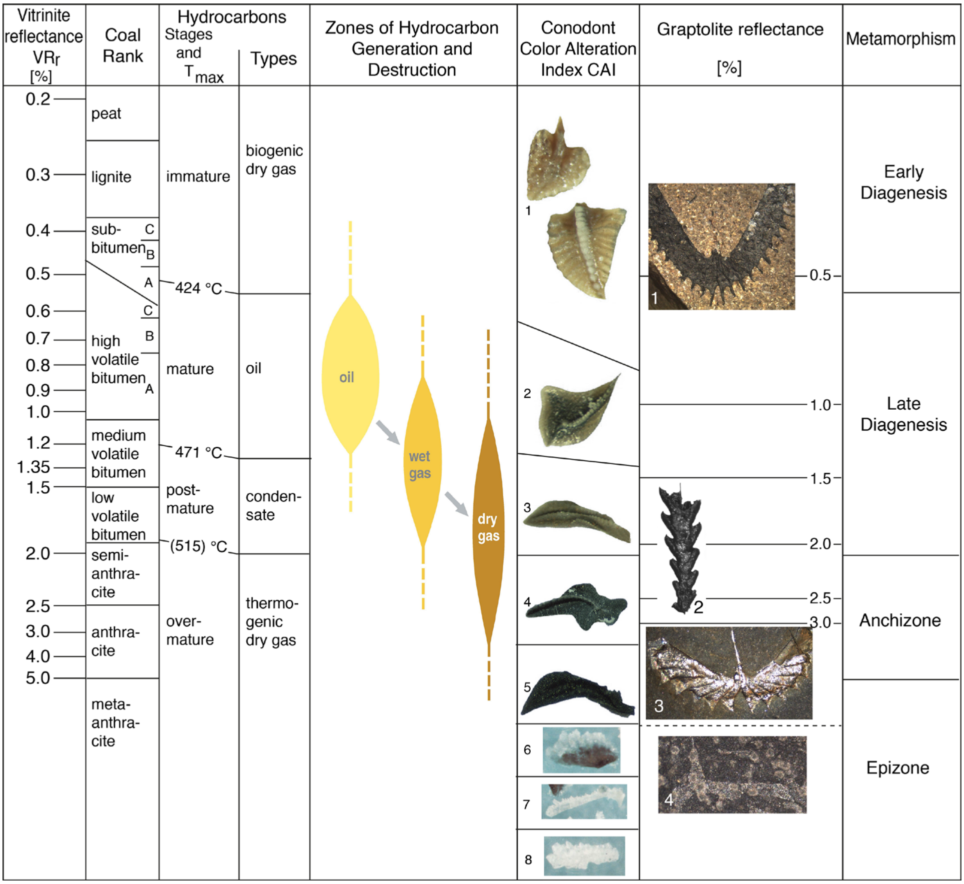

FIG. 3. Hydrocarbon generation and graptolite reflectance: a comparison. Conodont specimens from HARTKOPF-FRÖDER and others (2015) to demonstrate CAI values. Graptolites: *1*, *Parisograptus imitatus* (HARRIS, 1933) , GSC 139246, Cow Head Group, western Newfoundland; *2*, *Orthograptus apiculatus* ELLES & WOOD, 1907, PMU 35732, Gullhögen Quarry, Billingen, Västergötland, Sweden; *3*, *Isograptus rigidus* MALETZ, 2011, PMO 234.063, Slemmestad, Oslo Region, Norway; *4*, *Baltograptus geometricus* (TÖRNQUIST, 1901), LO 1585T, lectotype, Diabasbrottet, Hunneberg, Sweden. Specimens not to scale (adapted from Maletz, 2020, fig. 6).

be compared with the vitrinite reflectance of fossil plant material (GOODARZI & NORFORD, 1985, 1989). Graptolite reflectance data are compared to the CAI (color alteration index) in conodonts and may provide information on the maximum overburden of sedimentary successions through the known depth temperature gradient (BERGSTRÖM, 1980). Therefore, the graptolite fusellum provides important information on the burial history of sedimentary basins through changes in the optical properties of the organic material. Through paleo-temperature evaluation and thermal alteration, the metamorphism and overburden of the sedimentary succession can be evaluated. Important information for basin evolution and tectonics can be gained through the investigation of the thermal history as shown by the example of the central Andean Basin in Argentina (see HERRERA SÁNCHEZ & others, 2021). The color change of the graptolite tubaria through a temperature gradient is easy to recognize, from dark brown to black (unchanged) to a silvery hue (highly mature) resulting from deep burial or contact and regional metamorphism of the sediments (MALETZ, 2020). With increasing grade or depth, the original organic material of the graptolite disappears completely.

Schovsbo, Nielsen, and Gautier (2014) explored the potential of the Scandinavian Alum Shale Formation as an unconventional gas play in Denmark and provided a geological model that underlies this assessment. They showed the prospective areas for gas in the Norwegian-Danish Basin. The research is complimented by a discussion by Kosakowski and others (2017) of the Alum Shale Formation in the Baltic Basin and the Podlasie Depression as important petroleum source rocks.

Hydrocarbon exploration has also been the driving force behind the investigation of Silurian Hot Shales in northern Africa and Arabia in recent years (Lüning & others, 2000, 2005; Loydell, Butcher, & Al-Juboury, 2013; Loydell, Butcher, & Frýda, 2013). In these regions, early Silurian (Rhuddanian) successions have been identified as important hydrocarbon source rocks. They represent 80–90% of the Paleozoic hydrocarbons in Arabia and North Africa.

Discontinuous basins filled with organic-rich shales developed on the northern rim of Gondwana, where their thickness was controlled by an early Silurian paleorelief related to the Late Ordovician glaciation event. Extensional and compressional regional tectonics also influenced the distribution of these graptolitic shales. Detailed biostratigraphical correlation of the successions is important for understanding the source potential of these deposits for economic exploration in the regions (Lüning & others, 2000, 2005).

The most important recent development in the exploration for oil and gas comes from the South China Platform. The investigation has concentrated on the Longmaxi Formation (latest Ordovician to basal Silurian) in the Sichuan Basin, and also outside this region on the Yangtze Platform. Numerous gas and oil fields have been developed (Hu, He, & Chen, 2012; Chen, Lu, & Ding, 2014; Chen & others, 2014; Guo & others, 2014; Jiang & others, 2015; Shan & others, 2015; Tang & others, 2015; Zou & others, 2015; Ma, 2017; Sun & others, 2020).

BIO-SEQUENCE STRATIGRAPHY

Evolutionary studies on graptolites have often included origination and extinction events and their effects on the diversity of the faunas (see Chapter 10), but the connection with sedimentological research has usually been neglected even though it is urgently needed (see Holland & Allen, 2008). It is well known that graptolites are preserved more commonly and much better in certain sediment types, especially in black, anoxic shales (Maletz, 2020). This knowledge clearly indicates the need for closely connected sedimentological and paleontological research. Sedimentological research can indicate the effects of sea-level changes in fossiliferous successions, and the faunas provide a deeper insight into the amount of paleontological change and also allow an interpretation of the reasons behind this change. The effect of sea-level changes on the preservation of graptolite faunas, and especially their effect on the preservation of shallow-water and deep-water faunal elements in the successions, can help us understand graptolite distribution through time. Egenhoff and Maletz (2007) investigated the use of graptolites as indicators for maximum flooding surfaces in monotonous deep-water shelf successions in the Diabasbrottet section in Västergötland, Sweden. The authors noted the migration of shallow-water endemics and pandemics landward and the increasing frequency of deep-water pandemics in the succession. At the peak of the transgression, the deep-water pandemics dominated the faunas but were in turn replaced by endemic faunas when the sea level fell. Egenhoff and Maletz (2007) thus recognized four levels of deep-water faunas as maximum flooding surfaces in the Diabasbrottet section, combining a sequence stratigraphic approach with graptolite biostratigraphy and diversity studies.

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