2017

VOL. 319

Professional Papers
of the Geological Survey of Belgium

Geological Survey of Belgium

SCIENTIFIC REPORTS SERIES

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Series Editor in Chief: Xavier Devleeschouwer (Geological Survey of Belgium, RBINS)

Manuscript received 04.01.2017, accepted in revised form 15.09.2017, available online 15.12.2017

Revision and layout: Charlotte Gérard (RBINS)

Cover illustration: The Strassen Member on the top of the Florenville Member in the Tontelange quarry (Sinemurian) © Frédéric Boulvain

Printed by Peeters (Belgium)

Legal Deposit: D/2017/0339/4

ISSN: 0378-0902

29 Vautierstreet, 1000 Brussels | www.naturalsciences.be

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NEW SEDIMENTOLOGICAL DATA FROM TRIASSIC TO JURASSIC BOREHOLES (BONNERT, HAEBICHT, GROUFT, GRUND, CONSDORF) AND SECTIONS (TONTELANGE, DIFFERDANGE, RUMELANGE) FROM SOUTHERN BELGIUM AND LUXEMBOURG

by Frédéric BOULVAIN[1], Isabelle BELANGER[2], Robert COLBACH[3], Sylvain DECHAMPS[1], Dominique DELSATE[4], David DELIGNY[1], Pierre GHYSEL[2], Jonathan MICHEL[1,5], Simon PHILIPPO[4] & Benjamin RAMLOT[1]

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Abstract

This study offers a detailed description of a series of Triassic to Jurassic representative boreholes (Bonnert, Haebicht, Grouft, Grund, Consdorf) and sections (Tontelange, Differdange, Rumelange) from southern Belgium and the Grand-Duchy of Luxembourg. Investigations provide information about microfacies, paleoenvironments and magnetic susceptibility (MS). Three sets of microfacies, corresponding to three different sedimentary systems were needed in order to address the complexity of the paleoenvironments: a transgressive mixed siliciclastic-carbonate ramp system for the Triassic to Lower Jurassic (Toarcian) interval (microfacies TT1-8), and, for the Middle Jurassic, an early transgressive low productivity mixed ramp system for the Aalenian (microfacies A1-2) and a transgressive carbonate ramp for the Lower Bajocian (microfacies B1-3). A comparison of the MS and microfacies curves shows a clear correlation between the two, suggesting that the MS signal is primary. Moreover, the MS values regularly decrease from the marine distal (TT1) to the marine proximal microfacies (TT5), with relatively weak mean MS values for sandstones and limestones, and high mean MS values for marls, argillites and ironstone. This relationship is interpreted as the consequence of local water agitation in the shallower parts of a ramp, preventing the detrital particles from settling down and to the higher sedimentation rate that dilutes the magnetic and/or paramagnetic minerals.

Keywords: Microfacies, magnetic susceptibility, paleogeography, Triassic, Jurassic, Belgium, Luxembourg.

1. Introduction

This work follows up previous professional papers dedicated to major boreholes in Belgian Lorraine, the Latour borehole (Boulvain & Monteyne 1993, revised by Boulvain *et al.* 1995), the Neulimont, Aubange, Saint-Mard and Toernich boreholes (Boulvain *et al.* 1995), and the Villers-devant-Orval borehole (Boulvain *et al.* 1996). These studies, together with data resulting from the ongoing geological mapping project for Wallonia (Belanger *et al.* 2002; Ghysel *et al.* 2002; Belanger 2006a-b; Ghysel & Belanger 2006), led to a synthesis formalized by a new lithostratigraphical scheme for Belgian Lorraine (Boulvain *et al.* 2001a-b). Besides stratigraphical data, the borehole survey provided results for petrography, clay mineralogy, palynology and paleontology (Boulvain *et al.* 2001a).

The purpose of the current work is to present new data from a series of boreholes (Bonnert, Haebicht, Grouft, Grund, Consdorf) and sections (Tontelange, Differdange, Rumelange) representative of the Triassic to Jurassic of southern Belgium and Grand-Duchy of Luxembourg (fig. 1). Data include lithology, petrography, microfacies, paleoenvironments and magnetic susceptibility (MS). Two types of graphics are used: a detailed bed-by-bed description of lithology, fossils, sedimentary structures and sample position (scale 1/20 or 1/50), and a synthesis log (scale 1/400) for lithostratigraphy, chronostratigraphy, petrography, lithofacies,

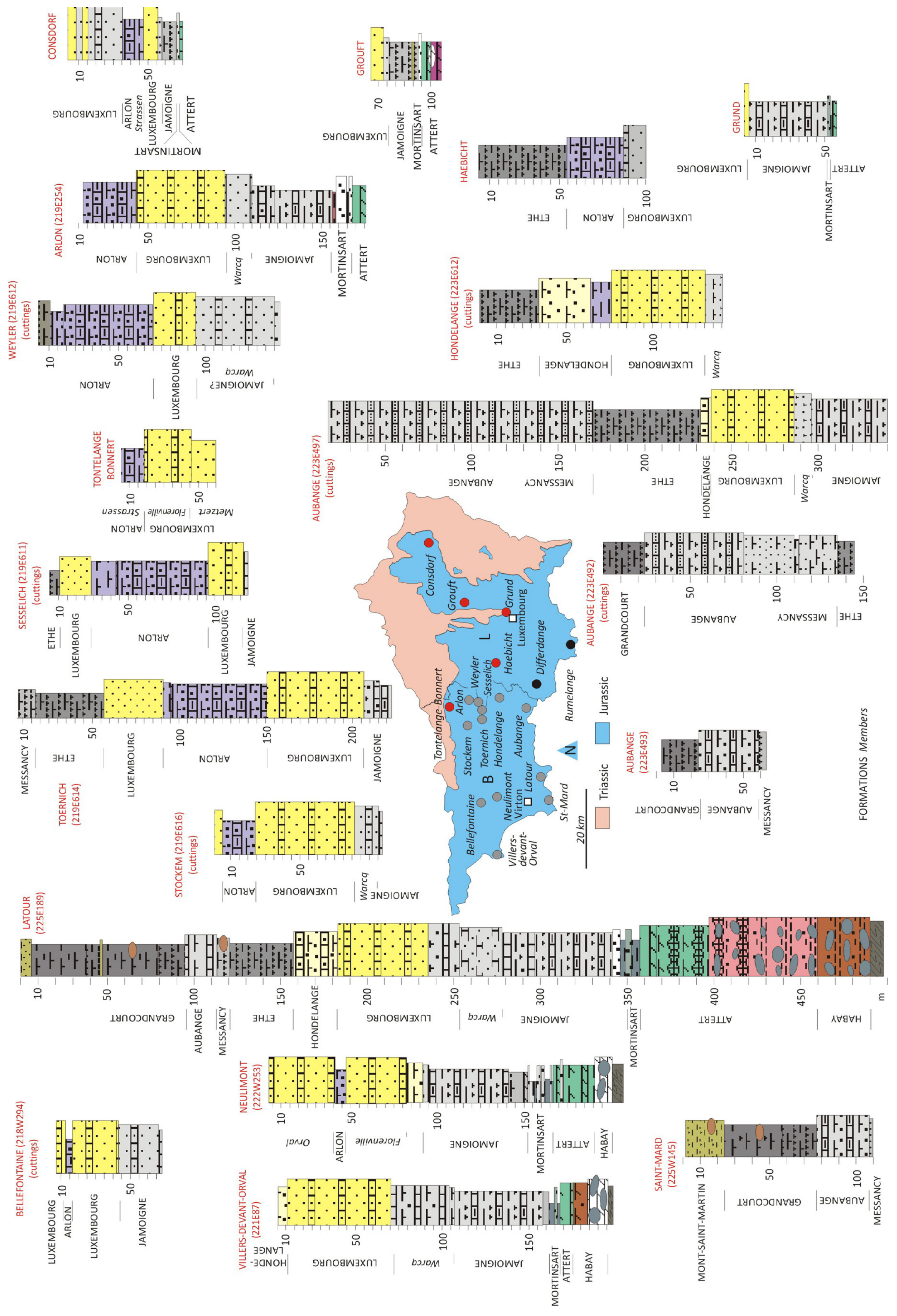

Figure 1. Location and schematic logs of selected boreholes from Belgian Lorraine and Guttland. Map: pink, Triassic; blue, Jurassic. Grey dots refer to published boreholes, red dots to the present work and black dots to sections. B = Belgium, L = Grand-Duchy of Luxembourg.

MS, and well logs when present. An integrated sedimentological model is also proposed herein based on these data.

2. Geological setting

The studied Triassic to Jurassic successions are confined to the south-eastern part of Belgium, *i.e.*, the Belgian Lorraine and to the Guttland region of Grand-Duchy of Luxembourg. The region is characterized by typical cuesta morphology due to the alternation of soft and hard sediments and a shallow dip to the South (Lucius 1952; Maubeuge 1954).

The oldest formation covering the Ardenne-Eisleck peneplaned basement corresponds to an alluvial system (clay and gravels of the Habay Formation in Belgium, red sandstones and gravels from the Buntsandstein in Grand-Duchy of Luxembourg) (fig. 2). The Triassic marine transgression progressed from SE to NW and most formations are diachronic. The first marine influence is recorded by the Muschelkalk Group in Grand-Duchy of Luxembourg, with dolostones, evaporite-bearing marls and encrinites. In Belgium, the first marine unit is the Attert Formation with clays and dolomitic marls including evaporitic pseudomorphs. This Triassic marine transgression comes to an end with the deposition of littoral sandstones and marls of the Mortinsart Formation which is topped by alluvial clay (Argile de Levallois).

The development of a shallow epicontinental sea covering the Paris basin (Purser 1975; Ziegler 1990) was initiated during the Early Jurassic through the transgressive pulse of the Ligurian major sedimentary cycle (de Graciansky *et al.* 1998). The globally warm climate (*e.g.*, Mouterde *et al.* 1980; Hallam 1985; Dera *et al.* 2011), among other factors, allowed the carbonate factory to start (Pomar & Hallock 2008). In the north-eastern part of the basin, carbonate sedimentation is associated with abundant influxes of siliciclastic sediments (Waterlot *et al.* 1973; Mouterde *et al.* 1980).

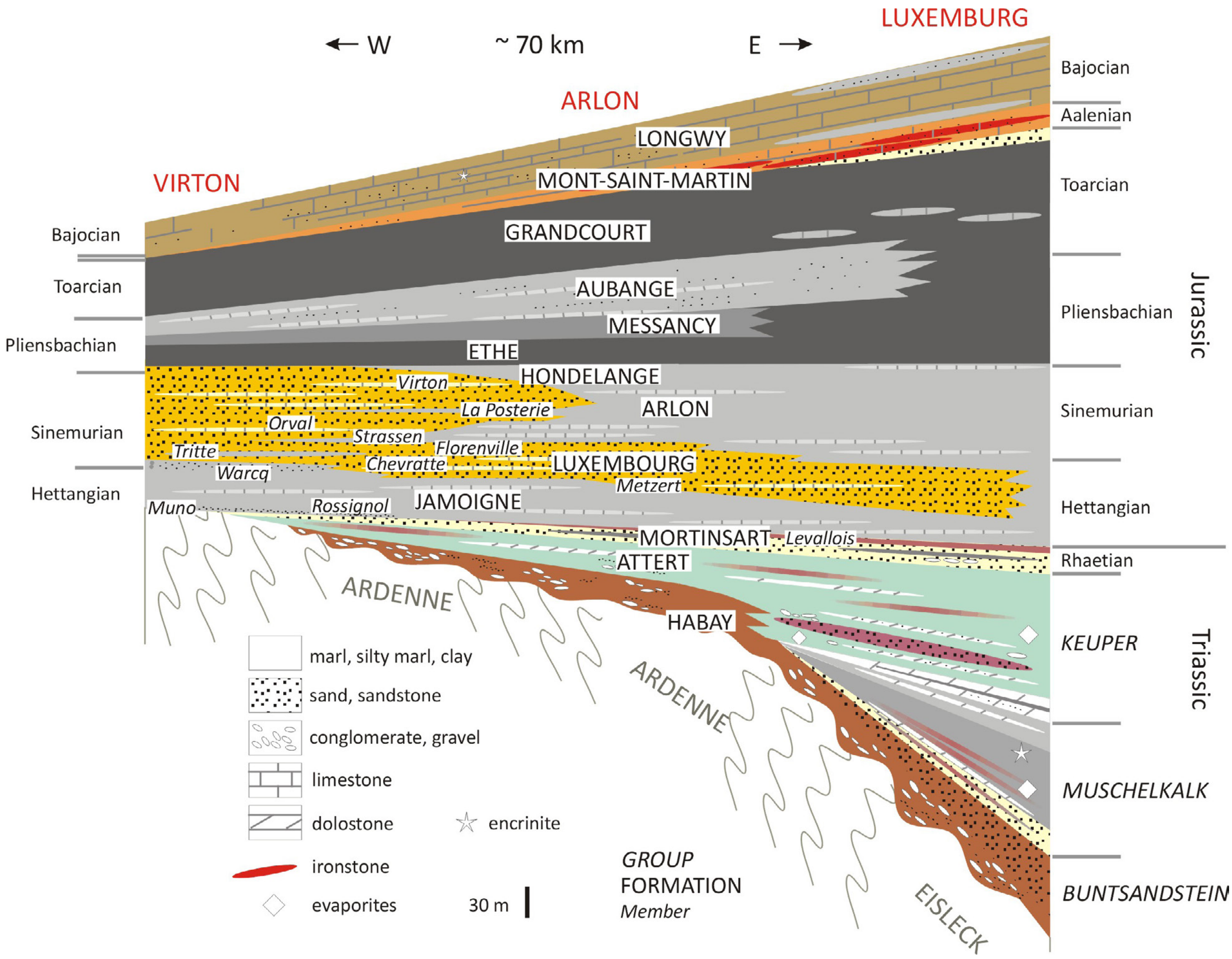

Figure 2. Schematic lithostratigraphic canvas of the Belgian Lorraine and Guttland.

The Hettangian Jamoigne Formation (Grand-Duchy of Luxembourg: Elvange Formation) shows a typical Lorraine facies with alternating marls and fossil-rich bioturbated argillaceous limestones. Above this unit, the Luxembourg Sandstone is a Hettangian and Sinemurian formation deposited in the Belgian Lorraine, in southern Luxembourg, north-eastern France, and westernmost Germany (Steininger 1828; Dumont 1842; Dewalque 1854). The sandy material was supplied from the German basin to the Paris basin across the Eifel depression (Muller *et al.* 1973), and deposited as subtidal sandbars in a vast deltaic system (Mertens *et al.* 1983; Berners 1983). The lenticular sandy facies shifted gradually from the centre of Luxembourg towards the NW, onto the Ardenne Massif. The diachronous pattern from East to West has been precisely determined using biostratigraphical data (Maubeuge 1965; Guérin-Franiatte & Muller 1986; Guérin-Franiatte *et al.* 1991).

In the central part of the Belgian Lorraine, interdigitations of the marly Lorraine facies (Arlon Formation) with the Luxembourg Sandstone define respectively the Tritte, Strassen, La Posterie marly units and the Metzert, Chevratte, Florenville, Orval, and Virton sandy units (Boulvain *et al.* 2001b) (fig. 2). The Pliensbachian Hondelange Formation is a mixed facies with marls and bioturbated calcareous sandstone.

Later Pliensbachian and Toarcian formations correspond to fine-grained dark argillaceous and marly units (Ethe, Messancy and Grandcourt formations) alternating with a mixed marly-sandstone unit (Aubange Formation). These units are locally rich in organic matter, indicating quiet sedimentation conditions on an anoxic sea floor. In Grand-Duchy of Luxembourg, the top of the Toarcian is sandy with ironstone beds (the well-known "Minette" iron ore), which when fully developed is of Aalenian age (Faber *et al.* 1999; Bintz & Storoni 2009). In Belgium, the contemporaneous beds were largely eroded during a significant emersion. The youngest Jurassic strata belongs to the Bajocian in both countries. This stage is characterized by the development of a carbonate platform: in Grand-Duchy of Luxembourg, the Audun-le-Tiche Limestone includes spectacular 20 x 200 m sized coral reefs.

3. Methods

Petrographic samples for thin sections (500, for the present study) were selected from all facies, even unconsolidated. In that case, samples were indurated with Geofix® resin. All the thin sections are preserved at the Sedimentary Petrology Laboratory in Liège. The MS measurements were made using a KLY-3 Kappabridge device (see Da Silva & Boulvain 2006). Three measurements were made on each sample weighed with a precision of 0.01 g. Sampling interval varies but is less than 1 m; 2360 samples were analyzed.

4. Boreholes and sections

4.1. The Bonnert borehole and Tontelange section

The Côte Rouge or Tontelange quarry is located 3.5 km north of Arlon, along the N4 road, at the base of the Lower Jurassic cuesta (Dewalque 1854). Once used as a sandpit, the front-slope of the cuesta is currently exploited for the carbonate sandstones and sands.

Since the end of the 19th century, the Sinemurian cuesta running north of Arlon has proved to be invaluable for the study of the Belgian Lower Jurassic. The Côte Rouge quarry provided the first description of the Metzert Member (Dormal 1894), abundant palaeontological material for the biostratigraphy of the Luxembourg Formation (Joly 1936; Maubeuge 1989), and an extended section improving the stratigraphic framework of Belgian Lower Jurassic (Maillieux 1948; Monteyne 1959; Mergen 1983; 1984).

The cleared cliff-side provides a unique section through the Metzert and Florenville members of the Luxembourg Formation and the Strassen Member of the Arlon Formation. Accordingly, this quarry has been selected as the stratotype of the Luxembourg Formation in Belgium (Boulvain *et al.* 2001b).

A borehole was drilled south of the Tontelange quarry, at 205 m from the crossroad between the N4 road and the Metzert street (Lambert 72: X = 253.375; Y = 45.825; WGS84: 5.8022 E; 49.7151 N). The drill core has a 9 cm diameter and is complete down to 44 m (figs 3A-B). Due to the lack of cementation in the Metzert Member, no continuous core was recovered deeper than 44 m. The borehole has then been completed with a section described in the Tontelange quarry (figs 3B-C). This section is 15 m thick and covers the upper part of the Metzert Member. The ages and biostratigraphic zonations follow Gradstein *et al.* (2004). Biozonations calibrations are inferred from Mergen (1983).

The two sections were precisely described bed-by-bed (fig. 3). Samples were collected on a regular base, for a total of 55 thin sections and 193 MS measurements. The synthesis log further provides an estimation of quartz grain size (cf. fig. 13).

4.2. The Haebicht BK-4A borehole

In the context of the search for a disposal site for industrial waste, a series of 5 drill holes was made in 1993 close to the highway service area of Capellen. The boreholes intersected the Hettangian-Pliensbachian beds over more than 100 m. The 10 cm diameter BK-4A drill cores (LuRef: X = 65752; Y = 77476; WGS84: 5.9709 E; 49.6317 N), are held at the Musée national d'Histoire naturelle du Luxembourg and were selected for the present work for which 101 thin sections and 394 MS measurements were performed (fig. 4). MS is supplemented by resistivity and X-ray data compiled from downhole well logs (cf. fig. 14). A former study of the same cores, focused on ammonites and a biostratigraphy is proposed by Guérin-Franiatte (2003).

4.3. The Grouft FR-204-032 borehole

The Grouft borehole (LuRef: X = 79452; Y = 84733; WGS84: 6.1605 E; 49.6971 N), located 7 km SE of Mersch, close to Lorentzweiler, is a piezometer installed during the construction of the Grouft Tunnel. This tunnel, with a length of nearly 3 km, is one of the major civil engineering works of the "Route du Nord" highway (A7), leading from Luxembourg City to the North of the country. Its purpose was to monitor the groundwater levels in the aquifers crossed by the tunnel. The 8.5 cm diameter core samples are stored at the Geological Survey of Luxembourg and range from the Middle Keuper to the Lower Sinemurian. It should be noted that cores were only obtained from 70-106 m depth (fig. 5). A total of 63 thin sections and 43 MS measurements were made. The synthesis log (cf. fig. 10) further provides an estimation of quartz grain size and sorting.

4.4. The Grund borehole

This 55 m deep borehole was drilled in 1994 on the yard of the former prison for women in Luxembourg City (LuRef X = 77640; Y = 75014; WGS84: 6.1355 E; 49.6097 N). The cores, of 8 cm diameter, range from the Triassic (Keuper) to the Upper Hettangian; 105 MS measurements and 52 thin sections were made from the cores. Well log data were acquired and included in this work (figs 6, 11).

4.5. The Consdorf FR-204-201 borehole

The Consdorf borehole (LuRef X = 94430; Y = 92835; WGS84: 6.3684 E; 49.7698 N) is one of several piezometer installations that were made during a hydrogeological survey related to the building of a waste dumpsite at Rosswinkel, SW of the Consdorf locality. The possible incidence of construction waste deposits on the underlying sandstone aquifer were investigated. The cores have a diameter of 10 cm and range from the Upper Keuper to the Lower Sinemurian and are preserved at the Geological Survey of Luxembourg; 115 MS measurements and 115 thin sections were made from the cores. Logs are complemented by petrographic data (sorting and quartz grain size) (figs 7, 12).

4.6. The Giele Botter quarry section

This section (Aalenian-Bajocian) is located in a protected area close to Niederkorn: the 255 ha Prënzebierg-Giele Botter nature reserve (LuRef: X = 59080; Y = 67880; WGS84: 5.879 E; 49.545 N), mainly dedicated to the "Minette" oolitic ironstone that made the wealth of the Luxembourg and French steel industries. In Grand-Duchy of Luxembourg, the Minette ironstone was deposited during the Late Toarcian-Early Aalenian in two basins: Esch-Ottange and Differdange-Longwy. The Differdange-Longwy iron ore is slightly older than the Esch-Ottange ore (Thein 1975; Achilles & Schulz 1980). Theyssen (1984), who made a detailed study of this famous section, proposed a model of subtidal sandwaves for the deposition of the oolitic ironstone. The present work is based on 62 thin sections and 186 MS measurements for section that is 41 m thick (fig. 8). The synthesis log is complemented with petrographic data (quartz grain size and sorting, clay content) (cf. fig. 15).

4.7. The Rumelange quarry section

The Rumelange section is 43 m thick, and surveyed in the Cimalux quarry close to Ottange (LuRef: X = 67350; Y = 57360; WGS84: 5.994 E; 49.451 N). The quarry works Bajocian limestone beds interbedded with marls for cement production. A bed-by-bed sampling led to the collection of 118 samples used for MS measurements, 54 of which were used for thin sections (figs 9, 16).

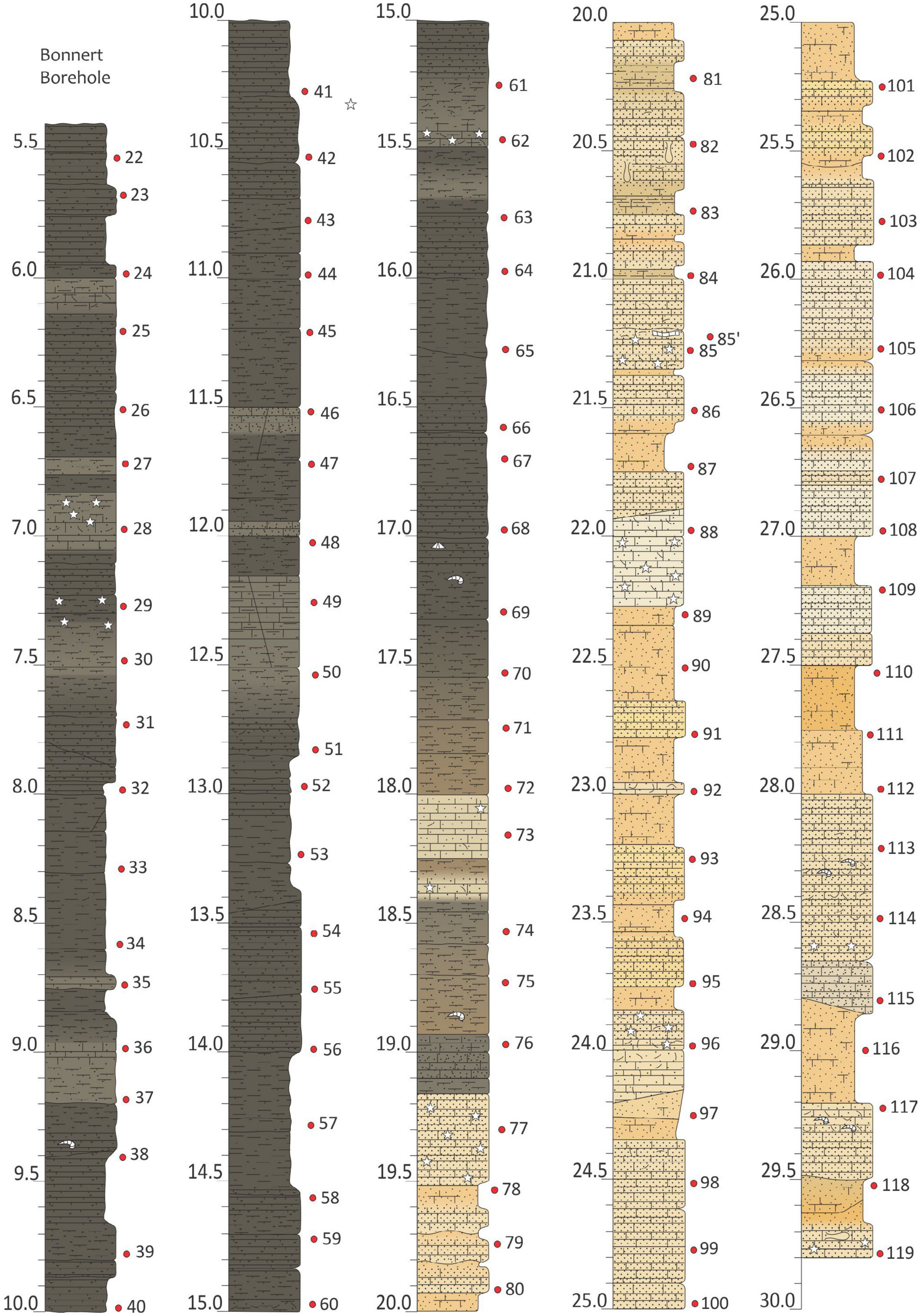

Figure 3A. The Bonnert borehole. Legend of symbols, cf. fig. 5.

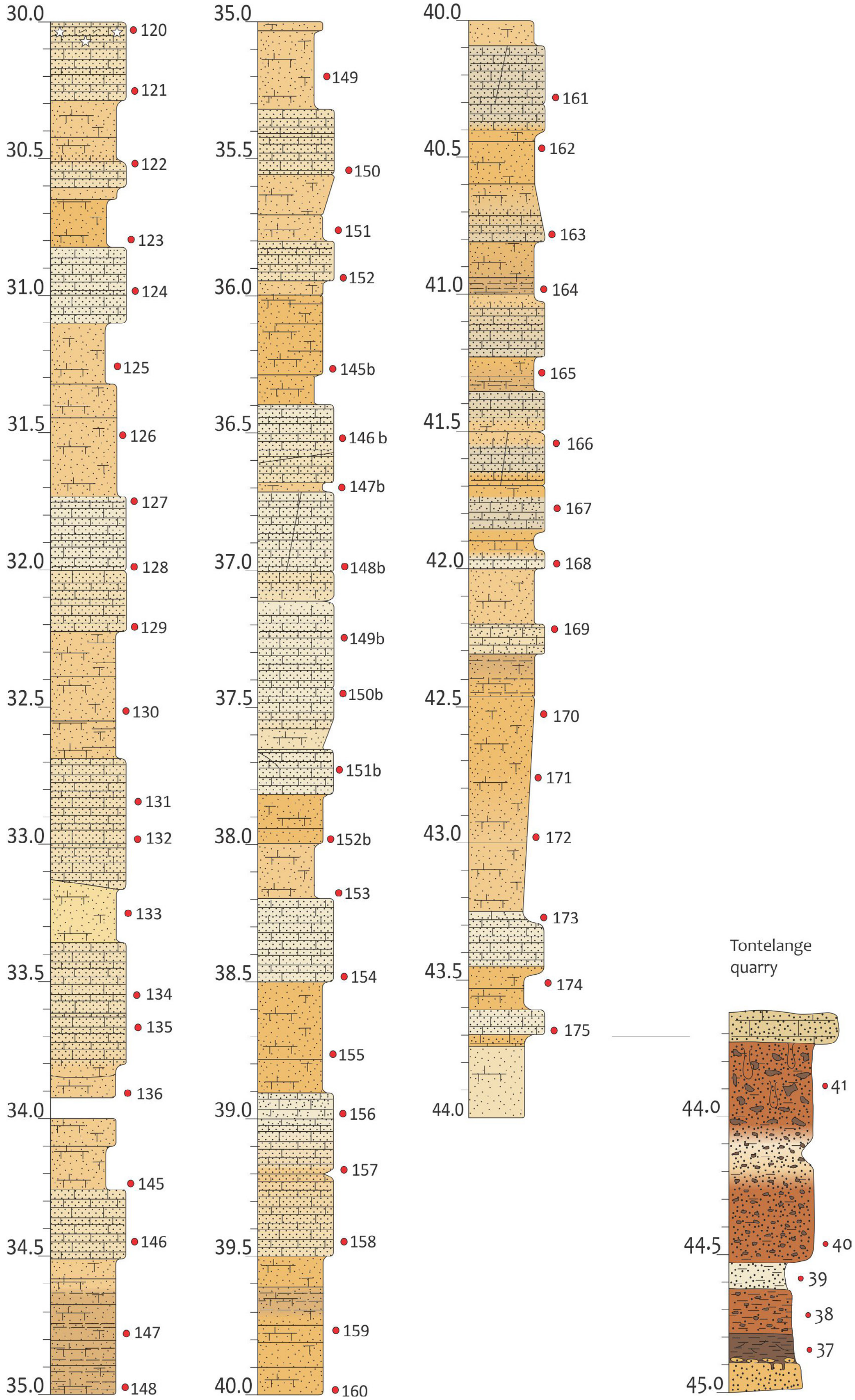

Figure 3B. The Bonnert borehole and Tontelange quarry section.

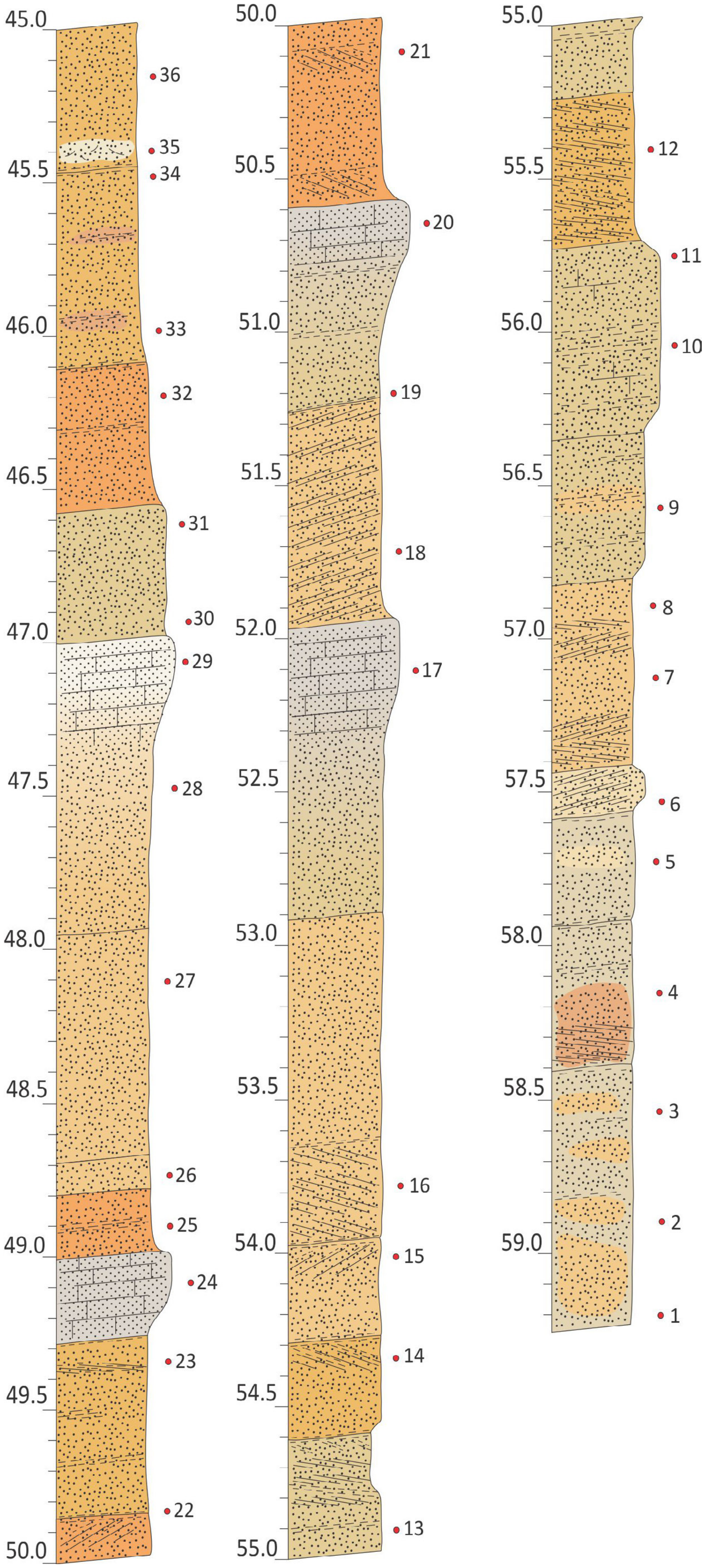

Figure 3C. The Tontelange quarry section.

Figure 4A. The Haebicht borehole.

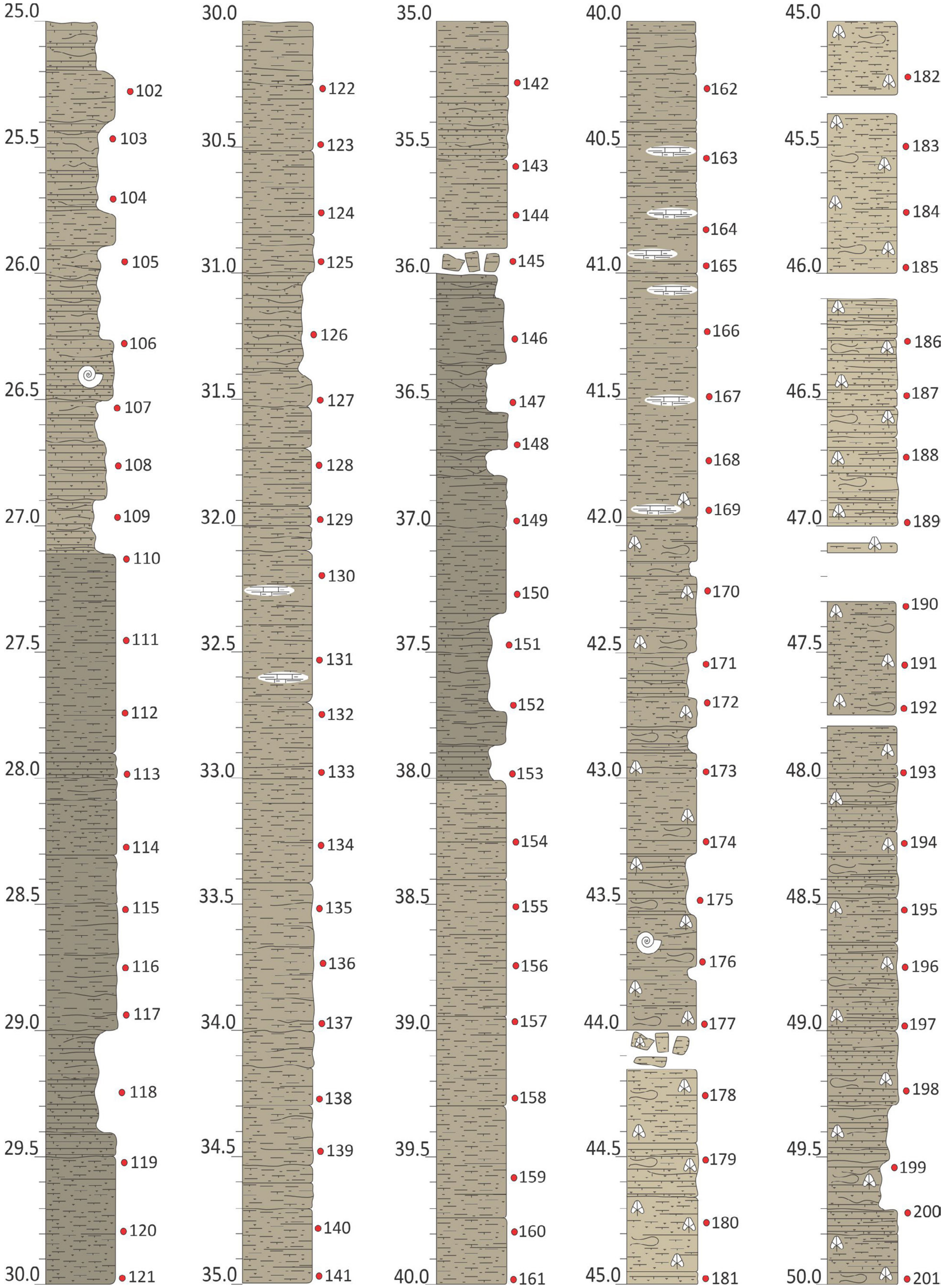

Figure 4B. The Haebicht borehole.

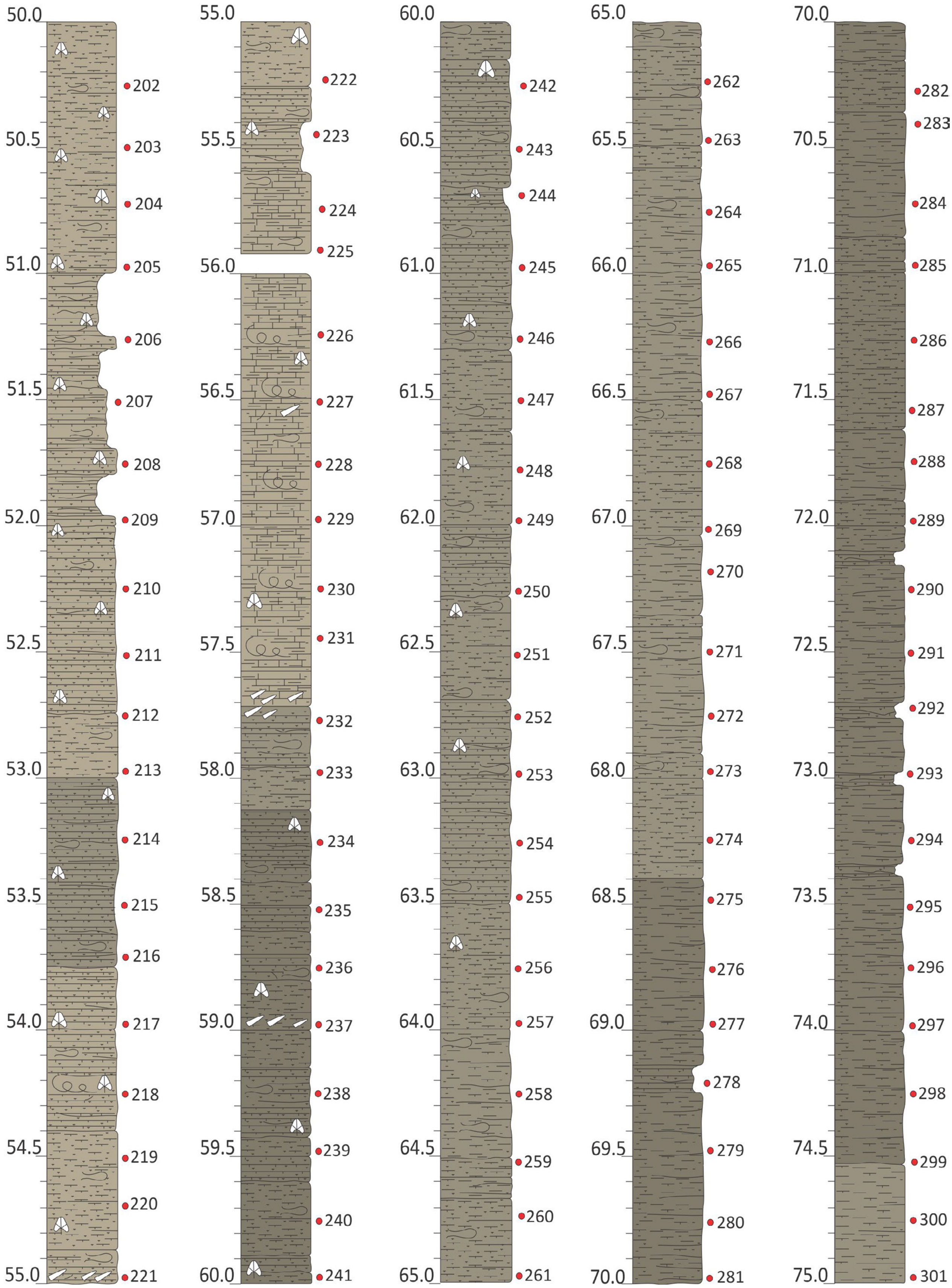

Figure 4C. The Haebicht borehole.

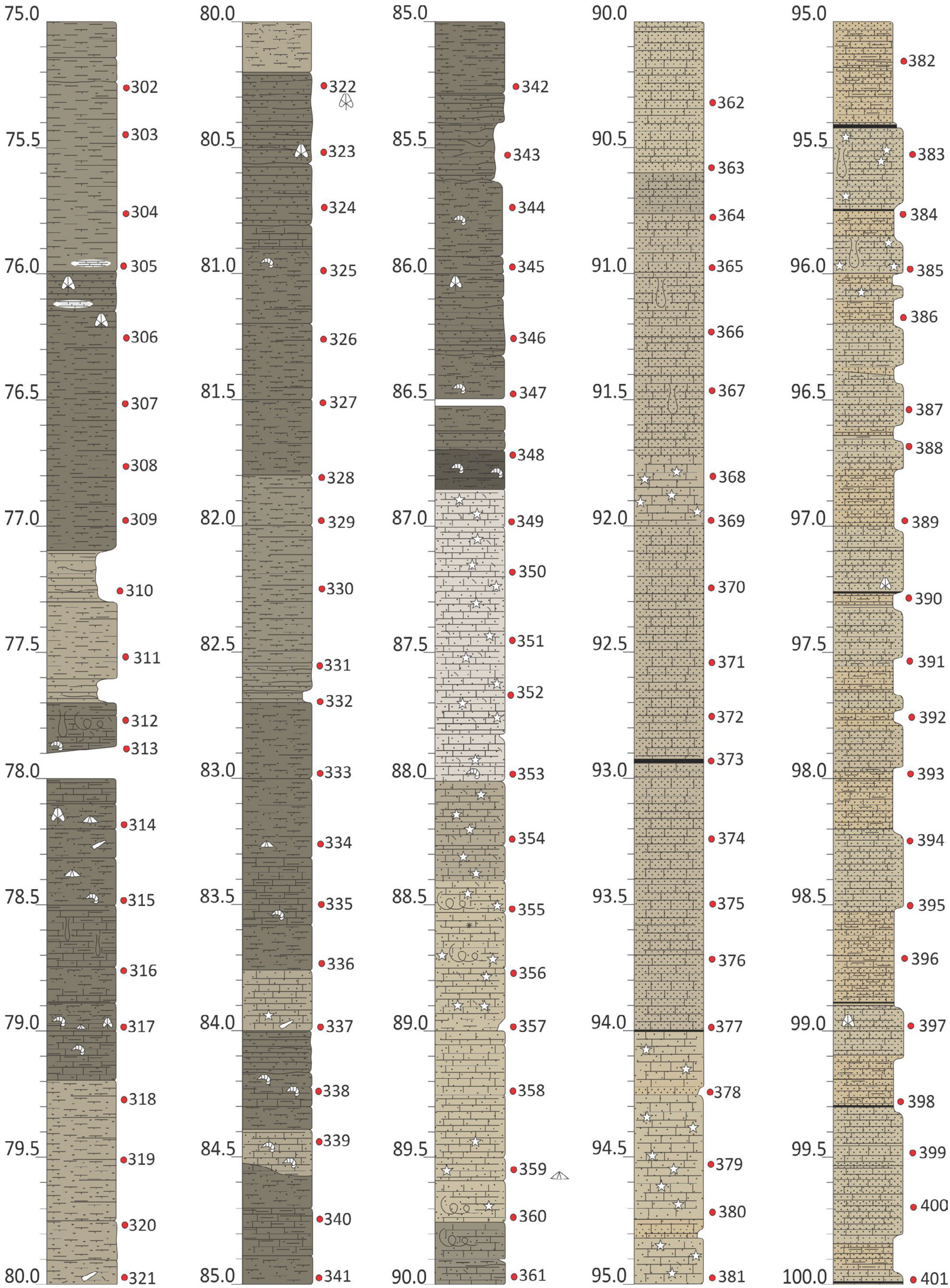

Figure 4D. The Haebicht borehole.

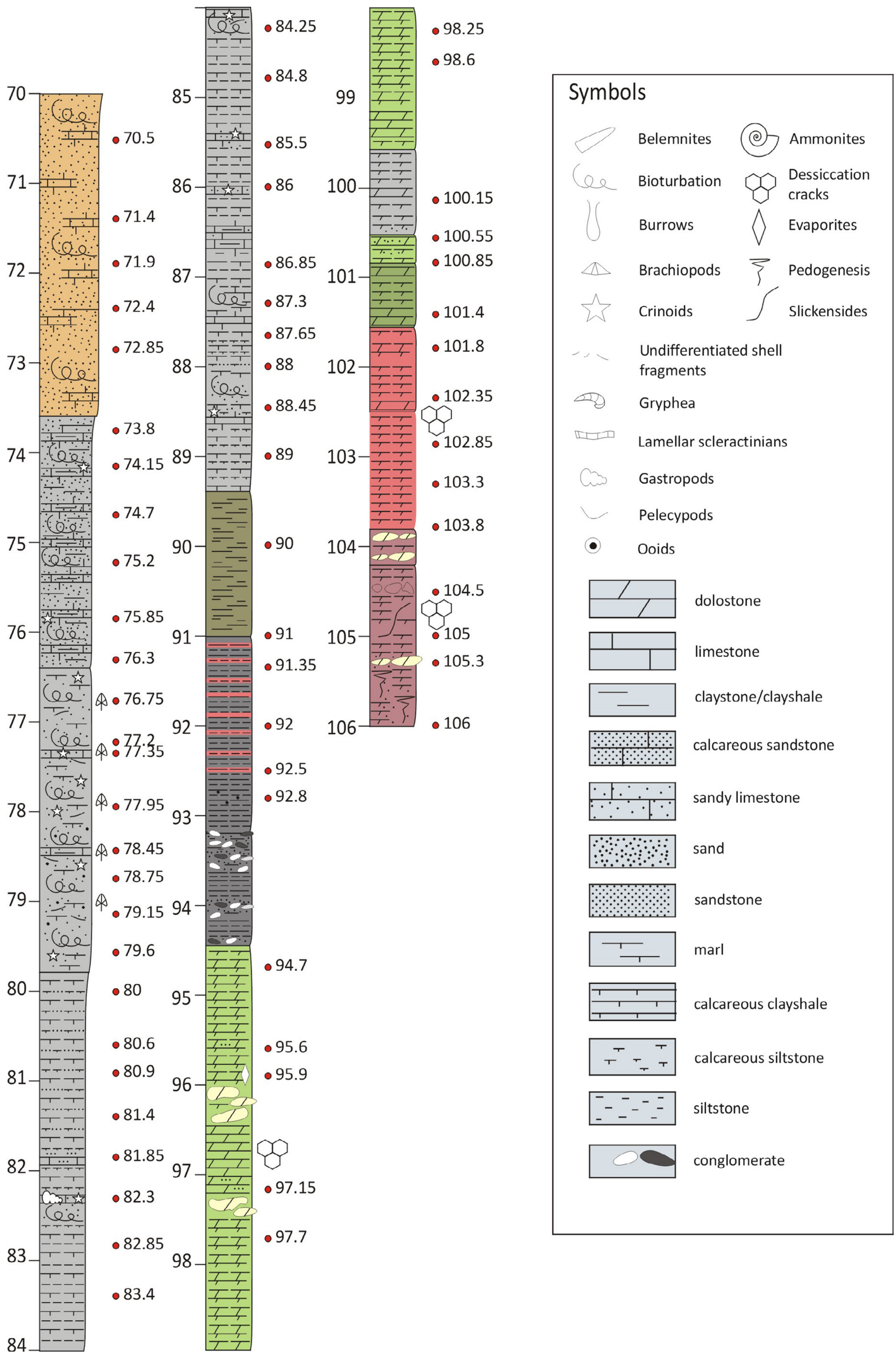

Figure 5. The Grouft borehole. Legend of symbols.

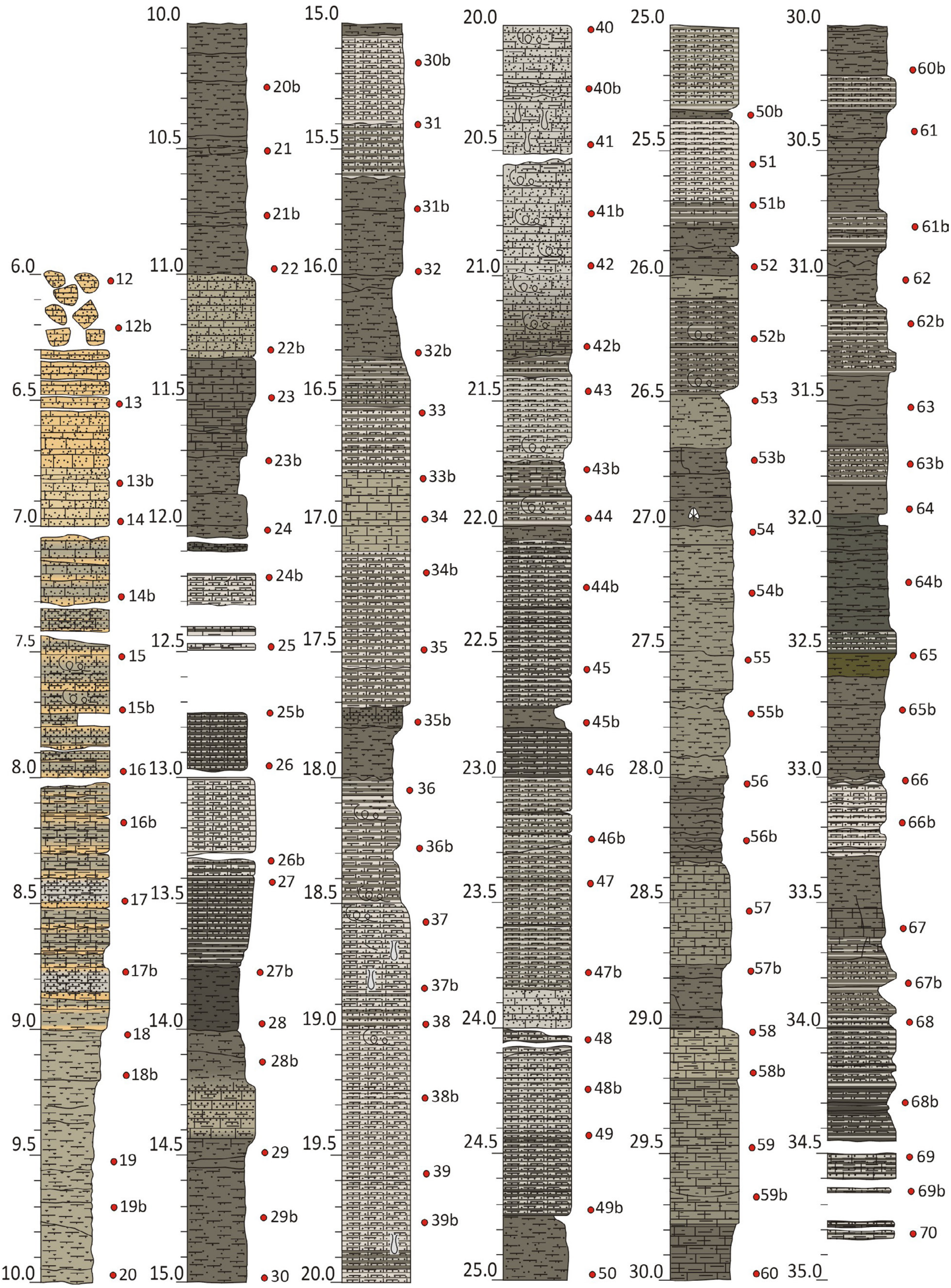

Figure 6A. The Grund borehole.

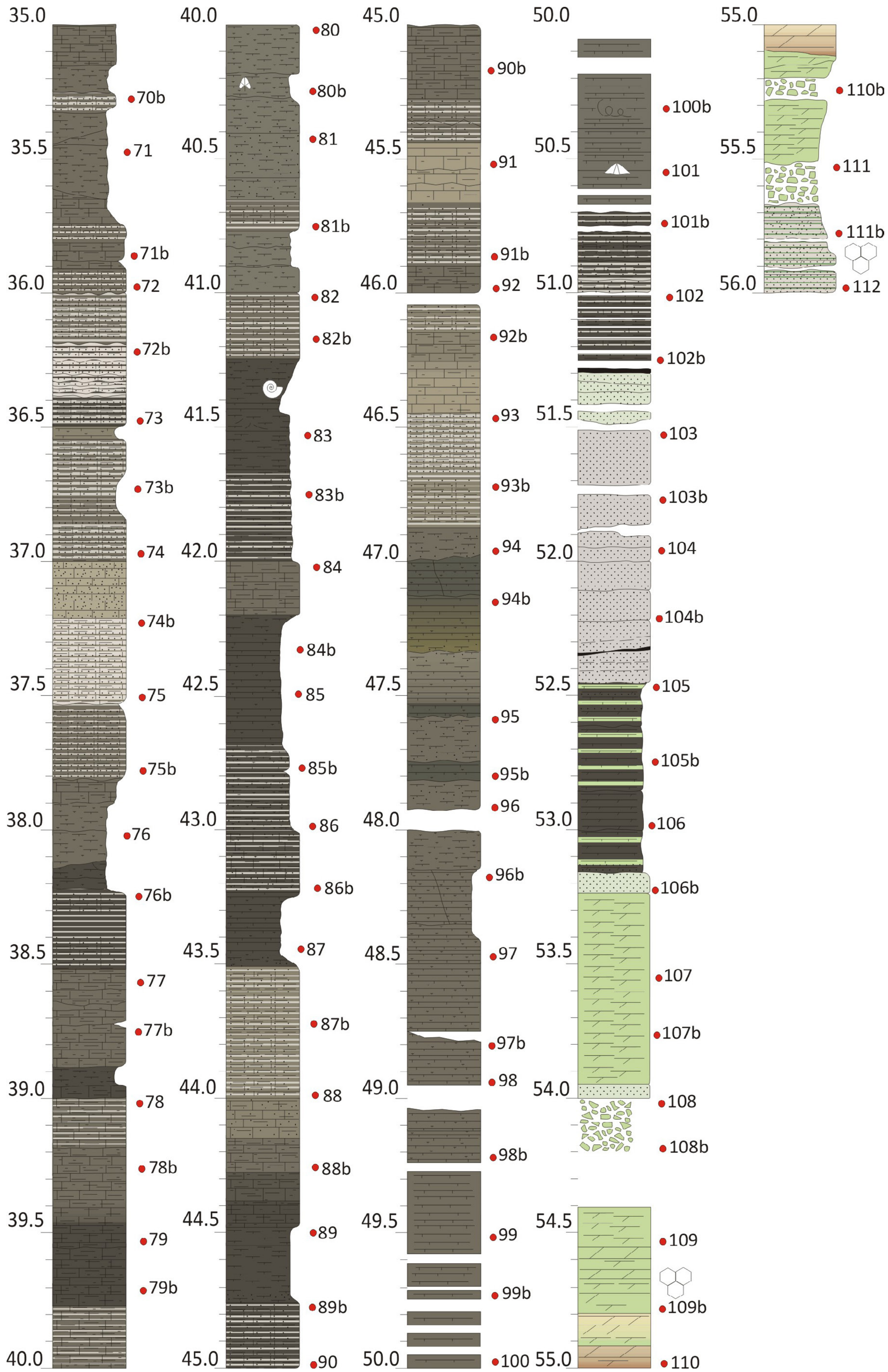

Figure 6B. The Grund borehole.

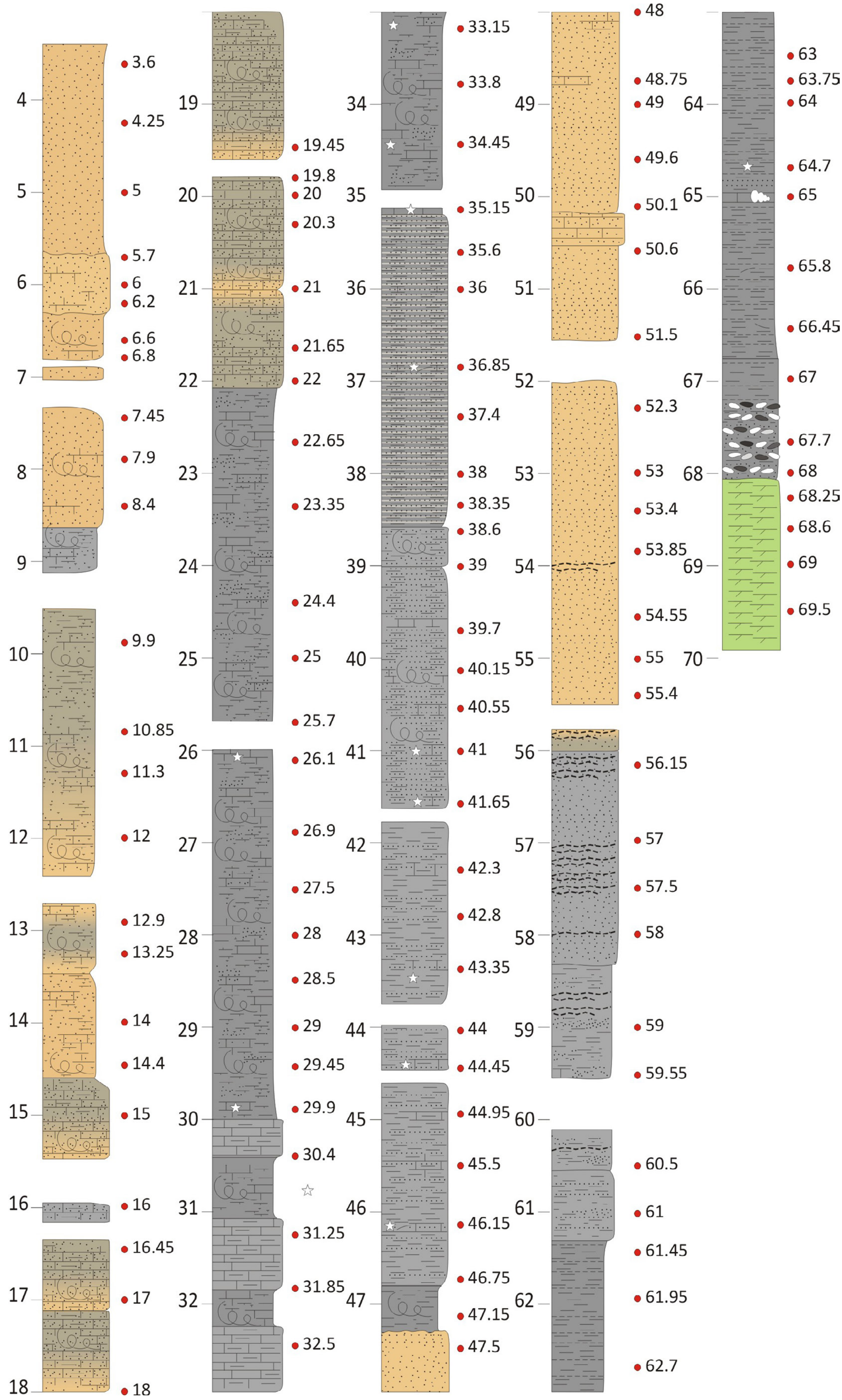

Figure 7. The Consdorf borehole.

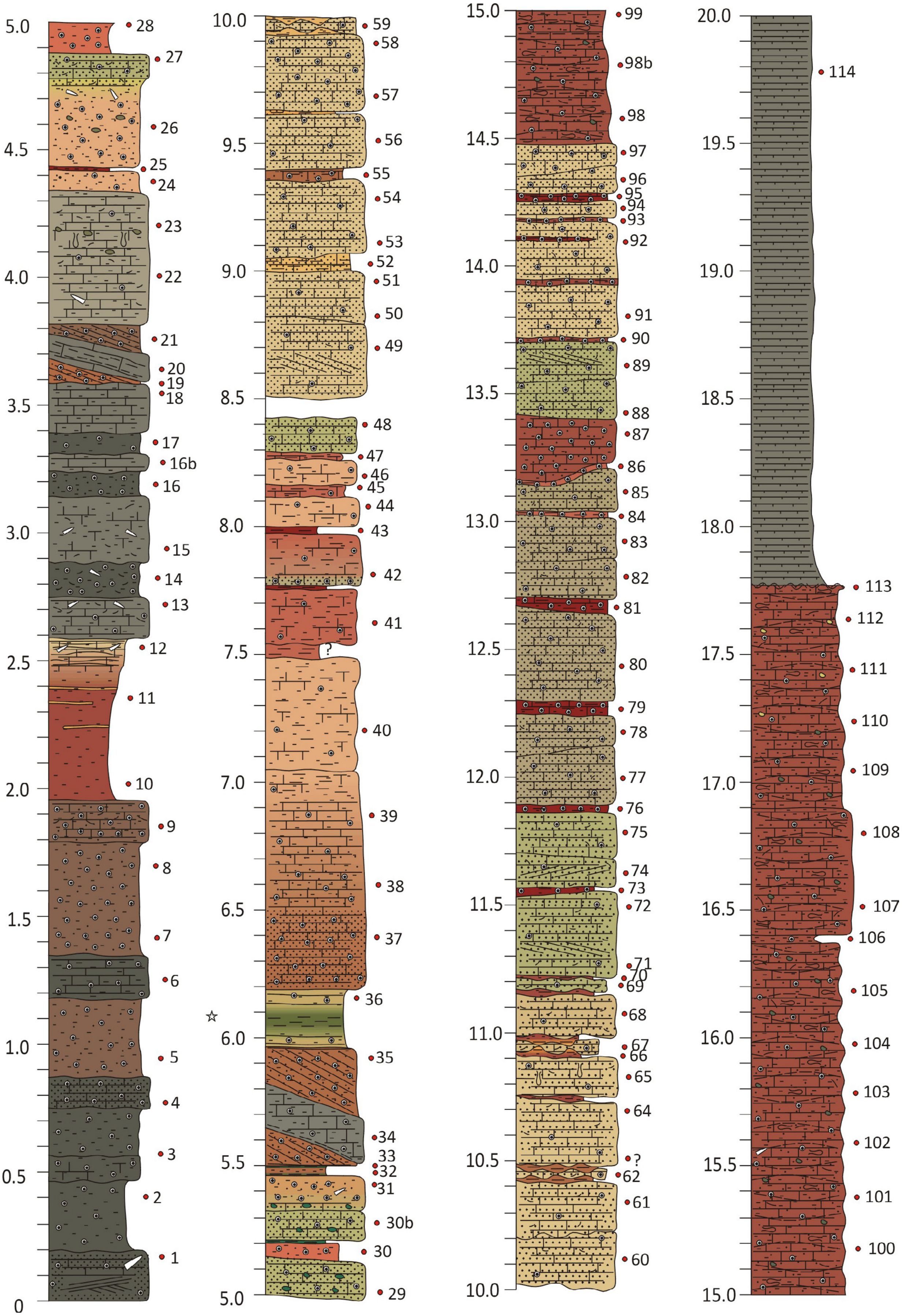

Figure 8A. The Differdange "Giele Botter" section.

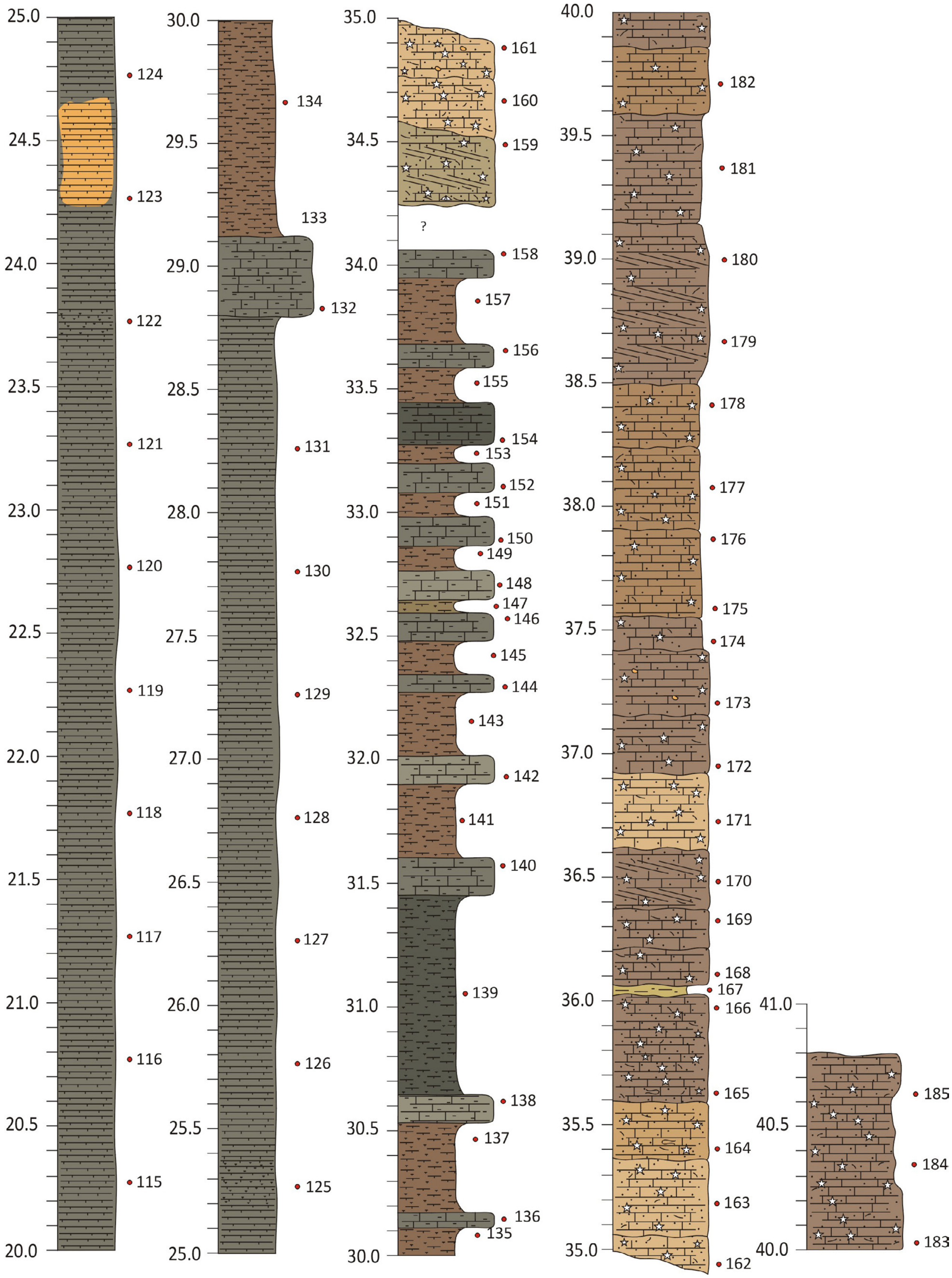

Figure 8B. The Differdange "Giele Botter" section.

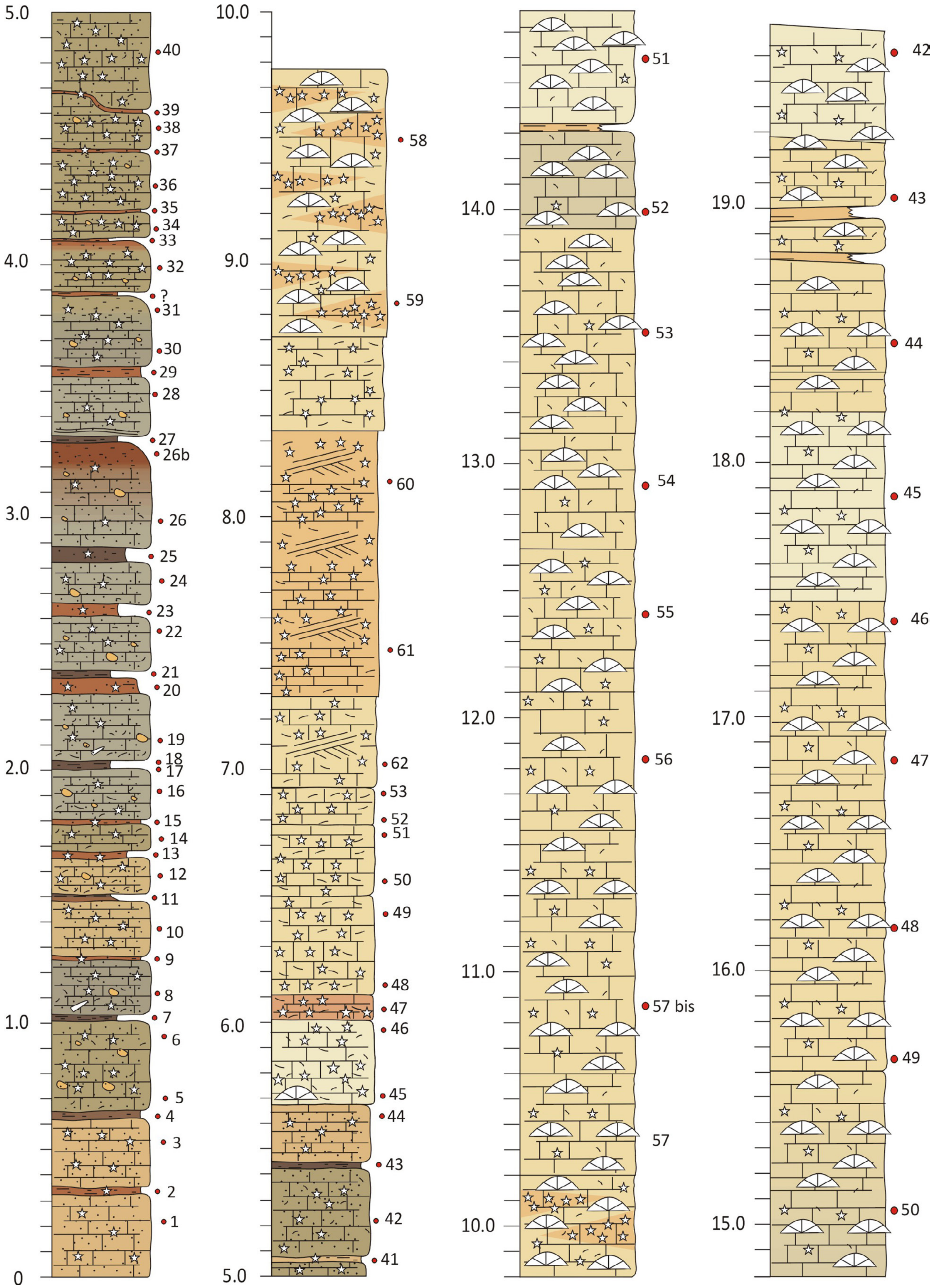

Figure 9A. The Rumelange Cimalux quarry section.

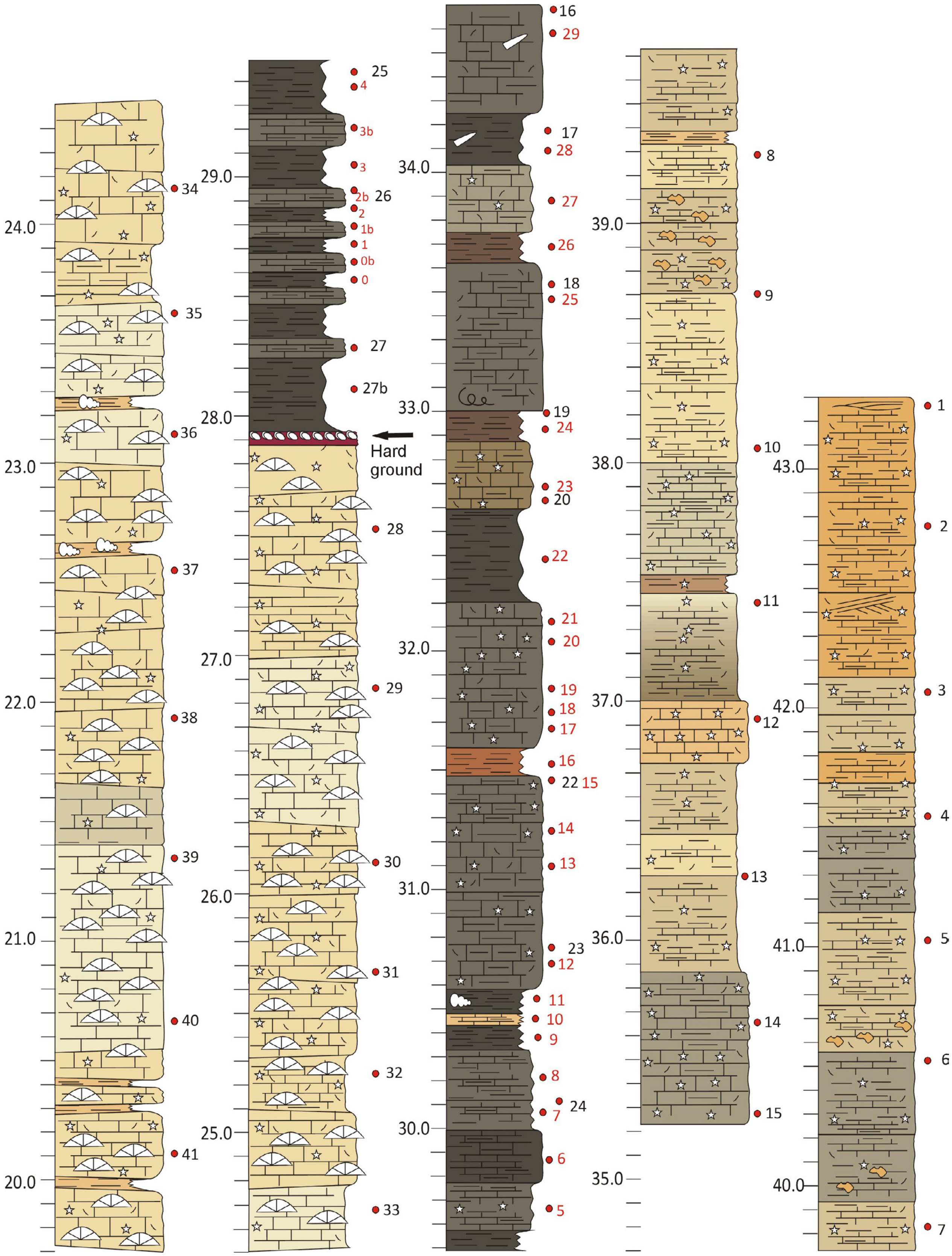

Figure 9B. The Rumelange Cimalux quarry section.

5. Petrography and microfacies

Three sedimentary systems, corresponding to nearly contemporaneous paleoenvironments, are recognized: a transgressive mixed siliciclastic-carbonate ramp for the Triassic-Toarcian interval, an early transgressive, low productivity, mixed ramp for the Aalenian, and a transgressive carbonate ramp for the Lower Bajocian. The different microfacies are described hereunder, from the most distal to the most proximal for each model. The Dunham (1962) textural classification for carbonates is used.

Similar microfacies, based on 150 thin sections from the Latour, Neulimont and Villers-devant-Orval boreholes were already described and interpreted by Boulvain *et al.* (2001a). The 500 new thin sections obtained from the present work are used to complement the study and generalize the paleoenvironmental models.

5.1. Triassic-Toarcian

The following microfacies were described from the Bonnert, Haebicht, Grouft, Grund, and Consdorf boreholes. The Triassic to Toarcian interval is characterized by high accommodation rates responsible for a progressive marine transgression on the Ardenne basement. Sedimentation is dominated by high detrital inputs coming from the Eifel depression zone (Mertens *et al.* 1983).

(TT1) Homogeneous argillite or sub-millimeter laminated silty argillite (silt ~15 µm). Locally, millimeter-thick lenses of poorly sorted quartz (50-100 µm) cemented by xenomorphic sparitic calcite are observed. Sporadic micas, pyrite, charcoal fragments, crinoids, peloids, ostracods, phosphatic grains may be present as well as 1 mm diameter horizontal burrows.

(TT2) This facies is a millimeter to several millimeter scale alternation of (A) silty argillite or microsparitic marl with sporadic charcoal debris and pyrite; (B) locally bioturbated microsparitic argillaceous packstone with bioclasts (crinoids, bivalves, gastropods, ostracods, brachiopods), peloids and pyrite. Sporadic 60-100 µm diameter quartz grains are observed; (C) poorly sorted cross-laminated argillaceous sandstone (quartz 50-300 µm diameter). Bioturbation locally obliterates sedimentary structures. Xenomorphic sparitic cement is present; (D) well-sorted (~300 µm) sandstone with sparry calcite cement and bioclasts (crinoids, bivalves, gastropods).

(TT3) Laminated or bioturbated wackestone in several cm-thick lenses included in (silty) argillite or marl. This wackestone is rich in well-preserved fossils: bivalves, ostracods, gastropods, crinoids, cephalopods, together with fragments of charcoal, glauconite, phosphatic debris, and 50-300 µm diameter quartz grains.

(TT4) Microsparitic to pseudosparitic (cf. Tucker 1981) laminar to bioturbated calcareous sandstone or sandy packstone with peloids. Quartz grains are angular and moderately to well-sorted (60-300 µm diameter). Peloids are ~100 µm micritized bioclasts or lithoclasts. Some fossils are observed: crinoids, bivalves, gastropods and charcoal fragments as well. Locally, oolites are present. Millimeter-thick irregular laminae of microsparitic marl are observed.

(TT5) Well-sorted laminar or bioturbated sandstone with bioclasts (bivalves, crinoids, gastropods, brachiopods). Locally, oolites and proto-oolites are very abundant (with quartz or bioclast nuclei). Detrital feldspar and micas may occur. The cement consists of calcitic pseudospar, xenomorphic spar, syntaxial quartz, microquartz, iron oxides/hydroxides, or pyrite. Quartz grains are well sorted (150-500 µm diameter) and well-rounded. Charcoal fragments are locally abundant, in mm-thick lenses or disseminated.

(TT6) Microsparitic dolostone. Bioturbation is frequently observed and corresponds to plant roots, locally filled with clay. Lithoclasts are common. Sand (~150 µm) or silt (30 µm) lenses are occasional.

(TT7) Laminar or massive argillite with glaebules, root structures, dolomitic nodules, iron oxides, lithoclasts. Sporadic lenses of silt (10-30 µm) or unsorted sand (up to 300 µm) are observed.

(TT8) Poorly sorted conglomerate with argillaceous or sparitic cement. Angular quartz sand is present. Gravels consist of quartzitic sandstone or quartz.

5.2. Aalenian

The following microfacies are representative of the "Minette" unit of the Differdange "Giele Botter" section. The Aalenian is characterized by low sedimentations rates, abundance of condensed ferruginous deposits and sedimentary hiatuses, related to a general decrease of accommodation, probably of tectonic origin. Climate was relatively humid (Martinez & Dera 2015; Andrieu *et al.* 2016).

(A1) Silty argillite or marl, with local millimeter-thick lenses of poorly sorted rounded quartz grains (up to 500 µm diameter). Uncommon bioclasts of crinoids or bivalves are observed. They are commonly replaced by iron oxy-hydroxides.

(A2) Oolitic ironstone. Ferruginous oolites are elliptical, with a highly visible concentric lamination of iron oxide. They are commonly well-sorted, with a diameter ranging between 100 to 600 µm. The nuclei of the ferruginous oolites are bioclasts, fragments of a former oolite or quartz. Beside the ferruginous oolites, the other grains are well-rounded bioclasts (bivalves, crinoids, brachiopods, ostracods, foraminifers), lithoclasts and well-rounded, poorly sorted quartz (up to several mm diameter). Lithoclasts and some bioclasts are replaced by iron oxides. The cement of this microfacies could be goethite, iron silicates (locally fibrous), or sparitic iron calcite. Siderite is observed as automorphic crystals in some oolites. Locally, oolites are squashed. Most bioclasts are imbricated, suggesting high energy environments (storm deposits).

5.3. Bajocian

The following microfacies are described from the upper part of the Differdange "Giele Botter" section and from the Rumelange quarry. The Bajocian age initiated a new cycle of renewed accommodation, drier climate and high carbonate sedimentation rates, dominated by photozoan reef builders (Martinez & Dera 2015; Andrieu *et al.* 2016).

(B1) Well-sorted grainstone with millimeter-sized rounded bioclasts: crinoids, bivalves, brachiopods, bryozoans, ostracods, gastropods, mud-coated grains. Rounded exoclasts (including ferruginous oolites, quartz, etc.) are locally observed. Some of the bioclasts or lithoclasts are replaced by iron oxy-hydroxides. Angular 100 µm-1 mm diameter quartz grains are locally present. The grainstone cement is a xenomorphic Fe-calcite, or an automorphic calcite in 30 µm-thick isopachous rims. Moldic porosity is important. Uncommon chalcedony spherules in fossils are observed.

(B2) Poorly sorted grainstone or packstone with rounded bioclasts (corals, bivalves, crinoids, brachiopods, codiacean algae) and lithoclasts. The coral fragments are abundant and several millimeters long. Poorly sorted quartz sand is locally present. The matrix consists of microsparite or pseudosparite and the cement varies from a xenomorphic sparite to an automorphic calcite in isopachous rims, as in (B1) microfacies. Moldic porosity is frequent. This facies is commonly recrystallized.

(B3) Microsparitic to pseudosparitic laminar to bioturbated calcareous sandstone or sandy packstone with peloids, similar to (TT4) microfacies. It may alternate with (B1) microfacies.

6. Microfacies and formations

6.1. Triassic-Toarcian

As a preliminary remark, it should be emphasized that thin sections were generally obtained from the most hardened sediments, and therefore their nature may not be representative of the most pelitic formations.

The oldest unit intersected by the Grouft (fig. 10), Grund (fig. 11) and Consdorf (fig. 12) boreholes is the Attert Formation (Middle Keuper). This formation is characterized by microfacies TT6 (microsparitic dolostone) and TT7 (pedogenetic argillite). These microfacies are mostly associated with moderately developed pedogenetic structures (Wright 1994). Equivalent microfacies were described in the Neulimont and Villers boreholes. Additionally, in the Latour borehole, poorly sorted quartzose or lithic arenites were observed, together with sandstones and conglomerates cemented by gypsum or dolomite. Anhydrite occurred as decimetric fractured nodules with gypsum filling. These microfacies and associated lithologies point to an arid lowland with sparse vegetation and limited precipitation of evaporites (fig. 17). Local and sporadic detrital supply is responsible for channelized or sheet-like immature sandstones and conglomerates (cf. Alsharhan & Kendall 2003; Donselaar & Schmidt 2005).

The next unit is the Mortinsart Formation (Rhaetian). It is characterized, in the Grouft and Consdorf boreholes, by microfacies TT7 (pedogenetic argillite) and TT8 (poorly sorted conglomerate). In the Villers, Neulimont and Latour boreholes, however, well-sorted pluridecimetric sandy or silty units are also observed, suggesting a first littoral influence, in addition to the Attert-like aridic continental facies.

The Jamoigne Formation shows a large spectrum of purely marine microfacies (Grouft, Grund: TT1-4; Consdorf: TT1-5). Similar microfacies were described from the Latour, Neulimont and Villers boreholes. The depositional environments proposed for the microfacies TT1 to TT5 are organized according to a ramp geometry (Burchette & Wright 1992) and range from the lower mid ramp to the inner ramp. TT1 (argillite or thinly laminated silty argillite) is a distal facies, located close to the storm wave base. The fauna is characteristic of open marine environments and the preserved lamination suggests a reducing sea bottom. TT2 (silty argillite alternating with bioclastic or peloidal argillaceous packstone, sandstone, and argillaceous sandstone), located in the storm wave zone (cf. Aigner 1985), recorded the starting of the carbonate factory on a more oxygenated and bioturbated sea bottom (Colombié *et al.* 2012). Lenses of TT3 (wackestones with well-preserved fossils) are associated with TT2 and correspond to periods with low detrital supply. The TT2 storm deposits are only distal tempestites (Reineck & Singh 1972; Guillocheau 1983) and no proximal tempestites were observed in this unit. The Jamoigne Formation was deposited on an offshore storm-controlled mixed detrital carbonate ramp, as were other similar facies (Calcaire à gryphées, cf. Hanzo *et al.* 2000).

The Luxembourg Formation was intersected by the Grouft, Grund, Consdorf, Bonnert (fig. 13) and Haebicht (fig. 14) boreholes. It was also present in Latour, Villers and Neulimont boreholes. This unit is an alternation of yellowish ochre, poorly cemented sandstones (10-20% carbonate) and grey to whitish, cement-rich sandy limestones (30-60% carbonate) (Colbach 2005). Microfacies correspond to TT4 (calcareous sandstone or sandy packstone with peloids) and TT5 (well-sorted bioclastic and oolitic sandstone), both located on the inner ramp. Oolites are a local constituent of the sandstone and were only observed in Tontelange, Villers-devant-Orval and Neulimont. Decimetric to metric coquina beds with bivalves (*Cardinia*) are present and represent proximal tempestites (cf. Brenner & Davies 1973; Mandic *et al.* 2004). Fauna has an open marine character with prevalent bivalves and crinoids. The moderate to good sorting and scarcity of mud is related to a relatively high energy, pointing to a fair-weather wave zone environment. The terrigenous clastic supply was abundant in both microfacies (Van Den Bril & Swennen 2009), and the efficient carbonate factory led to a high sedimentation rate. Due to the constant and high water agitation in the inner ramp, the coarse quartz grains were mixed with bioclasts and peloids. Sedimentation is most probably driven by longshore currents with the influence of storm waves. The longshore currents deposited sands in planar or cross bedded units, while short periods of calm allow the deposition of thin clay laminae. These facies are in agreement with the sandwaves facies model defined for the Luxembourg Sandstone (Berners 1983; Guérin-Franiatte *et al.* 1991). Unidirectional cross stratifications have been related to asymmetric tidal flows inducing a dominant current (Mertens *et al.* 1983) and also related to lateral migration of the bars following the transgressive trend (Berners 1983).

The Arlon Formation is present in the Consdorf, Bonnert and Haebicht boreholes. As in the Jamoigne Formation, a relatively wide variety of marine microfacies are observed (TT1-5), suggesting similar paleoenvironments, ranging from close to the storm wave zone to the fair weather wave zone. When compared with the Luxembourg Formation, most of the facies from the Arlon Formation are characterized by less sorted and finer-grained sand, together with more abundant organic matter and coal fragments (Boulvain *et al.* 2001a).

The Ethe Formation is only intersected by the Haebicht borehole and is fully characterized by microfacies TT1, deposited close or below the storm wave base. The lower part of the Ethe Formation (Haebicht 52.5-42 m) shows horizontal burrows of deposit-feeders, while its upper part is devoid of any endofauna, suggesting more reducing conditions in the sediment.

6.2. Aalenian

After a large stratigraphic gap, the next formation to be surveyed is the Minette, well exposed in the Differdange "Giele Botter" section (fig. 15). The main microfacies is A2, oolitic ironstone, locally interrupted by A1 (silty argillite or marl with scattered iron-rich bioclasts and ooids). Despite numerous works that aimed to discover their genesis (Hallam & Bradshaw 1979; Kimberley 1979; Van Houten & Bhattacharyya 1982; Teyssen 1984; Collin *et al* 2005; Reolid *et al.* 2008; Garcia-Frank *et al*. 2012, etc.), a comprehensive depositional model of oolitic ironstone has yet to be established. The purpose of the present work is only to bring some petrographical observations about this special ironstone. The well-sorted character of the oolites and bioclasts, the rounded aspect and pitting of the latter, and the grainstone texture all point to an open marine, well-agitated environment. Locally, a reworking by proximal storms is assumed to account for the imbrication of shells. The depositional environment of the ironstone is located in the fair-weather wave zone, on a

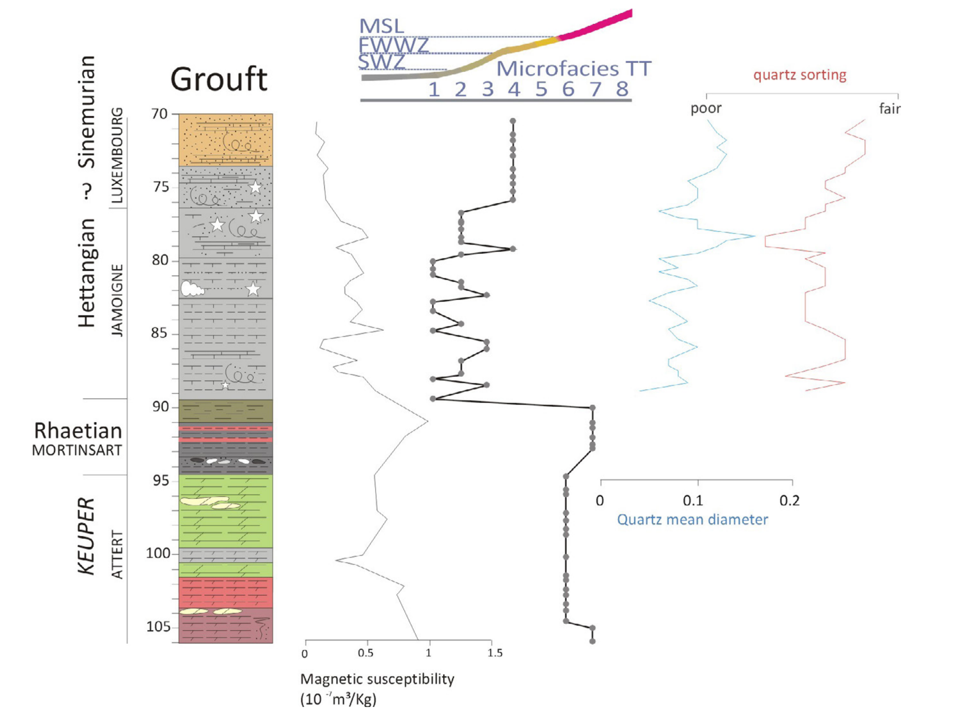

Figure 10. Synthesis log of the Grouft borehole with stratigraphy, magnetic susceptibility, microfacies, quartz mean diameter and quartz sorting (relative scale). MSL = mean sea level; FWWZ = fair weather wave zone; SWZ = storm wave zone.

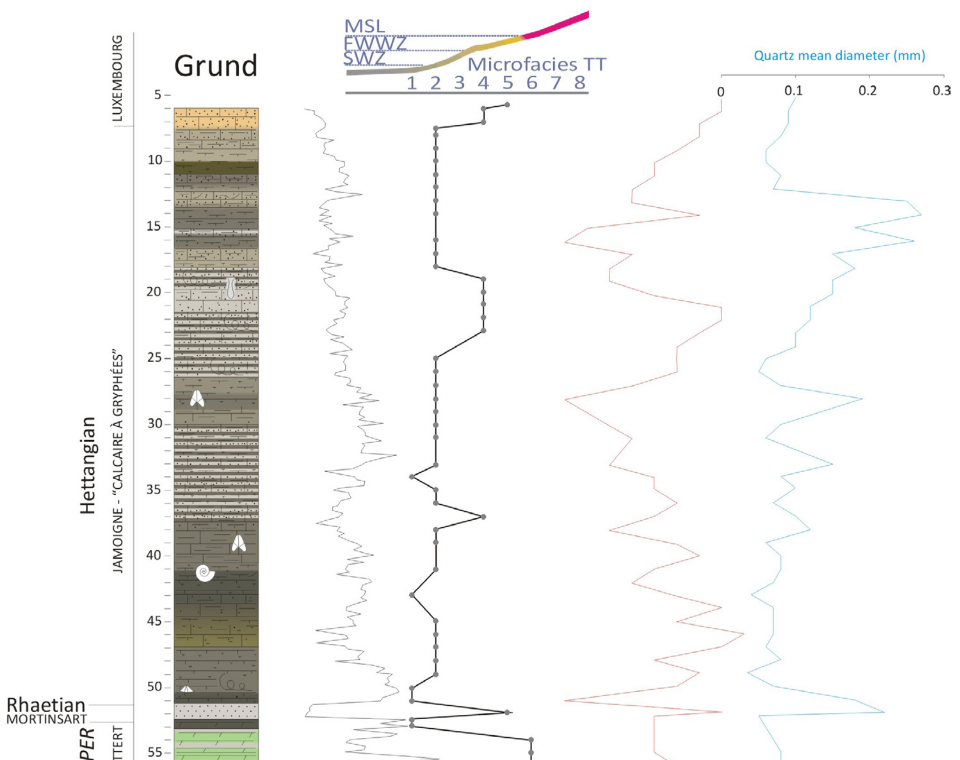

Figure 11. Synthesis log of the Grund borehole with stratigraphy, magnetic susceptibility, microfacies, quartz mean diameter and quartz sorting (relative scale). MSL = mean sea level; FWWZ = fair weather wave zone; SWZ = storm wave zone.

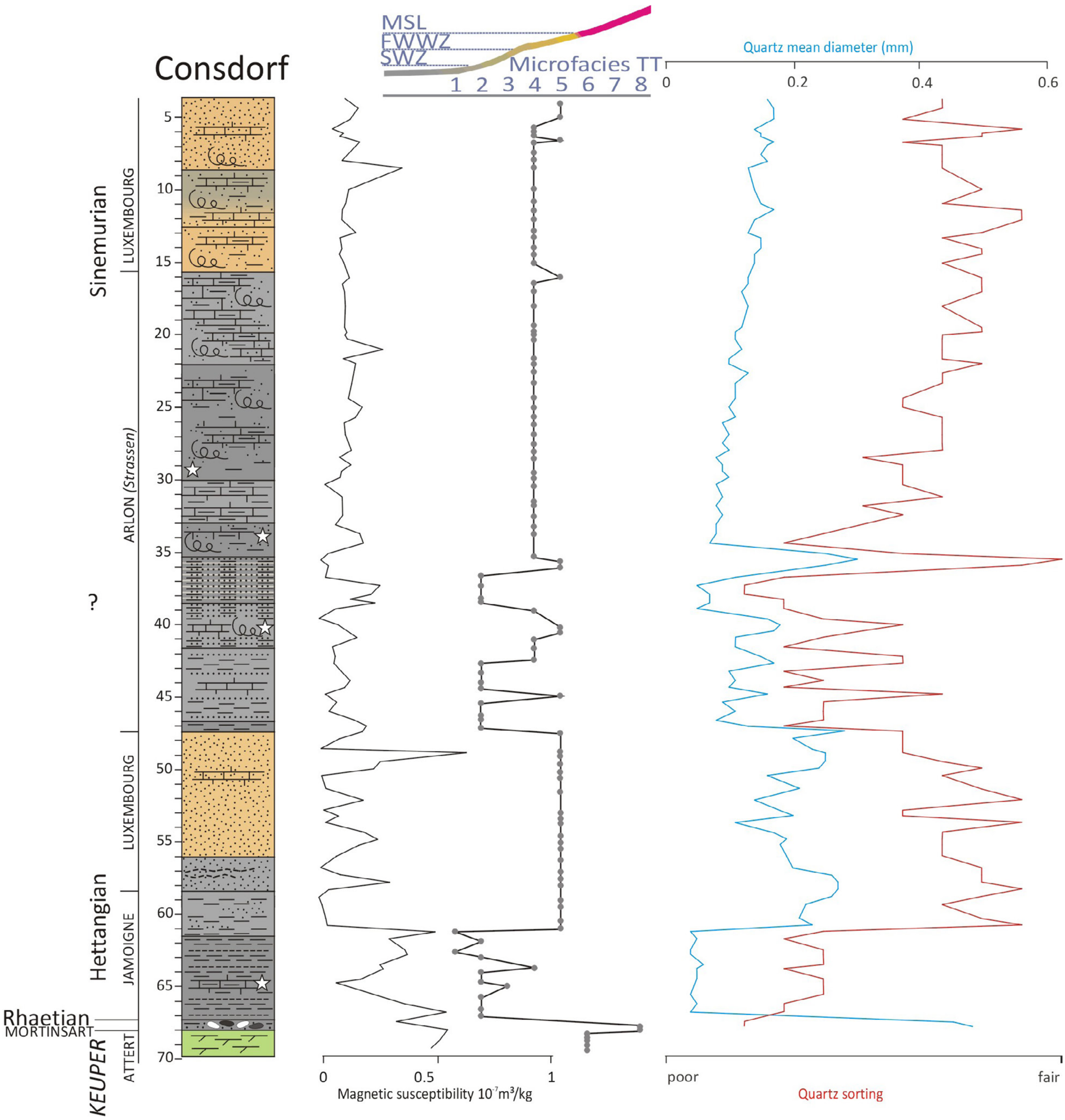

Figure 12. Synthesis log of the Consdorf borehole with stratigraphy, magnetic susceptibility, microfacies, quartz mean diameter and quartz sorting (relative scale). MSL = mean sea level; FWWZ = fair weather wave zone; SWZ = storm wave zone.

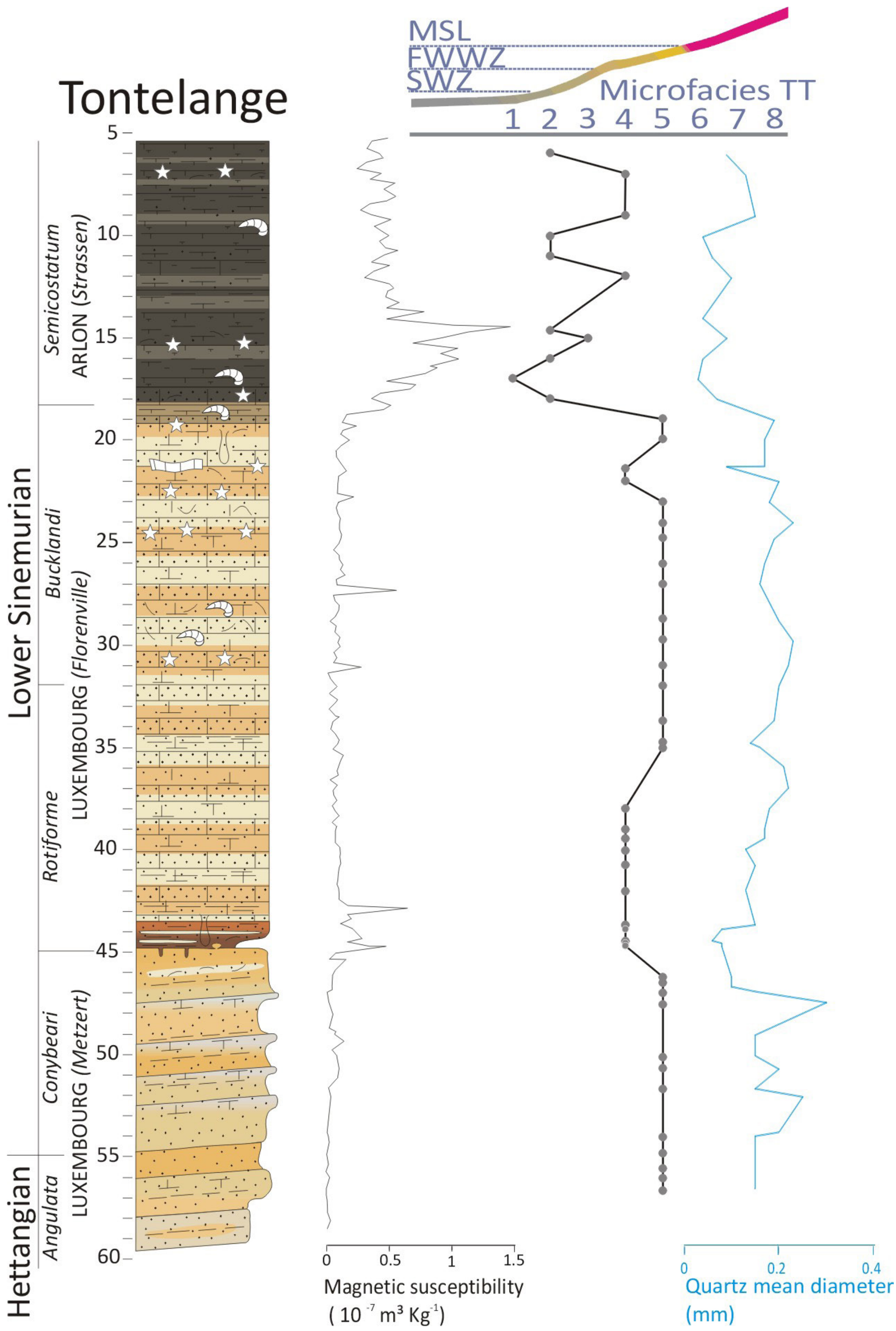

Figure 13. Synthesis log of the Bonnert borehole and Tontelange quarry section with stratigraphy, magnetic susceptibility, microfacies and quartz mean diameter. MSL = mean sea level; FWWZ = fair weather wave zone; SWZ = storm wave zone.

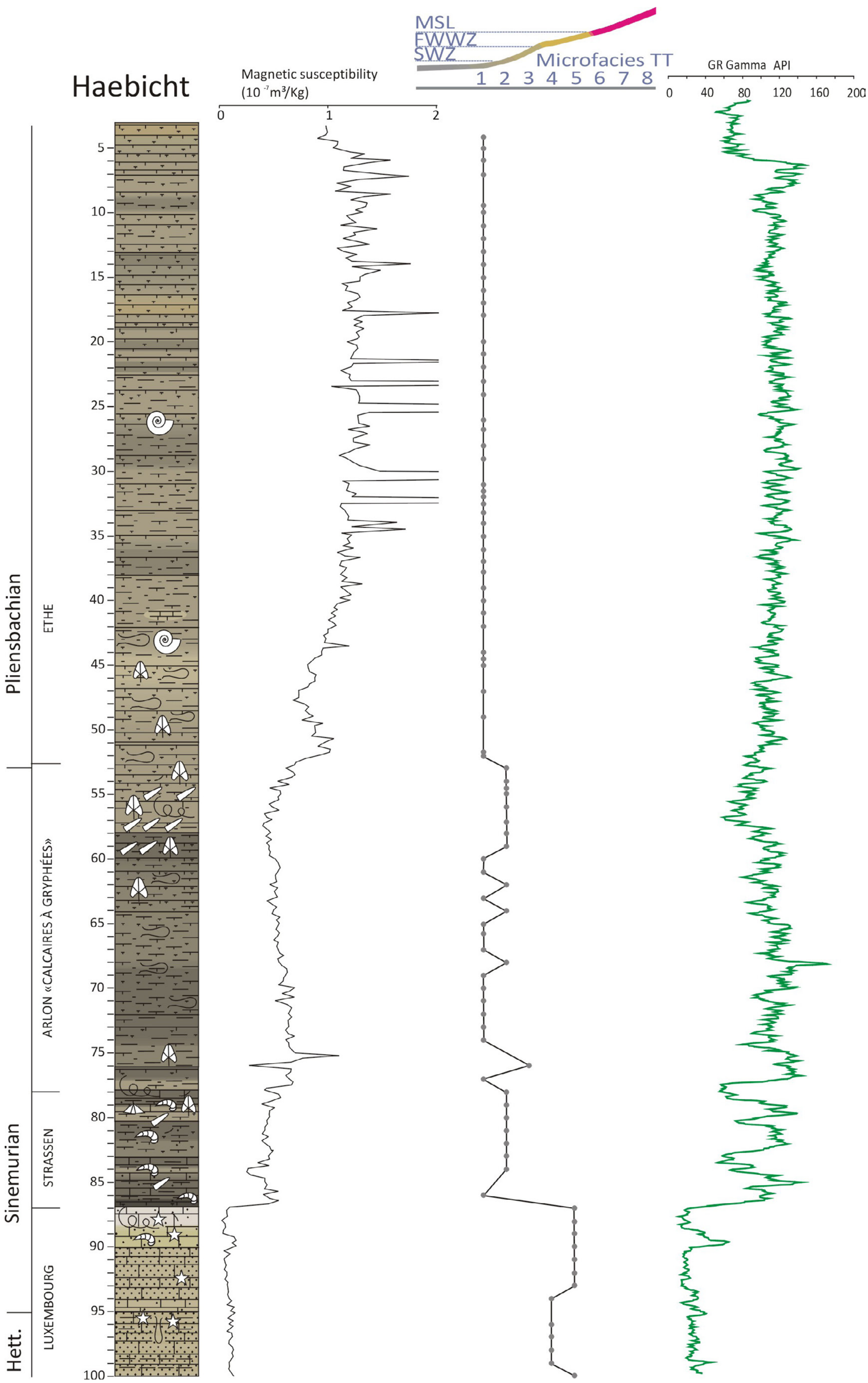

Figure 14. Synthesis log of the Haebicht borehole with stratigraphy, magnetic susceptibility, microfacies, and gamma-ray log. MSL = mean sea level; FWWZ = fair weather wave zone; SWZ = storm wave zone.

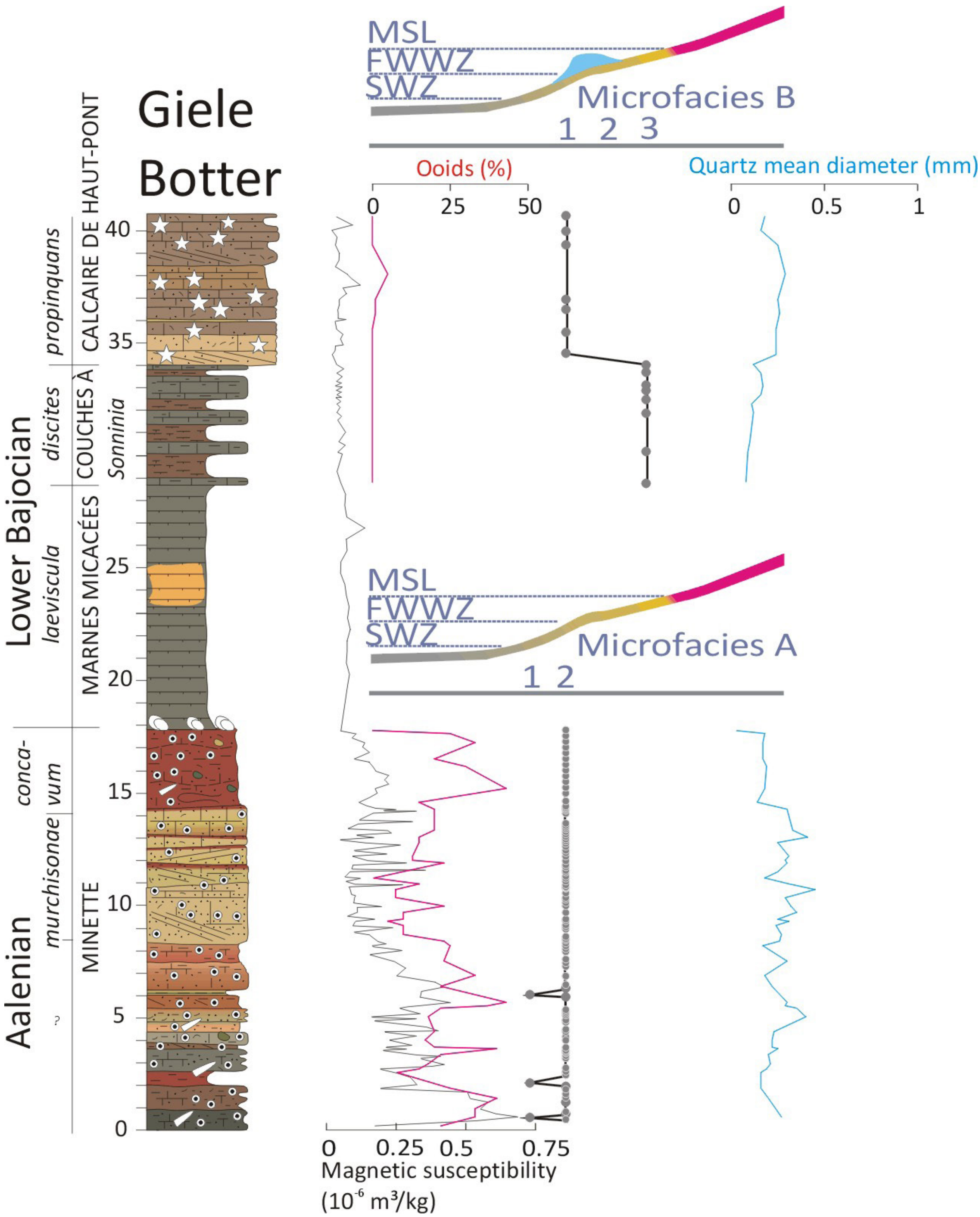

Figure 15. Synthesis log of the Differdange "Giele Botter" section with stratigraphy, magnetic susceptibility, ferruginous oolites content, microfacies (two models) and quartz mean diameter. MSL = mean sea level; FWWZ = fair weather wave zone; SWZ = storm wave zone.

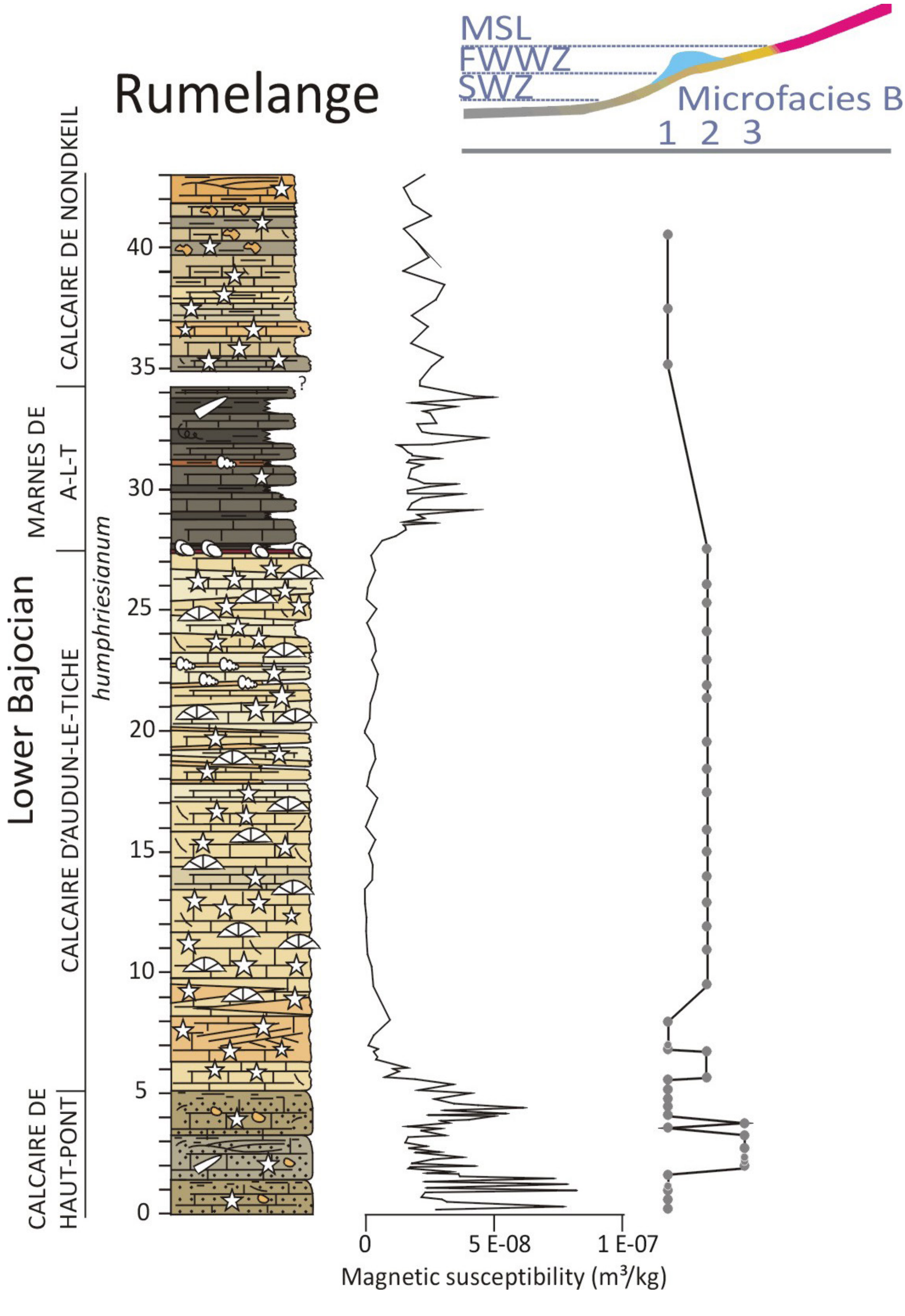

Figure 16. Synthesis log of the Rumelange Cimalux quarry section with stratigraphy, magnetic susceptibility and microfacies. MSL = mean sea level; FWWZ = fair weather wave zone; SWZ = storm wave zone.

storm-dominated ramp. However, no data are available on the genesis of the ferruginous oolites.

6.3. Bajocian

Petrographical information is available for the Bajocian Marnes à *Soninia* (fig. 15), Calcaire de Haut-Pont (figs 15-16), Calcaire de Audun-le-Tiche and Calcaire de Nondkeil (fig. 16).

The limestone beds from the Marnes à *Soninia* are characterized by microfacies B3 (laminar to bioturbated calcareous sandstone or sandy packstone with peloids), similar to TT4, deposited on an open marine mid to inner mixed ramp. The Calcaire de Haut-Pont shows microfacies B3 and B1 (well-sorted grainstone with rounded bioclasts). The latter corresponds to crinoid dominated bioclastic shoals formed in the fair-weather wave zone (Bintz 2001). If B3 is still indicative of a certain level of detrital supply, B1 is a purer limestone and announces the future development of a healthy carbonate platform.

The Calcaire d'Audun-le-Tiche, in addition to microfacies B1, is largely dominated by microfacies B2 (bioclastic grainstone or packstone with corals). This limestone is a peri-reefal facies, largely influenced by the well-known *Isastrea* reefs of the Rumelange area (Hary 1970).

Three synthesis conceptual depositional system models with the horizontal repartition of microfacies are proposed hereafter (figs 17-19).

7. Magnetic susceptibility, formations and microfacies

Changes in magnetic susceptibility (MS) in sedimentary successions are attributed to changes in ferromagnetic/paramagnetic mineral content, that in turn may reflect sea level variations (Ellwood *et al.* 1999). The major influence of sea level on the MS signal is related to the strong link between MS and detrital components, assuming that the detrital input is generally controlled by eustasy or climate. In this way, a lowering of sea-level (regression) increases the proportion of exposed continental area, increases erosion and leads to higher MS values, whereas rising sea level (transgression) decreases MS (Crick *et al.* 2001). Climatic variations influence MS through changes in rainfall (high rainfall increases erosion and MS), glacial-interglacial periods (glacial periods are related to glacier erosion

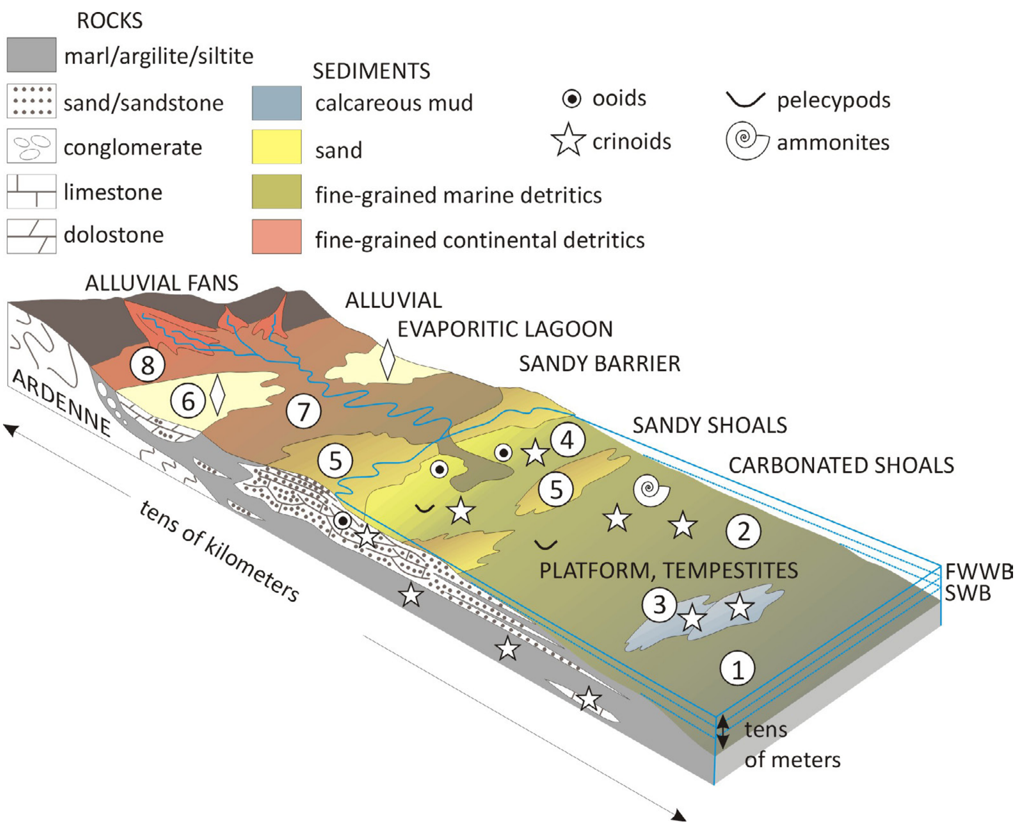

Figure 17. Depositional system model with microfacies (TT1-8) for Triassic to Toarcian formations. FWWZ = fair weather wave zone; SWZ = storm wave zone.

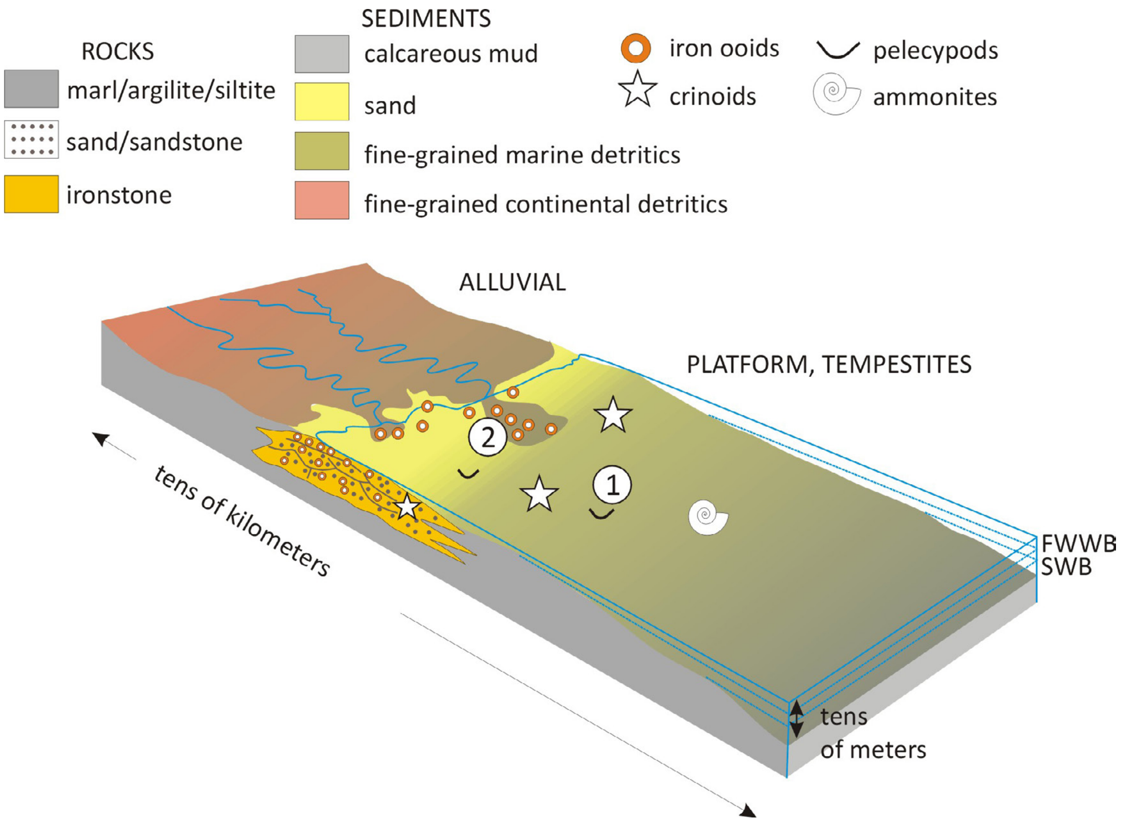

Figure 18. Depositional system model with microfacies (A1-2) for Aalenian formations. FWWZ = fair weather wave zone; SWZ = storm wave zone.

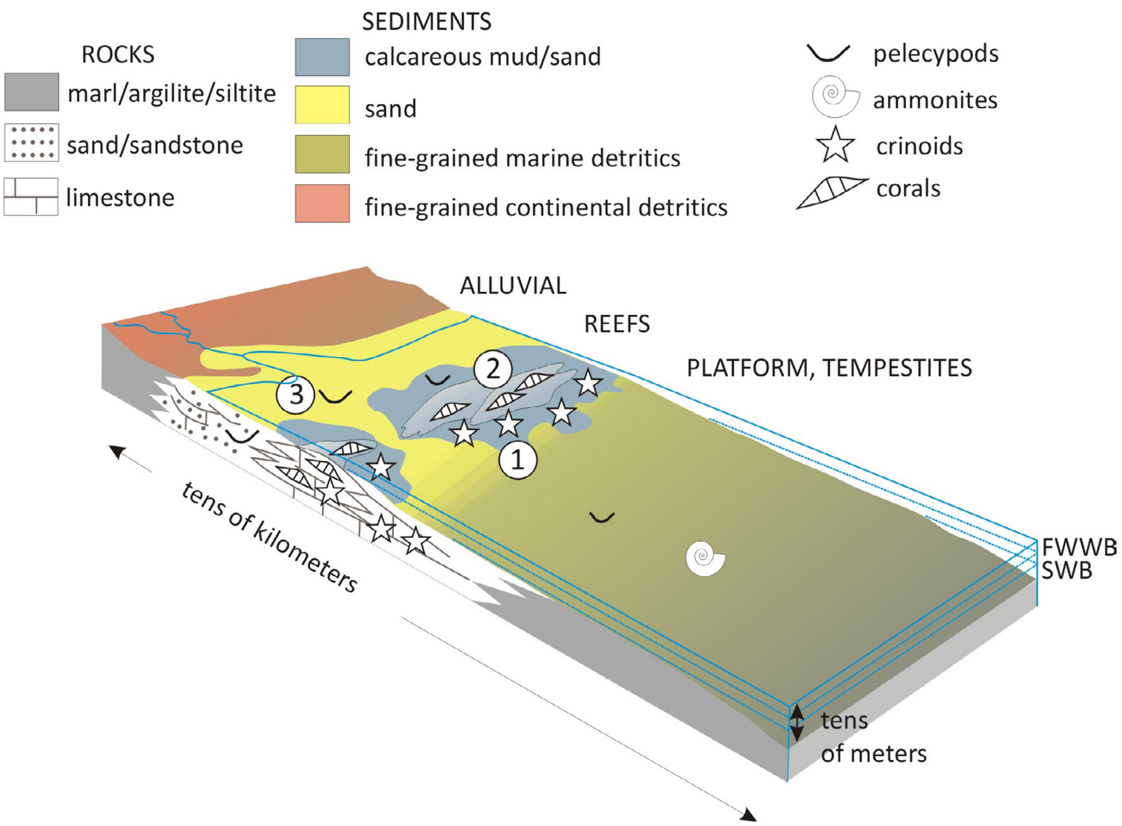

Figure 19. Depositional system model with microfacies (B1-3) for Bajocian formations. FWWZ = fair weather wave zone; SWZ = storm wave zone.

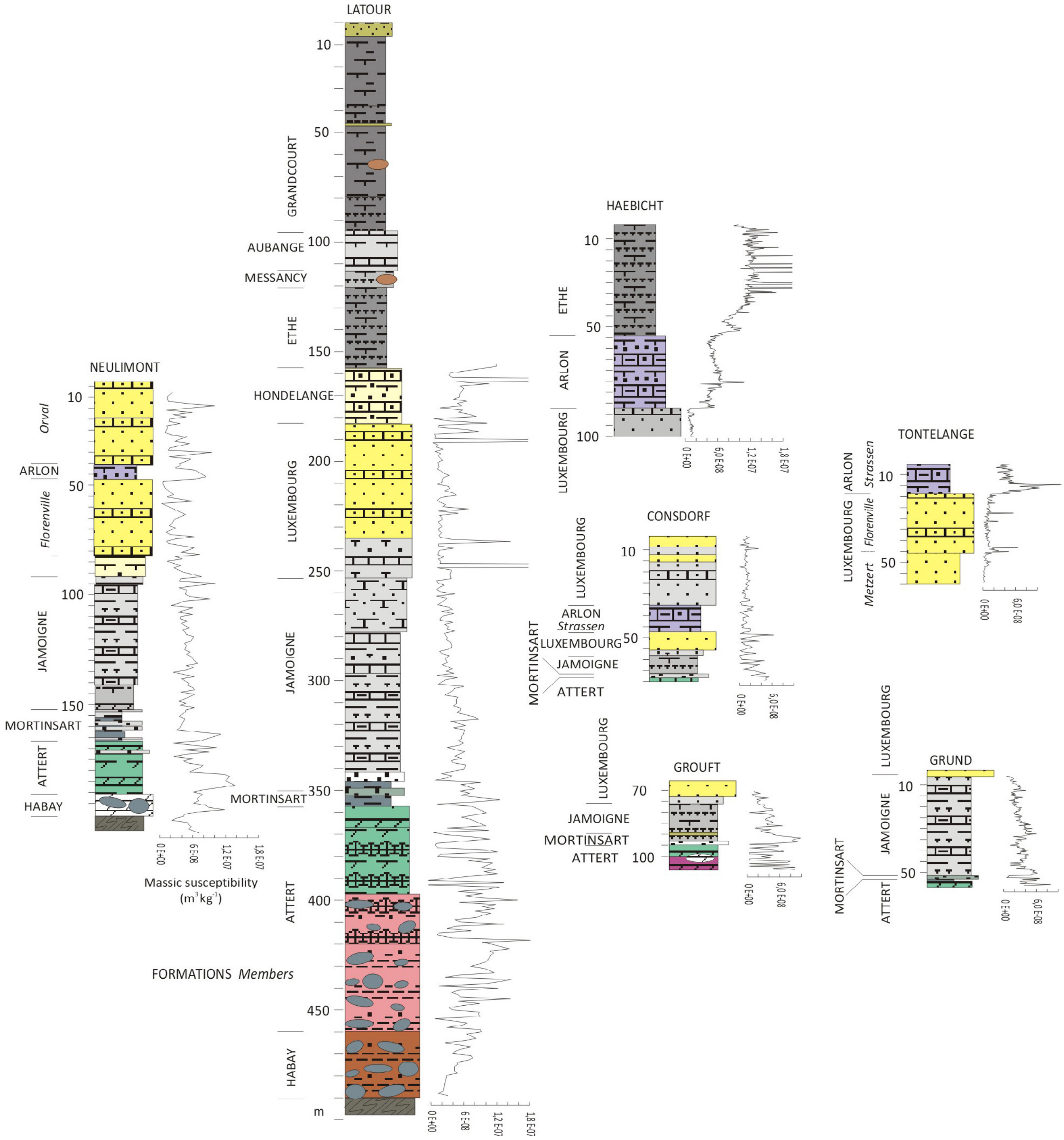

Figure 20. Summary of selected boreholes and magnetic susceptibility.

and to marine regression and both effects increase MS) and pedogenesis (formation of magnetic minerals in soils; Tite & Linington 1975). Furthermore, early and late diagenesis can be responsible for MS variations through mineralogical transformations, dissolution or authigenesis (McCabe & Elmore 1989; Zegers *et al.* 2003).

A series of 2360 samples coming from all the formations surveyed in this study were analyzed. Figure 20 proposes a summary of MS *versus* logs for Consdorf, Grouft, Grund, Haebicht, Tontelange and Rumelange boreholes, together with new MS data for Latour and Neulimont boreholes. Table 1 and figure 21 give the number of samples, mean values and standard deviation for all the formations intersected by all boreholes and sections (including Latour and Neulimont).

First observations show that MS values are relatively weak for the Luxembourg Formation (except for some peaks whose origin is not yet explained), Calcaire et Marnes d'Audun-le-Tiche and Calcaire de Nondkeil.

Table 1. MS (m^3/kg) *versus* formations for all sections and boreholes

Formations	Number of samples	Mean (m^3/kg)	Standard deviation (m^3/kg)
Calcaire de Nondkeil	15	2.23 E-08	5.47 E-09
Marnes d'Audun-le-Tiche	13	1.90 E-08	8.64 E-09
Calcaire d'Audun-le-Tiche	47	5.68 E-09	8.32 E-09
Calcaire Haut-Pont	70	4.06 E-08	2.14 E-08
Couches à Soninia	24	4.77 E-08	1.08 E-08
Marnes micacées	19	7.39 E-08	1.84 E-08
Minette	113	2.25 E-07	1.31 E-07
Ethe	213	1.442 E-07	1.665 E-07
Hondelange	22	7.282 E-08	9.490 E-08
Arlon	264	4.565 E-08	2.241 E-08
Luxembourg	668	2.024 E-08	6.163 E-08
Jamoigne	543	3.687 E-08	1.506 E-08
Mortinsart	73	5.420 E-08	3.538 E-08
Attert	220	7.317 E-08	3.578 E-08
Habay	58	6.265 E-08	3.898 E-08

MS values are high for the Ethe, Hondelange, Arlon, Attert formations, for the Minette and Marnes micacées.

A comparison between the MS and microfacies curves shows a clear positive correlation (figs 10-17), suggesting that the MS signal is primary, as already stated by Dechamps *et al.* (2015) for the Bajocian-Bathonian of the Azé caves. Moreover, the MS values regularly decrease from the marine distal (TT1) to the marine proximal microfacies (TT5) (table 2; fig. 22A). The same pattern was recorded earlier for carbonate ramps (Middle Devonian: Mabille & Boulvain 2007; Tournaisian: Bertola *et al.* 2013). This was interpreted by Da Silva *et al.* (2009) as the consequence of local water agitation in the shallower parts of a ramp, preventing the detrital particles from settling down and to the higher sedimentation rate that dilutes the magnetic minerals. More precisely, the sandstones and limestones show the weakest MS signal, while the argillaceous rocks are characterized by a strong and fluctuating MS signal. This was also observed in Lower Devonian sandstone-shale alternations by Michel *et al.* (2010; fig. 7). The stronger signal, also recorded from the Attert argillites and dolostones (microfacies TT6-7), is perhaps related to pedogenesis or proximity of the terrestrial sources (Tite & Linington 1975; Babek *et al.* 2013).

An important exception would be the ironstone, where the MS signal is directly influenced by the ferruginous ooids content (fig. 15). Concerning Bajocian

TT	Consdorf	n	Grouft	n	Grund	n	Haebicht	n	Bonnert /Tontelange	n
1	4.41 E-08	2	4.72 E-08	7	4.68 E-08	4	9.59 E-08	59	7.90 E-08	1
2	1.95 E-08	20	3.58 E-08	12	2.82 E-08	29	4.68 E-08	17	6.18 E-08	6
3	7.45 E-09	1	2.68 E-08	4						
4	1.18 E-08	47	1.35 E-08	11	1.68 E-08	10	1.03 E-08	5	1.84 E-08	16
5	1.19 E-08	30			7.15 E-09	2	7.68 E-09	8	7.63 E-09	26
6	5.26 E-08	4	6.31 E-08	15	3.17 E-08	3				
7			9.01 E-08	8						
8	3.38 E-08	2								
B	Rumelange									
1	2.30 E-08	17								
2	2.65 E-09	18								
3	2.07 E-08	18								

Table 2. Mean MS value (m^3/kg) *versus* microfacies for Consdorf, Grouft, Grund, Haebicht, Bonnert/Tontelange and Rumelange boreholes and sections. n = number of samples

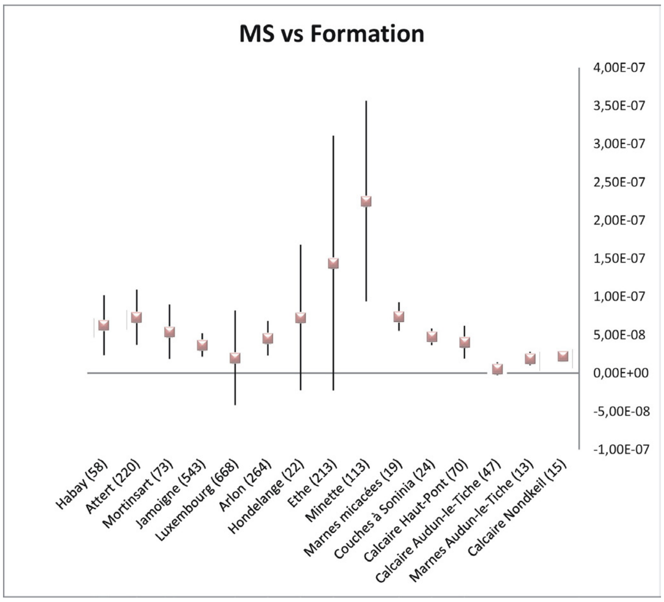

Figure 21. Mean MS and standard deviation (m^3/kg) *versus* formations for all sections and boreholes (number of samples).

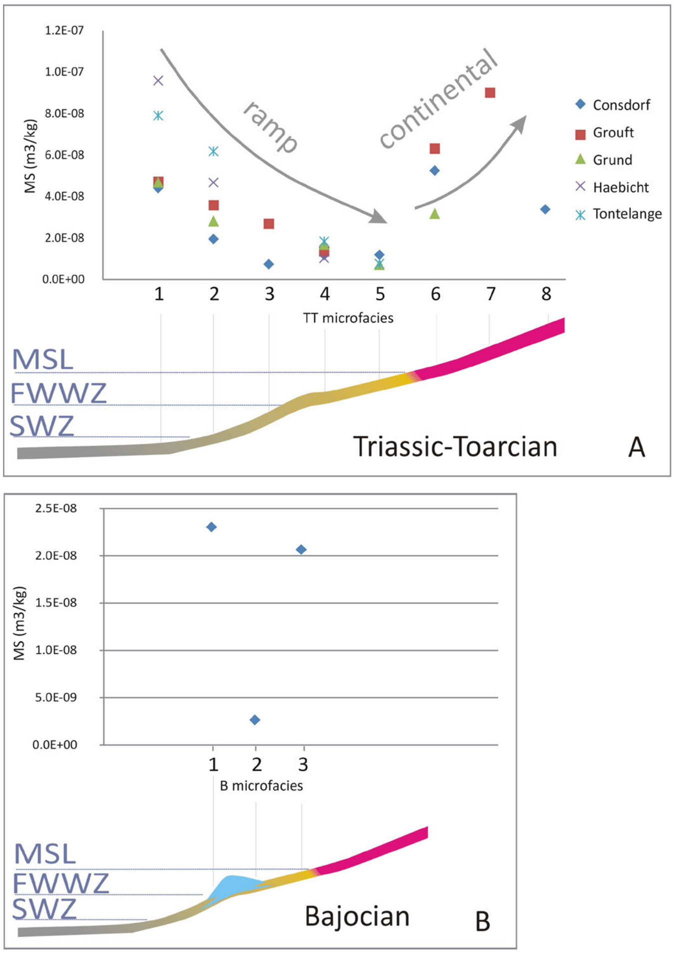

Figure 22. A: mean MS value (m^3/kg) *versus* TT microfacies for Consdorf, Grouft, Grund, Haebicht and Bonnert/Tontelange boreholes and sections. B: mean MS value (m^3/kg) *versus* B microfacies for the Rumelange section. MSL = mean sea level; FWWZ = fair weather wave zone; SWZ = storm wave zone.

microfacies B1-3, the argillaceous rocks are characterized by the highest MS signal, while carbonates show the weakest one (fig. 22B). This is probably related to the dilution of magnetic particles by carbonate production (Da Silva *et al.* 2009).

Conclusion

This study offers a detailed description of a series of boreholes (Bonnert, Haebicht, Grouft, Grund, Consdorf) and sections (Tontelange, Differdange, Rumelange) representative of the Triassic to Jurassic of southern Belgium and Grand-Duchy of Luxembourg. At a low resolution, synthesis logs provide information about microfacies and a framework for magnetic susceptibility (MS) curves. MS results from previous and unpublished studies of the Neulimont, Latour and Villers-devant-Orval boreholes were combined to expand the database of the present work. Three sets of microfacies, corresponding to three different sedimentary systems were necessary to address the complexity of the paleoenvironments: a transgressive mixed siliciclastic-carbonate ramp system for the Triassic-Toarcian interval (microfacies TT1-8), an early transgressive low productivity mixed ramp system for the Aalenian (microfacies A1-2) and a transgressive carbonate ramp for the Lower Bajocian (microfacies B1-3). This evolution reflects a combination of climatic and tectonic forcing on the sedimentation area (Martinez & Dera 2015; Andrieu *et al.* 2016). The TT1-8 microfacies range from the lower mid ramp to the inner ramp. TT1 (argillite or thinly laminated silty argillite) is a distal facies, located close to the storm wave base, TT2 (silty argillite alternating with bioclastic or peloidal argillaceous packstone, sandstone and argillaceous sandstone), located in the storm wave zone, recorded the initiation of the carbonate factory on a more oxygenated sea bottom. Lenses of TT3 (wackestones with well-preserved fossils) are associated with TT2 and corresponds to periods with low detrital supply. TT4 (calcareous sandstone or sandy packstone with peloids) and TT5 (well-sorted bioclastic and oolitic sandstone), are both located on the inner ramp and correspond to sandwaves development. TT6 (microsparitic dolostone) and TT7 (pedogenetic argillite) are supratidal or continental arid microfacies locally interrupted by sporadic detrital supply, responsible for the formation of channelized or sheet-like immature sandstones and conglomerates (TT8). The "Minette" main microfacies is A2, oolitic ironstone, locally interrupted by A1 (silty argillite or marl with scattered iron-rich bioclasts and ooids). Both correspond to an open marine environment, periodically agitated by storms. Bajocian formations are characterized by microfacies B3 (laminar to bioturbated calcareous sandstone or sandy packstone with peloids), deposited on an open marine mid to inner mixed ramp, microfacies B1 (well-sorted grainstone with rounded bioclasts), corresponding to crinoid dominated bioclastic shoals formed in the fair-weather wave zone, and microfacies B2, largely dominated by corals. This bioclastic grainstone or packstone is a peri-reefal facies, influenced by the well-known *Isastrea* reefs.

A comparison of the MS and microfacies curves shows a clear correlation between the two, suggesting that the MS signal is primary, or at least follows from the primary lithology. Moreover, the MS values regularly decrease from the marine distal (TT1) to the marine proximal microfacies (TT5), with relatively weak mean MS values for sandstones and limestones, and high mean MS values for marls, argillites, and for the ironstone. This relation was interpreted by Da Silva *et al.* (2009) as the consequence of local water agitation in the shallower parts of a ramp, preventing the detrital particles from settling down and to the higher sedimentation rate that dilutes the magnetic minerals.

Acknowledgements

S. Dechamps was financially supported by a grant from the Fonds national de la Recherche of Luxembourg. Reviewers Alain Préat and Stephen Hesselbo are warmly acknowledged for their accurate comments and suggestions and great linguistic help.

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Plate

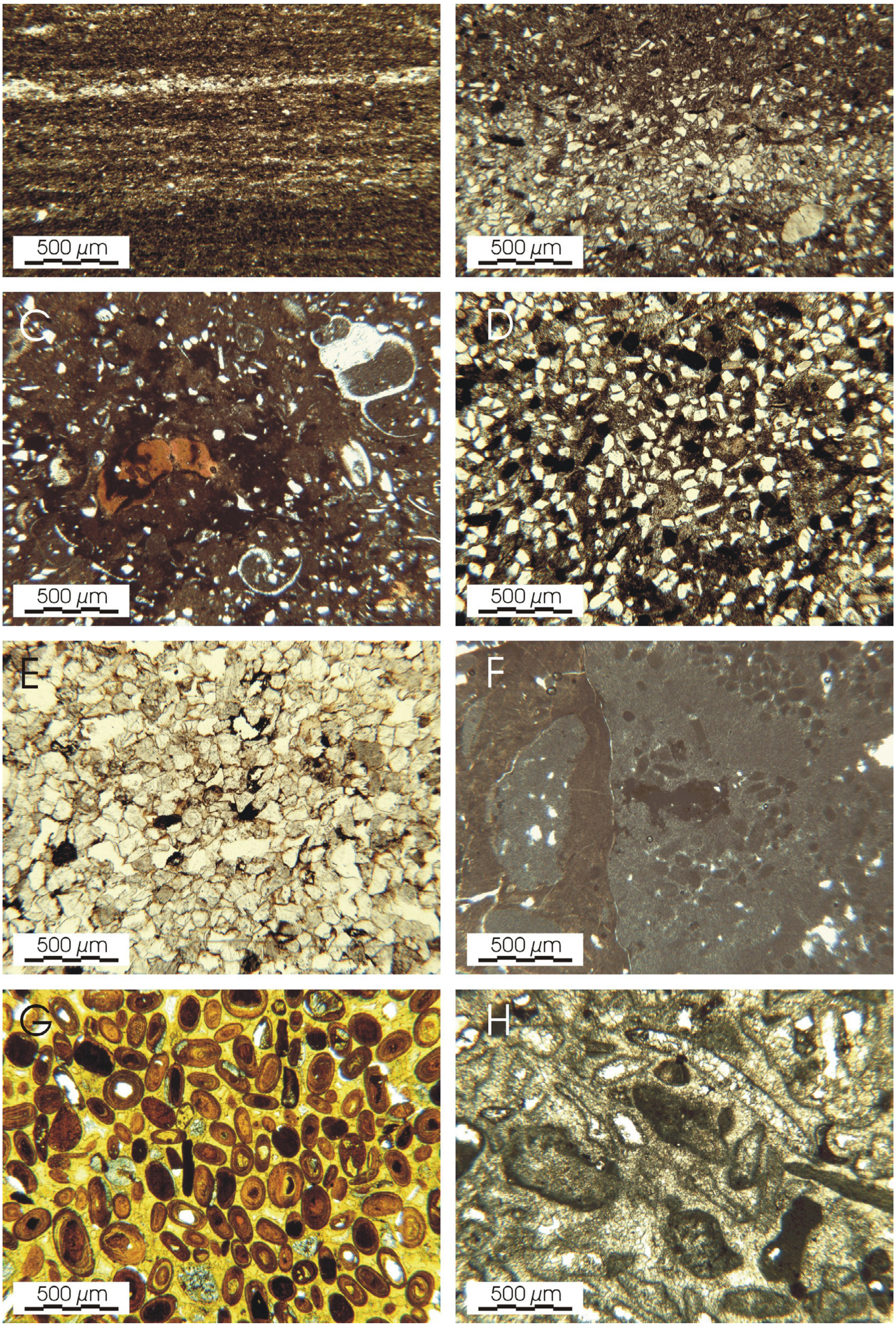

Plate. A: microfacies TT1: laminated silty argillite (Haebicht, 53); B: microfacies TT2: microsparitic marl and bioturbated marly siltstone with a few bioclasts (Consdorf, 45.5); C: microfacies TT3: bioturbated wackestone with gastropods, phosphatic debris and quartz (Grouft, 82.3); D: microfacies TT4: microsparitic bioturbated sandy packstone with peloids (Consdorf, 12); E: microfacies TT5: well-sorted sandstone with rare bioclasts and peloids (Consdord, 3.6); F: microfacies TT7: argillite with peloids, root structure and lithoclasts. (Grouft, 105.3); G: microfacies A2: oolitic ironstone with a Fe-silicate cement (Giele Botter, 5); H: microfacies B2: grainstone with rounded bioclasts, mud coated grains and lithoclasts; the cement is a 30-100 µm pseudosparitic to sparitic calcite (Rumelange, 28).

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This study offers a detailed description of a series of Triassic to Jurassic representative boreholes (Bonnert, Haebicht, Grouft, Grund, Consdorf) and sections (Tontelange, Differdange, Rumelange) from southern Belgium and the Grand-Duchy of Luxembourg. Investigations provide information about microfacies, paleoenvironments and magnetic susceptibility (MS). Three sets of microfacies, corresponding to three different sedimentary systems were needed in order to address the complexity of the paleoenvironments: a transgressive mixed siliciclastic-carbonate ramp system for the Triassic to Lower Jurassic (Toarcian) interval (microfacies TT1-8), and, for the Middle Jurassic, an early transgressive low productivity mixed ramp system for the Aalenian (microfacies A1-2) and a transgressive carbonate ramp for the Lower Bajocian (microfacies B1-3). A comparison of the MS and microfacies curves shows a clear correlation between the two, suggesting that the MS signal is primary. Moreover, the MS values regularly decrease from the marine distal (TT1) to the marine proximal microfacies (TT5), with relatively weak mean MS values for sandstones and limestones, and high mean MS values for marls, argillites and ironstone. This relationship is interpreted as the consequence of local water agitation in the shallower parts of a ramp, preventing the detrital particles from settling down and to the higher sedimentation rate that dilutes the magnetic and/or paramagnetic minerals.

The primary author: Frédéric Boulvain is a Professor in Sedimentology and sedimentary geology at the Université de Liège and a Member of the Royal Academy of Science, Letters and Fine Arts of Belgium. He leads the sedimentary petrology laboratory of the Department of Geology (Sciences Faculty). He has authored or co-authored more than 120 papers and 20 books dedicated to the geology of Belgium and abroad mainly in the Paleozoic and more specifically in the Devonian time interval.

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ISSN 0378-0902