DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2013/6

Alum Shale maps and diagrams

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GEUS

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Released 31.01.2018

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
DANISH MINISTRY OF CLIMATE, ENERGY AND BUILDING

GEUS

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1. Introduction

This report contains maps and diagrams illustrating the depositional environment, thickness, and palaeogeographical development during the Alum Shale deposition in southern Scandinavia.
The maps and diagrams are grouped into the following main themes:

Introduction
Stratigraphical subdivision
Lithostratigraphy
Depositional environment
Isochore maps
Palaeogeographical reconstructions
Localities

Geo-referenced versions of the maps are available on the attached DVD in Appendix B. In the digital version of the map compilation more detailed maps showing localities and wells are provided.

Alum Shale maps and diagrams

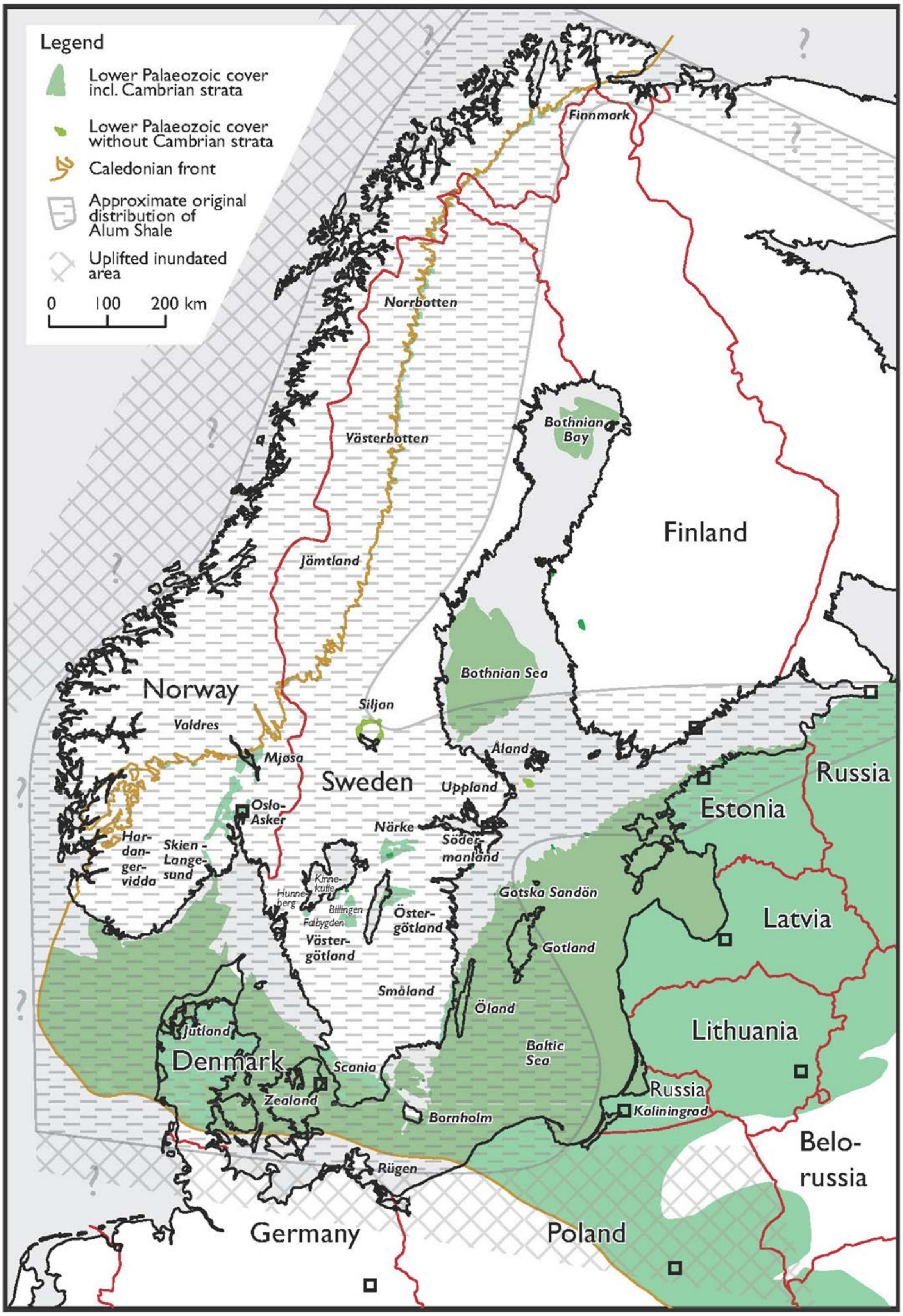

Figure 1: Map showing present-day distribution of Lower Palaeozoic strata in Baltoscandia. Approximate original extent of Alum Shale and inferred marginal uplifts also shown. For further details, see palaeogeographical maps (Fig. 43). Locations of regions referred to in the text are indicated. Map based on Nielsen & Schovsbo (2011, fig. 1). Localities are presented in Table 1.

Figure 2: Strongly folded Alum Shale, road section south of Heggedal, Oslo area. The section is about 6 m high. The Alum Shale Fm acted as decollement level during the Caledonian thrusting and is mostly strongly disturbed in the orogenic belt. Hence thickness data are mostly unreliable, making it difficult to extend the isopach mapping into the Caledonides.

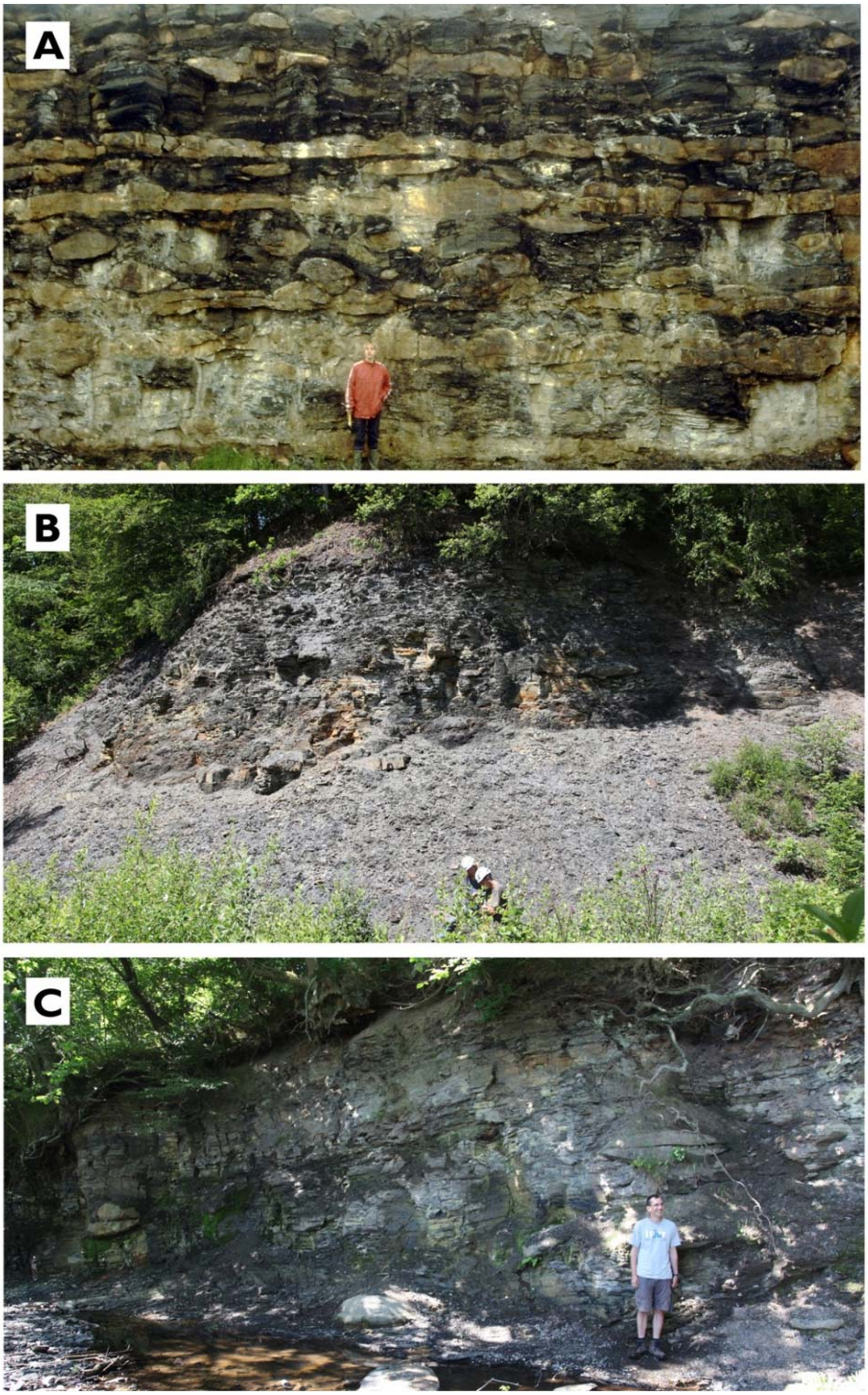

Figure 3: Alum Shale facies. A. Limestone-rich section at Brattefors, Kinnekulle, Västergötland (Furongian mid shelf facies, mainly *P. scarabaeoides* Superzone). B. Alum Shale with scattered limestone, Andrarum, Scania (Furongian outer shelf facies, *Olenus* Superzone). C. Alum Shale with scattered limestone, Læså, Bornholm (Furongian outer shelf facies, *Leptoplastus* to *P. scarabaeoides* superzones). See also Figs 14–16.

2. Stratigraphical subdivisions

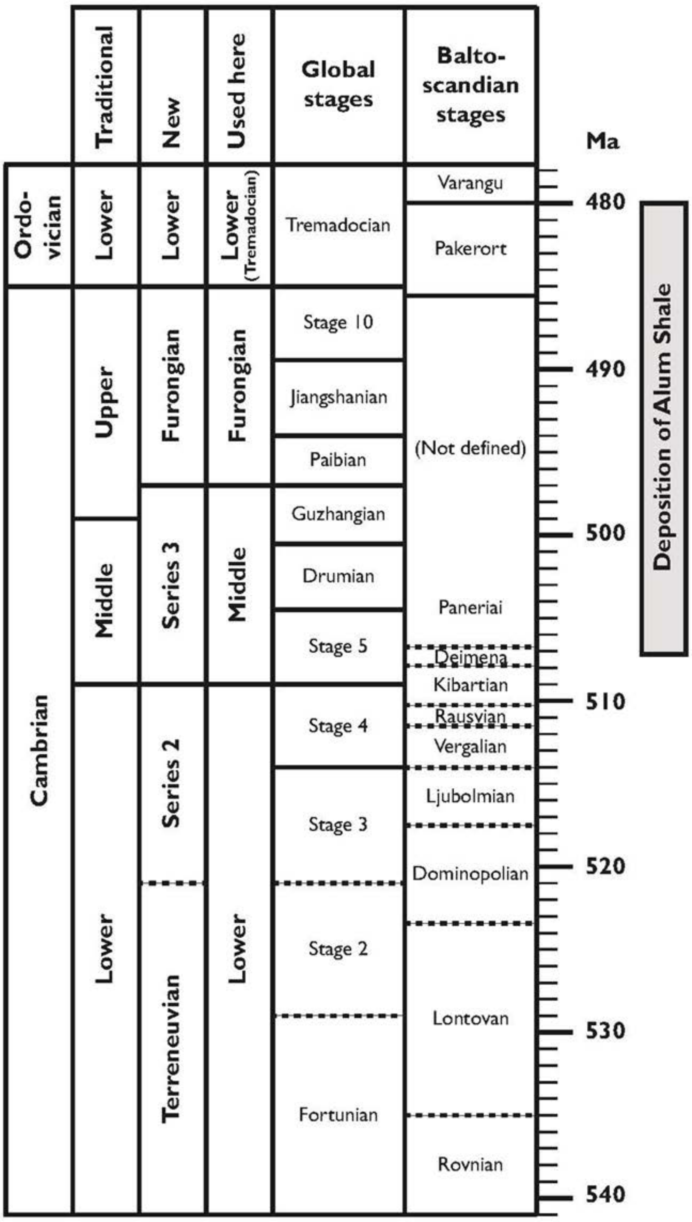

Figure 4: Chronostratigraphy of the Cambrian-Early Ordovician in Baltoscandia. Time interval with deposition of Alum Shale indicated by grey bar on the right hand side. Datings of series and global stages according to Peng et al. (2012). The local Baltoscandian stages have been used mainly in the East Baltic area. Nielsen & Schovsbo (2011) proposed adopting these stages also for the Lower Cambrian of Scandinavia with minor amendments.

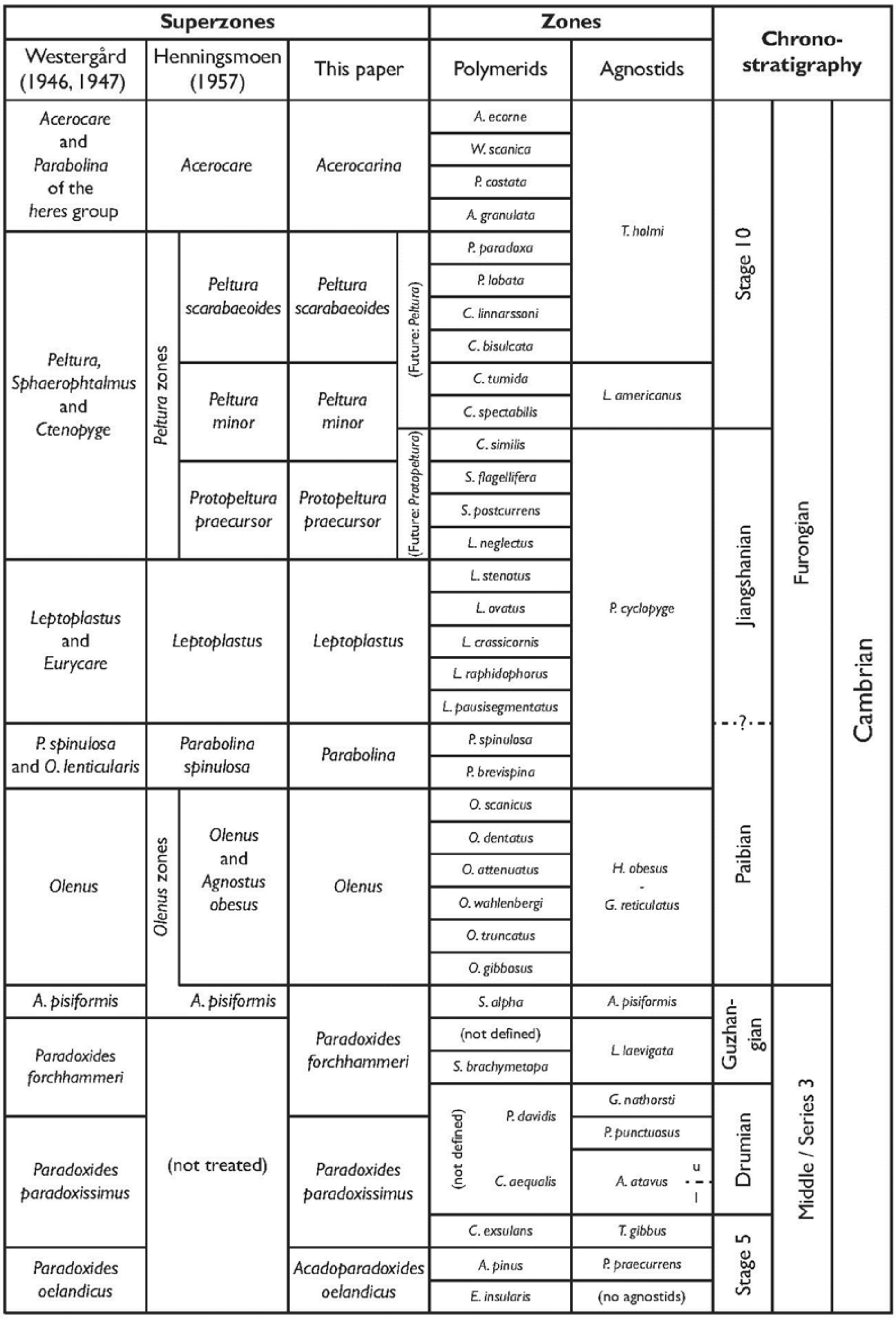

Figure 5: Middle Cambrian – Furongian trilobite biostratigraphy in Scandinavia. The youngest Furongian *Acerocare* Zone [now Superzone] was renamed as the *Acerocarina* Superzone by Weidner & Nielsen (in press b). These authors also replaced the *Peltura transiens* Zone at the base of the *Acerocarina* Superzone by the new designation *Acerocarina granulata* Zone. It is planned to replace the *Protopeltura praecursor, Peltura minor* and *Peltura scarabaeoides* superzones with two new units named the *Protopeltura* and *Peltura* superzones, see text for discussion. The ranges of the new units are shown, marked 'future'.

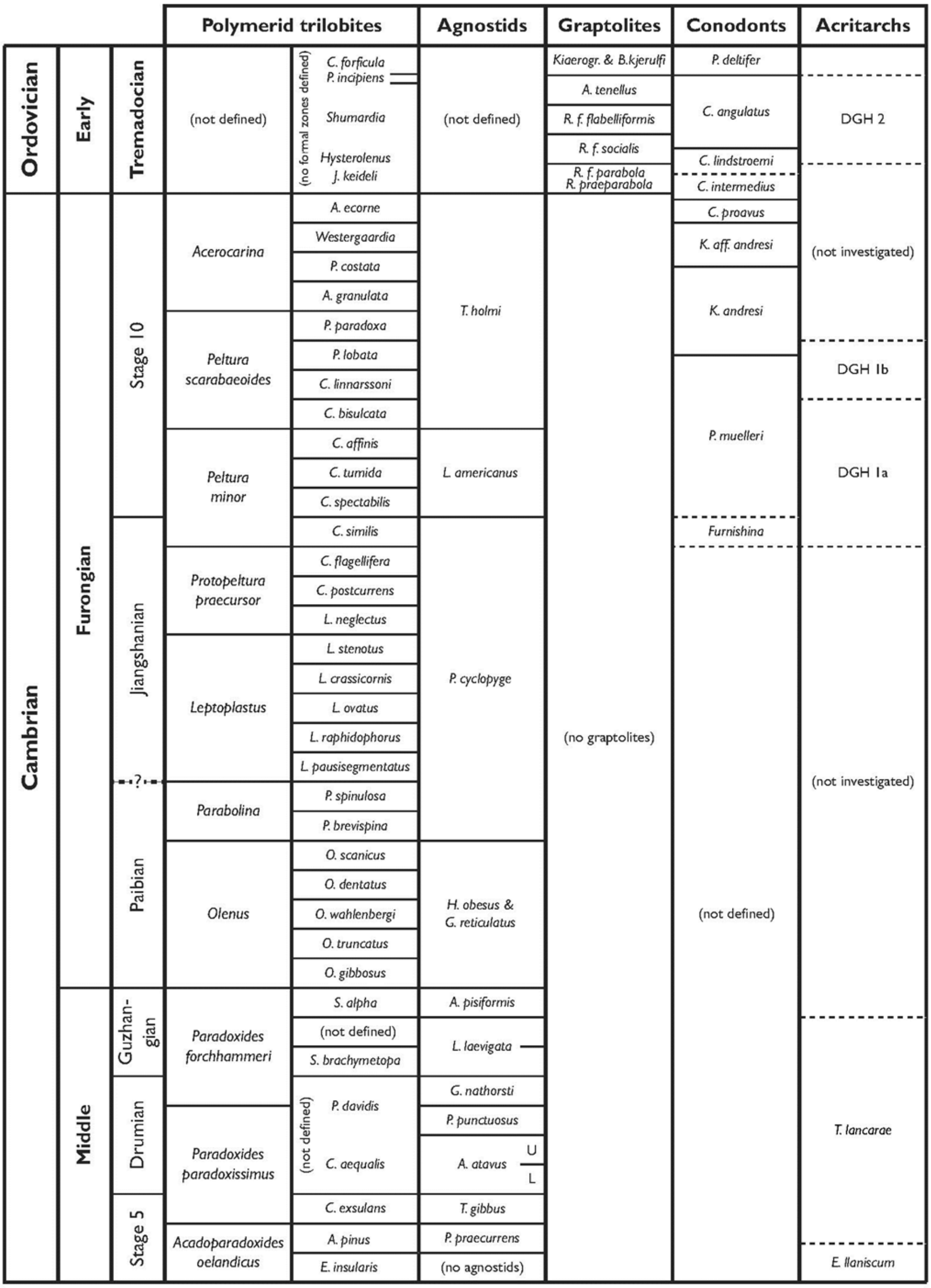

Figure 6: Comparison of biozonation established for the Middle Cambrian – Tremadocian Alum Shale in Scandinavia. No formal acritarch zones are defined for levels above the Middle Cambrian; shown Furongian – Tremadocian designations are from Milia et al. (1989).

3. Lithostratigraphy

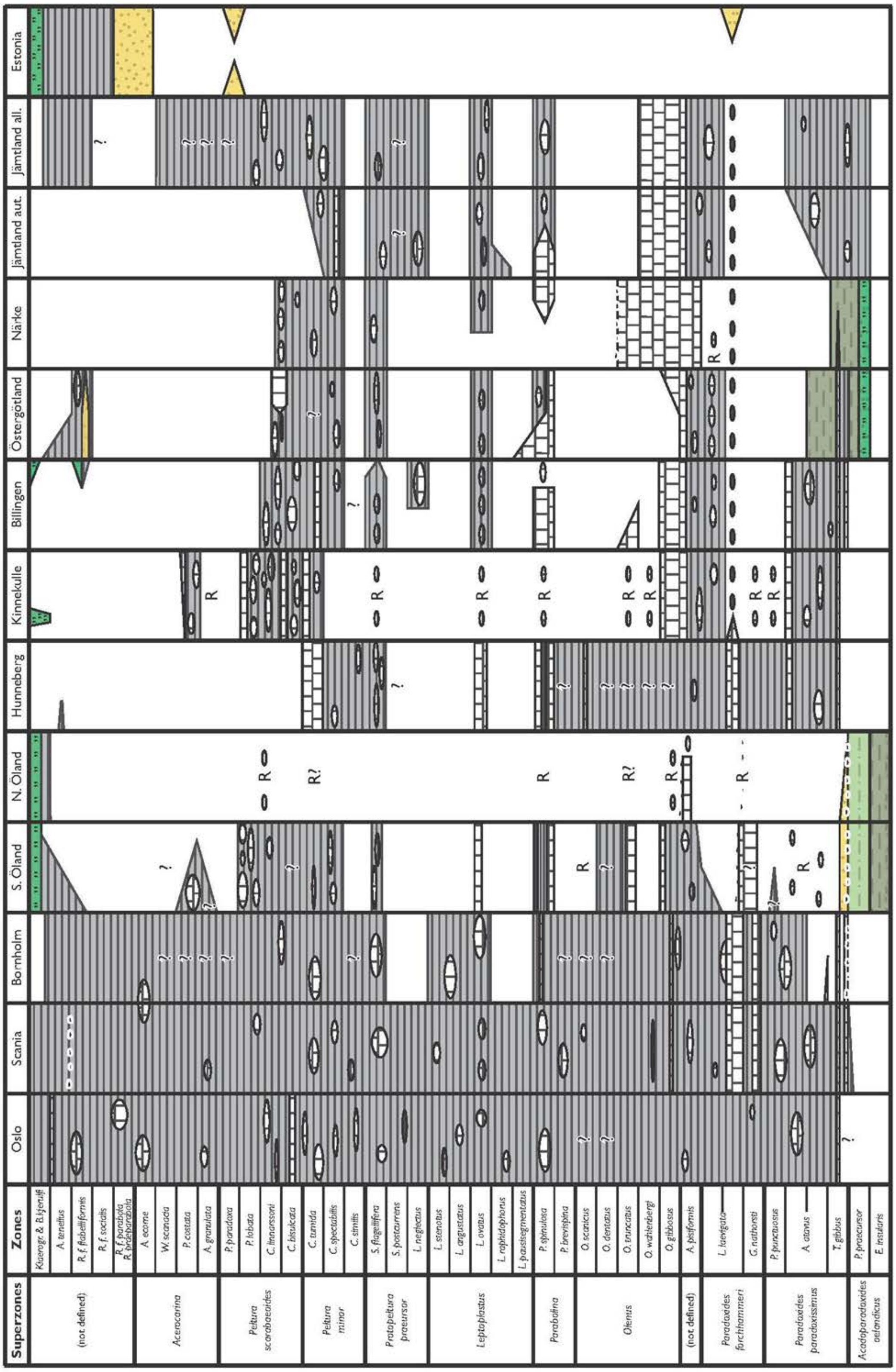

Figure 7: Correlation of the main Alum Shale districts in Baltoscandia. Based on data from Westergård (1922, 1940, 1944, 1947a a.o.), Henningsmoen (1957), Poulsen (1923), Karis (1998), Tjernvik (1958) and many other sources. Please note that the distribution of limestones in the Autochthon and Lower Allochthon in Jämtland is poorly constrained.

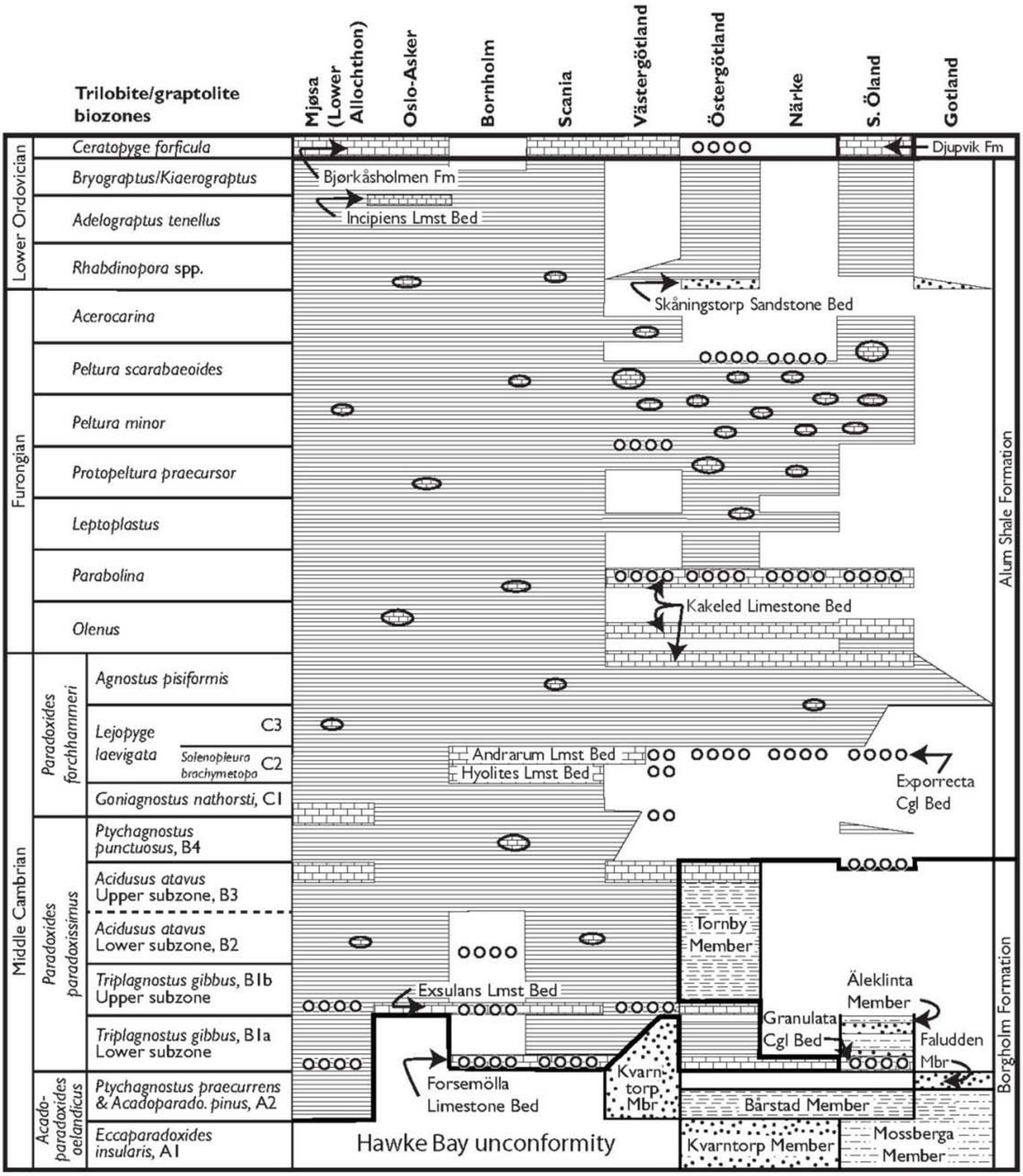

Figure 8: Lithostratigraphy for the Middle Cambrian and Furongian strata of southern Scandinavia (modified and updated from Nielsen & Schovsbo 2006).

4. Depositional environment

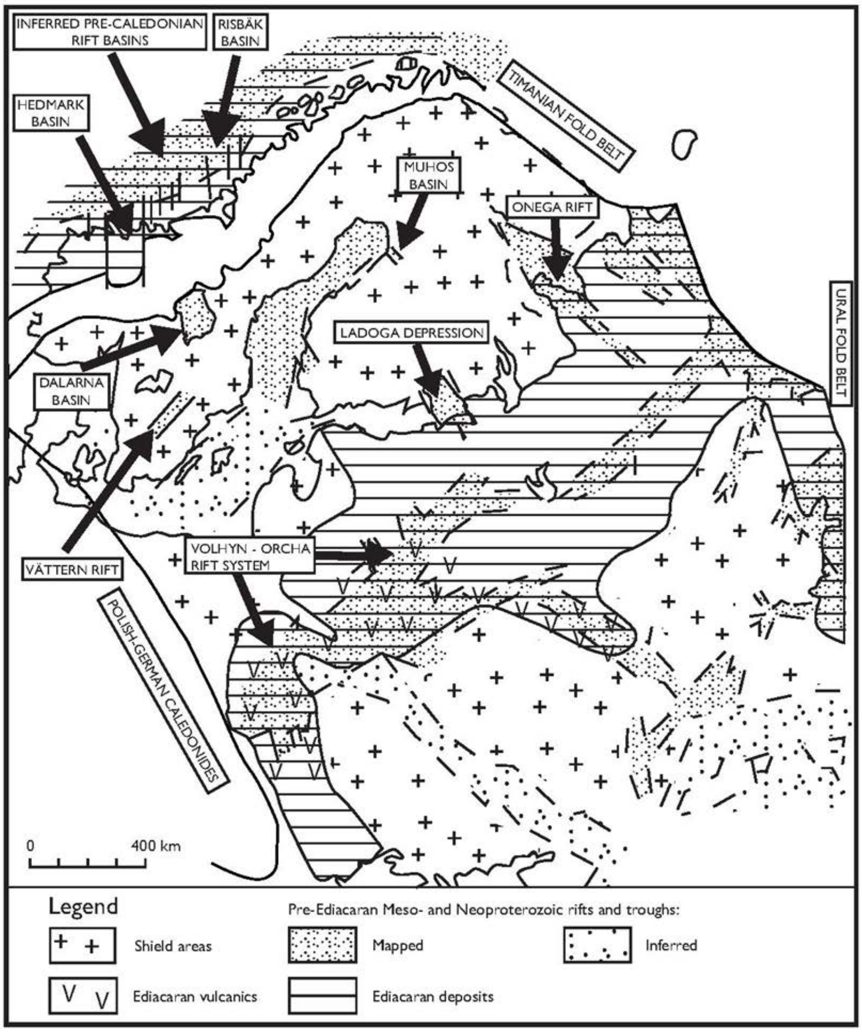

Figure 9: Late Precambrian basins in Baltica (Nielsen & Schovsbo 2011, fig. 4).

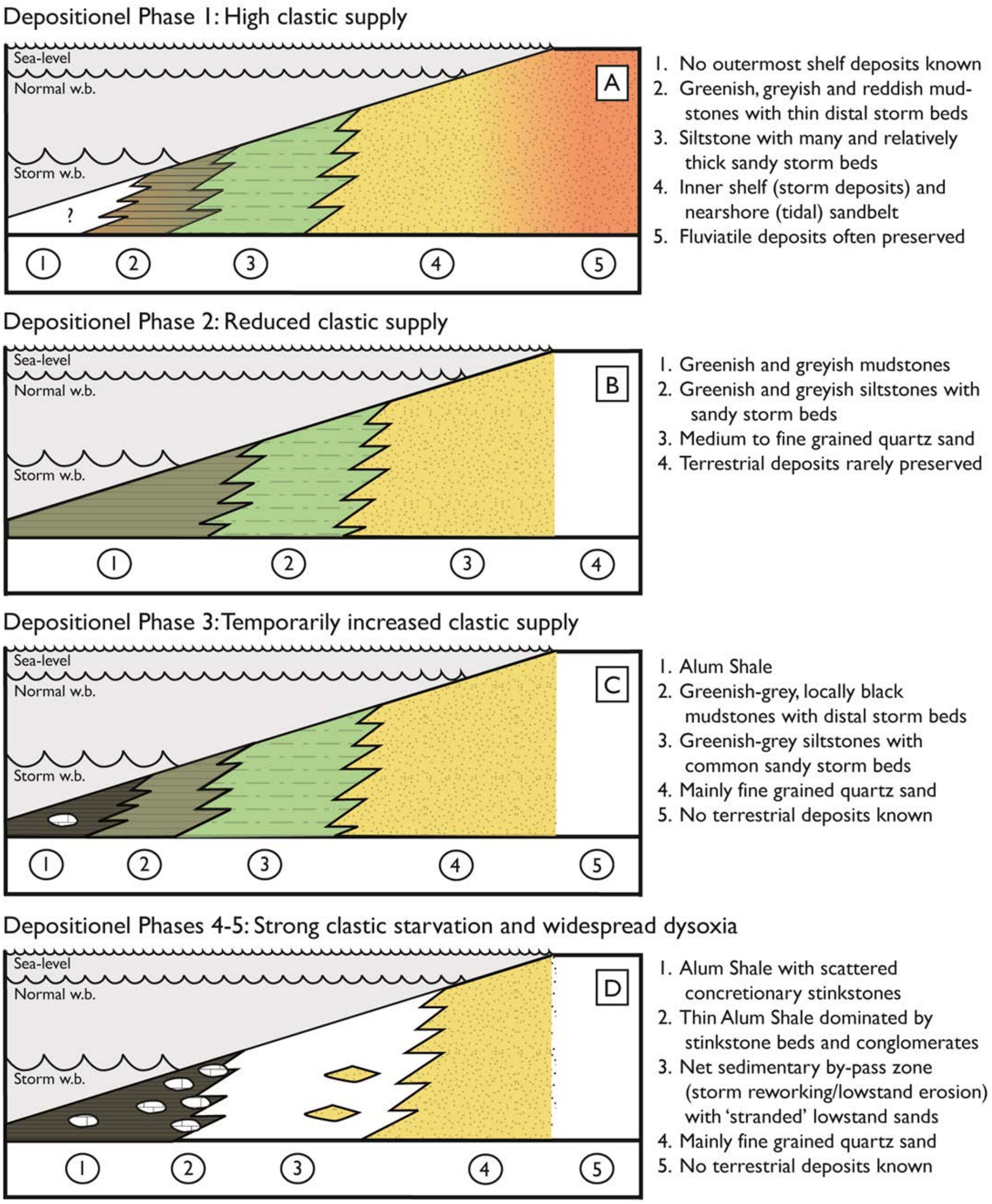

Figure 10: Idealized lithofacies distributions during Depositional Phases 1 to 5. Conceptual logs of sequences are shown in Fig. 46.

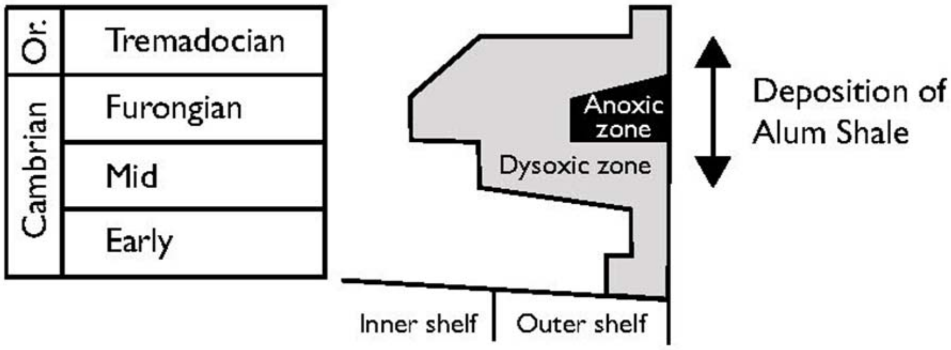

Figure 11: Schematic illustration of the expansion and intensification of the oxygen minimum zone in the Alum Shale Sea during the Mid Cambrian – Furongian.

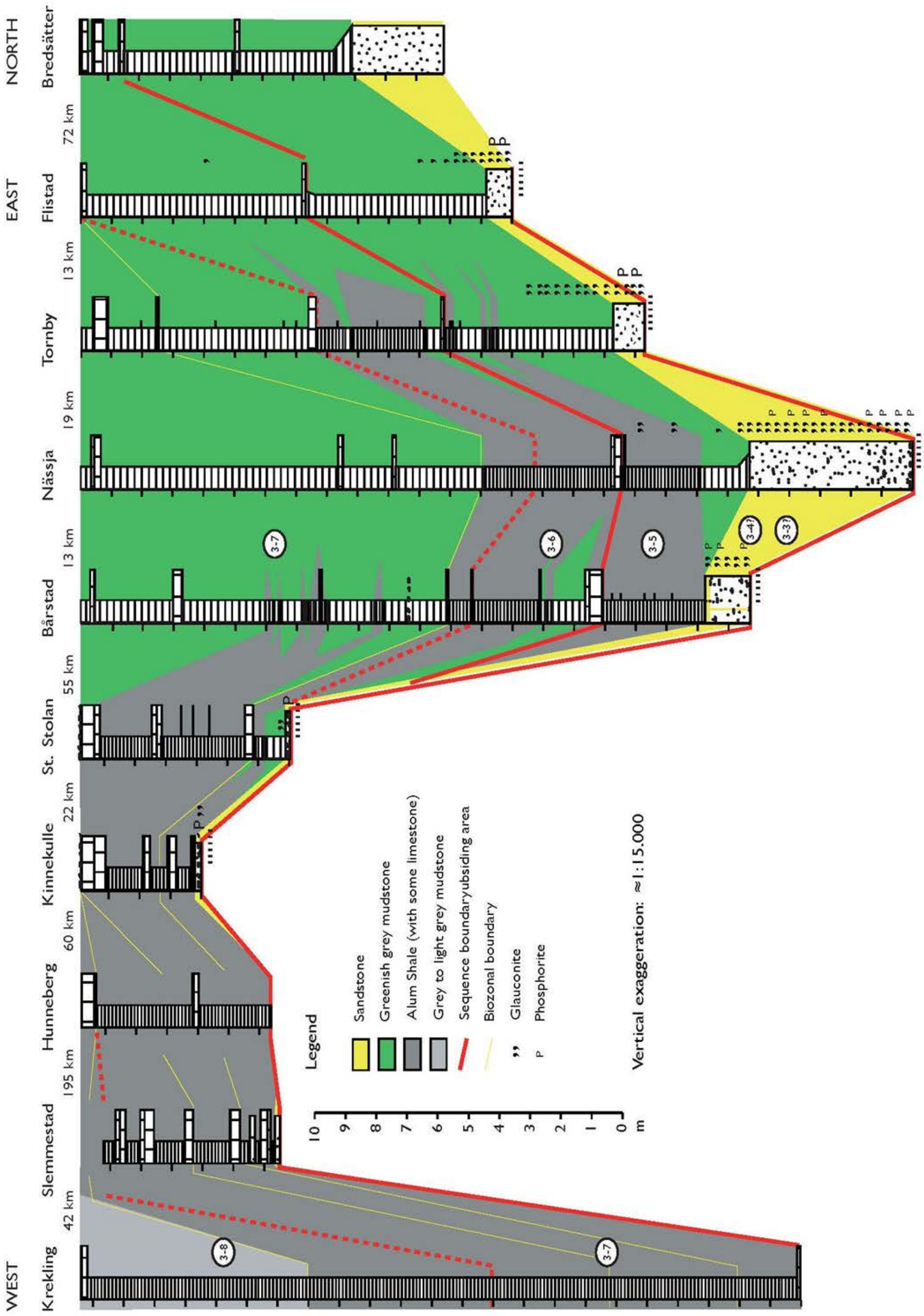

Figure 12: Section from southern Norway into Västergötland-Östergötland-Närke of central Sweden showing thickness distribution of Middle Cambrian sequences. Note that the earliest incursions of Alum Shale in Östergötland seemingly took place behind the uplifted area ("Hawke Bay uplift") to the west. For discussion of the Hawke Bay Event, see sections 8.1 and 9.2. Sections plotted below the Exporrecta Conglomerate and time equivalent strata.

Figure 13: A. Andrarum Limestone overlying Hyolithes Limestone and Alum Shale with anthraconite concretions. Middle Cambrian. Læså, Bornholm. B. Exsulans Limestone consisting of fragmented shelly fossils. The black clast is reworked phosphorite impregnated Lower Cambrian sandstone. Middle Cambrian. Øleå, Bornholm.

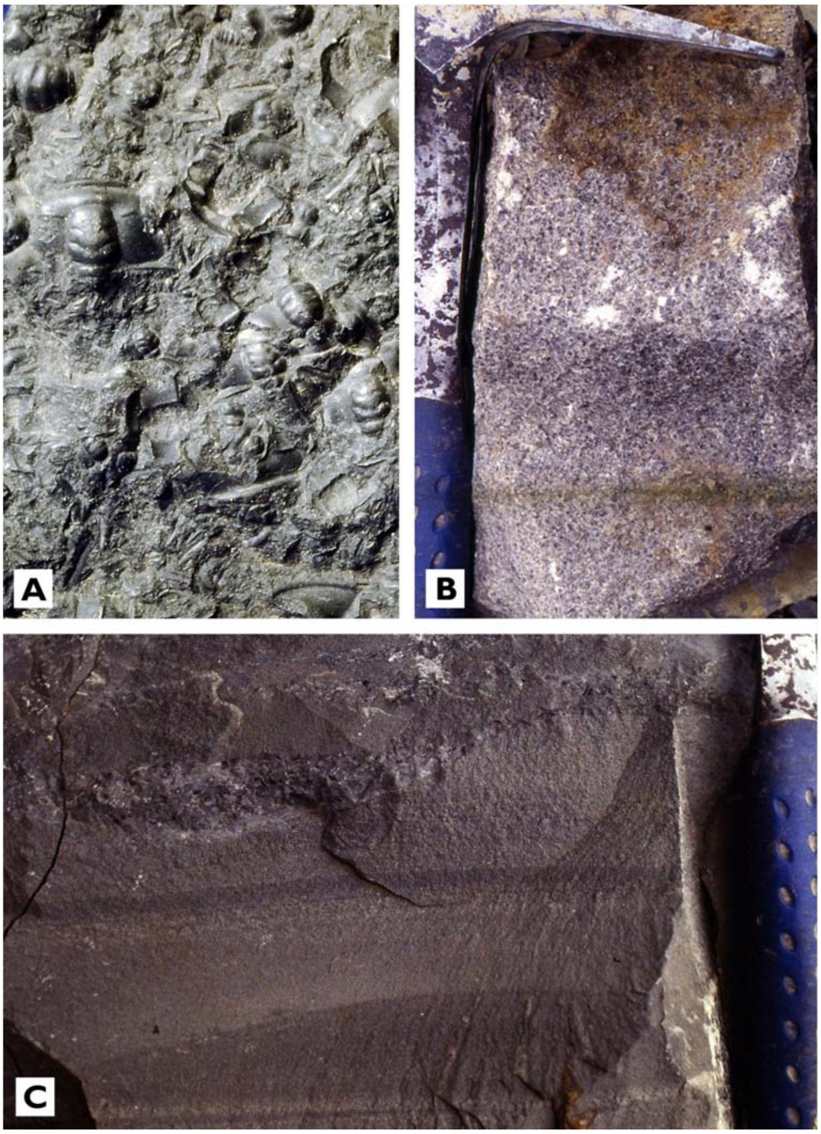

Figure 14: Olenid bioclastic limestone. A. Bedding surface showing more or less abraded skeletal parts of *Olenus*. B. Broken down hash of shelly fossils, mostly trilobites. C. Cross-section of fine-grained limestone showing erosive scour with accumulation of coarser shell material.

Figure 15: Kakeled Bed (”Great orsten bank” in older literature), Kinnekulle, Västergötland.

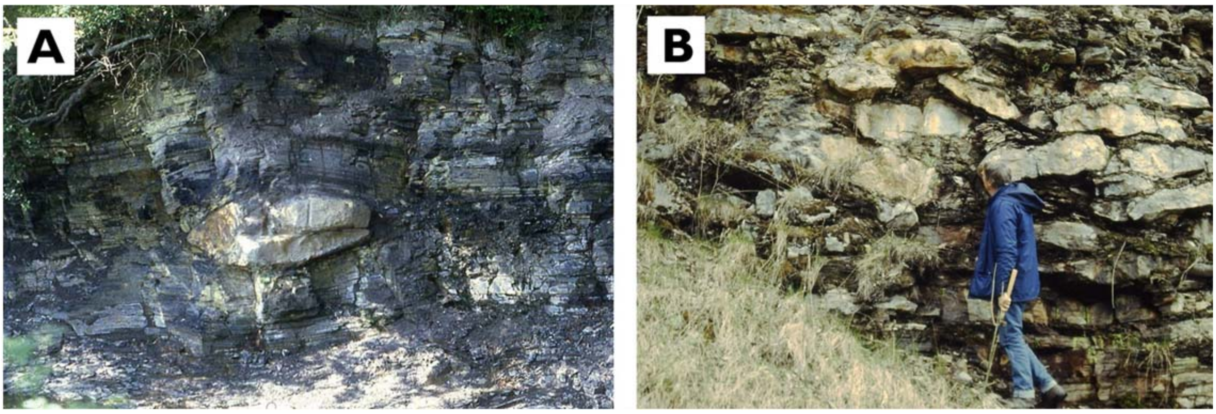

Figure 16: A. Anthraconite lens, offshore Alum Shale facies, Læså, Bornholm. B. Anthraconite layers and stacked lenses, midshelf Alum Shale facies, Kinnekulle, Västergötland.


Figure 17: Exhumed and partially dissolved limestone concretions, *P. minor* Superzone, Västergötland. A horizon with these characteristic exhumed limestones are seen in several abandoned quarries on Kinnekulle. They witness reworking of Alum Shale mud and at the same time the concretions seem to have suffered dissolution, probably because of introduction of oxygen, reacting with pyrite in the sediment.

Figure 18: Barite in Alum Shale, Billegrav-2 core (Bornholm), interval 100.115-100.20 m.

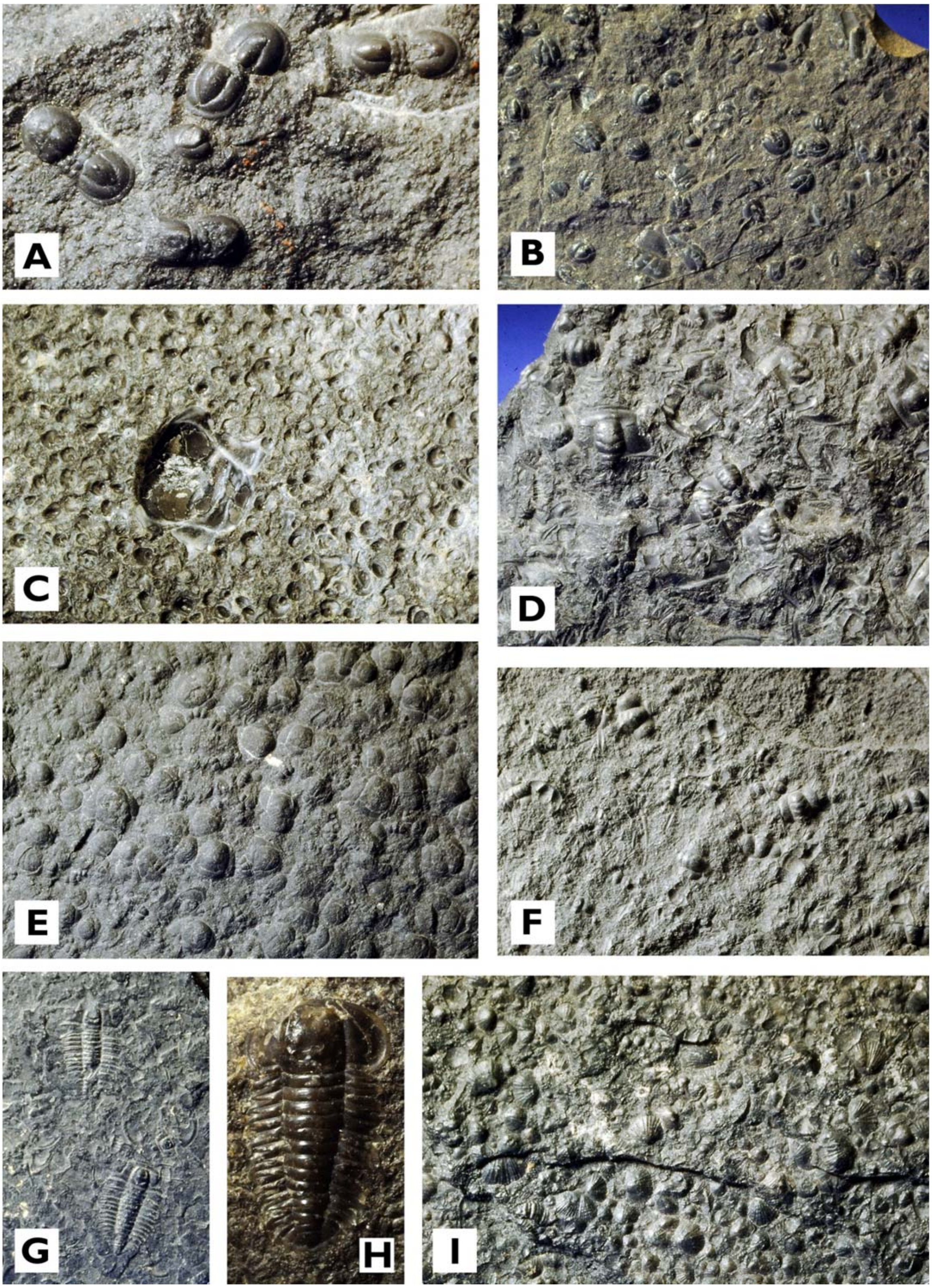

Figure 19: Examples of fossils, mostly trilobites, from the Alum Shale, showing the abundance of fossils on bedding planes. Not photographed at the same magnification. A-C: Middle Cambrian agnostids; on C also large head of *Paradoxides*. D-I: Furongian fossils. D: *Olenus*. E: *Peltura* and *Ctenopyge* (small), E: *Ctenopyge* and *Sphaerophthalmus* (small), G: *Olenus*, H: *Peltura*, I: *Orusia* (brachiopod).

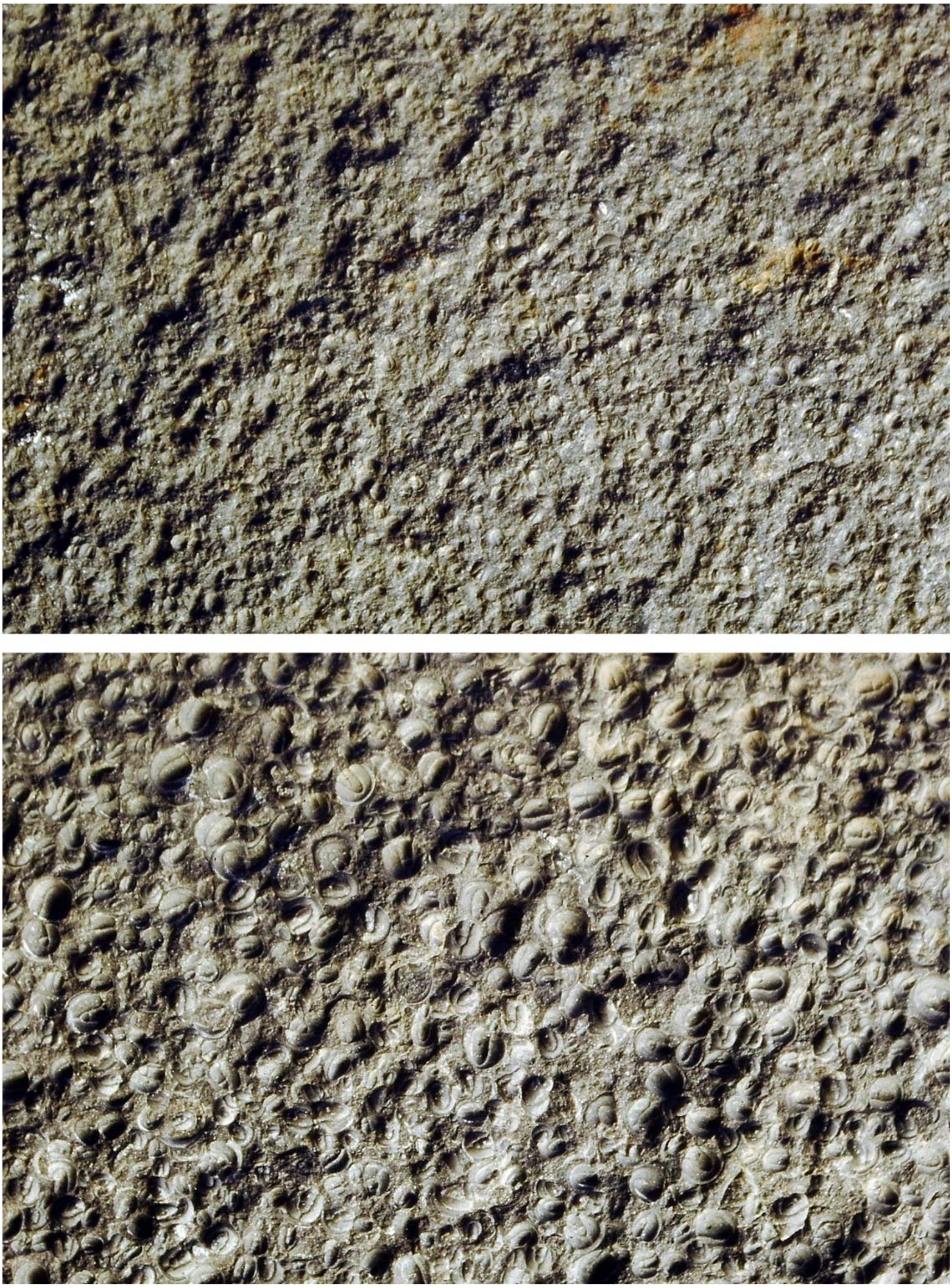

Figure 20: Two bedding surfaces photographed at same magnification, showing size sorting of *A. pisiformis* cephala and pygidia due to transport. Kinnekulle, Västergötland.

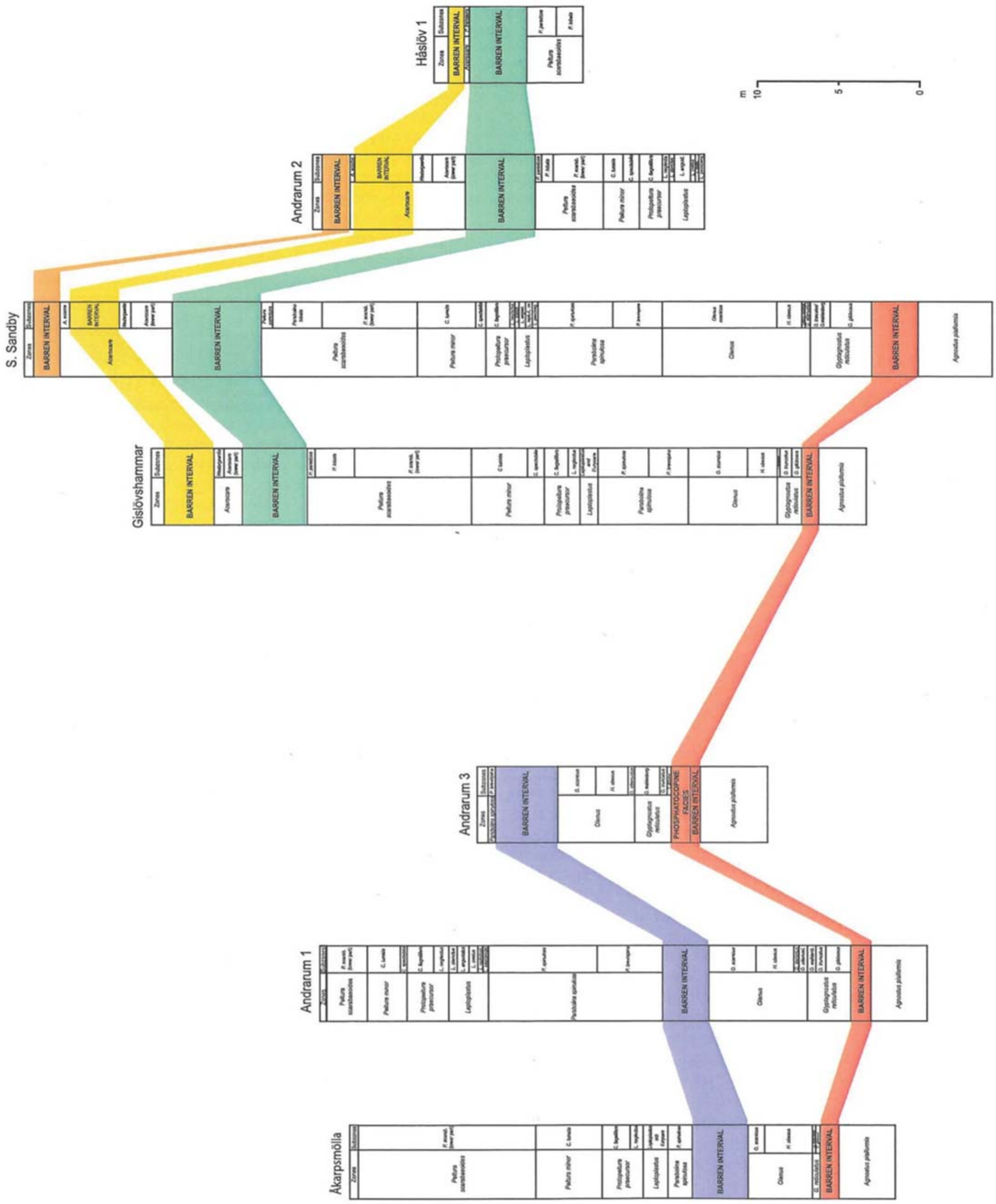

Figure 21: Stratigraphic distribution of Furongian unfossiliferous 'barren intervals' in Scanian drillcores. (From Terfelt 2006, fig. 9).

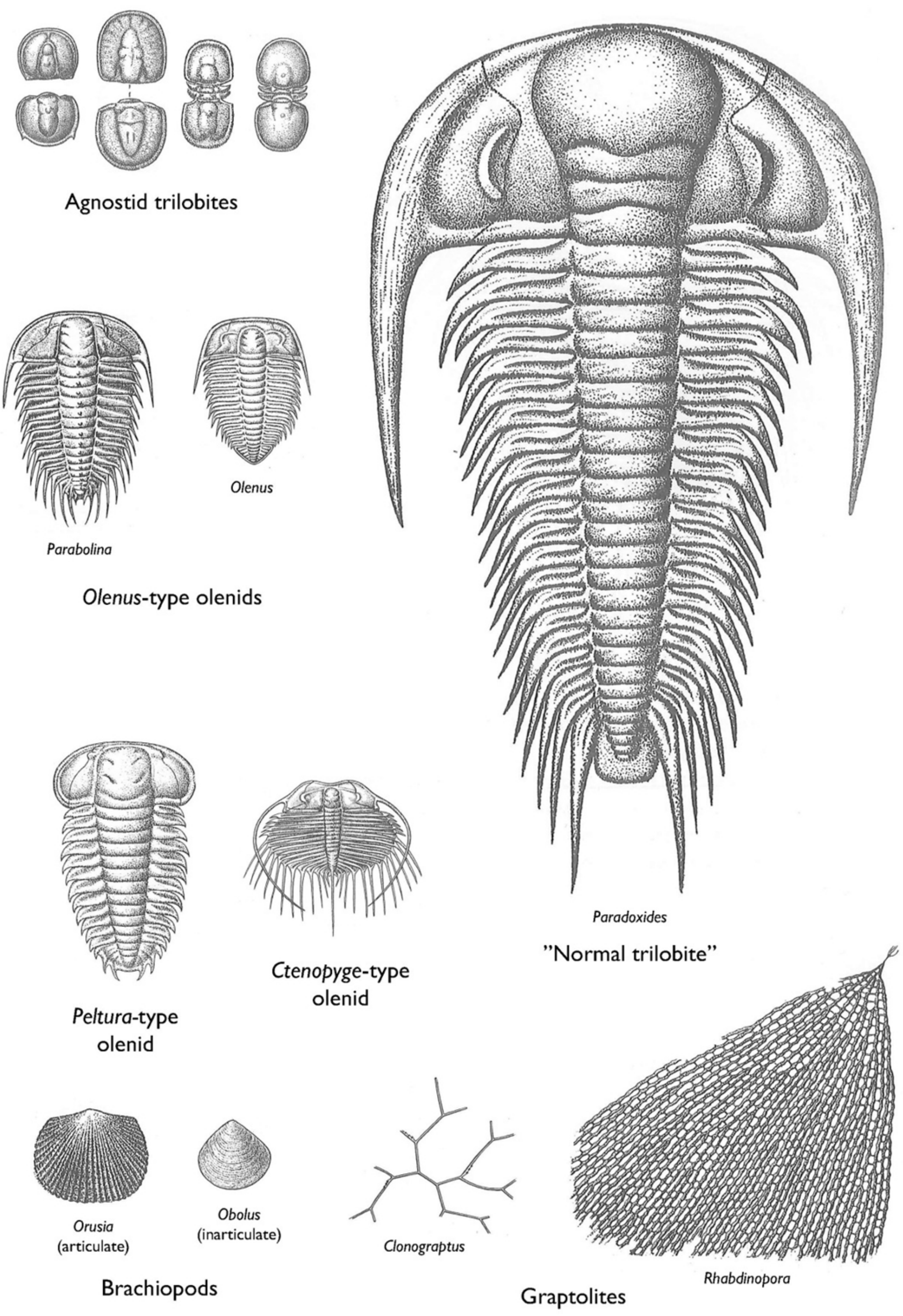

Figure 22: Common fossils from the Alum Shale; not to scale. In most agnostid trilobites the cephalon/pygidium is less than 5 mm long. Among olenids, representatives of *Peltura* and *Parabolina* attain the largest sizes, whereas *Ctenopyge* and *Sphaerophthalmus* (not shown) are smallish. The brachiopod *Orusia* is extremely common, even rockforming, in the *Parabolina* Superzone and *Obolus* (and allies) is very common in the Tremadocian.

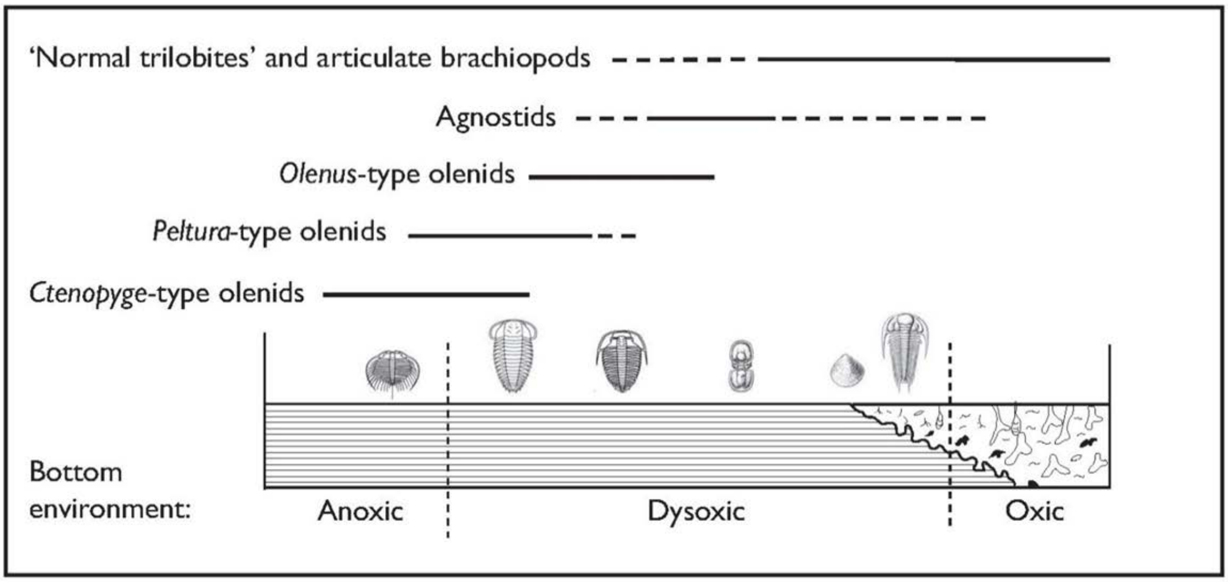

Figure 23: Schematic illustration showing inferred environmental tolerance of faunal types in the Alum Shale.

Figure 24: A. "Funnel graben" in Lower Cambrian sandstone, east coast of Scania, Sweden. Some of the larger cones in the area have a core of disturbed Alum Shale, showing that subsidence took place during the Furongian. See text for discussion. B. Clastic dyke on bedding plane adjacent to "funnel graben". Lower Cambrian sandstone, east coast of Scania, Sweden.

5. Isocore maps

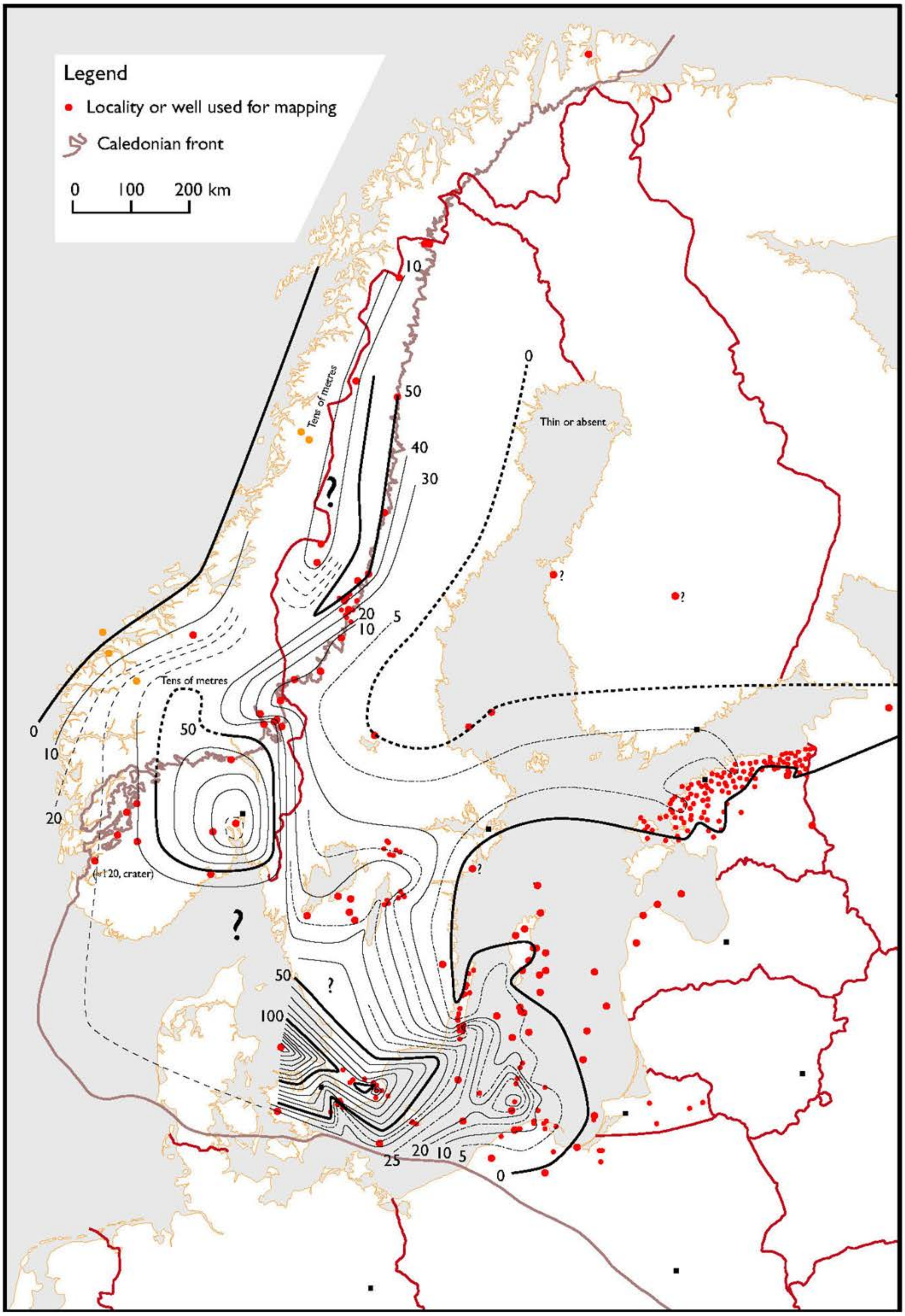

Figure 25: Isopach map showing the total thickness of the Alum Shale Formation in Baltoscandia. Data compiled from the literature and various unpublished well reports.

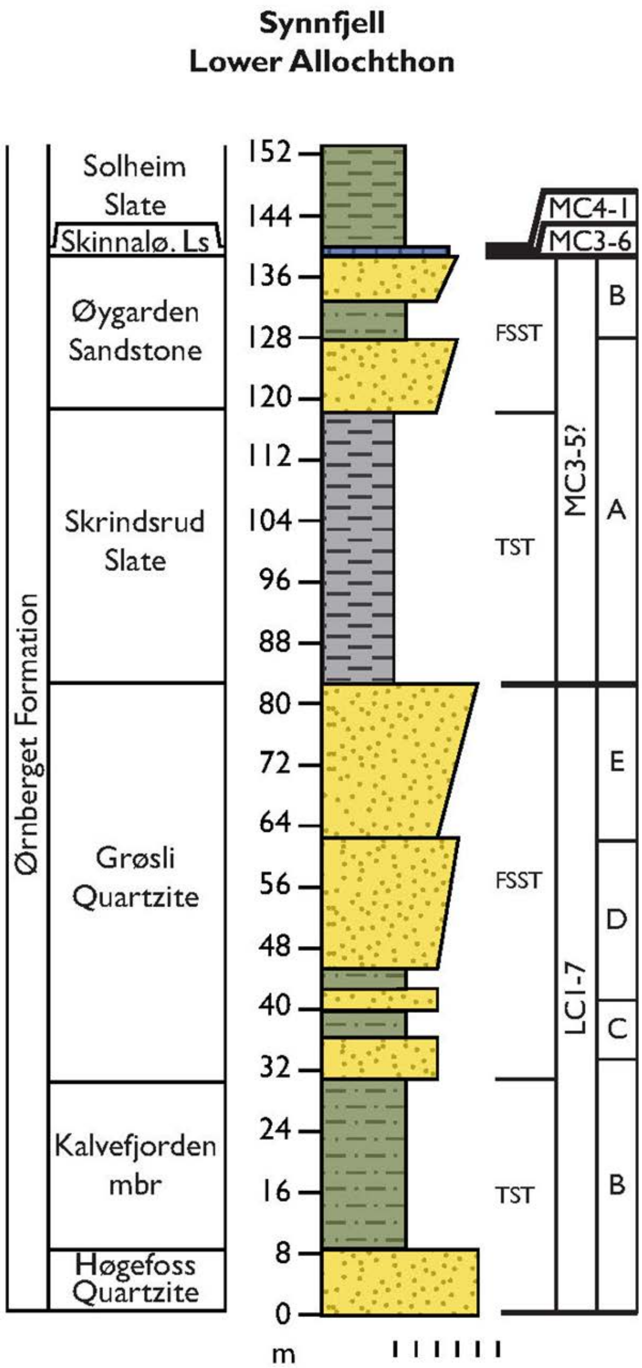

Figure 26: Tentative sequence stratigraphical interpretation of Middle Cambrian strata in the Lower Allochthon at Synfjell (from Nickelsen et al. 1985). Middle Cambrian paradoxidid trilobites have been found in the Skrindsrud Slate, but they could not be determined. The overlying thin Skinnaløkstølen limestone seems to consist of amalgamated limestones representing the *T. gibbus* Zone (Forsemölla or Exsulans equivalent) and the *S. brachymetopa* Zone (Andrarum Limestone equivalent) (unpublished data). The Øygarden Sandstone shows that sediment must have been supplied from the west in the early Mid Cambrian.

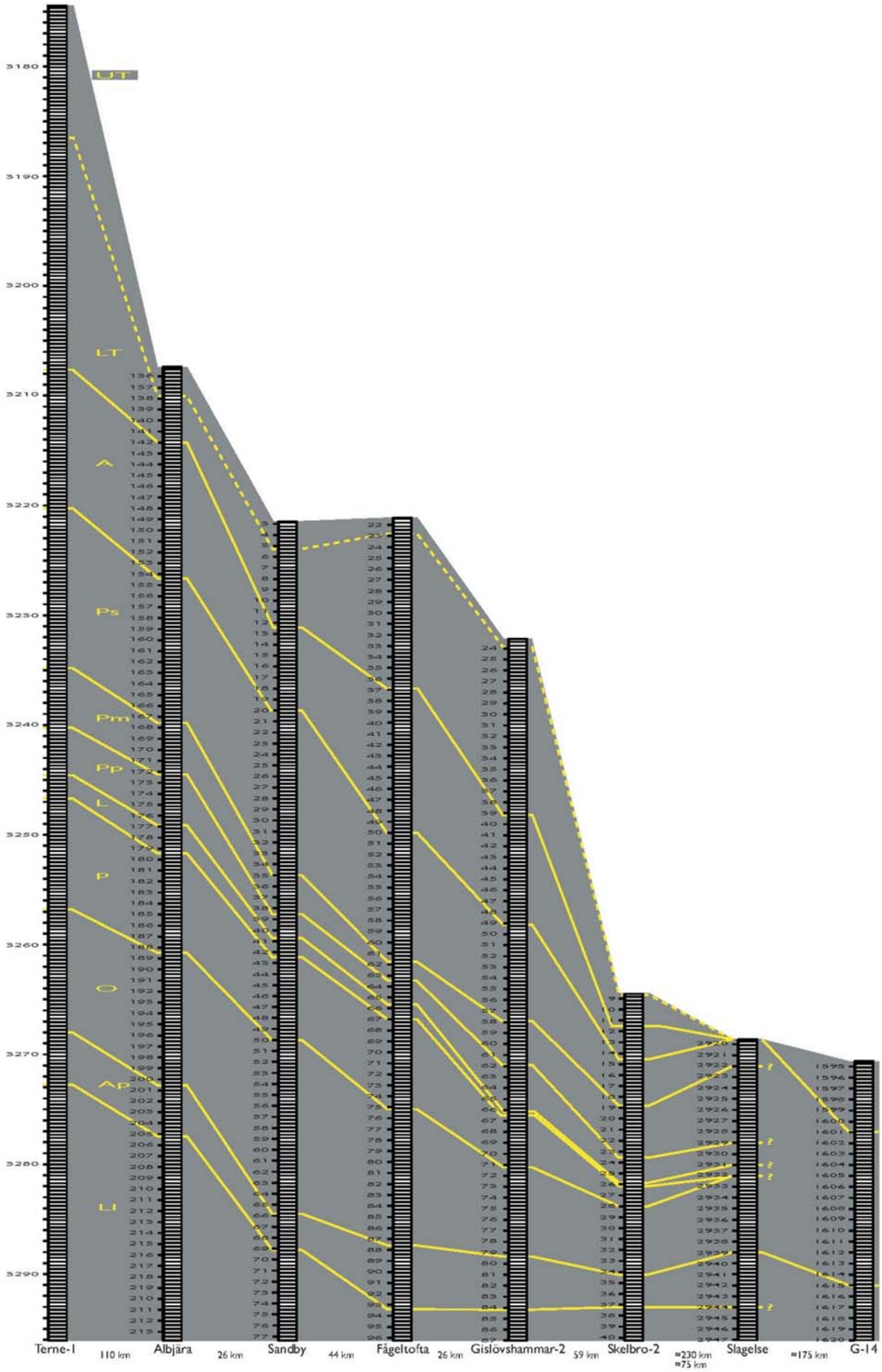

Figure 27: Section across southernmost Scandinavia from the offshore German well G-14 to Terne-1 showing thickness distribution of upper Middle Cambrian to Tremadocian strata. Yellow lines indicate biozonal boundaries. Sections plotted from the top of the Andrarum Limestone Bed. No sequence boundaries are indicated; they have no physical expression in this offshore area and must be tentatively deduced from the biostratigraphy. Note, however, that lowstand intervals are expanded and highstand intervals condensed (compare Fig. 56).

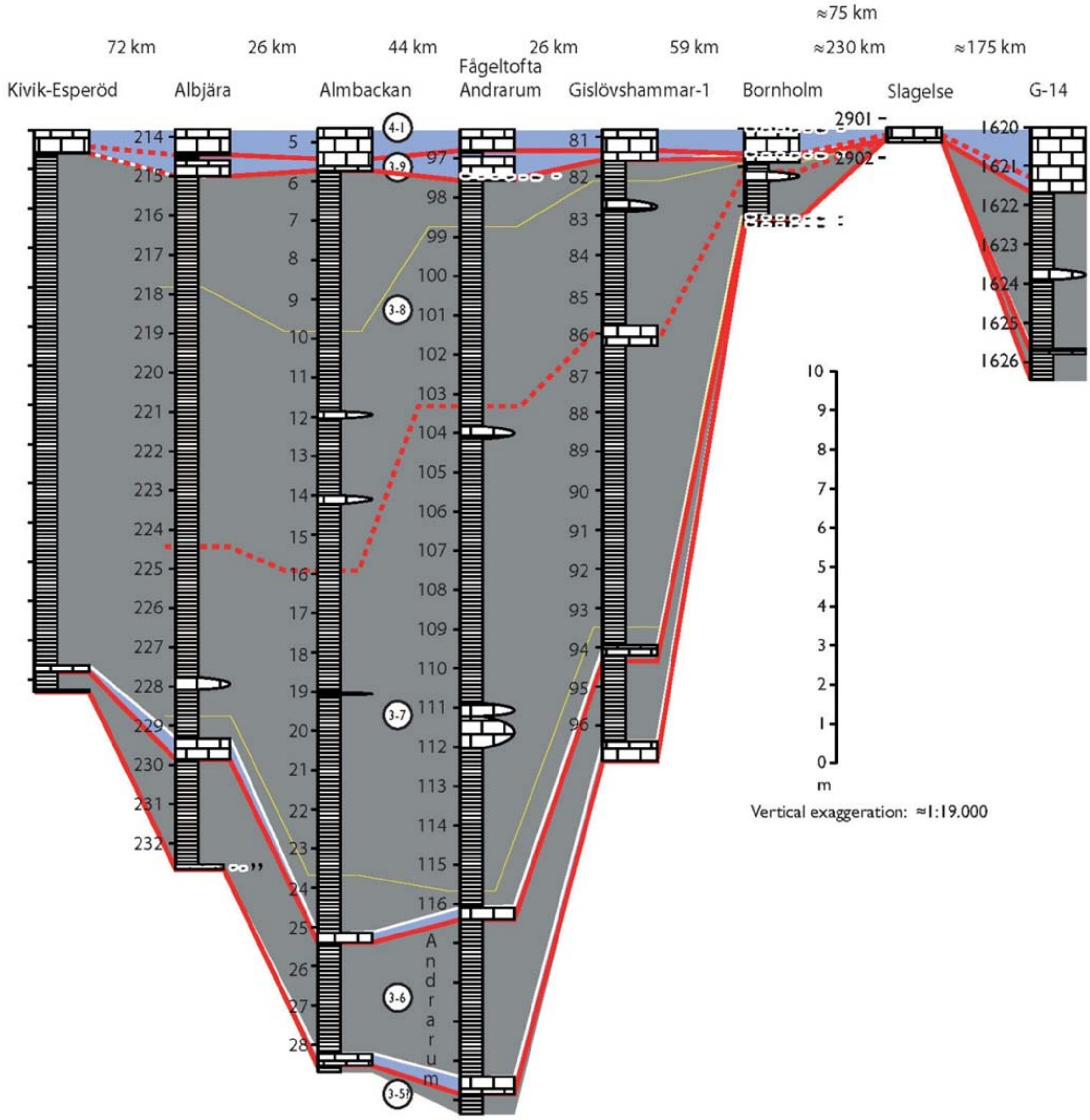

Figure 28: Section across southernmost Scandinavia from the offshore German well G-14 to NE Scania showing thickness distribution of Middle Cambrian sequences. Yellow lines show biozonal boundaries. Sections plotted up to the top of the Andrarum Limestone Bed.

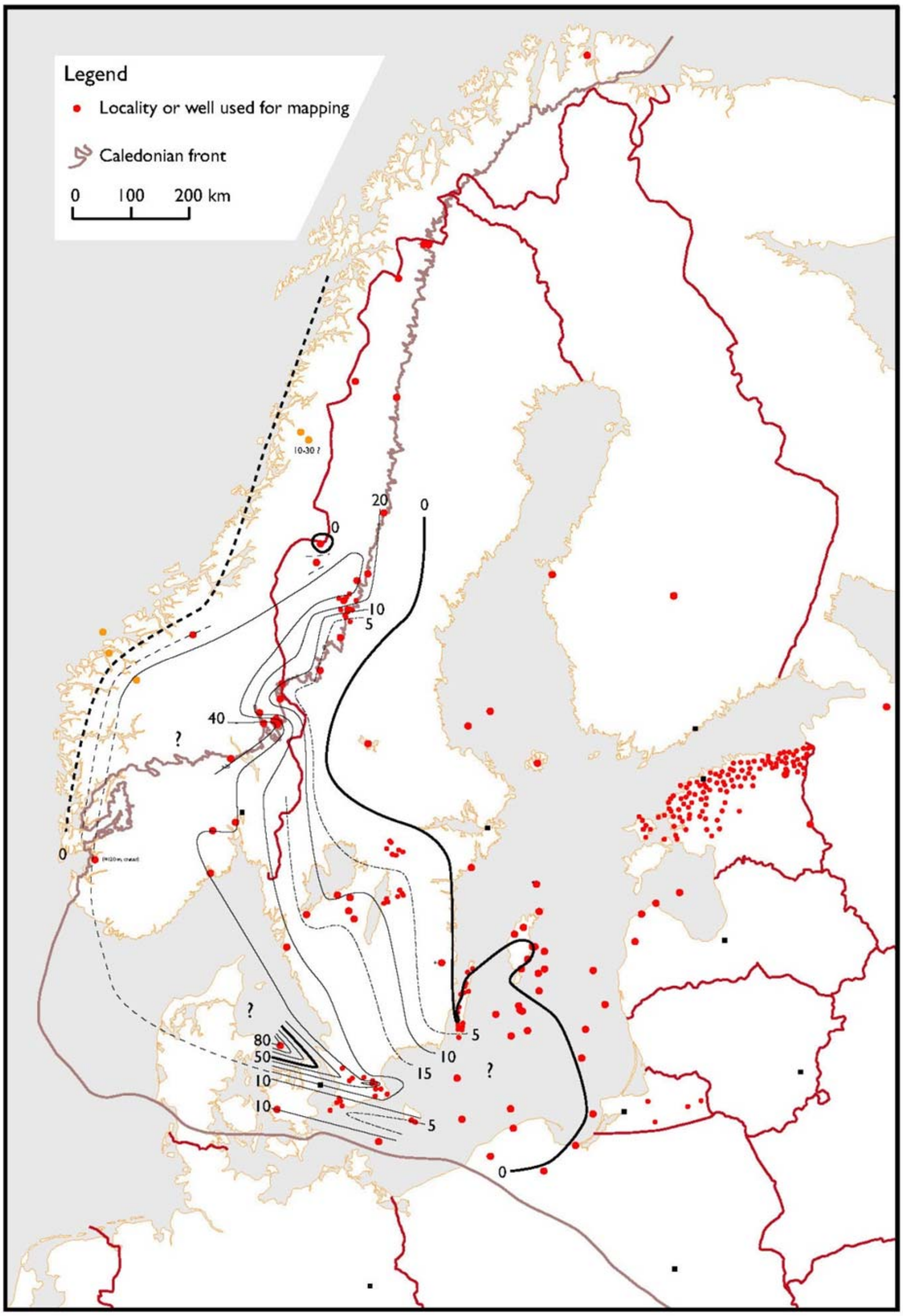

Figure 29: Isopach map showing the thickness of the Middle Cambrian interval of the Alum Shale Formation in Baltoscandia. Coeval mudstones of the Borgholm Fm are not included. The map outlines a depocenter in SW Scandinavia. Another Mid Cambrian depocenter was located in the Baltic area (Fig. 44). The presence of two depocenters reflects that much of central Scandinavia remained uplifted well into the Mid Cambrian (Hawke Bay Event) but sediment was also supplied from a western source early in the Mid Cambrian, as indicated by the local presence of sandstone units in the Lower Allochthon of southern Norway (Fig. 26). Some mining of sediments may also have taken place in the still uplifted area of Scandinavia. The Middle Cambrian of Jämtland includes thin interbeds of coarser, even gravelly sediment (Karis 1998), also suggestive of a not too distant source area.

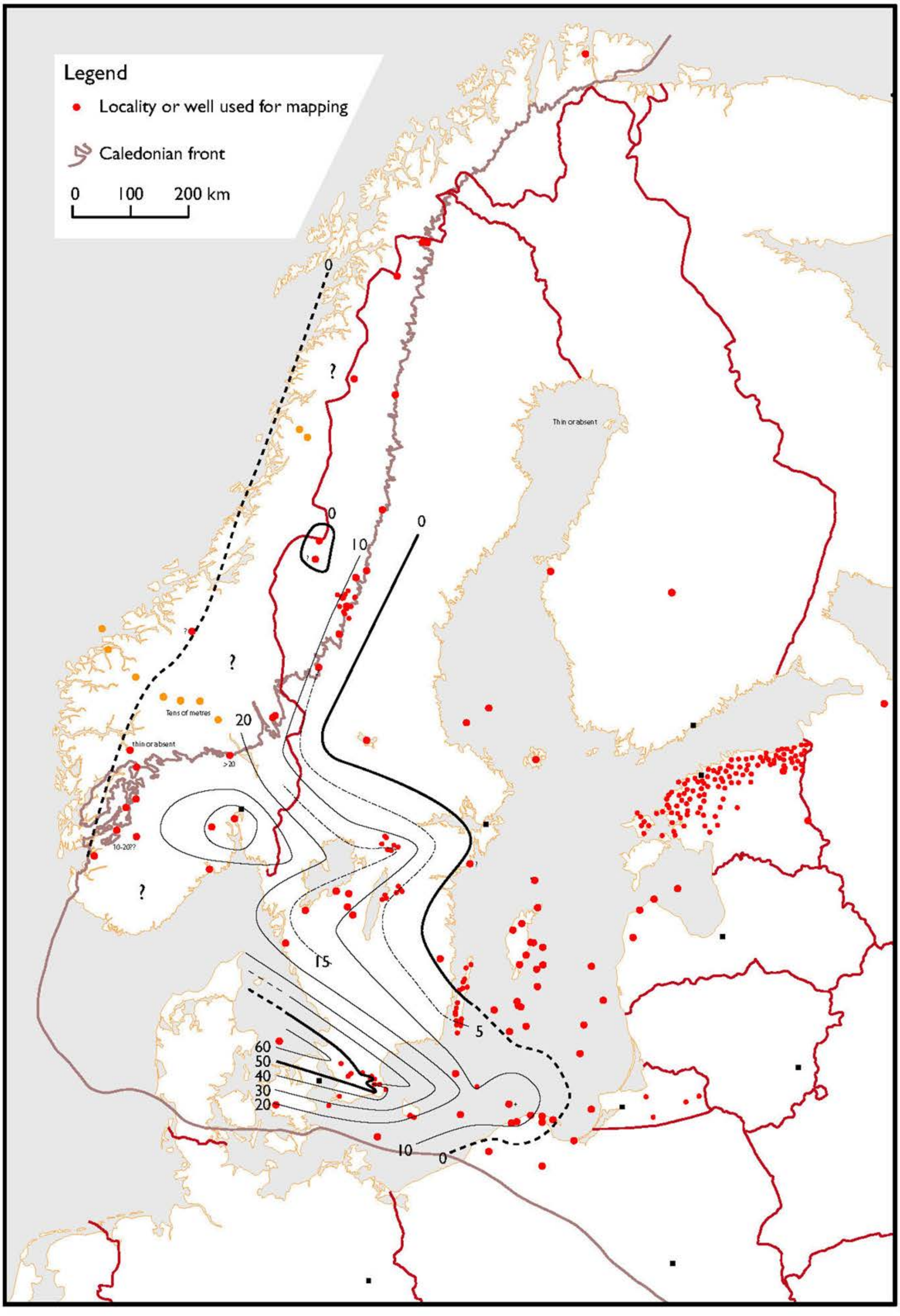

Figure 30: Isopach map showing the thickness of the Furongian interval of the Alum Shale Formation in Baltoscandia.

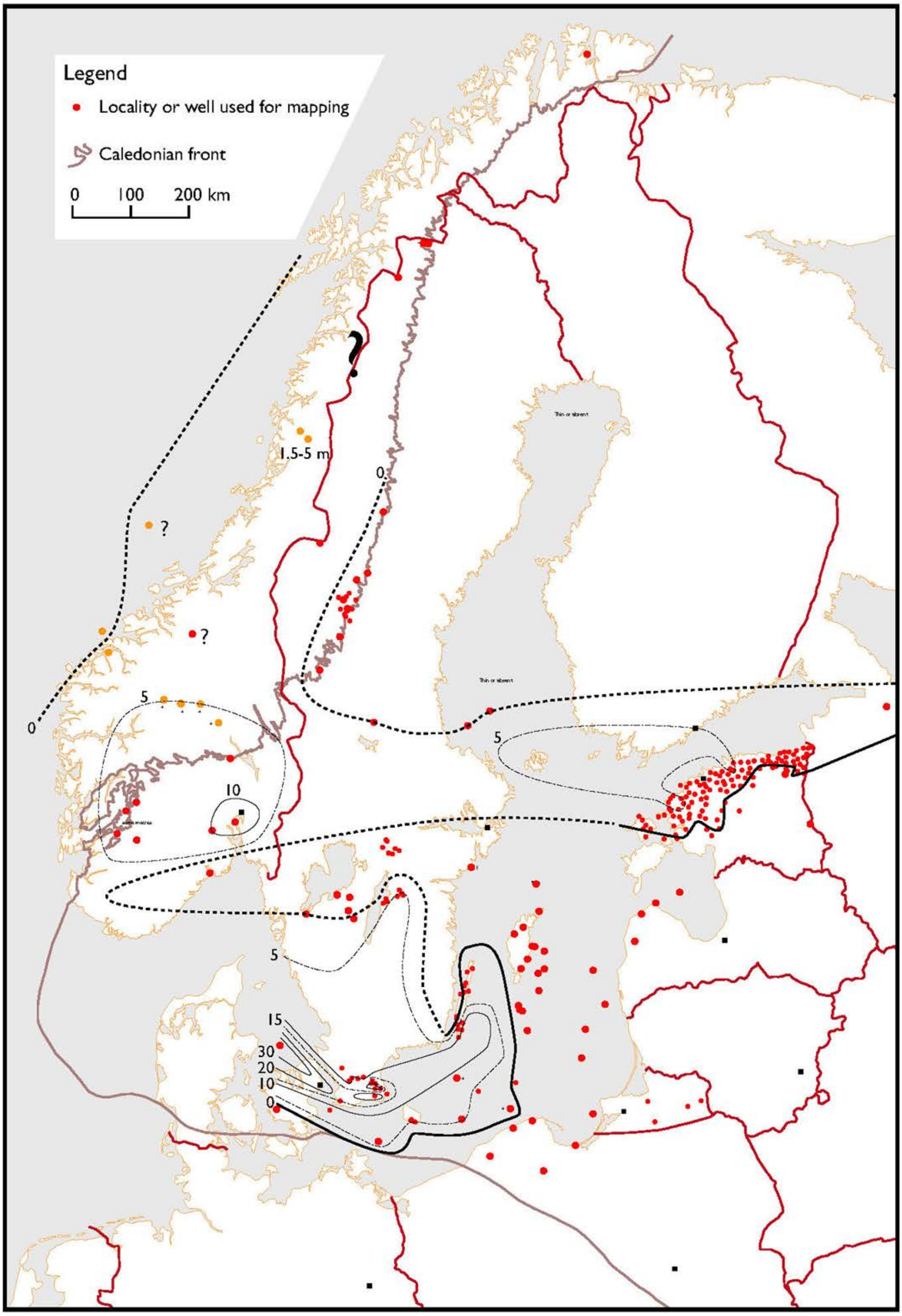

Figure 31: Isopach map showing the thickness of the Tremadocian interval of the Alum Shale Formation in Baltoscandia.

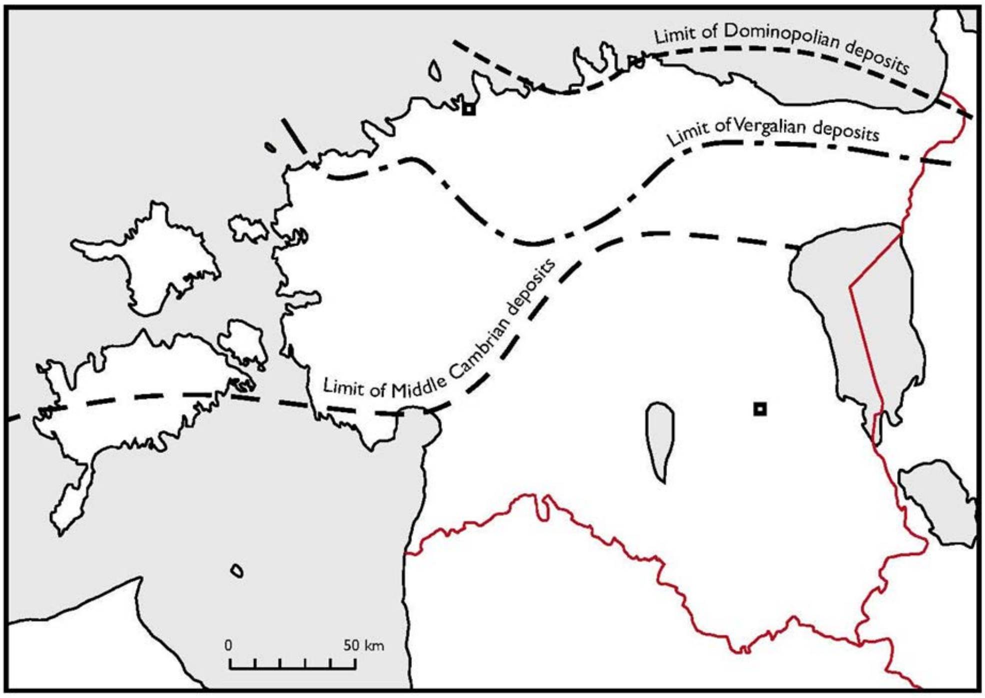

Figure 32: Map showing erosional limits of Lower and Middle Cambrian deposits in Estonia. The eroded units are unconformably overlain by various Middle Cambrian (Russia), Furongian and Ordovician units, evidencing that it is an angular unconformity. Uplift and erosion took place during the mid Middle Cambrian, see text for discussion. Map based on data from Mens & Pirrus (1997).

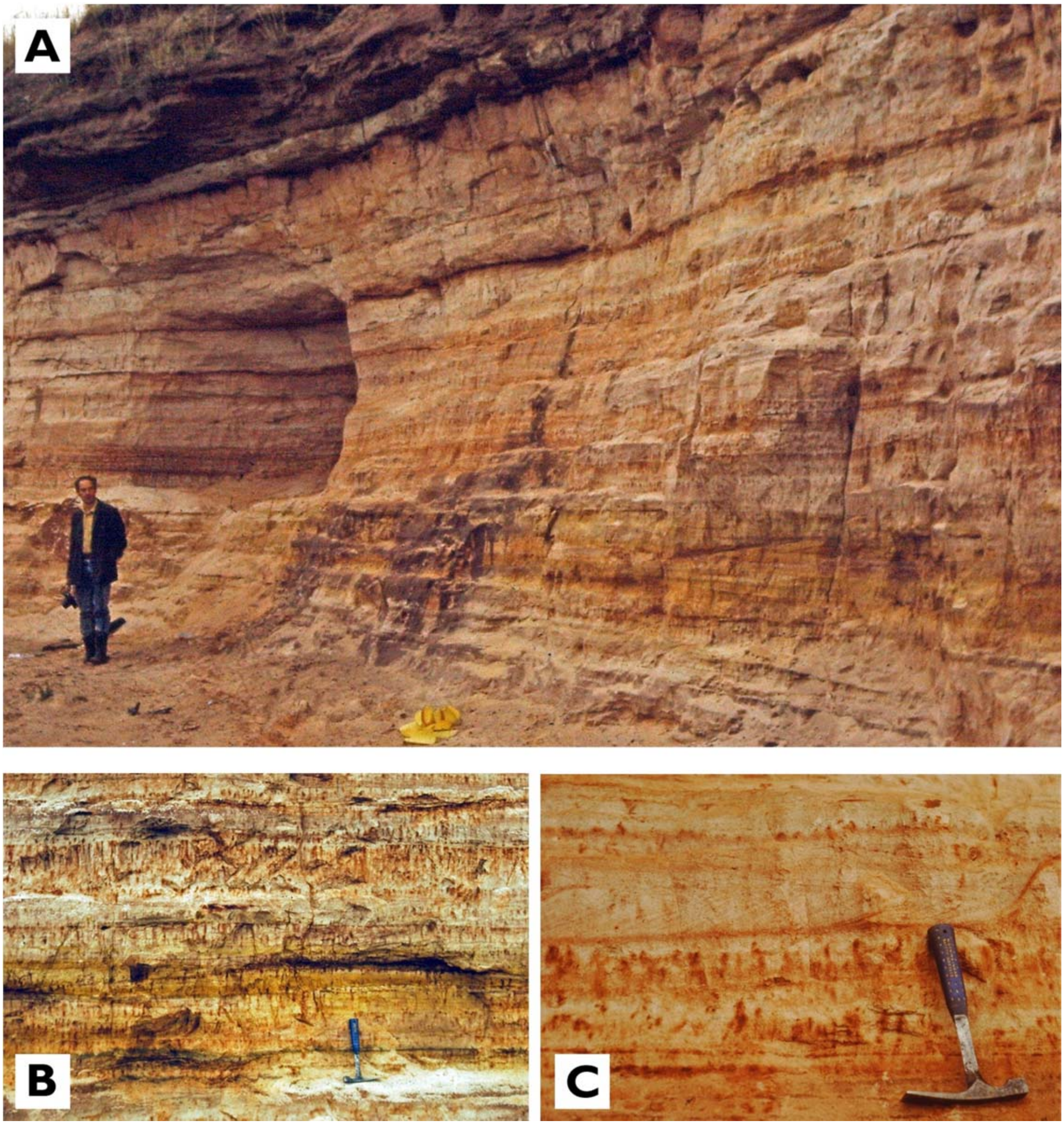

Figure 33: Shallow marine Sablinka Fm (Middle Cambrian), Tosna River, St. Petersburg district, Russia. The unit rests unconformably on the Lower Cambrian Lontova Fm. A. Section in sand pit (the unit is not cemented). The formation is overlain by a thin veneer of Furongian sand, the Ladoga Fm, in turn overlain by Tremadocian sand, the Tosna Fm. B. Close up of *Skolithos* in the Sablinka Fm. C. Close up of herringbone cross-stratification in the Sablinka Fm.

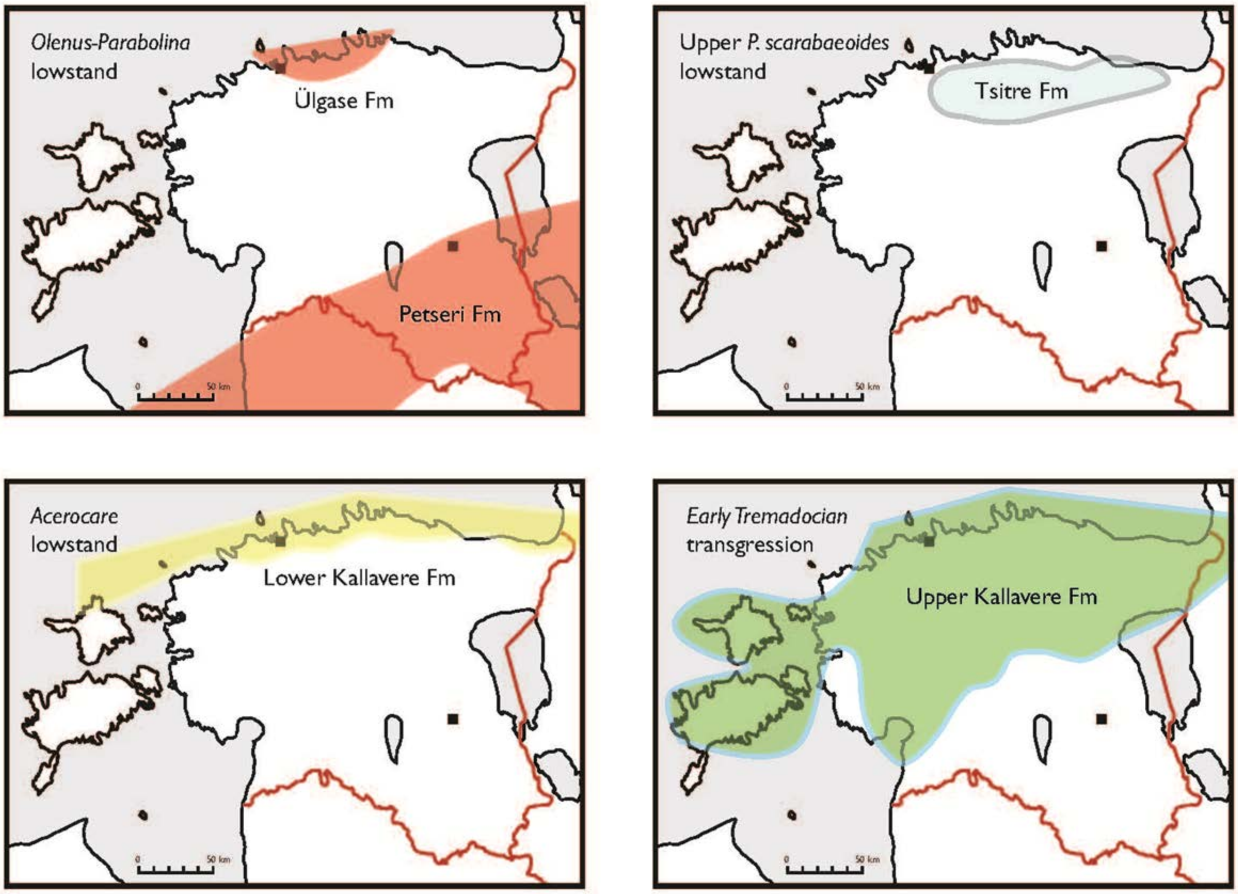

Figure 34: Map showing distribution of Furongian and Early Ordovician sand units in Estonia. The Furongian units are interpreted as detached lowstand sands, deposited on the flanks of the uplifted central part of Estonia during incipient sea level rise in the aftermath of major lowstands. The uplift collapsed at around the Furongian/Tremadocian boundary and Estonia subsided and Alum Shale was deposited during the Tremadocian. Map based on data from Mens & Pirrus (1997).

Figure 35: Holberg Quartzite, Hardangervidda, southern Norway. This unit is 15-60 m and overlies with a gradual contact the Alum Shale Formation (locally assigned to the Låven Fm) (Andresen 1978).

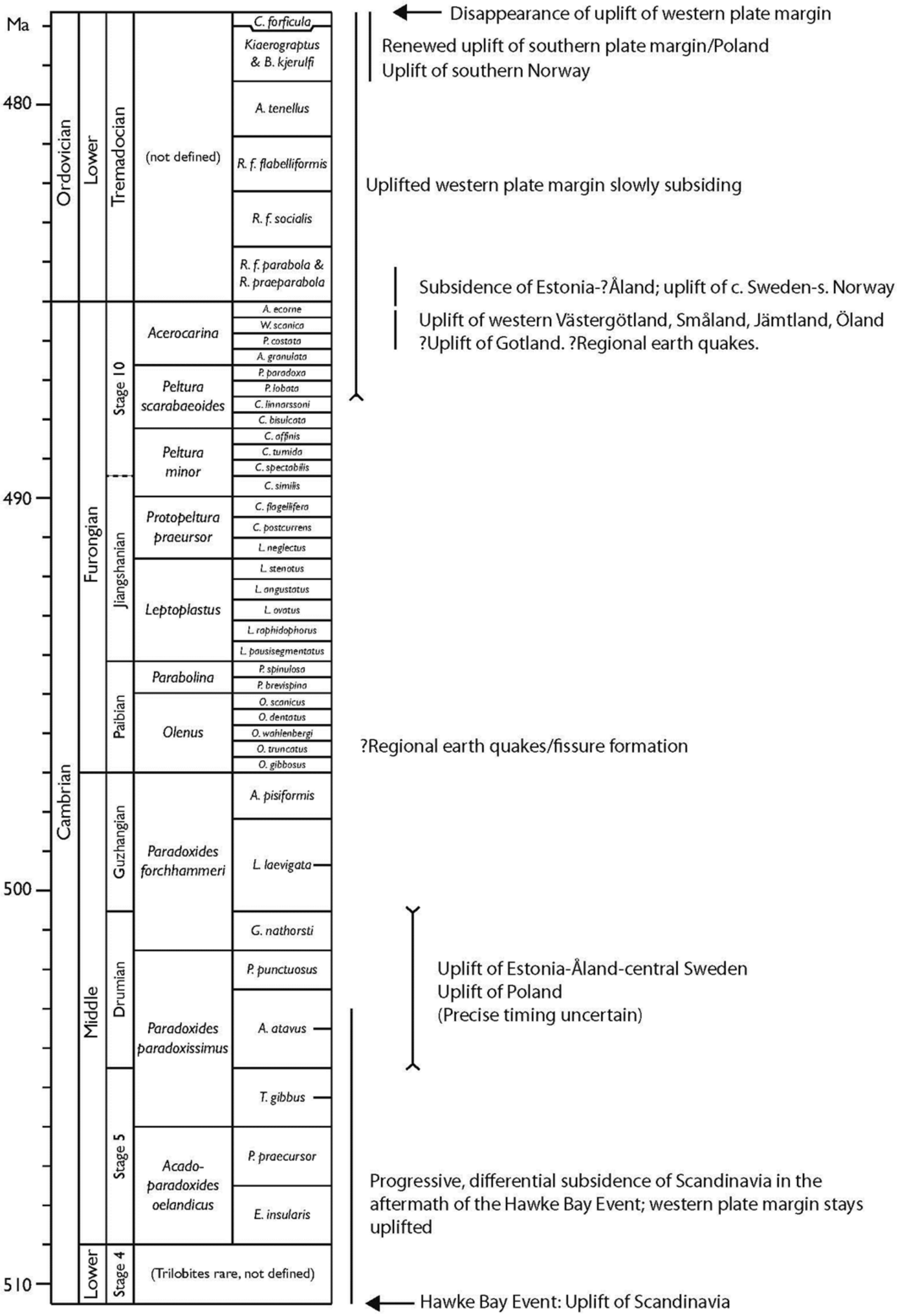

Figure 36: Timing of Mid Cambrian-Tremadocian isostatic disturbances in Baltoscandia, illustrated in Figs 37-38. See text for discussion. Time-lines bracketed by >< indicate that precise timing is uncertain within the indicated interval.

6. Palaeogeographical reconstructions

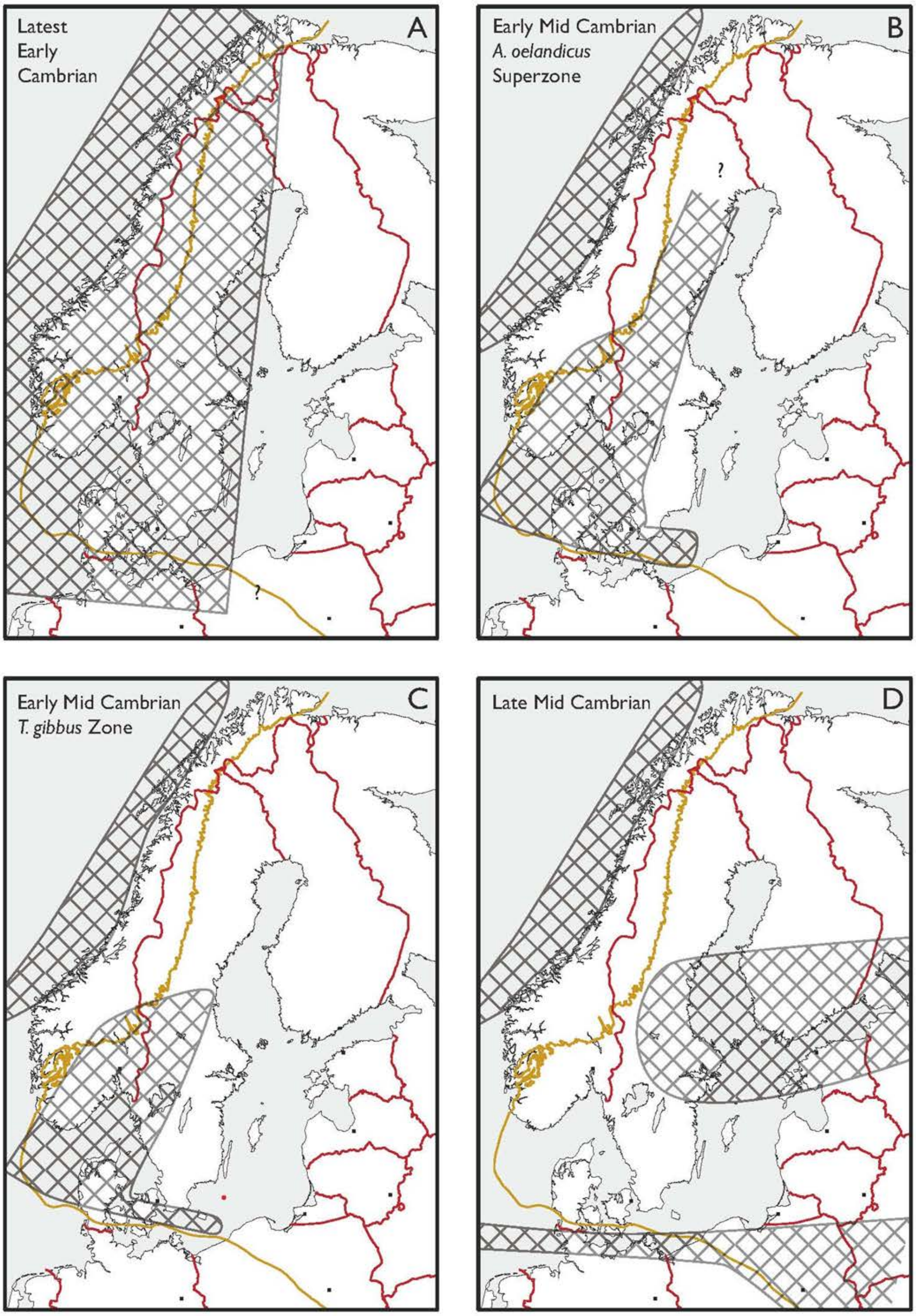

Figure 37: Synoptic maps showing uplifted areas in Scandinavia from latest Early Cambrian to Mid Cambrian, compare Figs 36 and 38. See text for discussion.

Alum Shale maps and diagrams

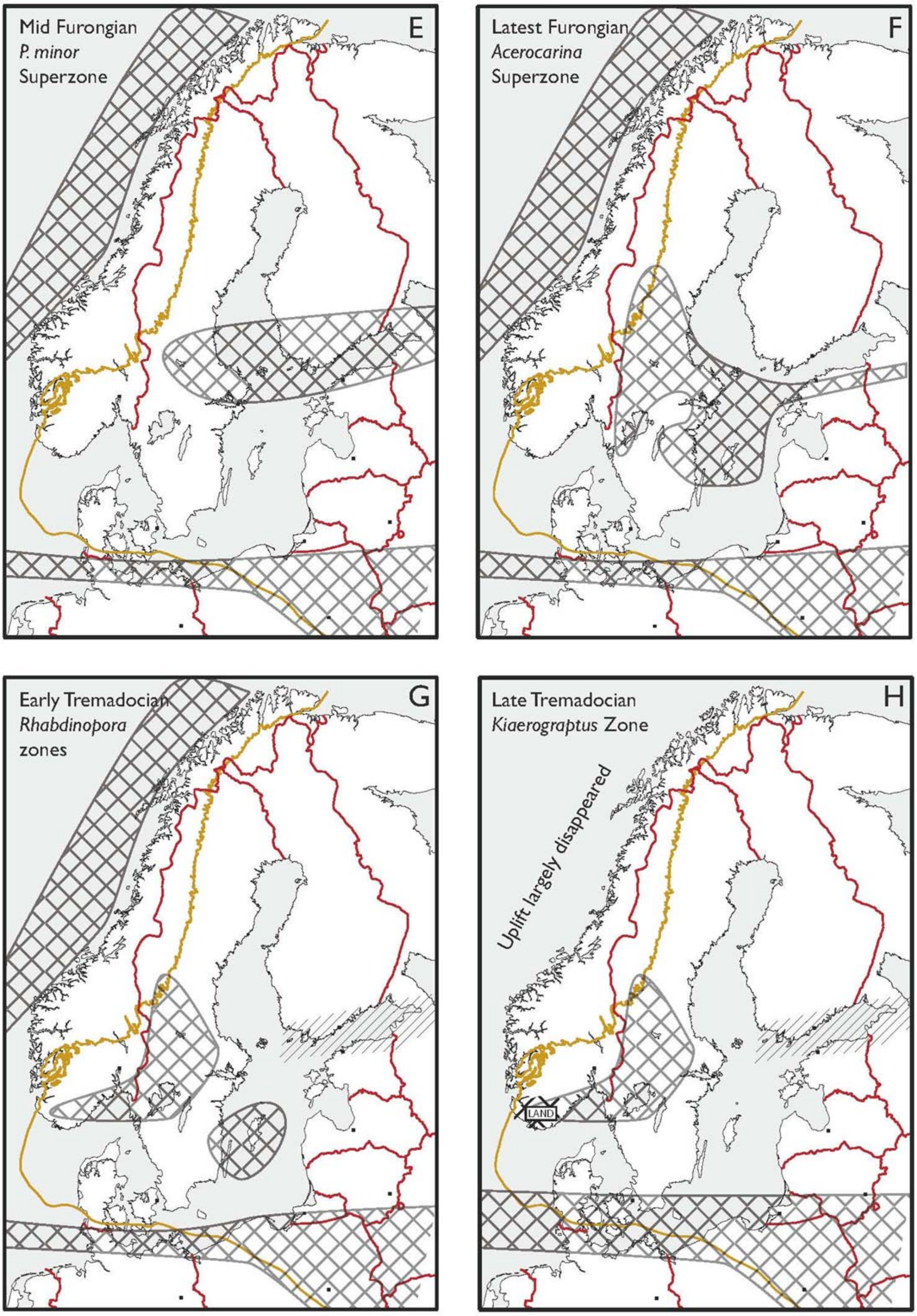

Figure 38: Synoptic maps showing uplifted and subsiding areas in Scandinavia during the Furongian-Tremadocian, compare Figs 36-37. See text for discussion.

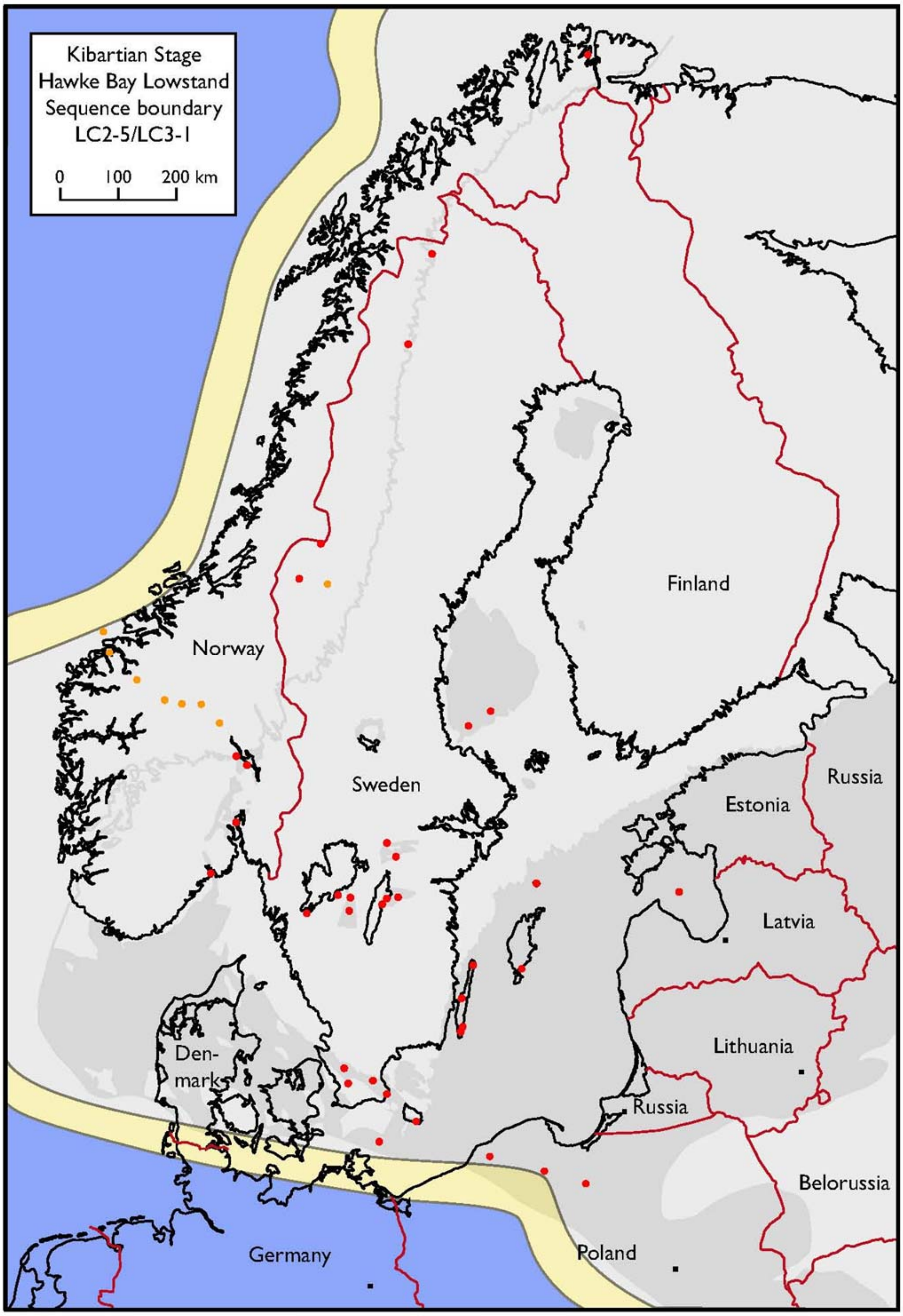

Figure 39: Map showing approximate extent of the Hawke Bay regression. Because of erosion during the following period with uplift precise data are scarce. It is uncertain whether the fringes of Baltica was uplifted but still submerged and characterized by non-deposition (see text). (From Nielsen & Schovsbo 2011, fig. 86).

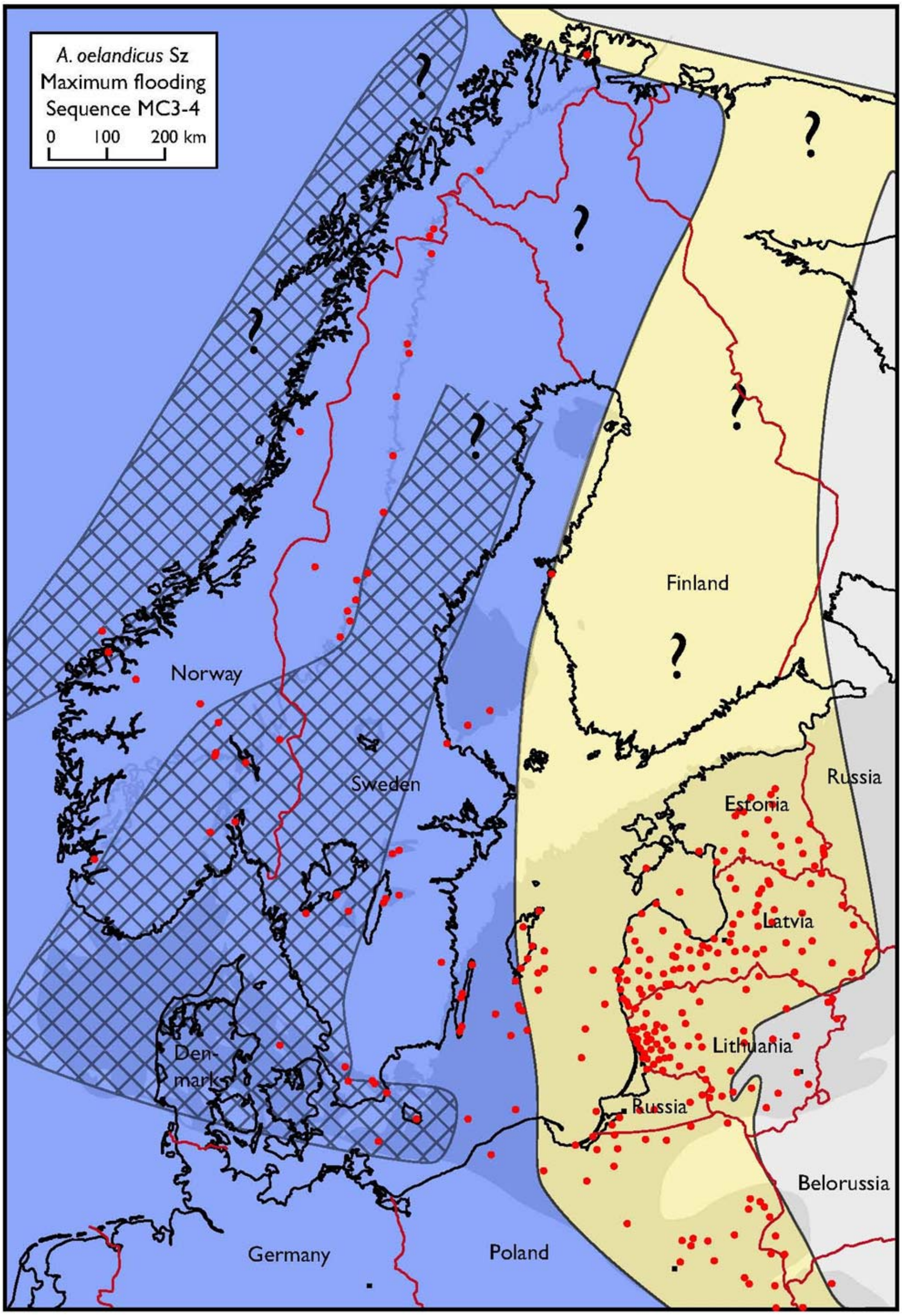

Figure 40: Palaeogeographical map showing maximum flooding conditions during deposition of sequence MC3-4. Regarding original positions of the displaced Parautochthon, Lower and Middle Allochthon, see Nielsen & Schovsbo (2011, p. 288). Interpretation of the northern part of the map area, including all of Finland, remains speculative. The inferred western uplift is also hypothetical. However, no Middle Cambrian strata have been recorded in the far-travelled Middle Allochthon of southern Norway, however (approximate original positions on the palaeoshelf suggested by the two most western orange locality markings on the map). Draft from unpublished manuscript on the Hawke Bay Event (Nielsen & Schovsbo in prep.).

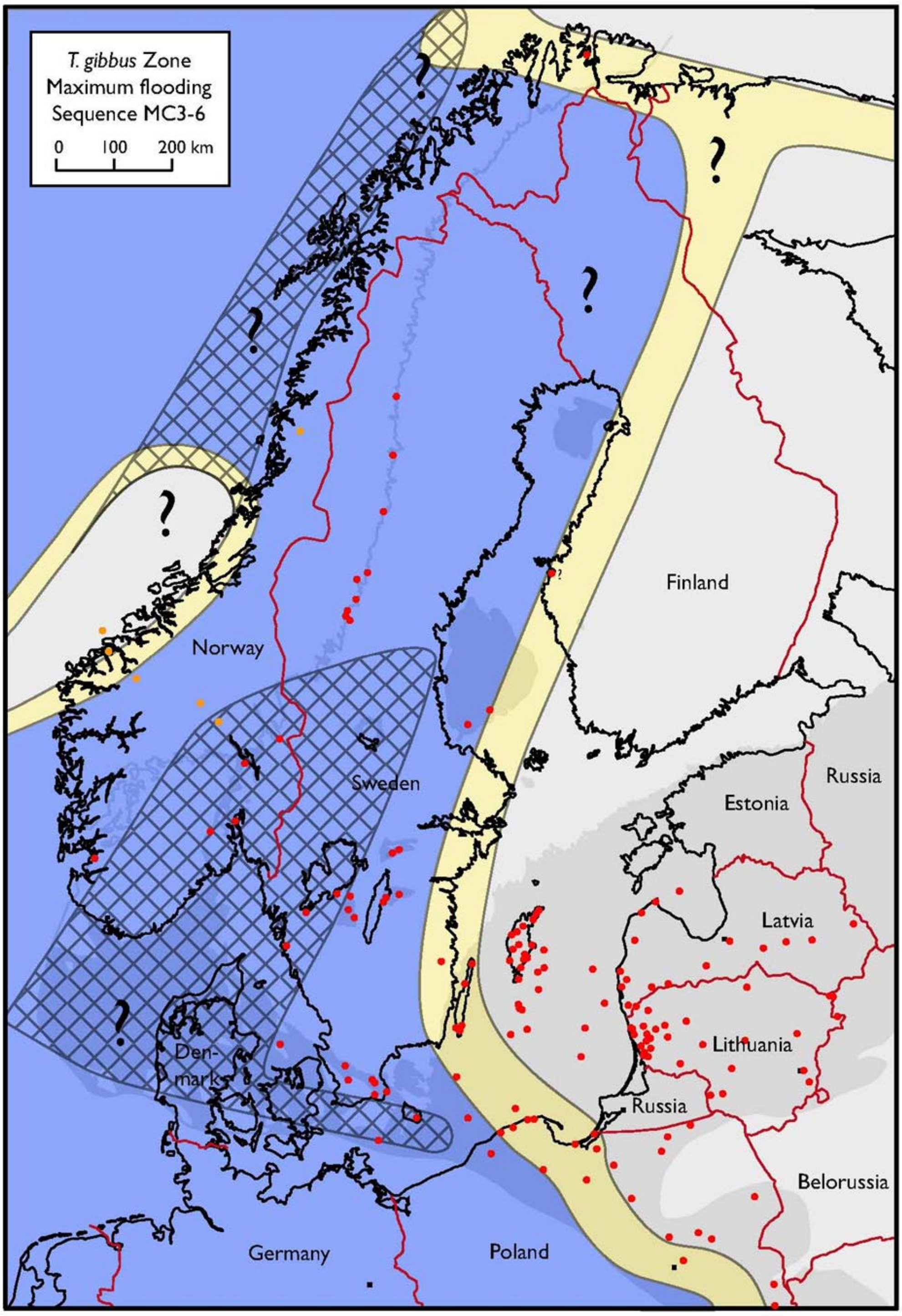

Figure 41: Palaeogeographical map showing maximum flooding conditions during deposition of sequence MC3-6. Regarding original positions of the displaced Parautochthon, Lower and Middle Allochthon (orange localities), see Nielsen & Schovsbo (2011, p. 288). Interpretation of the northern part of the map area, including all of Finland, remains highly speculative. The inferred western uplift is also hypothetical, but there must have been a land area west of the original position of the Lower Allochthon at Synfjell. No Middle Cambrian strata have been recorded in the far-travelled Middle Allochthon of southern Norway (approximate original positions on the palaeoshelf suggested by the two most western orange locality markings on the map). Draft from unpublished manuscript on the Hawke Bay Event (Nielsen & Schovsbo in prep.).

Figure 42: Basal conglomerate of the Alum Shale (locally referred to as the Türisalu Fm) at Paldiski peninsula, Estonia. The reworked boulders consist of Lower Cambrian Tiskre sandstone.

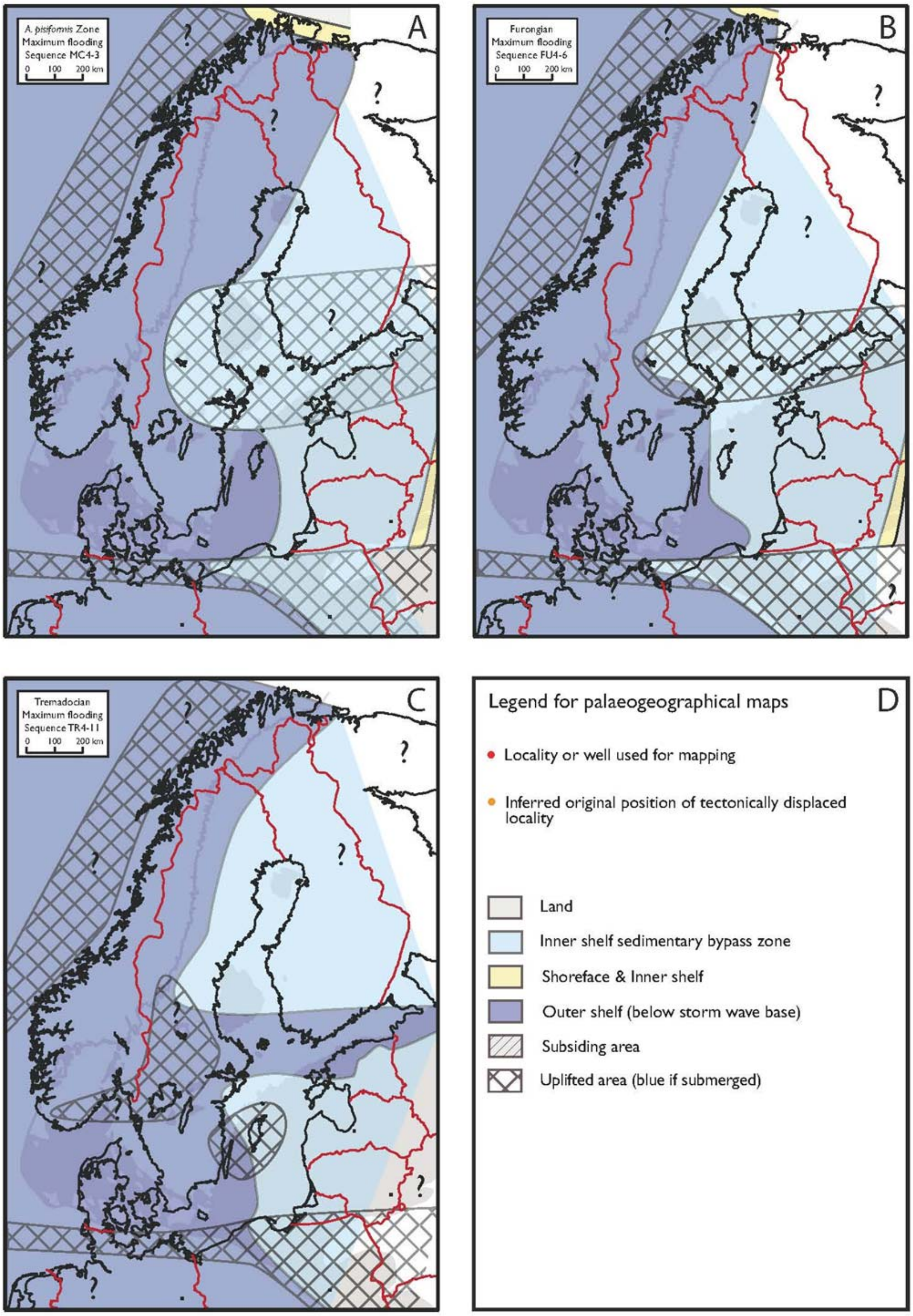

Figure 43: Conceptual palaeogeographical maps for the mid Mid Cambrian, Furongian and Tremadocian. It is unknown how deep the uplifted areas inferred along the western and southern margins were. The precise position of the eastern coast is uncertain. A. Maximum flooding conditions during deposition of sequence MC4-3 (*A. pisiformis* Zone). As far as can be established this was the highest sea level during the Mid Cambrian-Furongian. B. Maximum flooding conditions during deposition of sequence FU4-6 (*P. minor* Superzone). As far as can be established this was the highest sea level during the Furongian. C. Maximum flooding conditions during deposition of sequenceTR4-11 (*R. flabelliformis* Zone). As far as can be established this was the highest sea level during the Mid Cambrian-Furongian. D. Common legend for all palaeogeographical maps.

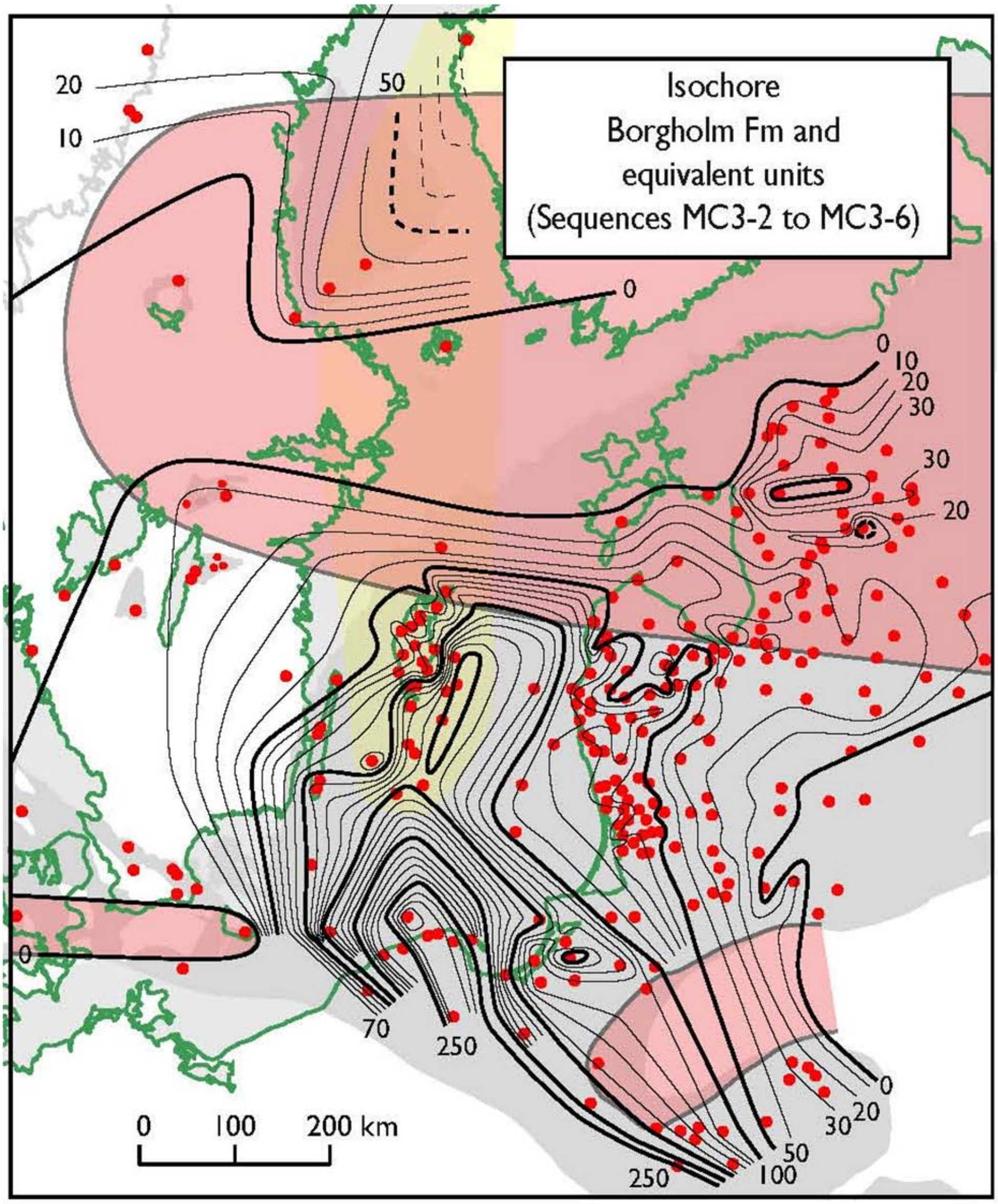

Figure 44: Isopach map of early Mid Cambrian strata (*A. oelandicus* Superzone). Please note that the thicknesses indicated for the Gotland area and adjacent offshore drillings as well as the Bothnian Sea includes the late Early Cambrian sequence LC2-5. These strata are just a few metres thick but cannot be differentiated unless detailed data are available. In the red-coloured areas (uplifts) the thicknesses are not original sedimentary thicknesses. Data compiled from Mens & Pirrus (1997), Brangulis (1985), Jankauskas (2002), Griegelis (1991), Hagenfeldt (1994), various unpublished OPAB well reports and other sources.

Figure 45: Alum Shale equivalent (Kaporye Fm), Tosna River, St. Petersburg, Russia. A thin veneer of Alum Shale extends as far east as to the Syes River at the southeastern part of Lake Ladoga.

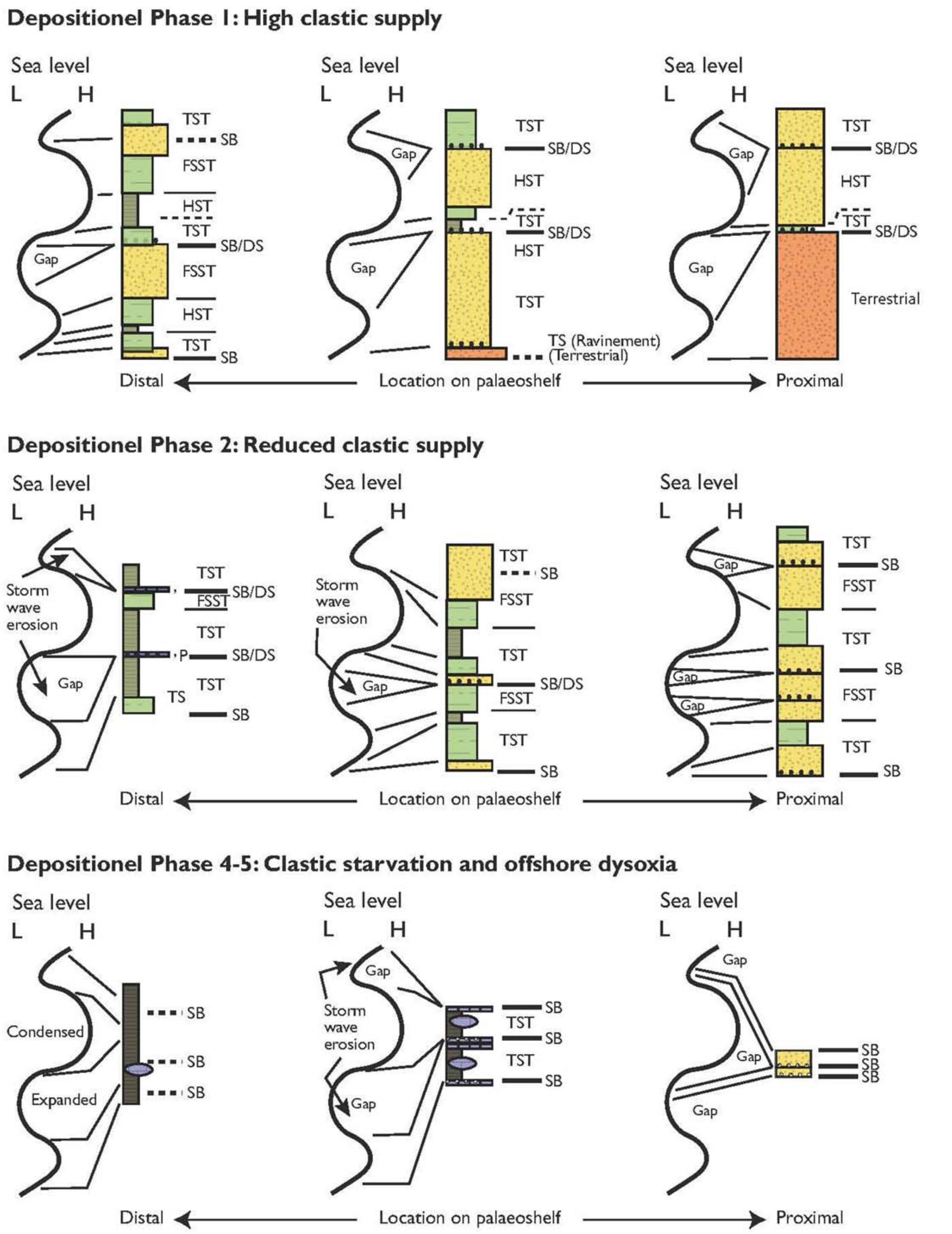

Figure 46: Conceptual logs of Cambrian sequences (compare Fig. 10). Standard sequence stratigraphical abbreviations explained in Nielsen & Schovsbo (2011) to whom the reader is also referred to for discussion of Lower Cambrian sequences. The preserved proximal successions shown for depositional phases 4-5 represent stacked lowstand sands (TST). It is likely that a quartz sandstone belt was located adjacent to the coast as hinted at in Fig. 10.

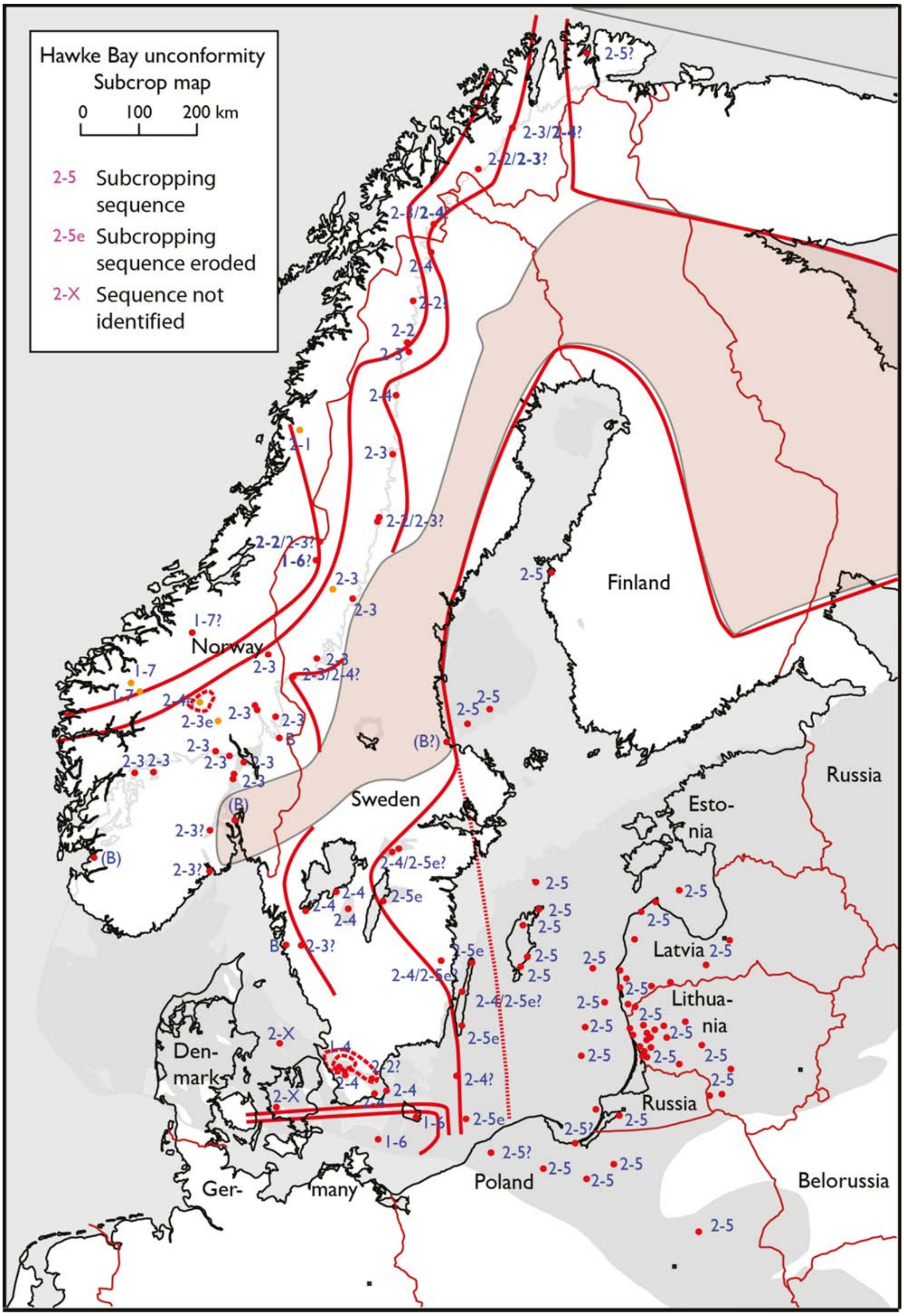

Figure 47A: Maps showing subcrop (age of sequence below unconformity). See Nielsen & Schovsbo (2011) regarding numbering of Lower Cambrian sequences (subcrop map). The central Swedish basement high without Lower Cambrian is shown in shading (from Nielsen & Schovsbo 2011). Several sites, where the Lower Cambrian has been removed by erosion during the Hawke Bay uplift so that Alum Shale rest directly on basement, have been omitted for simplicity. The Lower Cambrian west of the Bothnian Bay-Baltic Sea was eroded during the Hawke Bay uplift.

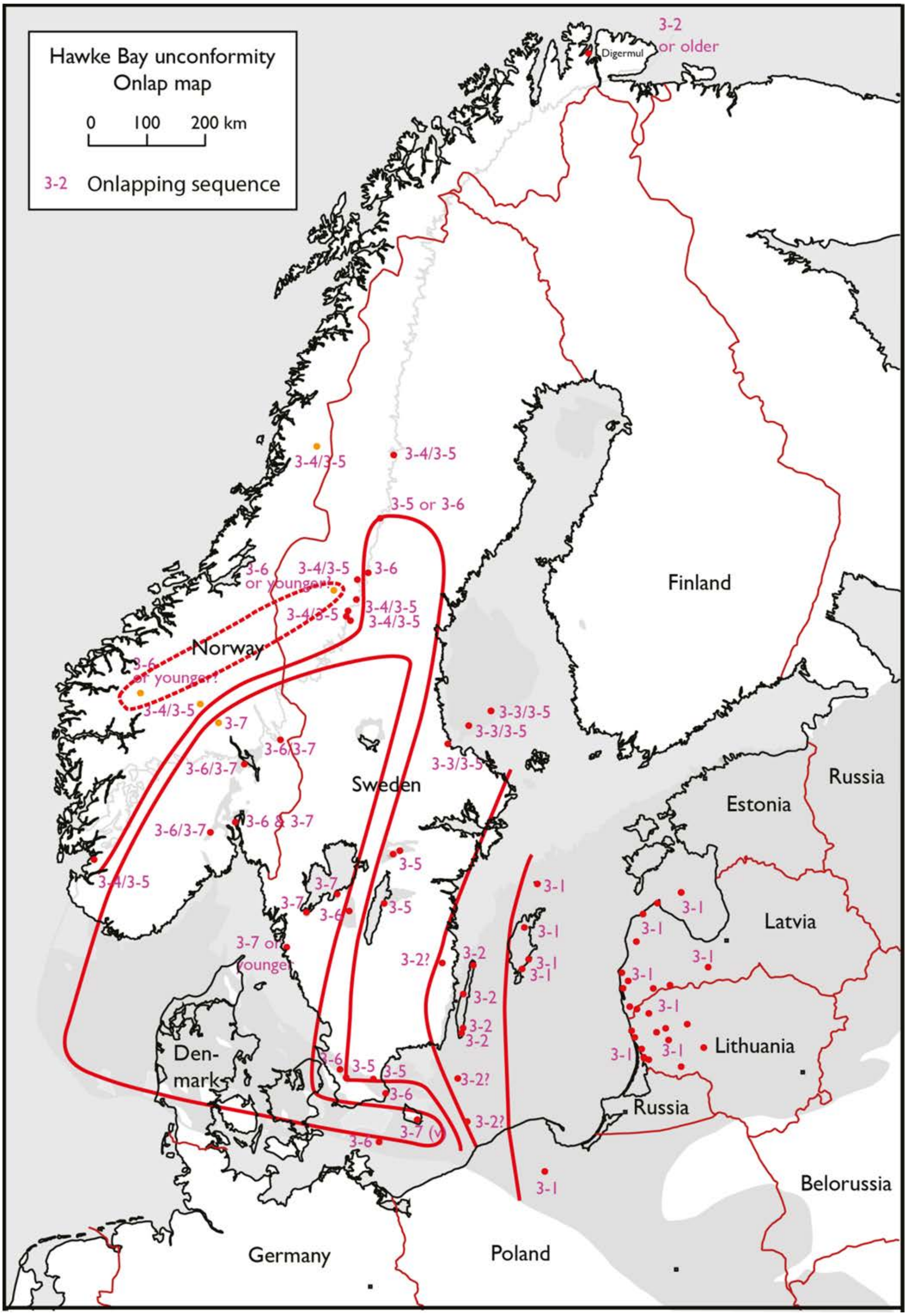

Figure 47B: Maps showing onlap (age of sequence above unconformity) of the Hawke Bay unconformity.

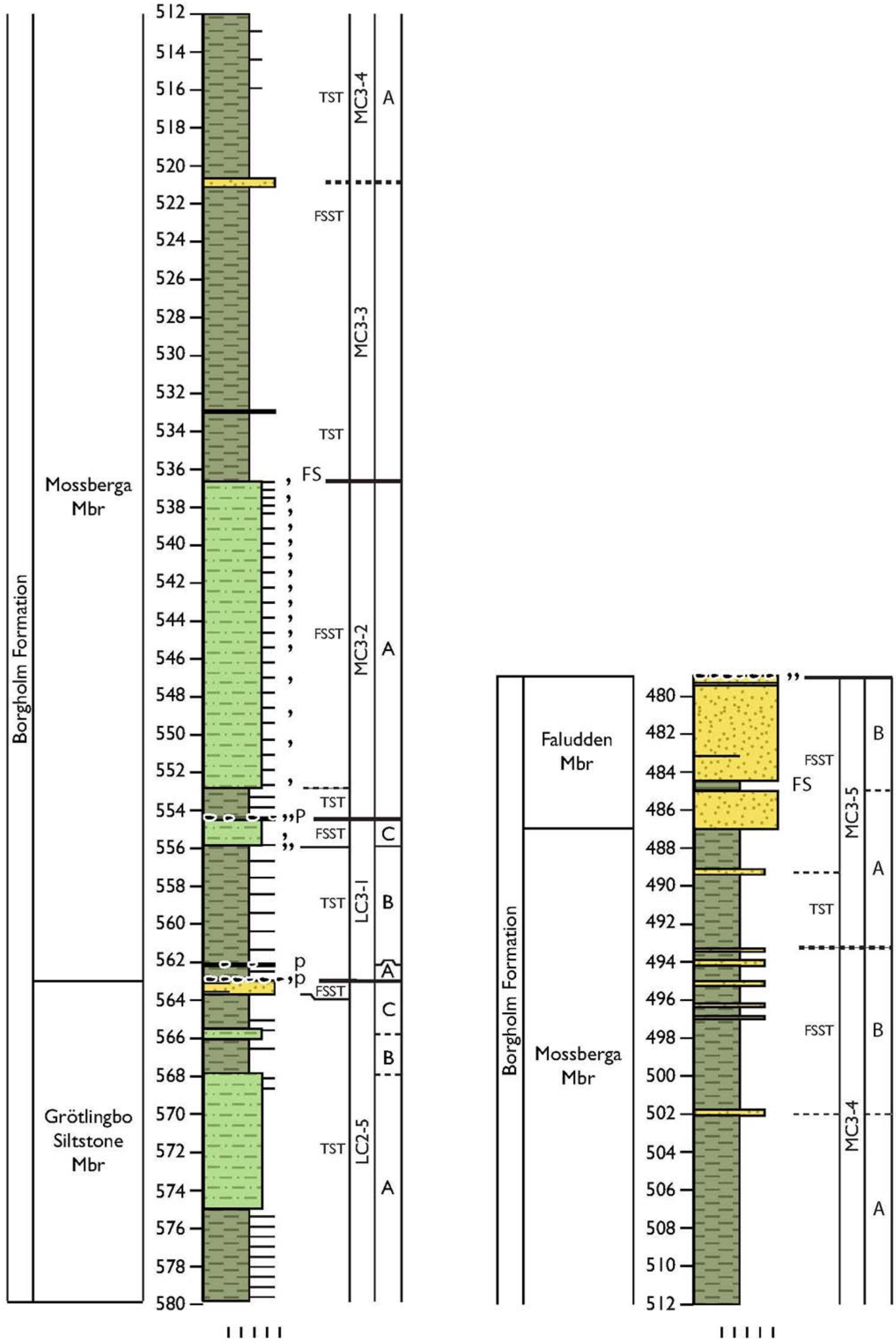

Figure 48: Sequence stratigraphical interpretation of the Middle Cambrian in the Grötlingbo-1 well, SE Gotland. Sequence LC3-1 is only developed in the Baltic area that was not or only little uplifted during the Hawke Bay Event.

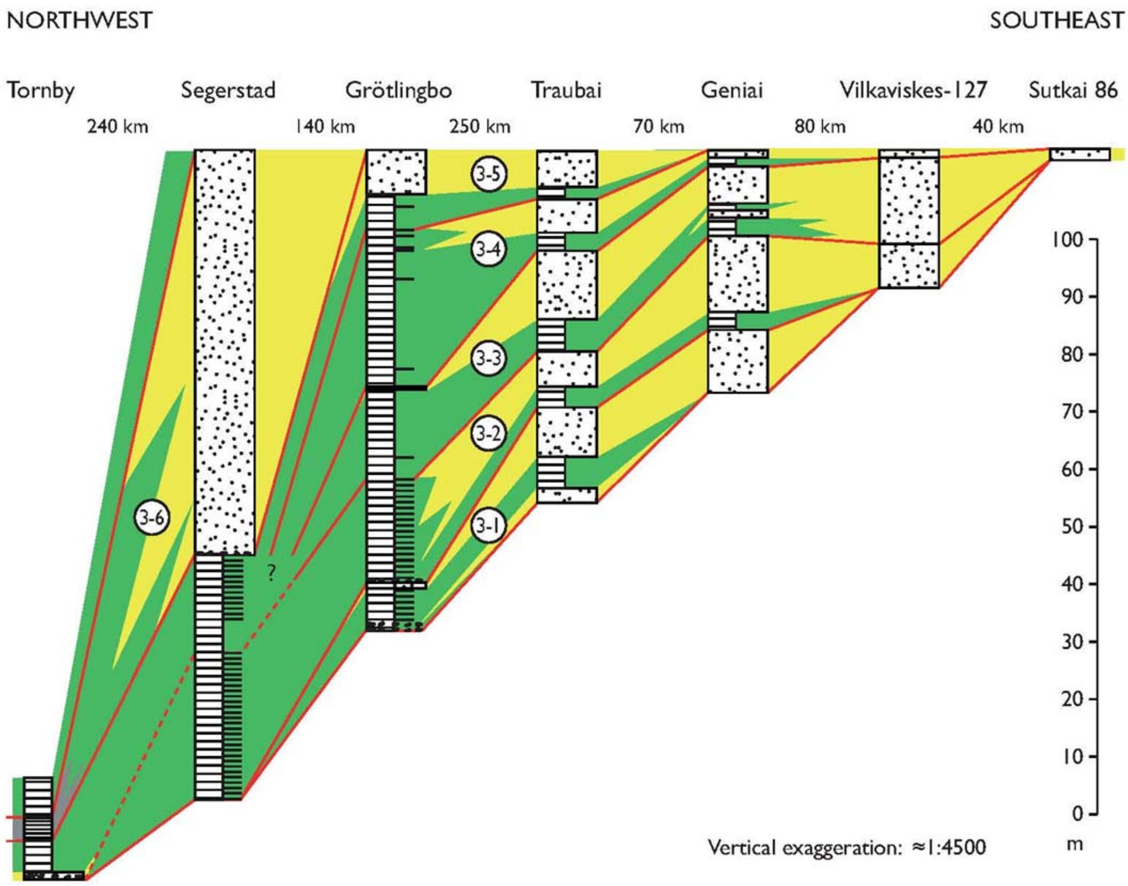

Figure 49: Profile from Lituania to Öland showing early Mid Cambrian progradation. The Lithuanian strata are assigned to the Deimena Group whereas the Swedish strata are assigned to the Borgholm with a thin incursion of Alum Shale in the Tornby core. It is emphasized that correlation remains model-driven.

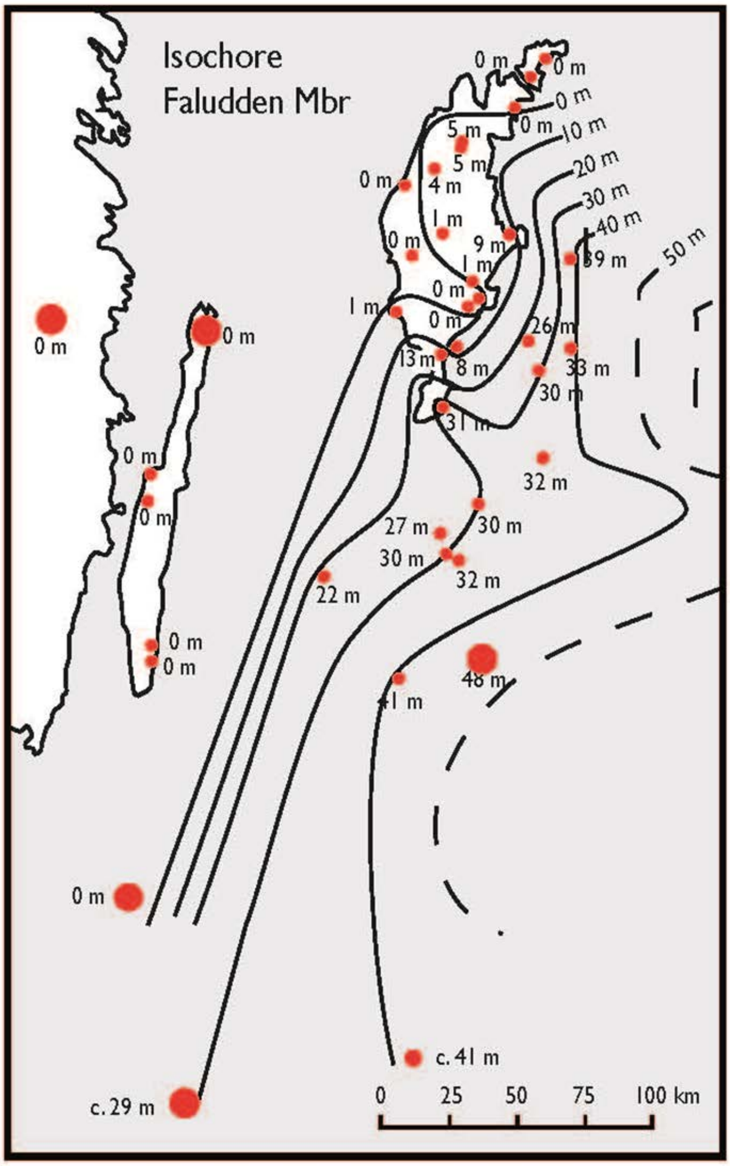

Figure 50: Isopach map of the Faludden Mbr, Borgholm Fm. The sandy member is a western tongue of the Deimena Fm.

Figure 51: Äleklinta Mbr at the type locality on northern Öland. This upper part of the member comprises siltstone with numerous thin sand beds (storm sand).

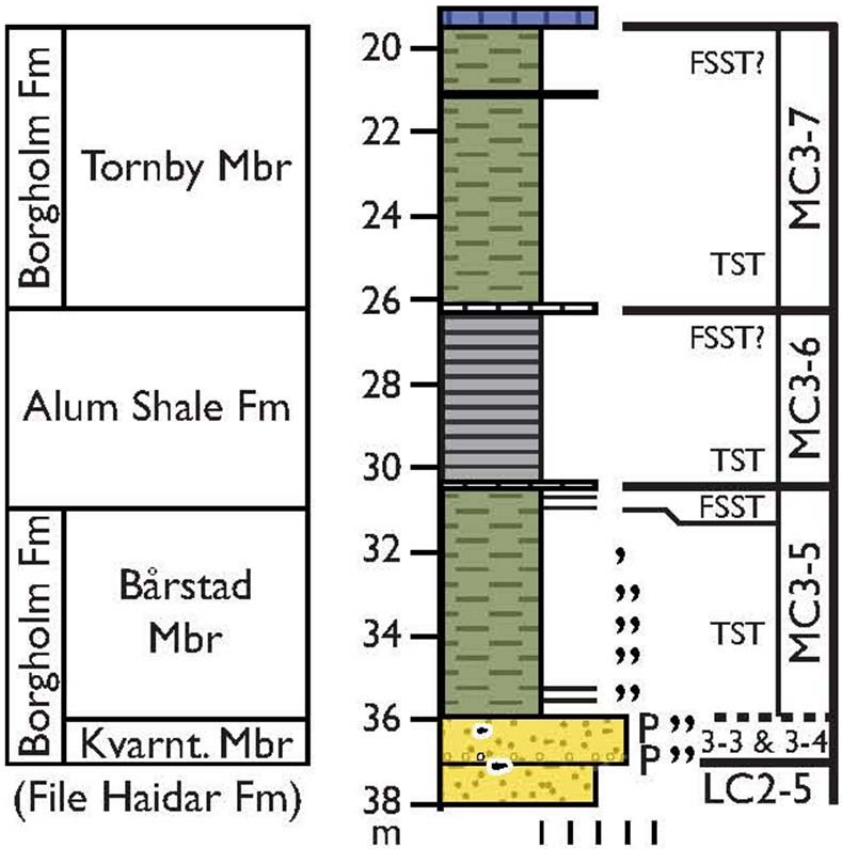

Figure 52: Sequence stratigraphical interpretation of the lower part of the Middle Cambrian in the Tornby core, Östergötland. See also Fig. 17.

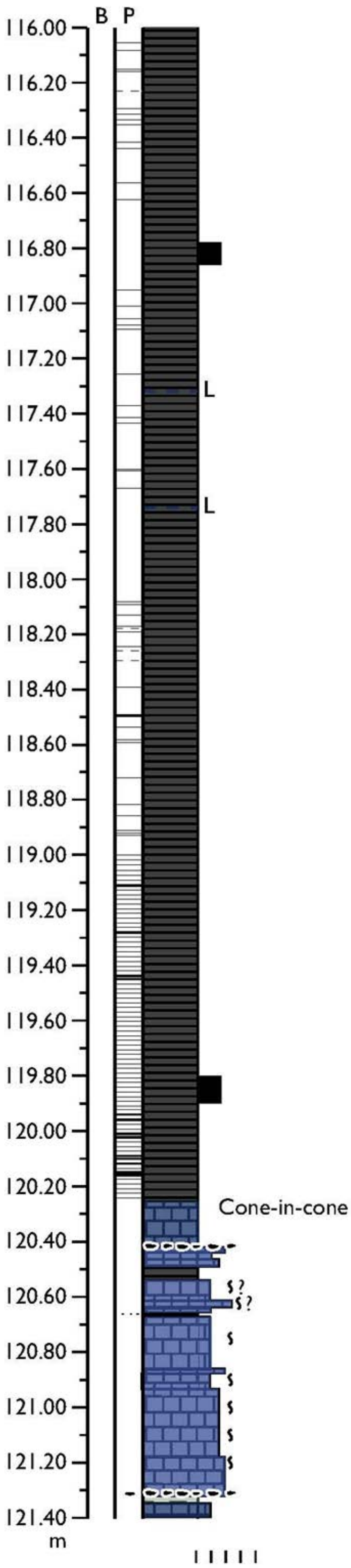

Figure 53: Middle Cambrian, Billegrav-2 core, Bornholm. Note the numerous pyrite laminae in the *L. laevigata* Zone immediately above the Andrarum Limestone (c. 119.0-120.25 m). This is interpreted as a condensed drowning 'surface'.

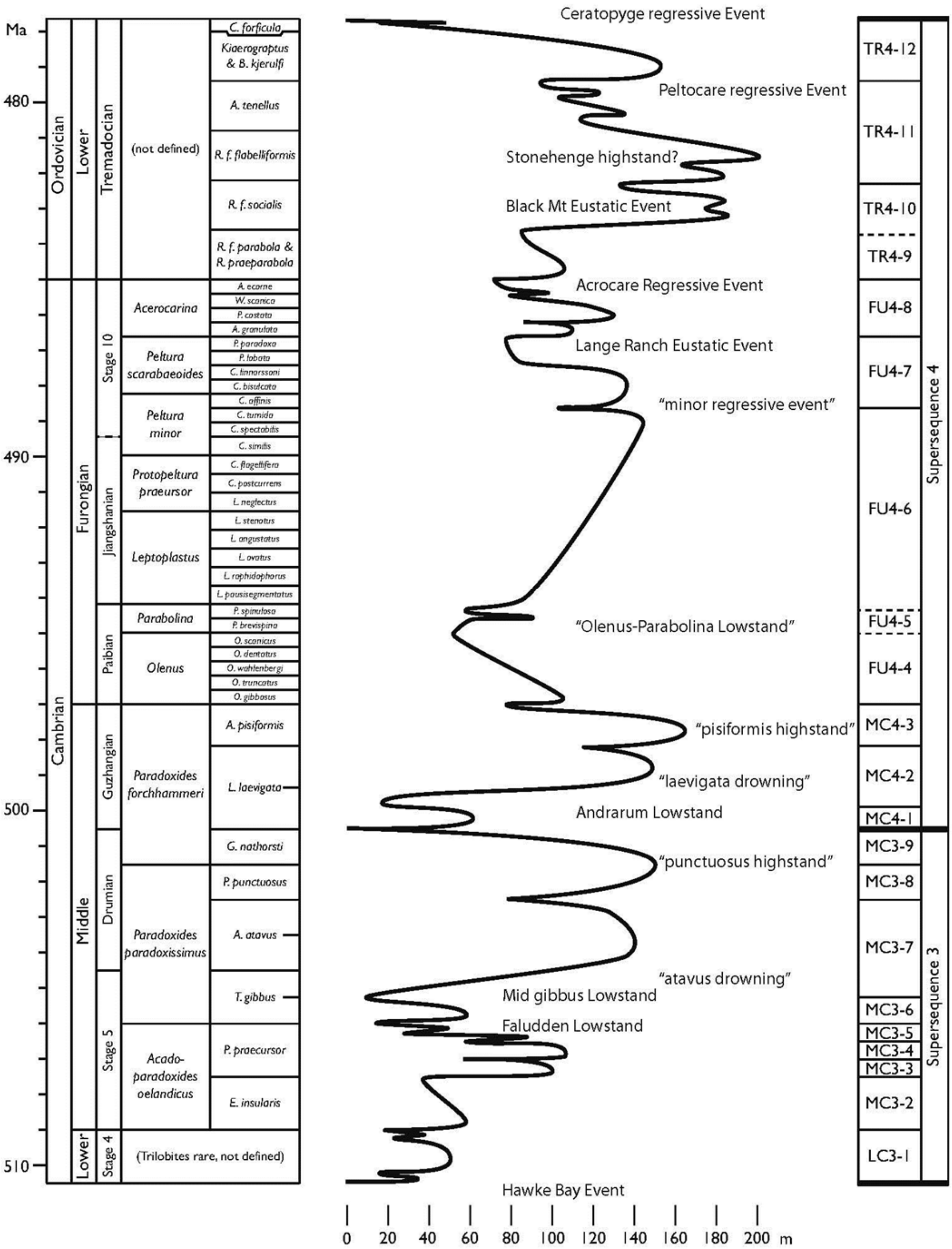

Figure 54: Mid Cambrian-Tremadocian sea level curve for Scandinavia. Defined sequences and sea level events referred to are also shown. See text for discussion. A 2nd order curve is shown in Fig. 56.

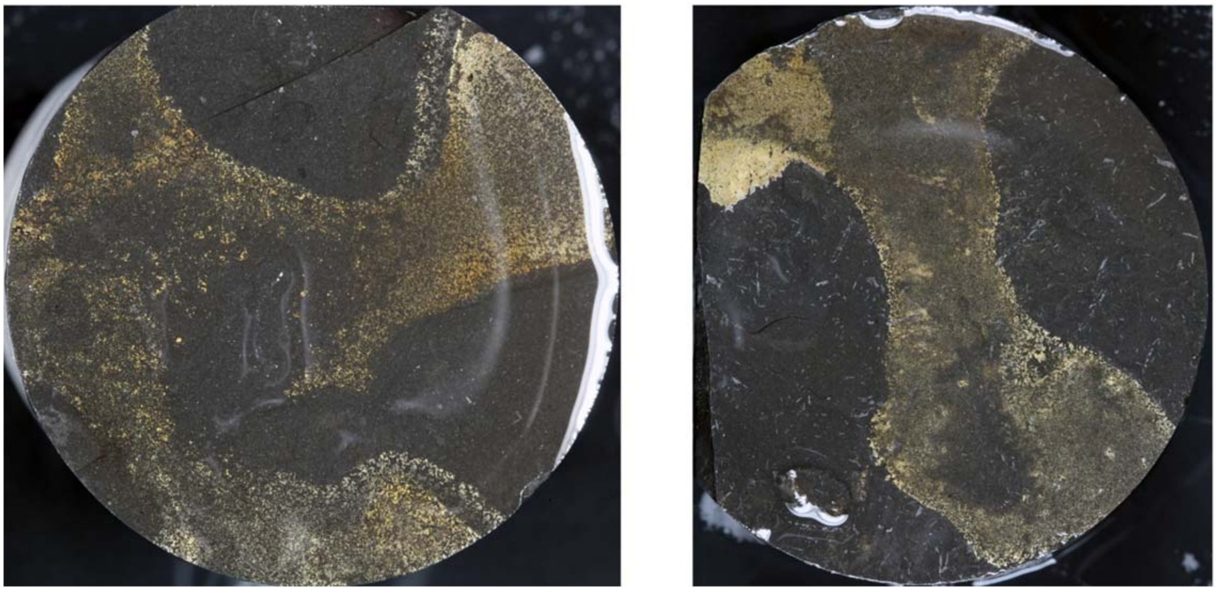

Figure 55: Bedding surfaces of Dicellograptus Shale with pyrite “smudges” that may represent pyritized bacterial mats. The same type of pyrite “smudges” occurs in the Alum Shale. Billegrav-2 core, Bornholm.

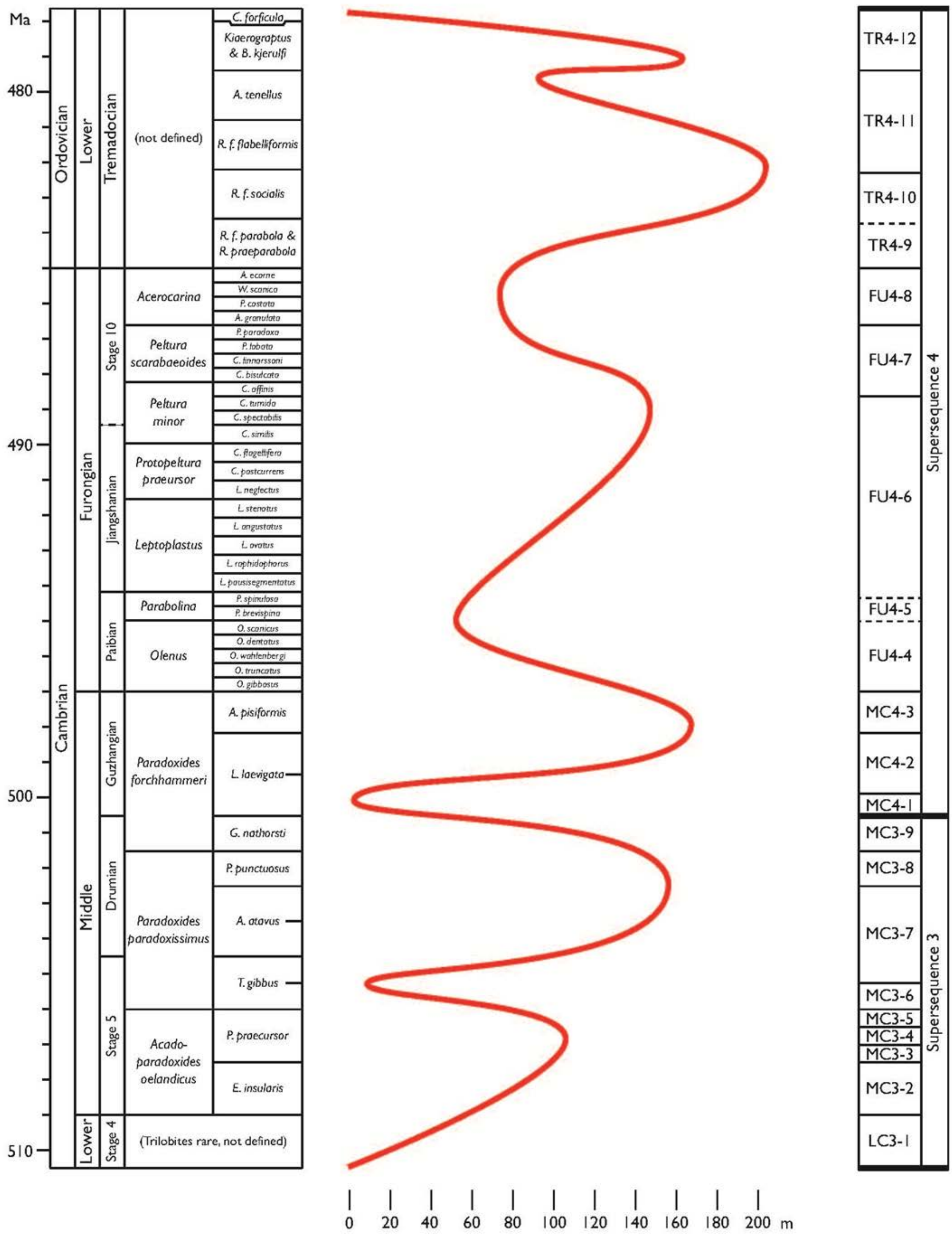

Figure 56: Second order sea level curve for the Mid Cambrian-Tremadocian of Scandinavia. A 3rd order curve is shown in Fig. 54.

7. Localities

Table 1. Alum shale localities and wells used in the map compilations.

Alum Shale maps and diagrams

Area	LOCALITY/WELL NAME	TYPE OF SECTION	Alum Shale thickness (m)	M. Cambr. (m)	Furongien (m)	Tremadoc (m)	Comments	Reference
Scania, S	Albjära	Shallow cored well	97,62	31,98	58,58	7,06		Lauridsen 2000
Scania, S	Hedeberga	Deep well, Alum Shale cored	Confidential				Confidential Shell data	Pool et al 2012
Scania, S	Oderup	Deep well, Alum Shale cored	Confidential				Confidential Shell data	Pool et al 2012
Scania, S	Lövestad	Deep well, Alum Shale cored	Confidential				Confidential Shell data	Pool et al 2012
Scania, S	Fågeltofta-2	shallow cored well	95 + c. 3 m	30 + c. 3 m	49,3	15,6	Basal c. 3 m faulted out as shown by nearby water well	Christensen 2003
Scania, S	Gislövshammer-2	shallow cored well	79,9	23,1	40,5	16,3		Nielsen & Buchardt 1994
Scania, S	Andrarum 1	shallow cored well		24,2	>36,2	Not drilled	Probably fault in Middle Cambrian	Westergård, 1942, 1944
Scania, S	Andrarum 2	shallow cored well		Not drilled	>26,3	>8,7		
Scania, S	Andrarum 3	shallow cored well	> 29 m	Not penetrated	Not penetrated	0	atavus to Parabolina zones	Ahlberg et al 2008
Scania, S	Andrarum compilation		C. 90	24,2	48,4	8,7+ c. 9 m	data all 3 wells	Westergård
Scania, S	Sandby-1	shallow cored well		>30,5	50,5	9,5	TD in diabase	Westergård, 1942, 1944
Scania, S	Almbackan	shallow cored well		>28	Not drilled	Not drilled		Meyerson 1997
Scania, S	Sandby+Almbackan compiled		98,25	38,25	50,5	9,5		
Scania, S	Gislövshammar-1	shallow cored well	77,4	22,5	38,4	16,5		Westergård, 1942, 1944
Scania, S	Gislövshammar-2	shallow cored well	79,9	23,7	39,9	16,3		Nielsen & Buchardt 1994
Scania, S	Åkarpsmölla	shallow cored well	>35,5	>8 m	>27,7	Not drilled	TD in diabase	Westergård, 1942, 1944
Scania, S	Tosterup	shallow cored well	95,3	21	51	22,8		Hessland & Armands 1978
Scania, S	Falsterborev 1	offshore Sweden	41	7	28	6		
Scania, S	Hammarlöv 1	Deep well	38					
Scania, S	Eskildstorp 1	Deep well	58					
Scania, S	Häslöv 1	Deep well, partially cored	62	9	37	16		
Scania, S	Höllviksnäs 1	Deep well	35					
Scania, S	Lyby	water well non-cored		Not penetrated	Not penetrated	11		Erlström et al. 2001

Area	LOCALITY/WELL NAME	TYPE OF SECTION	Alum Shale thickness (m)	M. Cambr. (m)	Furongien (m)	Tremadoc (m)	Comments	Reference
Scania, S	Killeröd	Cored shallow well					Fully penetrated, fully cored	
Scania, S	Flagabro	Cored shallow well		Not penetrated	Not penetrated	11,44		Tjernvik 1958
Scania, S	Fågelsång 1	Cored shallow well		Not penetrated	Not penetrated	5,87		Hede 1951
Baltic sea, S	B3 and B3a	Deep well, offshore, noncored	6					Completion report
Baltic sea, S	B5	Deep well, offshore, noncored	5					Completion report
Baltic sea, S	b6	Deep well, offshore, noncored	6,3					Completion report
Baltic sea, S	B7	Deep well, offshore, noncored	6,1					Completion report
Baltic sea, S	B9	Deep well, offshore, noncored	3,8					Completion report
Baltic sea, S	B10	Deep well, offshore, noncored	6,4					Completion report
Gotland S	När	Onshore deep well, cored	2,02	2,02			A. pisiformis Zone	Ahlberg 1989
Baltic sea, S	Yoldia	Deep well, offshore, partially cored	31					Completion report
Gotland S	Viklau-1	Onshore well, non-cored?	4,5					Andersson et al 1985
Gotland S	Lau-1	Onshore well, partially cored	4,5			(0.7 m sst)	Cambrian	Completion report
Gotland S	Långvät-1	Onshore well, non-cored	0,25	0			Cambrian	Completion report
Gotland S	Lukse-1	Onshore well, partially cored	3	0	3			Completion report
Gotland S	Bjärges-1	onshore well, non-cored?	2,4					Geothermal Energy report 1981
Gotland S	Nyudden-1	Onshore well, partially cored	0,66				Overlain by 0.35 m of sand; maybe Tremadocian	Completion report
Gotland S	Rings 1	Onshore well, partially cored	0				5 m of Furongian sandstone	Completion report

Alum Shale maps and diagrams

Area	LOCALITY/WELL NAME	TYPE OF SECTION	Alum Shale thickness (m)	M. Cambr. (m)	Furongien (m)	Tremadoc (m)	Comments	Reference
Kattegat. Dk	Terne	offshore DK	178	80	65	34		
Sealand, Dk	Slagelse	onshore DK	29	10	19	0		
Bornholm, Dk	Skelbro-1	Cored shallow well						
Bornholm, Dk	Skelbro-2	Cored shallow well	34	8	23	3		
Bornholm, Dk	Læså at Kalby	Outcrop						Grönwall 1902, Hansen 1945
Bornholm, Dk	Billegrav-2	Cored shallow well	27	7	17	3		
Bornholm, Dk	Øleå at Borggård	Outcrop						Grönwall 1902, Hansen 1945
Bornholm, Dk	Billeshøj	Non-cored water well, logged	28	7	17	5		Pedersen & Klitten 1990
Bornholm, Dk	Sommerodde	Cored shallow well	28	9	17	2		
Bornholm, Dk	Sømarken 2	Non-cored water well, logged	30	4	19	4		Pedersen & Klitten 1990
Bornholm, Dk	Sømarken 3	Non-cored water well, logged	30	4	18	4		Pedersen & Klitten 1990
Bornholm, Dk	Sømarken 4	Non-cored water well, logged	31	4	19	4		Pedersen & Klitten 1990
Bornholm, Dk	246.594 Store Bukkegård	Non-cored water well	c. 35 m					GEUS
Baltic Sea, Gr	G14	Offshore deep well, partially cored	32,3	c. 11.5	c. 14	c. 7	Tremadocian Alum Shale originally misidentified as Lower Didymograptus Shale	Piske & Neumann 1993; top of formation according to Stouge 2001
Öland, S	Ottenby	Cored well	23,8	7	6,7	10,1	Locally up to 0.7 m Alum Shale below Exporrecta Cgl (outcrop)	Westergård 1944
Öland, S	Gammalsby	Cored well	24	3,7	5,5	9,7		Westergård 1944
Öland, S	Degerhamn	Outcrop + well	16,8	3,5	5,4	7,9		Westergård 1944
Öland, S	L.Smedby	Cored well	11,2	?	7,2	4		Westergård 1944
Öland, S	Borgby borg	Outcrop	7	0	7	0		Westergård 1944, 1947
Öland, S	Böda hamn	Cored well	1,75	0	0	1,75		Hessland 1955
Öland, S	Segerstad	Cored well	25					Unpublished SGU log

Area	LOCALITY/WELL NAME	TYPE OF SECTION	Alum Shale thickness (m)	M. Cambr. (m)	Furongien (m)	Tremadoc (m)	Comments	Reference
Öland, S	Skärlöv	Cored well	15,4	2,5	3,3	9,6		Westergård 1947b
Öland, S	Mysinge Hög	Outcrop	2,2	Probably 0	2,2	0		Westergård 1947b
Öland, S	Eriksöre	Outcrop	3,35	1,2	2,15	(1,3)		Westergård 1922, 1947b
Öland, S	Glömminge kirke	Digged well	>2		>2			Westergård 1947b
Öland, S	Köpings Klint	Outcrop	0,3-1,1	0,3-1,1	0	0.05-0.2		Westergård 1922, 1947b
Öland, S	Äleklinta til Djupvik	Outcrop				0.8-1.4		Westergård 1947b
Öland, S	Djupvik	Outcrop	2,05	1,05	0	1		Westergård 1922
Öland, S	Äleklinta	Outcrop	1,7	0,9	0	0,8		Westergård 1922
Öland, S	Horns Udde	Outcrop	0,6			0,6		Westergård 1947b
Öland, S	Valsnäs	Deep well, non-cored	2,2	0?	2,2?	0?		Grossi 1973
Öland, S	Kvinnsgröta	Deep well, non-cored	19	0?	9	10		Completion report
Öland, S	Borgholm castle (ruin)	Outcrop	0				Conglomerate 0.45 m with clasts containing P. scarabaeoides and Orusia	Westergård 1922
Småland, S	Hummeln (impact crater)	Local ice-rafted boulders		Present	Present	Absent?		Westergård 1947b, see also Westergård 1922
Östergötland, S	Borghamn	Cored shallow well	19,8	9	5,6	5,2?	Tremadocian probably misidentified; much Middle Cambrian belongs to Borgholm Fm	Westergård 1940, but see also Wikman et al 1980
Östergötland, S	Motala	Cored shallow well	20,3	6,2	8,8	5,3	Much Middle Cambrian belongs to Borgholm Fm	Westergård 1944
Östergötland, S	Skåningstorp	Cored shallow well	19,4	5,8	6,1	7,5	Much Middle Cambrian belongs to Borgholm Fm	Westergård 1940
Östergötland, S	Tornby	Cored shallow well	14	6,5	4,1	3,4	Much Middle Cambrian belongs to Borgholm Fm	Westergård 1940
Östergötland, S	Grankulla	Cored shallow well	15	7,1	4	3,9	Much Middle Cambrian belongs to Borgholm Fm	Westergård 1944
Östergötland, S	Västanå	Outcrop	>15	>2,4	c. 7,5	5,1	Much Middle Cambrian belongs to Borgholm Fm	Westergård 1944

Area	LOCALITY/WELL NAME	TYPE OF SECTION	Alum Shale thickness (m)	M. Cambr. (m)	Furongien (m)	Tremadoc (m)	Comments	Reference
Östergötland, S	Knivinge	Outcrop	>11	>3,9	4,6	2,5	Much Middle Cambrian belongs to Borgholm Fm	Westergård 1944
Östergötland, S	Bårstad II	Cored shallow well	22,2	8,2	9,9	4,1		Wikman et al 1980
Östergötland, S	Nässja	Cored shallow well	24	6,8	8,4	8,8		Wikman et al 1980
Östergötland, S	Ekön	Cored shallow well	20,4	6,1	9	5,3		Westergård 1944
Östergötland, S	Flistad	Cored shallow well	13,8	6,7	4	3,1		Wikman et al 1980
Östergötland, S	Borensberg 2	Cored shallow well	19,7	7	7,6	5,1		Wikman et al 1980
Östergötland, S	Västanå	Outcrop		(Not fully exposed)	7,3	5,2		Westergård 1944
Närke, S	Hynneberg	Cored shallow well	19,3					Westergård 1941
Närke, S	Hällabrottet	Outcrop						
Närke, S	Lanna	Outcrop	14,2					Westergård 1922
Närke, S	Latorp	Outcrop	12,3	1	11,3	0		Westergård 1922
Närke, S	Garphyttan	Outcrop	15,6					Westergård 1922
Närke, S	Oxebackan	Cored shallow well	>9	Very thin				Westergård 1941
Närke, S	Hjortsberga I and II	Cored shallow wells	> 17	Very thin				Westergård 1941
Närke, S	Högtorp	Cored shallow well	> 5,6					Westergård 1941
Närke, S	Yxhylt	Outcrop	17,8					Lindegårdh et al 1973
Närke, S	Norrtorp	Cored shallow well	18					Lindegårdh et al 1973
Närke, S	Köpsta	Cored shallow well	16,2	2,5	13,7	0		Lindegårdh et al 1973
Närke, S	Bernstorp 2	Cored shallow well	15,7	2,3	13,4	0		Lindegårdh et al 1973
Närke, S	Tångsätter 2	Cored shallow well	14,7	1,6	13,1	0		Lindegårdh et al 1973
Närke, S	Tångsätter 4	Cored shallow well	14,9	2,5	12,4	0		Lindegårdh et al 1973
Närke, S	Menigasker 1	Cored shallow well	10,5	2,9	7,6	0		Lindegårdh et al 1973
Närke, S	Vilhelmsberg	Cored shallow well	15,7	2,6	13,1	0		Lindegårdh et al 1973
Närke, S	L fallet	Cored shallow well	13,5	2,9	10,6	0		Lindegårdh et al 1973
Närke, S	Stånger	Cored shallow well	12,9	0,6	12,3	0		Lindegårdh et al 1973

Area	LOCALITY/WELL NAME	TYPE OF SECTION	Alum Shale thickness (m)	M. Cambr. (m)	Furongien (m)	Tremadoc (m)	Comments	Reference
Närke, S	Rynninge	Cored shallow well	7,1	1,1	6	0		Lindegårdh et al 1973
Närke, S	Örsta	Cored shallow well	13,3	1,4	11,9	0		Lindegårdh et al 1972
Närke, S	Filipshyttan	Cored shallow well	13,5	1	12,5	0		Lindegårdh et al 1973
Närke, S	Bredsätter	Cored shallow well	17,55	0,05	17,5	0		Westergård 1940
Närke, S	Vrana	Cored shallow well	16,4	1,8	14,6	0		Westergård 1940
Närke, S	Tångsätter	Cored shallow well	15,1	2,2	12,9	0		Westergård 1940
Kinnekulle, S	Hällekis 1	Cored shallow well	22,01					Wilken & Buchardt 1994
Kinnekulle, S	Hönssäter	Outcrop		Only top exposed	>8,5	0		Westergård 1922
Kinnekulle, S	Trolmen-Råbäck	Outcrop		Only top exposed	>8	0		Westergård 1922
Kinnekulle, S	Gössäter	Outcrop		Only top exposed	>9	0		Westergård 1922
Kinnekulle, S	Per Månsgården	shallow cored well	21,45	9,35	12,1	0		Westergård 1943
Kinnekulle, S	Norra Skagen	shallow cored well	21,2	9,4	11,8	0		Westergård 1943
Billingen, S	Karlsfors							
Billingen, S	St. Stolan composite	Outcrop	22	12,2	9,8	0		Westergård 1922, 1931
Billingen, S	Ranstad	Outcrop		Not stated	10,4	0		Andersson et al 1985
Billingen, S	DBH65/77	Cored shallow well	22,3	13,4	8,9	0	Read from their Fig. 9	Andersson et al 1985
Billingen, S	Ödegården	Outcrop		>2	10,8	0		Westergård 1922
Billingen, S	Torbjörntorp	Outcrop			8,7	0		Westergård 1922
Billingen, S	Quarry c. 1 km SSW of Kleva Church	Outcrop			>7 m	1,2		Westergård 1922
Hunneberg, S	Nygård	Outcrop		Not exposed	>5,7	0,01	3 more m of Alum Shale below containing H. obesus; thickness at this locality largest on Hunneberg	Westergård 1922
Hunneberg, S	Munkestens dagbrott (quarry)	Outcrop		pisiformis Zone > 4.5 m				Westergård 1922

Area	LOCALITY/WELL NAME	TYPE OF SECTION	Alum Shale thickness (m)	M. Cambr. (m)	Furongien (m)	Tremadoc (m)	Comments	Reference
Hunneberg, S	Byklev	Outcrop		> 7,75				G. Budd pers com 2011
Hunneberg, S	Composite HUNNEBERG		23,76	min 10,4	min 5,7	0,01-0,09	Not possible to unravel thicknesses of pisiformis, Olenus and Leptoplastus zones	Lindström 1887, Westergård 1922
Baltic Sea, S	Finngrundet	Cored shallow well	0,54			0,54	0.5m sandstone	
Baltic Sea, S	Västra banken	Cored shallow well	0				sandstone	
Central Sweden	SILJAN	Outcrop	Very thin	0	0	Very thin	Sandy cgl up to 3 m	Thorslund 1936; Löfgren 1994
Jämtland, S	Glöte v Häggingåsen	Cored shallow well	5,8					Karis 1998
Jämtland, S	Häggenås 77001	Cored shallow well	35,3	c. 31	c. 4	0	Youngest Furongian: Parabolina Superzone	Gee et al. 1982b
Jämtland, S	Häggingsåsen	Cored shallow well	min 7,7	7,7??		0	Alum Shale maybe cut by thrust	Karis 1998, p. 47
Jämtland, S	Klövsjö 78002	Cored shallow well	7,9	c. 3	c. 5	0	Looks like intact /non tectonized ASF succession	Gee et al. 1982b
Jämtland, S	Klövsjö 78001	Cored shallow well	c. 10 m or more				Looks tectonically stacked, but ASF is c. 10 m	Gee et al. 1982b
Jämtland, S	Skålan 78001	Cored shallow well	19,3	c. 15	c. 4	0	Looks like intact /non tectonized ASF succession	Gee et al. 1982b
Jämtland, S	Stor-hallen 78001	Cored shallow well	9,2	c. 8	c. 1,2	0	Youngest Furongian: Leptoplastus Superzone	Gee et al. 1982b
Jämtland, S	Stor-hallen 78002	Cored shallow well	12,3	c. 9,8	c. 2,5	0	Youngest Furongian: Parabolina Superzone	Karis 1998
Jämtland, S	Tossåsberget 78001	Cored shallow well	19,5	c. 17	c. 2,5	0	Youngest Furongian: Leptoplastus Superzone	Gee et al. 1982b
Jämtland, S	Skålan profil i stor-hallens by	Outcrop	9,3	7,7	1,6	0	Thicknesses maybe from Stor-Hallen 78001	Karis 1998
Jämtland, S	Storkallhögen	Outcrop	7,2				Tectonically disturbed, maximum thickness	Karis 1998 p. 65
Jämtland, S	Bingsta area	Outcrop	<16	<16			Tectonically disturbed, maximum thickness	

Area	LOCALITY/WELL NAME	TYPE OF SECTION	Alum Shale thickness (m)	M. Cambr. (m)	Furongien (m)	Tremadoc (m)	Comments	Reference
Jämtland, S	Hoverberget	Outcrop	>5	>5			Cut by thrust; nearby strongly folded shale up to Parabolina Sz	
Jämtland, S	Mo	Outcrop	c. 20				Youngest Furongian: P. scarabaeoides Superzone, thicknesses from Hoverån north of Mo	
Jämtland, S	Mo 78001	Cored shallow well	> 20	> 20			Cut by thrust	
Jämtland, S	Kövra town	Outcrop	< 20	Lower Cambrian plus ASF together c. 20 m but strongly folded			Youngest Furongian: Leptoplastus Superzone	
Jämtland, S	Funäsudden	Outcrop					Section summarized by Westergård (1922), no thickness data, youngest level: P. minor Sz	Westergård 1922
Jämtland, S	Myrvikens western beach	Outcrop					Youngest Furongian: P. minor Superzone	
Jämtland, S	Gisselfors	Outcrop					Oldest zone present: T. gibbus	Karis 1998, p 72
Jämtland, S	Kläppeviken	Outcrop	>15				Youngest Furongian: P. minor Superzone; on nearby Moholmen Tremadocian with trilobites	Karis 1998, p. 74
Jämtland, S	Höla	Outcrop				0.5-0.8	Youngest Furongian: C. linnarssoni Zone, overlain by Tremadocian Alum Shale	
Jämtland, S	Billstaån/Näkten	Outcrops plus wells	max 35 m				Youngest Furongian: P. minor Superzone	Karis 1998 p, 79
Jämtland, S	Näkten 78001	Cored shallow well	28	c. 22	c. 6	0	Light grey near top, gammalog in well	Gee et al. 1982b

Area	LOCALITY/WELL NAME	TYPE OF SECTION	Alum Shale thickness (m)	M. Cambr. (m)	Furongien (m)	Tremadoc (m)	Comments	Reference
Jämtland, S	Näkten 78002	Cored shallow well	34,6	c. 24	c. 11	0	Light grey near top	Gee et al. 1982b
Jämtland, S	Sanne 78001	boring	45	c. 26	c. 19		Gammalog in well	Gee et al. 1982b
Jämtland, S	Lockne area	Outcrop	20-30		< 3.5		Furongian incl. Pisiformis Zone < 3.5 m at Mon; youngest level Parabolina Sz	
Jämtland, S	Klocksåsen	Outcrops plus wells	c 50		< 10		Youngest Furongian: P. minor Superzone; shale strongly tectonized and maybe stacked	Karis 1998 p. 80
Jämtland, S	Brunflo	Outcrop	c 19	16	3	0	Youngest Furongian: Parabolina Superzone, Furongian presumably incl. pisiformis Zone	Karis 1998 p. 84-85
Jämtland, S	Brynje-Kyrkås area	Outcrop	c 19	10	6	0	Thicknesses read from log	Karis 1998 p. 88
Jämtland, S	Målsta-Östersund area	Outcrop	c 11	7	4	0	Thicknesses read from log	Karis 1998 p. 89
Jämtland, S	Älsta verkön	Outcrop					Youngest Furongian: Seemingly Parabolina Superzone	Karis 1998 p. 97
Jämtland, S	Indalsälvens beach between Lit and Litsnäset	Outcrop					Youngest Furongian: P. minor Superzone	Karis 1998 p. 100
Jämtland, S	Lundkälen 77001	Cored shallow well	29,5		0.1 m?	0		Gee et al. 1982b
Jämtland, S	Branamyren 77001	Cored shallow well	33,1	min 33.4	max 0.6 m	0		Gee et al. 1982b
Jämtland, S	Branamyren 77002	Cored shallow well	30,6	c. 30.5	0.1-0,2	0		Gee et al. 1982b
Jämtland, S	Hammerdal, Strømsund	Outcrop	c. 50				Stacked?	Karis 1998 p. 112
Jämtland, S	Järvsand-Havsnäs	average for area	30	18	8	4	Thicknesses read from log; Tremadoc observed in Kalkberget	Karis 1998 p. 115
Jämtland, S	Hara 78001	Cored shallow well	64				Stacked?	Gee et al. 1982a
Jämtland, S	Hara 79001	Cored shallow well	73	44			Stacked;	Gee et al. 1982a
Jämtland, S	Hara 79002	Cored shallow well	38,8				This is only basal part of core; maybe close to original thickness; upwards stacked, gammalog	Gee et al. 1982a

Area	LOCALITY/WELL NAME	TYPE OF SECTION	Alum Shale thickness (m)	M. Cambr. (m)	Furongien (m)	Tremadoc (m)	Comments	Reference
Jämtland, S	Hara 79003	Cored shallow well	25,4				Maybe NO repetitions, gammalog available	Gee et al. 1982a
Jämtland, S	Marby 79001	Cored shallow well	87,9			Present	Stacked;	Gee et al. 1982a
Jämtland, S	Marby 79002	Cored shallow well	49				Maybe NO repetitions, gammalog available, looks like allochthon	Gee et al. 1982a
Jämtland, S	Myrviken 78006	Cored shallow well	81				This part maybe intact, upwards stacked, gammalog	Gee et al. 1982a
Jämtland, S	B361	Cored shallow well	> 79				Also ASF in B312, B247, B415 but closelying and fm cut by thrust	Gee et al. 1978
Jämtland, S	B642	Cored shallow well	> 104	Present	Present	Present	Stacked;	Gee et al. 1978
Jämtland, S	Djupdal	Cored shallow well	Nearly 80 m				Some siltstone and calcareous sst in ASF	Gee et al. 1978
Northern Sweden	Bjørnide area near Laisvall	Cored shallow well	54				Basal sandstone 0.14-0,92 m	Ljungner 1950
Northern Sweden	BH 168 m close to Bjørnide	Cored shallow well	16				Cut by thrust?	Ljungner 1950
Northern Sweden	Laisvall	Cored shallow well	> 10				Cut by thrust	marklund 1950
Northern Sweden	Nasafjället window	Outcrop	c. 8				Tectonized!	Marklund 1952
Northern Sweden	Tømmerås window	Outcrop	Present				Strongly folded	Gee 1980
Southern Norway	Oslo	Outcrop	c 80	around 30	around 40-45	5 to 10	Tectonized!	Bjørlykke 1974
Southern Norway	Slemmestad	Outcrop	87	around 30	around 45	12	Tectonized!	Bjørlykke 1974
Southern Norway	Eiker	Cored shallow well		28		13,75		Martinsson 1974, Wandås 1982

Area	LOCALITY/WELL NAME	TYPE OF SECTION	Alum Shale thickness (m)	M. Cambr. (m)	Furongien (m)	Tremadoc (m)	Comments	Reference
Southern Norway	Skien	Cored shallow well	17	2,5//11-12 m	14,5	0	Thickness NOT included	
Southern Norway	Hardangervidda	Outcrops	30-40	Present		Present		Andresen 1978
Southern Norway	Teigen Gård	Cored shallow well	70,5	19	44	7,5		unpublished log in thesis
Southern Norway	Stablum Gård	Cored shallow well	82,5	30	43	9,5		unpublished log in thesis
Southern Norway	Krekling	Outcrop	80	30	43	7		Øyvind Hammer unpublished data; NSC interpretation
Southern Norway	Lauselva	Outcrop	>52	>28	>20	>4	Thickness NOT included	unpublished log in thesis
Southern Norway	RavndaLSskollen	Outcrop		>9	>8	?	Thickness NOT included	unpublished log in thesis
Southern Norway	Nærsnes	Outcrop		Present	Present	>6		Bruton et al 1982
Southern Norway	Valdal 120	Cored shallow well	>5					Nystuen 1982
Southern Norway	Drevsjø 121	Cored shallow well	10	Present	Maybe present	0		Nystuen 1982
Southern Norway	Hylleråsen 128	Cored shallow well	>6					Nystuen 1982
Southern Norway	Vestby 148	Cored shallow well	24	Present	Present	0		Nystuen 1982
Southern Norway	Nordre Osen 137	Cored shallow well	>30					Nystuen 1982
Southern Norway	Oskjølen 133	Cored shallow well	>19					Nystuen 1982
Southern Norway	Kvernbekken 130	Cored shallow well	>6					Nystuen 1982
Southern Norway	Møra Andrå 129	Cored shallow well	>14		Maybe max 19 m			Nystuen 1982
Southern Norway	Storbekken 117	Cored shallow well	>10					Nystuen 1982

Area	LOCALITY/WELL NAME	TYPE OF SECTION	Alum Shale thickness (m)	M. Cambr. (m)	Furongien (m)	Tremadoc (m)	Comments	Reference
Southern Norway	Tufsingdalen 113	Cored shallow well	>4					Nystuen 1982
Southern Norway	Vakkerbekken bh5 131	Cored shallow well	>16					Nystuen 1982
Southern Norway	Ø. Æra bh7 132	Cored shallow well	>19					Nystuen 1982
Southern Norway	Osen 1970 bh4 140	Cored shallow well	>16					Nystuen 1982
Southern Norway	Osen 1970 bh2 141	Cored shallow well	>29					Nystuen 1982
Southern Norway	Osen 1970 bh3 142	Cored shallow well	>34					Nystuen 1982
Southern Norway	Osen 1973 bh3 144	Cored shallow well	>9					Nystuen 1982
Southern Norway	Osen 1970, bh 6 146	Cored shallow well	>46					Nystuen 1982
Southern Norway	Osen 1970 bh5 147	Cored shallow well	>44					Nystuen 1982
Southern Norway	Osen 1973 bh4 135	Cored shallow well	>33					Nystuen 1982
Southern Norway	Osen 1973 bh 5 136	Cored shallow well	>42					Nystuen 1982
Southern Norway	Tennåsen 138	Cored shallow well	>34					Nystuen 1982
Southern Norway	Kvislen bh4 124	Cored shallow well	>2					Nystuen 1982

8. Data included on DVD

Attached to this report is a CD that contains the following documentation:

Folders:

Appendix A: High resolution pdf versions of maps and diagrams presented in this report
Appendix B: Geo-referenced maps (as png files) of the maps presented in this report. The maps are available from the ArcGIS 9.3 file: ‘Alum Shale maps and diagrams.mxd’

Tables: Excel version of Table 1 in this report

The file: a pdf of this report ‘Alum Shale maps and diagrams.pdf’