Stratigraphy, facies and depositional history of the Colonus Shale Trough, Skåne, southern Sweden

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Cover Picture: Outcrop in Gislövshammar showing the Komstad Limestone.

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Eriksson M., 2012: Stratigraphy, facies and depositional history of the Colonus Shale Trough, Skåne, southern Sweden. *Dissertations in Geology at Lund University*, No. 310, 37 pp. 45 hp (45 ECTS credits).

Abstract: The Colonus Shale Trough (CST) is an important tectonic entity in the Sorgenfrei-Tornquist Zone (STZ) in Skåne, southernmost Sweden. The fill comprises a Cambrian through Silurian succession dominated by fine-grained clastic sediments and subordinate limestone. Three deep wells were drilled in 2009–2010 by Shell in order to investigate the possibilities of extracting shale gas from the Cambrian-Ordovician Alum Shale Formation. The three wells Oderup C4-1, Lövestad A3-1 and Hedeberga B2-1 are important in providing the first continuous stratigraphic data from the CST. The study presents lithostratigraphic correlation of the strata by means of gamma ray logs, cuttings and biostratigraphy. The sedimentary fill constitute 19 formations that can be subdivided into five larger-scale stratigraphic associations related to the major depositional development of the basin. The Cambrian Sandstone Association, Cambrian-Ordovician Alum Shale Association, Ordovician Shale and Limestone Association, Silurian Shale Association, and the Silurian Limestone and Sandstone Association. The gamma ray logs show little variation in the API values for the Silurian Shale Association, although a few marker beds are present. The Ordovician Shale and Limestone Association is a heterogenous unit recording a great variation in API value with the Komstad Limestone as the most important marker bed. The Cambrian-Ordovician Alum Shale Association consists of an organic-rich shale and record extremely high API values, especially in the Furongian part. In order to reconstruct the Palaeozoic tectonic evolution of Skåne a tectonic subsidence model was produced from backstripping analysis of the well data. Three successive tectonic phases have been identified: An early Cambrian post-rift phase characterized by relatively high subsidence rates (17 m/Ma). A Late post-rift phase that is characterized by extremely low subsidence rates (2–4 m/Ma). And lastly, a collisional phase related to the development a foreland basin due to the collision between Baltica and Avalonia plates. The latter tectonic phase is characterized by an exceptionally high subsidence rate, reaching a maximum of 120 m/Ma and represents the final infill of the Baltoscandian foreland basin. A local uplift is observed in the Early Ordovician Tøyen Shale.

Keywords: Colonus Shale Trough, Sorgenfrei-Tornquist Zone, Lower Palaeozoic, backstripping, gamma ray, tectonic subsidence, Sweden.

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Stratigrafi, facies- och depositionsutveckling i Colonusstråget, Skåne, södra Sverige

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Sammanfattning: Colonusstråget är en viktig tektonisk enhet i den s.k. Sorgenfrei-Tornquistzonen i Skåne, södra Sverige. Den sedimentära sekvensen består av en kambrisk till silurisk succession dominerad av finkorniga klastiska sediment samt en mindre del kalksten. Tre hål borrades 2009–2010 av Shell med avsikt att finna skiffergas i den kambrisk-ordoviciska alunskiffern. Borrhålen, benämnda Oderup C4-1, Lövestad A3-1 och Hedeberga B2-1, är viktiga för att utvidga den stratigrafiska kunskapen av Colonusstråget. Den här studien omfattar litostratigrafiska korrelationer av lagerföljden med hjälp av gamma ray loggar, borrkax och biostratigrafi. Den sedimentära lagerföljden består av 19 formationer som kan delas in i fem storskaliga stratigrafiska enheter vilka är relaterade till den regionala bassängutvecklingen: den kambriska sandstensassociationen, den kambrisk-ordoviciska alunskifferassociationen, den ordoviciska skiffer- och kalkstensassociationen, den siluriska skifferassociationen, och den siluriska kalkstens- och sandstensassociationen. Gamma ray loggarna visar små värdeförändringar i API för den siluriska skifferassociationen, men undantag av en del distinkta ledbäddar finns. Den ordoviciska skiffer- och kalkstensassociationen består av en litologiskt heterogen enhet som ger skiftande utslag i API värdena där Komstadkalkstenen är den viktigaste ledbädden. Den kambrisk-ordoviciska alunskifferformationen består av en organiskt rik skiffer som ger extremt stora utslag på gamma ray loggarna, speciellt under tidsavsnittet furongian. Baserad på borrdata genomfördes en tektonisk subsidensmodell, s.k. backstripping, i avsikt att rekonstruera den palaeozoiska tektoniska utvecklingen i Skåne. Tre tektoniska faser identifierades: en tidig kambrisk fas karakteriserad av relativt höga subsidenshastigeter (17 m/Ma), en passiv fas karakteriserad av extremt låga subsidenshastigeter (2–4 m/Ma), och slutligen en fas karakteriserad av exceptionellt höga subsidenshastigeter, uppemot 120 m/Ma, relaterat till kollisionen mellan Baltica och Avalonia. En lokal höjning av jordskorpan observerades i den äldre ordoviciska Tøyenskiffern.

Nyckelord: Colonusstråget, Sorgenfrei-Tornquistzonen, underpaleozoikum, backstripping, gamma ray, tektonisk subsidens, Sverige

Ämnesinriktning: Berggrundsgeologi

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1 Introduction

The Colonus Shale Trough (CST) is a distinct structural element along the Sorgenfrei-Tornquist Zone (STZ) in Skåne, southern Sweden. It is characterized by a northwest-southeast trending, fault bounded elongated trough structure (Fig. 1). This structure can be followed offshore Sweden to the Bornholm Gat where it terminates on the Rønne Graben. The CST is bordered to the northeast by the Kullen-Ringsjön-Andrarum Fault- Zone (KRAFZ) and the Christiansø Horst in the Bornholm Gat (Erlström et al. 1997). The southwestern border constitutes the Fyledalen and Romeleåsen Fault zones. The CST comprises a Lower Cambrian through Upper Silurian sedimentary succession. These deposits accumulated along the southern continental margin of the Baltic Shield and therefore record the tectonic evolution of this margin over a period of more than 100 Ma. The total preserved thickness of the basin fill is herein calculated to about 1600 m and is predominantly composed of low-permeable strata such as shale and mudstone with subordinate limestone and sandstone. Following a thin Cambrian (ca 220-250 m) and condensed Ordovician (ca 60-140 m) succession, the bulk of the basin fill is represented by monotonous, Silurian marine shales. The smaller scale fault systems within the CST follow the overall large-scale fault system of the STZ in a NW-SE and NE-SW pattern (Fig.2). Along these faults various movements have occurred resulting in the formation of numerous wedge-shaped minor troughs that are uplifted and slightly tilted. In the south-eastern and northwestern parts of the trough this has resulted in variously uplifted fault-blocks exposing the Cambrian through Ordovician part of the succession. The central area of the trough has encountered little or no uplift and is dominated by Silurian shale. A Quaternary succession, often exceeding 20 m in thickness, normally cover the CST and bedrock exposures are therefore rare and small and are commonly found near river troughs or coastal sections. Erlström et al. (1997) proved, in the Bornholm Gat, through seismic data that the crystalline basement/Cambrian quartzites locally go as deep as 1500 ms TWT indicating up to 3000 m of sediments.

Due to limited exposure, the stratigraphic details of the CST succession have for long been poorly known. In 2008, however, Shell received two exploration permits from Bergsstaten (the Mining inspectorate of Sweden) in order to investigate the occurrence of shale gas in the Alum Shale Formation and the possibility to recover this natural gas. Four seismic lines were shot to determine the overall subsurface geology of the trough and in order to establish where the wells should be located. These seismic data, however, is classified and have not been analysed in this study. Core drilling commenced in November 2009 and was finished in June 2010. The exploration work and analysis of the Alum Shale Formation was terminated in the spring of 2011 due to limited occurrence of shale gas. The new deep drillings performed by Shell contribute with much new data on the stratigraphy and facies of the trough; data that can form basis for an updated overview of the basin history. Based on these new data, along with previously published stratigraphic data on the Colonus Shale Trough, this thesis aims to provide an improved stratigraphy of the Colonus Shale Trough and tie the facies development to the larger scale, Palaeozoic tectonic evolution of Skåne. Comparison is made to wells in Bornholm and Sjælland and to outcrops in Skåne.

2 Geological setting

The studied area includes Skåne, southernmost Sweden, and Bornholm, Denmark. Skåne and Bornholm are situated near the margin of the independent plate Baltica. This plate separated from the Rodinia-Gondwana complex in Cambrian times and drifted from southern high latitudes to a position straddling the Equator in the latest Silurian. In association to this drift the continent rotated rapidly counter-clockwise until Early Ordovician when the rotation continued at a slower pace until Late Ordovician (Fig. 3; Cocks & Torsvik 2002). The parallel development of the Caledonian Orogeny and the closing of the Iapetus Ocean was a result of the collision of Baltica, Laurentia, and Avalonia in the Ordovician and Silurian (Cocks and Torsvik 2002). These events set the stage for the coeval paleogeography of Scandinavia as well as for the larger scale facies development in southernmost Sweden and Skåne.

Palaeogeographically Skåne and Bornholm belong to the southwestern part of the Baltic Shield, constituting Archaen and Proterozoic continental blocks and juvenile terrains (Berthelsen 1992). The most important structural lineament is the NW-SE trending Tornquist Zone (TZ), stretching from the North Sea through Skåne, into Poland and further southeast to the Black Sea. The TZ has long been associated to the Fennoscandian Border Zone, i.e. the continental margin of the shield, but has in more recent years been re-interpreted as a major intracratonic lineament (Erlström et al. 1997). The recurrent tectonic activity along this zone has resulted in a well-developed horst and graben system (Bergström et al. 1990 a,b; Erlström et al. 1997; Babuska & Plomerova 2004; Bergerat et al. 2007). The CST lies within the northwestern part of the TZ, a part that is referred to as the Sorgenfrei- Tornquist Zone (STZ). The southeastern prolongation of the TZ is called Teyssire-Tornquist Zone (TTZ) which is delimited by the Rønne Graben near Bornholm (Erlström et al. 1997; Fig. 1).

The STZ constitute a 20-50 km wide zone of intense faulting and by Late Cretaceous and Early Paleogene inversion tectonics (Erlström et al. 1997). The zone is bounded by the Kullen-Ringsjön-

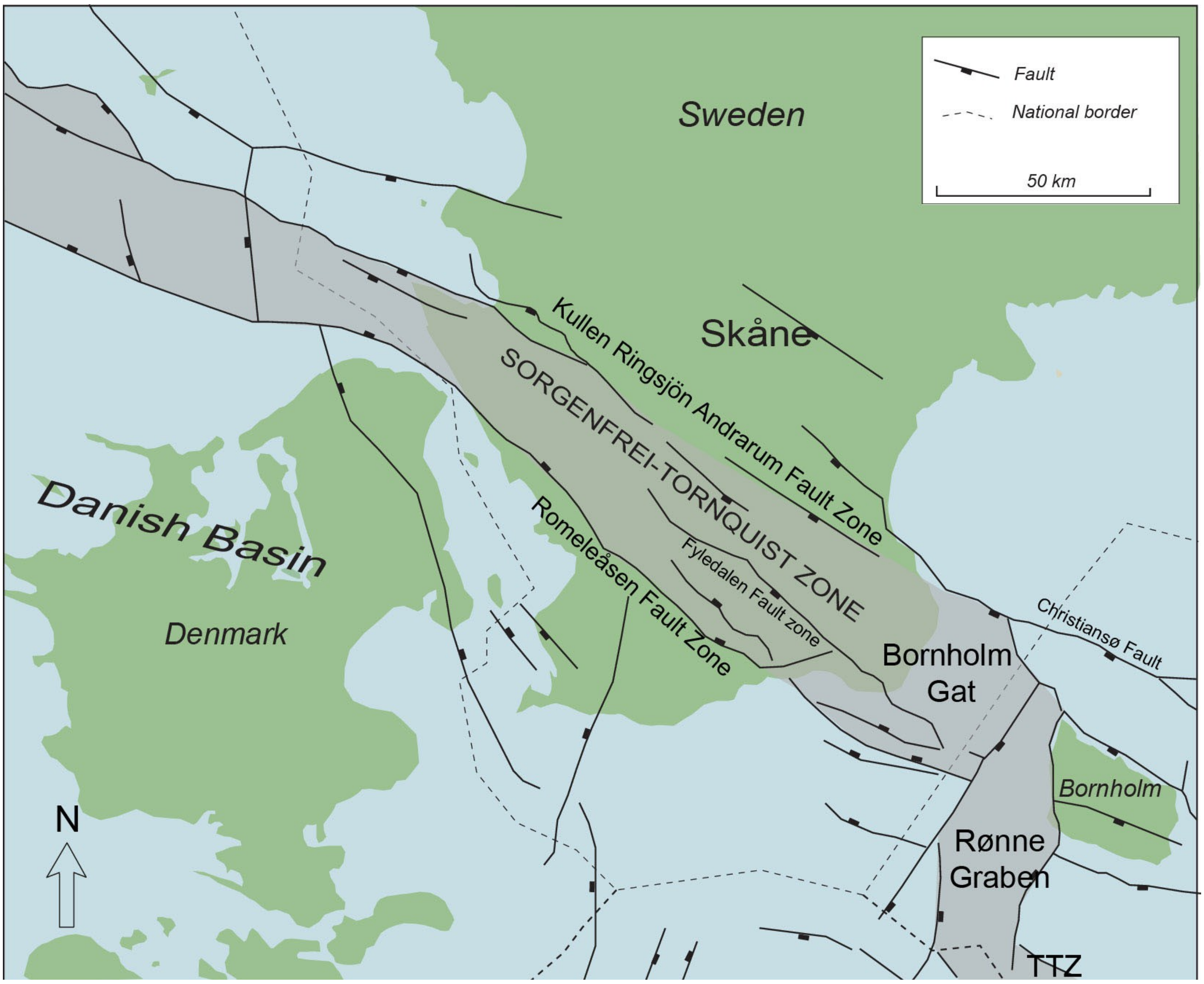

Fig. 1. Map showing the tectonic lineament of the Sorgenfrei-Tornquist Zone and adjacent fault zones. It is within the STZ the sediments in the Colonus Shale Trough has been preserved. (Modified from SGU unpublished report)

Andrarum Fault Zone (KRAFZ) and the Christiansø Fault to the Northeast. To the Southwest it is defined by the Romeleåsen Fault Zone (RFZ) and Rönne Graben, in fact the same as the CST. The STZ in Skåne is characterized by a number of tilted blocks, e.g. the Romeleåsen Block comprising the Romeleåsen Ridge, Vomb Trough and the Ystad-Rönne High.

3 Material and Methods

The primary material for this study includes three wells drilled by Shell in 2009-2010 as well as the geophysical and biostratigraphic data assembled from the corresponding wells. The three wells are Lövestad A3-1 (TD 955.17 m, 109.17 m cored, ca 5 Quaternary overburden, 130.1 m above MSL, N 55° 40' 03.85", E 13° 55' 12.53"), Oderup C4-1 (TD 917 m, 50 m cored, ca 33 m Quaternary overburden, 143.42 m above MSL, N 55° 46' 13.381", E 13° 43' 30.585") and Hedeberga B2-1 (TD 746 m, 53 m cored, ca 24 m Quaternary overburden, 77.52 m above MSL, N 55° 34' 24.936", E 013° 59' 55.713"). As a part of this project I visited the Shell Office (NAM) in Assen, Netherlands, in order to study the core sections, which is presented in Figure 4. The aim for the visit was to make stratigraphic logs from the core sections, gather biostratigraphic and gamma ray data, and to collect samples for preparation of thin sections. Thin sections were produced in the petrographic laboratory at GeoZentrum Bayern, Erlangen, Germany. The upper, not cored parts of each well has been studied and interpreted by means of cuttings, lithological descriptions and gamma-ray records.

In addition to the three Shell cores, data have been summarized from original research papers and coring protocols covering an additional 23 drillcores (Table 1 and Appendix I). The data gathered from the Shell office was supported by fieldwork in several outcrops in southeastern Skåne as well as by study of the Almbacken-1 and Röstånga-1 cores from Skåne and Billegrav-2 from Bornholm. The Cambrian biostratigraphy for Lövestad A3-1 was made by Arne Torshøj Nielsen at GEUS by the cost of Shell Exploration and Production AB. The chitinozoan biostratigraphy of the Ordovician and Silurian part of the Lövestad A3-1 well was analyzed by Fugro Robertson Ltd (Mullins 2010).

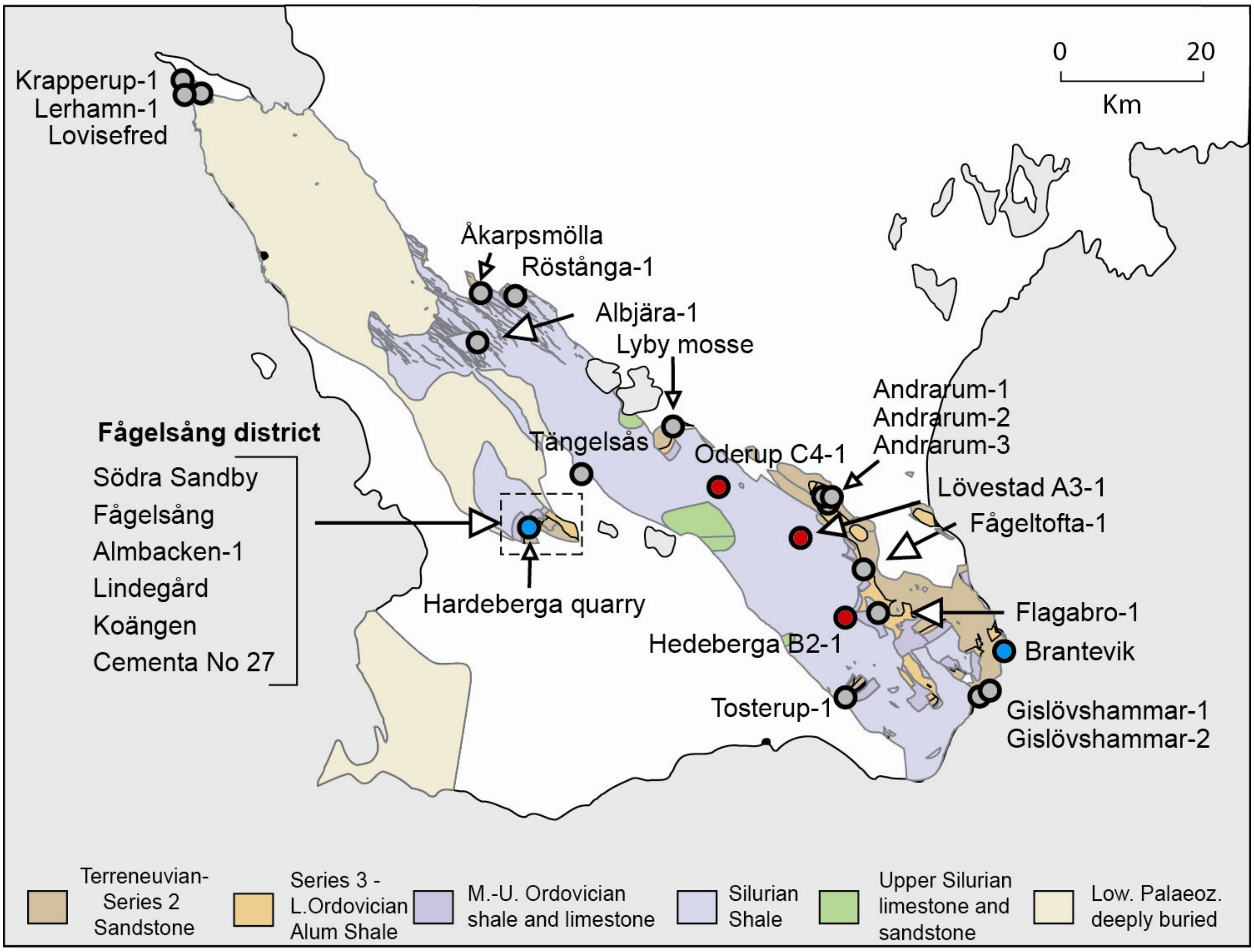

Fig. 2. Map of Skåne showing boreholes and outcrops, in the Colonus Shale Trough, discussed herein. (Modified M. Calner, unpublished Shell-report.

The backstripping model for tectonic evolution presented in this thesis was established by means of the software OSXBackStrip, downloaded from University of Georgia, and created by Nestor Cardozo.

4 Descriptive lithostratigraphy of the Colonus Shale Trough

Below follows an account of the stratigraphic units of the CST. The descriptions are based on previously published literature and expanded with new stratigraphic and facies data from the three Shell wells as well as from field observations and core logging.

The Cambrian part of the CST comprises the Nexø, Hardeberga, Læså, Gislöv and a major part of the Alum Shale Formation. The Ordovician comprise the uppermost Alum Shale Formation, Björkåsholmen Formation, Tøyen Shale, Komstad Limestone, Almelund Shale, Sularp Shale, Skagen Limestone, Mossen Formation, Fjäcka Shale, Lindegård Mudstone and the lower part of the Kallholn Formation. The Silurian of the CST consist of Kallholn Formation, Cytograptus Shale, Colonus Shale, and the Öved-Ramsåsa Group (Klinta Formation and Öved Sandstone Formation). A chronostratigraphic diagram of the CST is shown in Figure 5.

4.1 Nexø Formation

The Nexø Formation comprises the oldest strata of the CST, deposited immediately on top of the weathered and peneplained crystalline basement. The unit is about 15 m thick in Skrylle in central western Skåne, 1-10 m at Lunkaberg in southeastern Skåne, and ca 2 m at Rekekroken in northwestern Skåne (Nielsen & Schovsbo 2007 and references within). It constitutes a thin unit of coarse-grained and conglomeratic arkosic sandstone (Nielsen & Schovsbo 2007). The Nexø Formation has no subdivisions and is conformably overlain by the Hardeberga Formation.

4.2 Hardeberga Formation

The Hardeberga Formation is a classical sedimentary unit that forms the exposed bedrock in several parts of Skåne. It is a very hard rock and has therefore been quarried for a long time for its use as aggregates. The unit is about 105-120 m thick and subdivided into the Lunkaberg, Hadeborg, Vik, Brantevik and Tobisvik members (Nielsen & Schovsbo 2007). The formation is characterized by well-sorted strongly cemented or-

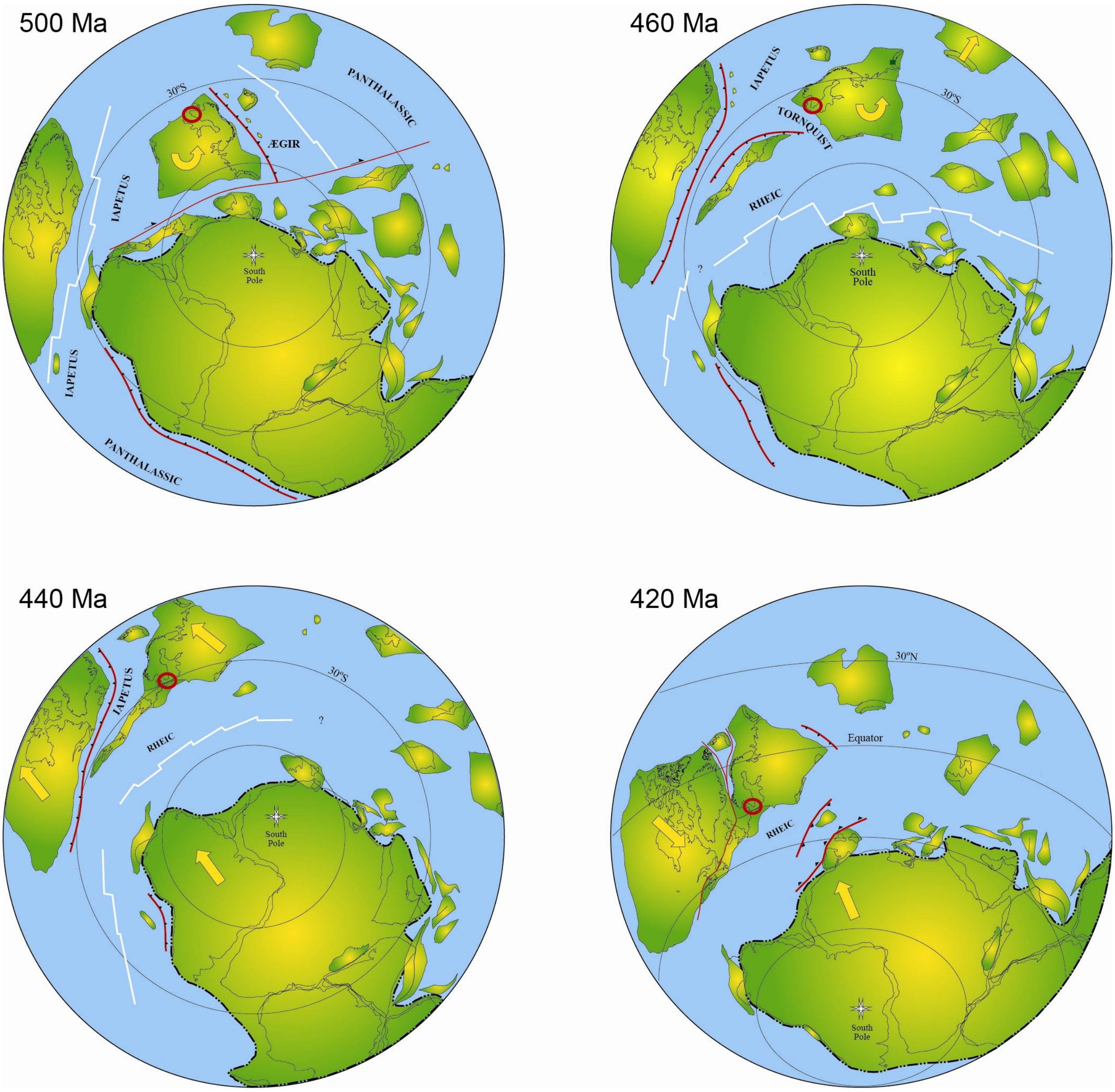

Fig 3. Lower Palaeozoic global palaeogeography (Skåne is marked by the red ring). Note the collision between Avalonia and Baltica between 460-440 Ma. Modified from Cocks & Torsvik (2002) – BATLAS (A-D).

thoquartzites with two major mud- and siltstone horizons; the Hadeborg and Brantevik members (Nielsen & Schovsbo 2007). The general colour of the Hardeberga Formation is typically whitish grey to grey but in some cases it could be dark grey or completely black due to interstitial pyrobitumen (Möller & Friis 1999). The formation tends to be more strongly bioturbated in Skåne than on Bornholm (Fig. 5A; Nielsen & Schovsbo 2007).

4.2.1 Lunkaberg Member

The Lunkaberg in Skåne has a thickness between 31 m and 44 m and is characterized by medium-grained slightly sparry and partly argillaceous quartzite (Lindström & Staude 1971; Nielsen & Schovsbo 2007). The member is bounded downwards by a sharp boundary to the Nexø Formation, typically with a rapid decline in feldspar content and by a shift to grey colour. It is sharply overlain by the more argillaceous Hadeborg Member. The Lunkaberg Member is only developed in Skåne and is corresponding in age to the Hadeborg member on Bornholm despite its depositional differences (Nielsen & Schovsbo 2007).

4.2.2 Hadeborg Member

The Hadeborg Member has a thickness of ca 3 m in southeastern Skåne, whereas in Bornholm it is thicker (Nielsen & Schovsbo 2007). In southeastern Skåne the member is characterized by dark mudstone with numerous sand beds containing scattered glauconites and phosporites (Nielsen & Schovsbo 2007). The lower boundary is defined by the shift from sandstone to mudstone. The upper boundary is transitional and is defined at the level where sandstone dominates.

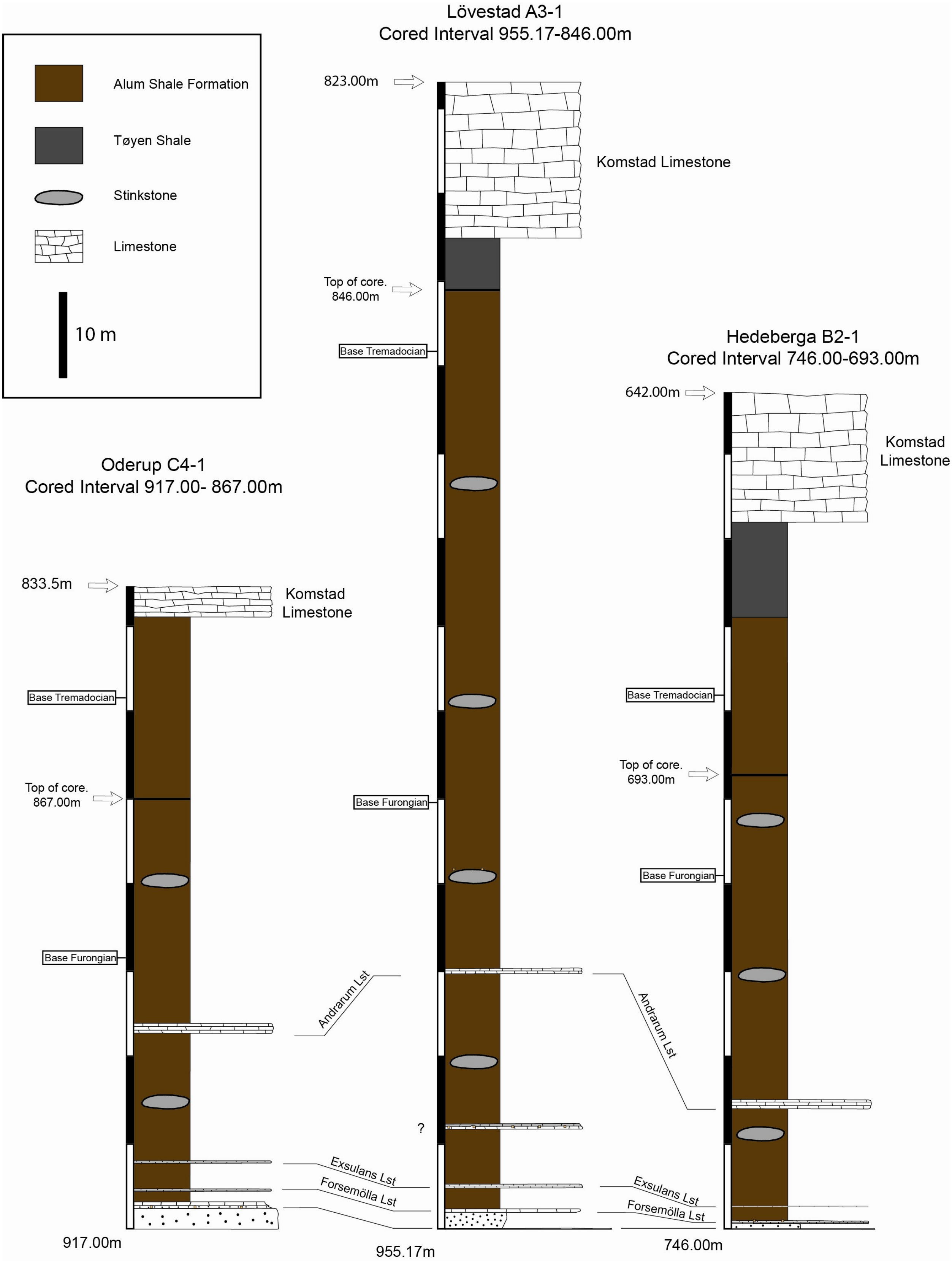

Fig. 4. Stratigraphic logs of the cored interval of the Shell wells Oderup C4-1, Lövestad A3-1, and Hedeberga B2-1. The upper non-cored interval is interpreted from gamma ray logs.

4.2.3 Vik Member

The Vik member is at least 34 m thick in southeast Skåne (Lindström & Staude 1971) whereas in the central parts of Skåne it is some 44 m thick (Nielsen & Schovsbo 2007). The member is characterized by fine- to medium-grained quartzite with couplets of whitish pure quartzite and greenish, slightly argillaceous bioturbated sandstone (Nielsen & Schovsbo 2007). It is conformably overlaying the Hadeborg Member and is unconformably overlain by the Brantevik Member. The member is characterized by high bioturbation.

4.2.4 Brantevik Member

The Brantevik Member is 2-3 m thick and is an important marker bed in the Hardeberga Formation. It is comprised of thin bedded, dark-coloured, locally strongly glauconitic silt and sandstone interbedded with thin mudstone. The member lies in between the quartzite-dominated Vik and Tobisvik members. A suggestion was made by Nielsen & Schovsbo (2007) to define the lower transitional boundary where mudstone dominates relative to sandstone. The lower boundary is also indicated by a phosphatic conglomerate and sandstone clasts. The upper boundary in Skåne is less distinct and is related to the gradual change from mudstone to quartzite.

4.2.5 Tobisvik Member

The Tobisvik Member has a thickness between 28-30 m in central Skåne, ca 25 m in southeastern Skåne, and about 77 m in Bornholm (Nielsen & Schovsbo 2007). It consists of pure, well cemented, comparatively coarse quartz-sandstone (Hamberg 1991). The lower boundary is gradual within a zone of 2-3 m whereas the upper boundary is sharp and unconformably overlain by the Læså Formation, Norretorp Member. The upper 5-6 m of the unit are thoroughly bioturbated and impure, reminding of the Vik Member (Nielsen & Schovsbo 2007).

4.3 Læså Formation

The lithology of the formation varies geographically throughout Skåne and the Bornholm area and comprises the Norretorp Member and the Rispebjerg Member.

4.3.1 Norretorp Member

The thickness of the Norretorp Member in Skåne has long been discussed and is believed to exceed 25.6 m in the central western part of the province (Falk 1993) and 16.5 m thick in southeastern Skåne (Shaikh & Skoglund 1974). The member has a proved thickness to103m on southern Bornholm (Nielsen & Schovsbo 2007) . In southeastern Skåne the Norretorp Member is dominated by glauconitic sandy siltstone somewhat dark and porous, whereas it is dominated by fine-grained sandstone in central western Skåne (Regnell & Hede 1960). Generally, the member is rich in irregularly rounded nodules of phosphorite, especially visible along the beach just a few hundred meters south of the small town Brantevik. The lower boundary is sharp and characterized by a thin phosphatic conglomerate (Hamberg 1991). The upper boundary to the Rispebjerg Member is generally sharp and well defined by high frequency of phosphorites and glauconite (Fig. 6B; Nielsen & Schovsbo 2007).

4.3.2 Rispebjerg Member

The Rispebjerg Member is a thin but characteristic sandstone unit with excellent exposures south of the Brantevik harbor. Its thickness varies from ca 1 m in Skåne to 3.7 m on Bornholm (Nielsen & Schovsbo 2007). It is at least 2.4 m thick in the Oderup C4-1 core. The member consists of whitish, medium- to coarse-grained quartz arenite (Fig. 8A). The sharp change from strongly bioturbated, glauconitic siltstones in the Norretorp Member to the clean, sometimes whitish arenite of the Rispebjerg Member defines the lower boundary. A conglomeratic phosphorite occurs at the base of Rispebjerg Member in Skåne, e.g. south of Brantevik (Fig. 6B). The nodules in the lower part seem to be reworked from the underlying Norretorp Member and the frequency of nodules decrease upwards. The topmost 0.1 m of the Rispebjerg Member is generally covered with abundant phosphorite nodules (Fig. 6D; Nielsen & Schovsbo 2007). This phosphorite horizon is present at the top of the Rispebjerg also in the Hedeberga B2-1, Oderup C4-1 and Almbacken-1 cores, with similar thickness, but is lacking in the Lövestad A3-1 core (Figs.10-11). Accordingly, the phosphorite forms an excellent regional marker bed.

4.4 Gislöv Formation

The Gislöv Formation is a heterogenous unit mainly known from Skåne. The thickness of the Gislöv Formation varies substantially within the CST and has a maximum thickness of 5.25 m in the Fågeltofta-2 core on Bornholm (Nielsen & Schovsbo 2007). It is 0.6 m in Shell's Oderup C4-1 core, 1.8 m in the Lövestad A3-1 and 0.8 m in the Hedeberga B2-1. The upper part of the Gislöv Formation in the Fågeltofta-2 core was faulted out suggesting an even greater thickness here. In the Slagelse-1 well on Sjælland the Gislöv Formation has a thickness ranging between 14-22 m (Bergström & Ahlberg 1981; Nielsen & Schovsbo 2007).

The lower part of the Gislöv Formation is generally characterized by mudstone and glauconitic siltstone whereas the upper part comprises conglomeratic bioclastic limestone that occasionally is intensely bioturbated (Figs. 6C, 6D, 8B). Pyrite and phosphorite nodules are common features throughout the formations as well as glauconite in the Shell cores. The lower boundary is clearly marked by the conspicuous

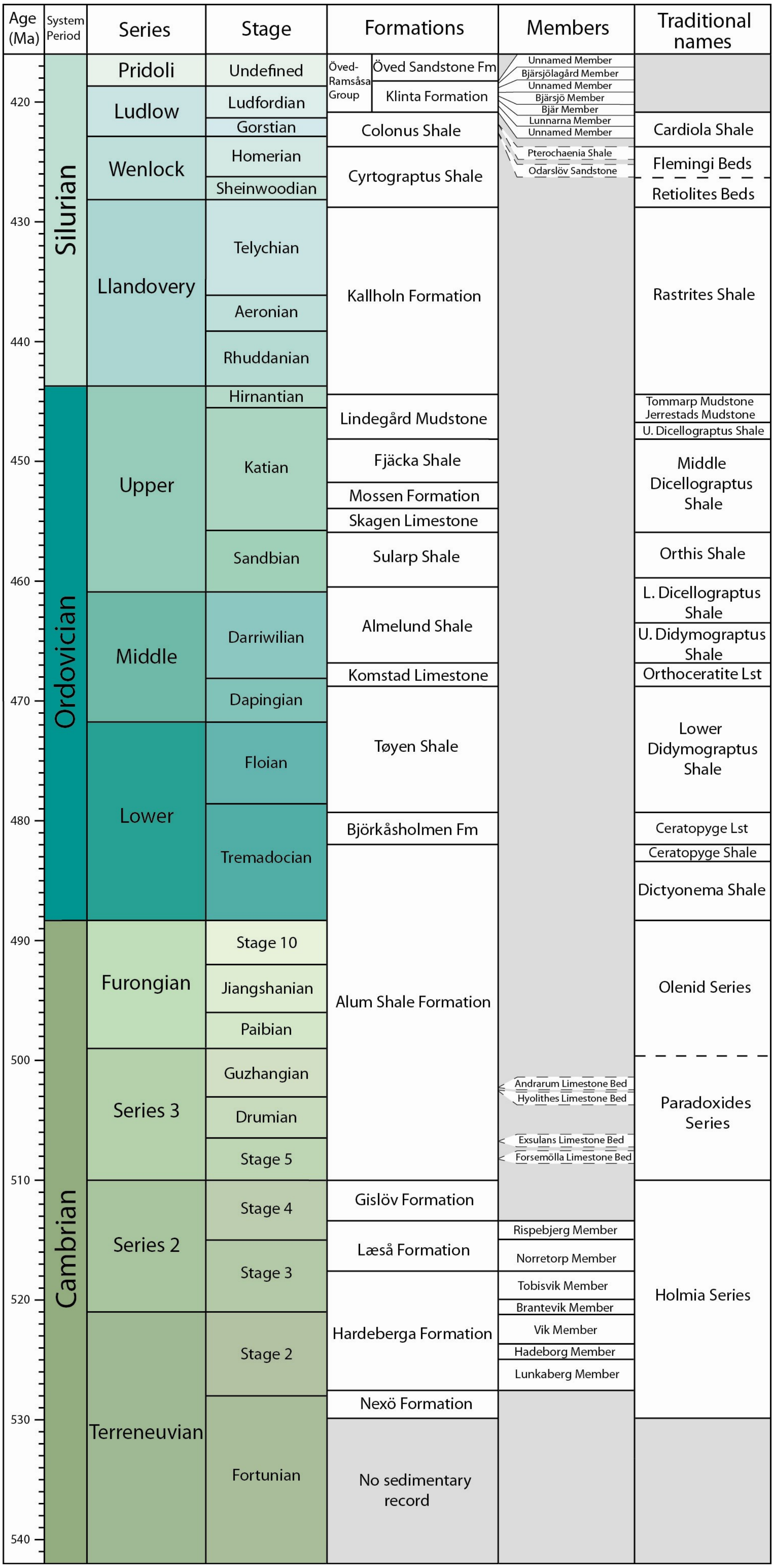

Fig. 5. Chronostratigraphic diagram of the Colonus Shale Trough.

phosphorite at the top of Rispebjerg Formation (Fig. 6D). The Gislöv Formation contains sand in the basal ca 0.1 m (Fig. 8C; Nielsen & Schovsbo 2007) but still has a sharp lower boundary from the Rispebjerg Member of the Læså Formation. This basal sand has been observed in Hedeberga B2-1, Oderup C4-1, Almbacken-1 cores and in the small outcrop at the old railway in the Hardeberga quarry, only with a slight difference in thickness (Figs. 10-11). The upper contact to the Alum Shale Formation is laterally variable. In the south-eastern parts of the CST (Lövestad A3-1 and Hedeberga B2-1), the Forsemölla Limestone Bed rests disconformably on top of the Gislöv Formation defined by a phosphatic laminae (Fig. 7A; Alvaro et al. 2009), whereas on Bornholm the Exsulans Limestone bed lies directly on top of the Gislöv Formation. In the Almbacken-1 and Oderup C4-1 core the Gislöv Formation is unconfomably overlain by the Alum Shale (Figs. 10-11).

4.5 Alum Shale Formation

The Alum Shale Formation is well known for its industrial use, such as production of kerogen and alum. It is a widespread unit present in many districts of Scandinavia. The unit generally thickens from ca 80 m in the south-eastern part of Skåne to about 100 m in the northwest. In the Oderup C4-1 core, however, it is ca 78 m thick, in Lövestad A3-1 ca 105 m, and in Hedeberga B2-1 it is ca 69 m (Fig. 4) implying an increase in thickness in the central parts of the CST. It is composed of kerogenous (up to 25% TOC, especially in the Furongian part) black, fissile shale with subordinate limestone (stinkstone or orsten) and a few primary, skeletal limestone marker beds such as the Forsemölla Limestone Bed, Exsulans Limestone bed, Hyolithes Limestone bed, and the Andrarum Limestone bed (Figs. 4, 7B-7D; Burchardt et al. 1997; Nielsen & Schovsbo 2007). Nielsen & Schovsbo (2007) stated that the base of Alum Shale Formation is diacronous, becoming younger in an eastward direction that complies with the three Shell cores. It is upwards variously overlain by Bjørkåsholmen Formation, Tøyen Shale or the Komstad Limestone.

4.5.1 Forsemölla Limestone Bed

The Forsemölla Limestone Bed is an important marker bed, in some literature known as "fragment limestone" (Axheimer & Ahlberg 2003; Nielsen & Schovsbo 2007; Alvaro et al. 2009). The bed is generally between 0.1-0.6 m thick (Nielsen and Schovsbo 2007) and in the Shell cores the bed is between 0.1-0.4 m (Fig. 4).

The Forsemölla Limestone bed is a bioclastic wackestone to packstone, displaying clay and carbonate mud contents ranging from 50-70% in volume (Alvaro et al. 2009). It sometimes contains phosphate clasts and glauconitic peloids and clasts making the surface look green (Figs. 6E, 7B).

In the south-eastern parts of the CST the Forsemölla Limestone Bed lies unconformably on top of the Gislöv Formation and on Bornholm it is missing (Figs. 10-11). The Forsemölla Limestone Bed unconformably superimpose the Gislöv Formation in the eastern Shell cores, Lövestad A3-1 and Hedeberga B2-1 wheras in the Oderup C4-1 the Forsemölla Limestone Bed first appear after ca 1 m into the Alum Shale Formation (Fig.10). The lower boundary of the Forsemölla Limestone Bed in the Lövestad A3-1 and the Hedeberga B2-1 is marked by a phosphatic laminae (Figs. 6E, 7A). The upper boundary is sharp and well defined and can be recognized with an authigenic pyrite inclusion in the Shell cores (Fig. 7B).

The Forsemölla Limestone Bed generally yields trilobite fragment, but most are not identifiable to a certain taxa (Fig. 8D.

4.5.2 Exsulans Limestone Bed

The Exsulans Limestone Bed is present in the Shell cores and is ranging 0.05-0.29 m in thickness (Figs. 7C, 10). The Exsulans Limestone bed is composed of bioclastic mudstone to packstone with larger bioclasts averaging about 2 cm in size (Alvaro et al. 2009). Trilobites are dominating the skeletal elements (up to 80 % in volume), and subsidiary calcite walled brachiopods and echinoderm ossicles, along with hyoliths and taxa of unknown affinity (Fig. 8E; Alvaro et al. 2009). The boundaries are sharp and easily recognizable. The Exsulans Limestone Bed on Bornholm is amalgamated with the Gislöv Formation since the Hawke Bay Event eroded Forsemölla Limestone Bed and parts of the Alum Shale Formation (Fig. 11).

4.5.3 Hyolithes Limestone Bed

The Hyolithes Limestone Bed has been described as a thin limestone bed underlying the well-known Andrarum Limestone Bed in the Andrarum area (Hadding 1958). However, it has not been recorded in any of the Andrarum borings (Ahlberg et al. 2009). It is generally a few decimeters thick often separated with a thin shale bed which could clearly be seen in the Hedeberga B2-1 and the Lövestad A3-1 cores whereas it seems to be amalgamated with the Andrarum Limestone in the Oderup C4-1 core. The Bed is a grey, crystalline limestone rich in fossils such as *Brachiopods* and *Hyolithes* shells where the name also is originated from (Hadding 1958).

4.5.4 Andrarum Limestone Bed

The thickness of the Andrarum Limestone Bed varies within the basin and is in Oderup C4-1 ca 1.2 m and Hedeberga B2-1 ca 0.9 m and Lövestad A3-1 ca 0.7 m. In Fågelsång area it is between 1.2- 1.5 m and at Albjära the thickness of the Andrarum Limestone bed is 1.2 m (Axheimer & Alhberg 2003) and the thickness is therefore increasing in the westward direction.

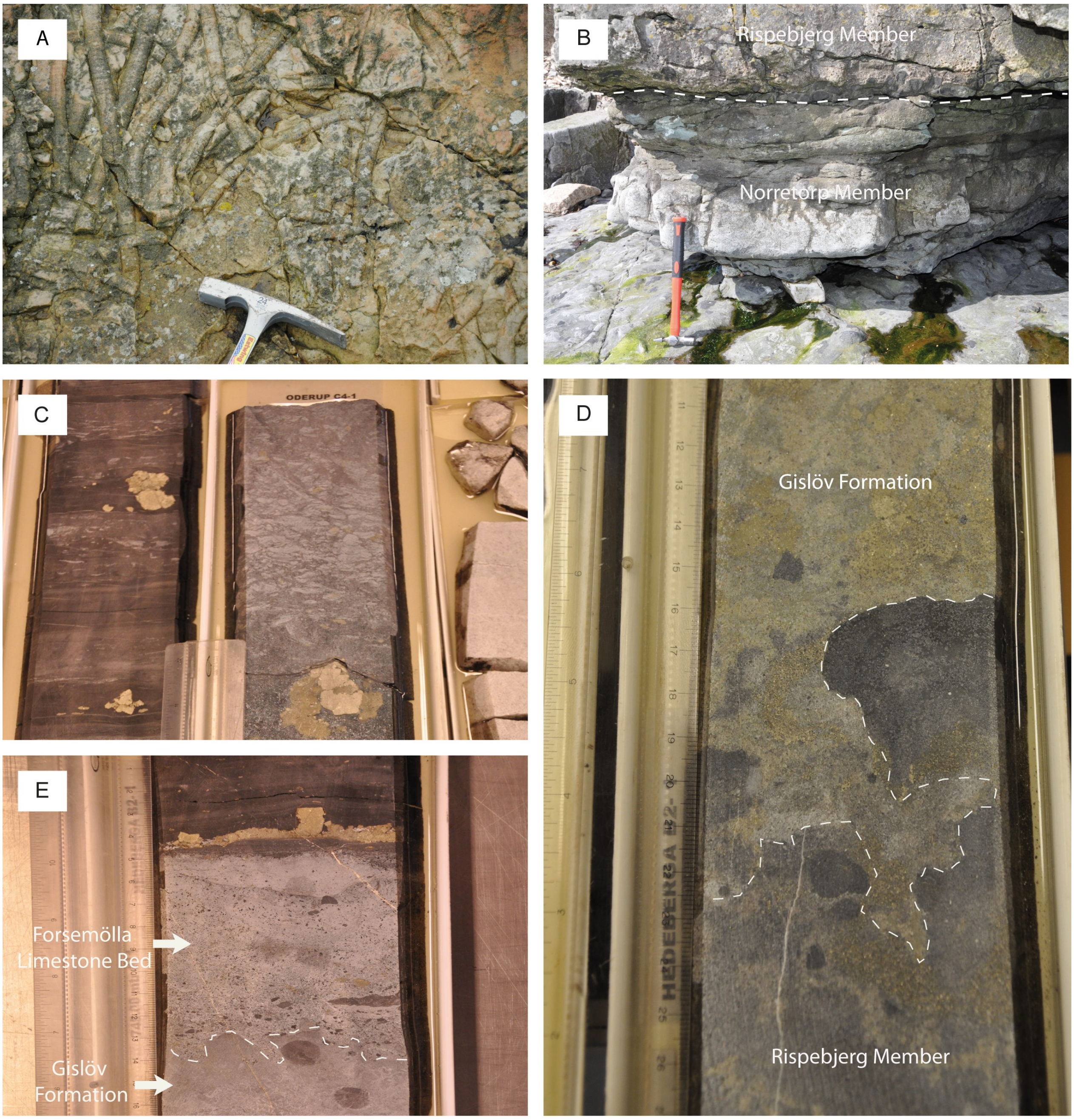

Fig. 6. Photo-plate showing outcrops and core sections. **A** Exposed surface from the Hardeberga Formation in Brantevik harbour. The sandstone is heavily bioturbated by the ichnofossil *Psammichnites gigas* typical for the Vik Member and the upper part of the Tobisvik Member. **B** Outcrop about one km south of the Brantevik Harbour. The photo shows the boundary between the silty glauconitic and bioturbated Norretorp Member (Læså Formation) and the medium- to coarse grained Rispebjerg Member quartz arenite. **C** Photo of the Oderup C4-1 core (10 cm core diameter) showing the upper part of the Gislöv Formation (middle core section), characterized by a glauconitic highly bioturbated limestone. The left core section shows the Alum Shale Formation and the rightmost core section the Rispebjerg Member. **D** Photo of the Hedeberga B2-1 core (core diameter 10 cm) showing the boundary between Rispebjerg Member and the Gislöv Formation. The boundary is defined by the uneven phosphorite surface and pyrite inclusions. **E** Photo of the Hedeberga A3-1 core (core diameter 10 cm). Note that the Forsemölla Limestone Bed rests directly and disconformably on top of the Gislöv Formation. Note the phosphatic clast in the Forsemölla Limestone Bed and the pyritic boundary between the Forsemölla Limestone and the Alum Shale Formation.

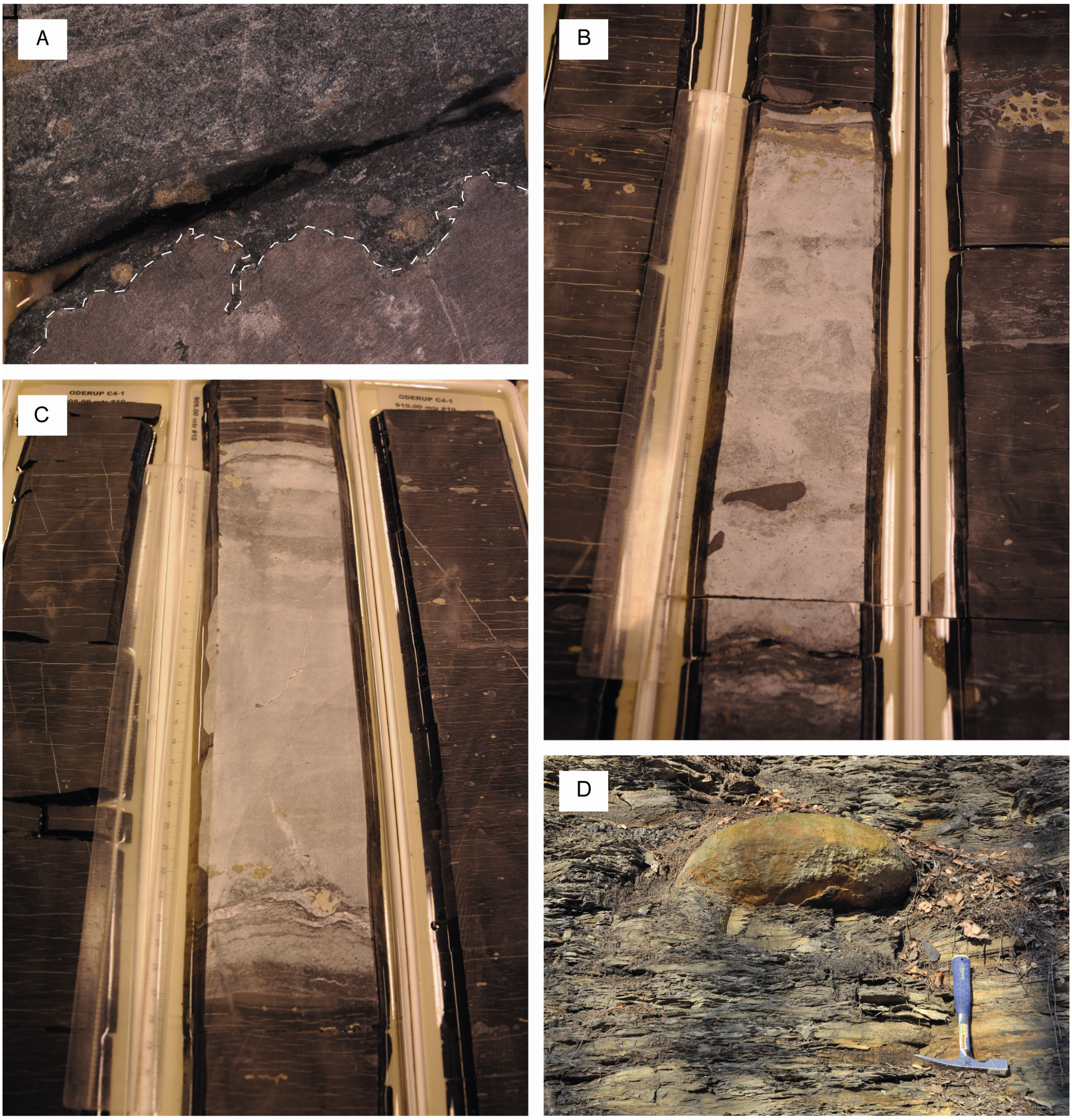

Fig. 7. Photo-plate showing outcrops and core sections. **A** Core sections from the Lövestad A3-1 core. The photo shows the phosphatic boundary between the Gislöv Formation and the Forsemölla Limestone Bed. Here the Forsemölla Limestone Bed is glauconitic and bioturbated. **B-C** Core sections from Oderup C4-1 core showing the Forsemölla Limestone Bed (7B) and the Exsulans Limestone Bed (7C) to illustrate the similarities of the beds (core diameter 10 cm). The two limestone beds are separated by 2.85 m black shale of the Alum Shale Formation. **D** The photo shows a diagenteic stinkstone (orsten) in the Alum Shale Formation in the Andrarum outcrop, at the "big quarry".

The Andrarum Limestone Bed is consisted of dark grey and richly fossiliferous limestone (Fig. 8F). The bed is well known for its rich fossil biotas comsisting of fossils such as agnostides, polymerids and brachiopods (Hadding 1958; Axheimer & Ahlberg 2003; Ahlberg et al. 2009).

4.6 Bjørkåsholmen Formation

The Alum Shale Formation is unconformably overlain by the ca 1 m-thick Bjørkåsholmen Formation in the south-eastern and central part of the CST whereas this unit seems to stratigraphically pinch out in the north-western part of the CST. It has not been confidently encountered in the Shell gamma ray. This unit constitutes dark-coloured, dense lithologies dominated by

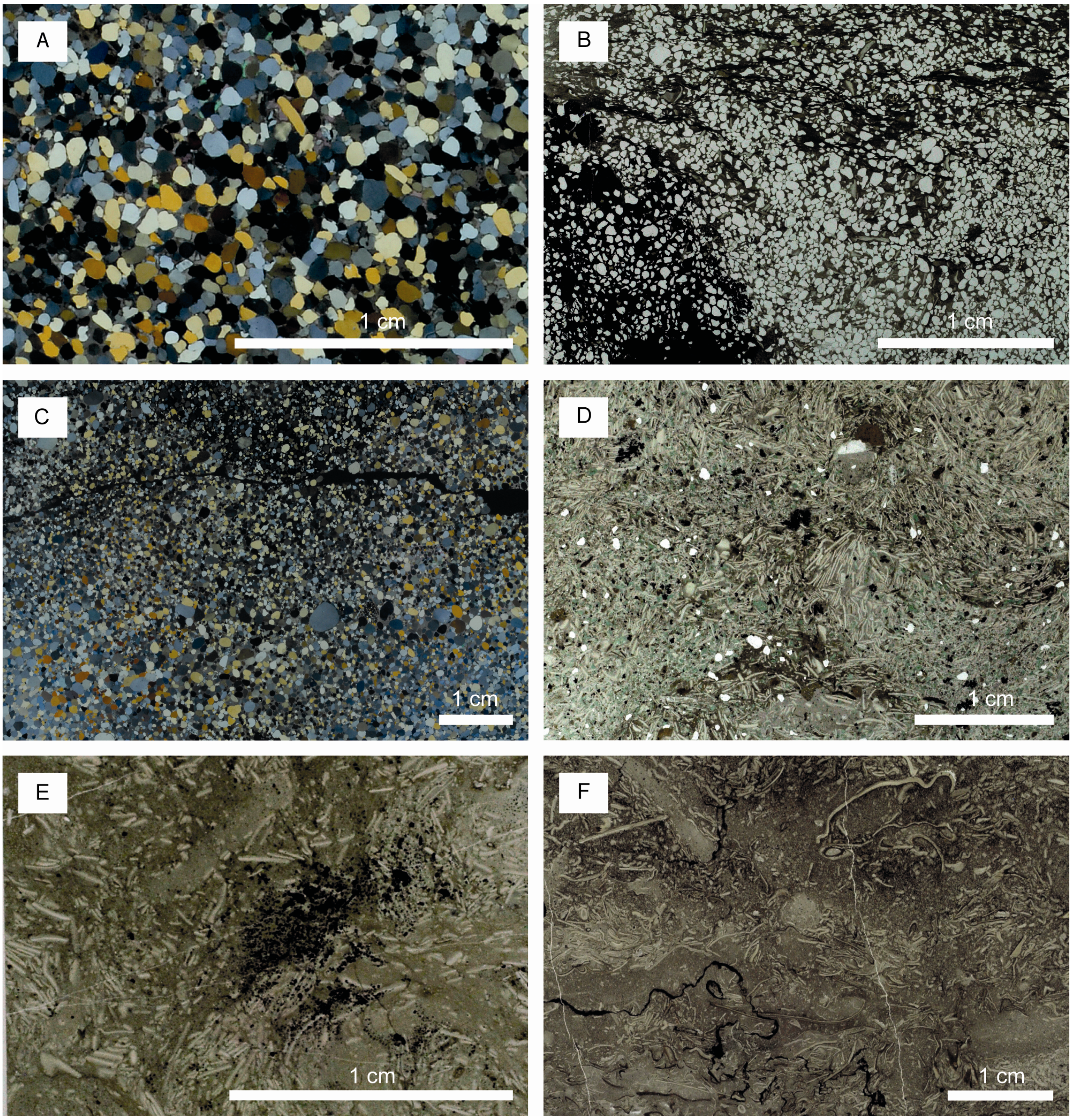

Fig. 8. Microphotographs of thin sections from the Shell core material. **A** Photo showing the mineralogy and texture of the Rispebjerg Member from the Hedeberga B2-1 core (crossed polarization). **B** Photo of the lower part of the Gislöv Formation with fossil fragments mixed with sand and fine-grained matrix. Oderup C4-1 core. **C** Photo from the Oderup C4-1 core showing the basal sand of the Gislöv Formation. Note the roundness of the grains (crossed polarization). **D** Photo taken from the Hedeberga B2-1 core showing the glauconitic bioclastic packstone (with subordinate quartz grains) of the Forsemölla Limestone Bed. **E** Photo of the Lövestad A3-1 core showing the bioclastic Exsulans Limestone Bed. **F** Photograph of the Oderup C4-1 core showing the Andrarum Limestone Bed. Some omission surfaces are present reflecting times of a starved depositional environment. Note the 'shepards hook' in the top right corner from a trilobite.

carbonates with subordinate shale intercalations usually containing glauconite, phosphate and pyrite (Hadding 1958). It is characterized by intense bioturbation and few preserved sedimentary structures and preserved fossils are mainly trilobites (Egenhoff et al. 2010). The Björkåsholmen Formation was previously termed Ceratopyge Limestone (Hadding 1958; Egenhoff et al. 2010).

4.7 Tøyen Shale

The Tøyen Shale is about 76.3 m thick in the Lovisefred-1 core (Nilsson unpublished), at least 80 m thick in the Lerhamn-1 core (Maletz & Ahlberg 2011) and at least 80 m thick in the Krapperup-1 core 80 m (Lindholm unpublished), all from the north-western

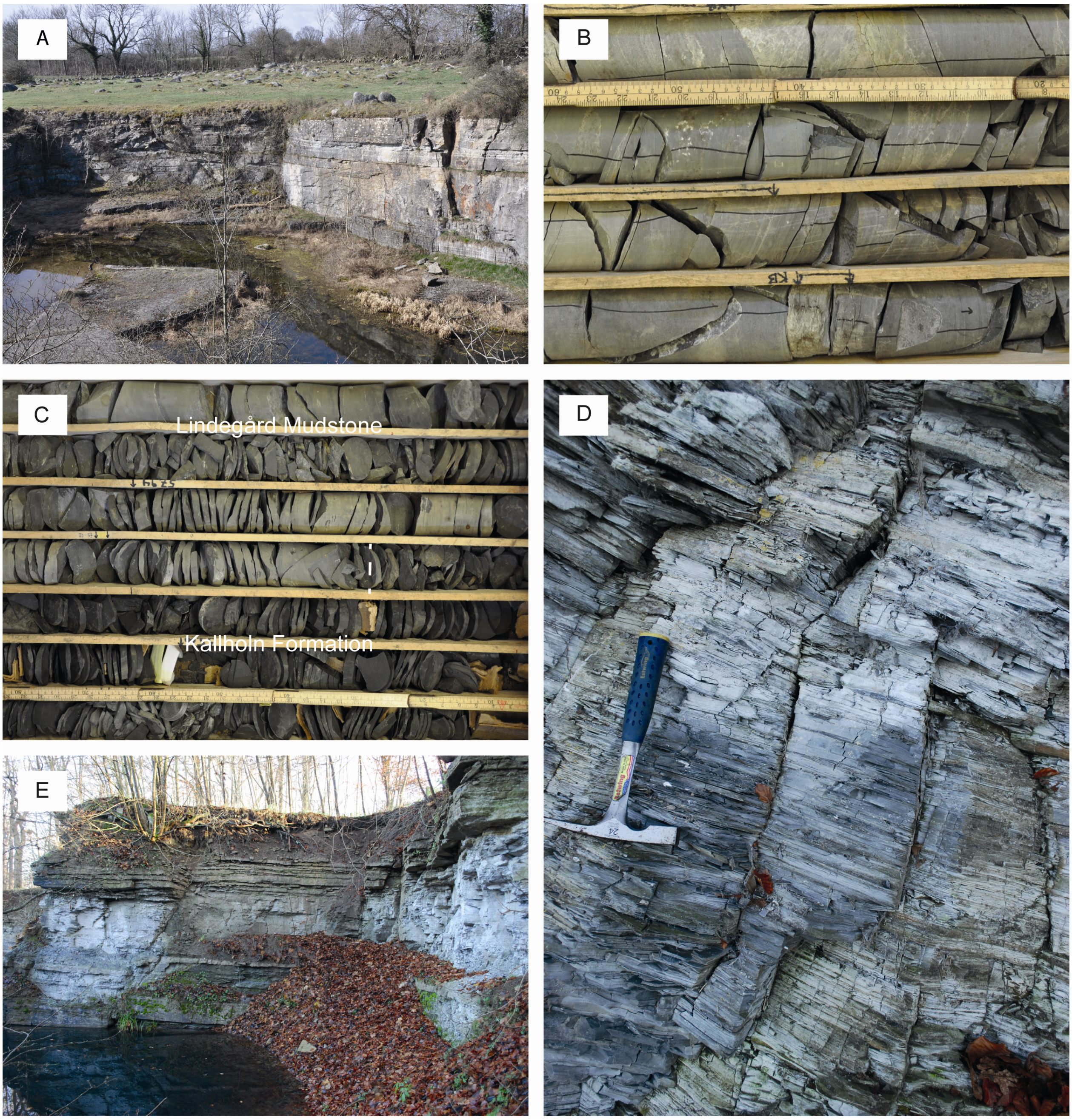

Fig. 9. Photo-plate showing outcrops and core sections. **A** The old quarry at Killeröd showing the Komstad Limestone, the only thick limestone unit within the Colonus Shale Trough. **B** Sularp Formation in the Röstånga-1 core. Note the greenish-colored K-bentonites. **C** Röstånga core with Lindegård Mudstone as the upper bright unit separated by a transitional boundary (marked with a dashed white line) overlain by the darker Kallholn Formation. **D** Photo from the Tolånga Rivulet where the Colonus Shale is exposed. **E** Photo from the old quarry at Bjärsjölagård showing the Bjärsjölagård Limestone Member of the Klinta Formation.

part of the CST. In the eastern part of the CST, a maximum recorded thickness of ca 23 m has been reported from the Flagabro core (Tjernvik 1958, 1960). The formation can be identified by means of gamma ray in Lövestad A3-1 and Hedeberga B2-1 were it reaches a maximum thickness of 6 m and 11 m, respectively. It was not, however, encountered in the Oderup C4-1 boring as well as the gamma ray (Fig. 12, Table 2). The Tøyen Shale is a black to light grey greenish rather homogenous shale, somewhat micaceous, pyritic and glauconitic with thin grey limestone beds (Tjernvik 1958; Regnell & Hede 1960; Maletz & Ahlberg 2011). It is generally rich in graptolites.

4.8 Komstad Limestone

The Komstad Limestone is the only thick limestone formation in the entire CST, and thus forms an excellent marker horizon in the shale-dominated trough (Fig. 9A). The limestone unit is absent, however, in the northwestern part of the trough, likely due to a normal stratigraphic pinchout. The unit is easily identified in the gamma ray records from Shell and reaches a maximum thickness of 18 m in the Lövestad A3-1 and a minimum of 3.5 m in the Oderup C4-1 (Fig. 12, Table 2). In the Billegrav-2 core it is comprised only by a 0.1 m thin conglomeratic horizon, also visible in gamma ray (Schovsbo 2011). The unit consists of fine- to medium-grained grey to black limestone, often with clay partings and sometimes with intercalation of dark grey shale that is occasionally bituminous (Hadding 1958). Glauconite and pyrite occurs at some levels. Notable for the succession is the presence of cephalopods up to several decimeters in length (Nielsen 1995). The lower boundary is a sharp unconformity, separating the unit from the underlying Tøyen Shale. The upper boundary, to the Almelund Shale, is a distinct unconformity in the south-eastern part of the CST, possibly associated with palaeokarst in the Killeröd area (cf. Nielsen 1995). The Komstad Limestone is regionally known as the Orthoceratite Limestone, which on Öland and in Västergötland have considerable thicknesses.

4.9 Almelund Shale

The Almelund Shale was designated as a new lithostratigraphical unit for a lithologically uniform sequence of dark-grey to black shale and mudstone with rare thin beds of impure limestone between the Komstad Limestone and Sularp Shale by Bergström et al. (2002). The shale unit thins substantially from the north-western parts of the CST towards the southeast; it is ca 80 m thick in the Albjära-1 core, ca 28 m thick in the Fågelsång district, and only between 7.5-13.5 m, based on the gamma ray records from Shell, in the south-eastern parts of the trough (Fig. 12, Table 2). The basal contact of the Almelund Shale is represented by a sharp lithological break towards the underlying Komstad Limestone. The upper boundary is deliminated by the Fågelsång Phosphorite (FPH), which is ca 0.15 m thick in the Fågelsång district (Hede 1951). Just below the FPH in the Fågelsång area the GSSP (Global section and stratigraphic position) for the boundary between Middle to Upper Ordovician can be found. The Almelund Shale contains a diverse graptolite fauna and yields only a few shelly fossils (mostly lingulate brachiopods) and biostratigraphically diagnostic conodonts and chitinozoans (Bergström et al. 2002). The formation name Almelund Shale was recently adopted by Bergström et al. (2002) instead of the outdated topostratigraphical designations Upper *Didymograptus* Shale and Lower *Dicellograptus* Shale. In the southeastern part of the CST the uppermost Almelund Shale contains a thin bed (up to 0.7 m) consisting of grey microcrystalline limestone and blue-grey shaly mudstone (Månsson 1995). This bed is termed the Killeröd Formation and is considered to be a discrete formation and is therefore not included as a stratigraphic unit in the CST.

4.10 Sularp Shale

The Sularp Shale is well known for its considerable amount of K-bentonites; no less than 33 in the Röstånga-1 core (Bergström et al. 1999). The unit is between 7.5 -12.5 m thick in the south-eastern and central parts of the CST, judging from gamma ray records, ca 27 m thick in the Fågelsång district (Nilsson 1977; Grahn & Nôlvak 2007), and between 20-30 m in the Röstånga area (Bergström et al. 1997, 1999). The unit consists of strongly silicified dark shale and mudstone, occasional beds of more or less impure limestone and is rich in shelly fossils (Fig. 9B; Bergström et al. 2002). The base of the Sularp Shale is defined by the Fågelsång Phosphorite (FPH). The upper boundary is marked by the Kinnekulle K-bentonite that has a thickness of 1.35 m in the Fågelsång district and 0.5 m in the Röstånga area (Bergström et al. 1997). The Kinnekulle K-bentonite was identified in all three Shell wells, from cuttings and by gamma ray, and thus is an excellent marker bed within the trough (Fig. 12). It has an estimated thickness in the Lövestad A3-1 and Oderup C4-1 well to ca 2 m.

4.11 Skagen Limestone

The Skagen Limestone is up to 14 m thick in Fågelsång district (Nilsson 1977; Grahn & Nôlvak 2007), ca 0.5 m thick in Kyrkbäcken rivulet at Röstånga (Pålsson 1996) and about 3 m in the Röstånga-1 core, in the latter containing seven bentonite beds (Bergström et al. 1999). The upper boundary is developed as a disconformity surface, with a few centimetres of corrosional relief, in the Röstånga-1 core. The Skagen Limestone has not been possible to identify in the gamma ray from Shell or by cuttings and may therefore be missing in the main part of the CST. The unit is a dark grey, calcareous mudstone or shale unit with phosphatic and pyritic interbeds of limestone (Bergström et al. 1997). Some levels are rich in trilobite fragments (Pålsson 2002).

4.12 Mossen Formation

This unit has a similar, somewhat limited, distribution as the Skagen Limestone. It is 6.65 m thick in the Fågelsång district (Nilsson 1977; Grahn & Nôlvak

Table 1. Compilation of cores and wells from the Colonus Shale Trough and the Fågelsång district. TD – total depth, CT – core thickness.

Core name	Location	TD/CT	Stratigraphic range	References
Krapperup-1	NW CST	155.06/~81	Tøyen Sh-Alum Sh	Lindholm Unpublished Maletz & Ahlberg (2011)
Lerhamn-1	NW CST	80/80	Tøyen Shale	Maletz & Ahlberg (2011)
Lovisefred-1	NW CST	503.40/485.28	Cyrtograptus Sh-Tøyen Sh	Nilsson (1984), Nilsson unpublished, Bergström et al. (1999)
Albjära-1	NW CST	237.40/~153	Almelund Sh-Gislöv Fm	Lauridssen (2000), Bergström et al. (2002), Maletz (2005)
Röstånga-1	NW CST	132.59/~99	Kallholn Fm-Sularp Sh	Bergström et al. (1997), Bergström et al. (1999)
Åkarpsmölla	NW CST	39.3/35.85	Alum Shale	Westergård (1944)
Södra Sandby	Fågelsång district	107/~92.00	Alum Shale	Westergård (1944)
Almbacken-1	Fågelsång district	32.70/~30	Alum Sh-Gislöv Fm	Axheimer & Ahlberg (2003)
Fågelsång-1	Fågelsång district	55/52.75	Sularp Fm-Alum Sh	Hede (1951), Bergström (2002), Grahn & Nôlvak (2007)
Koängen	Fågelsång district	70.30/70.3	Lindegård Ms-Almelund Sh	Nilsson (1977)
Lindegård	Fågelsång district	59.72/59.72	Lindegård Ms-Sularp Fm?	Glimberg (1961)
Cementa No27	Fågelsång district	22.15/20.0	Kallholn Fm-Lindegård Ms	Nilsson (1970), Bergström et al. (1999)
Lyby-1	Central CST	55.00/-	Almelund Sh-Alum Shale	Erlström et al. (2001)
Tängelsås-1	Central CST	140.00/ 97	Alum Sh-Hardeberga Fm	Erlström et al. (2001)
Oderup C4-1	Central CST	917/50	Alum Sh-Rispebjerg Mb	Calner & Pool (2011), Herein
Andrarum-1	SE CST	66.10/60.1	Alum Sh-Hardeberga Fm	Westergård (1944)
Andrarum-2	SE CST	40.7/35.1	Alum Shale	Westergård (1944)
Andrarum-3	SE CST	31.30/29.75	Alum Shale	Ahlberg et al. (1999)
Lövestad A3-1	SE CST	955.17/109	Alum Sh-Rispebjerg Mb	Calner & Pool (2011), Herein
Fågeltofta-2	SE CST	121.75/117.6	Komstad Lst-Rispebjerg Mb	Christensen (2003)
Hedeberga B2-1	SE CST	746.00/53.0	Alum Sh/Rispebjerg Mb	Calner & Pool (2011), Herein
Tosterup-1	SE CST	>95.5/>95.5	Tøyen Sh-Hardeberga Fm	Dahlman (1962) Unpublished, Andersson et al. (1985)
Flagabro-1	SE CST	54.33/35.63	Tøyen Sh-Alum Sh	Tjernvik (1958,1960)
Gislövshammar-2	SE CST	105.9/~103.9	Tøyen Sh-Rispebjerg Mb	Nielsen & Buchardt (1994)
Gislövshammar-1	SE CST	98.7/~92	Tøyen Sh-Rispebjerg Mb	Westergård (1944) Nielsen & Buchardt (1994)
Billegrav-2	Bornholm	125.9/121.4	Kallholn Fm-Norretorp Mb	Schovsbo (2011)

2007), whereas in the Röstånga 1 core it is about 0.5-0.75 m (Bergström et al. 1999; Pålsson 2002). The unit has not been recognized in the gamma ray from Shell or by cuttings. The Mossen Formation comprises a dark mudstone to calcareous shale, with thin shelly limestone beds, sometimes bituminous (Pålsson 1996). The unit is sometimes hard to distinguish from the overlaying Fjäcka Shale (Bergström et al. 1999) but is however in the Röstånga 1-core easily delimited with its dark greenish colour.

4.13 Fjäcka Shale

The Fjäcka Shale is in central Sweden a known petroleum source for the Upper Ordovician carbonate mud mounds (Vlierbom et al. 1986). This unit is an important marker bed throughout Baltoscandia and comprises dark brown to black shales and mudstone with a few thin interbeds of limestone (Calner et al. 2010). The Fjäcka Shale is about 14 m thick in the Röstånga area (Bergström et al. 1999; Pålsson 2002) and from 12.5-16.5 m in central-south-eastern CST judging from the gamma ray (Fig. 12, Table 2). The Fjäcka Shale contains a diverse fauna of shelly fossils but is dominated by graptolites (Bergström et al. 1999; Pålsson 2002).

4.14 Lindegård Mudstone

The Lindegård Mudstone is known from the Röstånga area where it is ca 27 m thick (Bergström et al. 1999), from the Fågelsång area where it is at least 27 m thick (Glimberg 1961), and from the central- to south-eastern CST where the gamma ray records suggest a thickness of between 7.5- 10 m (Fig. 12, Table 2). The unit comprises a light to medium-grey or grayish-green calcareous mudstone (Fig. 9C; Pålsson 1996, 2002; Bergström et al. 1999). The formation is often mottled, poor in fossil content and contains a few thin interbeds of limestones (Glimberg 1961).

4.15 Kallholn Formation

The Kallholn Formation has traditionally been classified as the Rastrites Shale but was renamed by Bergström & Bergström (1996). The thickness of the Kallholn Formation was estimated by Regnell & Hede (1960) to be between 110-130 m in the CST. This is concordant with our gamma ray records where the formation has a thickness between 114-126 m thick (Fig. 12; Table 2). The unit is ca 56 m thick in the Lovisefred-1 core in north western Skåne (Nilsson, unpublished report). The Kallholn Formation consists of dark grey and black shales and mudstones (Fig. 9C). The lower part yields subordinate seams of fine-grained, dark-coloured limestone. The upper part of the formation contains several thin K-bentonites (Bergström et al. 1999). Graptolites from the latest Ordovician (Hirnantian) has been found in the lowermost Kallholn Formation and it does not seem to be lithological evidence of a gap in the shale succession at the Ordovician- Silurian boundary (Bergström et al. 1999).

4.16 Cyrtograptus Shale

The Cyrtograptus Shale is the second thickest lithosome of the CST. It was estimated by Regnell & Hede (1960) to have a thickness of about 100-200 m but have a proved thickness of more than 300 m in the northwestern Lovisefred-1 core (See appendix I; Nilsson 1984). Our gamma ray records suggest a thickness between 282-305 m in the central- to south-eastern CST (Fig. 12, Table 2). The unit is a grey to black, occasionally brown or greenish shale, fairly coarse and rough to the touch (Regnell & Hede 1960). Thin beds of grey or yellowish, dense and hard limestone are common. The lowermost part of the Cyrtograptus Shale (Llandovery) locally contains thin lenses of bentonite and mudstone. The lower boundary from Kallholn Formation has been recognized by an increase in API in the Shell gamma ray (Fig. 12). This is also age correlated with the biostratigraphy by Mullins (2010) in the Lövestad A3-1 well. The upper boundary is characterized by an olive-grey, calcareous and slightly silty mudstone, less laminated than the shale (Laufeld et al. 1975). A clear API shift in gamma ray, especially in the Hedeberga B2-1 well (Fig. 12), is observed that mark the boundary between the Cyrtograptus Shale and the Colonus Shale (Fig.12). There is, however, no marked shift lithologically in the cuttings between the Kallholn Formation and the Cyrtograptus Shale, but the latter unit is most easily characterized by the first appearance of *Cyrtograptus* (Regnell & Hede 1960). Graptolites are common at different levels.

4.17 Colonus Shale

The Colonus Shale is the thickest lithosome in the CST and consists of variable shaly, silty and even sandy facies. The thickness is debatable since none of the cores in the central- or south-eastern CST has started at its top and only estimates can be done. Older literature (Tullberg 1882) suggested a thickness of 1100 m whereas more modern literature suggests a smaller thickness of about 600-700 m (Regnell & Hede 1960; Lindström 1971; Grahn 1996). None of the Shell wells were drilled from the top of the Colonus Shale but the minimum thickness is at least 364 m in the Lövestad A3-1 well, 332 m in the Oderup C4-1 and 177 m in the Hedeberga B2-1 (Fig. 12, Table 2). Based on chitinozoan biostra-

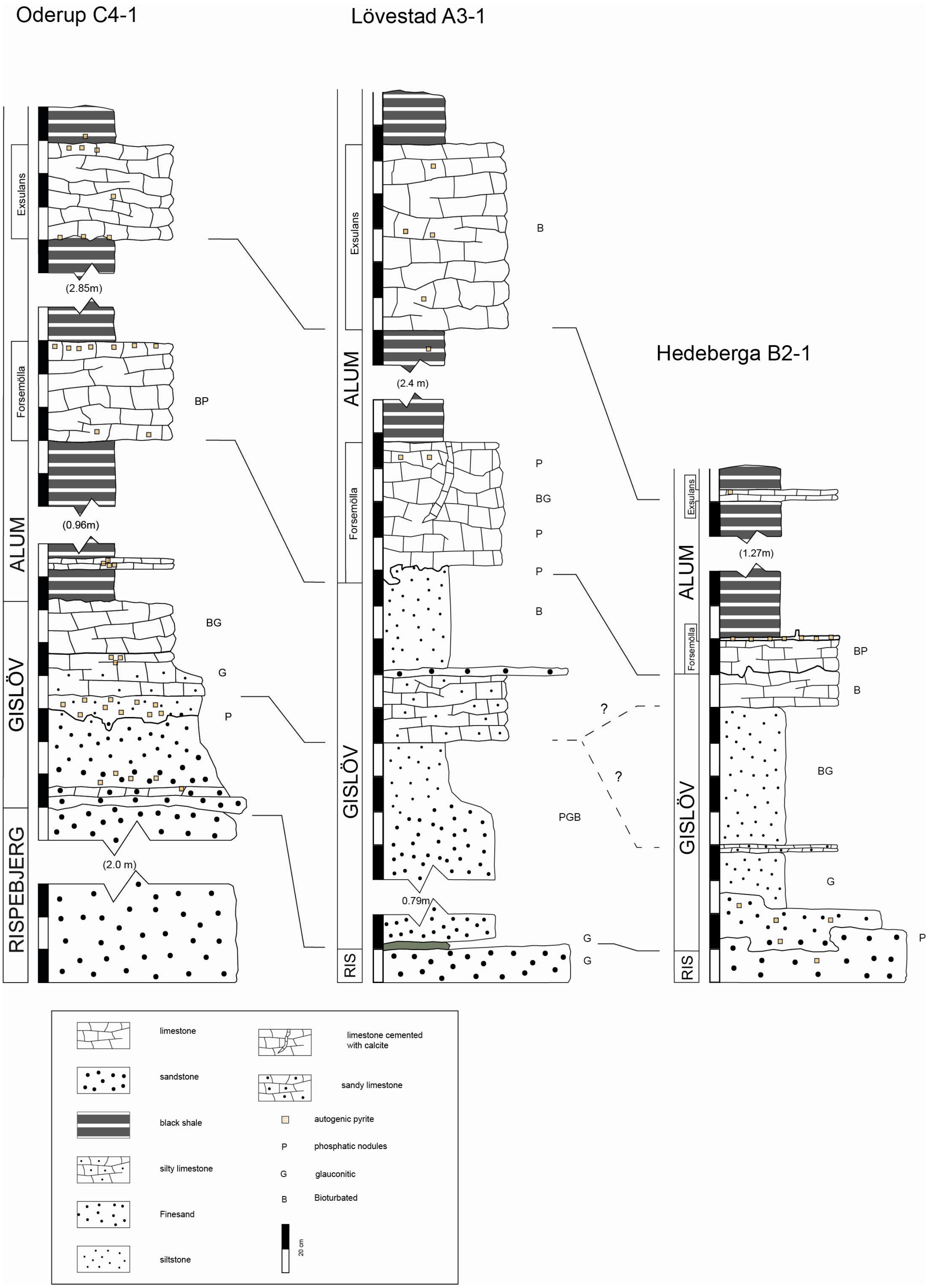

Fig. 10. Stratigraphic logs of the bottom part of the cored interval of the Oderup C4-1, Lövestad A3-1, and the Hedberga B2-1 cores. All of these logs show the change from the quartz arenitic Rispebjerg Member into the monotonous Alum Shale Formation. The interjacent Gislöv Formation is a laterally variable formation.

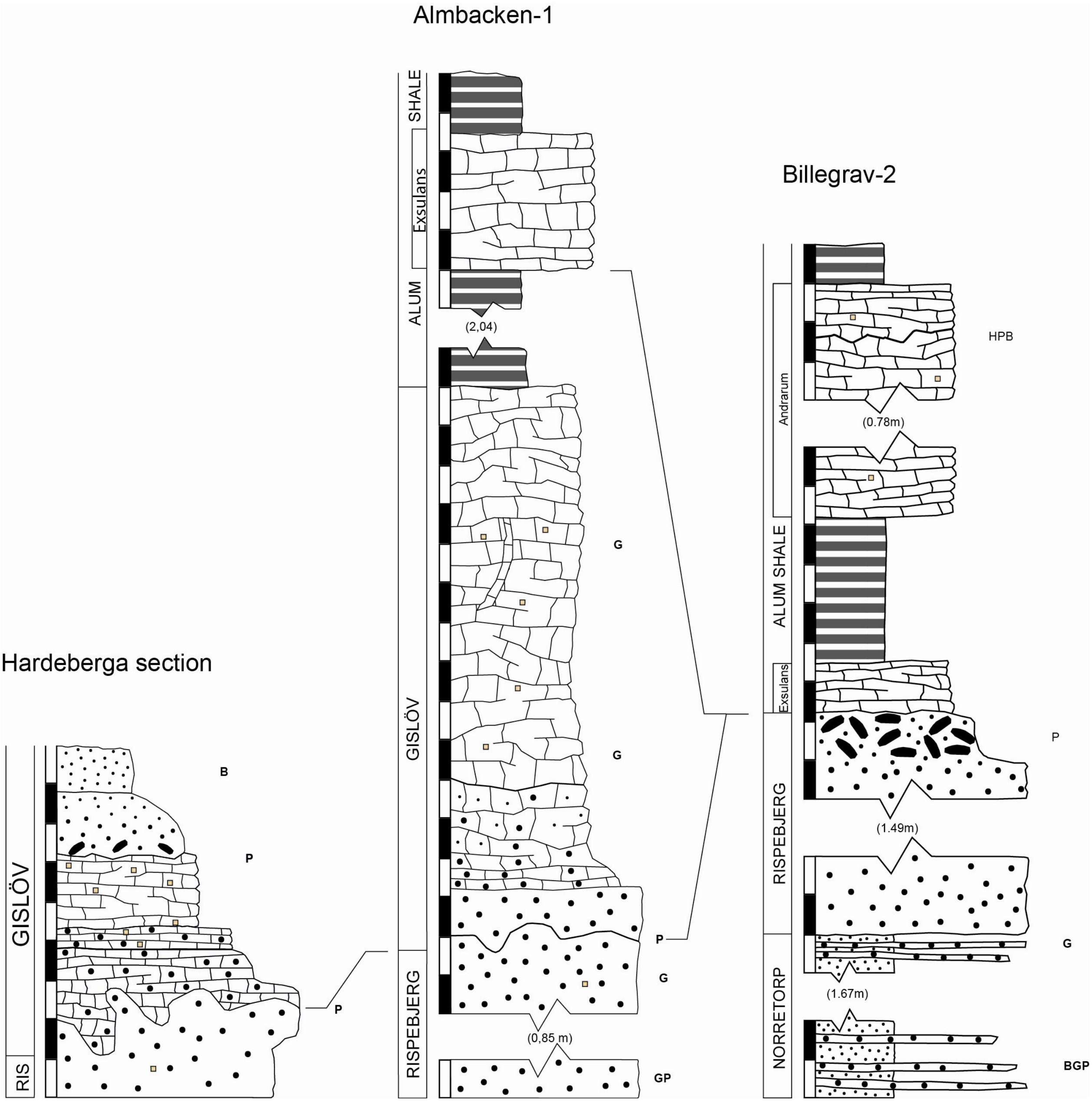

Fig. 11. Stratigraphic logs of the Billegrav-2 and Almbacken-1 cores and outcrop log of the Rispebjerg and Gislöv formations at the Hardeberga quarry. For legend, see Figure 10.

tigraphy by Mullins (2010) and Grahn (1996) the Shell wells stops in the middle to upper part of the Colonus Shale. The Colonus Shale is generally composed of a light-grey to greenish-grey, bluish, or reddish micaceous and slightly calcareous or arenaceous shale. Intercalated thin beds or lenses of grey limestone occur frequently (Fig. 9D; Regnell & Hede 1960). Graptolites are the dominating fauna in the Colonus Shale but it is generally poor in fossils except in its lower parts where it is fairly rich in bivalves and graptolites (Regnell & Hede 1960; Grahn 1996). The lowermost part of the Colonus Shale comprises a shelly mudstone but has less organic content and more benthic organisms than the underlying Cyrtograptus Shale. The lower boundary of the Colonus Shale is defined as the base of the *Pristiograptus ludensis* Zone.

Two stratigraphic varieties of the Colonus Shale are present, the Odarslöv Sandstone and the Pterochaenia Shale, however they not established as stratigraphic members.

4.17.1 Odarslövs Sandstone

The Odarslöv Sandstone is an informal stratigraphic unit known from several localities in the central and south-eastern part of the CST although the precise stratigraphic interval that it represents, as well as its lateral variation, remains uncertain. A maximum thickness of 1.8 m has been reported from the Odarslöv area, northeast of Lund (Regnell & Hede 1960). The unit comprises fine grained, brownish or red-brownish grey, argillaceous, calcareous and micaceous sandstone (Regnell & Hede 1960; Grahn 1996).

4.17.2 Pterochaenia Shale

The Pterochaenia Shale is a reddish marly shale yielding the bivalve *Pterochaenia glabra.* The unit contains a more varied fauna than the Colonus Shale such as graptolites and ostracods. The Pterochaenia Shale is restricted to the *C. colonus* Zone and is probably slightly younger than the Odarslöv Sandstone (Grahn 1996).

4.18 Öved-Ramsåsa Group

The Öved-Ramsåsa Group forms the youngest strata of the CST and crop out in three areas; the Ringsjö area, the Bjärsjölagård-Övedskloster area, and the Ramsåsa area (Regnell & Hede 1960; Jeppsson & Laufeld 1986). Due to many faults over short distances, and that the dip varies strongly in the different blocks makes it hard to estimate the total thickness of the group. However, it seems reasonable to be in the order of 200-300 m thick judging from core data (Jeppsson & Laufeld 1986). In contrast to the older Silurian units the graptolitic fauna is scarce in the Öved-Ramsåsa Group, whereas shelly faunas are rich and common (Jeppsson & Laufeld 1996). The group is not lithologically uniform and is rather characterized by its variation and is therefore divided into two subdivisions, the Klinta Formation and the Öved-Sandstone Formation. The Öved-Ramsåsa Group has not been encountered in the Shell borings.

4.18.1 Klinta Formation

The thickness of the Klinta Formation is estimated to 100 m or slightly more judging from the Bjärsjölagård 1 and 2 cores(Jeppsson & Laufeld 1986). The Klinta Formation is characterized by grey mudstone, sometimes fissile and approaching shale (Jeppsson & Laufeld 1986). Subordinate siltstone and limestone beds (often detrital) occur, except in the Bjärsjölagård Member which is dominated by impure limestone. The lower contact is not exposed but Jeppsson & Laufeld (1986) suggested drawing the contact above the highest graptolitifereous beds.
The Klinta Formation includes the following units in ascending order: an unstudied and unnamed interval, the Lunnarna Member, the Bjär Member, the Bjärsjö Member, an unnamed interval, the Bjärsjölagård Member, and an unnamed thin uppermost part.

4.18.1.1 Lunnarna Member

The thickness of the Lunnarna Member is not yet determined but could be up to 30 m thick (Jeppsson & Laufeld 1986). The general facies of Lunnarna Member is shale dominated with siltstone beds and some beds or lenses of detrital limestone (Jeppsson & Laufeld 1986). The lower part of the member comprise similar lithology as the Colonus Shale but crinoids and brachiopods, unknown from the Colonus Shale, occur (Grahn 1996). The member is characterized by abundant trace fossils and bioturbation.

4.18.1.2 Bjär Member

The Bjär Member is about 10 m thick and is known from Bjärsjölagård and at Klinta. It comprise of grey shale and thicker beds of hard, grey, micaceous shale and thin beds of detrital limestone (Jeppsson & Laufeld 1986).

4.18.1.3 Bjärsjö Member

The Bjärsjö Member has a thickness of between 4.1-13.4 m. The lower boundary into the Bjärsjö Member marks a transition in depositional environment into hard calcareous mudstone beds, many of which include limestone beds and lenses (Jeppsson & Laufeld 1986).

4.18.1.4 Bjärsjölagård Limestone Member

The Bjärsjölagård Limestone Member has a known thickness of about 25 m is only known from the Bjärsjölagård-Övedskloster area (Fig. 9E; Jeppsson & Laufeld 1986). It is characterized by abundance of limestone beds and mudstone in the Bjärsjölagård-Övedskloster area (Jeppsson & Laufeld 1986; Nilsson 2006) whereas in the Ringsjö area it is dominated by grey shales (Grahn 1996).

4.18.2 Öved Sandstone Formation

The Öved Sandstone Formation is known from Bjärsjölagård-Övedkloster area, Ramsåsa, Branstadholm and the Ringsjö area. The thickness has been estimated about 100 m by Jeppsson & Laufeld (1986). The Öved Sandstone Formation consists of grey sandstone and shale with subordinate thin limestone beds in the Ramsåsa and Bjärsjölagård-Övedskloster area (Jeppsson & Laufeld 1986) while grey shales dominate the Rinsgsjö area (Grahn 1996). The sandstone is easily weathered to a rusty red color unless it has been weathered earlier (Jeppsson & Laufeld 1986). The upper boundary of the Öved Sandstone Formation has not yet been described but it is generally assumed that the Triassic Kågeröd Formation directly overlies the Silurian Öved-Ramsåsa Group.

4.19 Summary of the lithostratigraphy of the Colonus Shale Trough

The Cambrian through Silurian sedimentary fill of the CST can be subdivided into five stratigraphic associations based on lithological characteristics. These informal associations represent a series of successive time intervals of stable depositional conditions in the basin and together reflect the longer term depositional evolution of the continental margin.

4.19.1 Cambrian Sandstone Association

The Cambrian Sandstone Association comprise the Nexø Formation, Hardeberga Formation, Læså Formation and The Gislöv Formation and has a combined thickness of about ca 150 m. The typical lithologies dominating this association are quartzites with abundant primary structures, such as tabular and trough cross bedding, and hummocky cross bedding. Some levels contain silty and shaly facies such as Hadeborg Member, Brantevik Member and the Norretorp Member.

4.19.2 Cambrian-Ordovician Alum Shale Association

The Cambrian Ordovician Alum Shale Association consist entirely of the Alum Shale Formation and ranges from ca 69 to ca 105 m in thickness. The base of the association is defined by the major shift in sedimentation that took place at the boundary of Cambrian Series 2 to Series 3when supply of coarse clastic material to the basin as terminated. Instead, deposition of uniform black, organic-rich shale took place during the remaining Cambrian into middle Tremadocian.

4.19.3 Ordovician Shale and Limestone Association

The Ordovician Shale and Limestone Association includes in ascending order the Björkåsholmen Formation, Tøyen Shale, Komstad Limestone, Almelund Shale, Sularp Shale, Skagen Limestone, Mossen Formation, Fjäcka Shale and Lindegård Mudstone. This association is a condensed unit (ca 45-130 m) consisting primarily of shale and mudstone with subordinate limestone. A substantial lateral thickness variation is seen in latest Tremadocian and Floian Stages when total thickness varies from ca 45 m in the southeastern CST (Lövestad A3-1 well) to at least 147 m in the Lovisefred-1 core in the northwestern part of the CST. The Björkåsholmen Formation, Komstad Limestone and Skagen Limestone are the only regionally important Limestone units of the CST and thus function as important marker beds. However, the Skagen Limestone does not appear in southeastern CST.

4.19.4 Silurian Shale Association

The Silurian Shale Association marks an increase of depositional rates hence producing a thick rather uniform unit with only slight variations in lithology. The sedimentation rates escalate in the latest Telychian through earliest Sheinwoodian, and continued to be high throughout the remainder of the Silurian. The Silurian Shale Association has a total thickness of at least 850-1000 m.

4.19.5 Silurian Limestone and Sandstone Association

The Silurian Limestone and Sandstone Association marks the shift from monotonous and graptoliferous shales in the Silurian Shale Association. It is comprised of the Öved- Ramsåsa group, including the Klinta Formation and the Öved Sandstone Formation and has a thickness of ca 300 m. The lower Klinta Formation is dominated by shale and fine-grained sandstone successively grading into limestone and sandstone. The upper Öved- Sandstone is the youngest strata in the CST and marks the end of the basin development.

5 Gamma ray results

The Shell bore holes were logged for natural gamma activity reported in API (American Petroleum Institute) units. The technique measures the natural occurrence of radioactive components such as potassium, uranium and thorium in the rocks. Accordingly, high API values are related to fine-grained deposits with abundant clay minerals whereas low API values are typical for limestone or sandstone. This method therefore provides a powerful tool to reveal subsurface stratigraphy and boundaries between formations. Organic-rich deposits, such as black shales, produce a marked reaction on the gamma log due to its enrichment in uranium. These deposits are therefore called “hot shales” (Bjørlykke 2010).

The CST is dominated by fine-grained mudrocks and shales with none or little facies variation and hence only small changes are observed in the gamma ray signal; the Alum Shale Formation being an important exception (Fig. 12). Generally the gamma ray values of the CST range as little as 50 API from the top of the Silurian down to the Kallholn Formation where the API values increases. A marked decreasing trend of the API value can be seen in the Hedeberga B2-1 gamma ray at the boundary between the Cyrtograptus Shale into the Colonus Shale, at 200 m. A similar trend change is not clearly visible in the other two wells. The Silurian Shale Association is generally quite homogenous but display a slow, decreasing trend, observed in all three gamma ray logs. The trend has a span of 10-20 API over a thickness of ca 600 m which would suggest a slightly progradational coastline with successively increasing influx of coarser grained material throughout the corresponding time interval.

A notably scattered interval is observed between 400-460 m in the Oderup C4-1 well. The scatter is also visible in Lövestad A3-1 between 415-500 m and between 210-315 m in Hedeberga B2-1, but less distinct. The increased input of silt and sand observed in the cuttings form this interval most likely explains this scatter. The influx of coarser siliciclastic material may be associated with the Mulde Event in the Homerian. The event was a period of instable climate characterized by glaciations causing a global sea level drop (Jeppsson & Calner 2002).

At 510 m in the Oderup C4-1 and Lövestad A3-

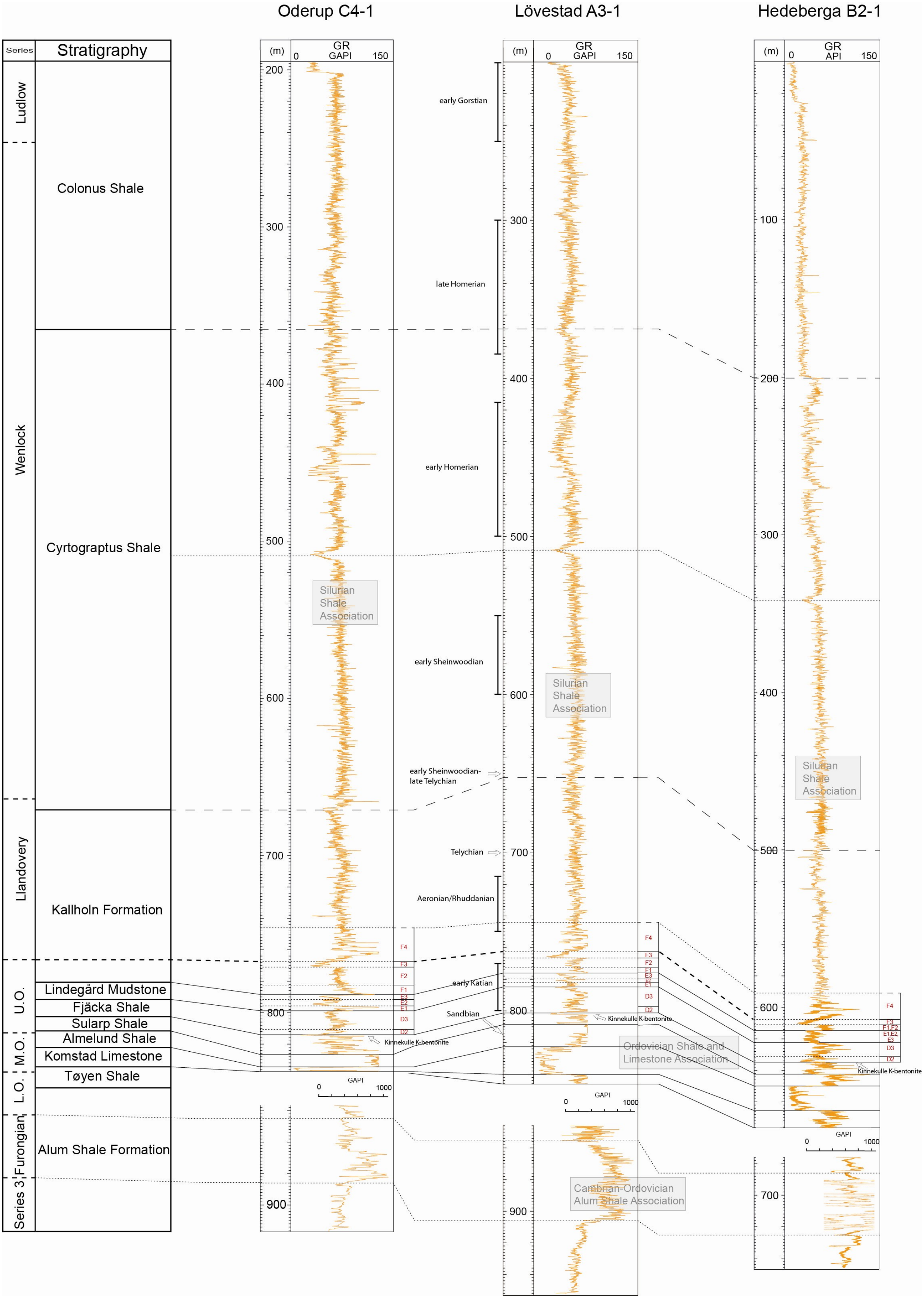

Fig. 12. Gamma ray logs from the Shell wells. The solid lines mark key points of correlation and dashed lines show inferred correlations between the various stratigraphic units. The red letters on the right-hand side of the logs mark the correlation to the Billegrav-2 core on Bornholm (Schovsbo 2011). Chronostratigraphic correlations from Mullins (2010) are illustrated on the left hand side of the Lövestad A3-1 well.

Table 2. Unit thicknesses in metres based on gamma ray logs and cuttings.

Unit	Oderup C4-1	Lövestad A3-1 Thickness (m)	Hedeberga B2-1
Quaternary overburden	33	5	24
Colonus Shale	>332	>364	>177
Cyrtograptus Shale	305	282	300
Kallholn Formation	117	126	114
Lindegård Mudstone	10	9	7.5
Fjäcka Shale	15	16.5	12.5
Mossen/Skagen	-	-	-
Sularp Shale	12.5	7.5	7.5
Almelund Shale	8	13.5	7.5
Komstad Limestone	3.5	18	15
Björkåsholmen Formation	-	-	-
Tøyen Shale	-	6	11
Alum Shale Formation	78	105	69
Gislöv Formation	0.6	1.8	0.8
Læså Fm (Rispebjerg Mb)	>2.4	>0.1	>0.1
Total	~917	~955	~746

1 and at 342 m in the Hedeberga B2-1 a notable dip in API value is observed. There is, however, no lithological changes observed from cuttings but the conspicuous dip is an important marker for the correlation of the gamma ray.

In the Billegrav-2 core from Bornholm, Nielsen (2011) subdivided the gamma ray log into units based on small-scale cyclicity in the API values. Some of these cycles have been identified in the Shell gamma ray logs and have accordingly been correlated to the Billegrav-2 gamma ray log, visible on the right hand side of the gamma ray log in Figure 12. In the gamma ray logs from Skåne the corresponding cycles appear in the lower Kallholn Formation and continuous to the boundary between Fjäcka Shale and Sularp Shale, just above the Kinnekulle K-bentonite. Below the Kinnekulle K-Bentonite the uncertainties are too high to make a correlation with the Billegrav-2 gamma ray, except the Alum Shale Formation.

The Ordovician Shale and Limestone Association is characterized by highly varying gamma ray values, reflecting the heterogenous lithological composition of this condensed unit. The most important marker horizons for subsurface correlation in the Ordovician are the Komstad Limestone and the Kinnekulle K-bentonite. The Komstad Limestone is associated with a substantial dip of the API values, in fact the lowest value in the entire gamma ray log data set. The Kinnekulle K-bentonite was identified in the cuttings and correlated with a small dip in all three gamma ray logs (Fig. 12). The Kinnekulle K-bentonite marks the boundary between Sularp Shale and the Fjäcka Shale since neither Skagen Limestone nor Mossen Formation was identified in the cuttings.

Shales normally contain less than 1 ppm uranium (Bjørlykke 2011), but the Alum Shale Formation in the CST contain up to 171 ppm uranium (Dahlman, unpublished). This explains the exceptionally high API values in the Alum Shale Formation (Fig. 12). The highest values found in the CST gamma ray logs are found in the Furongian part of the Alum Shale Formation and reaches above 1000 API units. The measurements were stopped before reaching the Rispebjerg Member of the Læså Formation. Table 2 outlines the thicknesses of the formations as determined from the gamma ray logs.

Some remarks are necessary to discuss in the chitinozoan biostratigraphy of the Lövestad A3-1 well (based on the information in Muller 2010). The indication of a Sandbian age at 815 m in the Lövestad A3-1 well is based on the occurrence of an age diagnostic taxa observed only in one sample. The age diagnostic taxa are *Conochitina conulus*, *Cyathochitina hunderumensis*, *Desmochitina erinacea sensu* Laufeld, 1967, *Desmochitina minor*, ?*Eisenackitina rhenana*. It was, however, implied from a few specimens that 815 m should not be older than late Darriwilian and no younger than late Sandbian. Considering the above mentioned and that the Kinnekulle K-bentonite appears at ca 800 m it is therefore reasonable to put the boundary Almelund Shale-Sularp Shale at around 808 m. This is concordant with the shift in gamma ray.

The biostratigraphy further implies that the interval between 770-800 m in the Lövestad A3-1 well belongs in the early Katian. This is based on one diagnostic taxon observed in only one sample, *Belonechitina robustus*. The LOD (last occurrence datum) of *Rhabdochitina gracilis* at 790 m suggest an Ordovician age for the succession below 770 m, but no precise age diagnostic chitinozoan are recorded. The gamma ray

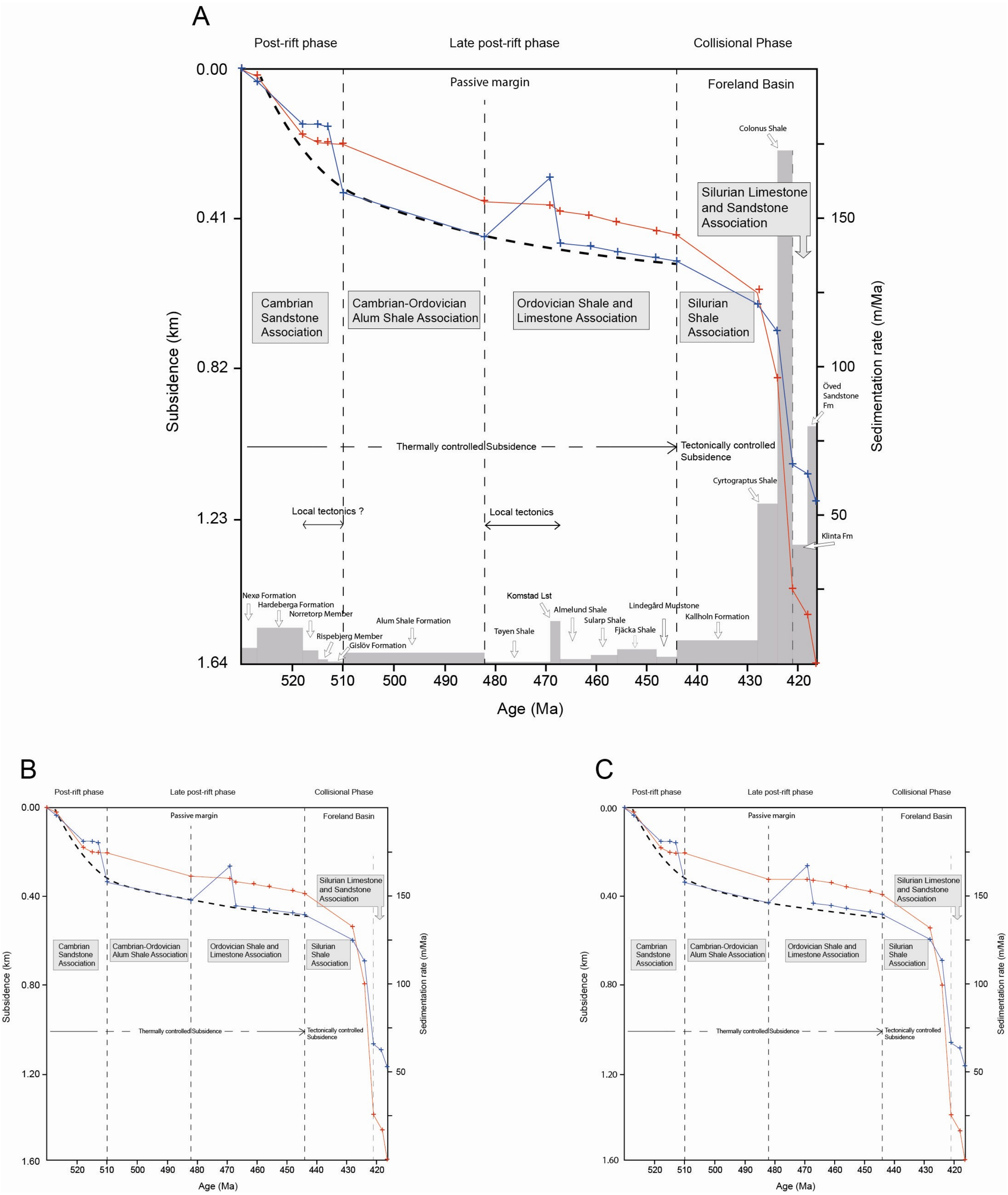

Fig. 13. Backstripping diagram showing the tectonic subsidence related to sedimentation rates. The blue curve represents tectonic subsidence and the red curve is total subsidence (inclusive flexural loading). **A** Lövestad A3-1 well **B** Hedeberga B2-1 well **C** Oderup C4-1 well. Note the similarities of the trend for the analysed wells.

interpretation and correlation of the succession with the Billegrav-2 well suggests that the early Katian is misplaced in the biostratigraphy. I would therefore suggest that the Ordovician-Silurian boundary in the Lövestad A3-1 well corresponds to the F3-F4 boundary in the Billegrav-2 well. As is evident from cuttings, the F3 dip in the Lövestad A3-1 well correlates with deposition of limestone most often seen in the lower part of the Kallholn Formation. The ages further upwards in the succession are quite certain and in the early Homerian interval, between 440-470 m, a poor biostratigraphic recovery was observed. Mullins (2010) suggested this to correlate with the Mulde secundo-secundo event.

Table 3. Backstripping data for the Lövestad A3-1 well. Abbreviations: Base: Base depth. AgeB: Age base. SLB: Sea-level base. WDB: Water depth base. Top: Top depth. AgeT: Top age. SLT: Sea-level top. WDT: Water depth top. ρ_c: Dry density. c: Compaction coefficient. Φ_0: Porosity at deposition. Type: Continental (1) or marine (0) setting.

Stratigraphical Unit	Base (km)	AgeB (km)	SLB (km)	WDB (km)	Top (km)	AgeT (Ma)	SLT (km)	WDT (km)	ρ_c kg/m³	c km^{-1}	Φ_0 (%)	Type 0 or 1
Nexö Formation	1.636	530.0	0.000	0.015	1.623	527.0	0.000	0.020	2120.000	0.900	35.0	0
Hardeberga Formation	1.623	527.0	0.000	0.020	1.503	518.0	0.000	0.030	2120.000	0.900	35.0	0
Norretorp Member	1.503	518.0	0.000	0.030	1.488	515.0	0.000	0.015	2000.000	0.920	40.0	0
Rispebjerg Member	1.488	515.0	0.000	0.015	1.486	513.0	0.000	0.020	2120.000	0.900	35.0	0
Gislöv Formation	1.486	513.0	0.000	0.020	1.484	510.0	0.000	0.200	2000.000	0.850	30.0	0
Alum Shale Formation	1.484	510.0	0.000	0.200	1.379	482.0	0.000	0.200	1890.000	0.990	50.0	0
Töyen Shale	1.379	482.0	0.000	0.200	1.373	469.0	0.000	0.030	1890.000	0.990	50.0	0
Komstad Limestone	1.373	469.0	0.000	0.030	1.355	467.0	0.000	0.200	2000.000	0.500	30.0	0
Almelund Shale	1.355	467.0	0.000	0.200	1.347	461.0	0.000	0.200	1890.000	0.980	50.0	0
Sularp Shale	1.347	461.0	0.000	0.200	1.334	456.0	0.000	0.200	1890.000	0.980	50.0	0
Fjäcka Shale	1.334	456.0	0.000	0.200	1.317	448.0	0.000	0.200	1890.000	0.980	50.0	0
Lindegård Mudstone	1.317	448.0	0.000	0.200	1.308	444.0	0.000	0.200	1890.000	0.980	50.0	0
Kallholn Formation	1.308	444.0	0.000	0.200	1.182	428.0	0.000	0.200	1890.000	0.980	50.0	0
Cyrtograptus Shale	1.182	428.0	0.000	0.200	0.900	424.0	0.000	0.100	1890.000	0.098	50.0	0
Colonus Shale	0.900	424.0	0.000	0.100	0.300	421.0	0.000	0.050	1890.000	0.980	50.0	0
Klinta Formation	0.300	421.0	0.000	0.050	0.200	418.0	0.000	0.030	2000.000	0.900	50.0	0
Öved Sandstone Fm	0.200	418.0	0.000	0.030	0.000	416.0	0.000	0.030	1890.000	0.900	35.0	0

Table 4. Backstripping data for the Hedeberga B2-1 well. Abbreviations: Base: Base depth. AgeB: Age base. SLB: Sea-level base. WDB: Water depth base. Top: Top depth. AgeT: Top age. SLT: Sea-level top. WDT: Water depth top. ρ_c: Dry density. c: Compaction coefficient. Φ_0: Porosity at deposition. Type: Continental (1) or marine (0) setting.

Stratigraphical Unit	Base (km)	AgeB (km)	SLB (km)	WDB (km)	Top (km)	AgeT (Ma)	SLT (km)	WDT (km)	ρ_c kg/m³	c km^{-1}	Φ_0 (%)	Type 0 or 1
Nexö Formation	1.597	530.0	0.000	0.015	1.584	527.0	0.000	0.020	2120.000	0.900	35.0	0
Hardeberga Formation	1.584	527.0	0.000	0.020	1.464	518.0	0.000	0.030	2120.000	0.900	35.0	0
Norretorp Member	1.464	518.0	0.000	0.030	1.449	515.0	0.000	0.015	2000.000	0.920	40.0	0
Rispebjerg Member	1.449	515.0	0.000	0.015	1.447	513.0	0.000	0.020	2120.000	0.900	35.0	0
Gislöv Formation	1.447	513.0	0.000	0.020	1.446	510.0	0.000	0.200	2000.000	0.850	30.0	0
Alum Shale Formation	1.446	510.0	0.000	0.200	1.377	482.0	0.000	0.200	1890.000	0.990	50.0	0
Töyen Shale	1.377	482.0	0.000	0.200	1.366	469.0	0.000	0.030	1890.000	0.990	50.0	0
Komstad Limestone	1.366	469.0	0.000	0.030	1.351	467.0	0.000	0.200	2000.000	0.500	30.0	0
Almelund Shale	1.351	467.0	0.000	0.200	1.343	461.0	0.000	0.200	1890.000	0.980	50.0	0
Sularp Shale	1.343	461.0	0.000	0.200	1.335	456.0	0.000	0.200	1890.000	0.980	50.0	0
Fjäcka Shale	1.335	456.0	0.000	0.200	1.322	448.0	0.000	0.200	1890.000	0.980	50.0	0
Lindegård Mudstone	1.322	448.0	0.000	0.200	1.314	444.0	0.000	0.200	1890.000	0.980	50.0	0
Kallholn Formation	1.314	444.0	0.000	0.200	1.200	428.0	0.000	0.200	1890.000	0.980	50.0	0
Cyrtograptus Shale	1.200	428.0	0.000	0.200	0.900	424.0	0.000	0.100	1890.000	0.098	50.0	0
Colonus Shale	0.900	424.0	0.000	0.100	0.300	421.0	0.000	0.050	1890.000	0.980	50.0	0
Klinta Formation	0.300	421.0	0.000	0.050	0.200	418.0	0.000	0.030	2000.000	0.900	50.0	0
Öved Sandstone Fm	0.200	418.0	0.000	0.030	0.000	416.0	0.000	0.030	1890.000	0.900	35.0	0

Table 5. Backstripping data for the Oderup C4-1 well. Abbreviations: Base: Base depth. AgeB: Age base. SLB: Sea-level base. WDB: Water depth base. Top: Top depth. AgeT: Top age. SLT: Sea-level top. WDT: Water depth top. ρ_c: Dry density. c: Compaction coefficient. Φ_0: Porosity at deposition. Type: Continental (1) or marine (0) setting.

Stratigraphical Unit	Base (km)	AgeB (km)	SLB (km)	WDB (km)	Top (km)	AgeT (Ma)	SLT (km)	WDT (km)	ρ_c kg/m³	c km^{-1}	Φ_0 (%)	Type 0 or 1
Nexö Formation	1.601	530.0	0.000	0.015	1.588	527.0	0.000	0.020	2120.000	0.90 0	35.0	0
Hardeberga Formation	1.588	527.0	0.000	0.020	1.468	518.0	0.000	0.030	2120.000	0.900	35.0	0
Norretorp Member	1.468	518.0	0.000	0.030	1.453	515.0	0.000	0.015	2000.000	0.920	40.0	0
Rispebjerg Member	1.453	515.0	0.000	0.015	1.451	513.0	0.000	0.020	2120.000	0.900	35.0	0
Gislöv Formation	1.451	513.0	0.000	0.020	1.450	510.0	0.000	0.200	2000.000	0.850	30.0	0
Alum Shale Formation	1.450	510.0	0.000	0.200	1.372	482.0	0.000	0.200	1890.000	0.990	50.0	0
Töyen Shale	1.372	482.0	0.000	0.200	1.372	469.0	0.000	0.030	0	0	0	0
Komstad Limestone	1.372	469.0	0.000	0.030	1.368	467.0	0.000	0.200	2000.000	0.500	30.0	0
Almelund Shale	1.368	467.0	0.000	0.200	1.360	461.0	0.000	0.200	1890.000	0.980	50.0	0
Sularp Shale	1.360	461.0	0.000	0.200	1.347	456.0	0.000	0.200	1890.000	0.980	50.0	0
Fjäcka Shale	1.347	456.0	0.000	0.200	1.332	448.0	0.000	0.200	1890.000	0.980	50.0	0
Lindegård Mudstone	1.332	448.0	0.000	0.200	1.322	444.0	0.000	0.200	1890.000	0.980	50.0	0
Kallholn Formation	1.322	444.0	0.000	0.200	1.205	428.0	0.000	0.200	1890.000	0.980	50.0	0
Cyrtograptus Shale	1.205	428.0	0.000	0.200	0.900	424.0	0.000	0.100	1890.000	0.098	50.0	0
Colonus Shale	0.900	424.0	0.000	0.100	0.300	421.0	0.000	0.050	1890.000	0.980	50.0	0
Klinta Formation	0.300	421.0	0.000	0.050	0.200	418.0	0.000	0.030	2000.000	0.900	50.0	0
Öved Sandstone Fm	0.200	418.0	0.000	0.030	0.000	416.0	0.000	0.030	1890.000	0.900	35.0	0

6 Backstripping

There are mainly three processes that control the subsidence of a sedimentary basin: tectonic subsidence, water and sediment loading, and sediment compaction (Miall 2000). Tectonic subsidence thus refers to the subsidence of the basement in the absence of water and sediments and is controlled by the tectonic forces associated with the formation and the evolution of the basin. Accordingly, the morphology of a tectonic subsidence curve will vary between different basin types. The water and sediment loading refers to the weight of the water and sediment in the basin. The sediment compaction is the decrease of the sediment volume as they are buried and compacted.

In order to reveal the tectonic driving mechanisms of basin subsidence a technique has been developed referred to as backstripping (Sleep 1971; Miall 2000; Bjørlykke 2010). This technique removes from each sedimentary unit the effects of sediment compaction, water and sediment loading. The result is extracted from a time-sediment thickness curve, which is constructed from stratigraphic sections, and a curve that represents tectonic subsidence is thereafter produced.

There are a few different types of backstripping technique. The technique used here is the simplest, commonly referred to as “1D Airy backstripping with exponential reduction of porosity” (Miall 2000). This technique assumes that water and sediment loads are compensated locally by the displaced weight of a column of the astenosphere and that the sediment porosity decreases exponentially with depth. The program used herein, OSX.BackStrip, requires knowledge of the stratigraphy, water depths of deposition, palaeo-sea-level, and changes of porosity with depths. These parameters are outlined in Tables 3-5.

The tectonic subsidence curve presented herein has been produced from the Lövestad A3-1, Oderup C4-well and Hedeberga B2-1. Thicknesses for the Hardeberga Formation, Læså Formation, Colonus Shale and the Öved-Ramsåsa Group have thicknesses based on literature. The other formation thicknesses are taken from the cores or interpreted from the gamma ray record from the wells. Ages are determined through the stratigraphic chart in Figure 5. The water depths of deposition are arbitrary depending on lithology, facies and depositional environment. Two water depths of the deposition of formations were based on the literature. A depositional depth not exceeding 200 m is inferred for the Alum Shale Formation (Buchardt et al. 1997), whereas a maximum 30 m is inferred from the Komstad Limestone, (Buchardt et al. 1997). The global sea-levels have been put to 0, because it is the relative sea-level change that is important in the model. No eustatic sea-level changes were considered when they had none or negligible effect for the modulation. The dry densities (ρ_c), compaction coefficient (c) and porosity (Φ_0) are arbitrarily produced depending on the different formation lithologies and facies.

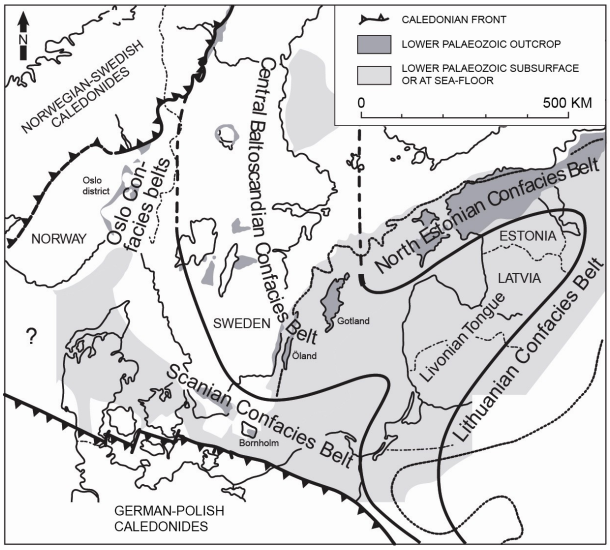

Fig. 14. The confacies belts of the Ordovician Baltoscandian basin first identified by Jaanusson (1976). Figure modified from Stouge (2004). Skåne belongs to the Scanian Confacies Belt.

Three subsidence curves were produced to establish the tectonic evolution of CST (Fig. 13). The plot shows the tectonic subsidence contra age and sedimentation rates. The subsidence rate is about 17 m/Ma in the Cambrian Sandstone Association (except Norretorp and Rispebjerg members), and decreases substantially into the Cambrian-Ordovician Alum Shale Association to ca 4 m/Ma. The Cambrian-Sandstone Association is characterized by a thermally controlled tectonic subsidence and relates to a post-rift phase. The Cambrian-Ordovician Alum Shale Association is characterized by a passive margin and enters the late post-rift phase with thermally controlled tectonic subsidence. A pronounced decrease in subsidence is observed in the Tøyen Shale whereas in the Komstad Limestone it reaches the general downward trend in the Ordovician Shale and Limestone Association. The subsidence rate in the Ordovician Shale and Limestone Association is extremely low, 2 m/Ma. An increase in subsidence rate, and an accompanying increase in sedimentation rate, is observed in the Silurian Shale Association and has a pronounced acceleration in the end of the association. The subsidence rates for the whole association is 24 m/Ma and in the end of the association, Colonus Shale it reaches 120 m/Ma. The sedimentation rates of the Cyrtograptus Shale and Colonus Shale reaches 55 m/Ma and 170 m/Ma respectively. The basin is at this point in a collisional phase with tectonically controlled subsidence and a foreland basin is developing. In the Silurian Limestone and Sandstone Association the tectonic subsidence decreases to 25 m/Ma, but the sedimentation rates are still quite high, with 38 m/Ma for the Klinta Formation and 78 m/Ma for the Öved Sandstone Formation.

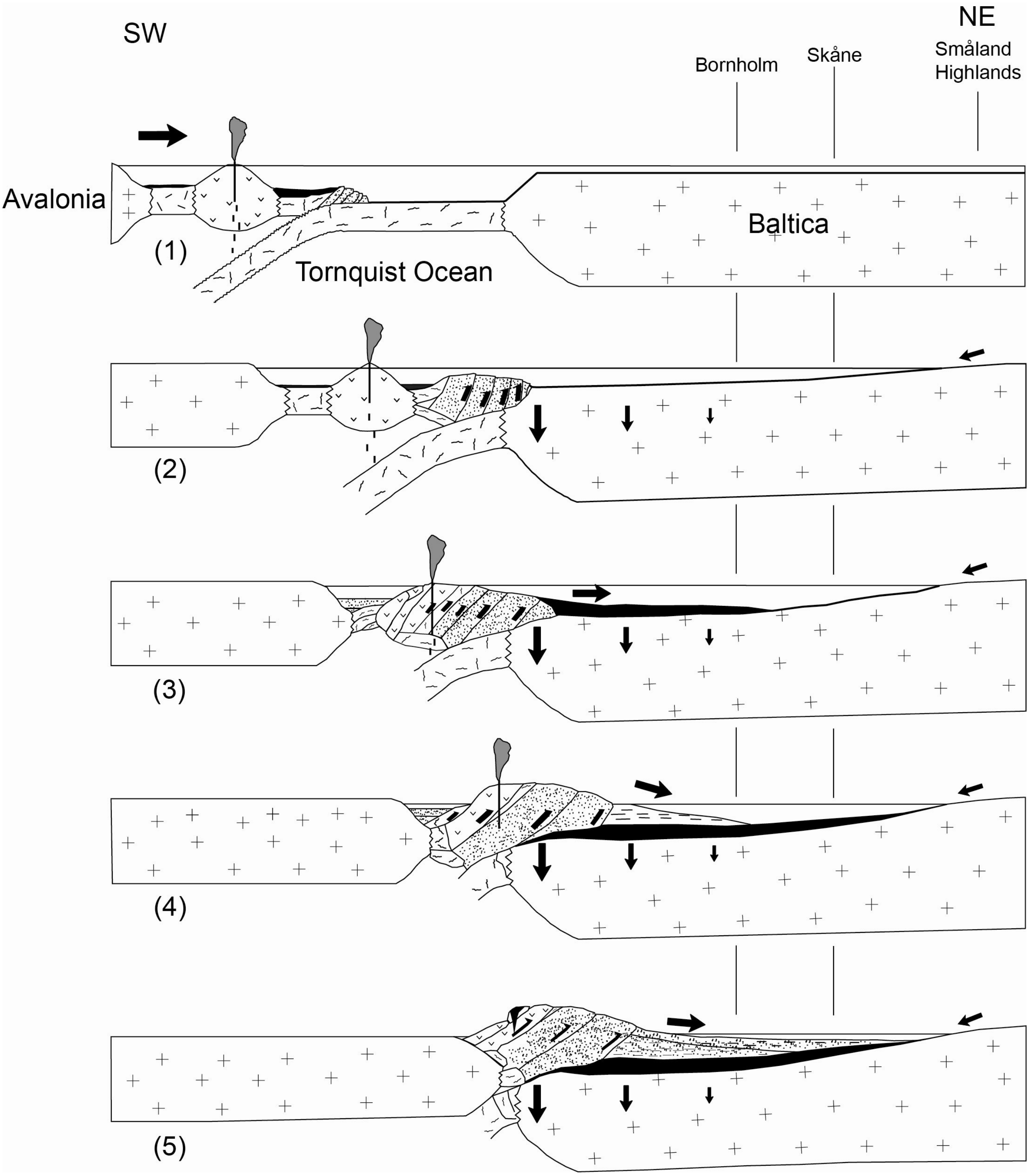

Fig. 15. Tectonic model showing the development of a foreland basin along the southwest margin of the Baltic shield. Modified from Beier et al. (2000). **1.** Cambrian to Early Ordovician- shelf sedimentation.**2.** Dapingian to middle Darriwilian characterized by slow subsidence. **3.** Middle Darriwilian to middle Llandovery characterized by increased subsidence and a deep water phase. **4.** Late Llandovery to Wenlock characterized by shallow water phase. **5.** Wenlock to Pridoli characterized by a shallow water phase.

7 Basin evolution

The Colonus Shale Trough formed part of the southern margin of the Baltic Shield and went through different stages of development from the Terreneuvian to the end of the Silurian.

The Terreneuvian first order transgression established an epi- to pericontinental sea that covered vast areas of present-day Scandinavia and which persisted until late Silurian. The transgression submerged the deeply weathered sub-Cambrian peneplain and resulted in maximum depositional depths of a few hundred meters (Erlström et al. 1997).

Much of the siliciclastic material from the weathered basement was reworked and must have been deposited along the continental margins. Only a thin veneer of clastic deposits – the Cambrian Sandstone Association – is preserved in southern Sweden, reaching from the Terreneuvian into Cambrian Series 2. Apart from a basal conglomerate and the arkosic, immature Nexø Sandstone, these strata are dominated by clean quartz arenites or qurtzites with abundant primary structures, such as tabular trough cross bedding of inner shelf origin and hummocky cross bedding of middle shelf origin, interrupted by finer grained material at a few levels. Hamberg (1991) suggested, based on the sedimentary structures, that the deposition was formed in a tidal influenced beach-barrier complex that from time to time prograded onto a storm-dominated shelf. As a result of the first order transgression a general fining upwards sequence prevailed in Cambrian with a marked shift into rather homogenous material in the Norretorp Member and the Gislöv Formation. This is evident from the tectonic subsidence curve where the general, thermally controlled trend shows a kink with an uplift that might be an eustatic effect (Fig. 13). This uplift, however, seems to be greater in the Norretorp and Rispebjerg members whereas in the Gislöv Formation it seems to catch up with the downward subsidence trend marked with the dashed line in Figure 13.

The Gislöv Formation is a conspicuous but thin unit where the upper boundary marks the shift from a inner-middle shelf setting into a more distal low energy environment, in which the Alum Shale Formation formed. The upper boundary of the Gislöv Formation is a distinct disconformity and hiatus related to a substantial sea-level fall associated with the Hawke Bay Event (Palmer & James 1981; Nielsen & Schovsbo 2007; Alvaro et al. 2009). This disconformity is well expressed in the Hedeberga B2-1 and the Lövestad A3-1 cores where it is marked by a phosphatic laminae (Figs. 6E, 7A, 10-11). The Gislöv Formation and the Forsemölla Limestone Bed is, however, missing in the Billegrav-2 core from Bornholm (Fig. 11). This would suggest either one of two things; first, because the hiatus was more pronounced at Bornholm or alternatively, that the deposition of Gislöv Formation and Forsemölla Limestone Bed never took place there. The upper boundary in Forsemölla Limestone Bed is extremely rich in pyrite outcrops south of Brantevik and also seen in Oderup C4-1 and Hedeberga B2-1 cores (Figs. 6E, 7B). This implies a lowering of sea-level at this time.

Based on the uniform thickness and monotonous deposition, the Alum Shale Formation was deposited in a tectonically stable basin at depths up to 200 m (Buchardt et al. 1997). The organic-rich shales are interrupted at a few levels by shallow-water limestone beds, such as the Forsemölla, Exsulans, Hyolithes and Andrarum limestones.

With an advancing Caledonian Orogeny, in the Ordovician, flexural loading along the western and southern margins of a subsidence differentiation and a pronounced depth zonation was established (Jaanusson 1976). The greatest depositional depths occurred along the active margins to the west and south and decreased successively towards the north and east. Jaanusson (1976) referred to this depth-zonation as 'confacies-belts', meaning belts with internally similar facies and named them Oslo-Skåne confacies belt, the Central Baltoscandian confacies belt and the North-Estonian confacies belt (Fig. 14). Skåne belongs to the Oslo-Skåne-confacies belt and is dominated by shale and mudstone. The Central Baltoscandian confacies belt represents an intermediate shelf setting and yields argillaceous limestone and shale, whereas the North-Estonian confacies belt is dominated by limestone and dolomite representing an inner shelf setting. Subsidence was more pronounced at the southern margin of the continent resulted in generally thicker Cambrian-Silurian succession in Skåne as opposed to central Sweden.

The deposition of Alum Shale was terminated by the Ceratopyge Regressive Event or successively replaced by the Tøyen Shale or Komstad Limestone depending on location. In either case a large regression or an uplift is seen from the upper Tremadocian into latest Dapingian or earliest Darriwilian. The backstripping analysis suggests a tectonic uplift during the time of deposition of the Tøyen Shale Formation (Fig. 13). This formation is in the Lövestad A3-1 well only 5 m thick and should correspond to substantial time span (~11 Ma). The uplift is concordant with the Tøyen Shale thickness variation within the CST where 80 m or more has been deposited in the northwestern part of the CST. The formation seems to be missing in the central CST (Lyby-1 and Oderup C4-1) whereas it comprises a maximum thickness of 23 m in the Flagabro-1 core in the southeastern part of the CST. In the G14 well north of Rügen the Tøyen Shale shows a substantial hiatus (Maletz 1997) and the unit is completely missing on Bornholm (Beier et al. 2001).

The Tøyen Shale is conformably overlain by the conspicuous Komstad Limestone. The limestone represents a condensed succession deposited in an extremely starved epicontinental sea, covering large parts of the Baltoscandian craton (Nielsen 1995). The classical opinion of depositional depths of the Komstad Limestone (Orthoceratite Limestone) has been of the order of several hundreds of metres (e.g. Lindström 1963) while other authors suggest a shallower deposition, generally within the photic zone (Jaanusson 1982), or less than 100 m (Nielsen 1995) and Buchardt et al. (1997) even suggested within less than 30 m. Nielsen (1995) identified two uplifts in the Skåne region during Ordovician times. The first occurred in late Tremadocian-early Floian times, concordant with the backstripping results of the present study. The upper boundary of the Komstad Limestone in the Killeröd area, southeastern Skåne, has possibly been exposed to karst weathering (cf. Nielsen 1995). The second uplift mentioned by Nielsen (1995) was somewhat prolonged and occurred in Darriwilian-Sandbian times. It especially affected the strata on Bornholm where there is a substantial gap in the succession. This could just be local tectonics not related to the collision between Baltica and Avalonia. The general tectonic subsidence rate in the Ordovician Shale and Limestone Association is decreasing until the end of Ordovician. This declining rate might have been complicated by eustatic sea-level changes but is not evidently seen in the backstripping results. The association was characterized by a thermally controlled subsidence in a passive margin setting.

An increase of subsidence and sedimentation rate in the early Silurian is observed in the backstripping results, a trend that is continuing throughout the Silurian (Fig. 13). The Kallholn and Cyrtograptus formations are interpreted as a distal, deep water facies of the basin with its dark graptolitic shales (Beier et al. 2001). Deposition of this facies was rather abruptly terminated in late Wenlock when deposition of the the Colonus Shale commenced. The Colonus Shale reflects a marked acceleration in sedimentation rate in the Late Wenlock (from ca 55m/Ma to 170m/Ma) enduring deposition of the upper parts of the Silurian Shale Association.

In the Late Silurian the Iapetus Ocean was subducted between the Baltica-Avalonia and Laurentia along the Iapetus Suture and the North German-Polish Caledonides and Scandinavian Caledonides was formed (Fig. 15). The continuing obduction of the accretionary wedge onto the southwest margin of the Fennoscandian Shield marked the transition from a thermally controlled passive margin to a foreland basin controlled by flexural loading. The orogenic belt supplied the foreland basin with huge amounts of sediments during a fairly short time interval (Beier et al. 2000), resulting in a many hundreds of metres thick shale succession within the CST.

The Colonus Shale was deposited in a shallow marine environment with turbidity influenced facies and sandy intercalations increasing upwards (Beier et al. 2000). These authors further state that Skåne at this time formed the depocenter of the basin, with the deposition of the 600 m Colonus Shale. At the end of Ludlow the sedimentation rates was higher than the tectonic subsidence rates which led to a decrease of accommodation space that in turn changed the depositional environment. The deposition of the Colonus Shale was thereby terminated by the Silurian Limestone and Sandstone Association, in latest Ludlow, which is characterized by shallow marine calcareous shales, siltstone and carbonates. These Ludlow-Pridoli deposits represent the final infill of the basin.

Poprawa et al. (1997) produced a tectonic subsidence plot, data taken from Polish onshore wells that show a similar type of curve as in the bakstripping results presented in Figure 8. The onset of rapid tectonic subsidence in Poland seems to occur somewhat earlier than in Skåne.

8 Conclusions

The Colonus Shale Trough is a distinct tectonic entity within the Sorgenfrei-Tornquist Zone in Skåne, Sweden. The more than 1500 m thick basin fill constitutes a Cambrian through Silurian sedimentary succession of fine grained clastics and subordinate limestone. Three deep wells, Oderup C4-1, Lövestad A3-1 and Hedeberga B2-1, drilled by Shell in 2009-2010, now provide new stratigraphic data from the trough structure. The result of study of these wells and associated geophysical and facies data can be summarized as followed:

- The Cambrian through Silurian sedimentary fill constitute 19 formations that can be subdivided into five larger-scale stratigraphic associations related to the major depositional development of the basin. The Cambrian Sandstone Association, Cambrian-Ordovician Alum Shale Association, Ordovician Shale and Limestone Association, Silurian Shale Association, and the Silurian Limestone and Sandstone Association.

- Backstripping analysis for tectonic subsidence shows that the Cambrian Sandstone Association correlates in time with a post-rift phase ranging from the middle Terreneuvian to the Series 2-Series 3 boundary and which is characterized by moderate to high subsidence rates (17 m/Ma). The Cambrian-Ordovician Alum Shale Association and the Ordovician Shale and Limestone Association are characterized by an extremely low subsidence rate, 4 m/Ma and 2 m/Ma, respectively, which is interpreted as reflecting a passive margin setting. The tectonic subsidence increases to 23 m/Ma in the Silurian when the Silurian Shale Association was deposited. This marks the increased proximity to a foreland basin. The tectonic subsidence increased substantially, to 120 m/Ma , in late Wenlock with the deposition of the Colonus Shale. The Silurian Limestone and Sandstone Association is characterized by the final infill of the foreland basin. The subsidence rate decreased to 25 m/Ma along with a decrease also in the sedimentation rate to 50 m/Ma.
- The gamma ray logs from the three wells, together with cuttings, provide the basis for a detailed correlation between the Colonus Shale Trough succession and the coeval succession in Bornholm. The gamma ray shows only small changes in the API values in the Silurian Shale Association, were lithological variation is small, although a few marker beds are present. The Ordovician Shale and Limestone Association is more heterogenous and therefore characterized by varying API values where the Komstad Limestone is the most distinct marker bed.

The Alum Shale Association record extremely high API values in the gamma ray, especially in the Furongian part.

- The Tøyen Shale reaches a maximum of 80 m in the northwestern part of the CST, missing in the central CST and maximum of 23 m in the southeastern part of the CST. The limited occurrence or absence of the Tøyen Shale in the Shell wells is observed as a tectonic uplift in the backstripping analysis suggesting local tectonics in the early Ordovician.

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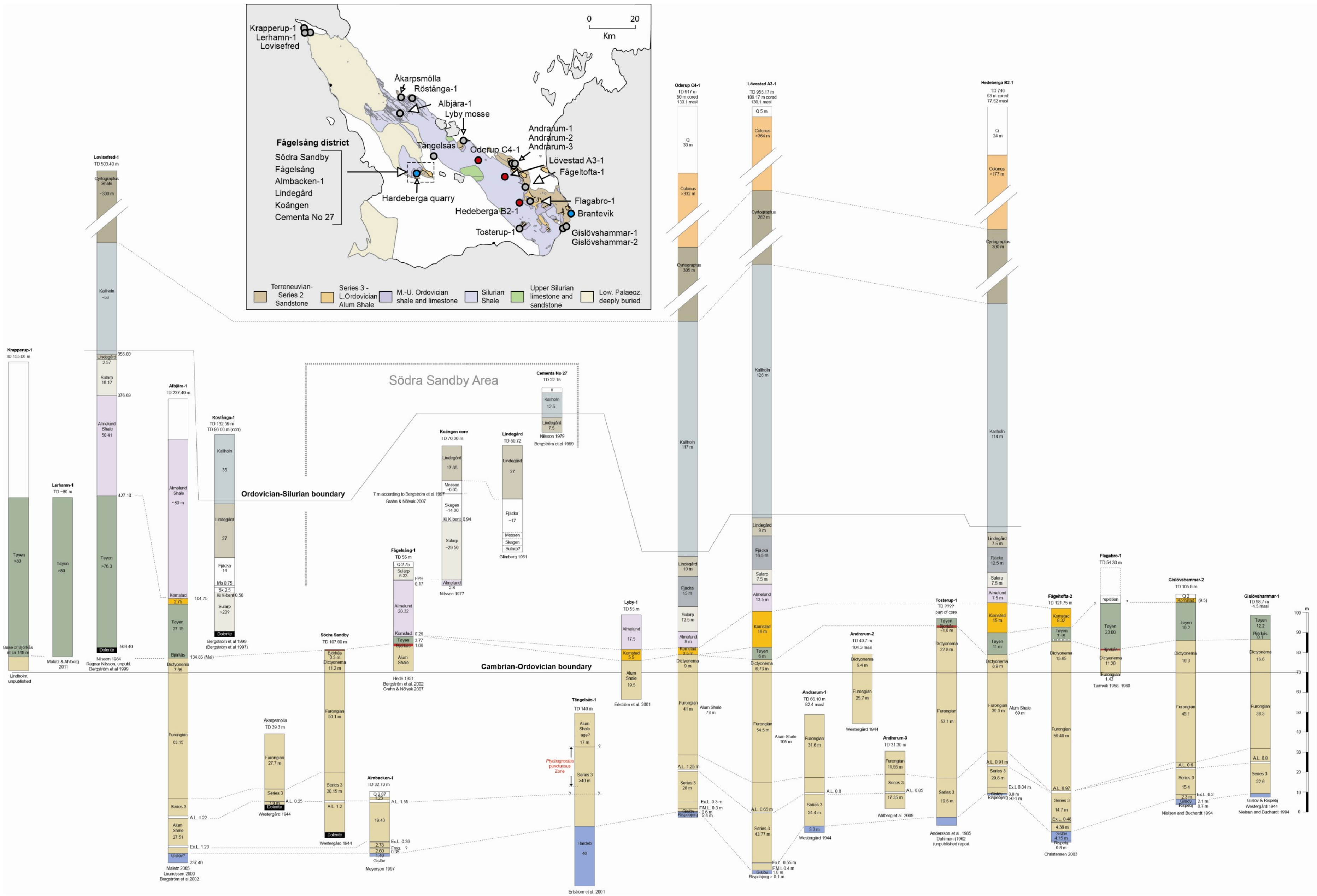
Appendix

Appendix I: Compilation of cores from the Colonus Shale Trough, including the three wells drilled by Shell. Expanded and revised from M. Calner in an unpublished Shell report.



Fågelsång district
Södra Sandby
Fågelsång
Almbacken-1
Lindegård
Koängen
Cementa No 27
Krapperup-1
Lerhamn-1
Lovisefred
Åkarpsmölla
Röstånga-1
Albjära-1
Lyby mosse
Tängelsås
Hardeberga quarry
Odarup C4-1
Andrarum-1
Andrarum-2
Andrarum-3
Lövestad A3-1
Fågeltofta-1
Flagabro-1
Brantevik
Hedeberga B2-1
Tosterup-1
Gislövshammar-1
Gislövshammar-2
0
20
Km
Terreneuvian-Series 2 Sandstone
Series 3 - L.Ordovician Alum Shale
M.-U. Ordovician shale and limestone
Silurian Shale
Upper Silurian limestone and sandstone
Low. Palaeoz. deeply buried
Södra Sandby Area
Ordovician-Silurian boundary
Cambrian-Ordovician boundary

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