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The Lower Palaeozoic of southern Sweden and the Oslo Region, Norway. Field Guide for the 3rd Annual Meeting of the IGCP project 591

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The Lower Palaeozoic of southern Sweden and the Oslo Region, Norway

Field Guide for the 3rd Annual Meeting
of the IGCP project 591

Mikael Calner, Per Ahlberg, Oliver Lehnert
& Mikael Erlström (eds.)



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**The Lower Palaeozoic of southern Sweden
and the Oslo Region, Norway**

Field Guide for the 3rd Annual Meeting of the IGCP project 591

Mikael Calner, Per Ahlberg, Oliver Lehnert
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Cover photograph: Large limestone concretion ('orsten' or stinkstone) enclosed in black, bituminous shale (Alum Shale Formation) in abandoned quarry at the farm 'Stenbrottet' near Falekvarna, Västergötland. Photo: M. Calner.

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Foreword and acknowledgements

This field guide was prepared for the Annual Meeting 2013 of the IUGS/UNESCO International Geoscience Programme Project 591 *'The Early to Middle Palaeozoic Revolution'*. The conference was held jointly with the annual meetings of the Cambrian, Ordovician and Silurian subcommissions on stratigraphy at the Department of Geology, Lund University, on June 9–12, 2013. This publication is the field guide produced for the post-conference excursion. It provides a general overview of the Lower Palaeozoic of southern Sweden and the Oslo Region and includes descriptions of the localities visited in Skåne, Västergötland and the Oslo Region on June 13–19. We would like to thank the organisation and scientific committee associated with the

meeting and also acknowledge financial support from the Swedish Research Council (grant D0013001 to MC), the Geological Survey of Sweden, the Geological Society of Sweden, the Department of Geology at Lund University and the municipality of Lund. For fabulous technical editing of the guide we are deeply indebted to Jeanette Bergman Weihed at the Geological Survey of Sweden, Uppsala.

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Lund, April 15th 2013

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Lower Palaeozoic geology of southern Sweden

Mikael Calner, Mikael Erlström, Oliver Lehnert & Per Ahlberg

Sweden and Norway form parts of the Baltica palaeo-continent, which encompasses a major portion of northern Europe and is limited by the Ural Mountains in the east, the Trans-European Suture Zone in the south-west, and the British and Scandinavian Caledonides in the north-west. The core of this continent consists of Archaean and Proterozoic rocks of the East European Craton (Cocks & Torsvik 2005).

The early and middle Palaeozoic history of Baltica starts with its rifting and separation from northern Gondwana during the 'early' Cambrian. The separation resulted in opening of the Tornquist Sea, which started to form as a narrow basin between the two continents (the Ran Ocean of Cocks & Torsvik 2005). Baltica then drifted across the southern hemisphere and made a counter-clockwise rotation of about 120° between 'middle' Cambrian and Middle Ordovician times (Cocks & Torsvik 2005 and references therein). There is little evidence for any major tectonic disturbances during this time interval, and the high levels of endemism in the Early Ordovician benthic fauna of trilobites, brachiopods and other phyla suggest wide oceanic basins surrounding the continent (Cocks & Torsvik 2005).

Baltica remained a separate continent until it amalgamated with Avalonia in the latest Ordovician (at c. 440 Ma, Cocks & Torsvik 2002). The subsequent closure of the Iapetus Ocean merged Avalonia and Baltica with Laurentia during the Scandian phase of the Caledonian Orogeny in the middle Silurian (425–420 Ma), leading to the formation of Laurussia. As a result, terrestrial deposition came to predominate in much of present-day Scandinavia and the East Baltic area in the latest Silurian and Devonian.

The larger scale tectono-environmental evolution of Baltica is accompanied by changes in sedimentary facies reflecting a wide spectrum of depositional environments. These include high latitude, storm and tidally dominated clastic shorelines and dysoxic shale basins in the Cambrian, mid latitude cool-water carbonates with mud mounds in the Ordovician, extensive carbonate platforms with reefs in the Silurian, and the expansion of terrestrial facies across wide areas as the Caledonian Orogeny closed the Iapetus Ocean in the late Silurian and Devonian. Baltica's journey across the southern hemisphere is well documented in many plate-tectonic reconstructions compiled and illustrated by Ron Blakey (Department of Geology, Northern Arizona University, Fig. 1).

Throughout most of the Early Palaeozoic, a shallow sea covered Baltica and marine deposits from this time interval are widely distributed in Scandinavia and adjacent areas (Fig. 2). This basin is variously termed the Baltic basin or the Baltoscandian basin, the latter preferred herein. The birth of the Baltoscandian basin is associated with the 'early' Cambrian first-order transgression. The basin then expanded to cover several hundred thousands of square kilometres at the time of the unusually high global sea-level in the Floian. During this time, the sea likely covered most of today's Scandinavian countries, the East Baltic area and north-eastern Poland. This shallow sea was fringed by the deep Tornquist Sea to the south and the Iapetus Ocean to the west. During the Cambrian and Early Ordovician, the Baltoscandian basin and its sedimentation patterns were unique in several aspects, resulting in unusual rock formations, such as the Alum Shale Formation and the 'orthoceratite limestone'.

Extensive weathering and peneplanisation of Baltica's basement in the Neoproterozoic created an extremely flat surface, the sub-Cambrian peneplain, which cuts across the crystalline basement as well as its Mesoproterozoic cover rocks (Jotnian sandstone and shale) in large parts of the continent (Lidmar-Bergström 1995, 1996). The onset of the marine transgression across this surface is marked by a thin but widespread basal conglomerate. This conglomerate is regionally overlain by arkoses and quartz arenites. These basal clastic units represent Terre-neuvian (Cambrian Series 1) and provisional Cambrian Series 2, and are the remnants of the saprolites that presumably covered large parts of the deeply weathered crystalline basement in the latest Neoproterozoic and earliest Phanerozoic.

Due to the peneplanisation, the regional relief was exceptionally low and sediment source areas were of limited extent in the Cambrian and Early Ordovician. The long-term rise of sea-level therefore resulted in substantial geographical expansion of the basin and successive drowning of source areas, which in turn led to extreme sediment starvation. For this reason, the Cambrian and Early–Middle Ordovician sedimentary cover of Baltoscandia is relatively thin. Net depositional rates for much of this time interval were low and became extremely low in Furongian through Floian times when the bituminous shales of the Alum Shale Formation and the Early–Middle Ordovician cool-water 'orthoceratite limestone' were formed. These units are relatively uniform and continuous across wide areas with little

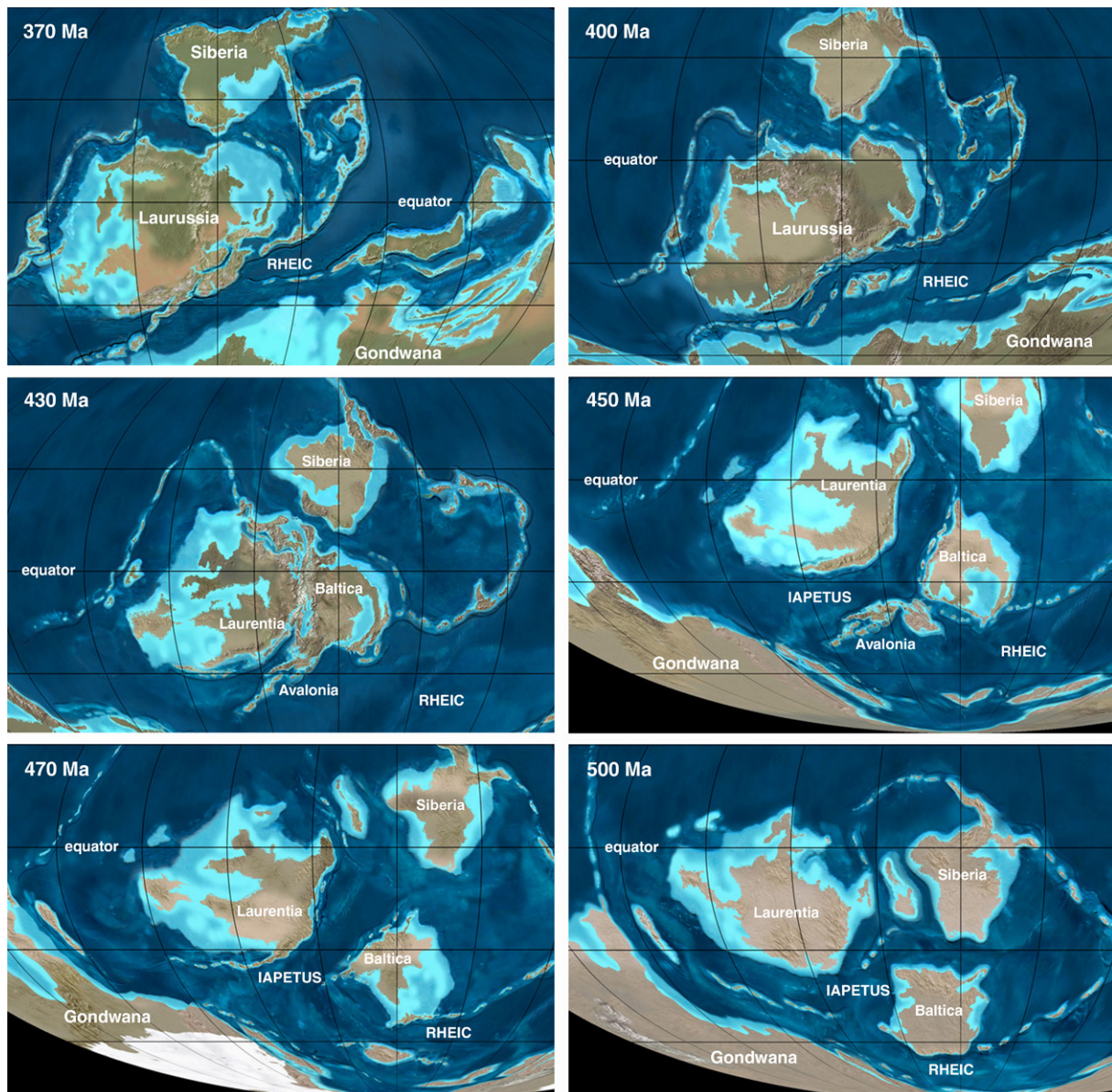


Fig. 1. Early Palaeozoic palaeogeography showing the drift of Baltica from low latitudes in the Cambrian to an equatorial position in the Silurian and Devonian. The figures of the separate time slices represent parts of the reconstructions (Molleweide projection) centred on Baltica (500 through 430 Ma) and on Laurussia (400 and 370 Ma). The palaeogeographic maps have been modified from the file available at the website of Ron Blakey (<http://www2.nau.edu/rcb7/>).

macroscopic variation. The Alum Shale Formation was deposited in a shallow, but low-energy restricted marine environment. Thickpenny (1987) calculated net depositional rates of 3–10 mm per 1000 years, for this black, organic-rich shale. Similarly low depositional rates have been suggested for the fine-grained ‘ortho-erite limestone’ (a few millimetres per 1000 years, Nielsen 2004).

The collision between Baltica and Avalonia and the successive closure of the Iapetus Ocean differentiated the Baltoscandian basin and created various distinct depth-related environments during Middle–Late Ordo-

vician and Silurian times. This evolution was related to the flexural loading on the continental margin from stacking of thrust sheets along the Norwegian-Swedish and German-Polish Caledonian deformation fronts (Fig. 2). This resulted in the development of foreland basins parallel to the orogens. Thick Lower Palaeozoic successions, dominated by fine-grained clastic sediments, are preserved in the Scandinavian parts of these foreland basins. The succession thins substantially cratonwards due to limited subsidence and accommodation space in the cratonic interiors. Hence, in Västergötland, Östergötland and Närke, the preserved Lower

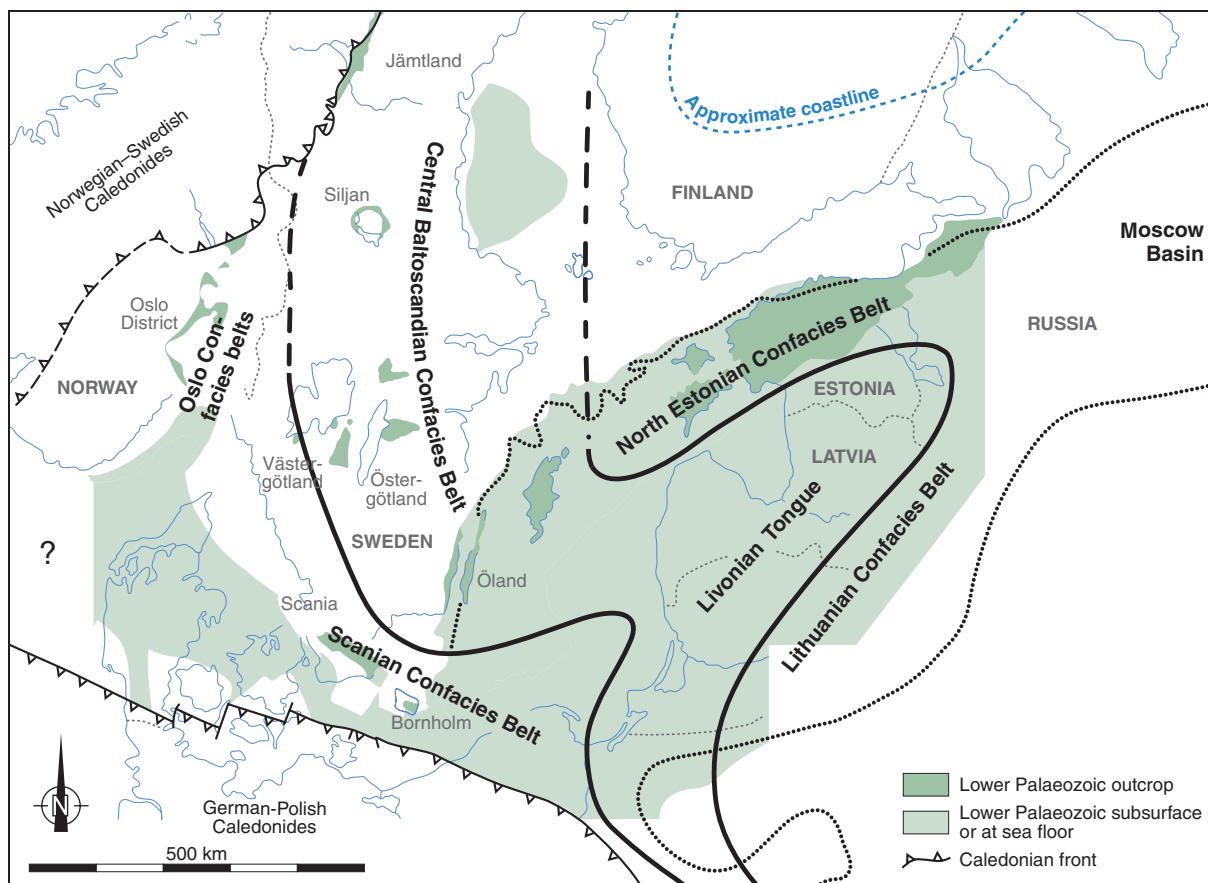


Fig. 2. Distribution of Lower Palaeozoic strata in Scandinavia and the East Baltic area (modified from Nielsen 2004 and Stouge 2004). The reconstruction of confacies belts during the Ordovician is based on the extensive work of Jaanusson (1976, 1995). Coherent covers of Lower Palaeozoic strata are today preserved in the East Baltic area and under the sea-floors of the Baltic Sea (including the classical exposures on the islands Öland, Gotland, Saaremaa and Hiiuma) and the Bothnian Bay (Fingrundet). Due to repeated uplift of the South Swedish Dome there are only scattered remnants of Lower Palaeozoic strata preserved in the southern part of the mainland of Sweden. These sediments occur in fault-controlled grabens along the southern margin of the shield area (Skåne province), in down-faulted blocks in the crystalline basement (Östergötland and Närke provinces), as erosional outliers (the table mountains in Västergötland province), in impact-related ring structures (Siljan and Lockne areas), and along the thrust belt of the Caledonides.

Palaeozoic succession is only slightly more than 200 m thick and hiatuses are common. As the orogeny continued, depositional rates became very high in the second half of the Silurian.

The tectonic pattern and structure of the preserved Lower Palaeozoic succession of the southern part of Sweden is a complex mixture of Precambrian inherited tectonic signatures and younger tectonic events. Phanerozoic tectonic events, including periods of tension, resulting in rifting and localised subsidence, as well as periods of inversion due to compression and fault reactivation, have resulted in a patchy and heterogenous preservation of Lower Palaeozoic strata. After the Caledonian Orogeny, younger tectonic events resulted in the break-up of the south-western margin of the Fennoscandian Shield, including Skåne (Scania), creating a complex crustal transition zone between the stable shield area to the north-east and younger tectonic provinces to

the south-west (Liboriussen et al. 1987, EUGENO-S Working Group 1988, Berthelsen 1992). The central part of Baltica acted as a rigid craton and was more or less unaffected. In contrast, the crust between the Trans European Suture Zone (TESZ) in northern Germany and the Skagerrak-Kattegat Platform acted as a buffer zone where the stresses in the crust were repeatedly released along the main fault zones (Berthelsen 1992). This weakened south-western part of the shield has previously been referred to as the Fennoscandian Border Zone, including the Skagerrak-Kattegat Platform and the Sorgenfrei-Tornquist Zone (Liboriussen et al. 1987). However, today the term Fennoscandian Shield Transition Zone is preferably used as describing a wider zone extending down to the Trans European Suture Zone south of the Ringkøbing Fyn High (Fig. 3). This is based on geophysical data suggesting that crystalline crust of the Fennoscandian Shield occurs at depth below sedi-

mentary cover rocks in the Norwegian-Danish Basin as far as to northern Germany, and into the eastern parts of the North Sea (EUGENO-S Working Group 1988, Lassen & Thybo 2004, Lyngsie et al. 2006). The transition zone is characterised by a relatively thin crust intersected by a splay of late Carboniferous and early Permian faults, extending north-west across the Norwegian-Danish Basin and significantly weakening the south-west margins of Baltica (Thybo 1997, Lassen & Thybo 2012).

The main tectonic phases affecting the Fennoscandian Shield Transition Zone are generally well established since they can be verified in the characteristics of the preserved bedrock. There are, however, gaps in the database for certain time intervals because pre-existing strata have been more or less completely removed by erosion during later tectonic events. The main tectonic phases are: (1) Ordovician to late Silurian Caledonian deformation, (2) late Carboniferous to early Permian rifting caused by the Variscan Orogeny, (3) late Permian to Early Jurassic subsidence, rifting and block faulting, (4) Jurassic block faulting and volcanism related to the Kimmerian Orogeny, (5) Late Cretaceous to Palaeogene inversion triggered by the Alpine Orogeny, and (6) Neogene uplift and faulting. These six phases have had a significant impact on the preservation, structure and diagenesis of the Lower Palaeozoic strata. During all of

these events, the Sorgenfrei-Tornquist Zone constituted an important structure around which most of the stresses were released as large-scale displacements in the crust.

The mechanisms of the main Early–Middle Palaeozoic faulting in the area were related to intra-plate reactions due to movements involved in the triple plate junction of Laurentia, Baltica and Avalonia, i.e. the Caledonian Orogeny and the subsequent amalgamation of Laurasia (Lassen & Thybo 2012).

Late Palaeozoic stress fields in northern Europe were related to the oblique collision between Gondwana and Laurasia resulting in the assemblage of the supercontinent Pangea, i.e. the Variscan Orogeny. The Sorgenfrei-Tornquist Zone is interpreted as originating from Variscan (Carboniferous–Permian) shear stresses due to the dextral translation between Europe and Africa (Ziegler 1990). The late Permian–Early Jurassic is characterised by regional subsidence. Within the Sorgenfrei-Tornquist Zone, the stress field associated with the break-up of Pangea led to dextral strike-slip fault reactivation, resulting in differentiated subsidence in the Late Jurassic. This was followed by Alpine inversion tectonics in the Cretaceous–Palaeogene. The last dramatic event within the zone, before the Quaternary glaciation, was the more than 1 km of Neogene uplift and extensive exhumation (Japsen & Bidstrup 1999).

Regional geology of the Skåne province, Sweden

Mikael Calner, Mikael Erlström, Magnus Eriksson, Per Ahlberg & Oliver Lehnert

The Lower Palaeozoic strata of Skåne (Scania) are confined to the Colonus Shale Trough (CST) and the Höllviken Halfgraben. The CST is one of the most distinct structural units in Skåne. It is an elongated, north-west–south-east-trending, fault-bounded trough structure. It is defined by the deep Kullen-Ringsjön-Andrarum Fault Zone (KRAFZ) to the north-east and the Fyledalen Fault Zone (FFZ) to the south-west. It stretches diagonally (north-west–south-east) through Skåne and can be traced into the Bornholm Gat where it terminates against the Rønne Graben (Erlström et al. 1997).

The smaller scale fault systems within the CST follow the overall large-scale fault system of the Sorgenfrei-Tornquist Zone in a north-west–south-east and north-east–south-west pattern (Fig. 3). 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 north-western parts of the trough, this has resulted in

variously uplifted fault-blocks exposing the Cambrian through Ordovician parts of the succession. The central area of the trough, however, has encountered little or no uplift and is dominated by Silurian shale in the surface whereas the basal Cambrian deposits are found at depths of c. 900 m.

Three deep wells have recently been drilled in this central area of the CST by Shell Exploration and Production AB as part of the increased international interest in shale gas (Calner & Pool 2011). The target was the organic-rich Alum Shale Formation, especially the Furongian part that is exceptionally enriched in organic matter. The three wells drilled were Lövestad A3-1, Oderup C4-1 and Hedeberga B2-1. The CST basin fill comprises thin Cambrian (c. 220–250 m) and Ordovician (c. 60–140 m) successions overlain by at least 1 200 m of Silurian marine shales. 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

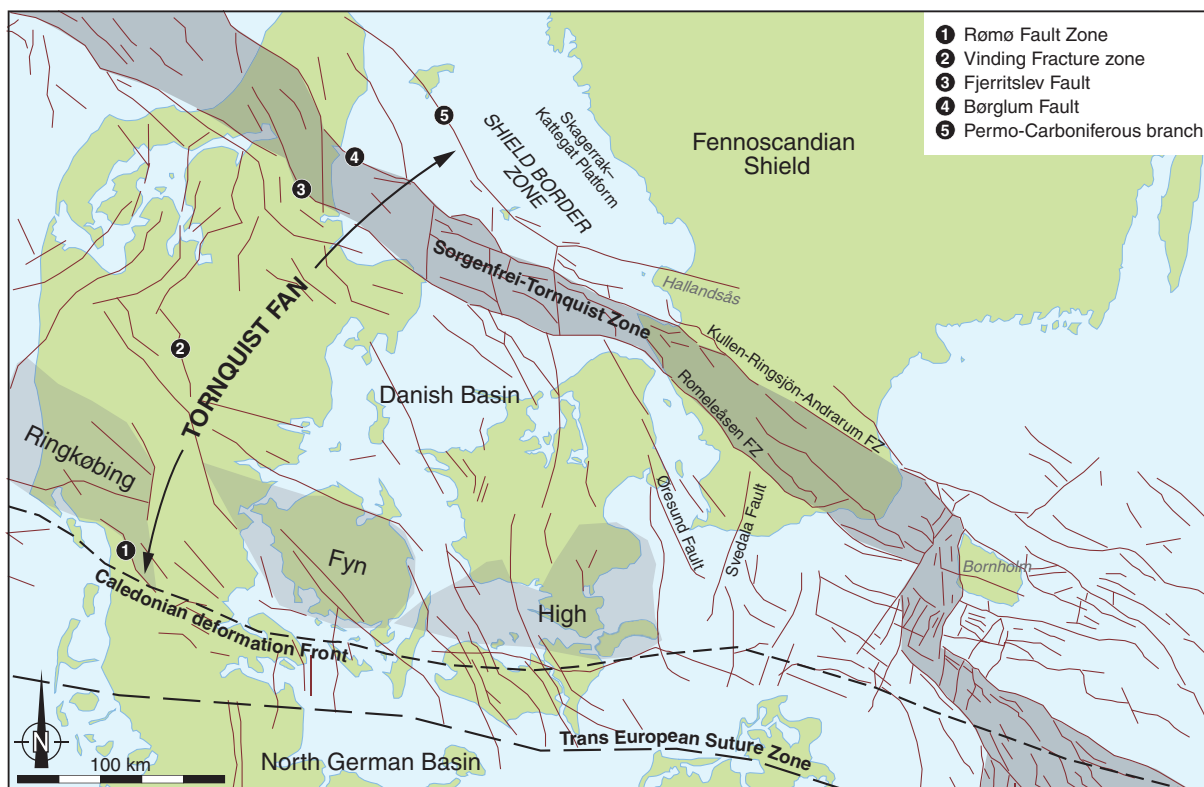


Fig. 3. Schematic map of the main tectonic elements and structures in the Fennoscandian Transition Zone.

100 Ma. The total preserved thickness of the basin fill is about 1 600 m and it is predominantly composed of low-permeable strata such as shale and mudstone with subordinate limestone and sandstone.

The Cambrian through Silurian sedimentary fill of the CST encompasses 19 main units that more or less have formational status. These can be grouped into five large stratigraphic associations based on lithological characteristics (Fig. 4). 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 (Fig. 5).

‘LOWER’ CAMBRIAN SANDSTONE ASSOCIATION

The ‘lower’ Cambrian Sandstone Association includes the Nexö, Hardeberga (Fig. 6), Læså and Gislöv formations and has a total thickness of about 150 m. Regolith from the Neoproterozoic weathering forms a basal Cambrian conglomerate which, in general, is only a few decimetres to a few metres thick. The lowermost parts of the overlying ‘lower’ Cambrian siliciclastic rocks typically have high feldspar content and are composed of reddish-coloured, coarse-grained arkoses. Above, the typical rock types dominating this

association are quartz arenites with abundant primary sedimentary structures, most notably tabular and trough cross bedding of inner shelf origin and hummocky cross bedding of middle shelf origin. Siltstones and shales are common in some intervals of the Hardeberga Formation. As a result of longer-term transgression, the higher parts of this association are typically more fine-grained (fine-grained sandstone and siltstone) and rich in glauconite and phosphorite. Bioturbation is very common at certain levels, generally seen as intensely reworked horizons with vertical burrows (e.g. *Skolithos* and *Diplocraterion*). Sedimentary structures suggest deposition in a tidally influenced beach-barrier complex that from time to time prograded out onto a storm-dominated shelf.

‘MIDDLE’ CAMBRIAN–LOWER ORDOVICIAN ALUM SHALE ASSOCIATION

A marked shift in the general sedimentation pattern occurred in the ‘middle’ Cambrian. The supply of coarser siliciclastic material to the basin was suppressed and deposition of black, organic-rich shale (Fig. 7) took place during the remaining part of the Cambrian and in the Early Ordovician (Tremadocian). Based on thickness data and biostratigraphy, the main depocentre was located along the southern margin of Baltoscandia from

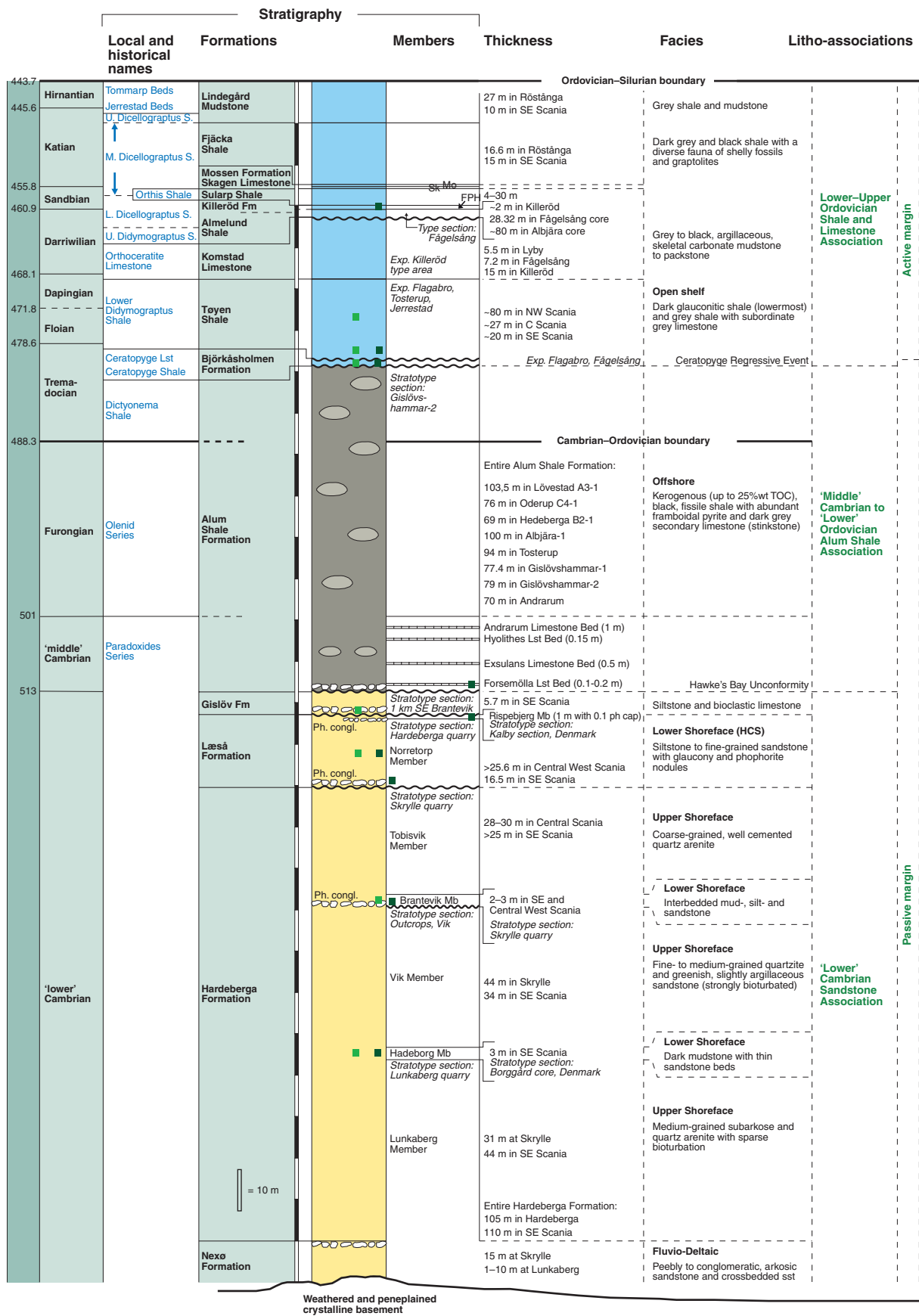


Fig. 4. Stratigraphical compilation of the Cambrian through Silurian sedimentary succession of the Colonius Shale Trough (CST) and its relationship to the new international, as well as the old traditional stratigraphic nomenclature. The succession can be subdivided into five large stratigraphic associations that reflect the long-term Lower Palaeozoic depositional history of southern Sweden. Note that the Ordovician is based mainly on the succession in the south-eastern part of the trough, an area that is characterised by an unusually thin Ordovician succession with several stratigraphic gaps. Light and dark green squares indicate stratigraphic levels rich in glauconite and phosphorite, respectively.

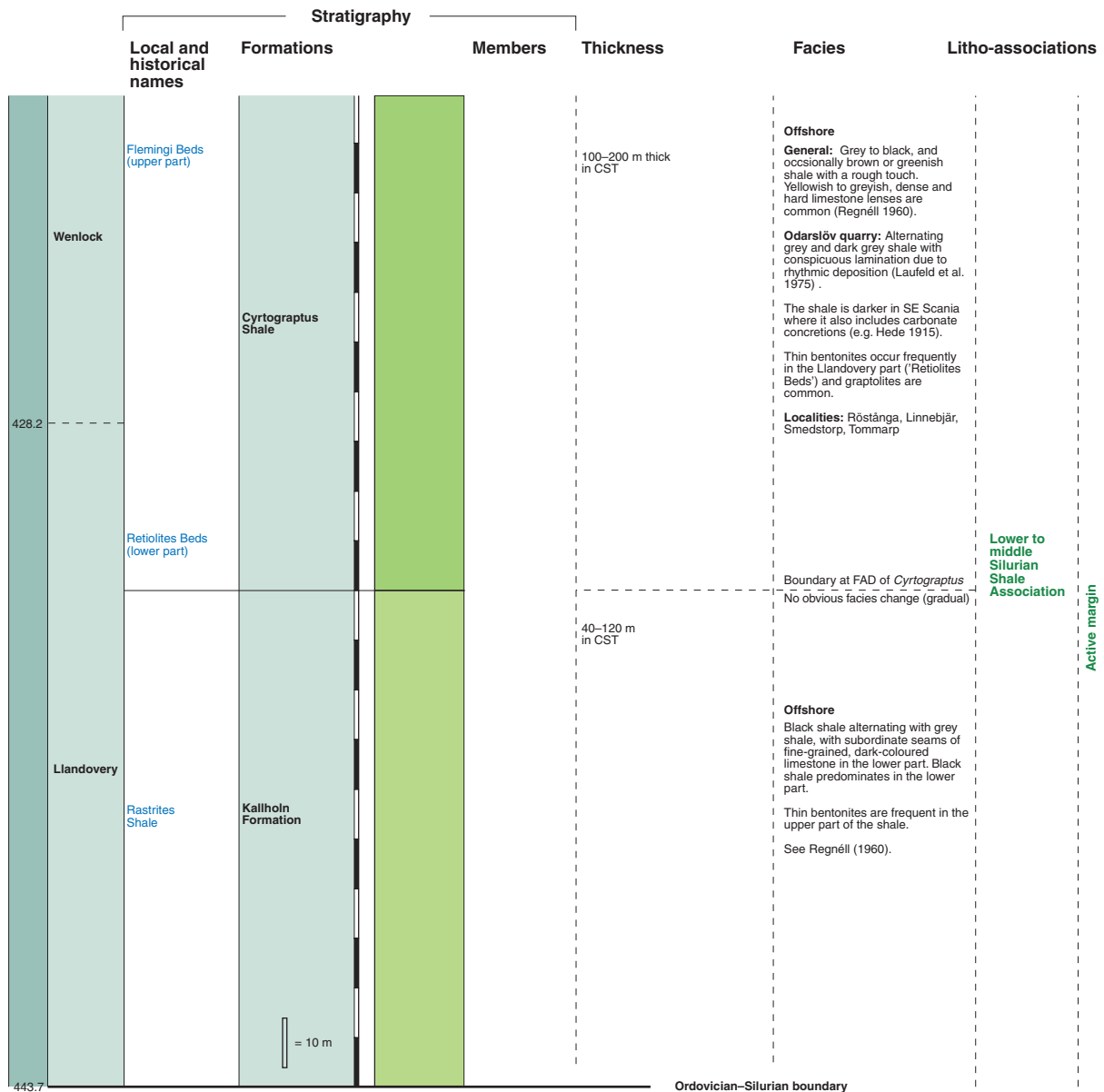


Fig. 4. Continued.

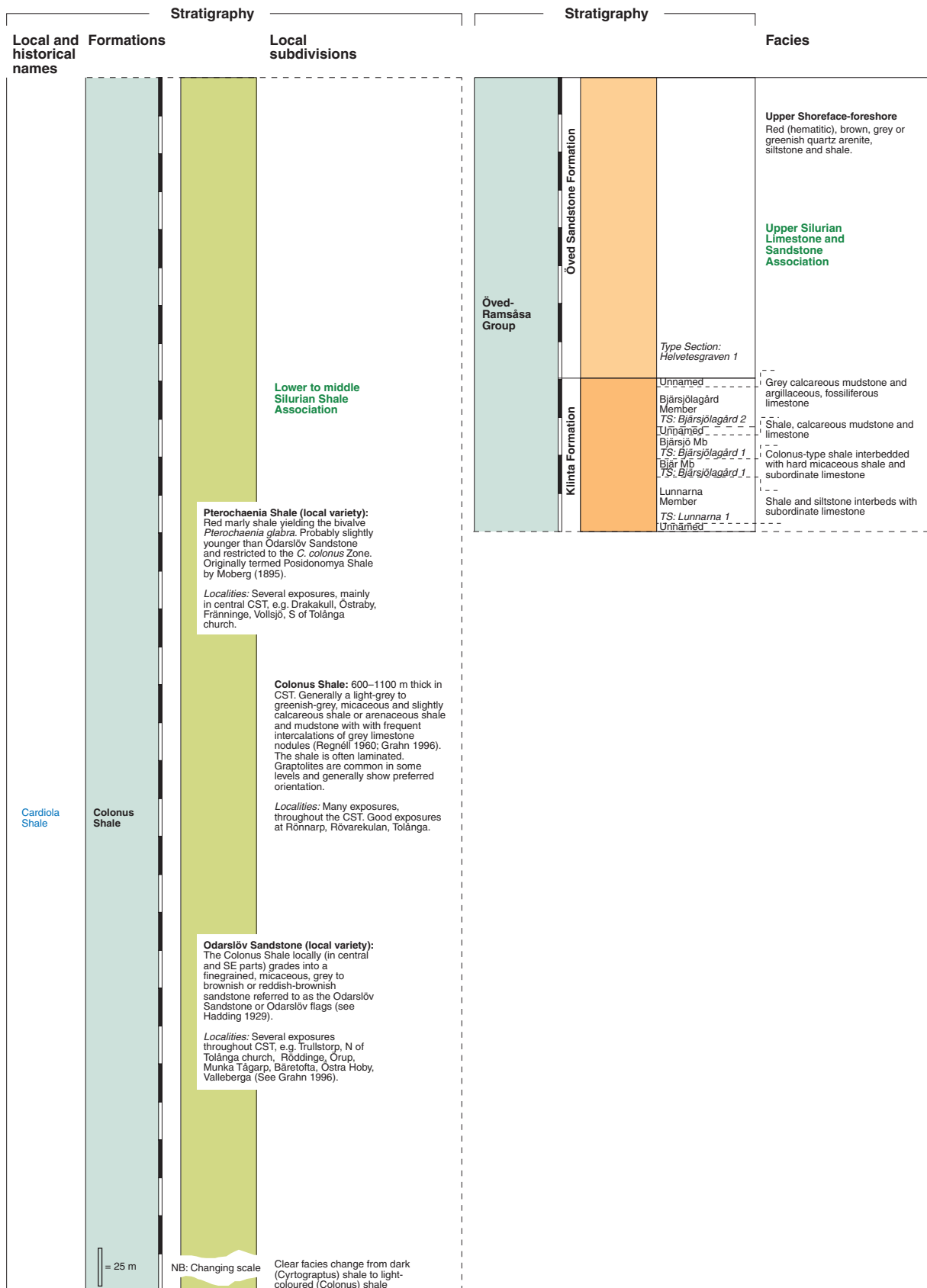


Fig. 4. Continued.

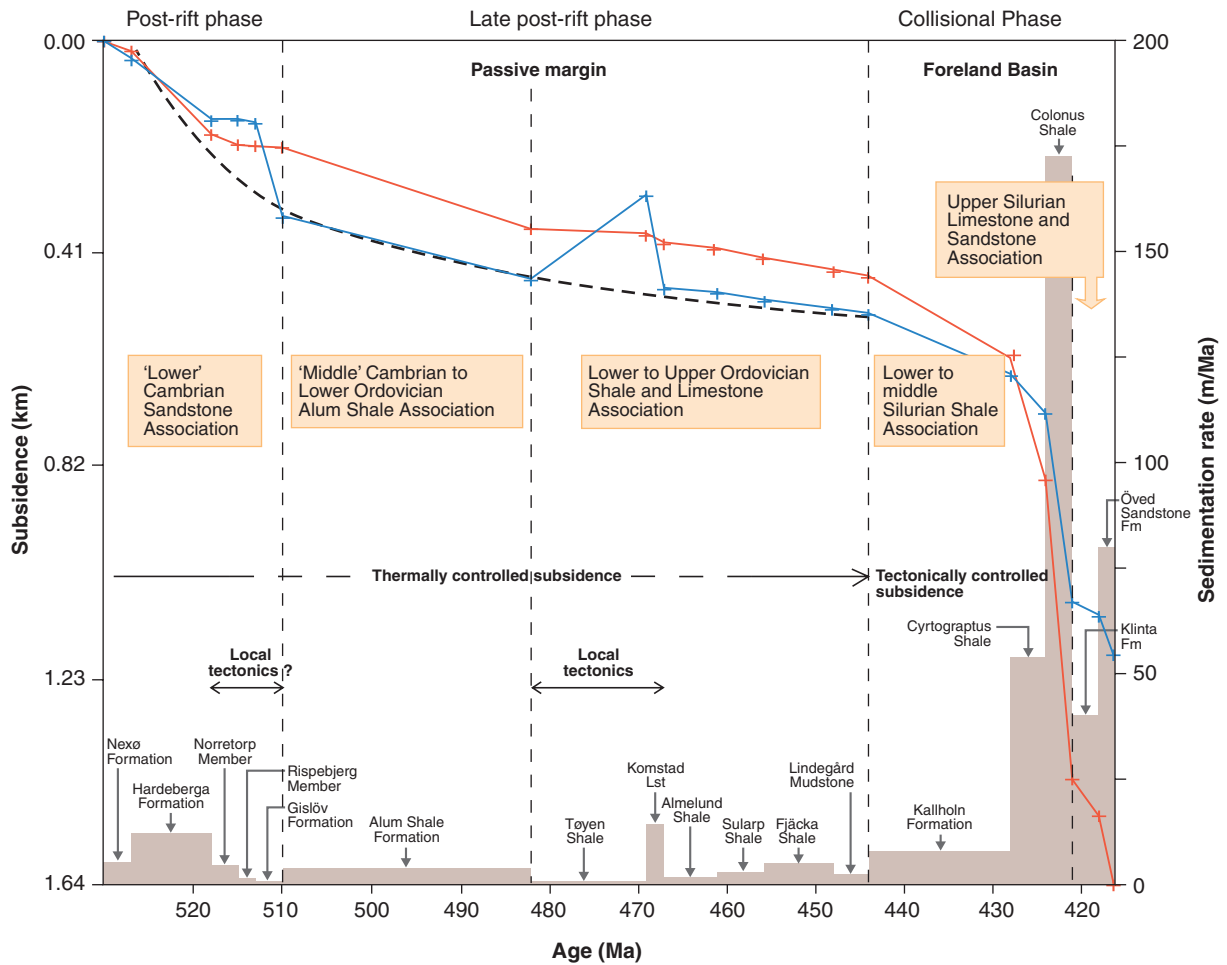


Fig. 5. Backstripping diagram showing the tectonic subsidence in the Lövestad A-3 well (south-eastern Skåne) related to sedimentation rates. The blue curve represents tectonic subsidence and the red curve is total subsidence, including flexural loading. From Eriksson (2011).



Fig. 6. Exposure of the Tobisvik Member (Hardeberga Formation) in the Skrylle quarry showing sets of tangentially cross-bedded strata formed in a shoreface environment (lowermost part of the section) overlain by hummocky cross stratified sandstone formed in the shoreface or lower shoreface. The boundary between the two facies associations is marked by a thin, intraformational conglomerate and ravinement surface, marking a slight deepening of the depositional environment. Photo: M. Calner.



Fig. 7. Bituminous shales of the Alum Shale Formation at Stora brottet, Andrarum. Photo: M. Calner.

where the sedimentation spread north- and eastwards with time. The most expansive onshore succession is found in Skåne where it reaches a thickness of c. 100 m within the CST. Thickness variations are also seen within the CST, with thicknesses increasing from c. 80 m in the south-east to c. 100 m in the north-west.

The substantial thickness of the shale succession suggests that some subsidence occurred during the late Cambrian–Early Ordovician. Local thickness variations within the CST and towards the Höllviken Graben (Alum Shale reduces to about 40 m in the Höllviken Graben) indicate an early movement along the German-Polish Caledonian front to the south.

LOWER–UPPER ORDOVICIAN SHALE-LIMESTONE ASSOCIATION

The Alum Shale Formation is overlain by the c. 45–147 m thick Lower–Upper Ordovician Shale-Limestone Association. It consists primarily of shale and mudstone with subordinate limestone. It includes, in ascending order, the Björkåsholmen Formation, Tøyen Shale, Komstad Limestone (Fig. 8), Almelund Shale, Sularp Shale, Skagen Limestone, Mossen Formation, Fjäckå Shale and the Lindegård Mudstone. The three limestone units, the Björkåsholmen, Komstad and Ska-

gen formations, represent the only regionally important limestone formations in the entire Ordovician of the CST and are thus important marker horizons on a regional scale.

The first pronounced lateral thickness changes in the CST are seen within this association in the uppermost Tremadocian and Floian. The total thickness varies from c. 45 m in the south-eastern part of the CST to at least 147 m in its north-westernmost part (Lovisefred-1 core). On a broader scale, the depth contours of the entire Baltoscandian basin changed in the Ordovician due to the Caledonian deformation along the western and southern margins of the continent (Norwegian-Swedish Caledonides and German-Polish Caledonides, respectively). Subsidence was greatest along the Caledonian front and in Skåne resulting mainly in shale deposition. Limestone sedimentation was successively more important towards the east of these areas. The depth contours are parallel to the orogeny and form broad belts characterised by specific litho- and biofacies, which have been denominated ‘confacies belts’ by Jaanusson (1976). Skåne is located within the Oslo and Scanian confacies belts. Orogenic activity is reflected by the frequent occurrence of K-bentonites in the Ordovician succession.

LOWER–MIDDLE SILURIAN SHALE ASSOCIATION

Subsidence curves from Poland (Poprawa et al. 1999) show that the main increase in subsidence and depositional rates along the southern margin of the Fennoscandian Shield occurred in the late Silurian (Ludlow). Accordingly, the Silurian is characterised by vastly increased depositional rates interpreted as a reflection of the advancing Caledonian nappe system and the establishment of a foreland basin. The deposition of the several hundred metres thick Colonus Shale (Fig. 9) corresponds well with an abrupt increase in both depositional rates and subsidence of the basin (Fig. 5). The laminated nature of the Colonus Shale in many sections and the ‘current-aligned’ graptolites conform well with deposition of low-density mass flows, such as distal turbidites. The Silurian Shale Association includes several shale formations (Fig. 4) and has a total thickness of 850–1 000 m.

UPPER SILURIAN LIMESTONE– SANDSTONE ASSOCIATION

The uppermost Silurian succession in the CST is in sharp contrast to the monotonous and graptolitiferous shale successions of the Llandovery through early Ludlow. This youngest association comprises the Öved-



Fig. 9. Rhythmically bedded Colonus Shale from a section along the rivulet Tolångaån near Tolånga Church. Abundant graded beds and sole marks suggest deposition by low-density turbidity currents. Photo: M. Calner.



Fig. 8. Coastal exposures of the Dapingian–Darrivilian Komstad Limestone. This is a thin wedge of the classical temperate water ‘orthoceratite limestone’ that is widespread in Baltoscandia. In Skåne, it is underlain by the Tøyen Shale and overlain by the Almelund Shale. Gislövshammar in south-eastern Skåne. Photo: M. Calner.

Ramsåsa Group, including the Klinta Formation and the Öved Sandstone Formation. The total thickness is estimated at c. 300 m. The lower part of the succession is dominated by shale and fine-grained sandstone, with more abundant limestone and sandstone intercalations towards the top. This sequence reflects a successive shallowing of the depositional environment. The upper part of this association constitutes a wide array of shallow-marine facies, notably with local occurrences of stromatolites associated with carbonate mounds yielding abundant macrofossils, including corals, crinoids, brachiopods and bryozoans (Bjärsjölagård Limestone, Fig. 10).

TECTONIC IMPACT ON THE PALAEOZOIC BEDROCK OF SKÅNE

Pre-rift evolution

Skåne is located in a key position between the Baltic Shield and the younger geological provinces to the south. Strata that are found at great depths in the Norwegian-Danish Basin constitute here the bedrock surface in tectonically uplifted areas associated with the Sorgenfrei-Tornquist Zone (Fig. 11). This makes Skåne a key area for studies regarding the interpretation of the tectonic evolution of the Fennoscandian Shield Transition Zone (e.g. Erlström et al. 1997).

The present distribution of Palaeozoic strata is related to a heterogeneous block-faulted terrain with several generations of faults suturing the bedrock of Skåne (Fig. 12). The dominant fault trend is north-west–south-east. However, north-north-east–south-south-west and north–south fault orientations are also common.

The tectonic history of Skåne includes phases of compression (thrusting) as well as extension (rifting) associated with the evolution of the Sorgenfrei-Tornquist Zone. Wrench faulting and strike-slip movement have been characteristic features along the main faults yielding a complex block geometry due to the existence of restraining and releasing bends and north–south oriented extension faults (Mogensen 1994, Berthelsen 1992).

The Palaeozoic rocks in Skåne include Cambrian, Ordovician and Silurian strata with a total thickness of c. 1 500 m. The deposits are primarily preserved in the so-called Colonus Shale Trough, in the Höllviken Halfgraben and in down-faulted halfgrabens in the Bornolm Gat and in the South Kattegat area (Fig. 11, Sivhed et al. 1999, Erlström & Sivhed 2001, Erlström et al. 2004). Palaeozoic rocks constitute the bedrock surface in central and south-east Skåne, in the north-west part of the Romeleåsen Ridge and as scattered outliers in north-west Skåne (Fig. 11).



Fig. 10. Exposure of the fossiliferous Bjärsjölagård Limestone Member (Klinta Formation) in the abandoned quarry at Bjärsjölagård, north-west of Sjöbo in south-central Skåne. The unit reflects rapid shallowing of depositional environments in the late Silurian of southern Scandinavia. Photo: M. Calner.

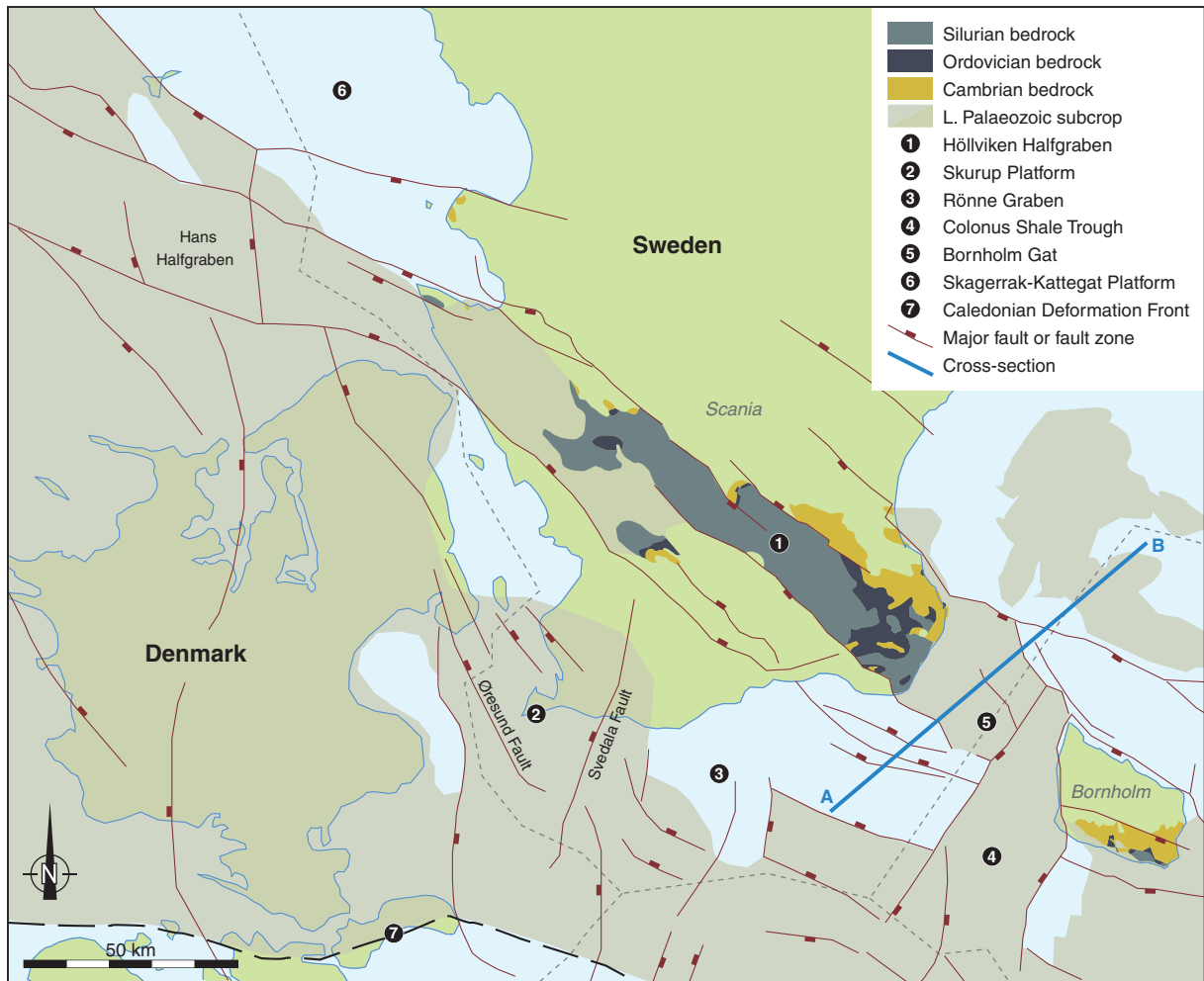


Fig. 11. Generalised map describing main faults and occurrences of Lower Palaeozoic strata, based on Nielsen & Schovbo (2011), Thomas et al. (1993) and Erlström et al. (2004). A cross section of the seismic line A–B and its interpretation is shown in Fig. 12.

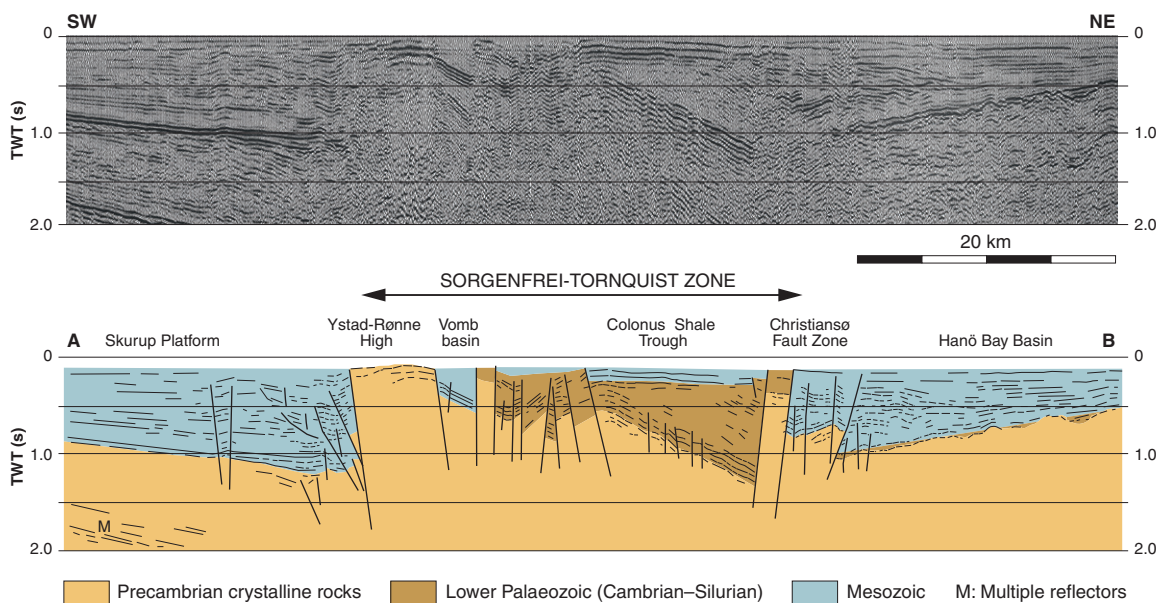


Fig. 12. Interpreted cross section showing the complex block geometry and distribution of Lower Palaeozoic rocks in the Sorgenfrei-Tornquist Zone. The interpretation is based on the Babel seismic profile crossing the Bornholm Gat. Location of the cross section A–B is shown in Fig. 11.

The preserved Cambrian–Silurian strata in Skåne are remnants of a previously much more extensive cover over large parts of Baltica. During the Early Palaeozoic (Cambrian–early Silurian), the evolution from a passive margin to a foreland basin setting, in conjunction to the Caledonian orogeny, is well reflected in the succession of strata displayed in Skåne. Large parts of Baltica represented extensive low-topography shelf areas at the beginning of the Cambrian (Jaeger 1984, Nielsen & Schovbo 2011).

Shallow marine arenaceous deposits dominate the ‘early’ Cambrian sedimentation in Skåne. The sandstone-dominated Cambrian sequence is here approximately 150 m thick and belongs to the upper Terrenewian–Cambrian Series 2 Hardeberga Formation followed by the Cambrian Series 2 Løeså and Gislöv formations (Hamberg 1991, Sivhed et al. 1999, Nielsen & Schovbo 2007, 2011). The succession is dominated by the up to 120 m thick Hardeberga Sandstone.

The Cambrian Series 3, Furongian and basal Ordovician (Tremadocian) strata are dominated in Skåne by outer shelf black shales with lenses and thin beds of limestone, i.e. Forsemölla, Exsulans, Hyolithes and Andrarum limestone beds of the Alum Shale Formation. In Skåne, the sequence varies in thickness between 40 and 100 m. The greatest thicknesses are found in drillings in the central parts of the Colonus Shale Trough (Erlström et al. 2004, Eriksson 2011). This has been interpreted as local subsidence related to early Palaeozoic activation and normal faulting along the Kullen-Ringsjön-Andrarum Fault Zone (Erlström et al. 2004).

The main part of the Ordovician succession is, apart from the limestones of the Björkåsholmen Formation, Komstad Limestone and Skagen Limestone, dominated by dark grey to black claystone, mudstone and dark grey shale. In the Middle and Upper Ordovician, numerous K-bentonite layers indicate extensive volcanic activity. Volcanic events in southern Scandinavia during Silurian times have been inferred from extrusive rocks in Silurian strata by, for instance, the EUGENO-S Working Group (1988) and by Michelsen & Nielsen (1993).

The Cambrian–lower Silurian sequence is fairly constant in thickness over the whole south-western part of Baltica (Bergström et al. 1982, Michelsen & Nielsen 1991). The subsidence culminated in the late Silurian (Michelsen & Nielsen 1991, 1993), as is verified by the increase in thickness of upper Silurian strata to the north-west and south. This corresponds to the development of a foreland deep in front of the Scandinavian Caledonides (Mogensen 1994). The thickness of the upper Silurian is estimated to be in the range of 2.5 km in the Swedish part of the Kattégat and 700–1 000 m

in central Skåne. Early Palaeozoic stepwise faulting towards the south is indicated in Skåne along the main faults which later were involved in the formation of the Sorgenfrei-Tornquist Zone (Erlström et al. 1999, 2001). Early Palaeozoic movements occurred especially along the Kullen-Ringsjön-Andrarum Fault Zone.

The North Polish Caledonides and the associated Caledonian Deformation Front, involving metamorphosed and thrust strata, evolved south of Skåne. Uplift terminated sedimentation on the Fennoscandian Shield and much of the Danish-Scanian area was incorporated in the so-called Old Red Continent. This resulted in a period of erosion, which is seen as a Devonian to Early Carboniferous regional hiatus in the area (Michelsen & Nielsen 1993, Erlström et al. 1997). The absence of Upper Palaeozoic strata in Skåne is probably due to extensive erosion during Triassic times. However, in the Kattégat part of the Sorgenfrei-Tornquist Zone, Upper Carboniferous to Lower Permian volcanic and volcanoclastic strata occur in down-faulted halfgrabens (Erlström & Sivhed 2001). The Upper Carboniferous volcanoclastic rocks are approximately time-equivalent to the volcanic activity in the Oslo Graben (Michelsen & Nielsen 1993) and to the extensive intrusion of north-west–south-east striking dolerite dykes in Skåne. These volcanoclastic deposits and intrusive rocks reflect the start of the rifting before the major phase of extension during Early Permian times. This major rifting is related to the Variscan Orogeny and the development of the Sorgenfrei-Tornquist Zone. In Skåne, the only presumed record of Permian sediments (probably Rotliegendes) is an undated, up to 50 m thick conglomeratic and silicified sequence (Sivhed et al. 1999). It rests on Silurian rocks in the Höllviken Graben and on the Precambrian crystalline basement of the Skurup Platform.

The pre-rift rock sequence experienced deep erosion during later tectonic events, especially in connection with peneplanisation and the formation of the unconformity at the base of Zechstein. This resulted in a patchy and generally incomplete representation of pre-rift strata on the south-western part of Baltica. Only at a few scattered locations along the Sorgenfrei-Tornquist Zone, where syn-rift deposits protected the pre-rift sequence in down-faulted halfgrabens, there is evidence for a complete thickness. One of these localities is in the Hans Half-Graben on the down-thrown side of the Børglum Fault in the southern part of Kattégat. Here, the whole succession is preserved and the thickness can be accurately estimated from seismic data. In the Swedish sector of Kattégat, this is in excess of 3.5 km (Erlström & Sivhed 2001). Nielsen & Japsen (1991) and Mogensen (1994) give a thickness of up to 4.0 km for adjacent Danish parts of Kattégat.

In Skåne, the thickness of the preserved pre-rift sequence is estimated to be in the order of 1.5 km, i.e. significantly less than in the Kattegat area. However, in Skåne, parts of the Silurian and all of the postulated Carboniferous strata have been removed by erosion. Seismic data from the Bornholm Gat, off south-eastern Skåne, indicate pre-rift sequences with a thickness of 1.8–2.0 km. Based on the information about the pre-existence of Carboniferous strata, it is unlikely that the whole sequence of pre-rift deposits in Skåne exceeded 2.5 km.

Syn-rift evolution

Late Palaeozoic stress fields in northern Europe during the Variscan Orogeny were related to the oblique collision between Gondwana and Laurasia, which resulted in the assemblage of the supercontinent Pangea. The Sorgenfrei-Tornquist Zone was presumably triggered by Variscan shear stresses (Carboniferous–Permian) due to the dextral translation between Europe and Africa (Vejbaek 1985, Ziegler 1990). The zone was part of a splay of faults and fault zones known as the ‘Tornquist Fan’ which developed during Late Carboniferous to Early Permian (250–300 Ma) in the Danish-Scanian and western Baltic area (Berthelsen 1992).

During the Early Mesozoic (Permian–Triassic), Palaeo-Europe was bounded by the active rift zones of the arctic North Atlantic and the Tethys, which led to unstable tensional regimes in north-western Europe. During the Early Permian there was rifting in the Oslo Graben and oblique dextral shear in the Sorgenfrei-Tornquist Zone. This caused uplift and subsidence in certain areas, accompanied by restraining and releasing bends along the main faults in the Sorgenfrei-Tornquist Zone.

The Lower Palaeozoic sequence was down-faulted along normal extension faults and within pull apart basins and, thus, more or less protected against denudation. Local depocentres formed along releasing fault bends and the north–south oriented extension faults. These received large amounts of clastic material derived from extensive erosion of the footwall blocks. Therefore, large amounts of Lower Palaeozoic strata were removed during this interval. Much of the material was deposited as alluvial fans which filled the basin when the subsidence ended during the Middle Permian.

Post-rift evolution

At the end of the rifting phase, probably in the Middle Permian (Michelsen & Nielsen 1991, Mogensen 1994, 1995), the area was eroded and a major regional erosional surface was formed, resulting in the pre-Zechstein unconformity (Britze et al. 1994).

During the Late Permian (Lopingian, ‘Zechstein’), the area underwent regional subsidence on the periphery of the Northern European Basin, and the Sorgenfrei-Tornquist Zone acted as an arbitrary north-eastern margin of the North Zechstein Basin. The Late Permian siliciclastic sediments in the border area grades into evaporitic sediments towards the south-west. During the Middle–Late Permian, the Sorgenfrei-Tornquist Zone and the Skagerrak-Kattegat Platform represented a marginal zone to the subsiding Norwegian-Danish Basin that was evolving to the south-west.

The Triassic tectonic realm in northern Germany, Denmark and within the Tornquist Zone was characterised by rifting which created north–south striking fault zones. In Skåne, east–west tension resulted in north-east–south-west striking extensional faults, e.g. the Svedala Fault and the Öresund Fault (Erlström et al. 1997, Sivhed et al. 1999). Much of the Late Triassic deposition in Skåne took place in pull-apart basins within the Sorgenfrei-Tornquist Zone (Mogensen 1995). This phase of dextral transtensional stresses continued intermittently into the Jurassic (Mogensen 1995). During the Triassic there was locally additional significant erosion of Palaeozoic strata. For instance, the pre-existing Palaeozoic strata on the Skurup Platform were likely removed by erosion during the Triassic.

The Jurassic stress field was associated with the break-up of Pangea and caused dextral strike-slip fault reactivation, resulting in different subsidence rates in different areas during the Late Jurassic, often referred to as the Kimmerian tectonic phase (Norling et al. 1993). This Kimmerian phase resulted in the formation of transtensional faults as well as in the reactivation of Permian fault systems, for instance, in the Sorgenfrei-Tornquist Zone (Vejbæk 1990, Mogensen 1994, Michelsen 1997). During the Middle Jurassic, local tectonic uplift was coupled with magmatic intrusions. These led to intense volcanism in central Skåne and the removal of pre-existing strata. Different subsidence in distinct areas continued into the Early Cretaceous with restricted fault activity (Mogensen 1995).

In the Late Cretaceous, the fault-controlled subsidence within the Sorgenfrei-Tornquist Zone terminated, and the Jurassic–Lower Cretaceous depocentre became inverted during the Late Cretaceous and Early Palaeogene. This was triggered by a change in regional stress orientations to a predominantly compressive regime, associated with the Alpine deformation in northern Europe and the opening of the North Atlantic. The inversion regained its force in northern Europe during the late Palaeocene–Eocene (50–55 Ma), particularly in the south-eastern part of the Sorgenfrei-Tornquist Zone, i.e. the Polish Trough. Vejbaek & Andersen

(2002) have identified a later inversion sub-phase during the early Oligocene (33 Ma). These events are effects of the Laramide and Pyrenean tectonic phases according to Norling & Bergström (1987), Ziegler (1990) and Vejbaek & Andersen (2002).

Compression was intense in the Skåne-Bornholm area where more than 2–3 km of uplift are observed, resulting in deep erosion of the uplifted strata within the Sorgenfrei-Tornquist Zone (Berthelsen 1992). It is generally accepted that the inversion began in the Turonian in the south-east and prograded to the north-west (Ziegler 1992, Mogensen & Jensen 1994), with a corresponding decrease in the intensity of deformation in the same direction (Mogensen & Jensen 1994, Michelsen 1997).

A major regional unconformity separates the Quaternary sequence from the Mesozoic succession and also from the Precambrian crystalline basement within

the Skagerrak-Kattegat Platform, the Sorgenfrei-Tornquist Zone (Jensen & Michelsen 1992, Michelsen 1997, Japsen 1997, Japsen & Bidstrup 1999) and the Norwegian-Danish Basin. This unconformity is the result of extensive Neogene uplift and erosion that affected the continental margins around the North Atlantic. Based on basin modelling and well data, Japsen & Bidstrup (1999) estimated that the missing sequence was 1.0–1.2 km thick in the Skagerrak-Kattegat area. Japsen et al. (2007) identified three main phases of uplift, at about 33 Ma, 24 Ma and 4 Ma, triggered by thickness variations of crust and lithosphere over short distances. This is particularly the case along the north-eastern margins of the Norwegian-Danish Basin at the border to the crystalline Fennoscandian terrane.

The stepwise geodynamic evolution of south-eastern Skåne displaying the different tectonic events is summarised in Fig. 13.

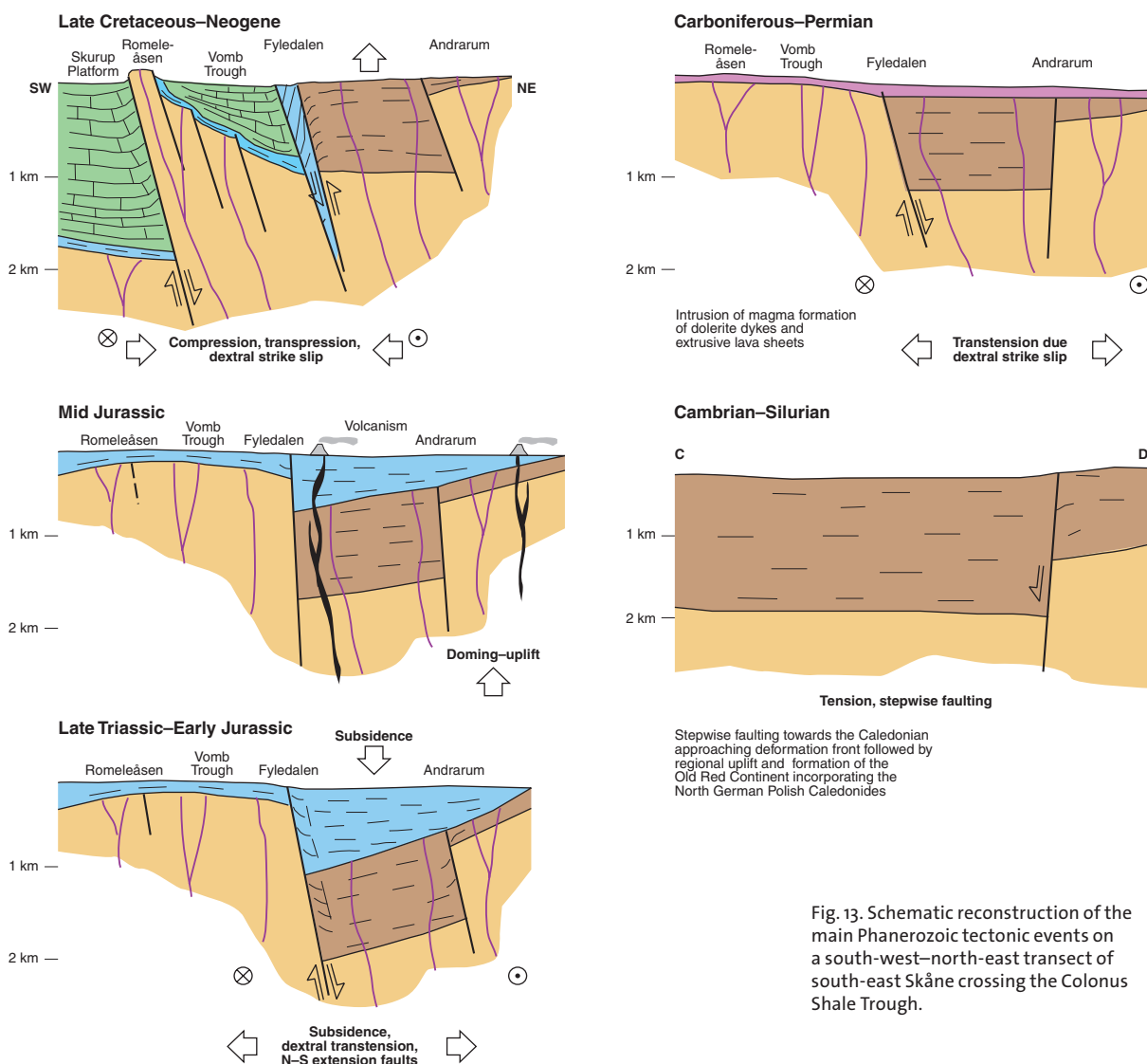


Fig. 13. Schematic reconstruction of the main Phanerozoic tectonic events on a south-west–north-east transect of south-east Skåne crossing the Colonus Shale Trough.

EXCURSION STOPS

During the excursion in Skåne, we will visit seven localities within the 'lower' Cambrian through Silurian succession (Figs. 14–15).

Stop 1. Brantevik

Per Ahlberg, Mikael Calner & Oliver Lehnert

Overview: Low coastal sections south-west of the southern harbour of Brantevik, south-eastern Skåne (N55°30'44.60", E14°20'56.51"), exposing provisional Cambrian Series 2 ('lower' Cambrian) strata formed in shallow marine environments. The successions belong to the Tobisvik Member (upper Hardeberga Formation), the Norretorp and Rispebjerg members (Læså Formation), the Gislöv Formation, and the base of the Cambrian Series 3 through Lower Ordovician (Tremadocian) Alum Shale Formation (Fig. 16). The unconformity separating the Gislöv and Alum Shale formations is prominent and correlates with the Hawke Bay Event as documented from Laurentia.

Description: Provisional Cambrian Series 2 ('lower' Cambrian) strata are well exposed along the shore south of Brantevik (Fig. 17). The succession dips gently towards the south-east and is dominated by arenaceous shallow marine deposits belonging to the Tobisvik Member of the upper Hardeberga Formation. This member has previously been referred to as the *Syringomorpha* sandstone (Hadding 1929) and the Hardeberga Sandstone (Lindström & Staude 1971).

In the southern harbour of Brantevik, there are excellently preserved specimens of *Psammichnites gigas*. These backfilled, looping and ribbon-like traces are 2–5 cm wide and predominantly horizontal. They were likely produced infaunally a few centimetres below the sediment–water interface, and show a narrow longitudinal median ridge and closely spaced, fine transverse ridges.

South of the harbour, the Tobisvik Member is exposed along the shore for about 600 m (Fig. 17). Then it is cut by an east–west striking fault. The Tobisvik Member consists of fine-grained, partly bioturbated sandstones with hummocky cross-stratification, and coarse-grained quartz arenites with large-scale 2D-dunes and oscillation ripples (see Hadding 1929, Figs. 28 and 40, and Lindström & Staude 1971, Pl. 1, Fig. 3). It was most likely deposited in the distal shoreface to innermost shelf under the influence of storms (Hamberg 1991, Nielsen & Schovsbo 2011).

The overlying Læså Formation, comprising the Norretorp and Rispebjerg members, is well exposed south of the fault. The Norretorp Member, measuring some 16 m in thickness in south-eastern Skåne, consists of glauconitic and phosphoric, generally bioturbated siltstones. Only the uppermost part of the member is exposed in the coastal sections south of Brantevik. It has yielded rare trilobites indicative of the *Schmidtellus mickwitzii* Zone. The Norretorp Member is capped by the Rispebjerg Member, which has a thickness of c. 1 m and consists of medium- to coarse-grained sandstones with well-rounded quartz grains (Fig. 18). The distinct

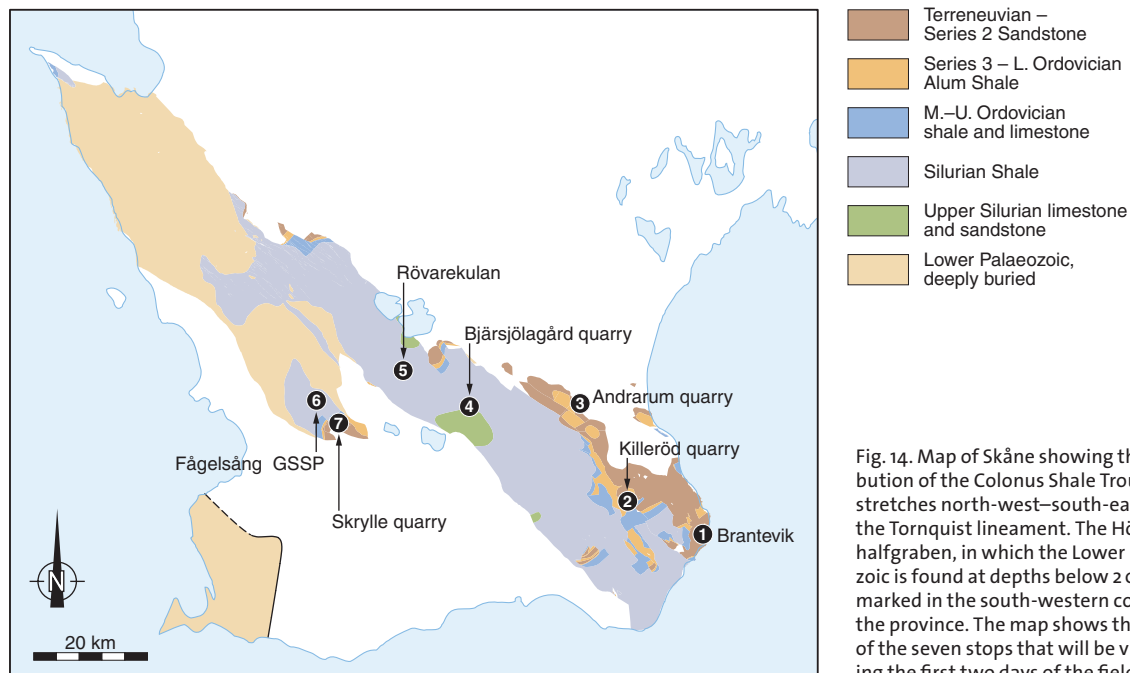


Fig. 14. Map of Skåne showing the distribution of the Colonius Shale Trough which stretches north-west–south-east along the Tornquist lineament. The Höllviken halfgraben, in which the Lower Palaeozoic is found at depths below 2 000 m, is marked in the south-western corner of the province. The map shows the location of the seven stops that will be visited during the first two days of the field trip.

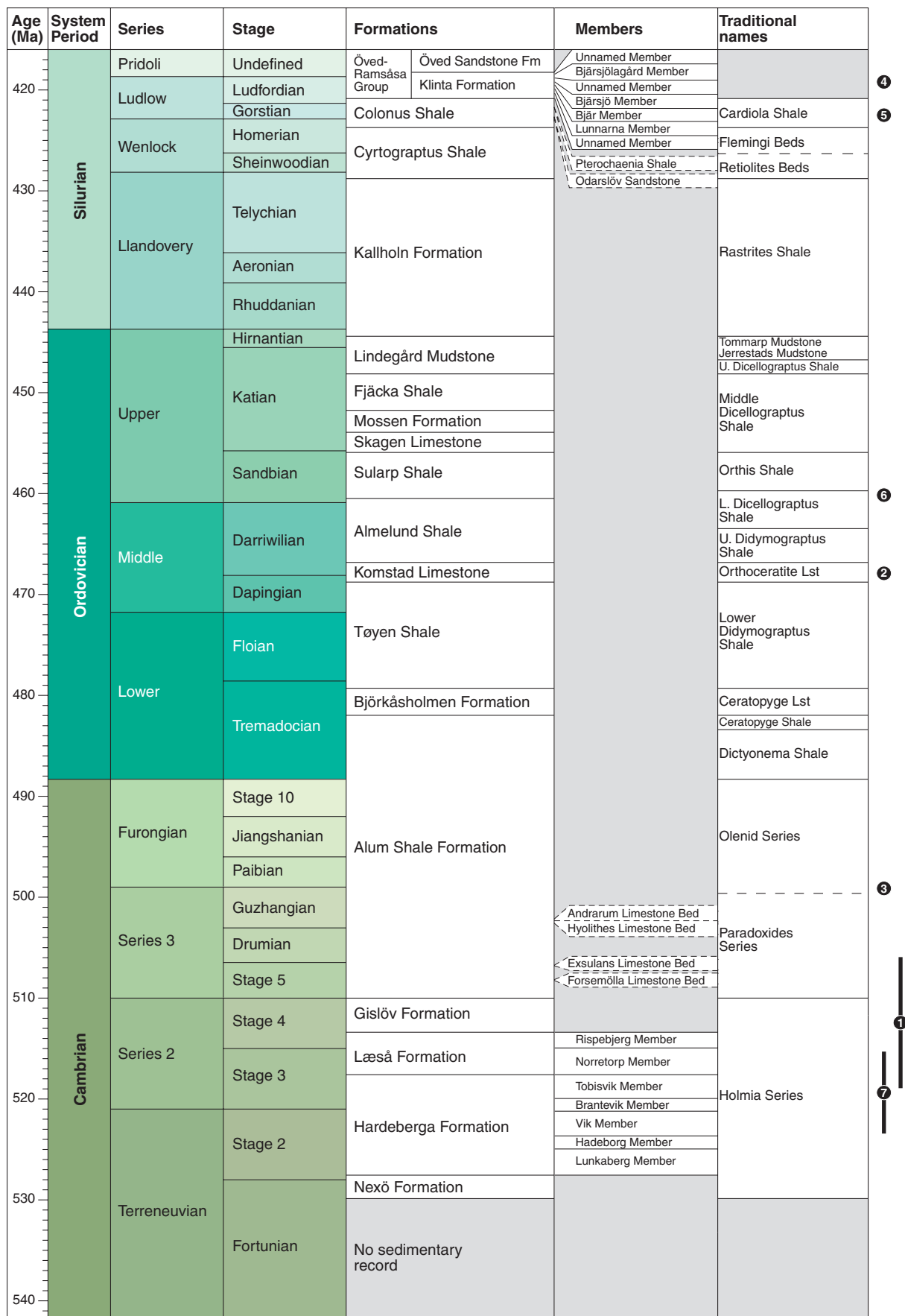


Fig. 15. Cambrian–Silurian stratigraphy of Skåne with the stratigraphic levels of the successions exposed in the visited outcrops (1 – Brantevik, 2 – Killeröd quarry, 3 – Andrarum quarry, 4 – Bjärsjölagård quarry, 5 – Rövarekulan, 6 – Fågelsång, 7 – Skrylle quarry).

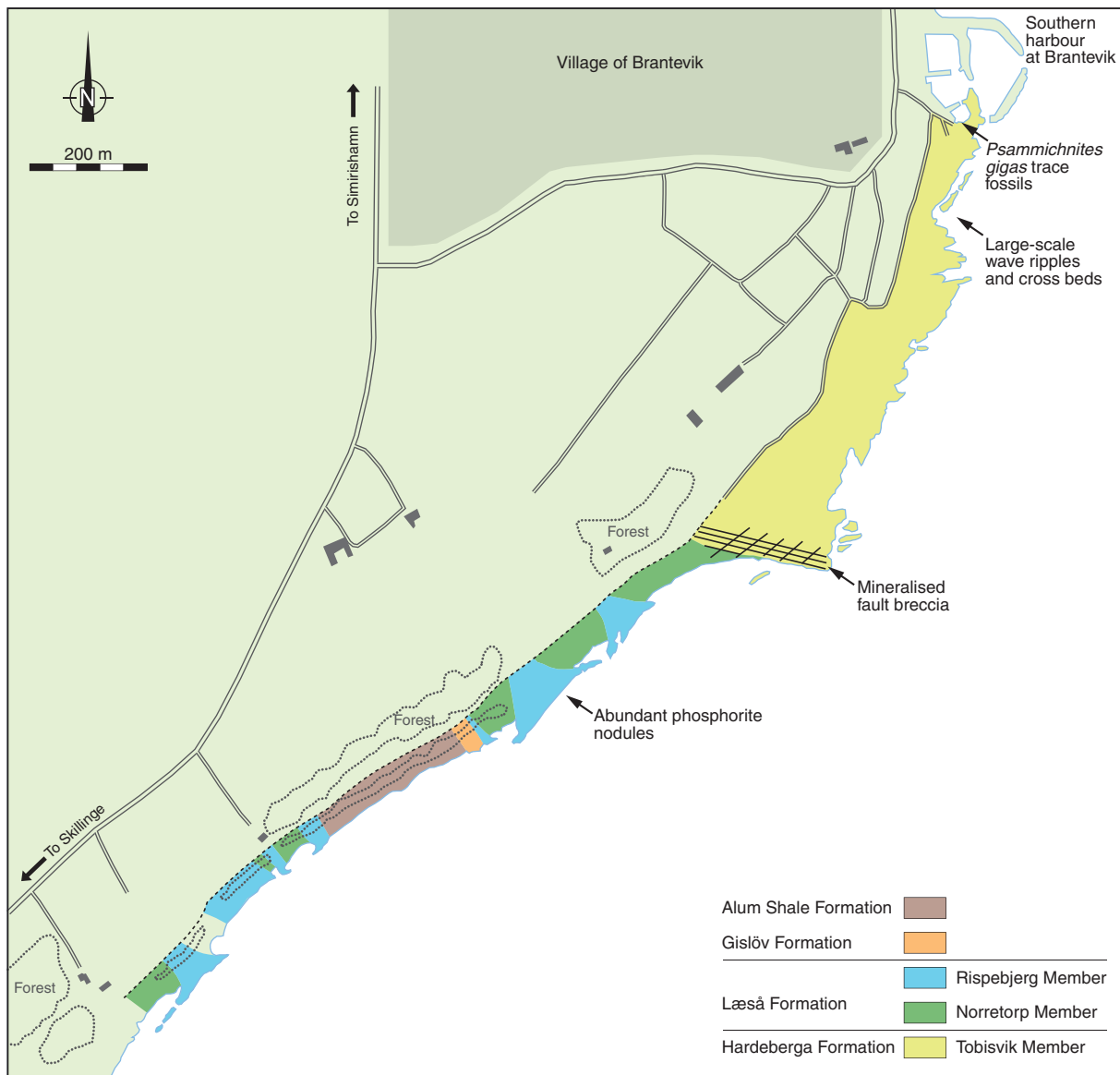


Fig. 16. Distribution of lithostratigraphical units in the low coastal sections south of Brantevik, south-eastern Skåne. The map is based on the geological mapping conducted in the area by Assar Hadding during a field course in 1938. Modified and expanded from an original by M. Calner in 2012.

change from bioturbated, glauconitic siltstone in the Norretorp Member to clean, whitish quartz arenite of the Rispebjerg Member defines the boundary between the members. A conglomeratic phosphorite occurs at the base of the Rispebjerg Member. The nodules in the lower part are reworked from the underlying Norretorp Member, and the frequency of nodules decreases upwards. The top of the Rispebjerg Member is bioturbated and impregnated by phosphorite nodules (Fig. 19, see Hadding 1929, Fig. 13, Lindström & Staude 1971, Pl. 1, Fig. 6, Nielsen & Schovsbo 2007), which formed during a succeeding drowning event (Nielsen & Schovsbo 2011). The topmost phosphorite horizon is c. 0.1 m thick and is an important regional marker bed.

The Rispebjerg Member is unconformably overlain by the Gislöv Formation, a thin (0.8 m south of Brantevik) heterolithic unit composed of fossiliferous silty limestone and shale (Bergström & Ahlberg 1981, Álvaro et al. 2010). It is rich in phosphorite clasts and glauconite, and has yielded trilobites indicative of the *Holmia kjerulfi* and *Ornamentaspis? linnarssoni* zones (latest 'early' Cambrian, provisional Cambrian Stage 4). The top of the Gislöv Formation is marked by another unconformity, capped by the 'middle' Cambrian (Cambrian Stage 5) Forsemölla Limestone Bed (in older literature referred to as fragment limestone), which is a less than 0.2 m thick, phosphoritic and bioclastic limestone that has yielded a fairly rich faunal assemblage, includ-



Fig. 17. Aerial photograph showing the Cambrian Series 2 Tobisvik Member (Hardeberga Formation) just south of the southern harbour in Brantevik. Note large wave ripple-field in the right part of the photograph. Photo: Bergslagsbild AB.



Fig. 18. Section showing the transition between the Norretorp and Rispebjerg members (Læså Formation). The hammer head rests on the greenish, fine-grained and bioturbated siltstones of the Norretorp Member. The boundary between the two members is at the base of the c. 1 m thick, coarse-grained and cross-bedded quartz arenite. Photo: M. Calner.

ing trilobites, echinoderm ossicles and various phosphatic microfossils (Fig. 20, e.g. Bergström & Ahlberg 1981, Streng et al. 2006, 2007, Álvaro et al. 2010). The regional unconformity separating the Gislöv Formation and the Forsemölla Limestone Bed is ascribed to non-deposition and erosion during the Hawke Bay Event (Bergström & Ahlberg 1981, Nielsen & Schovsbo 2007, 2011, cf. Álvaro et al. 2010). The top of the Forsemölla Limestone Bed exhibits wide epichnial trace fossils and abundant pyrite (Fig. 21). The Forsemölla Limestone Bed is overlain by kerogeneous shales (Alum Shale) that represent the onset of one of the major drowning episodes in the Baltoscandian basin.

Stop 2. Killeröd quarry

Per Ahlberg & Mikael Calner

Overview: Abandoned, partly water-filled limestone quarry, located 13 km west of the town of Simrishamn in eastern Skåne (N55°34'21.68", E14°7'50.72"), exposing a Middle Ordovician (Darriwilian) limestone succession (Komstad Limestone, Fig. 22).

Description: The Darriwilian Komstad Limestone is the only limestone unit of any considerable thickness in the Lower Palaeozoic of Skåne, reaching a maximum thickness of 17 m in the Lövestad A3-1 deep well (Calner & Pool 2011). Palaeogeographically it represents a distal, thin tongue of the 'orthoceratite limestone' that is widespread in Baltoscandia. The unit is well exposed in a partly water-filled quarry 800 m south-west of Listarum. The quarry corresponds to locality 2 of Regnéll (1960, fig. 4) and has generally been referred to as the 'Old quarry at Killeröd' (Nilsson 1951). The succession in the quarry is selected as the paratype section for the Komstad Limestone (Nielsen 1995). The strata dip gently towards the south, and the lowermost accessible part of the succession is in the northern part of the quarry. The western quarry face is a fault plane with slickensides and calcite veins (Nielsen 1995). In the east, the Komstad Limestone is cut off by a 23 m wide dolerite dyke, which is intersected by an old dump wagon track.

The Komstad Limestone predominantly consists of 2–20 cm thick limestone beds separated by hardground discontinuity surfaces. Nielsen (1995) logged a total of 9.6 m of limestone in the main quarry and 1.8 m of overlying strata at a water-filled quarry 60 m east-south-east of the main quarry. Thus, a composite section shows that 11.4 m of Komstad Limestone are exposed at Killeröd. The lowermost 1.7 m of the section is below the water table. Nielsen (1995) noted that the Komstad Limestone must have a maximum thickness of at least 15 m in the Komstad–Killeröd area. The succession at Killeröd spans the *Megistaspis simon*,



Fig. 19. Looking south. Extensive bed surface corresponding more or less to the top of the Rispebjerg Member in the coastal sections south of Brantevik. Note the extremely high abundance of phosphorite nodules. Photo: M. Calner.

M. limbata, *Asaphus expansus* and *A. raniceps* zones. The boundary between the *A. expansus* and *A. raniceps* zones is c. 1.2 m below the top of the composite section (Nielsen 1995, Häggström & Schmitz 2007). In terms of the regional British chronostratigraphy, the succession spans the upper Arenig and lowermost Llanvirn. The most common macrofossils are orthocone cephalopod conchs and trilobites, including for example asaphids, illaenids and nileids (Nielsen 1995). Agnostoids may be common in some beds belonging to the *A. raniceps* Zone (Nielsen 1995).

Sediment-dispersed extraterrestrial chromite (EC) grains recovered from the Darriwilian have been studied and analyzed by Häggström & Schmitz (2007), who showed that their distribution trends across the lower to middle Kundan beds are essentially identical to the trends recorded from Kinnekulle, 350 km to the north (Häggström & Schmitz 2007). EC grains are extremely rare in the lower to middle part of the Komstad Limestone but abundant in the upper part of the formation (upper *A. expansus* and *A. raniceps* zones, Häggström & Schmitz 2007).



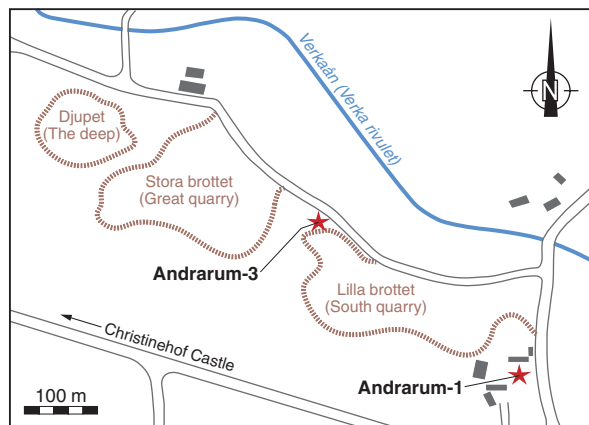
Fig. 20. Overview from south to north, showing the Gislöv Formation and the Forsemölla Limestone in the foreground and the Norretorp and Rispebjerg members in the background. The boundaries between these rock units are partly of a tectonic character. Photo: M. Calner.



Fig. 21. Top of the Forsemölla Limestone Bed, south to south-west of Brantevik, with *Thalassinoides*-like traces and abundant pyrite. This bed surface can only be seen at low sea level. Photo: M. Calner.



Fig. 22. The Darriwilian Komstad Limestone at the abandoned Killeröd quarry. Photo: M. Calner.



★ Drill core sites

Fig. 23. Sketch-map of the Andrarum area showing the old quarries and the location of the Andrarum-1 and Andrarum-3 boreholes. Modified from Ahlberg et al. (2009, fig. 1C).

At the entrance to the quarry, east of the dolerite dyke, there is a 2 m thick succession through the upper Darriwilian Almelund Shale and the overlying Killeröd Formation (Nilsson 1951, Månsson 1995). This locality was referred to as Killeröd site c by Nielsen (1995). The

Killeröd Formation has a thickness of at least 0.73 m and consists of alternating limestone and mudstone. It is richly fossiliferous and has yielded a fairly extensive fauna consisting of trilobites, brachiopods, ostracodes and conodonts (Nilsson 1951, Bergström 1973, Månsson 1993, 1995). The Killeröd Formation is restricted to south-eastern Skåne and is a lateral equivalent to parts of the upper Almelund Shale in west-central Skåne and the upper Elnes Formation in the Oslo Region of Norway (Bergström et al. 2002, Hansen 2009).

Stop 3. Andrarum

Per Ahlberg

Overview: Abandoned quarries with Cambrian Series 3 ('middle' Cambrian) through Furongian black shales (alum shales) and intercalated lenses and beds of organic-rich limestone, referred to as stinkstone or 'orsten'. The exposed succession in the central quarry (the Great quarry or 'Stora brottet', N55°42'57.02", E13°58'32.83", Fig. 23) spans the upper Guzhangian *Agnostus pisiformis* Zone through the Paibian *Olenus scanicus* Zone. Olenid trilobites and agnostoids oc-



Fig. 24. Limestone concretion (stinkstone) embedded in alum shale in the Great quarry at Andrarum. Photo: P. Ahlberg.

cur in great numbers. The Steptoean Positive Carbon Isotope Excursion (SPICE) has been identified in the Andrarum 3 core, which was drilled at the nearby South quarry (Ahlberg et al. 2009).

Description: The Forsemölla-Andrarum district in south-eastern Skåne, southern Sweden, is a classical lower Palaeozoic outcrop area in Baltoscandia. The undeformed and continuous Cambrian Series 3 ('middle' Cambrian) through Furongian succession is best exposed in the old quarries at Andrarum. These were exploited between 1637 and 1912 (Stoltz 1932, Andersson 1974), and were described in detail by Tullberg (1880), Moberg (1910) and Westergård (1922), all of whom provide maps of the quarries and the location of important sections. The three main alum shale workings lie in a north-west to south-east sequence parallel to the Verkaån rivulet; they form a protected site within the Verkaån Nature Reserve. Because the strata dip gently towards the south-east, virtually the entire 'middle' Cambrian through Furongian succession is present within the quarries (cf. Moberg 1910). Parts of the quarries are, however, now water-filled and much of the succession is covered by scree and soil, or is over-

grown, especially in the South quarry (Lilla brottet) near the ruined boiler house (Pannhuset). Two core drillings (Andrarum-1 and Andrarum-2) carried out in 1941–1942 have shown that the Alum Shale Formation in the Forsemölla-Andrarum district has a thickness of at least 76 m (Westergård 1942, 1944). Of this succession, approximately 24 m belong to the 'middle' Cambrian, 44 m to the Furongian, and more than 8 m to the *Dictyonema* Shale (Lower Ordovician: Tremadocian). Tremadocian strata are not exposed.

The central quarry (the Great quarry, Stora brottet) exposes a succession of alum shale and intercalated lenses and beds of organic-rich limestone, referred to as stinkstone or 'orsten' (Fig. 24). The exposed succession spans the upper Guzhangian *Agnostus pisiformis* Zone through the Paibian *Olenus scanicus* Zone. Some of the higher zones in the Furongian are locally exposed in the South quarry (Westergård 1922, Ahlberg et al. 2006). Cambrian Series 2 and 3 strata are exposed at Forsemölla, north of Andrarum (e.g. Bergström & Ahlberg 1981, Álvaro et al. 2010). The sequence of strata in the Forsemölla-Andrarum area was first elucidated by Nathorst (1869).

The best exposure is in the north-central part of the Great quarry. Trilobites and agnostoids are generally confined to the stinkstones, and the intervening shales are largely unfossiliferous. In other areas of the same quarry, however, there are parts of the succession where well-preserved though flattened trilobites and agnostoids are present in great numbers in the shales. In particular the northernmost end of the quarry, in which the *Agnostus pisiformis* Zone through the *Olenus dentatus* Zone is well exposed, yields abundant flattened trilobites and agnostoids, as well as numerous three-dimensional specimens in the stinkstones. Westergård (1922, profile 1, Fig. 4) documented one such section here, some 20 m east of the former tunnel (Pysslingahålet) connecting the Great quarry to the old workings at the Deep (Djupet), which is now a lake. *Agnostus* (*Homagnostus*) *obesus* and species of *Olenus* are very common in this part of the quarry, but their abundances fluctuate dramatically (Clarkson et al. 1998, Lauridsen & Nielsen 2005).

The phosphatocopine *Cyclotron* sp. has also been recorded from the *Olenus*-bearing interval but is restricted to particular levels (Westergård 1922, Clarkson et al. 1998). The cosmopolitan key agnostoid species *Glyptagnostus reticulatus* is generally rare and confined to the *Olenus gibbosus*, *O. truncatus* and *O. wahlenbergi* zones. Its first appearance datum (FAD) is close to the base of the *O. gibbosus* Zone (Lauridsen & Nielsen 2005, Eriksson & Terfelt 2007). The *Agnostus pisiformis* Zone is characterised by its low-diversity fossil content, with only the eponymous species occurring in abundance. A phosphatocopine-bearing interval (c. 40 cm), barren of trilobites, agnostoids and other calcareous fossils, occurs in the uppermost part of the zone (Eriksson & Terfelt 2007). This interval is referred to as a phosphatocopine facies, and is preceded by an interval completely barren of fossils (Eriksson & Terfelt 2007). The phosphatocopine facies in the uppermost *A. pisiformis* Zone correlates with the onset of the Steptoean Positive Carbon Isotope Excursion (SPICE) and presumably with the transition between the Marjumiid and the Pterocephaliid biomes in North America (Eriksson & Terfelt 2007, Ahlberg et al. 2009).

In the north-western end of the South quarry (Lilla brottet, sometimes referred to as 'Caroli Shaft'), there is a section through the *Parabolina brevispina* and *P. spinulosa* zones (lower Jiangshanian Stage). Stinkstone lenses in the lower part of the section yields *P. brevispina* followed by *Protopeltura aciculata* and an abundance of the orthide brachiopod *Orusia lenticularis* (Westergård 1922). Two geographically widespread agnostoids, *Tomagnostella orientalis* and *Pseudagnostus cyclopyge*, have been recorded from the *P. brevispina* Zone at this

locality (Ahlberg & Terfelt 2012). The uppermost part of the section contains *P. spinulosa* and *O. lenticularis*. A core drilling, referred to as Andrarum-3, was carried out a few metres north-east of the section in 2004 (Ahlberg et al. 2009). It reached a depth of 31.30 m and penetrated the *P. spinulosa* Zone down into the *Ptychagnostus atavus* Zone (Drumian Stage). Carbon isotopic analyses through the core revealed the presence of the SPICE excursion beginning near the first appearance of *Glyptagnostus reticulatus* and extending upward into the *Olenus scanicus* Zone (Ahlberg et al. 2009). Recent sedimentological research shows that the succession in the SPICE interval is bioturbated with little or no evidence for anoxic conditions. The sea floor was at least dysoxic as reflected mainly by low-diverse ichnofossil assemblages (Sven Egenhoff pers. comm.).

Stop 4. Bjärsjölagård quarry

Kristina Mehlqvist, Mikael Calner, Oliver Lehnert & Per Ahlberg

Overview: Small abandoned quarry (N55°43'32.26", E13°42'18.03") exposing the Ludfordian (late Ludlow) Bjärsjölagård Limestone Member of the Klinta Formation (Öved-Ramsåsa Group). The exposed strata are dominated by fossiliferous calcareous mudstone and argillaceous limestone with subordinate oncoid-rich limestone. Integrated conodont biostratigraphy and carbon isotope geochemistry has proved that the succession overlaps in time with the Lau Event (Jeppsson et al. 2012 and references therein). The bulk of the strata formed below the effective wave base in close proximity to carbonate mud mounds.

Description: The area around the village Bjärsjölagård in south-central Skåne represents an uplifted, fault-bounded block along the southern margin of the Colonus Shale Trough. This area has long been known for small, scattered outcrops with fossiliferous, slightly argillaceous limestone (Bjärsjölagård Limestone) and reddish, hematite-impregnated sandstone (Öved Sandstone), the latter an important building stone in Skåne. Outcrops are rare and the stratigraphy is based primarily on two shallow boreholes drilled by the Geological Survey in 1967 (Bjärsjölagårdborrningen 1 and 2, Larsson 1982).

Part of the succession is well exposed in the Bjärsjölagård quarry (Fig. 25) that was operated for lime-production during the latter half of the nineteenth century and the early twentieth century. The first geological descriptions from the area were by Bromell (1725–1729) in which several fossils from Bjärsjölagård are mentioned. Stobæus (1741, 1752) described a tabulate coral from Bjärsjölagård and published the first illustration of a fossil from these strata. The first age deter-



Fig. 25. Upper part of the Bjärsjölagård Limestone Member (Klinta Formation) in the south-western wall of the Bjärsjölagård quarry. The middle argillaceous unit is here overlain by cross-bedded oncogenic limestone. The white line separates the Upper Icriodontid Zone (below) from the *Ozarkodina snajdri* Zone (above, Jeppsson et al. 2012). Photo: M. Calner.

mination was subsequently published by Forchhammer (1846), dating the limestone at Bjärsjölagård to late Silurian. Tullberg (1882a, b) published a more detailed description of the strata and compiled a list of all previously described fossils from the locality. In a study by Eichstädt (1888), the exposed rocks in Bjärsjölagård are described.

More recent studies of the Bjärsjölagård quarry include: (1) the documentation of tentaculitids and their ranges by Larsson (1979), (2) the description of the lithostratigraphic succession and conodont biostratigraphy in the Öved-Ramsåsa Group by Jeppsson & Laufeld (1986), (3) the geochemistry and the stratigraphy of the Öved-Ramsåsa Group by Wigforss-Lange (1999, 2007), (4) a detailed compilation of the carbon isotope record in the Öved-Ramsåsa Group by Jeppsson et al. (2012) and (5) a vertebrate zonation based on fish remains by Vergoossen (2003, with references therein). The vertebrate zonation can be correlated into the East Baltic area (Märss & Männik 2013).

The entire Bjärsjölagård Limestone Member is only known from the Bjärsjölagård 2 drill core (Bh 2), taken c. 175 m south-east of the quarry's drainage outlet. In this core, the member can be subdivided into three distinct units: a lower c. 17 m thick unit rich in oncoids, a middle c. 4 m thick unit composed of mudstone and calcareous mudstone, and an upper c. 4 m thick unit composed of oncoid-rich limestone. The unusual abundance of microbial and non-skeletal carbonate microfacies was detailed by Wigforss-Lange (1999, 2007).

The exposed succession in the nearby Bjärsjölagård quarry is about 10 m in thickness, dips 8–10° to the south-east, and includes parts of all three units. Six main depositional microfacies have been identified through point-counting of petrographic thin sections from the western quarry wall (Nilsson 2006). These microfacies include oncoid rudstone, skeletal wackestone, calcareous mudstone, oolitic packstone–grainstone, coral boundstone and oncoid packstone.

The faunal assemblages include both vagile and sessile organisms and display different degrees of tiering (Nilsson 2006). Brachiopods comprise one of the most abundant fossil groups in all the described facies. *Atrypa* and *Howellella* are the most common genera, but rare specimens of *Craniops* also occur. Tentaculitids (*Tentaculites hisingeri* and *Lonchidium scanicus*) and trilobites, such as calymenids, represent other important groups. Ostracodes (e.g. *Hermannina* sp. and *Beyrichia* sp.) are locally abundant, bivalves (e.g. *Cardiolo* and *Pteronitella*) are rare, except in the mudstone, and only a few conulariids occur. Scolecodonts of the paulinitid genus *Kettnerites* occur in the more argillaceous levels. A rare non-calcified alga (*Chaetocladus*) was described from the mudstone unit by Kenrick & Vinther (2006). Sessile epifaunal organisms include locally abundant bryozoans, rare remains of siliceous sponges and a few cor-nulitids. Crinoids are locally abundant and both pentamer-ic and holomeric stems occur. In some specimens, a symplectial articulation can be observed. The amount of crinoidal debris increases along the western quarry wall towards the north-west. Tabulate and rugose corals are present and partly concentrated in specific intervals (see Nilsson 2006 for details).

In this area, the major $\delta^{13}\text{C}$ anomaly related to the Ludlow Lau Event (Calner 2005, 2008) is constrained to the Bjärsjö and Bjärsjölagård Limestone members and reaches a peak value of +11.2‰ in a stromatolitic sample from the quarry at Bjärsjölagård (Wigforss-Lange 1999). The exposed strata in the quarry correlate with the peak and falling limb of the $\delta^{13}\text{C}$ excursion of the Lau Event. In the lowermost ledge of the exposed succession (in the south-western corner of the quarry), the conodont fauna is of low diversity and dom-

inated by the species *Ozarkodina scanica*. This interval is correlated by conodonts with the Upper Icriodontid Subzone. In the upper part of the succession, the conodont fauna becomes more diverse and belongs to the *O. snajdri* conodont Zone (Jeppsson et al. 2012). Thus, the quarry section correlates with the late extinction and the post-extinction interval of the Lau Event.

In the Bjärsjölagård area, the Bjärsjölagård Limestone Member is overlain by a thin unfossiliferous sandstone (Martinsson 1967), which was informally denominated as unit 3 by Eichstädt (1888). This unit is covered by a 12 m thick siliciclastic succession of grey sandstone and shale (Öved Sandstone Formation). This uppermost part has been dated as Pridoli by Jeppsson & Laufeld (1986). More recently, taxonomical and stratigraphical studies on terrestrial spore assemblages from early land plants have confirmed these dates (Mehlgqvist et al. 2012).

Stop 5. Rövarekulan

Kristina Mehlgqvist, Per Ahlberg & Mikael Calner

Overview: This natural outcrop along the Bråån rivulet exposes parts of the upper Silurian Colonus Shale (N55°47'39.50", E13°29'52.36"). Main rock types are shale, mudstone and siltstone with graptolites, bivalves and flattened orthoceratites.

Description: Upper Silurian greyish shale, mudstone and siltstone are well exposed at Rövarekulan, a small nature reserve located c. 25 km north-east of Lund in central Skåne (Fig. 26). At Rövarekulan, the Bråån rivulet has cut out a 15–18 m deep ravine in the soft Colonus Shale. The strata dip 15–28° to the north-east and are especially well exposed in the steep north-eastern bank of the Bråån rivulet. Several smaller exposures can be found also in the south-western slope of the valley. Stratigraphically, some 15 m of the Colonus Shale are exposed at Rövarekulan.

The most common rock type is a light-grey fissile mudstone or siltstone, which easily splits along planes into thin sheets. Individual beds are massive or normally graded or laminated, locally with a scoured lower bedding plane, suggesting fall-out and deposition of the material from decelerating bottom currents and most likely representing distal turbidites. The most common macrofossils are graptolites (often found with preferred orientation), including *Colonograptus colonus*, *Bohemograptus bohemicus* and *Lobograptus scanicus*, bivalves of the genus *Cardiola* and flattened orthoceratites. Microfossils recovered from the succession include chitinozoans (Grahn 1996), acritarchs and scolecodonts. In addition, spores from early land plants have been recovered from the slightly coarser-grained parts of the succession. The Rövarekulan succession is, according



Fig. 26. Exposure of the upper Silurian Colonus Shale along the Bråån rivulet at Rövarekulan. Photo: M. Calner.

to graptolites and chitinozoans, of an early Ludlow age (Gorstian, Grahn 1996) and belongs to the *L. scanicus*/*Saetograptus chimaera* graptolite Zone.

Stop 6. Fågelsång

Oliver Lehnert & Per Ahlberg

Overview: Global Stratotype Section and Point (GSSP) for the base of the Sandbian Stage and the Upper Ordovician Series (section E14b of Moberg 1910, N55°42'57.24", E13°19'02.98") in the Fågelsång area, south-central Skåne. This is one of several sections along the southern slope of the Sularp Brook valley exposing the Amelund Shale, the Fågelsång Phosphorite and the lower part of the Sularp Formation (Fig. 27).

Description: The Lower Palaeozoic outcrop area near the settlement of Fågelsång, about 8 km east of Lund in south-central Skåne, is one of the most important in Sweden, especially with respect to Furongian and Ordovician stratigraphy and palaeontology. The exposures have attracted numerous researchers since the 18th century, in particular geoscientists from Lund University. Moberg (1910) provided a very useful summary of pre-1910 investigations and his locality designations are still in use. A detailed account on Cambrian and Ordovician localities in the Fågelsång area, including all relevant references until 2004, was published by Bergström & Ahlberg (2004) in association with the opening meeting and field trip of IGCP 503.

The sections along the Sularp Brook, 400–600 m west of the mouth of the Rögle (Fågelsång) Brook, expose the upper *Hustedograptus teretiusculus*, *Nemagraptus gracilis* and lower *Diplograptus foliaceus* zones. At the GSSP section (locality E14b of Moberg 1910), the base of the *Nemagraptus gracilis* Zone, representing the base of the global Upper Ordovician Series, is

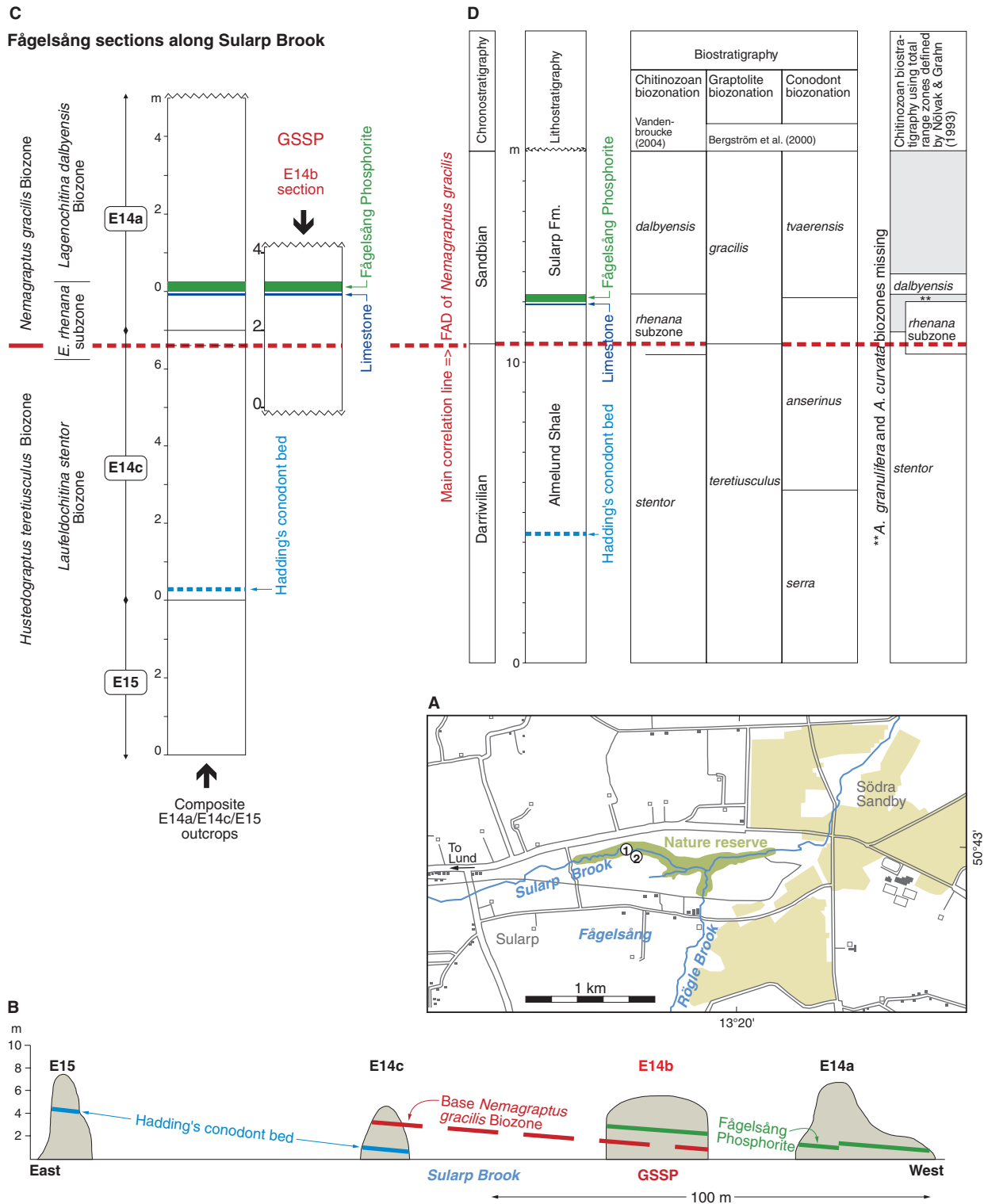


Fig. 27. Compiled information on selected sections in the Fågelsång area, south-central Scania. **A.** Sketch-map of the Fågelsång area showing the locations of the GSSP (1) and the new drill site (2). **B.** East-west transect showing Moberg's (1910) locations 14a-c and 15, displaying the Fågelsång Phosphorite and Hadding's conodont bed. The base of the *Nemagraptus gracilis* Zone marks the base of the Sandbian Stage and the Upper Ordovician Series (modified from Bergström et al. 2000). **C.** Composite section of the outcrops along the Sularp Brook shown in 27B. **D.** Chrono-, litho- and biostratigraphic classification of the GSSP section. All figures modified from the original files of Vandenbroucke (2004).

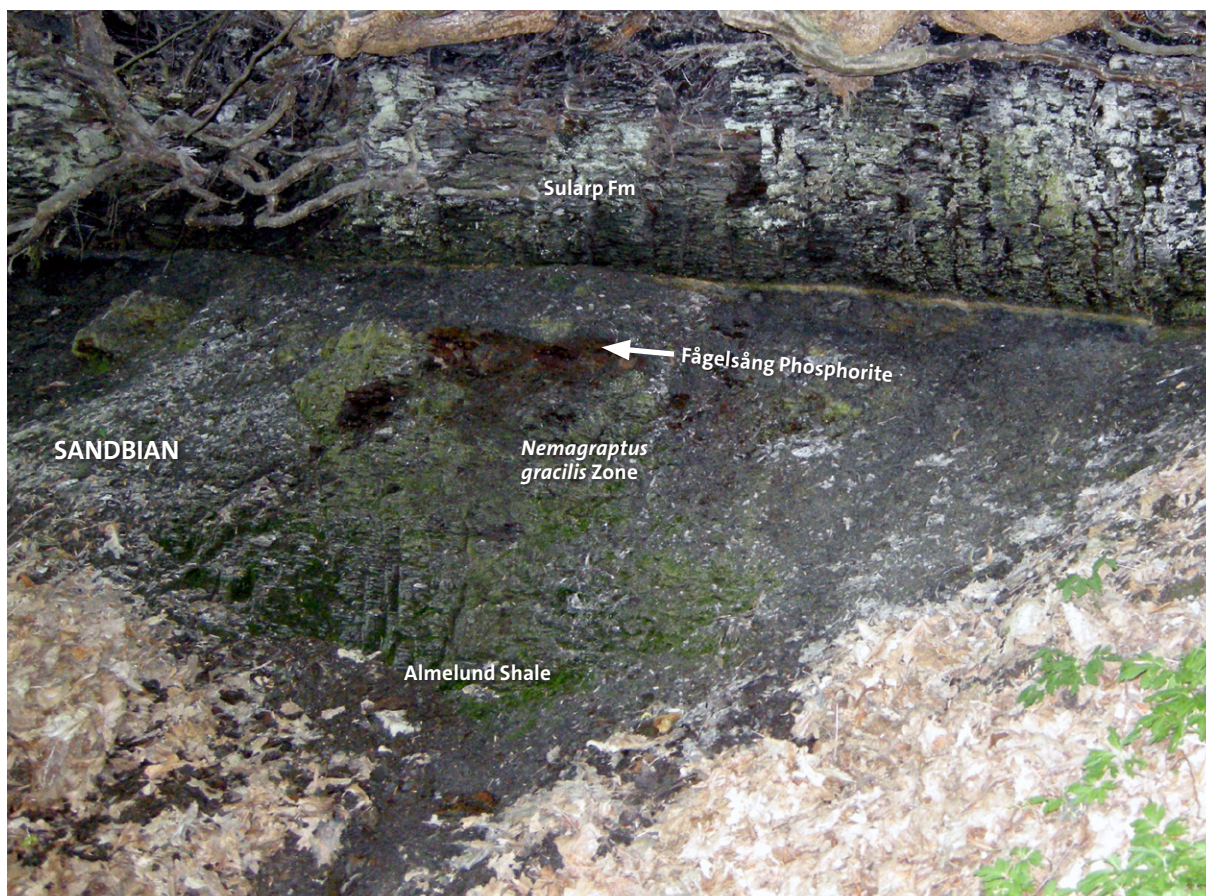


Fig. 28. Natural exposure along the Sularp Brook in the Fågelsång area west of Lund, showing the Almelund Shale, the Fågelsång Phosphorite and the Sularp Formation. The Global Stratotype Section and Point (GSSP) for the base of the Sandbian Stage is located 1.4 m below the Fågelsång Phosphorite. Photo: P. Ahlberg.

about 1.4 m below the Fågelsång Phosphorite (Fig. 28, Bergström et al. 2000). A detailed range chart for the distribution of graptolite species in the section was provided by Bergström & Ahlberg (2004, Fig. 8). The shale succession between the top of the Darriwilian Komstad Limestone (not exposed at the GSSP) and the phosphorite marker bed represents the Almelund Shale, a lithologically uniform unit of dark grey to black shale with rare carbonate interbeds (Bergström et al. 2002).

The succession above the Fågelsång Phosphorite is referred to as the Sularp Formation. Only the lowermost portion of the Sularp Shale is exposed in the GSSP section. The Sularp Shale is largely composed of hard and splintery, silicified shale and mudstone with intercalations of impure limestone beds, rich in shelly fossils. Its upper part is well known for its considerable number of K-bentonite beds; no less than 33 K-bentonite beds were recorded from the Sularp Shale in the Röstånga drill core from west-central Skåne (Bergström et al. 1999). A chitinozoan biozonation of the Fågelsång

sections, including the GSSP, was established by Vandenbroucke (2004), who also presented a detailed correlation chart for zonations based on the major fossil groups (Fig. 27D).

In April 2013, a 65 m long drillcore (63 mm in diameter) was recovered from just south-east of the GSSP (E14b section of Moberg 1910, 55°42'56.16"N, 13°19'6.29"E, Fig. 29). The core succession includes a substantial part of the Tøyen Shale Formation, the Komstad Limestone, the Almelund Shale and the lower Sularp Formation. The Komstad Limestone, which is c. 7.7 m thick in the core, consists of a succession of marl and shale with only a few prominent limestone beds.

Stop 7. Skrylle quarry

Mikael Calner & Oliver Lehnert

Overview: Large active quarry exposing provisional Cambrian Series 2 ('lower' Cambrian) strata of the Hardeberga Formation (Vik, Brantevik and Tobisvik members) and the lower part (Norretorp Member) of



Fig. 29. The recent drilling close to the GSSP was performed by the Engineering Geology group of the Department of Measurement Technology and Industrial Electrical Engineering, Lund University, with the new Atlas Copco CT20 drill rig that will be used for the Swedish Deep Drilling Programme (SDDP). Photo: O. Lehnert.

the Læså Formation (N55°41'54.91", E13°21'15.28"). Several thick Permian dolerites cut through the sequence (Fig. 30).

Description: The exposed succession in the quarry forms part of a raised horst block. The rocks are therefore intensely fractured and locally include mineralised fault breccias. The succession constitutes several tens of metres of medium to thick bedded sandstone with only very rare mudstone interbeds. The sandstone is generally mineralogically and texturally supermature (quartz arenites) but shows some stratigraphic variation. Heavy minerals are common at cer-

tain levels and hydrodynamically sorted to form dark laminae in the sandstone beds. Primary sedimentary structures and trace fossils are abundant and, based on their occurrence, two main depositional facies can be separated.

The first depositional facies yields simple bedsets of sandstone with multi-directional, tangential cross bedding with steep foresets (Fig. 31). Rip-up clasts of greenish mudstone are common along the foresets. Trace fossils of the *Skolithos* ichnofacies are abundant and the upper portion of each bed is commonly intensely burrowed and homogenised (bioturbation index 5). Individual trace fossils may reach one or two decimetres below the homogenised zone and locally more (Calner & Eriksson 2012). This facies represents deposition by strong tidal currents in the shoreface environment.

The second depositional facies includes thick, amalgamated sets of hummocky cross stratified sandstone (Fig. 32). Thin mudstone interbeds rarely separate hummocky beds, and associated wave and current ripples occur at several levels. The amalgamation of thick hummocky beds and rare interbeds of mudstone suggest high sand supply and rapid deposition in the upper part of the lower shoreface. The cyclic repetition of these two facies suggests low amplitude, short term sea-level changes superimposed on the long-term transgressive trend. Due to weathering and limited access to the high walls in the quarry, sedimentary structures are easiest to study in many large blocks that have been placed along the quarry roads.

The Norretorp Member of the Læså Formation can be seen as a dark unit high up in the north-westernmost part of the quarry. The unit consists of mica-rich, phosphoric siltstone and fine-grained sandstone, locally with thin and likely storm-derived monomict (quartz) gravel conglomerates, and represents a sediment-starved, transgressive subtidal setting. Thick, horizontal (hypichnial preservation) trace fossils and rare microbially induced sedimentary structures (wrinkle structures) occur in the Norretorp Member (Calner & Eriksson 2012).

The Permian dolerites cutting through the sedimentary succession are of Cisuralian age (294 ± 4 Ma, Asselian–Sakmarian, Klingspor 1976).



Fig. 30. Thick sequence of thin to medium bedded sandstone of the 'lower' Cambrian Sandstone Association cut by Permian dolerite dykes. Cambrian Series 2 Hardeberga Formation at Skrylle quarry. Photo: M. Calner.



Fig. 31. Thick, cross bedded quartz arenite bed with abundant rip-up clasts and a completely homogenised upper portion of the bed due to intense burrowing (*Skolithos* ichnofacies, ichnofabric index 5). Note isolated traces penetrating beneath the homogenised zone. Cambrian Series 2 Hardeberga Formation at Skrylle quarry. Photo: M. Calner.



Fig. 32. Thick set of hummocky cross stratified sandstone with abundant heavy minerals hydrodynamically sorted to form conspicuously dark laminae. Cambrian Series 2 Hardeberga Formation at Skrylle quarry. Photo: M. Calner.

Regional geology of the Västergötland province, Sweden

Per Ahlberg, Mikael Calner, Oliver Lehnert & Linda Wickström

The Province of Västergötland is located between the two biggest lakes of Sweden, Vänern and Vättern. The history of geological research in this area started in the early 18th century, and Carl von Linné described the stratigraphic succession of the now classical table mountains during his famous excursion to Kinnekulle, Billingen and the Falbygden areas in 1747. After the initial studies, Angelin (1851, 1854) was the first geologist who described and subdivided the succession based on fossils. Later, Linnarsson (1869) presented a paper in which he describes the stratigraphy of the Lower Palaeozoic in Västergötland and also makes correlations to equivalent strata in other parts of Sweden, Russia (including the Baltic states), Bohemia, North America, Norway (which at the time was a part of Sweden), Ireland and the British Isles. Mapping of the Falbygden, Billingen and Kinnekulle areas by the Geological Survey of Sweden started in the late 19th century (Holm 1896, Munthe 1905, 1906, Munthe et al. 1928, Lundqvist et al. 1931, Johansson et al. 1943). Tjernvik (1956) presented an

extensive study on the early Ordovician of Sweden, including the Västergötland strata, and Jaanusson (1963, 1964) reviewed and revised the upper Middle and Upper Ordovician of the province.

Prominent features in central Västergötland are the dolerite-capped table mountains that rise to elevations of more than 200 m above the peneplain and that are visible over large distances. The peneplanisation over a long period of time is the result of deep weathering and erosion during the late Neoproterozoic. The crystalline basement rocks are locally soft due to hydrolysis in the kaolinitisation process, for example at Lugnås where the rocks during a long time have been quarried to produce mill-wheels. Before the first major early Cambrian transgression, the peneplain covered large parts of the Fennoscandian shield with only scattered monadnocks rising above the regionally flat surface (e.g. the small island Blå Jungfrun in Kalmarsund between Småland and northern Öland in south-eastern Sweden). Due to tectonic processes, especially the uplift of the south-Swedish dome,

the peneplain has later been modified by renewed deep weathering affecting the Palaeozoic sedimentary cover as well as the crystalline basement (Lidmar-Bergström 1995, 1996). The duration of exposure together with the climate controlled the weathering rate. The peneplain is well preserved in Västergötland due to a long period of protection (probably until the Neogene) underneath the Palaeozoic sedimentary cover (Fig. 33).

The table mountains occur in three main districts: (1) Billingen–Falbygden, which comprises Mount Billingen in the north and Falbygden with its smaller mountains in the south, (2) Kinnekulle at Lake Vänern north-west of Billingen and (3) Halleberg and Hunneberg at the south-western end of Lake Vänern (Fig. 34). These outliers ('buttes', German term 'Zeugenberg') are relicts of the Palaeozoic cover, preserved due to their thick sheeted dolerite caps, which were intruded as sills at different levels into the sedimentary succession. Radiometric age determinations (K-Ar) of the dolerite gives an age of 282 ± 5 Ma suggesting intrusion in the early Permian (Artinskian Stage, Cisuralian Series, Priem et al. 1968). Lugnäsberget north of Billingen is an outlier without a dolerite cap.

The Lower Palaeozoic successions are flat-lying, or nearly so, and most complete on Kinnekulle and in the

Billingen–Falbygden area, where they range up into the lower Silurian Kallholn Shale (Llandovery). The total thickness of the sedimentary succession is approximately 215 m at Kinnekulle and some 150–160 m in the Billingen–Falbygden area. In the Halleberg–Hunneberg outliers, the dolerite intrusion cuts gently upwards from the north (Halleberg), where it rests on Cambrian strata, to the south (Hunneberg) where it rests on Lower Ordovician shales and limestones.

The Cambrian successions predominantly consist of siliciclastic deposits, which accumulated under generally shallow to moderately deep marine conditions at latitudes of 30–60°S (Torsvik & Rehnström 2001, Cocks & Torsvik 2005). Much of the traditional 'lower' Cambrian consists of sandstones (the *Mickwitzia* and Lingulid Sandstone members of the File Haidar Formation), whereas the 'middle' Cambrian and Furongian (uppermost Cambrian series) strata are largely represented by the Alum Shale Formation, a succession of dark grey to black, bituminous shales and limestones.

The Ordovician of Västergötland predominantly consists of limestones and mudstones, and a few graptoliferous shale units. For a long time the upper Lower through Middle Ordovician bedded limestones of Sweden have been collectively referred to as 'orthoceratite limestone'.



Fig. 33. The sub-Cambrian peneplain is exceptionally well preserved in parts of Västergötland due to late exhumation. The photograph shows the expression of the peneplain in the outskirts of Trollhättan where it is cut in Proterozoic gneiss. Local fissures in the peneplain are filled with Cambrian sandstone. Photo: M. Calner.

This is a temperate water limestone devoid of reef structures and with comparably low-diversity skeletal grain associations. The total thickness of the Ordovician succession is 104 m at Kinnekulle and 84 m in the eastern Billingen area (Jaanusson 1982). The Silurian succession is dominated by graptolitic shales (Kallholn Shale) and attains a maximum thickness of 56 m at Kinnekulle.

The last decades have witnessed major efforts to increase the knowledge of the stratigraphy, sedimentology, palaeontology and geochemistry of the Lower Palaeozoic in Västergötland. This extensive research has, for instance, resulted in the establishment of a GSSP for the upper stage (Floian Stage) of the Lower Ordovician Series at Hunneberg in Västergötland (Bergström et al. 2004), and in the identification of several Ordovician and Silurian K-bentonites with considerable event-stratigraphic and tectonomagmatic significance (e.g. Huff et al. 1992, 1996, Bergström et al. 1992, 1995, 1998). Furthermore, the Ordovician of Mount Kinnekulle is now world-famous because of its abundance of fossil meteorites. Almost one hundred fossil meteorites (1–21 cm in diameter) have been found during quarrying of ‘orthoceratite limestones’ of Kundan age at Österplana, Kinnekulle (Birger Schmitz, pers. comm. to A. Lindskog 2013). The meteorites originate from

the disruption of the L-chondrite parent body in the asteroid belt at this time. This is the largest documented disruption event in the asteroid belt for the past c. 3 billion years (e.g. Schmitz et al. 2008). About 20% of the meteorites that strike Earth today originate from this event. In connection with the disruption event in the Middle Ordovician, the flux of meteorites and larger asteroids increased substantially. This is supported not only by the occurrence of abundant fossil meteorites but also by many impact structures of this age (in Sweden: the Lockne, Tvären and Granby structures). It has been suggested by Schmitz et al. (2008) that the increased flux of asteroids may have spurred the ongoing Great Ordovician Biodiversification Event.

EXCURSION STOPS

During the excursion in Västergötland, we will visit seven localities within the ‘lower’ Cambrian through Silurian succession (stops 8 to 14, Figs. 35–36).

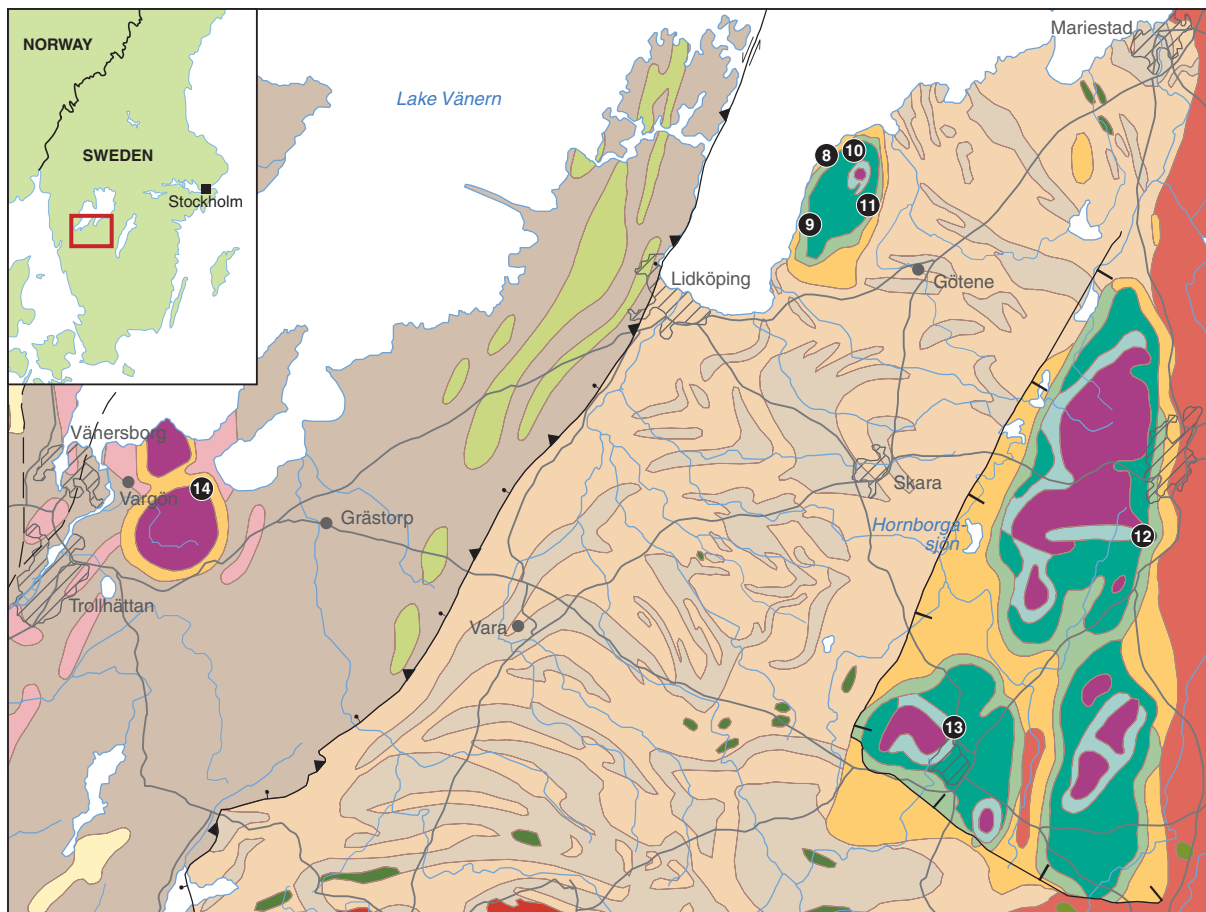
Stop 8. Råbäcks hamn

Mikael Calner, Oliver Lehnert & Per Ahlberg

Overview: The sub-Cambrian peneplain with remnants of the Cambrian basal conglomerate is exposed at the



Fig. 34. Mount Hunneberg near the village of Flo. Note the flat peneplain in the foreground, and the thick dolerite cap. Photo: M. Calner.



- Fault or ductile deformation zone with dip-slip movement, tag points to downthrown block
- Fault or ductile deformation zone, kinematics unspecified
- Fault or ductile deformation zone with combined thrusting and normal dip-slip movement
- Fault or ductile deformation zone with combined reverse and strike-slip movement, sinistral

NEOPROTEROZOIC AND PHANEROZOIC PLATFORMAL COVER AND IGNEOUS ROCKS

- Dolerite (Permian to Carboniferous)
- Limestone, shale, sandstone (Silurian)
- Limestone, shale (Ordovician)
- Bituminous shale (alum shale) and subordinate limestone (Cambrian Stage 5 to Tremadocian)
- Sandstone, conglomerate, siltstone, shale (Cambrian Stage 4)

SVECONORWEGIAN OROGEN

Idefjorden terrane

- Granite, syenitoid and metamorphic equivalents (c. 1.36–1.27 Ga)
- Gabbro, diorite, ultrabasic rock, dolerite (1.6–1.3 Ga), metamorphic
- Granitoid, metamorphic (1.6–1.5 Ga)
- Rhyolite, dacite, andesite, sedimentary rock (c. 1.66 and c. 1.61 Ga), metamorphic

Eastern Segment, middle and upper units

- Granite, granodiorite, syenitoid, quartz monzodiorite and metamorphic equivalents (1.7 Ga)
- Gabbro, dioritoid, dolerite, ultrabasic rock and metamorphic equivalents (1.7 Ga)

Eastern Segment, lower unit

- Granite, syenitoid and metamorphic equivalents (1.2 Ga)
- Amphibolite, garnet amphibolite, mafic granulite, eclogite (1.7–0.9 Ga)
- Granitic migmatitic gneiss, granite (1.7–1.0 Ga)
- Granitoid to syenitoid migmatitic gneiss (1.7 Ga)

- 8** Råbäcks hamn
- 9** Kakeled quarry
- 10** Hällekis
- 11** Thorsberg quarry
- 12** Skultorp quarry
- 13** Tomten quarry
- 14** Diabasbrottet

Fig. 35. Map showing parts of Västergötland and the locations of the plateau mountains and localities 8–14. Modified from Bergman et al. (2012).

Fig. 36. Cambrian–Silurian stratigraphy of Västergötland with the stratigraphic levels of the successions exposed in the visited outcrops (8 – Råbäcks hamn, 9 – Kakeled quarry, 10 – Hällekis quarry, 11 – Thorsberg quarry, 12 – Skultorp quarry, 13 – Tomten quarry, 14 – Diabasbrottet).

Age (Ma)	System Period	Series	Stage	Formations	Members	Traditional names		
420-430	Silurian	Pridoli	Undefined	No sedimentary record				
		Ludlow	Ludfordian					
			Gorstian					
		Wenlock	Homerian					
			Sheinwoodian					
		430-440	Llandovery		Telychian	Kallholn Formation		Retiolites Beds
					Aeronian			
Rhuddanian								
440-490	Ordovician	Upper	Hirnantian	Loka Formation Ulunda Formation Jonstorp Formation	lower, Skultorp, upper mbrs	Tommarp / Dalmatitina beds Stauropcephalus Shale Red Tretaspis Shale Tretaspis Limestone		
			Katian	Fjäckå Shale Bestorp Fm	Mossen Formation Freberga Formation	Skagen Limestone Molda Limestone	U. Dicclograptus Shale	
							Black Tretaspis Shale	
							Upper Chasmops Limestone & Shale	
			Sandbian	Dalby Formation	Lower Chasmops Lst or Ludibundus Lst			
			Middle	Darrivilian		Ryd Formation Gullhögen Formation	Skövde Lst Våmb Lst	Crassicauda Lst Schroeteri Lst
		Holen Limestone			'Täljsten'	Vaginatum Lst		
		Dapingian		Lanna Limestone	Limbata Lst			
		Lower	Floian	Tøyen Shale Latorp Limestone	Planilimbata Limestone			
			Tremadocian	Björkåsholmen Fm		Ceratopyge Lst		
						Ceratopyge Shale		
		490-540	Cambrian	Furongian	Stage 10	Alum Shale Formation	Kakeled Limestone Bed	Olenid Series
Jiangshanian								
Paibian								
Series 3	Guzhangian			Paradoxides Series				
	Drumian							
	Stage 5							
Series 2	Stage 4			File Haidar Formation	Lingulid Sandstone Mbr Mickwitzia Sandstone Mbr	Holmia Series		
	Stage 3			No sedimentary record				
							Stage 2	
	Terreneuvian			Fortunian	No sedimentary record			

12

11

10

14

13

9

8



Fig. 37. Erosional remnants of the Cambrian basal conglomerate resting on Proterozoic gneiss just north of Råbäck hamn. Note the occurrence of the conglomerate in topographical lows and fissures in the gneiss. The larger whitish quartz clasts originate from local pegmatites. Some of these clasts display features of eolian activity in a Cambrian terrestrial landscape and represent typical ventifacts. Photo: M. Calner.

shore of Lake Vänern (N58°36'26.65", E13°20'58.39", Fig. 37). In a small exposure, cross-bedded quartz arenites of the *Mickwitzia* Sandstone Member (File Haidar Formation) can be studied.

Description: Råbäck hamn has been an important port for the stone industry at Kinnekulle (Sundius in Johansson et al. 1943). Blocks of local Cambrian sandstone and Ordovician limestone can be studied in the vicinity of the old stone masonry (N58°36'21.34", E13°20'46.94"). Proterozoic gneiss forms the lake-shore cliffs a few hundred metres north of the factory. Remnants of a polymict paraconglomerate and of the *Mickwitzia* Sandstone Member (File Haidar Formation) resting on the gneiss imply that the surface of this gneiss is part of the sub-Cambrian peneplain. In the south-western part of the province, around Trollhättan, Halleberg and Hunneberg, the extremely flat surface of the peneplain is well visible (Fig. 33). The presence of a coarse-grained and poorly sorted conglomerate in depressions and fissures within the gneiss at Råbäck hamn displays that the surface in this area, on the contrary, was very irregular. The morphology of the surface

between the basement and its sedimentary cover represents a relict of an old landscape.

The clasts in the conglomerate mainly derive from the underlying gneiss. Several centimetres to one decimetre large quartz clasts derive from local pegmatites. These quartz clasts sometimes show typical facets of ventifacts (e.g. dreikants), formed through eolian silt and sand blasting in a sterile, rocky landscape before the Cambrian first order transgression reached the area. In Västergötland, the basal conglomerate has a maximum thickness of a few metres and can be studied in the old mines at Lugnås.

Bioturbation can be observed in small patches of the *Mickwitzia* Sandstone Member that is associated with the conglomerate or overlies the gneiss. Just south-east of this exposure along the shore, higher parts of the *Mickwitzia* Sandstone Member can be studied in a low cliff within the forest (Fig. 38). It is developed as a loosely cemented and texturally very mature quartz arenite with locally abundant *Skolithos* traces. Primary sedimentary structures include low-angle, tangential cross beds with abundant rip-up clasts of greenish mud-

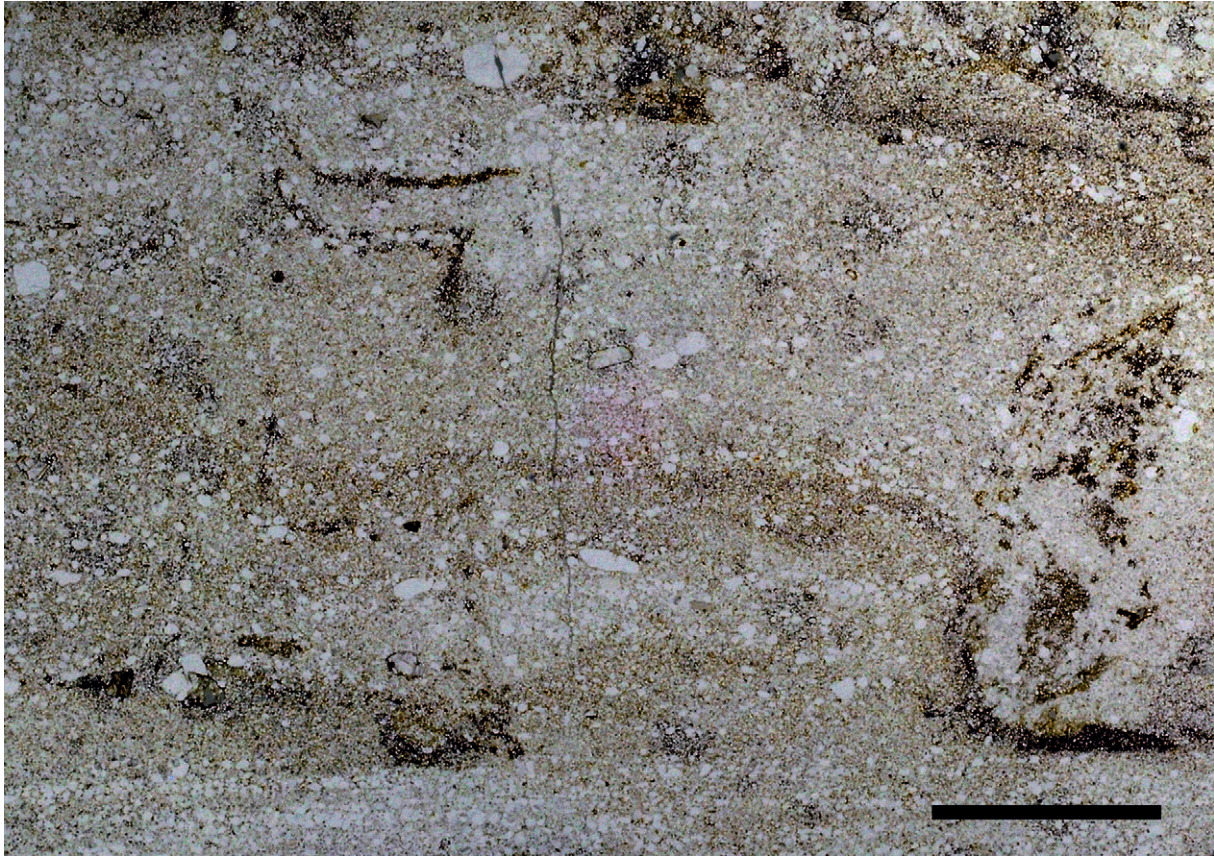


Fig. 38. Petrographic thin-section of the *Mickwitzia* Sandstone Member showing reworked local basement clasts as well as poor sorting and common angular grains due to short transport. Scale bar equals 1 cm. Photo: O. Lehnert.

stone, as well as hummocky cross stratification, suggesting deposition in the shoreface to lower shoreface environment.

Stop 9. Kakeled quarry

Per Ahlberg, Oliver Lehnert & Mikael Calner

Overview: Abandoned quarry (N58°33'31.13", E13°20'0.37") with provisional Cambrian Series 3 (Guzhangian) and Furongian black shale and mudstone (alum shale) with lenses and beds of dark grey limestone (stinkstone or 'orsten'). Stratigraphically, this succession of the Alum Shale Formation spans the upper Guzhangian *Agnostus pisiformis* Zone through the middle Furongian *Ctenopyge linnarssoni* Zone. A prominent karstic surface in the upper Paibian–lowermost Jiangshanian stages provides evidence for transgression after a major regression, regionally exposing the sea floor of the Alum Shale Basin.

Description: The Alum Shale Formation has a wide distribution on Mount Kinnekulle, and already during the 18th century there was intense mining activ-

ity for alum production (Sundius in Johansson et al. 1943). Provisional Cambrian Series 2 and Furongian Alum Shales are well exposed in several of the old quarries around the mountain. One of the best exposures through this interval is the Kakeled quarry on the south-western slope of Kinnekulle. The quarry exposes a 6.2 m thick interval through the Alum Shale Formation (Terfelt 2003).

In the lower half of the succession there is a 1.50 m thick stinkstone unit referred to as the Kakeled Limestone Bed (formerly known as the 'Great Orsten Bank', Terfelt 2003, Nielsen & Schovsbo 2007). This unit extends from the upper *A. pisiformis* Zone (Fig. 39) through the *Parabolina spinulosa* Zone. Nine additional stinkstone beds, with thicknesses varying between 1.10 and 0.55 m, are present above the Kakeled Limestone Bed. These are separated by alum shale.

The limestones are generally richly fossiliferous and together they have yielded a fairly diverse trilobite fauna, in the Furongian completely dominated by olenid trilobites (Fig. 40). The Kakeled succession has also yielded phosphatocopines, conodonts (including



Fig. 39. Mass occurrence of *Agnostus pisiformis* in the Kakeled Limestone Bed (uppermost Guzhangian). Photo: P. Ahlberg.

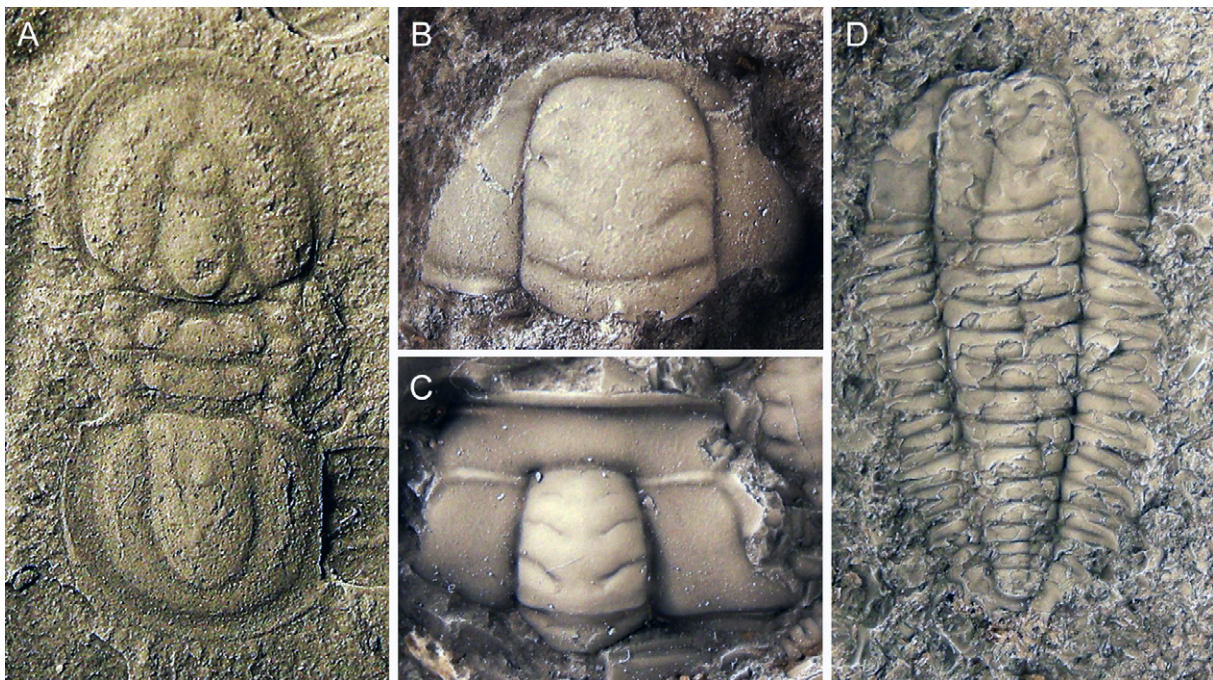


Fig. 40. Agnostoids and trilobites from the Kakeled quarry. A. *Agnostus pisiformis*, $\times 8.6$. B. *Peltura minor*, $\times 7.0$. C. *Olenus gibbosus*, $\times 6.7$. D. *Peltura scarabaeoides*, $\times 4.5$. Photo: P. Ahlberg.

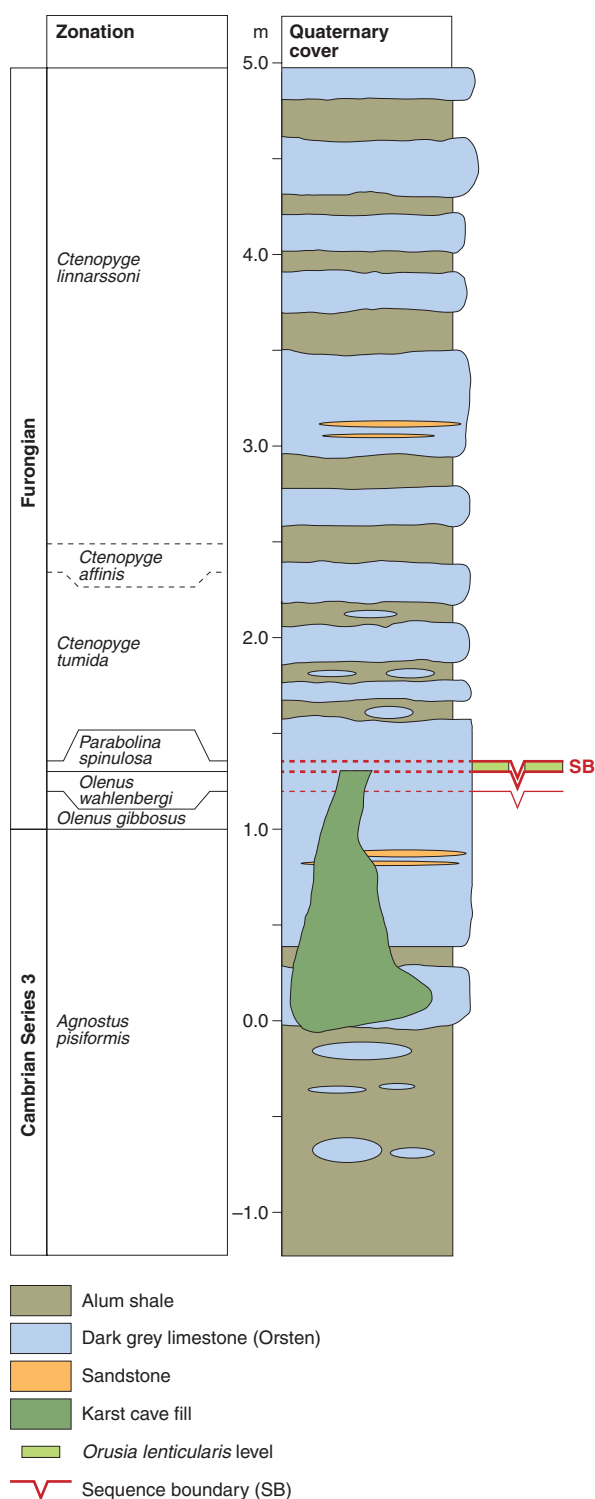


Fig. 41. Cambrian succession exposed in the Kakeled quarry (modified from Terfelt 2003). Note the disconformities and the appearance of a palaeokarst cave at a discontinuity surface near the top of the Kakeled Limestone Bed (upper Paibian–lowermost Jiangshanian).

protoconodonts and paraconodonts) and a few species of brachiopods such as the orthide *Orusia lenticularis*.

The succession of trilobites, described in detail by Terfelt (2003), is incomplete and there are several gaps

of various magnitudes in the Furongian part of the succession (Fig. 41). Strata with *Leptoplastus* and *Protopeltura praecursor* are for example missing, and the lowermost part of the Furongian is represented only by the *O. gibbosus* and *O. wahlenbergi* zones (Fig. 42).

In terms of stratigraphical completeness, the Kakeled succession is comparable to other Furongian successions in the area. The percentage of stinkstones (about 70% of the succession) appears, however, to be higher at Kakeled than in most other coeval sections on Kinnekulle (Terfelt 2003). Lithologically, the stinkstones can be subdivided into primary coquinooid limestone, which is generally richly fossiliferous, and early diagenetically formed limestone (Dworatzek 1987, Terfelt 2003).

The presence of coquinooid limestones with current oriented agnostoid shields and several gaps in the succession point towards a shallow water environment, and the presence of structural highs with current-influenced deposition in Västergötland during latest ‘middle’ Cambrian and Furongian times (Terfelt 2003).

An irregular, 1.4 m deep palaeokarst cave (Lehnert et al. 2012, Figs. 41 and 43) with a breccia fill yielding large, angular ‘*orsten*’ clasts in a mud- to wackestone matrix (Fig. 44) was recently discovered beneath a karstic surface in the Kakeled quarry. The karstic surface occurs near the top of the Kakeled Limestone Bed. Mass occurrences of *O. lenticularis*, a shallow-water brachiopod that settled on hard substrates, in the karst pockets together with a brecciated or conglomeratic interval above the karstic surface have provided evidence for transgression after a major regression, regionally exposing the sea-floor during the early Jiangshanian Age (Lehnert et al. 2012).

The documentation of palaeokarst challenges the general view that the alum shale formed in a deep and quiet basin, as postulated in earlier sedimentological publications (e.g. Thickpenney 1984, Gill et al. 2011), or at least that the basin was shallow enough to be exposed at low sea-level. Although the fine-grained facies and its lateral consistency suggest that the overall environment over time was calm and starved of sediments, there is a wide range of facies in the Alum Shale succession that reflect a more complex depositional setting. This includes proximal carbonate to distal siliciclastic mudstone environments and lagoonal settings reflecting evaporation and the formation of gypsum, now preserved as barite pseudomorphs (Newby 2012). There are also typical shallow water indications in this unit such as mud cracks (Egenhoff & Maletz 2012) and typical grainstone deposits that formed in high-energy environments (Newby 2012).

Series	Zonation	
	Agnostoids	Polymerids
Furongian	<i>Trilobagnostus holmi</i>	<i>Acerocare ecorne</i>
		<i>Westergaardia scanica</i>
		<i>Peltura costata</i>
		<i>Peltura transiens</i>
		<i>Peltura paradoxa</i>
		<i>Peltura lobata</i>
	<i>Lotagnostus americanus</i>	<i>Ctenopyge linnarssoni</i>
		<i>Ctenopyge bisulcata</i>
	<i>Pseudagnostus cyclopyge</i>	<i>Ctenopyge affinis</i>
		<i>Ctenopyge tumida</i>
		<i>Ctenopyge spectabilis</i>
		<i>Ctenopyge similis</i>
		<i>Ctenopyge flagellifera</i>
		<i>Ctenopyge postcurrents</i>
		<i>Leptoplastus neglectus</i>
		<i>Leptoplastus stenotus</i>
		<i>Leptoplastus ovatus</i>
		<i>Leptoplastus crassicornis</i>
		<i>Leptoplastus rapidophorus</i>
<i>Leptoplastus paucisegmentatus</i>		
<i>Glyptagnostus reticularis</i>		<i>Parabolina spinulosa</i>
	<i>Parabolina brevispina</i>	
<i>Agnostus pisiformis</i>	<i>Olenus scanicus</i>	
	<i>Olenus dentatus</i>	
	<i>Olenus attenuatus</i>	
	<i>Olenus wahlenbergi</i>	
	<i>Olenus truncatus</i>	
Cambrian Series 3	<i>Olenus gibbosus</i>	

Fig. 42. Uppermost Guzhangian–Furongian biozonation in Scandinavia (modified from Terfelt et al. 2008). In the Kakeled quarry, the six uppermost polymerid zones are not exposed (white). Zones in yellow are present, and zones in grey are missing. Stippled red lines indicate discontinuity surfaces.

Stop 10. Hälleklis

Anders Lindskog, Per Ahlberg, Mikael Calner & Oliver Lehnert

Overview: Large abandoned quarry on the north-western slope of Kinnekulle, with Dapingian–Darriwilian (Volkhovian–Uhakuan) cool-water carbonates (‘orthoceratite limestone’) and calcareous mudstones formed in a sediment-starved intracratonic basin (N58°36’31.05", E13°23’41.81"). The succession spans the Lanna and Holen limestones, and the Gullhøgen and basal Ryd formations (Fig. 45).

Description: The Hälleklis quarry, which supplied materials for the cement industry between 1892 and 1979, hosts a c. 40 m thick exposure of Lower to Middle Ordovician rocks. The succession is one of the best sections of this interval in Sweden. The oldest strata in the quarry can be found in trenches at the north quarry entrance and represent the upper part of the Lower Ordovician (Floian Stage) Tøyen Shale (*Didymograptus hirundo* Zone). Tjernvik (1956) briefly discussed the graptolite fauna from the Tøyen Shale at Hälleklis.

Above the Tøyen Shale the main part of the succession consists of c. 27 m of brown- to rusty red-coloured, condensed and variably marly ‘orthoceratite limestone’. In stratigraphically ascending order, these limestones are divided near-equally into the Lanna (formerly *Limbata* Limestone) and the Holen limestones (formerly *Vaginatium* Limestone), each about 13–14 m in thickness. They correspond to the Volkhov (Dapingian–lowermost Darriwilian, see Bergström et al. 2009) and Kunda Baltoscandian stages (lower–middle Darriwilian, *ibid.*), respectively. Macrofossils are typically rare, but orthocone cephalopod conchs and



Fig. 43. The palaeokarst cave exposed in the eastern quarry wall at Kakeled. Stippled white line shows the related discontinuity surface near the top of the Kakeled Limestone Bed (DS). Photo: O. Lehnert.

asaphid and nileid trilobites, mainly disarticulated, are relatively common. Zhang (1998a) outlined part of the conodont biostratigraphy and Tinn & Meidla (2001) discussed the succession of ostracodes in the Lanna and Holen limestones. Löfgren (2003, 2004) described conodont associations from the upper Lanna Limestone and the lower Holen Limestone. The 'orthoceratite limestone' is generally composed of wackestone

and packstone with fine-grained fragments of trilobites, echinoderms, brachiopods, ostracods and gastropods. Corrosional hardgrounds are common. These are typically weakly mineralised by phosphate or iron, and locally capped by millimetre-sized microstromatolites. The hardgrounds frequently cut through orthoceratite conchs and several generations of hardgrounds may be amalgamated where minor topography has existed in



Fig. 44. Breccia fill of the Cambrian palaeocave showing large, angular 'orsten' clasts in a mud- to wackestone matrix. Photo: O. Lehnert.



Fig. 45. The Hällekis quarry, view towards the southeast. The dominant, mainly reddish strata comprise the Lanna and Holen limestones, the latter of which is disconformably overlain by the grey Gullhögen Formation. The Gullhögen Formation is in turn overlain by the Ryd Formation (not in picture). Photo: A. Lindskog.

the sea-floor. Microstratigraphical relationships and local sedimentation patterns can be revealed also from internal sediments in chambers in the many preserved orthoceratite conchs.

In the lower part of the Holen Limestone, in beds transitional between the lower and middle Kundan (uppermost BIII_α to lowermost BIII_β), a conspicuous grey, c. 1.5 m thick band of relatively coarse packstone occurs (Figs. 46 and 47). This limestone forms a distinctive marker bed in the Darriwilian succession of Kinnekulle and is through local quarry tradition called the 'Täljsten' (Hadding 1958). Conodonts from the 'Täljsten' are indicative of the *Lenodus variabilis* and *Yangtzeplacognathus crassus* zones (Löfgren 2003, Mellgren & Eriksson 2010, Eriksson et al. 2012). The 'Täljsten' records notable changes in carbonate facies and faunal abundance, composition and diversity, likely due to a significant drop in sea-level (e.g. Dronov et al. 2001, Tinn & Meidla 2001, Mellgren & Eriksson 2010, Eriksson et al. 2012). *Sphaeronites* cystoids are highly concentrated in some beds (Paul & Bockelie 1983). The facies changes associated with the 'Täljsten' can be traced throughout large parts of the Baltoscandian palaeobasin.

The 'Täljsten' and its enclosing strata are significantly enriched in extraterrestrial chromite grains (Schmitz et



Fig. 46. The conspicuous grey band that is visible throughout the quarry has traditionally been referred to as the 'Täljsten'. In comparison to the general lithology of the Lanna and Holen limestones, the 'Täljsten' consists of an unusually coarse-grained packstone. Photo: M. Calner.



Fig. 47. Thin-section of a bioclastic limestone from the lower part of the 'Täljsten' (Arkeologen) in the Hällekis quarry. To the naked eye, the 'orthoceratite limestone' often looks plain and poorly fossiliferous, but the density of skeletal grains in thin sections implies that benthic life flourished. Photo: O. Lehnert.

al. 2003, Schmitz & Häggström 2006, stop 11). The topmost metres of the Holen Limestone record the onset of the Middle Darriwilian Isotopic Carbon Excursion (MDICE, Schmitz et al. 2010).

A flatly eroded discontinuity surface at the top of the Holen Limestone marks a considerable hiatus in the Darriwilian succession at Kinnekulle (Jaanusson 1964, Holmer 1983). This hiatus spans the topmost Kunda through the Aseri Baltoscandian Stage, and only a small part of the succeeding Lasnamägi Baltoscandian Stage (Skärlöv Limestone) is preserved (Zhang 1998a). On top of the Holen Limestone follows disconformably a c. 7 m thick succession of grey to red calcareous mudstones and very fine-grained, well bedded to nodular limestones of the Gullhögen Formation (Figs. 48 and 49).

The Gullhögen Formation can be considered as a wedge of the upper part of the Middle Ordovician Elnes Formation in southern Norway (Hansen 2009), and has yielded a diverse trilobite fauna, including species of *Ogygiocaris*, *Pseudomegalaspis*, *Nileus* and *Botrioides* (e.g. Jaanusson 1964, Owen 1987). The Gullhögen Formation is exposed in the upper level at the southern

end of the quarry and is overlain by c. 3 m of thick-bedded limestones belonging to the latest Darriwilian Ryd Formation (Fig. 49). This unit is generally poor in macrofossils other than *Nileus* (Jaanusson 1964). Both the Gullhögen and the Ryd formations belong to the Uhaku Baltoscandian Stage (uppermost Darriwilian, Jaanusson 1964, Zhang 1998b).

Stop 11. Thorsberg (Österplana) quarry

Anders Lindskog, Per Ahlberg, Mikael Calner & Oliver Lehnert

Overview: Small active quarry 500–800 m north of Österplana Church on the south-eastern slope of Kinnekulle (N58°34'42.37", E13°25'43.27") exposing a large part of the Holen Limestone, including the 'Täljsten'. The locality is famous for its record of numerous fossil meteorites in the quarried beds. Cut rock surfaces display fine details and the microfacies of the 'orthoceratite limestone'.

Description: In the active Thorsberg quarry, only part of the Middle Ordovician (Darriwilian) 'orthoceratite limestone' is exposed (Fig. 50). The grey 'Täljsten' is found at the ground level, and the c. 6 m



Fig. 48. Uppermost Holen, Gullhögen and Ryd formations in the south-eastern wall of the Hällekis quarry. Holen Limestone corresponds to the slightly reddish coloured rocks in the lowermost portion of the section. The transition to the Gullhögen Formation is marked by a discontinuity surface. The thicker, more weathering resistant and protruding beds in the uppermost part of the section belong to the Ryd Formation. Photo: M. Calner.



Fig. 49. Close-up of very fine-grained limestone interbedded with calcareous shale of the Gullhögen Formation. Photo: M. Calner.

thick succession ranges up into the middle part of the Holen Limestone (*Eoplacognathus pseudoplanus* conodont Zone, Schmitz & Häggström 2006). Beds immediately below the 'Täljsten' have also been quarried in some parts of the location. A few intervals, for instance the 'Täljsten', are relatively fossiliferous. Orthoceratites, cystoids and asaphid trilobites are the most abundant macrofossils. Less common groups include gastropods, brachiopods, and raphiophorid trilobites.

In essence, the succession at Thorsberg quarry may be regarded as a high-fidelity cutout from that at the Hällekis quarry; the freshly cut, flat rock surfaces reveal many details which are not visible in the weathered and fouled rough surfaces at Hällekis, and ongoing quarry activity continuously exposes new surfaces and features (see Eriksson et al. 2012, fig. 4). The latter include trace fossils and diagenetic patterns, for instance greenish reduction features within the Holen Limestone (Fig. 51). Individual beds and specific lithologic and sedimentologic features are typically traceable between the two localities. The *Sphaeronites*-rich beds of the 'Täljsten' are especially conspicuous at the Thorsberg quarry. Two species occur: *Sphaeronites pomum* and *S. minor* (Paul & Bockelie 1983).

The Thorsberg quarry has gained much attention through the findings of nearly a hundred fossil meteorites (Fig. 52, see Nyström et al. 1988, Schmitz et al. 1996, 1997, 2001, 2003, Heck et al. 2010, B. Schmitz pers. comm. 2013). Thus, the quarry is one of the most meteorite dense areas known in the world. Together with enhanced concentrations of sediment-dispersed extra-terrestrial chromite grains, the fossil meteorites indicate a significantly enhanced influx of ordinary chondritic matter following the disruption of the L-chondrite parent body in the asteroid belt around 470 Ma (Schmitz et al. 1997, Schmitz et al. 2003, Schmitz & Häggström 2006). Petrographic details together with geochemical analyses of relict chromite grains indicate that all or most of the fossil meteorites are L-chondrites (Schmitz et al. 2001, Bridges et al. 2007, Greenwood et al. 2007). New meteorite specimens are continuously uncovered as the strata are quarried and handled.

Stop 12. Skultorp quarry

Per Ahlberg, Mikael Calner & Oliver Lehnert

Overview: Abandoned quarry exposing Upper Ordovician (Katian–Hirnantian) mud- and limestones about 900 m north-west of Norra Kyrketorp Church on the

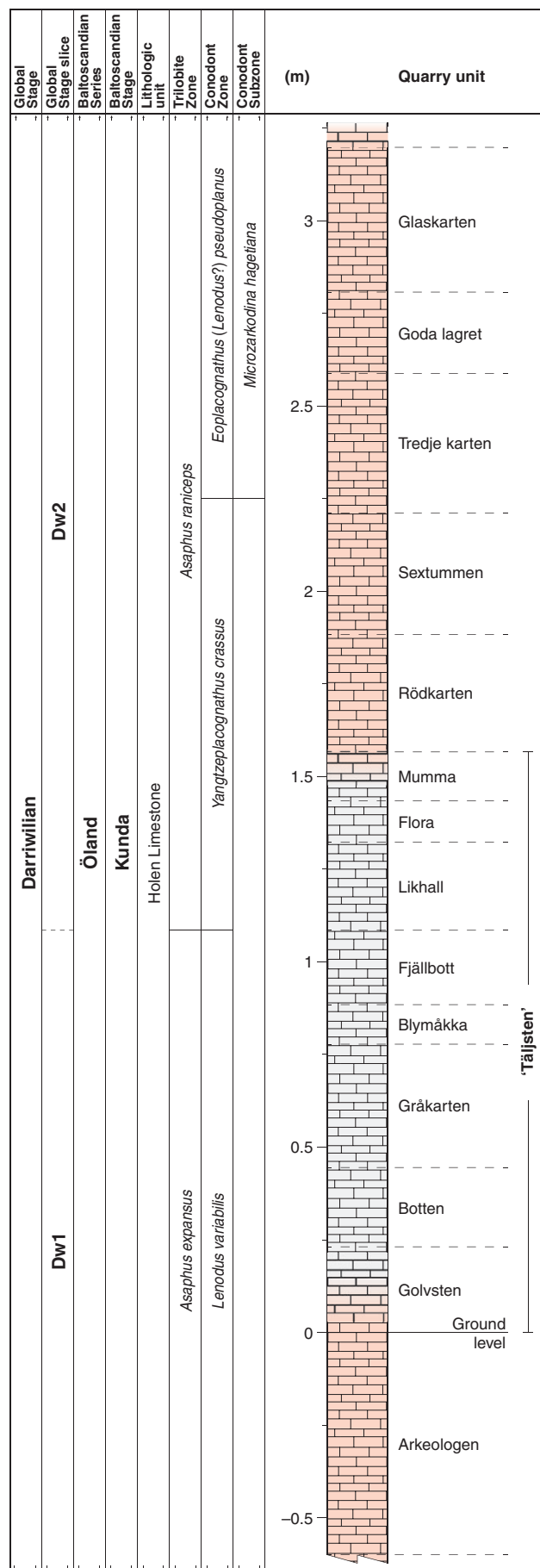
eastern slope of Mount Billingen (N58°20'54.42", E13°49'01.94"). The succession includes the late Katian Ulunda Formation, the Hirnantian Loka Formation, and the basal Silurian Kallholn Formation (Fig. 53).

Description: In the Billingen–Falbygden and Kinnekulle areas there are several well-exposed Ordovician–Silurian boundary sections. One of the best outcrops across this interval is the abandoned quarry at Skultorp. The lower part of the exposed succession consists of dark grey siliciclastic mudstones with a few limestone and siltstone interbeds. This part is referred to as the Ulunda Formation (Jaanusson 1963), which has its type locality near Ulunda on the western slope of Billingen. This formation is of late Katian age and is poor in macrofossils. However, a diverse trilobite fauna, comprising at least 20 species, has been recorded from a siltstone bed 2.7–3.0 m below the top of the formation (Bergström 1973). It is a typical *Tretaspis* fauna dominated by trinucleid, raphiophorid, encrinurid and cheirurid trilobites (Fig. 54). The Ulunda Formation is overlain by the Hirnantian Loka Formation (Bergström & Bergström 1996, Bergström et al. 2011). This is an up to 1.5 m thick, light grey limestone unit with ooids in the upper part (Stridsberg 1980). The lower contact of the Loka Formation is sharp and represents a regional discontinuity surface (HA unconformity of Bergström et al. 2006a). In the Mount Kinnekulle area, there is a conglomerate associated with the contact (Wærn 1948) and on Mount Ålleberg the boundary is a distinct discontinuity surface (Bergström 1968). This break in sedimentation was discussed by Stridsberg (1980).

The prominent discontinuity surface forming the top of the Loka Formation probably represents a stratigraphical gap corresponding to the HB Lowstand of Bergström et al. (2006a, 2011) and Schmitz et al. (2007). This surface has recently been documented also in the Siljan area and is known from several palaeocontinents (Bergström et al. 2012). Several metres of the early Llandovery Kallholn Shale rest on top of this discontinuity surface.

At the type locality on the nearby Mount Ålleberg, the Loka Formation is divided into three subunits (Stridsberg 1980). The lower and the upper members of the Loka Formation are composed of mudstones and they are poorly developed or missing in the Skultorp quarry. The middle member is a limestone unit which, at least partly, consists of an oolitic, cross-bedded grain-

Fig. 50. Simplified log of the lower half of the succession at the Thorsberg quarry, with traditional quarry units indicated (after Zhang 1998a, Heck et al. 2004, Bergström et al. 2009, Mellgren & Eriksson 2010). Additional minor quarry units have also been named (see Lindström et al. 2008, fig. 6).



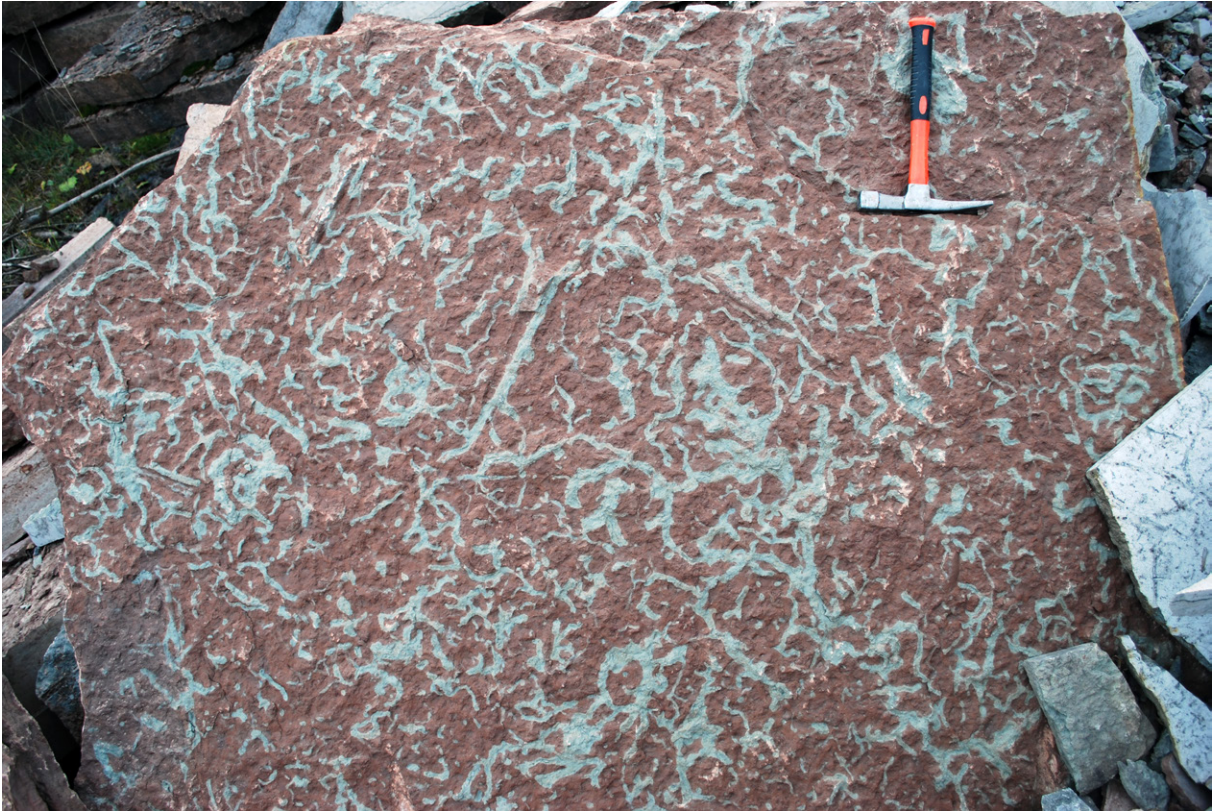


Fig. 51. Red 'orthoceratite limestone' slab from the Hølen Limestone in the Thorsberg quarry showing numerous greenish–greyish, presumably diagenetic, reduction features. These patterns are often related to bioturbation. Photo: M. Calner.

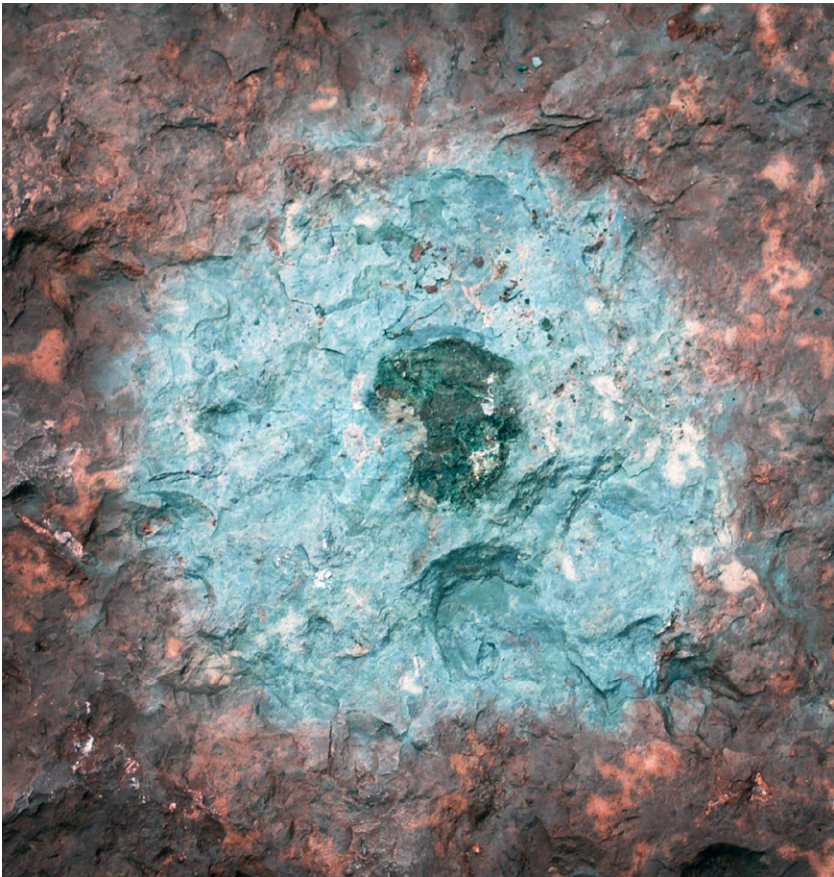


Fig. 52. Fossil meteorite embedded in the Hølen Limestone found by quarry workers in the Thorsberg quarry in 2010. The meteorite is c. 3 cm across and surrounded by a reduction halo. Photo: M. Calner.



Fig. 53. The western wall of the Skultorp quarry exposing the Ulunda Formation (main part of the section). The boundary to the overlying Loka Formation is close to the thin but distinct light bed where the trees begin. The softer shales of the Kallholn Formations form the slope above the section. Photo: M. Calner.

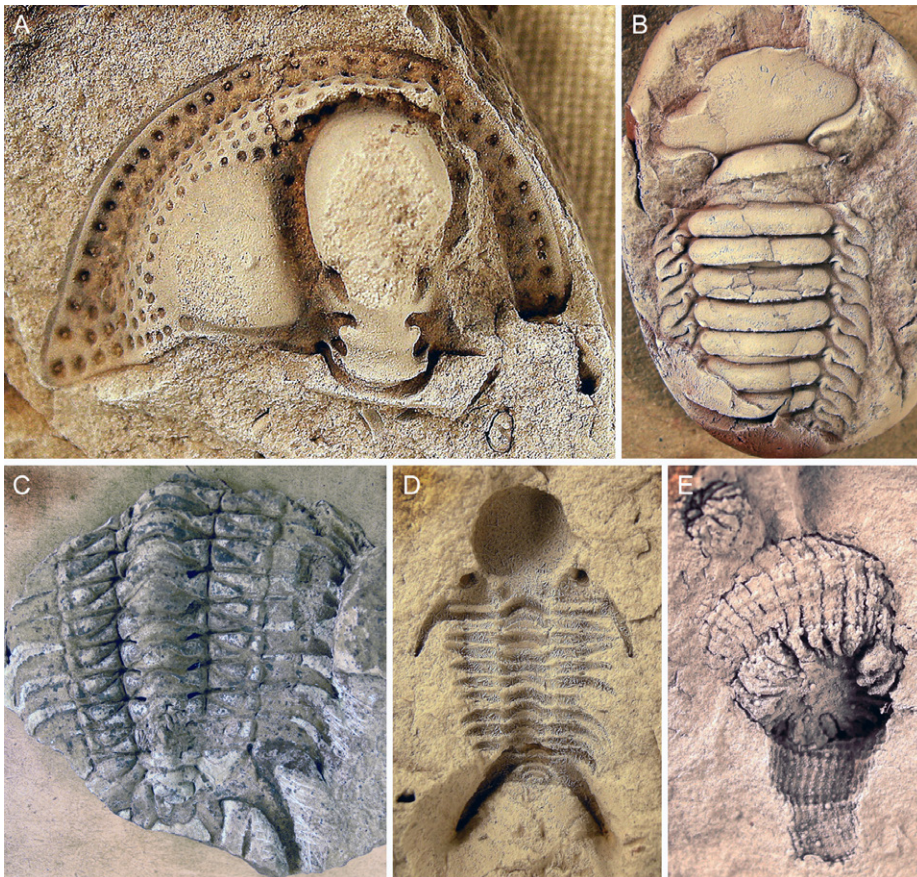


Fig. 54. Upper Ordovician fossils from Skultorp quarry (A–D from the Ulunda Formation, E from the Loka Formation). A. *Tretaspis latilimba*, $\times 5.2$. B. *Remopleurides* sp., $\times 2.6$. C. *Hadromeros subulatus*, $\times 1.1$. D. *Sphaerocoryphe dentata*, $\times 3.1$. E. Solitary coral, $\times 3.2$. Photo: P. Ahlberg.

stone that contains relatively abundant corals (Stridsberg 1980). This represents the first tropical carbonate elements in the Lower Palaeozoic of Baltoscandia and is evidence for deposition in warm and shallow waters, possibly during an interglacial between the two major Hirnantian glaciations (e.g. Bergström et al. 2006a, Schmitz et al. 2007). Based on its distinctive lithology and wide geographical distribution, Bergström et al. (2011) proposed the designation Skultorp Member for this calcareous middle member of the Loka Formation. It consists of a micritic limestone rich in peloids in its lower part and is characterised by ooids in its upper part (Stridsberg 1980, Bergström et al. 2011). Bergström et al. (2011, 2012) provided an intercontinental correlation of the Loka Formation.

Stop 13. Tomten quarry, Torbjörntorp

Oliver Lehnert, Per Ahlberg & Mikael Calner

Overview: Abandoned limestone quarry north of Falköping, about 2.5 km east of Gudhem and 1.3 km north of Torbjörntorp (N58°13'25.10", E13°36'28.77"). The exposed succession includes the uppermost Guzhangian and Furongian part of the Alum Shale Formation, a thin bed of the upper Tremadocian Björkåsholmen Formation and the Middle Ordovician Holen Formation (Figs. 55 and 56), all separated by conspicuous karst surfaces. These disconformities reflect long periods of subaerial exposure and non-deposition in the area and are associated with substantial hiatuses.

Description: The lower part of the succession belongs to the Alum Shale Formation (Fig. 57) and it is rich in stinkstone concretions. Its trilobite faunas have been studied by Westergård (1922, pp. 70–71). This part of the succession is partly covered but extends from the



Fig. 55. The western wall of the Tomten quarry displaying the Furongian Alum Shale Formation unconformably overlain by the late Tremadocian Björkåsholmen Formation (not visible) and the Middle Ordovician Holen Formation. Note abundant limestone concretions ('orsten') in the alum shale. Photo: M. Calner.



Fig. 56. Close up of the western wall in the Tomten quarry. Photo: O. Lehnert.



Fig. 57. The higher parts of the Alum Shale Formation in the Tomten quarry. Note the distinct bedding-plane fissility. Photo: M. Calner.

Series	Zonation		
	Agnostoids	Polymerids	
Furongian	Trilobagnostus holmi	Acerocare ecorne	
		Westergardia scanica	
		Peltura costata	
		Peltura transiens	
		Peltura paradoxa	
		Peltura lobata	
	Pseudagnostus cyclopyge	Ctenopyge linnarssoni	Ctenopyge linnarssoni
			Ctenopyge bisulcata
		Lotagnostus americanus	Ctenopyge affinis
			Ctenopyge tumida
			Ctenopyge spectabilis
		Pseudagnostus cyclopyge	Ctenopyge similis
			Ctenopyge flagellifera
Ctenopyge postcurrens			
Leptoplastus neglectus			
		Leptoplastus stenotus	

Fig. 58. Chart showing the upper Furongian biostratigraphy of Scandinavia and the zones missing above the discontinuity surface (stippled red line) on top of the *Ctenopyge linnarssoni* Zone (grey) in the Tomten quarry.

uppermost Guzhangian (*Agnostus pisiformis* Zone) into the *Ctenopyge linnarssoni* Zone. Therefore, the upper six polymerid trilobite zones in the Furongian are missing (Fig. 58). Westergård visited the quarry in 1918 and sketched the distribution of ‘Orsten lenses’ within the 9 m thick Alum Shale succession exposed in the quarry at the beginning of last century (Westergård 1922, Fig. 35).

The sedimentology in the Furongian *Peltura scabraeoides*-bearing interval was recently the subject of a master thesis (Newby 2012) which demonstrated that the Alum Shale succession includes not monotonous and undisturbed shales but shows a wide range of different facies. The Alum Shale Formation is truncated by a distinct irregular disconformity (Fig. 59). This surface, which can be studied just south of the small, unpaved entrance ramp at the western wall, is eye-catching and resembles ‘Schrattenkalk’ in vertical section (Figs. 59 and 60). However, when combined with cuts parallel to the bedding plane, a karren system of cockling features (‘Napfkarren’) can be reconstructed. The palaeokarst surface is overlain by a thin bed of glauconitic limestone that represents the Bjørkåsholmen Formation in this area. The hiatus between the top of the Alum Shale Formation (*Ctenopyge linnarssoni* Zone) and the late Tremadocian Bjørkåsholmen For-

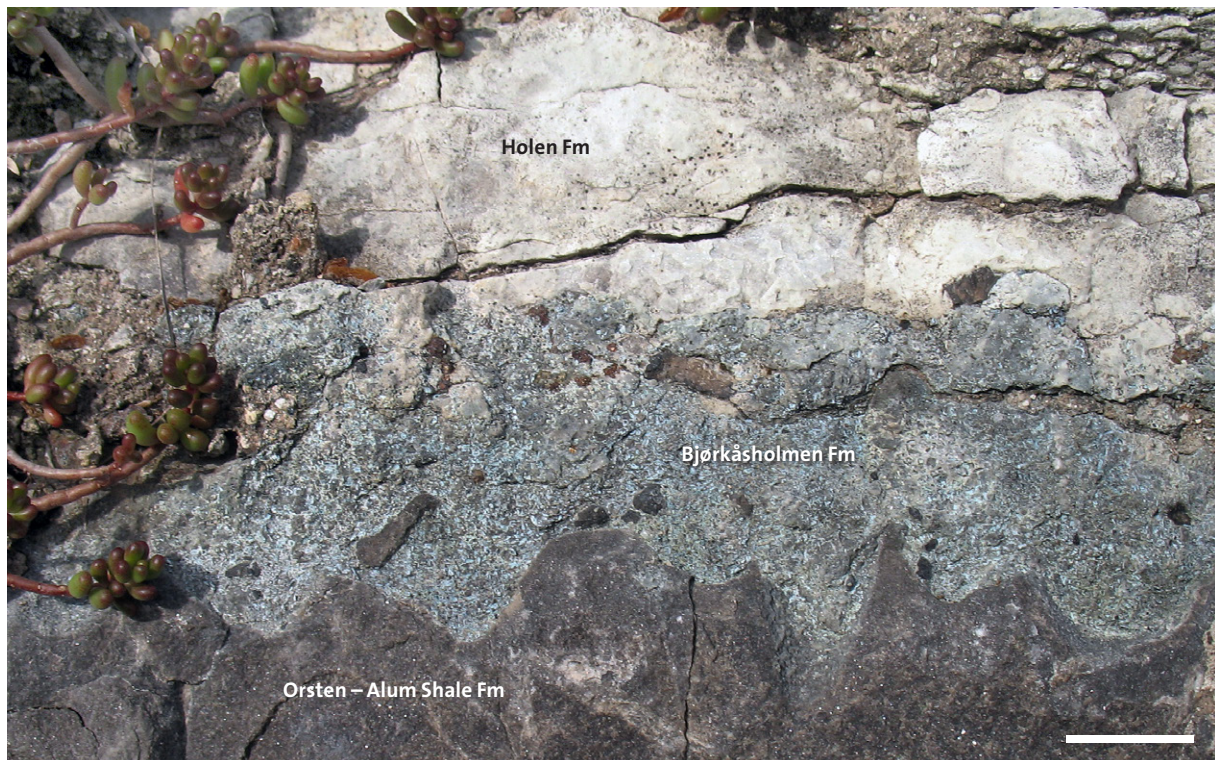


Fig. 59. Distinct irregular disconformity on top of the Alum Shale Formation, showing a typical ‘Schrattenkalk’ palaeokarst surface, overlain by an about two centimetres thick relic of the late Tremadocian Bjørkåsholmen Formation, which in turn is covered by the Darrivilian Holen Limestone. Scale bar equals 1 cm. Photo: O. Lehnert.



Fig. 60. Thin-section of part of the critical interval shown in Fig. 59 (scale bar equals 1 cm), sampled from the Tomten core, which was drilled in 2005 and is stored at the Department of Geology, Lund University. Photo: O. Lehnert.

mation (*P. deltifer* Conodont Zone) includes the upper six polymerid trilobite zones of the Furongian and most parts of the Tremadocian (Fig. 61). The top of the Björkåsholmen Formation represents a second disconformity. Preliminary biostratigraphic data, including the occurrence of advanced species of *Microzarkodina*, suggest that the overlying 8 m of grey limestone is coeval with the Holen Limestone.

Stop 14. Diabasbrottet

Per Ahlberg, Mikael Calner, Oliver Lehnert & Jörg Maletz

Overview: Abandoned dolerite quarry near the north-eastern end of Mount Hunneberg (N58°21'32.2", E12°30'08.6") with a long and well exposed succession of Lower Ordovician graptolitic shales and siliciclastic mudstones with several thin interbeds of dark, fossiliferous limestone. The ratified Global Stratotype Section and Point (GSSP) for the upper stage (the Floian Stage, Bergström et al. 2004) of the Lower Ordovician Series

Global Div.	Regional Division	Conodont zones	Tomten Quarry Västergötland, Sweden		
Series	Series	Stages	Stages		
Middle Ordovician	Darrwillian	Uhaku	<i>Pygodus anserinus</i>	not exposed	
		Lasnamägi	<i>Pygodus serra</i>		
		Aseri	<i>Eoplacognathus suecicus</i>		
	Dap.	Ontika	Kunda	<i>E. pseudoplanus</i>	Holen Lst.
			Volkhov	<i>Yangtzepl. crassus</i> <i>Lenodus variabilis</i> <i>Baltionodus norlandicus</i> <i>Parioistodus originalis</i> <i>Baltionodus navis</i> <i>Baltionodus triangularis</i> <i>Oepikodus evae</i>	Hiatus (palaeokarst)
			Billingen	<i>Prioniodus elegans</i>	
Hunneberg	<i>Parioistodus proteus</i>				
Early Ordovician	Floian	Varangu	<i>Paltodus deltifer</i>	Björkåsholmen Fm.	
		Pakerort	<i>Cordylodus angulatus</i> <i>C. lindstroemi</i>	Hiatus (palaeokarst)	

Fig. 61. Stratigraphic chart showing in dark grey the hiatus beneath the Björkåsholmen Formation (extending down into the upper Furongian, Fig. 58) and the substantial gap between the discontinuity surface on top of the Björkåsholmen Formation (stippled red line) and the Holen Limestone.

is at the top surface of a laterally persistent limestone (the E Bed) in the lower Tøyen Shale (Fig. 62).

Description: Hunneberg is one of the famous table mountains in Västergötland, capped by a thick sheet of Permian dolerite. The Cambrian to Lower Ordovician succession beneath the dolerite cover is highly condensed, essentially flat-lying and tectonically undisturbed. This sedimentary succession crops out at numerous localities along the slopes of Mount Hunneberg, particularly in old and abandoned quarries (e.g. Westergård 1922, Tjernvik 1956, Maletz et al. 1996). The best localities are in the north-eastern corner of Mount Hunneberg, between the Diabasbrottet quarry in the north and the village of Floklev in the south.

A long and continuous Lower Ordovician exposure is located along a quarry wall that extends for more than 1 km from Diabasbrottet to south of Mossebo (e.g. Tjernvik 1956, Tjernvik & Johansson 1980, Maletz et al. 1996). The GSSP for the upper stage of the Lower Ordovician Series (Floian Stage) is at Diabasbrottet (Bergström et al. 2004, 2006b). The Floian Stage was ratified by the IUGS in 2002 and is named after the village of Flo located 5 km south-east of the GSSP in Diabasbrottet quarry.

Furongian strata are exposed at Floklev and Mossebo. The succession consists of black siliciclastic mudstones (Alum Shale) with nodules and beds of dark grey, frequently fossiliferous limestone. Trilobites recovered from near the top of the Furongian at Mossebo, about

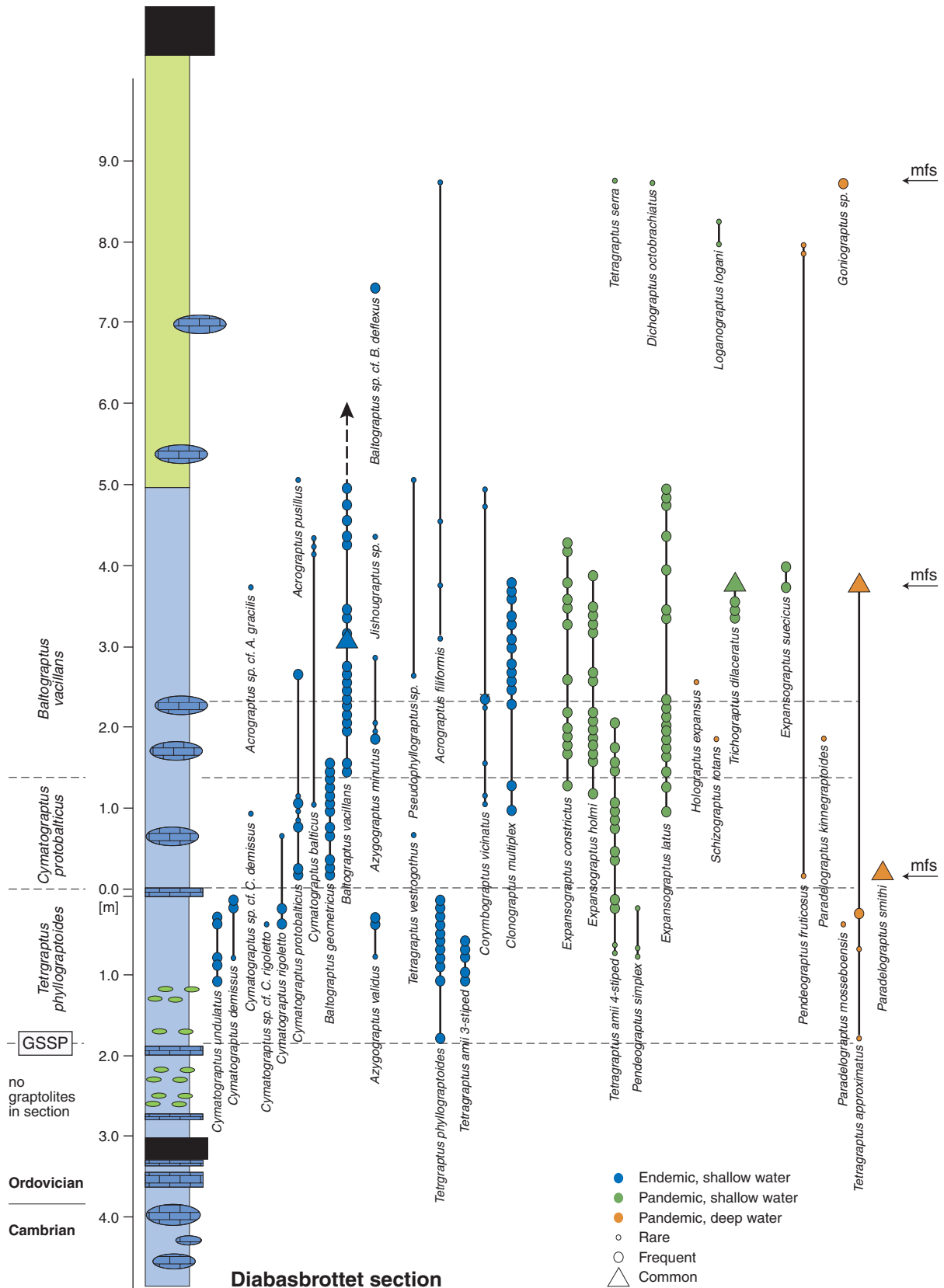


Fig. 62. Lithologic succession and graptolite zonation in the Diabasbrottet section (modified from Egenhoff & Maletz 2007, fig. 3). The GSSP for the Floian Stage is located within the lower Tøyen Shale and well exposed in the quarry wall. mfs = maximum flooding surface.

1 km south-east of Diabasbrottet, are indicative of the *Ctenopyge tumida* Zone. Thus, latest Furongian strata are not represented (Tjernvik 1956) and, according to the recent zonation of the Furongian in Baltoscandia by Terfelt et al. (2008), nine polymerid trilobite zones are missing beneath the contact with the Ordovician. The hiatus records subaerial exposure by the presence of mudcracks (Egenhoff & Maletz 2012). At some sections around Mount Hunneberg, but not at 'Diabasbrottet', the Furongian shales and limestones are overlain by a less than 1 m thick, black and very hard shale that forms the top of the Alum Shale Formation. It has yielded basal Ordovician (early Tremadocian) graptolites such as *Rhabdinopora flabelliformis* and *Adelograptus tenellus* (Maletz et al. 1996).

The lithologically variable succession overlying the Cambrian–Ordovician unconformity consists of a thin (less than 1 m) unit of mostly dark limestone, which can be subdivided into the Bjørkåsholmen Formation (*Ceratopyge* Limestone) and the Latorp Limestone. These units are of late Tremadocian age. The Latorp Limestone is overlain by the Tøyen Shale Formation. This formation is more than 10 m thick and composed of dark grey, siliciclastic mudstones with graptolites intercalated by several thin layers of dark, fossiliferous carbonate storm beds (Lindholm 1991a, b, Maletz et al. 1996, Egenhoff & Maletz 2012). Throughout

deposition of the Tøyen Shale Formation, there was an increase in the amount of siliclastic mudstone, probably due to an overall deepening of the environment (Egenhoff & Maletz 2012). The Permian dolerite cover on top of the Tøyen Shale has a thickness of 60–70 m.

For the limestone units, a biostratigraphy based on trilobites (Tjernvik 1956, Tjernvik & Johansson 1980) and conodonts (Lindström 1971, Löfgren 1993) has been established. The graptolites from the overlying Tøyen Shale have been investigated in great detail by several authors (e.g. Tjernvik 1956, Lindholm 1991a, b, Maletz et al. 1996, Egenhoff & Maletz 2007).

The GSSP with its 'golden spike' is well-exposed in the quarry wall just adjacent to the southernmost underground mine in the Alum Shale Formation (Bergström et al. 2004). The GSSP is located 2.1 m above the top of the Alum Shale Formation and within the lower Tøyen Shale Formation (Fig. 62), just at the top of the laterally persistent limestone 'bed E' (Bergström et al. 2004). The GSSP is defined by the first appearance of *Tetragraptus approximatus*, a distinctive graptolite with a pandemic distribution. The richly fossiliferous stage boundary interval was deposited under offshore conditions. A highly diverse graptolite fauna and biostratigraphically significant conodont and trilobite species are present (Lindholm 1991a, b, Löfgren 1993, Maletz et al. 1996, Bergström et al. 2004, Egenhoff & Maletz 2012).

Oslo Region, Norway

Hans Arne Nakrem & Jan Audun Rasmussen

INTRODUCTION TO THE GEOLOGY OF THE OSLO REGION

The Oslo Region (Oslofeltet) is a geological structure that varies in width from 40 to 70 km and extends approximately 115 km both north and south of Oslo. The region is fault controlled (the Oslo Graben) and covers an area of roughly 10 000 km². It is bordered by Precambrian rocks to the east and west, and by the Caledonian nappes to the north (Fig. 63). The Oslo Region also extends out into the fiord to the south (the Skagerrak Graben). The Lower Palaeozoic succession is approximately 2 500 m thick (Fig. 64, Worsley et al. 1983, see also Nakrem 2009). The rocks were folded, faulted and thrust during the Caledonian orogeny, as well as rifted during the Late Palaeozoic rifting phase. Local and regional thermal metamorphism is evident due to the Late Palaeozoic magmatic activity.

The following review paragraphs are in general based on Nielsen & Schovsbo (2007) and Terfelt et al. (2008) for the Cambrian, Owen et al. (1990) for the Ordovician and Worsley (1982) and Worsley et al. (1983) for the Silurian part. Revisions and amendments are from Bruton et al. (2008, 2010). References are in general omitted in this part, but these key publications should be consulted for more detailed information.

CAMBRIAN

The oldest Cambrian deposits of the Oslo Region are preserved in the Mjøsa area some 100–130 km north of Oslo. The 'lower' Cambrian is either allochthonous, as in the Osen-Røa Nappe Complex, or autochthonous to parautochthonous overlying a Precambrian peneplain with a basal conglomerate always present. In older literature, several formations were included in the former

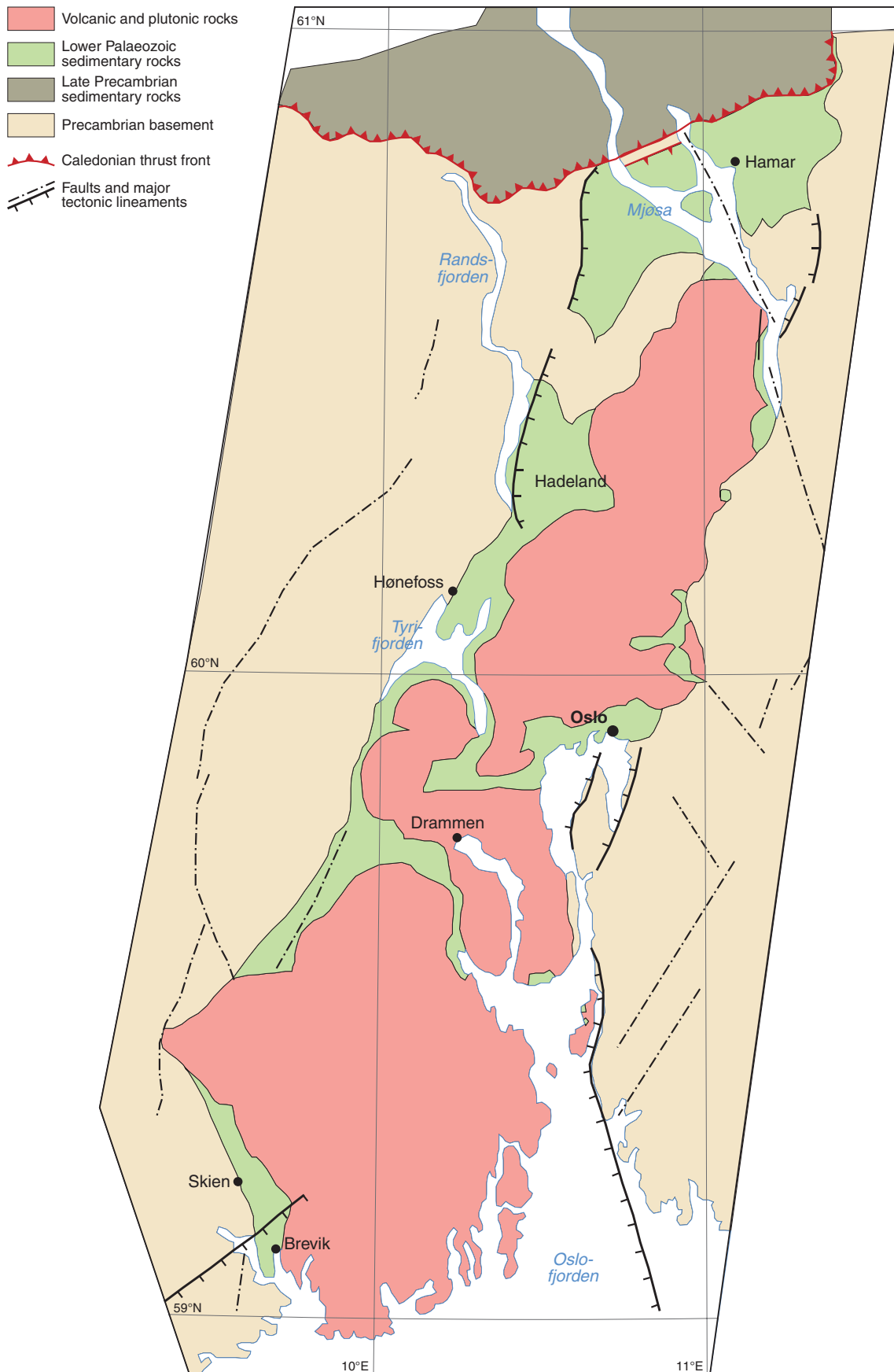


Fig. 63. Simplified geological map of the Oslo Region showing the distribution of Lower Palaeozoic sedimentary rocks, Permo-Carboniferous magmatic rocks, as well as relations to adjacent Precambrian and Caledonian terrains. From Worsley & Nakrem (2008).

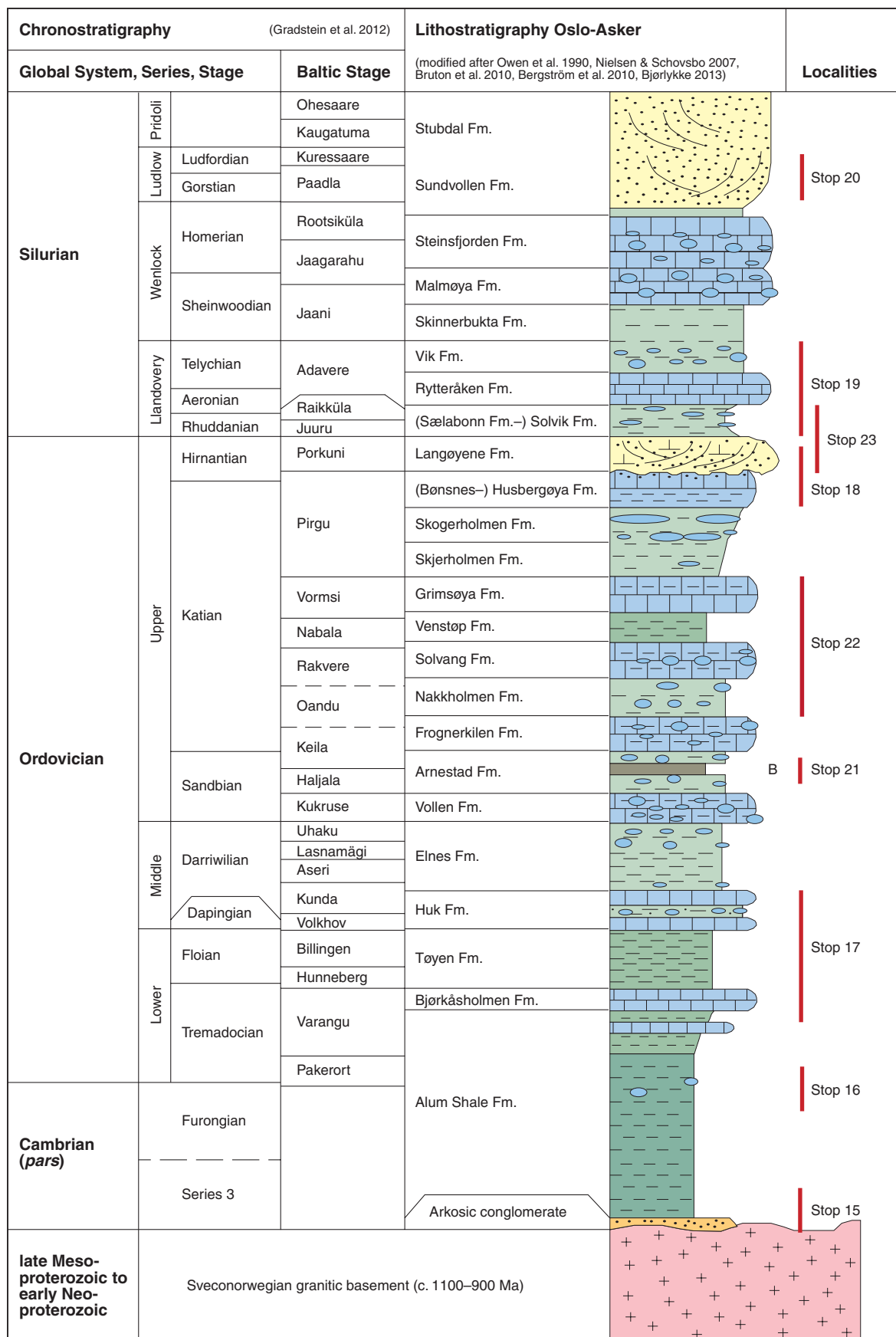


Fig. 64. Stratigraphy of the Lower Palaeozoic succession of the Oslo–Asker district, Oslo Region. B = bentonite.

Holmia Series between the Vangsås Formation and the 'middle' Cambrian portion of the Alum Shale Formation. These are now re-grouped into the five members of the Ringstrand Formation, estimated to be about 50–60 m thick in the Lower Allochthon (Nielsen & Schovsbo 2007).

The Cambrian succession exposed in the Oslo area consists of dark shales with intermittent dark, bituminous limestone beds and concretions (stinkstones) of the Alum Shale Formation, which constitutes the traditional 'middle' and 'upper' Cambrian and the overlying Tremadocian strata. Recently, however, it was suggested that an up to 1.5 m thick sandstone unit observed locally, for instance in the Røyken area just south of Slemmestad, is of late Epoch 2 age (late 'early' Cambrian), and thus correlates with a level within the Ringstrand Formation of the Mjøsa area (Nielsen & Schovsbo 2011). In the Oslo area, the alum shale succession may attain a thickness of nearly 100 m (Owen et al. 1990).

The proposed global agnostoid zonation can be applied in Norway although in the Oslo area the 'middle' Cambrian sections are fragmented by faults.

The Furongian alum shale facies is characterised by a low diversity fauna dominated by trilobites of the family Olenidae with subordinate agnostoids (Henningsmoen 1957, Bruton et al. 2010, Høyberget & Bruton 2012). The Furongian has been divided into four agnostoid and 28 polymerid trilobite zones (Terfelt et al. 2008), the latter based on easily recognisable species with short ranges. The Oslo area is represented by some of the thickest and stratigraphically most complete Furongian successions in Baltoscandia. The thickness approaches 45 m in the Oslo–Asker district, but tectonic dislocations make precise measurements difficult.

ORDOVICIAN

The Ordovician succession of the Oslo–Asker and the Ringerike districts comprises c. 400 m of fossiliferous, alternating limestone and shale units (Bockelie 1982, Figs. 65 and 66). Throughout the world, the Ordovician is transgressive on underlying rocks, but a conspicuous break occurs at the base all across Scandinavia except at Nærnes, near Oslo, for many years a strong contender as the type reference section for the Cambrian–Ordovician boundary (e.g. Bruton et al. 1982). Well documented dendroid graptolites, trilobites and conodonts occur in a continuous section of the upper part of the Alum Shale Formation (formerly *Dictyonema* Shale) with stinkstone concretions showing that deeper water prevailed here, while elsewhere the process of transgression may have been complex and iterative rather than gradual. The alum shale ends abruptly with the development of the Tremadocian Bjørkåsholmen Formation, a thin (0.6–1.3 m),

richly fossiliferous, micritic limestone with trilobites of the widespread *Euloma-Niobe* fauna (Ebbestad 1999).

A sequence of pale grey and black silty shales with a thickness of more than 20 m in the Oslo Region (Owen et al. 1990) constitutes the uppermost Tremadocian–Floian Tøyen Formation, which was deposited near the western edge of the Baltic platform. Both the Bjørkåsholmen Formation and the Tøyen Formation can be traced westwards into the allochthonous units of the Norwegian Caledonides (Bruton & Harper 1988, Bruton et al. 1989, Ebbestad 1999, Rasmussen 2001) and eastwards where they form part of the autochthon of the Baltoscandian platform. Generally, the limestone horizons in the shale succession contain trilobites, brachiopods and conodonts, whereas graptolites and acritarchs are generally common in the shales.

The shales of the Tøyen Formation are succeeded by a widespread tripartite limestone unit, the Huk Formation and its equivalents. This unit covers the Volkhov and Kunda stages of the Baltic terminology and spans the Arenig–Llanvirn boundary as well as the Dapingian–Darriwilian boundary. The biostratigraphy of the Huk Formation is based on trilobites, conodonts, chitinozoans and acritarchs, all indicating both transgressive and regressive events during deposition. Large endocerid nautiloids characterise the upper part of the unit.

Detailed correlation of the Tremadocian to mid-Darriwilian units with equivalents in Sweden has been possible, but for the overlying part of the Ordovician succession, correlation becomes less precise. This is due to a combination of syn-depositional faulting causing changes in the topography of the sedimentary basin and varying sedimentary regimes to the west (Bruton et al. 2010). Lateral and vertical facies changes are more marked with alternating mudstones and commonly nodular limestones. Siliciclastic strata are primarily associated with the Elnes Formation, in which small-scale current ripples and turbiditic beds have been observed (Maletz & Egenhoff 2004, Hansen 2009). To the north and south within the Oslo Region, limestones and rocks enriched in quartz sand dominate in the Mjøsa and Skien areas, respectively, which are thought to reflect more shallow conditions. In addition, the sediments are arranged in a series of facies belts from east to west representing different depositional palaeoenvironments (Størmer 1967, Bockelie 1978).

The facies distribution in the Oslo–Asker area is considered to reflect synsedimentary tectonic activity of north–south oriented basement blocks (Bockelie & Nystuen 1985) or may be related to early nappe movements, loading of the western margin and shedding of clastic material from local and exotic terranes (Bruton et al. 2010).

Beginning in the Darriwilian of the Oslo Region, a progressive but gradual increase in metallic elements, such as manganese, iron, nickel and chromium, in detrital minerals, notably chromite, and higher chlo-

rite to illite ratios in the sediments is observed. This may be related to the erosion of earlier or coeval island-arc sequences (Bjørlykke 1974a, b).

Absolute age (Ma)	System	Global Series	Global Stages	British Series	Series	Baltic Stages	Graptolites	Lithostratigraphy of the central Oslo region (stage for reference only)			
443.7	Ordovician	Upper	Hirnantian	Ashgill	Harju	Porkuni	<i>persculp.</i> <i>extraordi.</i>	Langøyene Fm (5b)			
445.6						Pirgu	(<i>anceps</i>)	Husbergøya Fm (5a)			
			Vormsi				<i>complanatus</i>	Skogerholmen Fm (4d)			
								Nabala	<i>linearis</i>	Skjerholmen Fm (4cγ) Grimløya Fm (4cβ)	
			Caradoc			Sandbian	Llanvirn	Viru	Rakvere	<i>clingani</i>	Venstøp Fm (4cα)
									Oandu	<i>foliaceus</i>	Solvang Fm (4bδ ₁₋₂) Nakkholmen Fm (4bγ)
									Keila		Frognerkilen Fm (4bβ)
		Darriwilian		Häljälä Jöhvi Idavere	Kukruse	<i>gracilis</i>			Arnestad Fm (4bα)		
460.9					Uhaku	<i>teretiusculus</i>			Vollen Fm (4aβ)		
									Lasnamagi	<i>distichus</i> <i>elegans</i>	Elnes Fm (4aα)
		Aseri									
		Dapingian	Kunda Aluoja Valaste Hunderum	Öland	Billingen	<i>fasciculatus</i>	<i>hirundo</i>	Svartodden Mbr (3cγ) Lysaker Mbr (3cβ) Huk Fm Hukodden Mbr (3cα)			
468.1						<i>lentus</i>					
						<i>elongatus</i> <i>densus</i> <i>balticus</i>					
471.8											
		Floian	Hunneberg	Öland	Billingen	<i>phylograptoides</i>	<i>copiosus</i> <i>murrayi</i>	Galgeberg Mbr (3bβ) Tøyen Fm Hagastrand Mbr (3bα)			
478.6	Lower	Tremadocian	Tremadoc	Varangu	<i>supremus</i>	<i>hunneberg.</i> <i>Rhabdinop.</i>	Bjørkåsholmen Fm (3aγ)				
							Alum Shale Fm (2e–3aβ)				
488.3					Pakerort						

Fig. 65. Ordovician lithostratigraphy and correlations, Oslo–Asker area. From Bruton et al. (2010).

Extensive volcanic ash beds have been known for many years from sections of the Arnestad Formation (zone of *Diplograptus multidens*, Caradoc) in and around Oslo. With respect to these outcrops, the Sinsen section yielded four beds or complexes of beds, identified as K-bentonites (Hagemann & Spjeldnæs 1955). The thickest bed at Sinsen (the Kinnekulle K-bentonite) occurs just above the middle part of the Arnestad Formation and has been directly correlated with the Millbrig K-bentonite in eastern North America.

The vent responsible for producing the type of explosive pyroclastic eruptions needed for such widespread bentonites was centred in the Iapetus Ocean,

somewhere between Laurentia and Baltica. A reconstruction of the palaeogeography and depositional environments shows the presence of a more than 200 m deep foreland basin, bordered to the south-east by the main Baltoscandian carbonate platform, and a land area to the west (Telemark Land). The Telemark Land not only formed a barrier to the Iapetus Ocean, but was also an important source area for siliciclastic material for the deposition of the Holberg Quartzite Formation of Hardangervidda west of the Oslo Region, the Huk Formation in the southernmost part of the Oslo Region, and the turbiditic siltstones of the Elnes Formation.

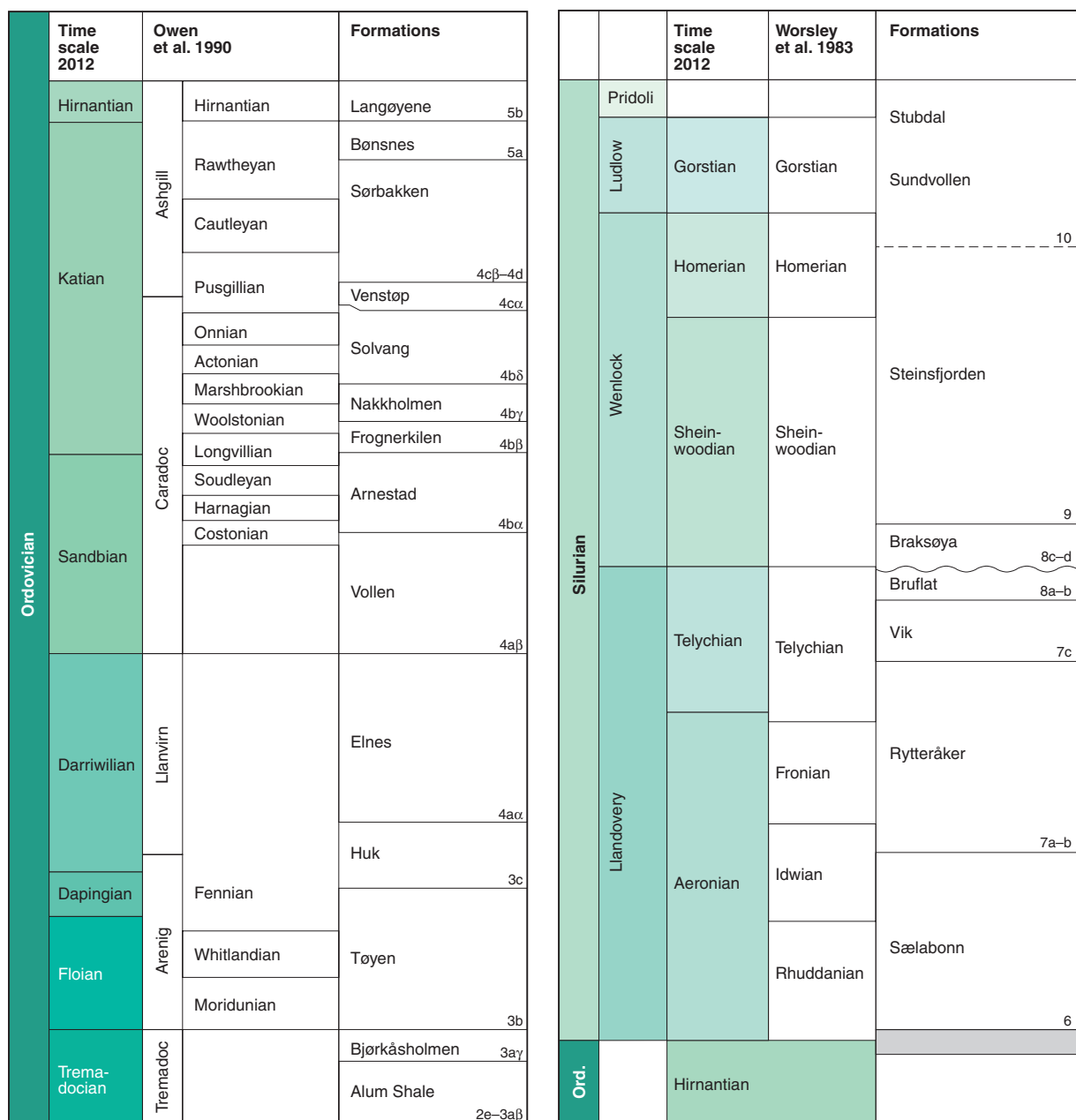


Fig. 66. Ordovician–Silurian lithostratigraphy and correlations, Ringerike area. Based on Owen et al. (1990) and Worsley et al. (1983).

Palaeoecological studies on conodonts from the Bjørneskalla Formation of Hardangervidda indicate that this formation probably was located on the north-western margin of the Telemark Land during the Darriwilian and was deposited under more shallow conditions than the contemporary Huk Formation of the Oslo–Asker district (Rasmussen et al. 2011). It is possible that the Telemark Land also influenced the terminal Ordovician major incursion of sand bars, with well-worked, millet-seed quartz grains, deposited during a marked phase of shallowing. These sediments are presumably glacioeustatic in origin and deposition was also related to syn-sedimentary faulting and resultant channelling with local block infill. Outside the Oslo–Asker area, the Hirnantian regression is recorded by sand infilling a karst surface in limestones containing corals and stromatoporoid bioherms in Ringerike, Hadeland and Skien–Langesund. To the north, the Mjøsa Limestone with constituent reefs has yielded a warm-water, Laurentian Midcontinent conodont fauna (Hamar 1966, Bergström et al. 2010).

SILURIAN

Silurian rocks form a roughly 1 950 m thick sedimentary succession consisting of marine shales and limestones (Llandovery–Wenlock), and a transition to non-marine and red-bed facies at or just below the Wenlock–Ludlow boundary (Fig. 67). Deposition of the marine rocks took place in a foreland basin with a palaeo-coastline to the west and a series of constantly shifting facies towards the east.

There is a notable hiatus between the Ordovician and the Silurian in the Mjøsa area (Owen et al. 1990) and in Ringerike (Worsley et al. 1983). Timing of the early Silurian transgression may be equivalent to either the *persculptus* or the *acuminatus* graptolite zones. The trilobite *Acernaspis*, considered to be indicative of the *acuminatus* Zone, occurs in the overlying *atavus* Zone in the middle of the Solvik Formation in the Oslo–Asker area, and immediately above the base of its shallower water equivalent Sælabonn Formation in Hadeland. The shelly fauna of the lower Sælabonn Formation in Hadeland comprises a mixture of environmentally very tolerant Ordovician survivor genera that continued to thrive during the Silurian together with pioneer taxa (*Acernaspis* and the brachiopod *Zygospirella*). These have no unequivocal Ordovician record but diversified rapidly and became common during the early Silurian (Rhuddanian) in many parts of the world (Heath & Owen 1991, Thomsen et al. 2007).

The overlying Rytteråker Formation is traceable over the whole region, and varies in thickness from 15 m in the north to over 80 m in the south (Möller 1989).

Interbedded limestones and shales pass rapidly into massive bioclastic limestones with brachiopod coquinas of complete and isolated valves of the genera *Borealis* and *Pentamerus* covered by small patch reefs, with stromatoporoids and halysitid corals as frame builders together with favositids, rugose corals and bryozoans. These build-ups are found down slope on the seaward side of the carbonate shoals which acted as protection from an easterly terrigenous land source. This dynamic model suggests a shelf lagoon to the east where terrigenous sediments were buried under the foreshore deposits of a retreating barrier belt which, in turn, was covered with patch-reef and open shelf deposits. The remaining Llandovery units (the Vik, Ek, Bruflat and Porsgrunn formations) are composed of nodular limestones, sandstones and shales.

The units of the Vik Formation, in its type area of Ringerike, are characteristically red in colour, whereas those of the Ek (Hamar district) and Porsgrunn (Skien area) formations are dark grey to black and contain diagnostic graptolites. The 80 m thick succession of the Skinnerbukta Formation belongs entirely to the Wenlock, but both top and bottom are diachronous. The Bruflat Formation (Toten district) has a strong clastic component suggestive of a shallow-water and near-shore environment (Worsley et al. 2011). It contains a shelly fauna with brachiopod and coral elements indicating a Llandovery or Wenlock age. Both the Vik and the Ek formations contain numerous, thin bentonite beds. Thirteen of these beds from the middle member of the Vik Formation in Ringerike have been geochemically analysed and the results indicate two volcanic sources to the south or south-west of Oslo. Comparison with similar bentonites from the island of Gotland, Sweden, allows a tentative correlation with beds belonging to the *Monograptus spiralis* Zone (Batchelor et al. 1995, Batchelor & Evans 2000).

Throughout the region, the boundary between the Llandovery and the Wenlock is marked by a depositional break before the establishment of open marine carbonate sedimentation environments. The carbonates are manifested in the Braksøya Formation, which formed in an outer belt from Ringerike via Holmstrand to Skien, and by the Malmøya Formation in the Oslo–Asker area, which formed in a shoaling in the central part of the basin.

In the type area of Ringerike, the Braksøya Formation is a biohermal unit composed of stromatoporoid patch reefs and beds indicative of short periods of very shallow water as reflected by the occurrence of pseudomorphs from evaporite minerals. There is a transitional unit of interbedded shales and limestones separating the Skinnerbukta Formation from the overlying

System	Series and stages		Baltic regional stages	Central Oslo region (stage for reference only)	Standard graptolite zones	
Silurian	Pridoli		Ohesaare	Stubdal Fm	<i>transgrediens</i> <i>-perneri</i>	
			Kaugatoma		<i>bouceki</i> <i>lochkovensis</i>	
			Kuressaare		<i>pridoliensis</i> <i>-ultimus s.l.</i>	
			Paadla		<i>formosus/balticus</i>	
	Ludlow	Ludfordian	Sundvollen Fm	<i>koslowskii-auriculatus</i>		
		Gorstian		<i>bohemicus/aversus</i> <i>leintwardinensis</i>		
	Wenlock	Homerian	Rootsiküla	10	<i>scanicus/chimaera</i> <i>nilssoni/colonus</i>	
			Jaagarahu	Steinsfjorden Fm	<i>ludensis</i> <i>nassa</i> <i>lundgreni</i>	
			Malmøya Fm	9	<i>ellesae</i> <i>linnarssoni</i>	
			Jaani	8c-d	<i>rigidus</i>	
		Sheinwoodian	Raiküla	Skinnerbukta Fm	8a-b	<i>riccartonensis</i> <i>murchisoni</i> <i>centrifugus</i>
				Vik Fm	7c	<i>crenulata</i> <i>griestoniensis</i> <i>crispus</i>
				Rytteråker Fm	7a-b	<i>turriculatus</i> <i>maximus</i> <i>sedgwickii</i>
				Solvik Fm	6a-c	<i>convolutus</i> <i>argenteus</i> <i>magnus</i> <i>triangulatus</i> <i>cyphus</i> <i>acinaces</i> <i>atavus</i> <i>acuminatus</i>
	Llandovery	Aeronian	Juuru			
		Rhuddanian				

Fig. 67. Silurian lithostratigraphy and correlations in the Oslo-Åsker area. From Bruton et al. (2010).

Malmøya Formation, which in its type area and to the west in Bærum, consists of bioclastic limestones and stromatoporoid biostromes. In Bærum, the top of the unit shows evidence of restricted marine environments of the succeeding Steinsfjorden Formation. This formation includes seven lithofacies types deposited in supratidal, intertidal and subtidal environments. The base of the Steinsfjorden Formation has yielded a variety of marine invertebrates including eurypterids (Tetlie 2002, 2006). The well defined cyclicality in the upper

part of the formation is attributed to either prograding events of the overlying, diachronous Old Red Sandstone deposits of the latest Silurian Ringerike Group or basal subsidence caused by local folding. The Steinsfjorden Formation, with its interbedded, red-coloured, dolomitic shales, marks the beginning of the end of marine deposition in the area. The Ringerike Group comprises the Sundvollen and Stubdal formations north of Oslo, where the group attains its maximum thickness of approximately 1 000 m, and the progres-

sively thinner Årøya and Holmestrand formations to the south (Davies et al. 2005).

The age of the Ringerike Group is still open to debate, but there is enough evidence to suggest that the base of the Sundvollen Formation is no older than latest Wenlock and no younger than early Ludlow in age. The exceptional Rudstangen Fauna from the base of the Sundvollen Formation contains well preserved eurypterids, arthropods and fish, presumably of Ludlow age, whereas the abundant articulated specimens of *Hemicyclaspis kiaeri* from the Holmestrand Formation at Jeløya, near Moss, provide a conclusive Pridoli age. Thus, a north–south oriented diachronism between the sediments at Ringerike and Holmestrand fits well with the model of the Ringerike Group being a siliciclastic sequence that prograded southwards over the underlying Steinsfjorden Formation. The sedimentary rocks of each of the formations were deposited in a complex of coastal or fluvial palaeoenvironments in which a north–south variation can be explained by tectonic activity controlling a rapid shift in sediment transport directions in a foreland basin. The basin was divided into two subbasins by the Caledonide thrust front, partially separating a northern piggyback basin from the basinal area south of Oslo. The topographic barrier between the two basins forced the Ringerike Group fluvial systems to divert down a palaeoslope from a southward (Stubdal Formation) to an eastward (Årøya Formation) direction as they drained from a Caledonide source.

Palaeoenvironmental indicators from both invertebrates and vertebrates include the eurypterid tracks in the basal Sundvollen Formation, which are presumably the earliest examples of invasion of the land in a muddy coastal plain setting.

EXCURSION STOPS

In total, nine localities will be visited (Fig. 68). During the first day we will make three stops in the Oslo–Asker district near Slemmestad and three stops in Ringerike. The next day we will visit three localities, one at Vollen and two in the Oslo Fjord. They are all situated in the Oslo–Asker district.

Stop 15. Cambrian–Ordovician boundary, Nærsnes beach section

David L. Bruton, Hans Arne Nakrem & Jan Audun Rasmussen

Overview: Alum Shale with stinkstone concretions and the Cambrian–Ordovician boundary interval (N59°45'43.6" E10°30'03.3"). The site is protected. Note: If the water level in the Oslo Fjord is high, some parts of the section will be inaccessible.

Description: This locality was a paratype section used in connection with the unsuccessful attempt to define the Cambrian–Ordovician boundary in the Oslo area (Bruton et al. 1982). Here, a succession of alum shales with limestone concretions occurs to the north and south of a metre-thick Permian maenaite sill (Fig. 69). Bruton et al. (1988) outlined the biostratigraphy and described graptolites, trilobites and conodonts from the locality (Fig. 70). A section south of the sill shows concretions containing the trilobites *Acerocare ecorne* and *Parabolina acanthura* on the beach, just below the high water mark, succeeded by a horizon with large concretions containing the Ordovician trilobite *Boeckaspis hirsuta*. *Rhabdinopora flabelliforme parabola* occurs in the shales at three levels: at 2.0 m and 2.1 m above the *Acerocare* layer and at 10 cm below the sill. The first occurrence of the conodonts *Cordylodus lindstroemi* and *Iapetognathus preaengensis* coincides with that of *Boeckaspis hirsuta* and marks the base of the Ordovician. This section and others nearby are unique within the Acado-Baltic faunal province, because they provide abundant trilobites together with graptolites and conodonts in an apparently continuous and monofacial sedimentary succession across the Cambrian–Ordovician boundary interval.

Stop 16. Sub-Cambrian peneplain, road cut at Slemmestad Torg

David L. Bruton, Hans Arne Nakrem & Jan Audun Rasmussen

Overview: ‘Middle’ Cambrian Alum Shale overlying weathered Precambrian, metamorphic basement (N59°46'52.1" E10°29'55.7"). The upper part of the section constitutes a Permian maenaite sill intrusion. The site is protected.

Description: The exposure is a road cut at the centre square of Slemmestad (Fig. 71). Sediments of the Cambrian Series 3 rest unconformably upon weathered Proterozoic granite and belong to the *Ptychagnostus* (*Triplagnostus* of some authors) *gibbus* Zone. The succession consists of a basal arkose followed by a thin interval with shale and a 20–40 cm thick limestone bed, which is fragmental in the lower part (Høyberget & Bruton 2008, Bruton et al. 2008). The limestone possibly corresponds to the Forsemölla Limestone Bed in Skåne, Sweden (Nielsen & Schovsbo 2007). The fragments have yielded numerous broken shields of *Paradoxides paradoxissimus*, solenopleurids, *Ptychagnostus gibbus*, hyoliths, brachiopods and a rare helcionellid. *P. gibbus* occurs in great abundance above the fragmental layer. The thin arkosic layer is separated from the limestone by up to ten centimetres of shale. Indeterminable trilobite fragments occur in the arkose from which Spjeldnæs

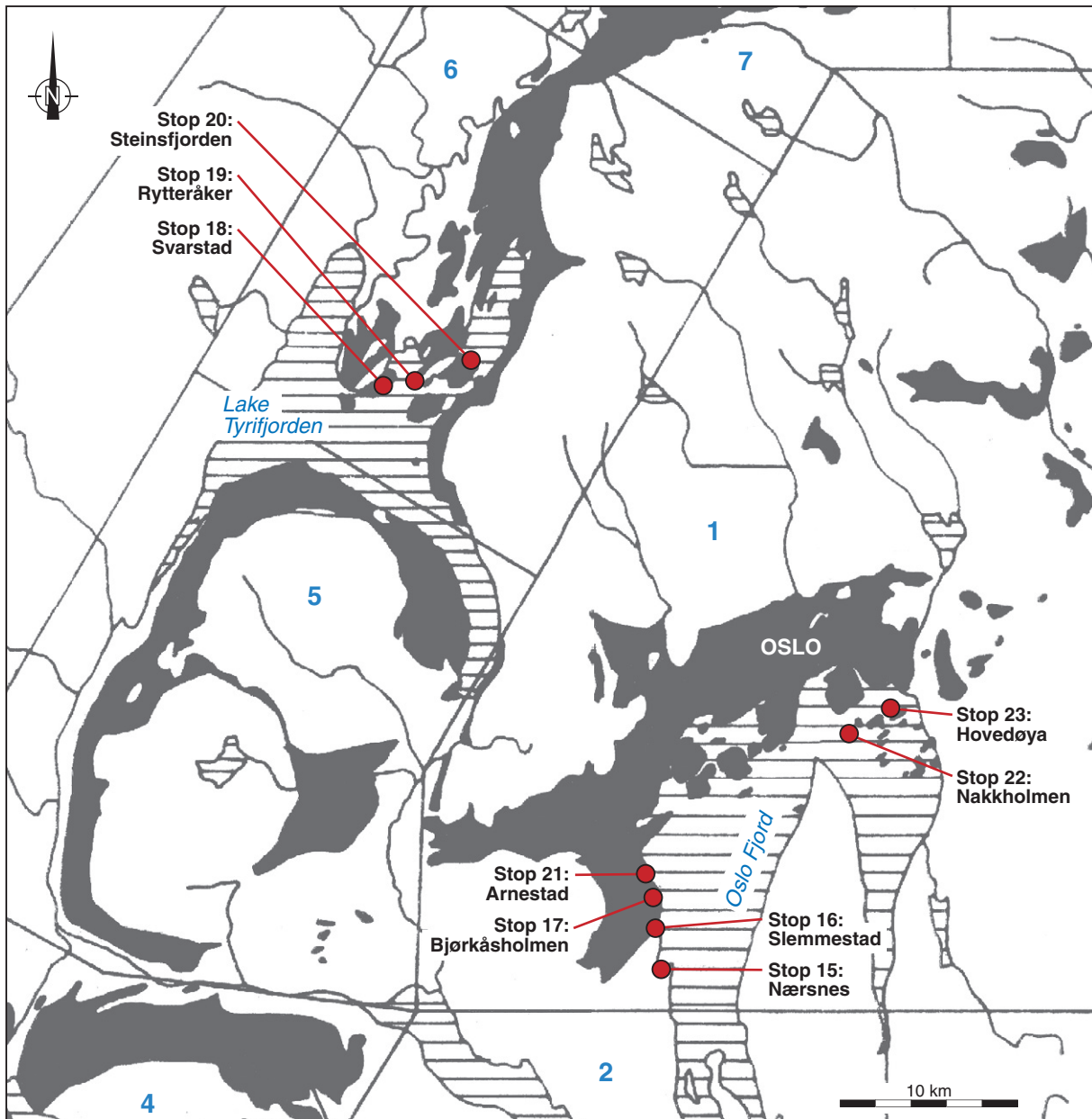


Fig 68. Locality map of the Oslo Region. Black areas show Lower Palaeozoic outcrop areas. The numbers 1–7 show the different geological 'districts' of the Oslo Region as defined by Størmer (1953). District 1: Oslo–Asker, District 6: Ringerike. Horizontal lines represent sea or lakes. Modified from Henningsmoen (1960).

(1955) reported a pygidium of *P. paradoxissimus*. Above the arkose is an up to 1.5 m thick shale sequence containing scattered limestone lenses which was metamorphosed by an overlying 3 m thick Permian maenaite sill. The *Ptychagnostus atavus* Zone has not been identified, indicating a poorly developed or missing part of the 'Middle' Cambrian at Slemmestad. However, the metamorphosed limestone lenses contain trilobites indicative of the upper part of the *P. atavus* Zone (formerly the *Hypagnostus parvifrons* Zone). At Nærnes south of Slemmestad, Høyberget & Bruton (2008) made the

first recording of the *Agnostus pisiformis* Zone in the Slemmestad area.

Stop 17. Tremadocian to Darriwilian units, Bjørkåsholmen and Djuptrekkodden, Slemmestad

Jan Audun Rasmussen, David L. Bruton & Hans Arne Nakrem

Overview: The two neighbouring peninsulas Bjørkåsholmen (N59°47'31.0" E10°30'07.7") and Djuptrekkodden (N59°47'37.5" E10°30'06.9") exhibit an instruc-



Fig. 69. The Nærnes beach locality. The black Alum Shale Formation is intruded by a light coloured Permian, syenitic maenaite sill. Photo: H.A. Nakrem.

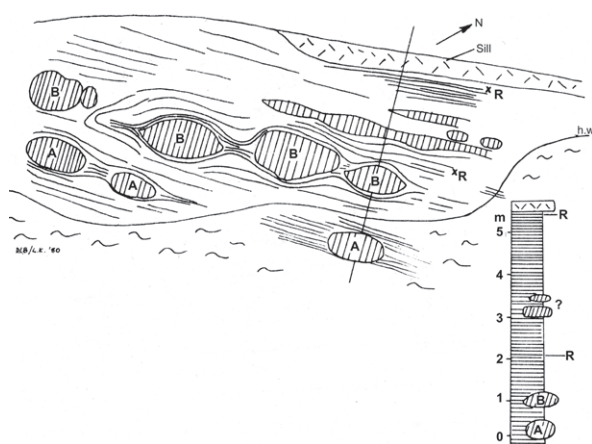


Fig. 70. Sketch of the Nærnes beach section south of the maenaite sill. From Bruton & Williams (1982).

tive Lower and Middle Ordovician succession including the upper Alum Shale, Bjørkåsholmen, Tøyen, Huk and basal Elnes formations. The description below is based mainly on Rasmussen (1991), Tongiorgi et al. (2003) and Bruton et al. (2008). The localities are protected.

Description: Both the Bjørkåsholmen and the Djup-trekkodden peninsulas display very scenic views displaying the upper Tremadocian through the Floian, Dapingian and lower Darriwilian succession of the Oslo–Asker district.

The Bjørkåsholmen Formation (Fig. 72) contains a varied shelly fauna of trilobites (see Ebbestad 1999) including *Ceratopyge forficula*, *Euloma ornatum*, *Symphysurus angustatus* and *Niobe insignis*. A thin interval with dark concretions at the base of the formation represents a marker horizon recognised across the entire region, containing the olenid trilobite *Bienvillia angelini* (Linnarsson, Bruton et al. 2008). The limestone is glauconitic (Egenhoff et al. 2010) and arrow-like pseudomorphs, presumably after gypsum, are present. Bjørkåsholmen is the stratotype for the Bjørkåsholmen Formation (Owen et al. 1990). The overlying Tøyen Shale yields only scattered fossils in this location. The green-grey-black transition between the Hagastrand Member and the overlying Galgeberg Member is obvious.

Tongiorgi et al. (2003) identified a microflora comprising 52 taxa of acritarchs from the Tøyen Formation (Tremadocian–Floian) in the Oslo Region. The preservation is generally poor but most taxa were identified to the species level. It was shown that samples from the Hunneberg Stage contain a mixed cold-water (elements of the *messauoudensis-trifidum* assemblage) and warm-water (*Aryballomorpha-Athabascaella-Lua* assemblage) microflora. Samples from the Billingen to lower Volkhov Stages contain species recorded from the Yangtze Platform (South China), which is considered to be part of the cold-water realm (or ‘Mediterranean Province’)

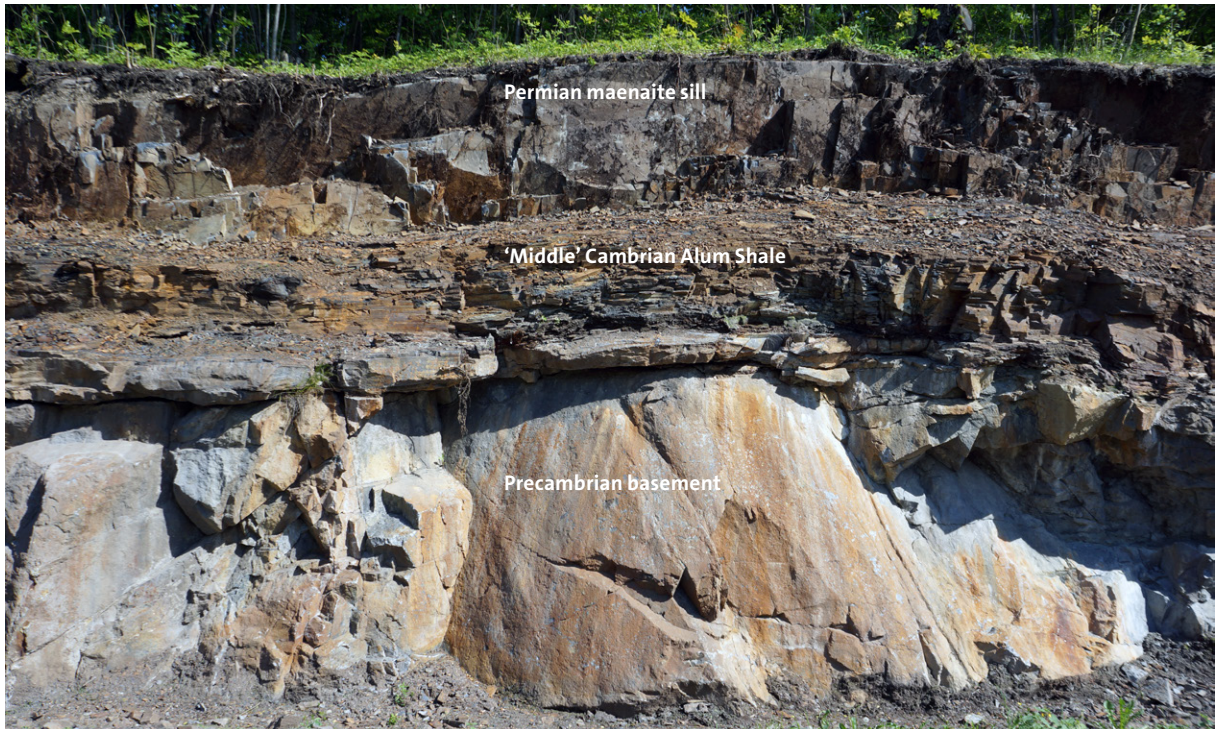


Fig. 71. Black 'Middle' Cambrian Alum Shale Formation resting directly on Precambrian basement and covered by an intrusive Permian sill of light maenaite at Slemmestad. Photo: H.A. Nakrem.



Fig. 72. Alum Shale Formation (left) succeeded by the light-coloured, partly glauconitic limestone of the Bjørkåsholmen Formation and brownish shales of the Tøyen Formation (right). Photo: M. Calner.

Djuptrakkodden section (after Rasmussen 1991)	Conodonts (Rasmussen revised from Rasmussen 1991)	Trilobites (Nielsen 1995)	Global stages (Cooper & Sadler 2012)
	No diagnostic conodonts		
	<i>L. crassus</i>	Not studied	
	<i>L. variabilis</i>	<i>A. expansus</i>	Darriwilian (<i>partim</i>)
	<i>B. norrlandicus</i>	<i>M. limbata</i>	
	<i>P. originalis</i>	<i>M. simon</i>	Dapingian
	<i>B. navis</i>	<i>M. polyphemus</i>	
	Not studied	Not studied	Floian (<i>partim</i>)

Fig. 73. Stratigraphy of the Huk Formation, Djuptrakkodden.

located at high southern latitudes around the margin of Gondwana (Tongiorgi et al. 2003). However, because the samples from the Oslo area lack the typical cold to cool temperate-water indicators from Perigondwana, such as *Arbusculidium*, *Aureotesta*, *Coryphidium*, *Striatorbecha* and *Vavrdovella*, the flora was regarded as compatible with a mid-latitude position of Baltica during the Floian–Darriwilian. Presumed ocean currents caused a climate warmer than in China at this time. In contrast, the late Dapingian to early Darriwilian (late Volkhov to early Kunda) Baltic microflora belongs neither to the cold-water Perigondwana realm nor to a less well-defined warm-water realm. Evolution in the composition of phytoplankton from a middle Floian ‘Mediterranean microflora’ to an early Darriwilian ‘Baltic microflora’ occurs on both palaeocontinents (South China and Baltica). This implies a reciprocal exchange

within a mid-latitude realm controlled more by the pattern of subtropical oceanic gyres rather than just latitudinal position. A similar evolution of acritarch assemblages is also noted across the East European Platform in Russia and Poland.

The tripartite division of the Dapingian to lower Darriwilian Huk Formation (Fig. 73) is best seen along the northern flank of the Djuptrakkodden Peninsula. The lowest of the three members, the Hukodden Member, is succeeded by the nodular and shaly Lysaker Member (Fig. 74), and the limestone of the Svartodden Member (Fig. 75). The formation is very fossiliferous and contains conodonts (Rasmussen 1991), trilobites (Nielsen 1995), brachiopods (e.g. Öpik 1939, Hansen et al. 2011), endoceratid cephalopods (may exceed 1 m in length) and ostracodes (Öpik 1939) among other groups. Because of postdepositional heating and oxi-

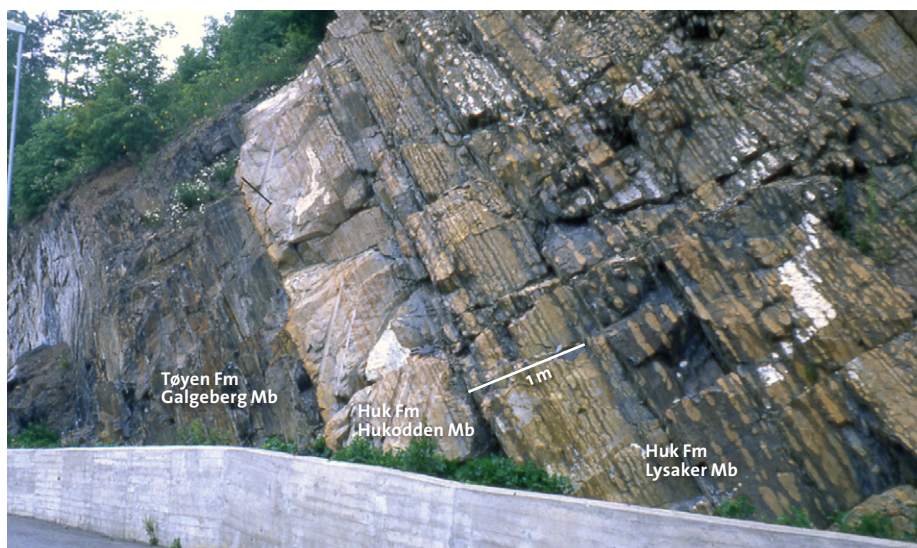


Fig. 74. Tøyen Formation succeeded by the Hukodden and Lysaker members of the Huk Formation. Roadcut near Djuptrekkodden. Photo: J.A. Rasmussen.



Fig. 75. The Lysaker and Svartodden members of the Huk Formation succeeded by the Helskjer Member of the Elnes Formation. Roadcut near Djuptrekkodden. Photo: J.A. Rasmussen.

dation, organic-walled fossils are in general very rare in the Huk Formation. The Hukodden Member is 1.6 m thick and consists of c. 24 irregular beds of mainly dark grey mud- and wackestone (Rasmussen 1991, Nielsen 1995). Several bedding planes are developed as discontinuity surfaces, commonly with pyrite impregnations. A prominent discontinuity surface separates beds 3 and 4 about 0.15 m above the base of the member. The discontinuity surface represents a conspicuous hiatus which, at least partly, covers the time from the middle *B. navis* Zone to the basal *P. originalis* Zone. The overlying 4.4 m thick Lysaker Member is composed of 57 nodular limestone layers surrounded by terrigenous mud and siltstone. The main constituent of the nodules is wackestone and mudstone, but a few layers are dominated by packstone. The trilobite *Asaphus expansus* occurs regularly in the upper part of the member.

The uppermost member, the Svartodden Member, is c. 2.6 m thick and generally consists of dark grey wackestone (Fig. 75) whereas packstone is rare. The unit comprises five limestone beds separated by thin muddy laminae (Rasmussen 1991). Haematite impregnated bands are common in the middle part of the member whereas phosphoritic horizons occur in the lower and middle parts. The unit is bioturbated and rich in large cephalopods and trilobites. A new study of the conodont succession from Djuptrekkodden reveals that the *Lenodus crassus* Zone characterises the upper 1 m or possibly 1.4 m of the Svartodden Member.

The Svartodden Member is succeeded by the Helskjer Member of the Elnes Formation (Fig. 75). In the roadcut section between Bjørkåsholmen and Djuptrekkodden, the Helskjer Member is c. 1.2 m thick and composed

of nine mudstone beds with a gradually higher content of terrigenous material towards the top.

In the Oslo–Asker area, the Elnes Formation comprises the Helskjer, Sjøstrand, Engervik and Håkavik members (Owen et al. 1990). The beach section north of Djuptrekkodden presents a nearly complete exposure from 26.75 m above the base of the Elnes Formation and up into the overlying Vollen Formation. The Elnes Formation is largely dominated by fossiliferous mudstone reaching a thickness of nearly 100 m in the central Oslo Region. Some of the best documented fossil groups are trilobites (e.g. Hansen 2009, Hansen et al. 2011), graptolites (e.g. Berry 1964, Maletz et al. 2007, 2011) and brachiopods (Candela & Hansen 2010). At Djuptrekkodden, the Elnes Formation comprises the upper 28 m of the Sjøstrand Member (Fig. 76), the 16 m thick Engervik Member and the 14 m thick Håkavik Member (Hansen 2009). According to Owen et al. (1990), the boundary between the Sjøstrand and Engervik members is taken at the first continuous limestone bed, whereas the boundary between the Engervik and Håkavik members is defined at the appearance of the first calcarenite bed. This horizon is identical with the

level where the trace fossil *Chondrites* disappears (it reappears in the overlying Vollen Formation).

Stop 18. Tyrifjorden, Ringerike, Svarstad

Hans Arne Nakrem, David L. Bruton & Jan Audun Rasmussen

Overview: Bønsnes Formation, Hirnantian. Late Ordovician transition from inner shelf mudstones to shoreline sandstones and to a carbonate platform with well-developed reef deposits (N60°03'47.6" E10°13'01.7"). Langøyene Formation with oil stained limestones.

Description: The Upper Ordovician at the Svarstad locality (Fig. 77) is fairly similar to the one at Ullertangen (Hanken & Owen 1982). The base of the c. 100 m thick Bønsnes Formation is at the first development of dark, platy limestones containing the alga *Palaeoporella* (Owen et al. 1990). These strata are overlain by lighter coloured limestones containing silicified corals. At Svarstad, higher levels in the Bønsnes Formation include rubbly limestones with interbedded calcareous shales which have yielded very diverse shelly faunas. The highest part of the formation comprises calcareous (more than 45 cm thick) shales with



Fig. 76. The lower part of the Elnes Formation exposed at the Djuptrekkodden locality. Photo: H.A. Nakrem.

scattered limestone nodules. In addition to algae and stromatoporoids, the Bønsnes Formation contains trilobites, brachiopods, cephalopods, gastropods and monoplacophorans, bryozoans, corals and ostracodes (Owen et al. 1990, and references therein). The trilobite fauna indicates a Rawtheyan age and includes species of *Stenopareia Remopleurides*, *Eobronteus*, *Stygina*, *Holotrachelus*, proetids, *Erratencrinurus* (*Celtencrinurus*), *Atractopyge* and *Amphilichas*.

The Langøyene Formation (Fig. 78) in the Ringerike area is marked by a gradational change from limestones and shales of the Bønsnes Formation to sandstones overlain by limestones with a basal conglomerate composed of locally derived material. The various limestone facies pass north-eastwards into sandstones. The base of the overlying Silurian Sælabonn Formation is an irregular karst surface at the top of the limestone succession. The diverse sedimentary environments from inner shelf to tidal channels present in the Langøyene Formation are also reflected in the faunas. These range from the moderately diverse brachiopod dominated *Hirnantia* Association in the basal part of the formation in the east to faunas rare in body fossils but containing a variety of

trace fossils including *Monocraterion*, *Planolites*, *Chondrites* and *Teichichnus*.

Pedersen et al. (2007) analysed oil stained carbonate rocks from the Langøyene Formation in the Ringerike district. The oils were presumably sourced from the 'upper' Cambrian to Lower Ordovician Alum Shale Formation, and their results show that they share several geochemical characteristics with oils from the Baltic states and northern Poland. The Langøyene Formation oil sample was shown to have a considerably higher degree of thermal maturity (late oil- or even gas-window maturity) than Lower Palaeozoic samples from central Sweden.

Small argillaceous mounds on Ullerntangen, north of Svarstad (Hanken & Owen 1982) are overlain by an extensive carbonate bank which is at least 350 m long and 100 m wide. This structure is interpreted as an extensive carbonate bank because it lacks a framework and has a very high percentage of transported faunal elements. The bank is very fossiliferous and dominated by the stromatoporoid *Pachystylostroma* sp., the colonial rugose corals *Palaeophyllum insertum*, *Cyathophylloides* sp. and *Tryplasma* sp., and the tabulate corals *Saffordophyllum kiaeri*, *Rhabdotetradium frutex*,



Fig. 77. The Bønsnes Formation exposed at the Svarstad locality. Photo: H.A. Nakrem.



Fig. 78. The organic-rich limestones of the Langøyene Formation exposed at the Svarstad locality. Photo: H.A. Nakrem.

Lyopora incerta, *Reuschia* sp., *Catenipora* sp., *Proheliolites* sp. and *Plasmopora* sp. (Owen et al. 1990, and references therein). Locally isolated patches of cystoids and inarticulate brachiopods are found in great numbers. The carbonate bank is overlain by sandy crinoidal biosparite facies. Fissures that are up to 5–6 m deep have steep sidewalls indicating subaerial erosion of the already lithified bank.

The carbonate bank passes northwards into a sandstone facies, which contains a rich fauna close to the bank (the faunal diversity diminishes northwards). The fauna is dominated by transported disarticulated brachiopods. The brachiopods commonly show signs of bioerosion. Other elements of the fauna include bryozoans, solitary rugose corals and gastropods.

Stop 19. Tyrifjorden, Ringerike, Rytteråker (Limovnstangen)

Hans Arne Nakrem, David L. Bruton & Jan Audun Rasmussen

Overview: Early Silurian siliciclastic shelf deposits passing upwards to a carbonate platform with shoal and bioherm facies. Red coloured shelf deposits, the

Vik Formation. Mixed coral and stromatoporoid build-ups overlying carbonate shoals (N60°03'52.2" E10°15'13.7").

Description: The limestone dominated sequence of the Rytteråker Formation is approximately 50 m thick in the type area (Worsley et al. 1983); Kiær's (1908) tripartite division (7a, 7b α , 7b β) was based both on faunal composition and on varying proportions of limestone and calcareous shale within the unit. The stratotype is defined on the northern tip of Limovnstangen. The top is seen under the basal stratotype of the overlying Vik Formation on the limb of a small syncline. Its axis defines the northern coast of Limovnstangen.

The Rytteråker Formation represents the establishment of relatively shallow carbonate depositional environments throughout the Oslo Region at a time when earlier source areas for coarse clastic material were submerged (Möller 1989). The pentamerid biosparites of Hadeland and Ringerike represent high-energy shoals, with crests which may have been intermittently emergent (e.g. in Hadeland). Biohermal development on the upper surfaces of the shoals in Ringerike was probably initiated subsequent to a relative rise in sea level which

resulted in stabilisation of the shoals' highly mobile substrates. Abundant pentamerids, corals and stromatoporoids together with benthic algae in all districts indicate that the formation was not deposited in water of any great depth.

Occurrences of the pentamerid genera *Borealis* and *Pentamerus* suggest a somewhat diachronous base for the Rytteråker Formation, ranging from middle to late Idwian (Aeronian) in Ringerike.

The transition to the Vik Formation is dated by graptolite and brachiopod faunas. The formation is Telychian in age and generally corresponds to stage 7c of Kiær (1908) in the Ringerike, Oslo, Holmestrand and Skien districts and to Kiær's 7bβ and 7c in Asker (Worsley et al. 1983). The Vik Formation is approximately 80 m thick in its type area and shows a tripartite development with varying proportions of red and greenish grey shales, marls and limestones. The base of the Vik Formation is defined at the sharp transition from a limestone to a shale dominated succession 4 m below the lowermost red shales. The red shales of the Storøysundet Member contain minor bioclastic limestone lenses, small calcareous nodules and local greenish-grey shale interbeds. A diverse but sparse fauna includes crinoids, brachiopods, stromatoporoids and tabulate corals. The middle 13 m of the Garntangen Member are exposed in a road-cut along the E16 near Garntangen at the coast of Steinsfjorden. The Garntangen Member is approximately 25 m thick and consists of thinly bedded limestones and calcareous nodules with minor greenish-grey marls. Fresh exposures in the road section near Garntangen display 19 bentonitic horizons that vary in thickness from a few millimetres to 12 cm. This part of the Vik Formation has a more rich and diverse fauna than the adjacent members. Both, corals and stromatoporoids are abundant, and brachiopods (especially *Pentamerus oblongus*, *Pentameroides* cf. *subrectus* and *Costistricklandia lirata*) are common in certain beds.

The upper Abborvika Member consists of greenish grey to red shales with interbedded, finely nodular limestones. A sparse fauna of crinoids, cephalopods and brachiopods is observed. The upper 3 m of the member consist of greenish grey shales, which are sharply overlain by siltstones of the Bruflat Formation.

Sediments and faunas of the Vik Formation suggest slightly deeper depositional environments than those of the underlying Rytteråker Formation, with greater (although still fine-grained) clastic influx. The presence of abundant corals and stromatoporoids (and associated benthic algae) suggests the development of shallow marl banks in the Garntangen Member. The age of the Vik Formation is constrained by the presence of the brachio-

pods *Pentamerus*, *Pentameroides* and *Costistricklandia* and on conodonts (*Pterospathodus amorphognathoides*).

Stop 19A. Limovnstangen (Rytteråker and Sælabonn formations)

Overview: Early Silurian siliciclastic shelf deposits passing upwards into a carbonate platform with shoal and bioherm facies (N60°03'37.2" E10°14'29.3").

Description: The western tip of this peninsula shows a section perpendicular to the axis of a gently plunging anticline. Exposures in the anticlinal core show the upper beds of the Sælabonn Formation, passing northwards and southwards into the Rytteråker Formation (Worsley et al. 1983). Thin to medium-thick siltstones with various sedimentary structures are seen in the upper part of the Sælabonn Formation (Fig. 79). Brachiopod faunas are most common in bioclastic lags of siltstone beds and are dominated by *Rostricellula* sp. and *Pholidostrophia* (*Eopholidostrophia*) *cocksii* (Thomsen et al. 2006). There is a gradational but clear junction to the overlying Rytteråker Formation, passing from interbedded siltstones and shales into limestone sand shales. The base of the Rytteråker Formation is defined at the start of the quantitative dominance of limestone over siltstone interbeds in the shale. The pentamerid brachiopod *Borealis borealis* is found immediately above the formational boundary (Fig. 80). The interbedded limestones and shales grade upwards into medium to thickly bedded bioclastic limestones with crinoid debris and fragmented shells of *Pentamerus oblongus*. Small bioherms are developed on the top surface of the bank. These contain stromatoporoids and halysitids as frame-builders, algal binders dominated by *Girvanella* and a rich interstitial fauna of brachiopods, gastropods, trilobites, bryozoans and cephalopods (Fig. 81). The entire Rytteråker Formation is approximately 50 m thick in its type area. The upper 17 m of the formation, directly overlying the bioherms, are found to the east and northeast of Limovnstangen (Worsley et al. 1982). Exposures show interbedded limestone beds and nodular horizons with shales. The shale content increases upwards to the gradational contact with the overlying Vik Formation.

Stop 19B. Vik Formation

Overview: Locality showing the Vik Formation (N60°03'46.0" E10°14'50.9").

Description: A marked colour change is seen at the transition of the interbedded limestones and greenish-grey shales of the Rytteråker Formation to the red shales of the basal Storøysundet Member of the Vik Formation (Fig. 82). The formational contact is taken at the change from limestone to shale dominance. Sections through this 20 m thick lower red shale unit of the Vik Forma-



Fig. 79. The siliciclastic upper part of the Sælabonn Formation exposed at the Rytteråker locality. Photo: H.A. Nakrem.



Fig. 80. Accumulations of brachiopod valves (*Borealis borealis*) in the lowermost part of the Rytteråker Formation at the Rytteråker locality. Photo: H.A. Nakrem.



Fig. 81. A small bioherm developed in the Rytteråker Formation. Photo: H.A. Nakrem.



Fig. 82. Red-coloured shales in the lowermost part of the Vik Formation at the Rytteråker locality. Photo: H.A. Nakrem.

tion display a relatively diverse fauna of brachiopods, crinoids, halysitid corals and stromatoporoids (Worsley et al. 1982).

Stop 20. West side of Steinsfjorden, Tyrifjorden

Hans Arne Nakrem, Jan Audun Rasmussen & David L. Bruton

Overview: The latest basin fill of the Lower Palaeozoic of the Oslo Region (N60°04'21.9" E10°18'09.4". Fig. 83). Late Silurian fluvial sandstone of the Sundvollen Formation (Ringerike Group).

Description: The Ringerike Group is a succession of upper Silurian terrigenous sedimentary rocks that crop out discontinuously throughout the Oslo Region of southern Norway. The base of the group lies conformably on top of the limestones and marls of the Wenlock Steinsfjorden Formation, and thus marks the cessation of marine carbonate deposition in the Silurian of the Oslo Region (Davies et al. 2005).

The Sundvollen Formation is the oldest unit of the Ringerike Group. The base of the formation is defined at the first appearance of red beds in the type section along the E16 road section between Kroksund and Vik in Ringerike (Fig. 84). Davies et al. (2005) retained the definition of the formational base further and defined it as the top of the last carbonate bed formed in situ in the Steinsfjorden Formation. In its type area, the Sundvollen Formation consists of red and locally drab-coloured

blocky siltstones and mudstones and very fine-grained drab-coloured sandstones (mature quartz arenites with c. 5% mica according to Davies et al. 2005). Within the lower Sundvollen Formation there are also some grey, medium-grained, cross-bedded calcarenite horizons. A wide variety of cross-stratifications and ripple forms are present throughout the formation, and desiccation cracks and intraformational mudflake conglomerates are common. In the upper part of the formation, many of the siltstones show palaeosol horizons, and sandstone units representing in-channel fill become more common. The only fossils known from the siliciclastic rocks of the Sundvollen Formation are from the lower part of the succession. The exceptional Rudstangen Fauna of arthropods and vertebrate fish has been described by Kiær (1911, 1924), but fragmentary bryozoans (*Monticulipora* sp.) and specimens of the green alga *Chaetocladus* are more common.

Field observation: Whitaker's (1977) 228 m level is a large bedding plane with bryozoans and stromatoporoids (Fig. 85). Along the north-facing edge of this bed, well developed ball-and-pillow structures may be seen. There is an abrupt change from greenish-grey beds of marine and lagoonal origin (top of Steinsfjorden Formation) to red siltstones and sandstones of continental origin (base of Ringerike Group), transported mainly by meandering rivers onto a subsiding alluvial floodplain. The only fossils in these red beds are trace fossils

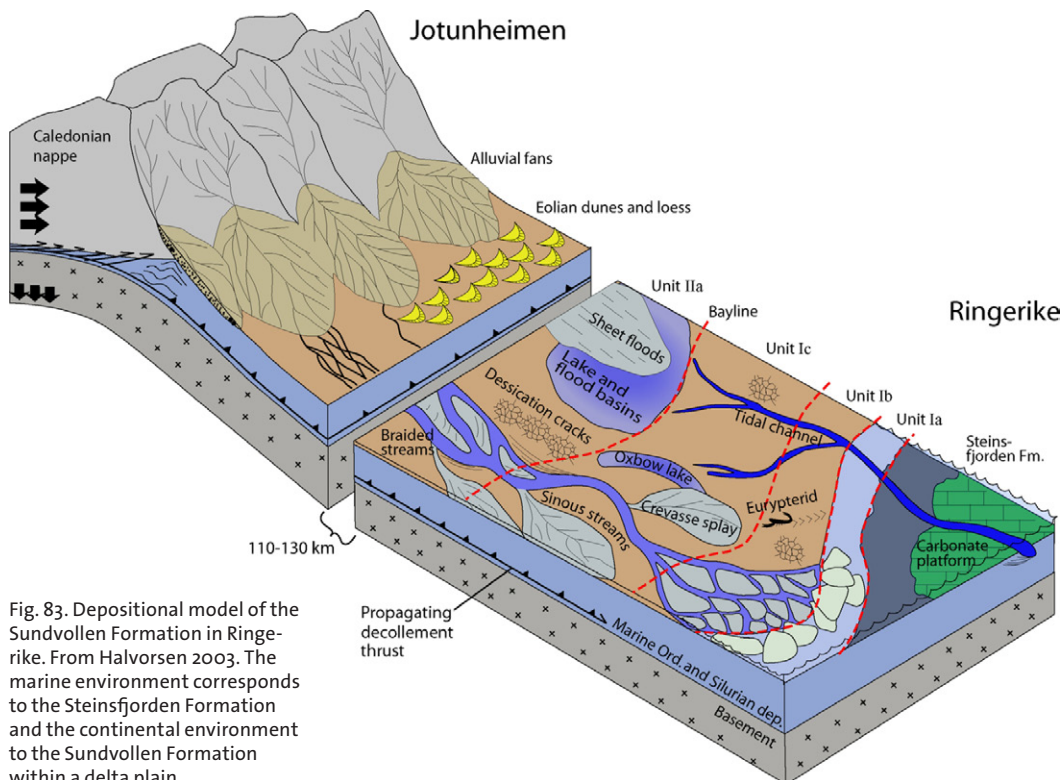


Fig. 83. Depositional model of the Sundvollen Formation in Ringerike. From Halvorsen 2003. The marine environment corresponds to the Steinsfjorden Formation and the continental environment to the Sundvollen Formation within a delta plain.



Fig. 84. Transitional beds from the marine Steinsfjorden Formation ('Etg. 9d') to the continental redbeds of the Sundvollen Formation ('Etg. 10'). Photo: H.A. Nakrem.



Fig. 85. Bedding plane with ripple marks, top of the Steinsfjorden Formation. Photo: H.A. Nakrem.

(burrows and eurypterid tracks). There are small ripple marks on the lowest large red bedding plane and 'Bentonite 3' of Hetherington et al. (2011) occurs just below this transition.

Stop 21. Upper Ordovician Arnestad Formation with Kinnekulle bentonite

Hans Arne Nakrem, Jan Audun Rasmussen & David L. Bruton

Overview: Middle Ordovician nodular limestone and shale (Arnestad Formation) interbedded by volcanic tuff or bentonite (N59°48'12.6" E10°29'12.6"). Vollen bentonite bed.

Description: The base of the Arnestad Formation is defined at the development of thick dark shales with subordinate limestone horizons (Owen et al. 1990). In Oslo, the shales are dark grey to light grey whereas in the west, in Asker and Ringerike, they are green-grey in colour and this becomes more pronounced with weathering. Bentonites are developed in the formation at various localities in the Oslo–Asker area. The thickness of the formation is difficult to estimate due to tectonism and poor exposure. It was estimated to a maximum of about 45 m by Brøgger (1882), although Kvingan (1986) assumed a thickness of about 22 m.

The Arnestad Formation contains a rich shelly fauna with both diversity and abundance generally increasing westwards from Oslo into Asker. References in Owen et al. (1990) include conodonts, cystoids, ostracods, over 30 trilobite species and more than 56 brachiopod species. The tremendous increase in diversity of shelly fossils seen in the Arnestad Formation compared to older units may reflect the 'Skagenian' immigration documented by Jaanusson (1976) elsewhere in Baltoscandia, but the precise level of this change has not yet been determined.

Widespread volcanic ash beds, perhaps representing volcanic eruptions lasting a couple of weeks or less, in sections of the upper Sandbian Arnestad Formation (*Diplograptus multidentis* Zone, Owen et al. 1990, Hansen 2007) in and around Oslo have been known for many years. Several bentonite layers occur at Vollen (Fig. 86) and the thickest probably represents the same bentonite as that reported at Sinsen (the Kinnekulle K-bentonite = BXX1 of Hagemann & Spjeldnæs 1955). This bentonite occurs slightly above the middle part of the Arnestad Formation and has been directly correlated with the Millbrig K-bentonite in eastern North America (Huff et al. 1992). However, a recently published study of trace elements in apatite phenocrysts



Fig. 86. A greenish, readily weathering bentonite bed (Kinnekulle K-bentonite), approximately 1 m thick, within the dark shales of the Arnestad Formation. Photo: H.A. Nakrem.

from the Kinnekulle and Millbrig K-bentonites indicates that the two K-bentonites should be regarded as representing two or more different eruptions (Sell & Samson 2011). Comparative maximum thicknesses between the southern Appalachians and southern Sweden suggest that the vent responsible for producing the type of explosive pyroclastic eruption needed for such widespread K-bentonites, was centred in the Iapetus Ocean somewhere between Laurentia and Baltica.

Stop 22. Beach sections on Nakkholmen (island in the Oslo Fiord)

Hans Arne Nakrem, David L. Bruton, J. Fredrik Bockelie & Jan Audun Rasmussen

Overview: Nakkholmen island has natural exposures of the Arnestad, Frognerkilen, Nakkholmen, Solvang, Venstøp, Grimsøya, Skjerholmen, Skogerholmen, Husbergøya and Langøyene formations (Upper Ordovician, N59°53'20.8" E10°41'40.0"). The Nakkholmen, Solvang, Venstøp and Grimsøya formations will be visited (loc. A in Fig. 87). The detailed descriptions of the units by Owen et al. (1990) served as the main source for the information given for this locality.

Description: The base of the Nakkholmen Formation is defined by the development of thick dark shales which typify the unit in the eastern part of the Oslo–Asker area where they are more than 1 m thick in some horizons (Owen et al. 1990). Black limestone nodules occur at various levels and pyrite nodules are present throughout the unit. In the western part of the Oslo–Asker area, the formation becomes calcareous with common nodular limestone horizons and a shale that is thinner

and paler in colour. The Nakkholmen Formation contains a shelly fauna of brachiopods and trilobites which increases in diversity westwards and indicates a Woolstonian–Actonian (early Katian) age (Harper et al. 1985). The brachiopod faunas share few elements with contemporaneous units elsewhere in the Oslo Region and differ markedly from west to east within the formation. In contrast, many of the trilobites are also known from the upper Furuberget Formation in Hadeland.

The Nakkholmen Formation, at its type locality on the island of Nakkholmen, consists of 13–14 m of dark shales with a few horizons of limestone nodules. The low-diversity but locally abundant fauna includes the brachiopods *Hisingerella nana*, *Onniella* cf. *bancrofti* and *Sericoidea gamma*, the trilobites *Broeggerolithus discors* and *Lonchodomas* aff. *rostratus*, and the graptolites *Amplexograptus rugosus*, *Climacograptus antiquus lineatus* and *Corynoides incurvus* (for references see Owen et al. 1990). The shelly and graptolite faunas suggest a correlation with the early Katian (Woolstonian–Actonian stages of the Caradoc Series) and the lower part of the *Dicranograptus clingani* Zone respectively. The assemblage represents a deep-water, euxinic biofacies offshore from the well-developed shelly associations in coeval strata in Asker, Ringerike and Hadeland. The brachiopod fauna is markedly different to coeval associations elsewhere in the region, but the trilobite faunas have many elements in common. Conodonts, ostracods, gastropods, bivalves and scolecodonts are also known from the formation.

The Solvang Formation is a limestone unit containing a varying degree of interbedded calcareous shales that contrast markedly with the shale-dominated units

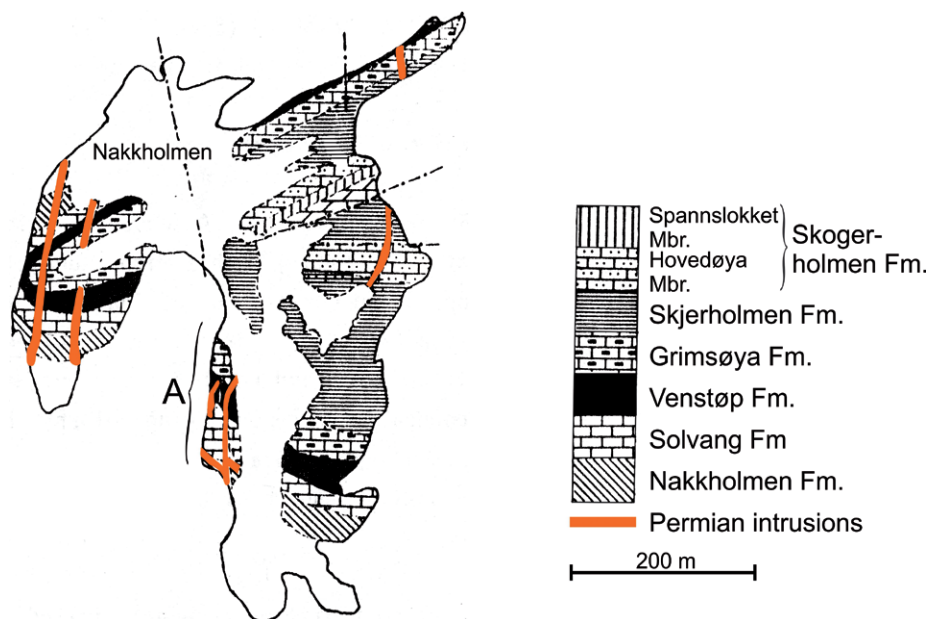


Fig. 87. Geological map of Nakkholmen Island. Modified from Bruton & Williams (1982).

both above and below (Owen et al. 1990). The base of the Solvang Formation in Oslo is taken at a conspicuous pyrite band which is overlain by nodular and bedded limestones with subordinate shale horizons. This basal boundary is unequivocally seen on Nakkholmen, Persteilene and Bygdøy. However, further to the west, e.g. at Fornebu and on Raudskjer, several pyrite horizons are present and the base of the Solvang Formation is drawn at the top of the last thick shale of the underlying Nakkholmen Formation. There is a pyrite horizon within 1 m above this level at most localities. The Solvang Formation is one of the most fossiliferous units in the Oslo Region. Trilobites, brachiopods, ostracodes, echinoderms and conodonts are described (Owen et al. 1990, and references therein). Bruton & Owen (1979) interpreted the trilobite distribution in the Solvang Formation in terms of the progressive immigration of species with an abrupt faunal shift marked by the base of the overlying Venstøp Formation. They argued that the Solvang Formation trilobites in the Oslo–Asker area indicate a westward younging of the top of the unit and an overall correlation with the Actonian and Onnian stages in Britain (late early–middle Katian).

The Venstøp Formation is a dark, locally graptolitic, shale that occurs in the Skien–Langesund, Eiker–Sandsvær Modum (Sylling), Oslo–Asker and Ringerike areas. In all areas the Venstøp Formation is bounded by limestone formations. In the Oslo–Asker area there is a thin phosphorite conglomerate at its base. Graptolites of the *Pleurograptus linearis* Zone are abundant at some levels in the Venstøp Formation in the Oslo–Asker area (Williams & Bruton 1983) which together with the trilobites, notably species of *Tretaspis*, indicate a middle Katian (early ‘Ashgill’, Purgillian) age. Williams & Bruton (1983) argued that the phosphorite conglomerate in the Oslo–Asker area represents a hiatus equivalent to the upper *D. clingani* and lowest *P. linearis* graptolite zones. The shelly fauna is commonly one of high abundance but low diversity with brachiopod species of *Onniella* and *Hisingerella* along with rarer specimens of *Sericoides*, *Dalmanella* and inarticulates, as well as the scattered occurrence of species of the trilobites *Tretaspis*, *Flexicalymene* and *Primaspis*. The formation contains a relatively higher proportion of articulated trilobite individuals compared to other Upper Ordovician units, suggesting quiet conditions of deposition. Orthocone nautiloids, gastropods, bivalves and conularids are also known from the formation, and some horizons, especially bedded limestones, are bioturbated with *Chondrites* being particularly common.

The lower part of the Grimsøya Formation comprises thin nodular limestone horizons with rusty weathering shale partings. This contrasts with the

shale–limestone alternations at the top of the underlying Venstøp Formation. The upper part of the Grimsøya Formation is composed of an alternation of limestone and shale. Siltstone beds are also present in this upper part of the succession. As Brøgger (1887) indicated, the formation thins eastwards from more than 46 m at Odden at the Asker coast to as little as 10 m on Rambergøya, Oslo. Much of the Grimsøya Formation is unfossiliferous but trilobites, corals, echinoderms and cephalopods have been described from various horizons. None of the faunal groups is particularly diagnostic in terms of the position of the unit within the middle Katian.

Stop 23. Beach sections on Hovedøya (island in the Oslo Fiord)

J. Fredrik Bockelie

Overview: The Upper Ordovician Langøyene Formation is overlain by the Silurian Solvik Formation. The visit will include a ‘channel’ on the south-east coast of Hovedøya (N59°53'29.8" E10°43'46.1") and basal Silurian beds on the east coast of Hovedøya (N59°53'35.7" E10°44'12.4").

Description: At the southern part of Hovedøya Island, the Ordovician–Silurian sequence is exposed in an overturned, inverted and complexly deformed syncline (Figs. 88 and 89). The late Ordovician in this area was deposited in a subtropical setting, and there are local coral and stromatoporoid reefs as well as large green algae (*Palaeoporella*) accumulations. Hovedøya is the type locality for the Ordovician–Silurian boundary in Norway. It has been defined and described by Kiær (1908) based on a lithological change from a principally massive limestone unit (*Langøyene Formation*) to the overlying *Solvik Formation* shale. There is a transitional unit with a 60 cm thick brown dolomitic(?) siltstone overlain by a 60 cm thick nodular limestone and subsequently succeeded by the shale of the Silurian Solvik Formation (Fig. 90). The Ordovician–Silurian boundary was originally defined at the top of the brown siltstone (Kiær 1908), but was later redefined by Worsley (1982) at the top of the nodular limestone. However, no detailed faunal logs have yet been presented.

Further to the south-west of the type locality, a channel (Fig. 91) cuts through the upper part of the Ordovician (Hirnantian). The width of the exposed part of the channel is 135 m and the maximum depth is about 15 m. The channel is almost symmetrical and a crude description of this channel was given and commented on by Spjeldnæs (1957). He introduced a separate name for the channel fill and called it ‘Stage 5c’. He proposed that the channel was filled during the latest Ordovi-

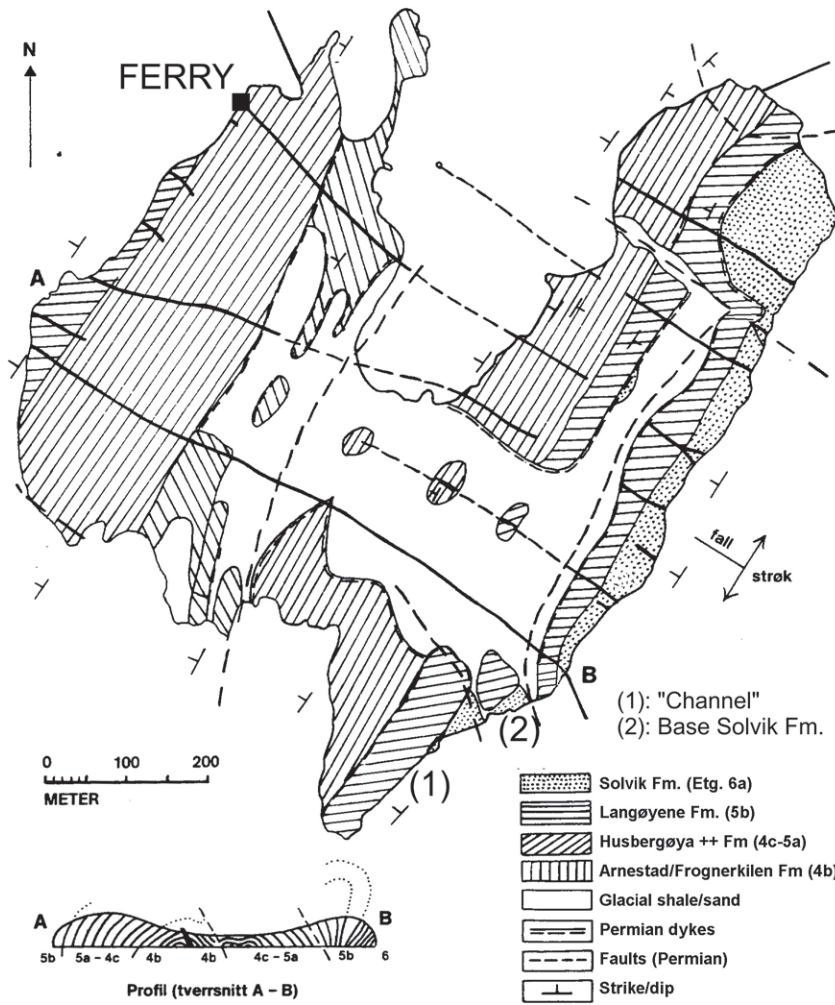


Fig. 88. Geological map of Hovedøya Island. Modified from Bruton & Williams (1982).



Fig. 89. Inverted Ordovician–Silurian boundary beds in the south-eastern part of Hovedøya. Photo: H.A. Nakrem.



Fig. 90. Close-up of the Ordovician–Silurian boundary beds in the south-eastern part of Hovedøya. Photo: H.A. Nakrem.



Fig. 91. Inverted Upper Ordovician strata with small incised valley ('channel') filled with limestone boulders at the base and mixed siliciclastics and carbonates in upper part. Photo: H.A. Nakrem.

cian and may have been open as a channel into the early Silurian. Work by Brenchley & Newall (1975) dismissed this interpretation and suggested that it was a tidal channel within the Hirnantian, and referred its fill to their Langøyene Formation. Their interpretation has since then been widely accepted and now represents the general understanding.

Recent studies by J.F. Bockelie include metre-scale measurements of the channel and its fill. The result shows a very complex system of sediment infill between the massive limestone unit (4–5 m at the type locality, but eroded in the channel) at the type locality and within the channel, indicating a major break between the massive limestone unit and the brown silt. In fact, the brown siltstone, the overlying nodular limestone and the Silurian Solvik Formation are all found within the uppermost part of the channel sequence.

An analysis of the channel geometry and fill has given some important conclusions:

1. The cross sectional shape of the channel corresponds to that of typical incised valleys.
2. The largest blocks of the conglomerate (more than a cubic metre) are found in the deepest part of the channel and are the same rock types as seen in the massive limestones at the type locality.
3. 'Basal conglomerates' in the channel are not continuous, and are in several places elongate and oriented in unstable positions, indicating possible storm infill or mass flow.
4. Coarse sand deposits within the channel (called millet seed sands by Brenchley & Newall 1980) represent eroded and reworked sand from the limestone unit further to the east.
5. The lower part of the channel shows sediment input from both sides of the channel, and represents an early phase of fill.
6. There appears to be an erosional contact between the early fill unit and the later, more passive fill which was probably deposited continuously into the Silurian shale.
7. The passive fill phase contains a variety of sediments and fossils (including Hirnantian faunas) which also may indicate a continuous deposition into the Silurian.
8. The brown siltstone, nodular limestone and overlying shale are found partly on land, but also into the sea along the eastern part of the channel.

At the type locality it can also be demonstrated that the massive limestone (4–5 m thick) with very coarse

sand (millet seed sand) is deposited with an angular unconformity on the finer grained sandstone below. This unconformity has been mapped by Bockelie for more than 20 km along strike into Asker south-west of Oslo as a part of an ongoing regional analysis.

The consequence of the observations made so far is that there may be at least two, possibly three phases of exposure with erosion and subsequent fill as a result of both eustatic and isostatic processes during the Hirnantian. This is in line with studies in Dalarna (Sweden), Estonia and elsewhere.

The lowermost Silurian Solvik Formation (Worsley et al. 1983) corresponds essentially to 'stage 6' of Kær (1908) in the Oslo, Asker and Holmestrand districts. The formation is dominated by shales with thin siltstone and limestone intercalations. The lithological variation suggests a threefold division into the Myren and Spirodden and the laterally equivalent Leangen and Padda members (Baarli 1985). A complete type section cannot be designated and the basal stratotype of the Solvik Formation is defined on the south coast of Hovedøya Island.

The lower boundary is defined at the sharp contact between underlying calcareous sandstones of the Langøyene Formation and the dark grey silty shales with minor siltstones of the Solvik Formation. Body fossils are generally rare in the lower parts of the member whereas high-diversity trace fossil associations can be observed on Hovedøya.

The shale-dominated sequence of the Solvik Formation reflects the rapid early Silurian transgression of the Oslo, Asker and Holmestrand districts and the establishment of sublittoral depositional environments in these areas. Siltstones of the Myren Member in the type area (Hovedøya) were storm generated and deposited in quiet muddy environments below normal wave base. Graptolites, conodonts and abundant brachiopods form the basis for the dating of this unit. *Climacograptus transgrediens* is present 11 m above the base of the formation on Ormøya. This graptolite ranges from the ?upper *persculptus* to lower *acuminatus* biozones elsewhere and the base of the Solvik Formation therefore approximates to the Ordovician–Silurian boundary as taken at the base of the *persculptus* Biozone. Conodonts (*Distomodus kentuckyensis* and *Icriodella discrete*, Aldridge & Mohamed 1982) typical of the *O. hassi* Zone support an earliest Silurian age for the Solvik Formation. Occurrences of subspecies of *Stricklandia lens* in the Asker district indicate that the top of the formation there approximates the transition between the Idwian and Fronian regional stages (Aeronian).

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