Climate archives and the Late Ordovician Boda Event

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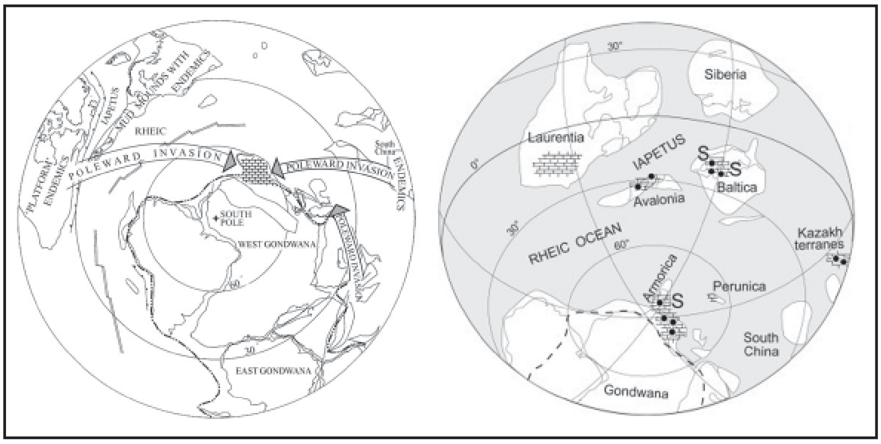

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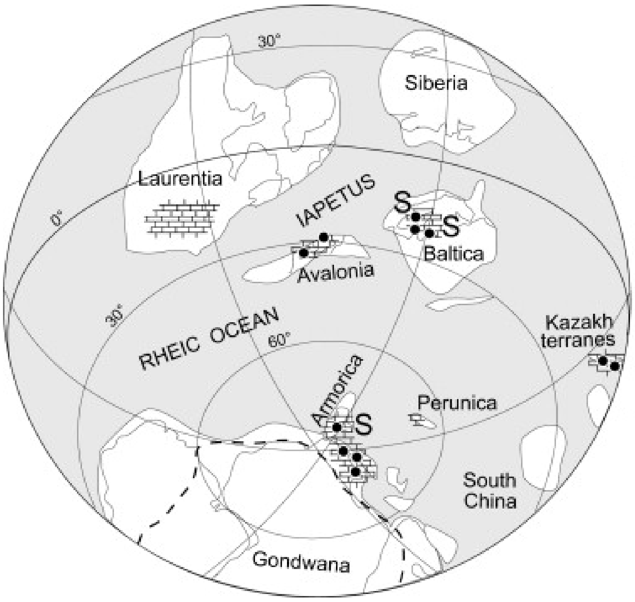

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Bachelor Thesis
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Contents

Cover Picture: The Late Ordovician Earth, showing faunal migration patterns (left; Fortey and Cocks 2005) and distribution of cool-water carbonates (right; Cherns and Wheeley 2007).

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HÅKAN OLSSON

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Abstract: Climate change has become an increasingly important subject in geological research as past climates can teach us about the global climate systems. This thesis is a literature study on natural climate archives with examples from the Late Ordovician Boda Event. The Ordovician Period represented a greenhouse world with atmospheric CO_2 levels almost twenty times higher then today. The climate became cooler in the Late Ordovician and the period was terminated by a global ice-age in the Hirnantian. Much of the studies of Ordovician climate have focused on this glaciation. Recent studies have, however, revealed another drastic climatic change preceding the terminal Ordovician glaciation. In the pre-Hirnantian (latest Katian) there was an episode of increased carbonate deposition worldwide. Reefs and carbonate mud-mound developed in high latitudes in several areas that were previously associated with siliciclastic sedimentation. There was a contemporaneous pole-ward migration of marine faunas, resulting in a breakdown of climatically controlled endemism. These drastic changes have been termed as the Boda Event by Fortey and Cocks (2005) who interpreted this as an episode of global warming. They argue that higher ocean temperatures would allow carbonate producers to spread into higher latitudes. Cherns and Wheeley (2007) on the other hand, suggested that the Boda Event represented a cooling event, resulting in lowering of global sea-level and increased oceanic circulation and overturn. This would oxygenise bottom waters and allow carbonate production and faunal migration. In this thesis the contradicting theories are evaluated and exemplified by the Swedish Boda Limestone that formed during this time interval.

Keywords: Climate, Boda Event, Late Ordovician, Siljan district, Carbonate mud-mounds

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Klimatarkiv och det sen-ordoviciska Boda Event

HÅKAN OLSSON

Olsson, H., 2009: Klimatarkiv och det sen-ordoviciska Boda Event

Sammanfattning: Klimatförändringar har under de senaste decennierna blivit ett allt hetare forskningsämne och man har då även studerat hur klimatet förändrats genom årmiljonerna. Ett spännande kapitel i jordens historia är ordovicium som karaktäriserades som en växthusvärld med koldioxidhalter nära tjugo gånger dagens. Denna varma period avslutades med en global istid som resulterade i ett av de största massutdöendena i Jordens historia där över 80 % av alla arter dog ut. Mycket av klimatstudierna har fokuserat på denna del av ordovicium. Lika fascinerande är tidsavsnittet precis innan Hirnantian. Då skedde en klimatförändring som resulterade i uppkomsten av kalkstenar och rev världen över, t o m på höga latituder nära sydpolen, i dagens Nordafrika och Sydeuropa. Även i Sverige, som vid denna tid låg precis söder om ekvatorn, hade vi flera revliknande miljöer i både Siljansområdet och på Gotland. Förutom ökad karbonatproduktion skedde en drastisk förändring i havens faunasammansätting. Faunor som dittills varit endemiska för enskilda regioner i låga latituder spreds plötsligt till höglatitudsområden. Den bakomliggande orsaken till dessa händelser var enligt Fortey och Cocks (2005) en global uppvärmning som höjde havets temperaturer nära sydpolen. De namngav detta som Boda Event. Cherns och Wheeley (2007) hävdade det motsatta, att det var en kall episod innan Hirnantian-glaciationen som genom ökad cirkulation och syresättning i haven globalt främjade artspridning och kalkavsättning. I detta arbete diskuteras de två teorierna, bl.a. med exempel från Bodakalkstenen i Siljansområdet.

Nyckelord: klimat, Boda Event, Siljanområdet, sen-ordovicium, rev

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1 Introduction

The use of many climate archives is limited by their range in time. Historical data goes back only as far as people have made and recorded observations whether it is temperature readings or sea-level stands. Complete series of tree-rings go back as far as 12,460 years (Freidrich et al. 2004). The use of annual ice-layers in retrieved ice-cores from Vostok, Antartica provides a climatic record for the last 420 000 years (Petit et al. 1999). But many archives also provide information of the climate situation several hundreds of million years back in time. The use and interpretation of these form the basis of our understanding of past climates.

This thesis addresses natural climate archives and the difficulties in reconstructing Palaeozoic climates. Focus will be on the Late Ordovician Boda Event, named by Fortey and Cocks (2005) after the Boda carbonate mud-mounds situated in the Siljan district, Sweden (Figs. 1, 2). This is an example of a climatic perturbation that has been variously interpreted by different authors, using the same available climate archives. The primary character for this event is widespread deposition of limestone and build-up of reefs and carbonate mud-mounds in high latitudes of Gondwana, such as in North Africa, the Iberian plate, Sardinia and Armorica (Webby 2002; Villas et al. 2002) as well as in low latitudes, e.g. the Boda Limestone in Baltoscandia. The event corresponds to the 6a-6b time slices according to Webby et al. (2004) or the Ka4 stage slice (Bergström et al. 2009). This makes it possible to correlate the event with a still un-named but prominent positive carbon isotope excursion between the Whitewater and HICE excursions *sensu* Bergström et al. (2009; Fig. 3).

2 Material and methods

This is primarily a literature study taking its starting point in two publications that are central for interpreting the Boda Event: Fortey and Cocks (2005) and Cherns and Wheeley (2007). In addition, three core sections (KBH 1-3) have been briefly studied. These core sections, which goes through parts of the Boda mounds, were provided by Svenska Mineral and comes from an area near the town Boda in the eastern Siljan district (Fig. 1B). 14 representative sections from the cores were polished and scanned in order to show the main facies types of the mounds. In addition, 13 thin sections were produced to study grain types and fossils in better detail. The thin sections were prepared at Department of Geology, GeoZentrum in Erlangen, Germany. Macrofossils have been identified to a basic taxonomical level.

3 Natural climate archives

Natural climate archives can be grouped as physical, geochemical or biological and examples from these groups are listed below.

3.1 Physical archives – Climate specific facies

A variety of facies can only be formed during specific climatic and environmental conditions. For this reason they provide a natural climate archive that can be used in climate reconstructions. The formation of clay minerals is often bound to special climatic conditions regarding temperature and precipitation. Kaolinite and bauxite are examples of minerals that can only be formed through chemical weathering processes in warm and wet areas. Chlorite on the other hand, is commonly found in polar-regions. The problem with using clay minerals as climatic indicators is that they may be reworked and therefore reflect weathering processes that took place during earlier times (Singer 1984). Evaporite minerals like halite or gypsum develop in lagoons, lakes and fluvial systems where evaporation is high, often indicative of arid climates. Due to their biological origin most carbonates are useful climate archives. These are discussed further in the section 'Carbonate sedimentation and climate'. Carbonates formed through chemical precipitation, e.g. oolitic and calcite spar form in waters that are oversaturated with respect to $CaCO_3$. For this to occur, the waters need to be subjected to high temperatures and evaporation-rates for the ions to precipitate spontaneously. As such, these type of carbonates as well as evaporites are frequently used in climate reconstructions e.g. Meng et al. (1997) and Sinha et al. (2006).

Tillites and glaciomarine sediments containing drop-stones are associated with cold climate in near glacial settings and the abundance of such facies can be used to estimate the distribution of glaciations (Frakes et al. 1992).

When climate specific facies is lacking, facies analysis can be an indirect method for interpreting climate change. For example, karstification

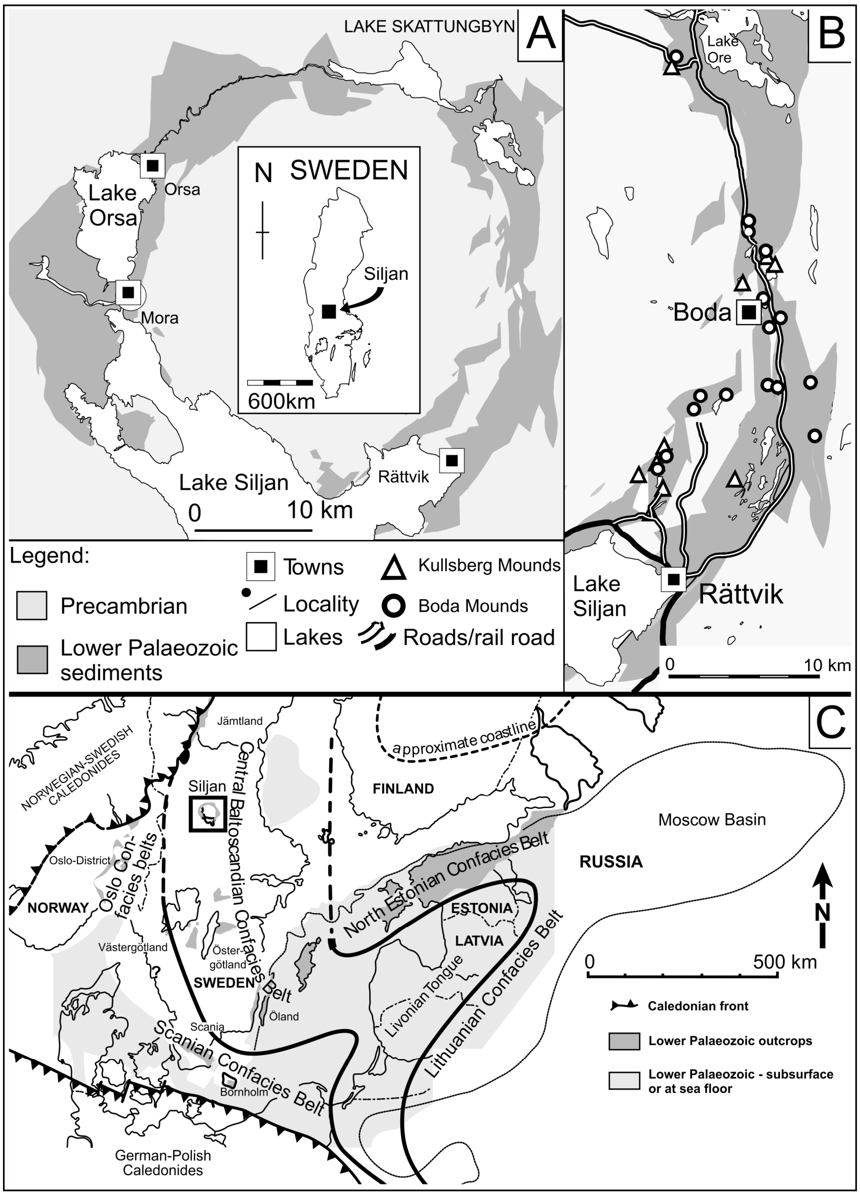


Fig. 1. Map of the discussed location and paleaeogeography of Baltoscandia. **A.** The Siljan district of Dalarna, central Sweden. A continuous record of Cambro-Silurian sediments is preserved within the remnants of the Siljan crater. **B.** Close-up showing the distribution major Boda and Kullsberg mounds and the town of Boda. **C.** Map showing the Baltoscandian Confacies Belts. Modified from Ebbestad et al. (2007).

and sharp erosional surfaces are interpreted as indicating regression of sea-level (e.g. Molina et al. 1999). Global sea-level falls can be the result of cooling climate as a result of oceanic water being trapped in growing ice-caps.

Furthermore, when it comes to facies of biological origins things get more complicated. As the biological parameters changed through the process of evolution and extinctions, interpreting biofacies become more difficult as recent analogous becomes rarer the further back in time we go (see further under 'Migration patterns of temperature specific faunas').

This divides facies studies into two parts; one, the interpretation of physical processes, and two, the interpretation of biological processes, with the latter being more speculative.

3.2 Geochemical archives – stable carbon and oxygen isotopes

Since the 1940's radiometric datings have been one of the most important tools in age determination of geological and archaeological materials. This method of dating is based on the half-life of radioactive or instable isotopes. But also *stable* isotopes have proven to be a valuable source of information. Not least for palaeoclimate studies. Different isotopes of the same element may have slight differences in their physical properties. In nature this may result in a fractionation of certain isotopes, either by biotic or abiotic processes.

Fluctuations in the ratio between stable ^{12}C and ^{13}C have proven to reflect major biological changes as the ^{12}C is fractionated by living organ-

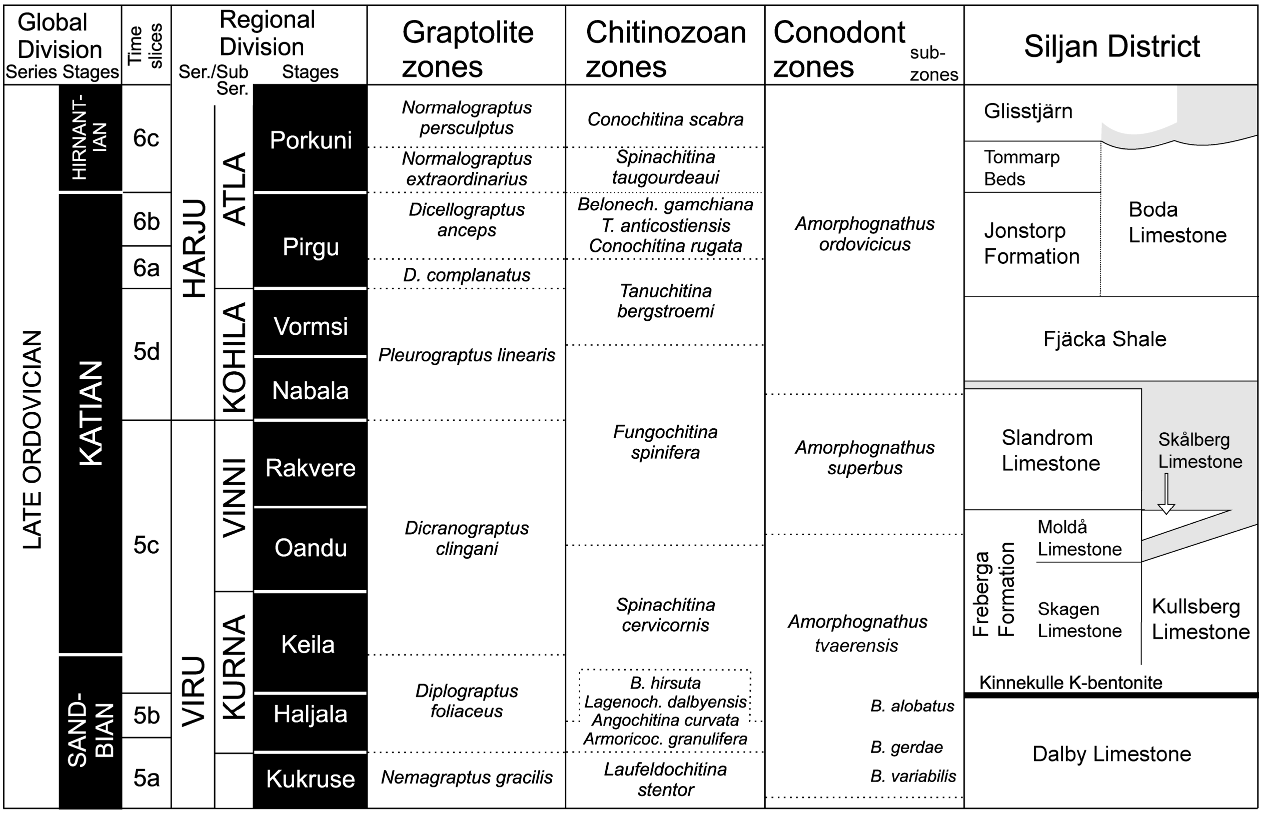


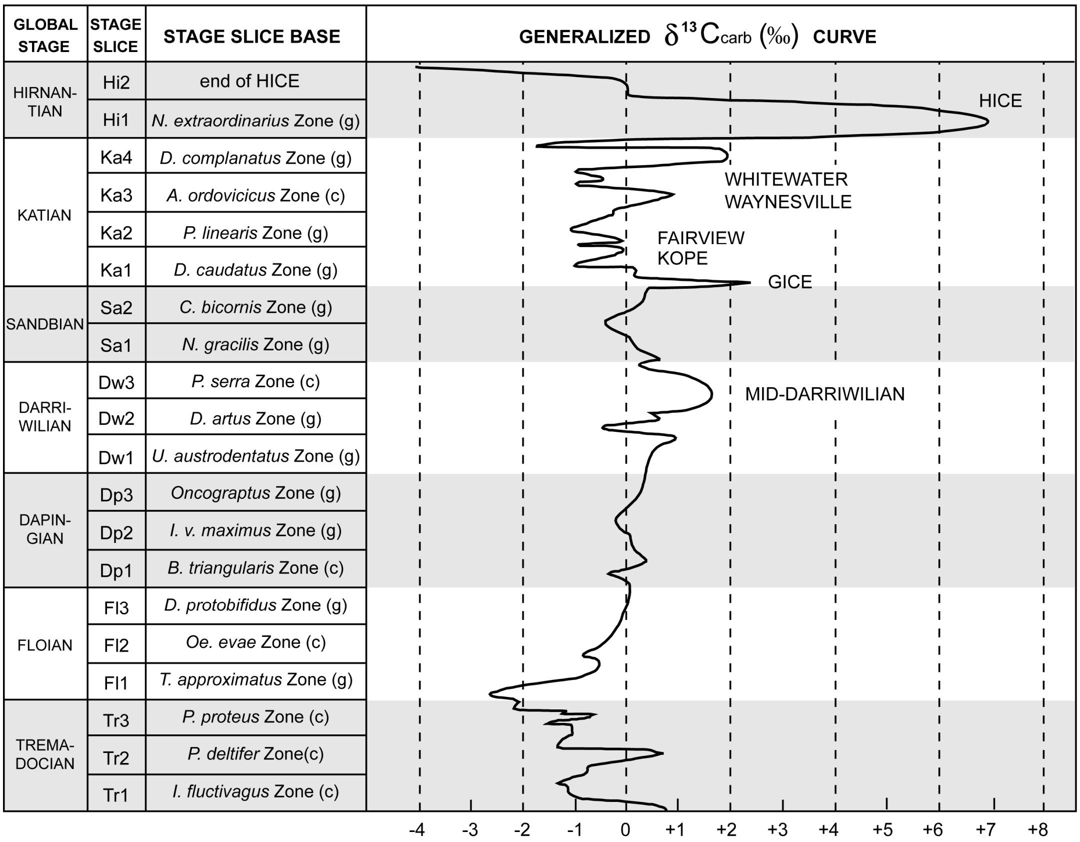
Fig. 2. Late Ordovician correlation chart showing regional zonation of the Siljan district and international standard, time slices and stage names (from Ebbestad et al. 2007 with data from Calner et al. 2009).

isms. Major fluxes in the ratio are termed carbon excursions and are often presumed to be closely related to global climatic changes as they often are recorded globally. Thus they can be used as a complementary tool for correlation.

The use of stable oxygen isotopes as a proxy-method for reconstructing past ocean temperature or the amount of water trapped as glacier ice, have proven to be an extremely valuable tool for geological science. There are two common naturally occurring stable oxygen isotopes that are used in theses studies; ^{16}O and ^{18}O. The ratio between these two isotopes in ocean waters differs from that of ice, since the heavier ^{16}O is more susceptible to evaporation because of smaller mass. The ratio between these isotopes when measured in biological materials like shells and other hard parts was found to be proportional to the temperature of the surrounding waters where the organisms lived. Hard parts need to be resilient to diagenesis and often comes from calcite shells from brachiopods and ostracodes or phosphatic conodont elements. Preferably, the same genus/group should be sampled when establishing an isotope curve. Although they can locally deviate, these stable isotope ratios are generally the same on a global scale. Thus, by measuring stable oxygen isotopes in fossils we can get a very good estimation of changes in ocean temperature and/or ice volume (Brenchley et al. 2003).

3.3 Biological archives – Migration patterns of climate specific faunas

The use of fossils as climate archives is widely used in historical geology and palaeontology. By determining the climatic and environmental needs of a now living species we can apply this knowledge to climate reconstructions, when finding the species as a fossil. Furthermore, migration patterns of temperature dependent species can suggest a change in climate, local, regional or global. A tropical species found in increasingly higher latitudes, indicates a warming trend as temperature rises and climate belts move pole-wards. The further back in time we go, however, the fewer recent species also occur in the fossil record. Yet, if an extant species is found associated with species that also occur today, it can be assumed that it had similar environmental requirements and can thus be indicative of a certain climate. Fur-



GLOBAL STAGE	STAGE SLICE	STAGE SLICE BASE
HIRNANTIAN	Hi2	end of HICE
	Hi1	*N. extraordinarius* Zone (g)
KATIAN	Ka4	*D. complanatus* Zone (g)
	Ka3	*A. ordovicicus* Zone (c)
	Ka2	*P. linearis* Zone (g)
	Ka1	*D. caudatus* Zone (g)
SANDBIAN	Sa2	*C. bicornis* Zone (g)
	Sa1	*N. gracilis* Zone (g)
DARRIWILIAN	Dw3	*P. serra* Zone (c)
	Dw2	*D. artus* Zone (g)
	Dw1	*U. austrodentatus* Zone (g)
DAPINGIAN	Dp3	*Oncograptus* Zone (g)
	Dp2	*I. v. maximus* Zone (g)
	Dp1	*B. triangularis* Zone (c)
FLOIAN	Fl3	*D. protobifidus* Zone (g)
	Fl2	*Oe. evae* Zone (c)
	Fl1	*T. approximatus* Zone (g)
TREMADOCIAN	Tr3	*P. proteus* Zone (c)
	Tr2	*P. deltifer* Zone(c)
	Tr1	*I. fluctivagus* Zone (c)

Fig. 3. Ordovician global stages in relationship to a generalized $\delta^{13}C$ curve. The stage slices are defined by the base of graptolite (g) and conodont (c) zones with the exception of Hi2, which is defined by the end of HICE. Modified from Bergström et al. (2009)

thermore, groups that appear to have undergone only minor morphological and physiological changes can be assumed to have the same lifestyle as their now living counterparts. For instance, crocodiles and palm trees are indicative of warmer climates as neither can survive in freezing climates.

Most modern corals are photozoans and often, but not exclusively, restricted to tropical and subtropical regions. We can only assume that the majority of the reef-builders in the Palaeozoic, like the tabulate and rugose corals and the stromatoporoids, were mostly tropical photozoan species as well. Of course many facts support this interpretation: they are generally found in low palaeo-latitudes, presumably grow within photic depths and are often associated with high diversity communities. Yet, some modern reefs like the *Lophelia*-reefs in Norway occur in deep and cool, nutrient-rich waters (Freiwald et a. 1999; Hovland et al. 2005). Kiessling (2001) compared the latitudinal range of 2,910 Phanerozoic reefs with established climatic curves. He concluded that there was no significant correlation between the global palaeoclimate and the latitudinal expansion/ contraction (width) of the tropical reef zone. Hence, it is difficult to correlate a species or assemblage to specific physical conditions such as sea-water temperature.

4 Ordovician climate

Studies have shown that CO_2 in the atmosphere could have been as high as almost twenty times the present atmospheric levels (PAL; referring to pre-industrial levels), in the early Ordovician decreasing only slightly towards the end of the period (Berner and Kothavala 2001, fig. 13; cf. deviating data in Berner 1994). This trend is supported by the long-term evolution of stable oxygen isotopes, which indicate a cooling of sea-water through the Ordovician (Trotter et al. 2008).

Ever since the discovery of glacial sediments in western Africa by Beuf et al. (1966, cited not seen) the state of the Upper Ordovician global climate has been debated. A late Ordovician glaciation has for long times been known. During this time interval, western Gondwana was situated at

Fig. 4. Palaeogeographical map showing the distribution of continents in the Late Ordovician. Modified from Cocks and Torsvik (2002) and Torsvik et al. (2002) BATLAS.

the South Pole (Fig. 4) and is thought to have undergone several glacial advances leading to global sea-level falls exceeding 30 meters (Caputo 1998). The glaciation resulted in the emersion of land and palaeokarst morphologies developed in exposed limestone-successions such as in the Cystoid limestone in the Iberian Chains of NE Spain (Villas et al. 2002). This Hirnantian glaciation was first considered to be a short-lived period of icehouse conditions in a longer-term (~250 Myr) Greenhouse cycle (Fisher 1981). Brenchley et al. (1994, 2003), was of the same opinion and argued that the major glaciations where confined to the Hirnantian and only lasted 0.5 – 1 Myr. They suggested that it was brought on by a lowering of atmospheric CO_2. A possible CO_2-sink that could explain such a lowering was suggested by Villas et al. (2002). They suggested that the extensive carbonate sedimentation that took place in the pre-Hirnantian would have trapped vast amounts of atmospheric CO_2 in the form of carbonates. Frakes et al. (1992) suggested that this cooling spanned over a period of ~35 Myr starting in the earliest Late Ordovician and continuing into Early Silurian with cold conditions culminating in the Hirnantian. This was partially based on the occurrence and distribution of glacial deposits for this interval. More recently, Saltzman and Young (2005) proposed a ~10 Myr transition into icehouse conditions preceding the main Hirnantian glaciation. Hermann et al. (2004) used computer generated models to simulate Late Ordovician climate in response to changes in atmospheric CO_2, sea-level and continental drift. They concluded that a drop in CO_2 was not sufficient to trigger a glaciation. Combined with a sea-level fall, however, a major glaciation could develop since this would result in a decrease of oceanic heat transport into higher latitudes.

It should be noted that the climatic changes at the end of the Ordovician resulted in one of the major extinction events of the Phanerozoic. Possibly as much as 86% of all species became extinct during this event (Jablonski 1991). The extinction can be divided into two main phases, the first being caused by climate deterioration and the regression in the onset of the glaciation. The second extinction phase is associated with the deglaciation, resulting in continental flooding associated with anoxic waters (Brenchley et al. 2003). Yet, minor carbonate build-ups continued into the Latest Ordovician mostly represented by patch reefs and low relief mud-mounds (Copper 2001).

A significant aspect of the Hirnantian climatic changes is the association to carbon isotope anomalies. Brenchley et al. (1994) presented isotopic data of what now have been termed as the Hirnantian carbon excursion (HICE). It is therefore intriguing that recent studies have revealed several additional major carbon isotope excursions in the Late Ordovician (Fig. 3). These are likely also the result of climatic perturbations. Facies evidence for sea-level changes associated with these isotopic excursions exists in several places in Baltoscandia: A regression that terminated the carbonate mud-mounds of the Kullsberg limestone

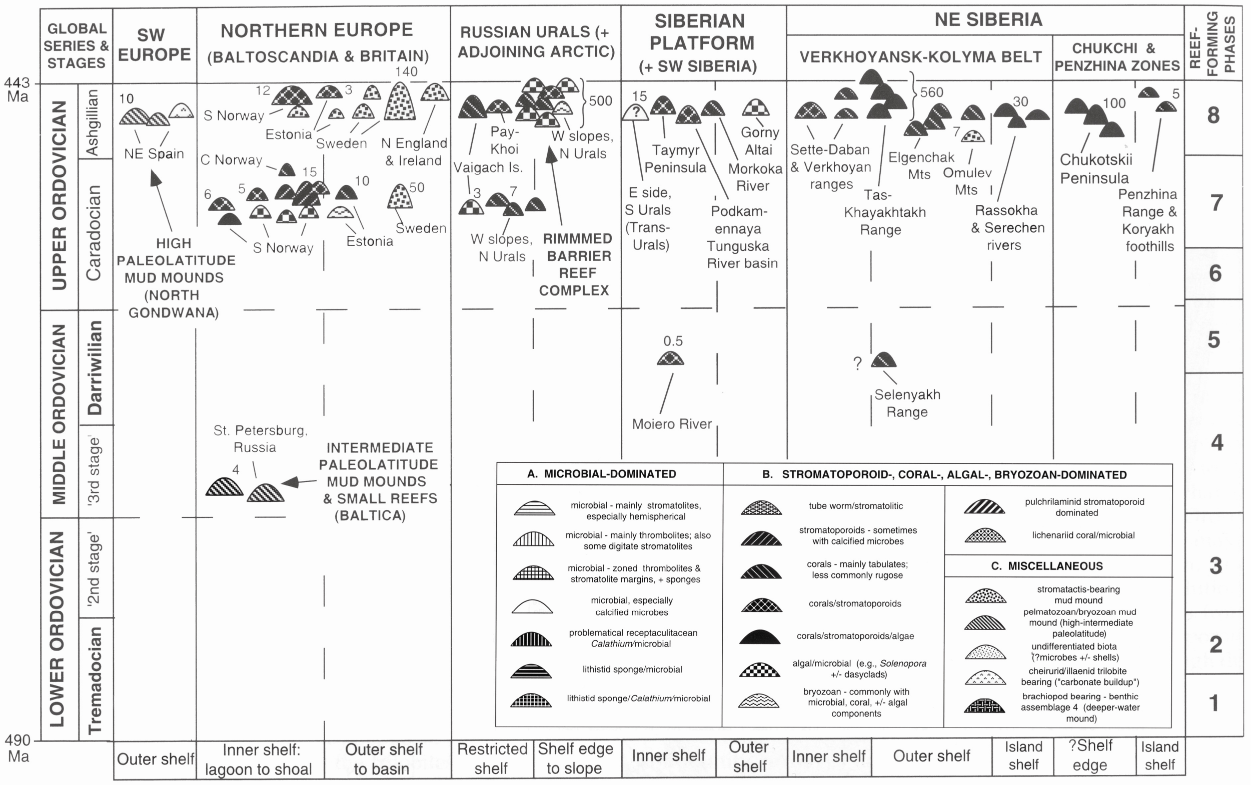


Fig. 5. The occurrence of reefs and carbonate mud-mounds in the Ordovician of southwestern and northern Europe, the Urals and Siberia. Notice the dramatic increase of carbonate build-ups from reef forming phases 1-6 to 7 and 8, the latter representing the Boda Event. Modified from Webby (2002).

(Fig. 2) follows immediately after the Guttenberg carbon isotope excursion (GICE). Another regression is indicated by palaeokarst morphologies in the Slandrom limestone. This limestone was developed close in time of the Waynesville positive carbon excursion. The cause of these regressions has been suggested to be falling global sea-levels brought on by glaciations (Calner et al. 2009).

5 The Boda Event

In 2003 it was suggested that there was a short-lived warming event of pre-Hirnantian age (Boucot et al. 2003). This was based on dramatic changes in sedimentary facies and fossil associations in the Mediterranean region. The appearance of carbonate rocks containing fossils associated with warmer marine environments were found sandwiched between tillites and clastic sediments. Boucot et al. (2003) interpreted this as only a regional event. Two following scientific papers, published by different research groups are of prime interest for interpreting this anomaly in the latest Katian. Fortey & Cocks (2005), who named this climatic anomaly the Boda Event, interpreted it as a global climatic warming event. Cherns & Wheeley (2007) has more recently made the opposite interpretation, that the Boda Event was a global climatic cooling event. These two papers are discussed below although no final conclusions will be drawn as to what climatic explanation is correct.

5.1 Fortey, R.A. and Cocks, L.R.M. (2005): Late Ordovician global warming – the Boda Event. Geology 33, 405-408.

Fortey & Cocks (2005) suggested a brief episode of global warming, preceding the end-Ordovician (Hirnantian) glaciation, which they termed the Boda Event. These authors showed that the increased carbonate deposition was associated with a widespread breakdown of endemism as a result of faunal migrations. Benthic trilobites and brachiopods confined to lower latitudes progressively spread into higher latitudes. This migration is shown as a pole-ward invasion into high latitude western Gondwana by hitherto endemic faunas originating from Laurentia, Avalonia, Baltoscan-

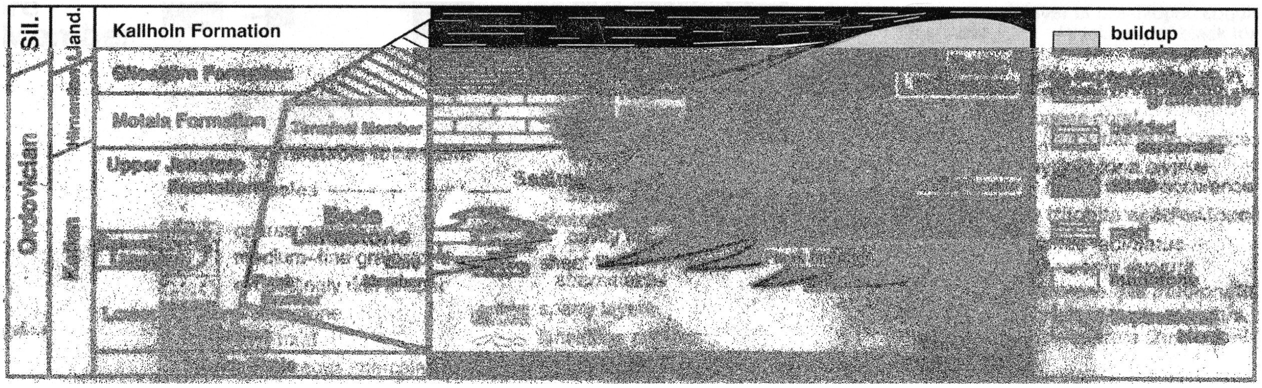


Fig. 6. Morphology of a typical carbonate mud-mound as demonstrated by a Boda-type mound. From Suzuki et al. (unpublished).

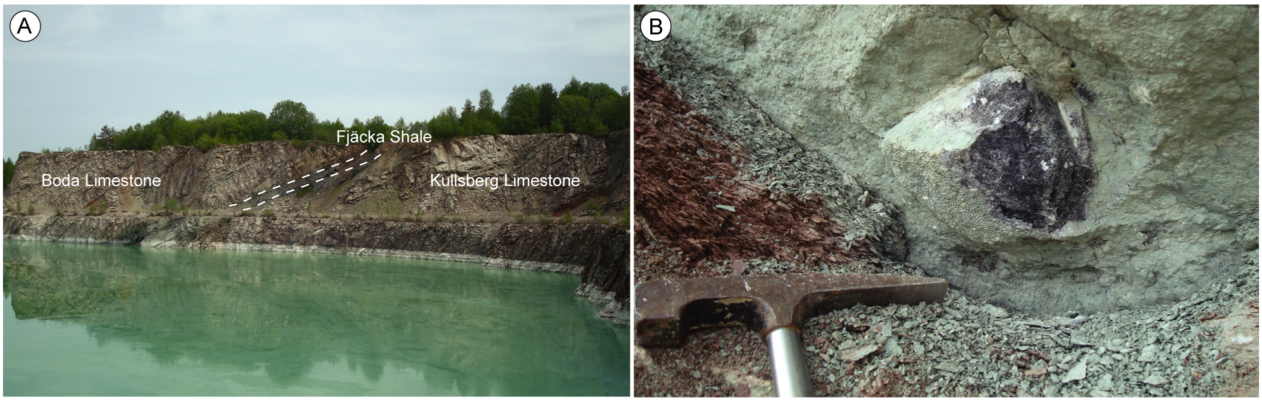


Fig. 7. Photographs of the Katian Boda Limestone in the Siljan district (photos: Mikael Calner). **A.** View and stratigraphy of the tilted late Katian succession in the Osmundsberget quarry. **B.** Close-up of a tabulate coral in the Boda Limestone. Note petroleum trapped in the pores of the coral. Osmundsberget quarry.

dia, South China and Kazakhstan. Fortey and Cocks (2005) suggests that this migration of tropical faunas from lower to high latitudes is indicative of a breakdown of climatically controlled barriers as a result of global warming. Before the Boda Event there were different endemic suites of taxa also in the high– and low latitudes of Gondwana itself. The occurrence of pan-Gondwanan species, capable of transgressing the climatic zones (e.g. the gastropod *Peelerophon* and the trilobite *Hungioides*) shows that there was no physical barriers (e.g. Mountain chains) separating the faunas. Thereby, the tropical and boreal faunas before the event where likely separated by climatic differences (Fortey and Cocks 2003, 2005).

Fortey and Cocks (2005) reported a find of a stromatoporoid from the bryozoan-dominated mud-mounds at Khabt Lahjar, Anti Atlas Morocco, showing that this group could occur in environments that are thought to have been situated less then 1000 km from the Ordovician South Pole. Stromatoporoids are usually associated with tropical latitudes and thereby indicate warm marine conditions (Webby 2002). Fortey and Cocks (2005) also refer to Boucot et al. (2003) who reported Sudanese kaolinite and laterites that may have developed during the pre-Hirnantian, even though correlation is problematic.

Fortey and Cocks (2005) also took other processes than climate into account to explain the widespread carbonate sedimentation: Carbonate production is usually hampered in regions with major clastic input (Hallock and Schlager 1986), and a decrease of such interference may very well allow carbonates, mud-mounds and reefs to develop. However, the North Gondwana platform is calculated to have extended over 240,000 km^2 (Villas et al. 2002), and Fortey and Cocks (2005) argue that it seems unlikely that carbonate sedimentation over such a vast area could be explained by a decrease in clastic input rather then a climatic amelioration.

As can be seen in Figure 5, the carbonate build-up associated with the Boda Event is not limited to the regions of Western Gondwana, hence the effects the event seems to be global, thus demanding a global cause.

Baltoscandia, migrating north and just barely reaching the equator at this time (Cocks and Torsvik 2002, 2005), housed a number of carbonate mud-mounds. These include the Boda Limestone of Sweden and the Pirgu mud-mounds of Estonia. The Boda mud-mounds in particularly demonstrates high diversity faunas with trilobites and brachiopods some of which are endemic. One of the most diverse groups is the brachiopod superfamily Strophomenoidea represented by more then 20 species (Cocks 2005).

The distribution of deep-water faunas remained stable until the Hirnantian, when they finally were extinguished. This suggests that deep-water environments were not affected by the warming event (Fortey and Cocks 2005).

5.2 Cherns, L. and Wheeley, J.R. (2007): A pre-Hirnantian (Late Ordovician) interval of global cooling – the Boda Event re-assessed. Palaeogeography, Palaeoclimatology, Palaeoecology 251, 449-460.

Cherns and Wheeley (2007) presented an opposite interpretation of the Boda Event as an interval of global cooling. To support this they proposed a global model where the observed limestone deposition and pole-ward migration are explained by polar ice expansion, eustatic sea-level fall and intensified thermohaline circulation. Based on facies and faunal composition they suggest that limestone and mud-mounds formed during the Boda Event have a dominantly cool water origin. In particular, the lack or scarcity of colonial corals and calcareous algae indicate a non-tropical environment. Bryozoan mud-mounds of Katian age in NW Libya demonstrate several similarities with Pleistocene bryozoan mud-mounds of the Great Australian Bight. In the latter area, cool water bryozoans flourished during the last glacial maximum at depths of 80-200 m. These mud-mounds where developed in cool-water zones of ocean current up-welling (James et al. 2000, 2004). Cherns and Wheeley (2007) also put forward that there are facies evidence suggesting that the Katian limestone and mud-mounds of Laurentia developed in upwelling-zones. These carbonates, which outcrops in New Mexico, Texas and Oklahoma, are characterised by high contents of chert and phosphate, which suggest up-welling in this area. This up-welling started already before the Boda event, at ca 454 million years ago (Pope and Steffen 2003). Similar carbonates associated with mud-mounds also began to develop along the Avalonian margin, facing the Iapetus Ocean, meaning the Welsh Basin, Ireland and northern England, in Katian. Also in these areas, up-welling is indicated by the occurrence of phosphate and pyrite in the sediments (Cherns and Wheeley 2007). In the Welsh Basin late Katian carbonates are intercalated within dark shale and siltstone successions. These where deposited in deep dysoxic, yet eutrophic waters and the carbonate deposits have been attributed to falling sea-level. This shallowing would oxygenise the seafloor through oceanic overturn and up-welling (Brenchley and Pickerill 1993; Zalasiewicz et al. 1995). A fall in global sea-level would then allow euthermal faunas to spread more easily across continents. Warm water carbonates associated with corals did develop in Avalonia but are explained as due to local warm surface waters in more shallow areas of the ramp setting according to Cherns and Wheeley (2007). Cherns and Wheeley (2007) further suggested that a reduction in clastic input into the margin high latitude western Gondwana was a response to regression and expanding terrestrial ice. Such a reduction would facilitate the development of carbonate sediments. The growing ice-sheets would give rise to the “microbrecciated” facies (Cherns and Wheeley 2007, fig. 3) associated with the Libyan carbonates which where suggested to possible be glacial diamictites by Buttler et al. (2007).

6 Carbonate sedimentation and climate

Based on the grain composition, carbonate sediments can be subdivided into two broad associations dependent on temperature. These are referred to the Foramol association (temperate waters) and the Chlorozoan association (warm waters) (Lees and Buller 1972). These associations were redefined as the Heterozoan (temperate waters) and Photozoan (warm waters) associations by James (1997). In modern times there is usually higher diversity at low latitudes then in higher. The situation can be assumed to have been similar in the Ordovician as well. Modern high diversity communities do, however, also occur in cold regions. Reef may develop in various environments neither associated with high temperatures or photic depths as demonstrated by the Sula-reef of the coast of Norway (Freiwald et al. 1999). Furthermore, harsh environments e.g. anoxic or hypersaline waters have generally low diversity faunas. As such, directly linking high diversity to warmer climate can be risky. But different communities can still be linked to specific environments. The organisms that we associate with carbonate production in warm Palaeozoic environments include stromatoporoids, rugose and tabulate corals as well as green calcareous algae while carbonates developed in cool waters are dominated by e.g. pelmatozoans, bryozoans and calcareous red algae (James 1997; Pedley and Carannante 2006). None the less, factors like nutrient availability, salinity, oceanic circulation, water motion and depth also plays an important role in carbonate production. The growth of corals may be hampered by falling sea-levels. A regression can lead to a reduction of water transparency caused by increased water-motion steering up fine materials or by an increased input of eroded and transported siliciclastic material. The latter can also cause nutrient excess allowing other photozoan organisms take over and competing with corals (Hallock and Schlager 1986). Carbonate platforms can be killed off if they should be entirely emerged.

The growth of a carbonate build-up is limited by the accommodation space. Thus, reef growth and development of carbonate platforms is favoured by rising sea-levels as the carbonate producers race towards the water-surface to compete for light and available space. For instance Calner et al. (2009) suggested that the Kullsberg mounds formed during transgression and sea-level high-stand. A rapid rise in sea-level may, however, kill of photozoan reef-builders if they are not able to grow up to reach photic depths (Hallock and Schlager 1986). Mound growth during transgression is also suggested by the sea-level curve in Villas et al. (2002) in which the Cystoid Limestone and associated carbonate mud-mounds is indicated to have developed during rising and high sea-levels. These authors further suggests that the carbonates in western Gondwana where able to develop as a result of a deflection of a warm equatorial current into this region. They propose that this deflection was caused by the northward migration of Baltoscandia and its supposed docking with Avalonia. This explanation is somewhat speculative due to the uncertainties in geographical reconstructions of the Ordovician world. Even so it remains a potential cause that can account for the increased carbonate sedimentation in western Gondwana during the Boda Event. Furthermore, if we compare the patterns of migration as presented by Fortey and Cocks (2005, fig 1) with the proposed oceanic currents in Villas et al. (2002, fig. 2) these corresponds quite well to each other, suggesting that faunal migration was assisted by ocean currents.

5.1 Carbonate mud-mounds, general description

The term *reef* basically refers to calcareous build-ups consisting of sessile organisms that essentially grow *in situ*. Carbonate mud-mounds are distinguished from reefs in their lack of a skeletal framework composed of any sessile organisms. They are instead composed mainly of mudstone with only few grains mainly from benthic organisms (Riding 2002). Otherwise, their morphology greatly resembles that of a bioherm-type reef. It should be noted, however, that carbonate mud-mounds are sometimes included together with reefs in figures and dataset compilations (e.g. Kiessling 2001; Webby 2002).

The majority of Lower Palaeozoic mud-mounds contain elements associated with warm-water temperatures, such as corals, stromatoporoids and calcareous algae. The pelmatozoan/bryozoan dominated mud-mounds of NE Spain and the associated carbonates of western Gondwana indicate cool/ temperate climate (Vennin et al. 1998; Cherns and Wheeley 2007).

The distribution of Palaeozoic carbonate mud-mounds is widespread as they have been reported from every modern continent except South America. They are also represented throughout Phanerozoic times. Their palaeographical distribution show that they occurred everywhere from the equator to the polar circle, but are more commonly found between 30° N and 30 ° S (Krause et al. 2004).

One enigmatic feature of the carbonate mud-mounds is the stromatactis structures found within the core facies. Many different origins have been suggested for these structures which will be discussed further under “Boda carbonate mud-mounds”.

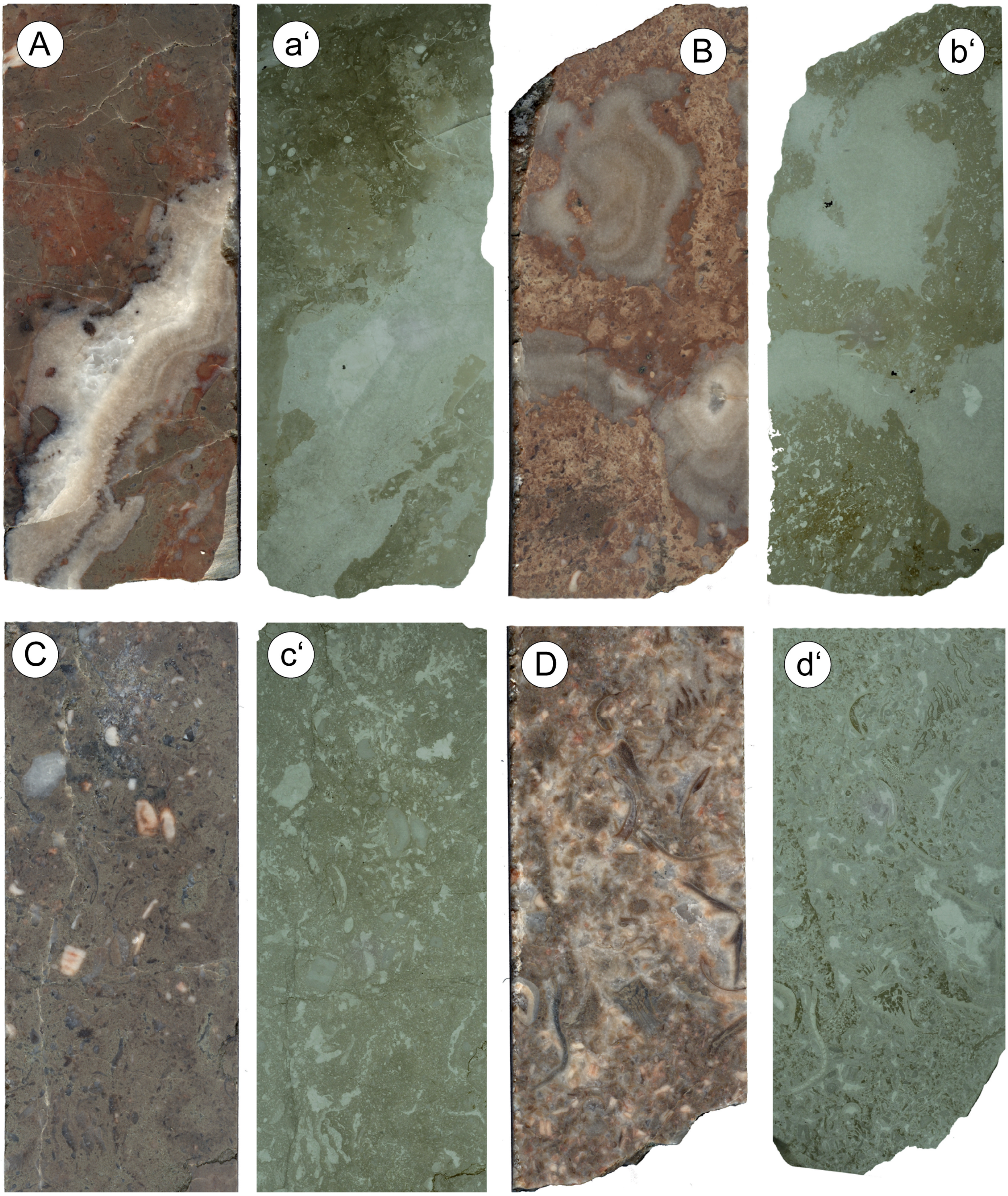
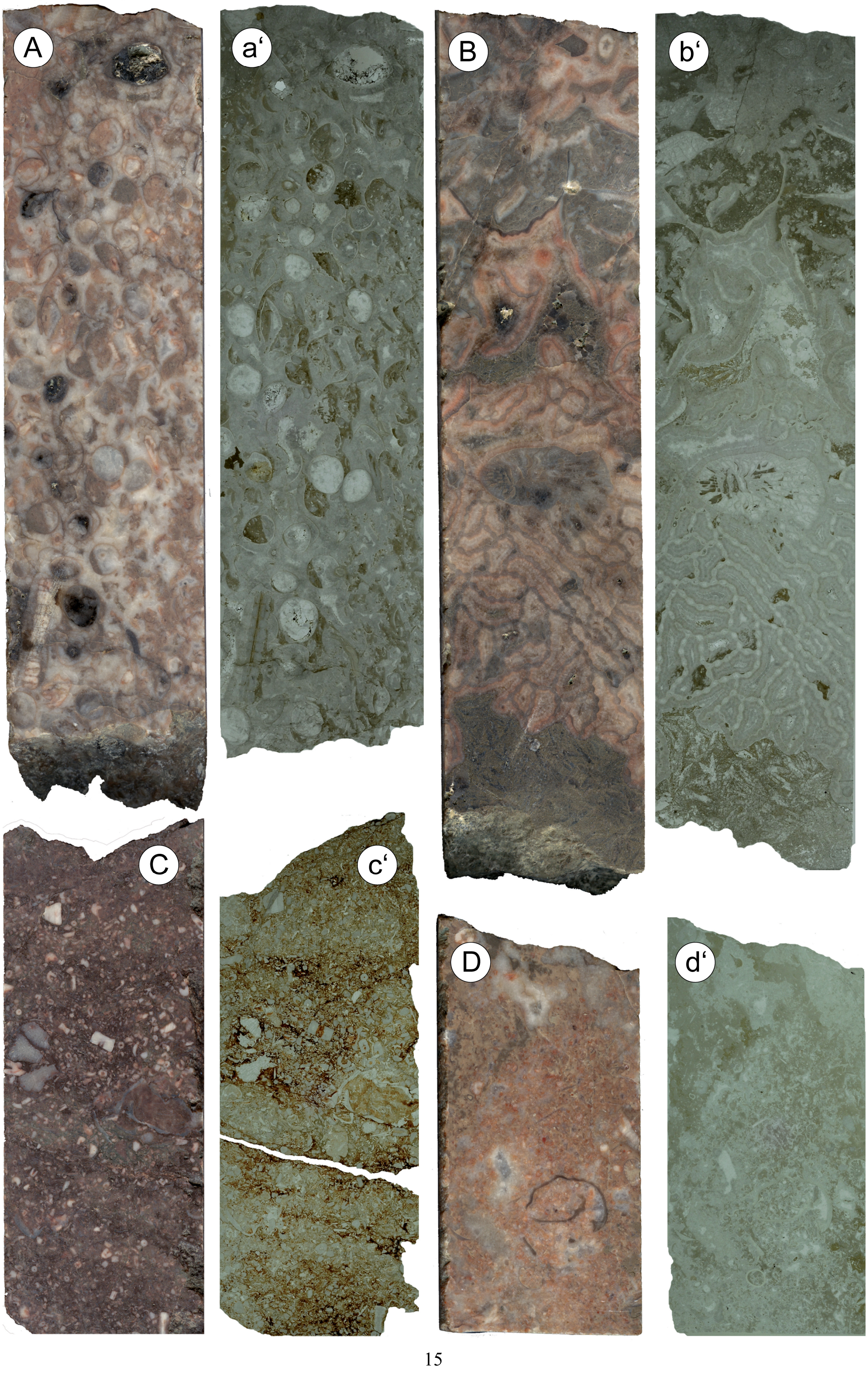


Fig. 8. Representative polished core slabs (capital letters) and thin sections (lower case letters) from the Boda carbonate mud-mounds in the Siljan district. Width is 4 cm in all samples. **A** and **a’.** Core facies with typical stromatactis structure showing clear cement zonation (KBH3). **B** and **b’.** Core facies with rounded stromatactis structures. (KBH3). **C** and **c’**. Flank facies with pelmatozoan fragments.**D** and **d’.** Flank facies with an abundance of skeletal grains (KBH3).

Fig. 9. (facing page) Representative polished core slabs (capital letters) and thin sections (lower case letters) from the Boda carbonate mud-mounds in the Siljan district. Width is 4 cm in all samples. **A** and **a’**. Core facies rich in brachiopods. Note geopetal structures and petroleum-filled cavities (KBH3). **B** and **b’**. Core facies showing large tabulate (halysitid) coral possible growing on top of favosites-type coral. Note also the crystal-like structures in the lowermost part (KBH3). **C** and **c’**. Flank facies rich in pelmatozoan debris (KBH2). **D** and **d’**. Core facies with a large brachiopod and stromatactis-like structures (KBH3).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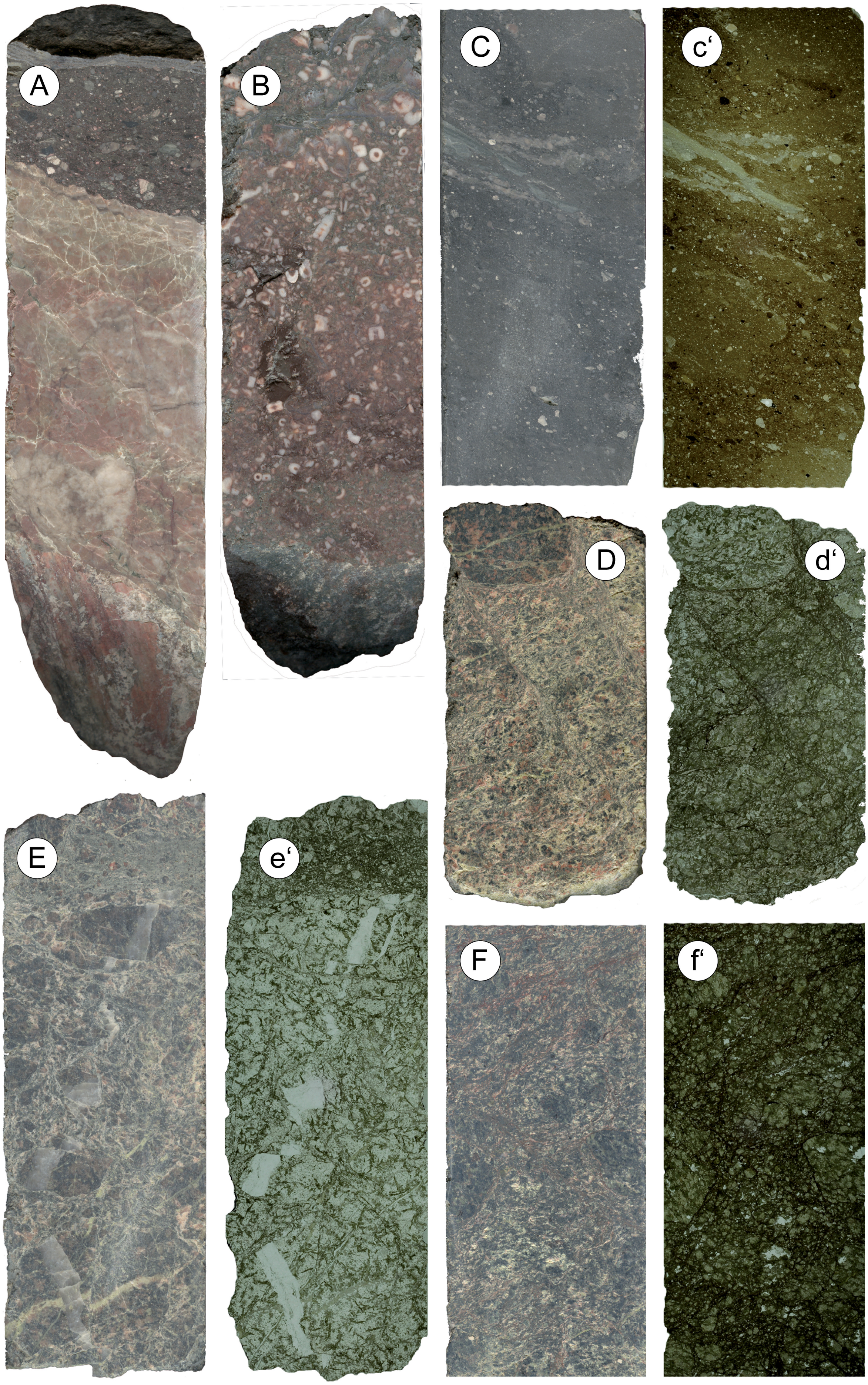
7 The Siljan district

The Lower Palaeozoic of the Siljan district is preserved in an astrobleme (Svensson 1971). The crater was formed during an impact event in the Devonian and has a diameter of 65-75 km (Henkel and Aaro 2005). Subsequently the sediments have undergone severe faulting and are as such tectonically tilted to various degrees (Fig. 7). Yet, the Ordovician succession remains practically unaltered and is remarkably complete. The Boda limestone belongs to the Central Confacies Belt as described by Jaanusson (1976) and about twenty mud-mounds are known in the area (Jaanusson 1982; Suzuki and Bergström 1999). Other similar build-ups of equal age are also known from drillcores and seismic data from the Gotland-Estonia area (Suzuki & Bergström 1999; Tuuling and Flodén 2000; Bergström et al. 2004; Sivhed et al. 2004).

7.1 The Boda carbonate mud-mounds

The Boda carbonate mud-mounds usually form great lens-like structures of various sizes, not seldom reaching dimensions over 100 meters in height and 1000 meters across (Jaanusson 1982; Suzuki and Bergström 1999). Their internal structure and their relationship to Upper Ordovician stratigraphy have recently been outlined by Suzuki et al. (unpublished; Fig. 6). They subdivide the mounds into a core member, a flank member, and a terminal member, representing different facies. The core facies of the Boda mud-mounds consists of a grey to reddish mudstone, with only a scarce presence of identifiable grains of fossils. The fossil fauna predominately represent benthic faunas such as trilobites (Fig. 8D), brachiopods (Fig. 9A-D) and crinoids (Fig. 8C). At least three different species of corals have been observed, representing what appears to be isolated specimens (Figs. 7B, 8D, 9B). One of these corals is associated with elongated calcite crystals that may represent recrystallised evaporate minerals (Fig. 9B; cf. Calner 2002, p. 397). Petroleum filled pores and cavities occur sporadically (Fig. 9A-B). The associated, pelmatozoan-rich flank facies, as well as any caverns and pockets in the mound core, displays high diversity in fossils (Suzuki and Bergström 1999; Eriksson and Hints 2009). Hence, the environments where build-ups develop often provide refugia for various organisms (Eriksson and Hints 2009). For example, Suzuki and Bergstöm (1999) described a high diversity trilobite fauna of about 90 trilobite species found in pockets and caverns within Boda mud-mound, a high number of species, considering that the following Hirnantian *Dalmanitina* fauna only yield around 10 species. Contemporaneous mud-mounds are known from several locations in Baltoscandia, including subsurface Gotland (Sivhed et al. 2004) Estonia, Norway, Novaya Zemlya, the Urals, and in the Avalonian British Isles (Ireland and England) (cf. Cocks and Torsvik 2005, fig. 8). There are some important differences between the mud-mounds of these areas. In Norway stromatoporoids and corals dominate as a diverse and common biota unlike those of Sweden where corals are scarce and stromatoporoids are possibly lacking (Webby 2002). Furthermore, the Avalonian mud-mounds are dominated by pelmatozoans, bryozoans and brachipods (Webby 2002) and associated beds also contain phosphatic materials and pyrite nodules (Cherns and Wheeley 2007). Based on the polychaete assemblage, Eriksson and Hints (2009) argued that the subsurface mounds of Gotland developed in more shallow waters, placing them within the North Estonian Confacies Belt (Fig. 1C). The stromatactis structures, being a typical feature associated with carbonate mud mounds around the world, have been greatly discussed since they were first described by Dupont (1881). An example of such a structure can be seen in Figure 8A-B. They are usually formed by cavity-filled spars that often demonstrate clear stratification.

Fig. 10. (facing page) Representative polished core slabs (capital letters) and thin sections (lower case letters) from the Boda carbonate mud-mounds in the Siljan district. Width is 4 cm in all samples. **A**. Core facies (lower) with sharp erosional transition into fine-grained allochthonous facies (KBH1). **B**. Flank facies rich in pelmatozoan fragments (KBH2). **C** and **c'**. Fine-grained intermound(?) facies with stratification (KBH1). **D** and **d'**. Terminal facies with large clast (top left) (KBH1). **E** and **e'**. Terminal facies with various clasts (KBH1). **F** and **f'**. Terminal facies with various clasts (KBH1).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7.2 Climatic implications

The presence of corals in the Boda carbonate mud-mounds indicates a warm, tropical to subtropical climate. Cherns and Wheeley (2007) pointed out that single specimens of warm water species may be overemphasized when interpreting climate. The occurrence of at least three different species of corals (Figs. 8D, 9B), however, suggests warm conditions. This is possibly augmented by the rich and diverse trilobite fauna. It is, however, also conceivable that this high diversity community could have occurred in cooler waters.

Many suggestions have been made to the origin of stromatactis structures, but few have been widely accepted. Krause (2001) and Krause et al. (2004) proposed a frost heave originating from syn-sedimentary cryoturbation of gas clathrate. Should this be the case, mud mound would in fact have to be formed during cold conditions. Today gas clathrates occur in deep cold waters but in order for them to form in shallow depths (~300 meters) the water temperature must be close to the freezing point (Krause 2001). Baltoscandia was during this time just south of the equator (Cocks and Torsvik 2005). In low-latitude upwelling zones, water temperatures may be much lower then expected, but sediments formed in these zones are often associated with cherty carbonates and phosphate beds (Pope and Steffen 2003). Such sediments occur in Avalonia (Cherns and Wheeley 2007) but are lacking in the Boda mounds. Carbonate mud-mounds where mainly formed in mid and outer shelf setting (Webby 2002; Cherns and Wheeley 2007). The lack of high energy facies and absence of clear stratification indicate depths below storm weather wave base (Suzuki and Bergstöm 1999). The presence of corals and bottom-dwelling trilobites with well developed eyes, such as *Illeanids* (Suzuki and Bergstöm 1999), and calcareous algae suggest that the mud-mound was situated well within photic depths. These factors together makes it difficult to explain that stromatactis structures could develop in low latitude, warm and shallow conditions using the origin proposed by Krause (2001).

8 Discussion

As the majority of modern carbonates and reefs are found in the tropical and subtropical regions, their occurrence in the fossil record has traditionally been interpreted as indicative of warmer climates. Yet, cool water carbonates are known to develop in temperate zones, and reefs and mud-mounds may also form in cold environments (e.g. Freiwald et al. 1999). We still don’t have a complete understanding of carbonate production in modern times. Neither do we fully know the environmental requirements of the different Ordovician faunas. The importance of factors like temperature, depth, nutrient availability and water-chemistry still is not fully understood. This makes past climates and drastic climatic shifts, like the Boda Event, difficult to interpret (e.g. Lindström 1984). This is well exemplified by the completely opposite interpretations, based on the same facts, of the Boda Event by Fortey and Cocks (2005) and Cherns and Wheeley (2007). Much evidence can be said to directly contradict each other. In the case of the Boda mud-mounds the presence of corals indicate tropical climate whereas stromatactis structures indicate cool conditions, if the interpretation made by Krause (2001, 2004) is correct. Another problematic contradiction is the presence of the Sudanese kaolinites of possible late Katian age (Boucot et al. 2003). Considering all evidences of glacial activity, e.g. tillites and striated pavements (Frakes et al 1992), the environmental requirements for kaolin to form, i.e. in wet and warm climates, seem unlikely to have persisted in Polar Regions. Boucot et al. (2003) pointed out that there is, however, great uncertainties in knowing the exact time when these kaolinites formed. An episode of global warming in the late Katian would explain how low latitude faunas where able to migrate into higher latitude through the breakdown of temperature barriers. During an event of global cooling it would be expected that faunas adapted to cooler climate could migrate towards the equator, which only occurred on a minor basis during this time interval. On the other hand the environments in and around Laurentia was relatively cold to begin with, considering it was an upwelling zone. Hence, the migrating faunas may already consist of several genera adapted to cool water settings. If a cooling event promoted increased ocean circulation and bottom oxygenation, the Laurentian cool water faunas could migrate into western Gondwana. Furthermore, species derived from warm waters could also migrate into higher latitudes if they required oxygenated, nutrient-rich environments rather then being temperature dependent. The fact that the Hirnantian glaciation resulted in such a great extinction might indicate that the Boda Event was a warm period: If the pre-Hirnantian was cool/cold, the faunas at that time would already be adapted to lower temperatures, thus being less sensitive to the following glaciation. A warm-water fauna could be expected to be much more vulnerable to climate deteriorations, going from warm to cold conditions.

Green algae are associated with warm waters, e.g. the photozoan assemblage, which makes their presence or absence valuable when interpreting climate. In most publications algae is just referred to as calcareous algae and it is therefore impossible to judge weather it is green algae or red algae, which can indicate cool water, they refer to.

One key factor in this discussion is how global sea level varied during this time interval. A rise in sea level would indicate warming due to melting of glacier ice and thermal expansion of ocean waters and thereby would a lowering of sea level indicate a cooling. When facies changes from siliciclastic sediments or organic shales to carbonate beds it is often interpreted as a fall in sea level. With more shallow conditions ocean bottoms may be oxygenated and phototrophic communities may be established. Even if carbonate precipitation is favored by warmer temperatures carbonates may develop in cooler environments especially in up-welling zones. But the reef and mound build-ups associated with the Boda Event formed high relief structures occasionally over 100 meters in height. If sea-level dropped continuously the carbonates would surely expand horizontally and later migrate outwards, rather then form build-ups growing towards the surface waters. In any case the timing and correlation of sea-level fluctuations during the Katian needs to be improved.

Cherns and Wheeley (2007) proposed that the carbonates developed during the Boda Event in Laurentia, Avalonia, Baltoscandia and western Gondwana where cool-water carbonates. Those of Baltoscandia, however, demonstrate warm-water characteristics such as high diversity faunas, stromatoporoids, corals, calcareous algae and chemically precipitated spars (Webby 2002; Sivhed et al. 2004), suggesting a tropical, photozoan association.

The carbonate mud-mounds of Baltoscandia and Avalonia demonstrate great variability. The rich coral diversity and abundance in Norway contrasts to the phosphate and chert associated beds in Avalonia even if corals occurred in more shallow areas. The first seems to represent a fairly warm environment while the latter likely formed in cool up-welling waters. The Norwegian and Estonian carbonate mud-mounds contain stromatoporoids, which are lacking in the Boda mounds. Polychaete assemblage suggest the carbonate mud-mounds in sub-surface Gotland occurred in shallow to transitional shelf settings much like those of nothern Estonia (Eriksson and Hints 2009). As mentioned earlier, the Boda mounds are situated in the Central Confacies Belt and thus developed in deeper waters then the ones in northern Estonia (Fig 1C.). The lack of stromatoporoids in Boda mounds may then perhaps be seen as indicative to stromatoporoids being limited to more shallow conditions then corals?

The carbonates of western Gondwana have a typical heterozoan faunal association, which suggest temperate to cold environments. And unlike the carbonates that formed in Laurentia and Avalonia, Cherns and Wheeley (2007) did neither report any occurrence of phosphate, chert or pyrite associated with these carbonates. Such occurrences have been reported from the area but attributed to hiatuses rather than up-welling (Àlvaro et al. 2007). This may suggest that western Gondwana was a region associated with down-welling and that warm-water current into this region allowed carbonates to develop even if they hade a heterozoan association.

Cherns and Wheeley (2007) suggested that in response to regression and expanding terrestrial ice there was a reduction in clastic input into the high latitude western Gondwana margin. This is not an impossible scenario, with glaciofluvial materials being trapped on the emerged land between the basin and the glacier margin. It is, however, more likely that expanding glaciers can produce more melt-water, which would lead to more clastic material being transported into the basin.

9 Further research

Much more research needs to be done to fully understand the Boda Event as well as the climate during the Ordovician. This period in Earth's history might have been much more oscillating than we previously thought, possibly with dramatic shifts between greenhouse and icehouse conditions which culminated with the Hirnantian glaciation and continued into the Silurian.

Since the main question now is whether Boda Event represents was warm or cold event, high resolution oxygen isotope studies needs to be done not only for this interval but the entire Katian as many facts points to earlier glacial events. Such studies need to be done for as many regions as possible to identify global events. We also need to improve our knowledge and understanding of the ecology of the species and what faunal migrations can tell us. We need a better understanding of the palaeogeography of the Ordovician to fully understand oceanic currents and how they interact with climate. This is knowledge could help us to discard or accept whether deflected equatorial currents could warm high latitude shelves.

10 Conclusions

During the Ka4 stage slice, there was a global increase in carbonate sedimentation associated with extensive reef and mud-mound development. This is thought to be caused by a global climatic shift and was termed the Boda Event by Fortey and Cocks (2005). The nature of this event remains disputed.

The high diversity faunas and abundance of calcareous algae, corals and stromatoporoids across Baltoscandia indicate that these areas had a warm climate during the Boda Event.

The scarcity of corals and calcareous green algae in western Gondwana during the Boda Event suggest temperate to cold environments for this region. Contemptuous carbonates in Laurentia and Avalonia where likely developed in up-welling zones as indicated by the presence of chert, pyrite and phosphate.

The worldwide carbonate development during the Boda Event was a major sink of atmospheric CO_2. This should have had a major impact on global climate and thus play an important role in the triggering of the Hirnantian glaciation.

The carbonate production associated the Boda Event was most likely terminated by a global fall in sea-level caused by vast volumes of water being trapped in ice-caps during the Hirnantian glaciation. This seemed to have occurred also in the early and middle Katian.

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