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SEDIMENTOLOGY AND DIAGENESIS OF MINIJA REGIONAL STAGE (SILURIAN) CARBONATES IN LITHUANIA

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MINIJOS REGIONINIO AUKŠTO (SILŪRAS) KARBONATŲ SEDIMENTOLOGIJA IR DIAGENEZĖ LIETUVOJE

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ABSTRACT

As long as alternative energy sources for our society such as wave or tidal, wind and solar power cannot play a significant role in the energy supply human kind will remain dependent on hydrocarbons and other fossil fuels such as coal. It is crucial to further develop existing oil and gas resources and find new techniques to extend their economic life. The study is focused on the Minija regional stage, which belongs to the lower Pridolian series of the Silurian. The Minija regional stage carbonate facies in the Silurian Baltic basin ranges from shallow in the east to deep marine in the western part. Based on the study, a depositional and diagenetic model for the Silurian carbonate system was built and was in particular focused on interpreting the Minija regional stage in central Lithuania. This augments the undertanding carbonate depositional systems in general and the development of petrophysical properties, mainly porosity and permeability. The central stromatoporoidal facies belt most probably were mainly stromatoporoidal biostromes instead of classic reefs. These were continuously reworked by storm induced currents into widespread proximal skeletal rudstones to more distal packstones. The entire carbonate system is more likely to be a ramp instead of a platform, because the biostromes had little or no relief because of continuous reworking. The reservoir quality of the limestones in the studied area is not good, with low porosity and low permeability. This is because of the intense diagenesis including early marine cementation of part of the coarser grained limestones, mechanical compaction, chemical compaction and almost complete cementation by calcite during burial. The best reservoir properties are found in the dolostones in the eastern shallow parts of the basin.

REZIUMĖ

Kol alternatyvūs energetiniai ištekliai, tokie kaip bangų, potvynių, vėjo ar saulės energija, negalės atstoti tradicinių, tol šiuolaikinė visuomenė priklausys nuo iškastinio ar angliavandenilių kuro. Kitaip tariant, žmogui be galo svarbu vystyti jau egzistuojančių naftos ir dujų išteklių gavybą bei ieškoti naujų technologijų, kurios tam pagelbėtų. Tyrimai buvo koncentruoti į Minijos regioninį aukštą, kuris priklauso silūro periodo pržidolio serijos apatinei daliai. Minijos regioninio aukšto karbonatinės facijos Baltijos silūro sedimentaciniame baseine kinta nuo seklių rytinėje dalyje iki giliavandenių vakarinėje. Remiantis tyrimų duomenimis, buvo sudaryti silūro karbonatų sistemos sedimentacinis ir diagenetinis modeliai. Diagenetinis modelis pagelbės geriau suprasti karbonatų sedimentacinę sistemą bei petrofizinių savybių, tokių kaip poringumas ir skvarbumas, vystymąsi. Centrinė stromatoporų facijos juosta greičiausiai yra biostroma, o ne klasikinis rifas. Pastoviai ir intensyviai veikiama audrų sukeltų srovių, ji transformavosi į skeletinius *rudstone* ir *packstone*. Karbonatų sistema yra daugiau rampa nei platforma, nes biostromos virš jūros dugno gali būti iškilusios mažai arba lygios su juo. Tyrimų metu nustatyta, kad karbonatines uolienas veikė intensyvi diagenezė – ankstyvoji jūrinė ir vėlyvoji cementacija bei mechaninė ir cheminė kompakcija. Šie procesai lėmė mažas uolienų poringumo ir skvarbumo reikšmes. Dėl šios priežasties Minijos regioninio aukšto karbonatinių uolienų potencialas naftos kolektoriui yra menkas. Geriausiomis kolektoriaus savybėmis pasižymi dolomitai, slūgsantys rytinėje, sekliausioje baseino dalyje.

CONTENTS

INTRODUCTION

Energy plays a major role in our society since it strongly depends on energy. Because the demand on energy is still increasing, also because of economic growth and demand of a number of large third world countries, the energy supply is critical to the survival of the society. As long as alternative energy sources such as wave or tidal, wind and solar power cannot play a significant role in the energy supply on short term, human kind will remain dependent for the coming decades on hydrocarbons and other fossil fuels such as coal. In other words, it is crucial to further develop existing oil and gas resources and find new techniques to extend their economic life.

A number of large and giant oil reservoirs in the world are in carbonate sediments, such as the well-known oil fields in the Middle East and the more recently discovered oil reservoirs in the Caspian Sea area. Besides these large fields, there are numerous smaller carbonate reservoirs in North America. In general, about 50% of the oil and gas reservoirs in the world are in carbonates (Mazzulo, 2004). It is a common saying in science that the present is the key to the past. This might however not always be directly applicable since past chemical and environmental conditions might have been different from present day ones, and surely the fauna and flora has been modified through evolution. One major reason for this is the organic evolution of the fauna and flora that produces sediments and modifies depositional textures. In particular, for carbonates this is relevant since most of the carbonate components are biogenically produced. All too often, recent sedimentary environments and their sedimentary deposits are taken as model to explain fossil sedimentary deposits. It is however questionable if the recent carbonate depositional systems that are dominated by coral-red algal reefs and are dominated by platforms, and the sub recent repeated glacial periods of sea level fluctuations are representative for the Mesozoic and especially Palaeozoic carbonate systems. Ice caps at both poles are for instance a rare phenomenon in the geological past. The major carbonate factories show a distinct number of significant changes throughout the Phanerozoic (Kiessling, 2009). Therefore, the mineralogy and texture of carbonate components changed as well as the influence of the carbonate factories on their environment and the type of carbonate systems.

The relevance of the study

The Silurian carbonates in Lithuania may be important as it is assumed to contain oil reservoirs such as in the Kudirka structure (Stentoft et al., 2003; Jacyna et al., 2004; Kaminskas et al., 2015). Fortunately, in the past a lot of deep wells were set through the Silurian and cores taken. This study focusses on a number of wells along an east-west transect through central Lithuania to study the Silurian carbonates north of the Kudirka structure.

It has been suggested that despite of the usually tight carbonates in the Silurian succession, towards the south an oilfield exists in the so called Kudirka reef structure because of dissolutional secondary porosity (Stentoft et al., 2003). This study therefore explores the potential of the central Lithuanian Silurian by mean of analysing the diagenesis and the influence of diagenesis on reservoir properties. Here should be noted that the study is concentrated just on conventional reservoir properties.

The aim

The aim of this study is to build a diagenetic model for the Silurian carbonate system and specifically interpret the Minija regional stage in central Lithuania. Such models help to better understand carbonate depositional system in general and the development of petrophysical properties, mainly porosity and permeability.

Specific attention is paid to the so-called reefs in the Silurian and in Palaeozoic deposits in general. The presence or absence of true reefs is an important factor in determining the nature of the carbonate systems (platform versus ramp), the distribution of depositional facies (as reefs form hydrodynamic barriers) and the development of porosity (e.g., since modern reefs grow up to sea level and thus often develop secondary porosity).

Tasks

The work was done by describing the (micro)facies and their distribution in the Silurian Baltic basin based on the Dunham carbonate classification system expended by Embry and Klovan (1971); by interpreting the facies and presenting a carbonate depositional system; by describing and interpreting the major diagenetic processes and assessing their impact on the petrophysical properties; by describing the types of pores and the porosity and permeability in the system, and linking that to the (micro)facies.

Novelty of the research

So far Silurian carbonate system was interpreted as platform. Here, arguments will be presented for a different carbonate system. There are just few publications regarding to the diagenesis of the Silurian carbonates in Lithuania. This study present the most comprehensive diagenesis description of Silurian carbonates in Lithuania so far.

Positions to be defended

- The central stromatoporoidal facies belt is rather a biostrome than reef.
- The carbonate system is interpreted as ramp rather than platform.
- Porosity and permeability of the carbonates were lost during diagenesis and reservoir potential of these carbonates is very low.

- Most of the microfacies, with exception of the shallow dolostones have similar petrophisical properties, with little differences.

CHAPTER 1

1.1. Target of the study

The study is focused on the Minija regional stage, which belongs to the lower Pridolian series of the Silurian (Fig. 1.1). The Silurian Baltic basin forms an excellent study object because of almost complete stratigraphic successions (Paškevičius, 1997; Lapinskas, 2000) and the availability of abundant core material from the lower Llandovery to the upper Pridolian. The Silurian stratigraphy has been studied for decades resulting in an excellent stratigraphic framework (Paškevičius, 1997; Brazauskas et al., 2004). The Silurian deposits of the Baltic basin are part of the Baltica palaeocontinent, which was situated just south from the equator in Silurian time (Cocks, Torsvik, 2005). Silurian sediments in Lithuania occur exclusively in the subsurface and thus are available only from core material. For many decades of the last century the Silurian Baltic carbonates in Lithuania were extensively drilled and cored in the eastern part of the basin for hydrocarbon exploration and production that mainly targeted the oilfields in the Cambrian siliciclastic sandstones in Lithuania, Kaliningrad and Poland. Also, Silurian and Ordovician sediments were extensively cored because they contain several oil shows and bitumen. Still the expectation is that Silurian carbonate might contain economic oil reservoirs (Вала, Коркутис, 1963; Сакалаускас, 1968; Лапинскас, 1970; 1972; 1973; 1977; 1983; 1987; Lapinskas 1998; 2000; Лапинскас, Чехавичюс, 1981; Lapinskas et al., 1994). Also in other parts of the Silurian Baltic basin oil spots have been found, for example on Gotland (Sweden) (Paškevičius, 1997; Zdanavičiūtė, Bojesen-Koefoed, 1997; Zdanavičiūtė, 1998; Lapinskas, 2000; Stentoft et al., 2003; Sivhed et al., 2004). Besides the occasional oil and bitumen occurrences, the lower Silurian shales contain organic rich intervals that are considered as one of the source rocks for much of the Cambrian and other oil shows in the region (Zdanavičiūtė, Lazauskienė, 2004).

System Period	Series Epoch	Stage Age	Regional stage	Biozones: Graptolites	Biozones: Conodonts	
DEVONIAN			TILŽĖ			
SILURIAN	PRIDOLI		JŪRA		O. e.remscheidensis	
SILURIAN	PRIDOLI		MINIJA	N.lochkovensis	O. e.eosteinhornensis	
SILURIAN	PRIDOLI		MINIJA	N.ultimus-N.parultimus	O. e.eosteinhornensis	
SILURIAN	LUDLOW	LUDFORDIAN	PAGĖGIAI	M.formosus M.valleculosus	O.crispa	
SILURIAN	LUDLOW	LUDFORDIAN	PAGĖGIAI	M.balticus	R.dubia	O.tillmani
SILURIAN	LUDLOW	LUDFORDIAN	DUBYSA	P.tauragensis	P.siluricus	O.tillmani
SILURIAN	LUDLOW	LUDFORDIAN	DUBYSA	L.scanicus	K.variabilis	O.tillmani
SILURIAN	LUDLOW	GORSTIAN	DUBYSA	L.progenitor	K.variabilis	O.tillmani
SILURIAN	LUDLOW	GORSTIAN	DUBYSA	N.nilssoni	O.bohemica	

Fig. 1.1 The Stratigraphic scheme of Baltic Silurian after Paškevičius (1997).

The Minija regional stage carbonate facies in the Silurian Baltic basin ranges from shallow in the east to deep marine in the western part. Due to the geographical position of the basin on the relatively stable Baltica palaeocontinent, tectonic activity was relatively minor. Also because of this minor tectonic impact onto the carbonates, Minija regional stage carbonates form an excellent research target where the effects of burial conditions on the carbonate sediments and their properties can be studied without 'disturbing' influence of tectonic processes. Silurian deposits from the same sedimentary basin occur in North Estonia, Gotland (Sweden) and Podolia (Ukraine). These rocks are cropping out and were extensively studied for decades, especially notable in Gotland (as will be dealt with in the next paragraphs). But still there is no common opinion about the nature of the Baltic Silurian carbonate system. This study intends to answer this matter.

It is often stated that Silurian carbonates could be economic potential of oil reservoir because of the occurrence of oil or bitumen in Silurian and Ordovician carbonates and also because Silurian shales are partly organic rich and could be one of the source rocks for the Cambrian sandstone reservoirs (Zdanavičiūtė, Lazauskienė, 2004). Moreover, the literature has suggested that good porosity and permeability can be found in Silurian carbonates without giving much data for that supposition. Because of the deep crisis in oil resources and the expectation that demand will further increase, new reservoirs would be very welcome. This study will check the assumption that Silurian carbonates in Lithuania could contain hydrocarbon reservoirs and still has good reservoir properties.

The studied stratigraphic interval is not exceptionally thick ranking from 15 m in eastern part to the 144 m in the west part of the Lithuania, but the sedimentation rates were relatively high and this interval forms a complete and good example of a typical Palaeozoic carbonate system.

1.2. Previous studies

The first studies on the Silurian in the Baltic region start in the middle of the 19th century with F. Schmidt (Paškevičius, 1997), who separated the Silurian succession into different units in Estonia and tried to correlate them with other Silurian successions from other regions. Silurian studies in Latvia came later when the first boreholes were drilled in Daugpilis in 1932 (Paškevičius, 1997). Understanding of the Silurian sediments in Lithuania began even later and started with the first deep-drilling projects in 1949 (Lapinskas, 2000). Since then a new era of Silurian research in Lithuania started too. Before that it was just fauna description from boulders. Here should be note that the late start of the studies is merely due to local circumstances: the lack of outcrops in Silurian deposits but not due to a shortage of specialists. For example, the Silurian on Gotland (Sweden) was investigated for centuries due to the excellent outcrops along most of the shorelines. The application of new techniques such as seismic profiling and deep drilling led to a big progress in the Silurian Baltic research that started after Second World War when the deep drilling projects were in operation. The availability of core material enabled to do systematic fauna descriptions and recognize fauna associations, to do systematic research on the lithology of the

Silurian succession, and establish the biostratigraphy and lithostratigraphy and eventually to produce regional stratigraphic schemes and correlate succession on a regional scale. These projects were made possible by the oil occurrences in the Silurian, Ordovician and particular the oilfields in Cambrian siliciclastic sandstones.

There are a number of legendary researchers or better called coryphaeus in the Baltic region who spent most of their professional life time dealing with the Baltic Silurian. To mention a number of them: D. Kaljo, R. Einastor, H. Nestor worked mostly on lithology in Estonia; L. Gailite, M. Rybnikova and R. Ulst in Latvia. A number of scientists worked on the Silurian in Lithuania too. Some of them even devoted the biggest part of their scientific life to a study of various aspects of the Silurian succession: J. Dalinkevičius, J. Paškevičius, P. Lapinskas, A. Brazauskas, N. Sidaravičienė, P. Musteikis, a younger generation S. Radzevičius, A. Spiridonov and many others. J. Dalinkevičius worked mainly on lithological aspects, J. Paškevičius on lithology and graptolites, P. Lapinskas on the lithology. A. Brazauskas on conodonts and lithology, N. Sidaravičienė on ostracods, P. Musteikis on brachiopods, S. Radzevičius on graptolites, A. Spiridonov on conodonts. Some researches like T. Martma, D. Kaljo, A. Brazauskas, D. Kaminskas studied isotopes trends and stratigraphy in Silurian successions. E. Kadūnienė and O Zdanavičiūtė worked on organic matter in Silurian rocks. Thanks to these scientists a detailed regional bio- and lithostratigraphic scheme of the Silurian succession was established. A number of publications were devoted to the Silurian in scientific journals. Under the supervision of these people, many bachelor, master and PhD theses have been produced.

The Silurian Baltic basin was not just explored in Lithuania and in the other Baltic countries, but also in Podolia (Ukraine), and in Gotland (Sweden). Silurian sediments are cropping out in these territories and were subject of numerous studies, in particular palaeontological studies. From these various publications resulted in the last decades, especially focused on Gotland probably mainly because of the excellent outcrops. Some of these publications are merely of descriptive character and, although they are comprehensive, with the improvement of the research methods and techniques and the availability of new data, the interpretations of the Baltic Silurian deposits may need to change accordingly.

During the last few years, there was more focus on shale gas potential of Lithuania, a main target formed Lower Silurian shales.

1.3. Geological setting

This study is restricting to the Lithuanian territory although some overview on Silurian deposits in Estonia and Gotland is given, which are all part of the same sedimentary basin. This study is concentrated onto the Minija regional stage, which forms the lower sequence of the Pridoli.

The Silurian Baltic basin is located at the margin of the East European craton, which was in the tropical climate belt just south from the equator during Silurian (Cocks and Torsvik, 2005).

The time interval of the Minija regional stage is according to the latest geological time scale only about 1.35 million years (Gradstein, Ogg, Smith, 2004), but sedimentation rate was relatively high. The thicknesses of Minija regional stage rocks in Lithuania vary from 15.5 m in most shallow part of the basin to 144 m in the deepest part of the basin. Here should be taking into account that most shallow part was partly eroded due post depositional uplifting. Sedimentation rate is about 0.1 m per 1000 years. The total thickness of the Llandovery, Wenlock and Ludlow in the deepest part of the basin is about 429 m, which gives an average sedimentation rate of about 0.021 m per 1000 years. And this is about ten times less than during Early Pridoli time. Here should be noted that the sediment thicknesses are not corrected for the dewatering and compaction of the sediments and that is why it cannot be directly compare to modern ones. According to the point count results the average IGV (intergranular pore volume) in carbonates with a grain-supported framework (i.e. carbonate sands including grainstones and packstones) is about

43 percent (less than the original about 50 or more % pore space) and the average crinoid grain volume that was dissolved in sediments affected by pressure dissolution during burial diagenesis is about 27 percent. These values show that sediments could lose a substantial part of their original volume after sedimentation.

Tectonic activity in the study area was relatively minor, especially onto sediments itself due to the deposition along relatively passive cratonic margin but the changes in sedimentation rates suggest that tectonic activity or subsidence increased towards the end of the Silurian because of the onset of the collision. During the Caledonian Orogeny, the Baltica continent collided with Laurentia in the west and with Avalonia in the south. This collision led to the closure of the Iapetus Ocean in the early Devonian (Cocks and Torsvik, 2005). This explains the progressive increase in subsidence and accommodation during late Silurian. The most proximal facies in the east part of the basin are partly lacking due to the post-depositional uplift and denudation (lower Devonian) (Lapinskas, 2000).

The Minija regional stage forms a good example of a carbonate ramp system, as will be discussed, with a stromatoporoid-crinoid-coral dominated carbonate factory. The studied carbonates represent depositional environments ranging from proximal, shallow marine in east Lithuania to distal marine in west Lithuania. The Minija regional stage succession consists of parallel facies belts, which range from dolostones in the east, passing into marine bioclastic limestones with variable dolomite content and with increasing numbers and thickness of marl or sometimes marly shales interbeds towards the west part of the basin, bioclastic limestones change into nodular limestone. Shales and black shales occur in the deepest part of the basin. According to the regional stratigraphic scheme, the Minija regional stage consists of few formations which occur from east to west in this order: Pabradė, Vievis and Minija. The Minija formation is further subdivided into Šilalė and Varniai beds. The present study does not use these formations, but instead focuses on the depositional facies and their lateral and vertical distribution.

1.4. Methods and data

742 core hand samples from cores with good core recovery about 74 percent from a number of wells (N=47) throughout Lithuania (Fig. 1.2) have been selected for this study to assess the various depositional carbonate facies from the shallow basin margin in the east towards the deeper parts of the basin in west Lithuania. All core material was collected by author. In total 323 thin sections (20 µm thick) from 36 wells were prepared for standard petrographic analysis. Biggest part of thin sections was done by author himself. Some of the thin sections were selected for scanning electron microscopy (SEM), which was done by author himself. Small numbers of the thin sections were partly stained with Alizarine red S for easy recognition of dolomite. The sediments were classified using the Dunham (1962) carbonate classification system expanded by Embry and Klovan (1971). This system classifies carbonate sediments mainly according to their depositional texture, i.e., mud-supported or grain-supported framework and the abundance of detrital grains and matrix. The carbonate classification in the Minija regional stage was done by author. The texture as such is linked to the initial type of pores. Selected core samples in particular from the reef-like intervals were slabbed and polished (slabbing and polishing were performed by author) for detailed study of the macroscopic features.

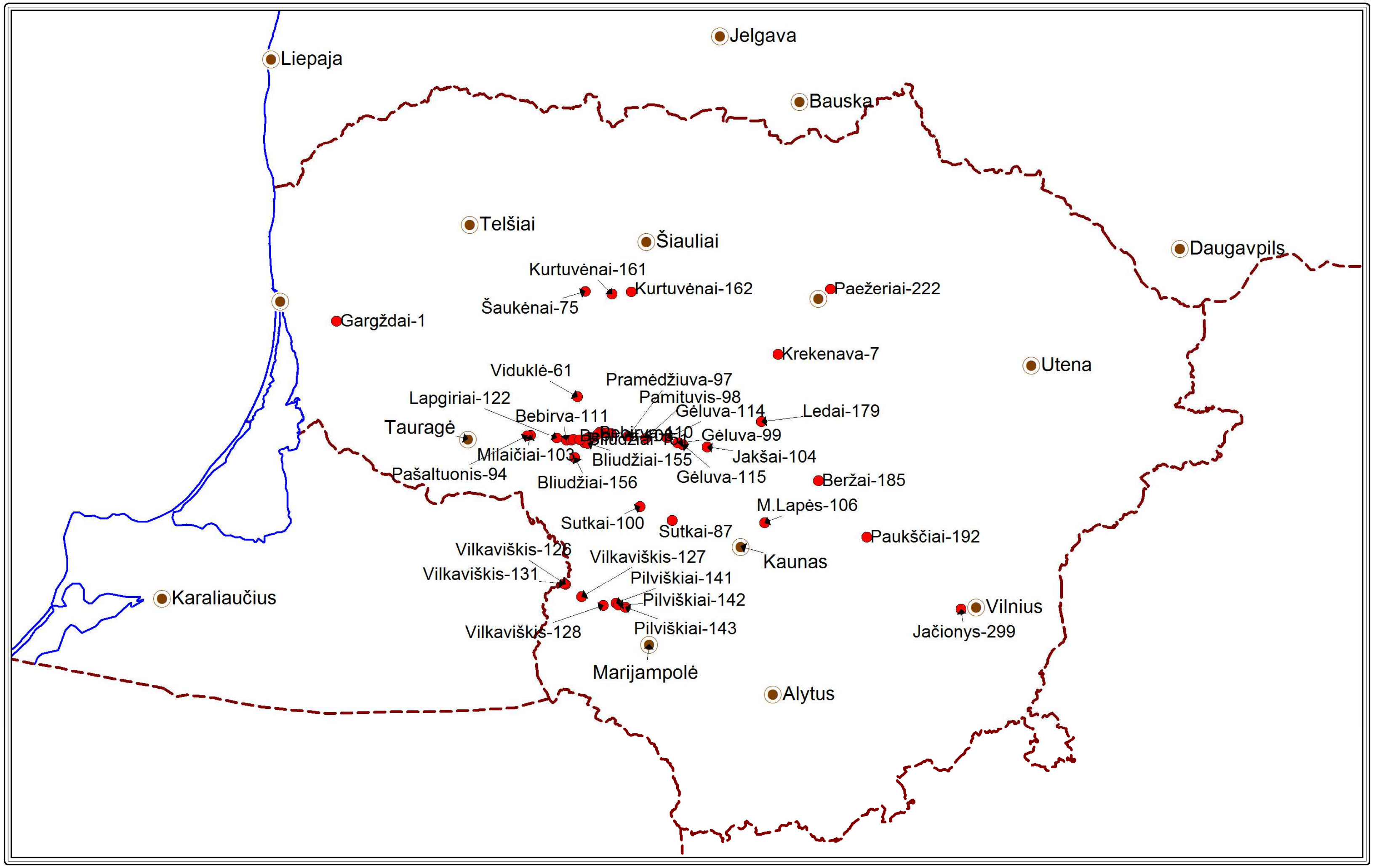


Fig. 1.2 Locations of the wells, which have been investigated during the study.

In total 80 thin sections (20 µm thick) from 16 wells ranging from proximal to the distal parts of the basin were studied by cathodoluminescence (CL) microscopy. CL microscopy was done by author. The latter was done with a cold luminoscope (TECHOSYN) attached to a standard polarized light microscope equipped with a digital camera. Standard operating conditions for cathodoluminescence were 12-15 kV accelerating voltage and 200-600 µA beam current. The CL microscopy was performing in University of Manchester.

To measure porosity for this, study a Helium porosimeter HGP 100 was used. The plugs must be 1 inch diameter (for industry standard equipment) and maximally 7 cm long cylinders (plugs). Prior to analysis the plugs were dried for 48 hours at 50° C. The Helium-porosimeter measures the grain volume of the samples. Porosity was determined from values of grain volume and total plug volume. By weighing the sample the mass was obtained, which gives the opportunity to calculate the grain density. In total 508 new porosity measurements were done at the Technical University of Denmark, part of the porosity measurements was done by author himself, part by students of Technical University of Denmark. Two plugs were selected for repeated (100 time each) measurements of relatively high (22.8%) and relatively low (2.2%) porosity for the reliability of the equipment (standard error). The results of equipment reliability analysis are summarized in Table 1.2. These measurements were done to test the assumption if there is any influence on porosity by plug length. There was not found any influence on porosity values but if the plug is particularly small it is technically difficult to obtain perfect cylinder in particular to obtain two parallel end surfaces. In plugs, thinner than about 5 mm the volume measurements are not sufficiently correct anymore and obtained porosity values become unreliable. Standard deviation for the high porous sample is 0.209% and for the low porous sample it is 0.061%. Industry reports from deep drilling projects provided additional porosity data (N=252). Beside that some permeability data were measured also at the Technical University of Denmark (N=46), the measurements were done by author.

Additional permeability data were gathered from industry reports (N=209). The porosity values are reported in percent and permeability in mD (milli Darcy).

Table 1.2 The results of the porosity equipment reliability.

Well/Depth	BER185/416.2	BEB108/953.3
Average	22.83354	2.19911
Minimum	22.37437	2.04796
Maximum	23.45376	2.36615
Standard deviation	0.20889	0.06136
Number of analyses	100	100
Sample length, cm	4,447	3,825

The precision of the porosity analyses was assessed because of the generally low porosity values measured. Also, the influence of the plug length has been analysed.

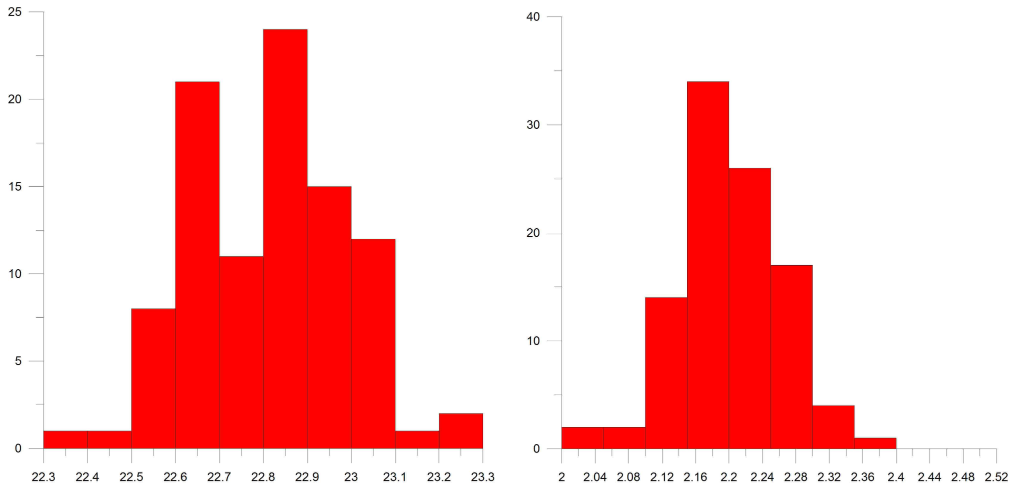


Fig. 1.3 Histograms of 100 measurements from the same sample with relatively high porosity value (left) and with relatively low porosity (right) value. The histograms show log normal distribution of values with very low standard deviation.

The figure 1.3 shows that there is no influence of the plug length on the porosity values.

A number of thin sections (16) from 16 wells and a number of stubs (45) with 3-7 samples in each stub from 24 wells were used for chemical (EMP – electron micro probe) analysis of calcite and dolomite minerals (stubs were done by author). All geochemical data were collected with electron micro probe (EMP) equipment from two stages: first was gathered in the University of Manchester and second one in the Copenhagen University. Six major elements (Ca, Mg, Fe, Mn, Sr and Na) were measured in Manchester, whereas in Copenhagen five elements were measured (Ca, Mg, Fe, Mn and Sr). Some data were collected from the same wells in thin sections and stubs. EMP data from thin sections were gathered in the University of Manchester and from stubs in the University of Copenhagen. All EMP data were collected by author himself.

The quantity of sediments components such as grain, early calcite cement, late calcite cement, late dolomite cement, intraparticle cement, intraparticle matrix, interparticle matrix, replaced bioclasts and interparticle pore space was analyzed by point counting using photomicrographs. To get more objective quantitative results, three photomicrographs from each thin section were used for point counting. In total 174 photomicrographs were counted from 58 samples and from 15 wells. These wells represent a cross section from the proximal shallow (inner ramp) to the distal deep (outer ramp) part of the basin. Point counting analysis from photomicrographs was performed by author.

Ordinary microscopy of the thin sections gives better total view and understanding of facies themselves. Whereas cold cathode luminescence gives general view about cement evolution and partly about geochemistry, because non luminescent carbonates usually are enriched in Fe, whereas very bright luminescent carbonates are iron free and enriched in Mn. Electron microprobe analyses give exact quantities of main elements in carbonate minerals. Point count results give idea about primary pore space, early and late cements. To get a better idea about the quantity of dissolved material through pressure solution (at the grain contacts) and stylolitic (seams) contacts the case of a carbonate with grains of known, regular shapes (crinoid grains are most suitable for this purpose) were used too. Ordinary microscopy as well as cathode luminescence was performed by author.

CHAPTER 2

2. MICROFACIES, LITHOFACIES AND DEPOSITIONAL MODEL

In the beginning for better understanding it is a wish to defined what the microfacies is: it is regarded as the total of all sedimentological and palaeontological data which can be described and classified from thin sections, peels, polished slabs or rock samples (Flügel, 2004). In the study, all components were used except peels. Lithofacies refer as rock type of any particular sedimentological environment, including physical and organic characteristics.

The following microfacies were distinguished using the Dunham (1962) carbonate classification system expanded by Embry and Klovan (1971): marly shales, mudstones, brachiopod-crinoid wackestones, crinoid-brachiopod packstones, crinoid grainstones, stromatoporoid-crinoid or coral-crinoid float-rudstones and dolomudstones. The main characteristics of these microfacies are summarised in table 2.1 and typical examples are given in figures 2.1 and 2.2. It appears that most of the microfacies are mud-dominated and have a matrix-supported fabric. The dolomudstone microfacies is laminated (Fig. 2.1 I), indicating the stromatolitic origin of the laminae with inter- to supratidal conditions.

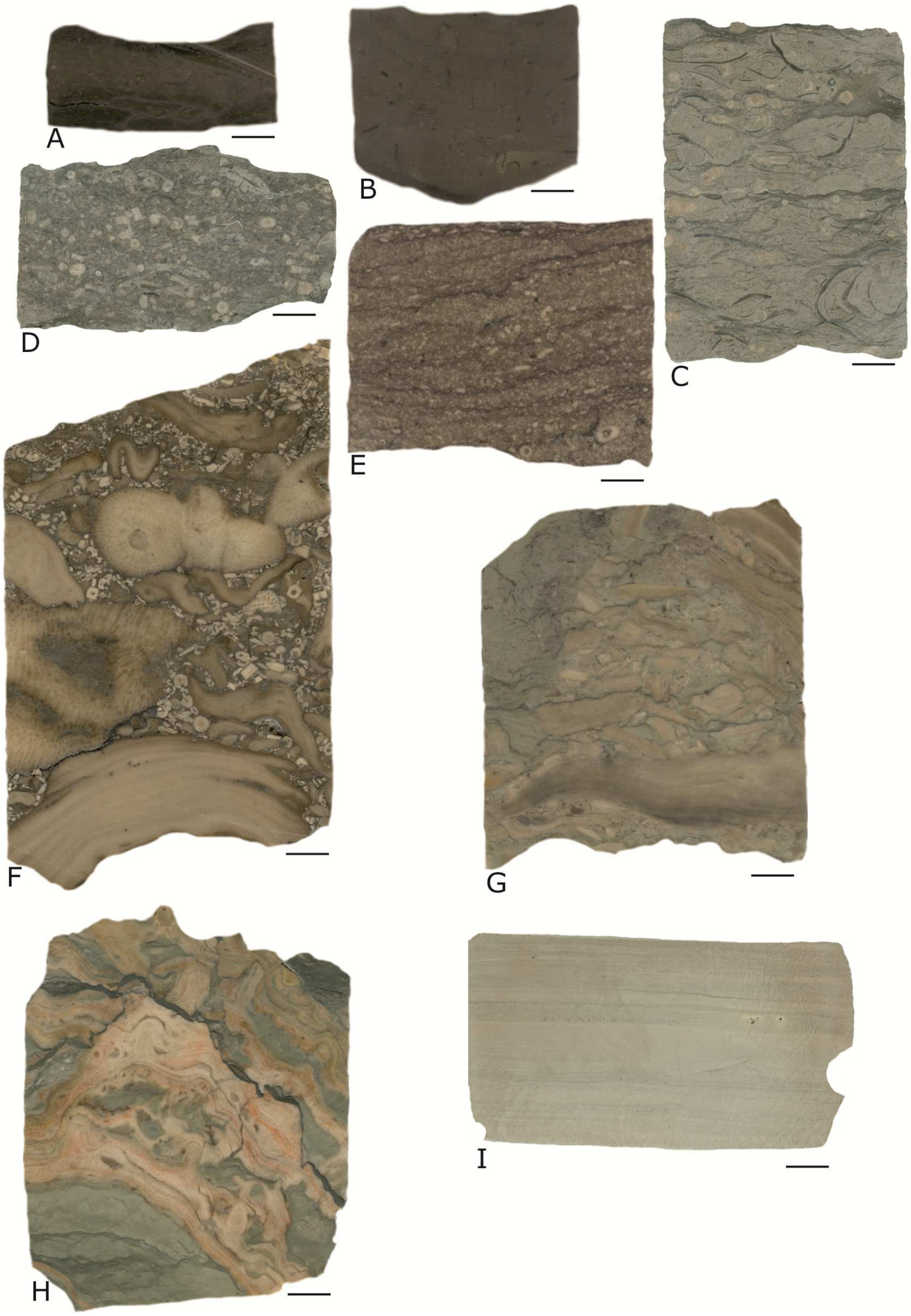


Fig. 2.1 Core slabs of typical microfacies (scale bar 1 cm): A- marly shale from well Viduklė 61 depth 1048.1 m; B- mudstone from well Viduklė 61 depth 1044.7 m with some detritus and brachiopod shell fragments; C-wackestone from well Bliūdžiai 157 depth 935.25 m with crinoids and brachiopods fauna surrounding by micrite; D-packstone from well Bliūdžiai 158 depth 953.05 m with dominant crinods grains and some brachiopod fragments with minor of micrite; E-grainstone from well Vadžgiris 95 depth 971.9 m - the rock consists entirely from the crinoids grains; F-rudstone from well Bliūdžiai 158 depth 916.2 m with large stromatoporoid and coral grains and smaller crinoid grains; G-floatstone from well Šaukėnai 75 depth 1153.9 m with large fragments of stromatoporoid and coral surrounding by micrite mud; H-floatstone from well Bliūdžiai 158 depth 919.0 m - the rock is matrix supported with large stromatoporoids; I-dolomudstone from well Jačonys2 99 depth 97.5 m the rock consist micro dolomite with horizontal lamination.

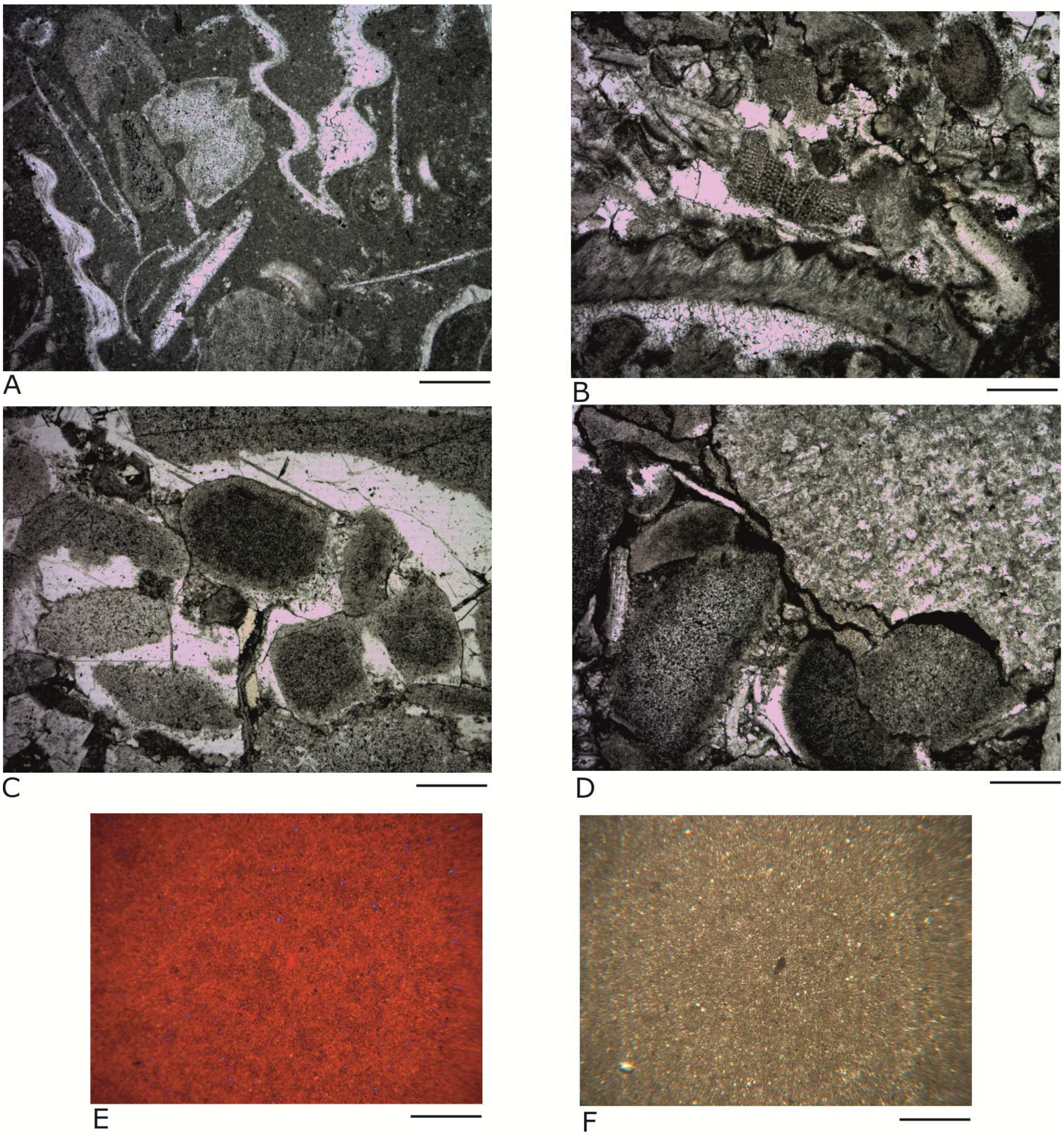


Fig. 2.2 Microphotographs of typical microfacies (scale bar 1 mm): A-wackestone from well Bebirva 111 depth 986.6 m with micrite dominant matrix with crinoids and brachiopods grains; B-packstone from well Bliūdžiai 157 depth 914.7 m - the rock consist mostly of the grains of crinoids, brachiopods and trilobite with a little bit of micrite; C-graistone from well Bliūdžiai 152 depth 940.4 m - the rock consists from crinoid grains cemented by calcite cement; D-graistone from well Bliūdžiai 151 depth 945.8 m - the rock consists of the large stromatoporoid grain and smaller ones crinoid grains; E-dolomustone from well Beržai 185 depth 434.2 m - the rock consist entirely from the microdolomite crystals (cathodoluminescence (CL) microscopy); F-dolomustone from well Beržai 185 depth 434.2 m - the rock consist entirely from the microdolomite crystals.

The coarser carbonate material is exclusively bioclastic, produced by a non-photic macrofauna association comprising flat to domical and irregular stromatoporoids, crinoids, brachiopods and bryozoans. Such a fauna is not bound to a specific water depth or the euphotic zone. In parts of the basin, some tabulate and rugose corals also occur. Most of the rugose corals are solitary, but some small colonies occur as well. All corals and stromatoporoids are relatively small (mainly cm-sized and rarely up to domical forms 5-10 cm in diameter) and often occur in sediments with a mud-supported texture or mudmatrix. In addition, trilobite, gastropod, ostracod and pelecypoda shell remains occur. The main fauna groups which dominant in the study area are shown in the figures 2.3 and 2.4.

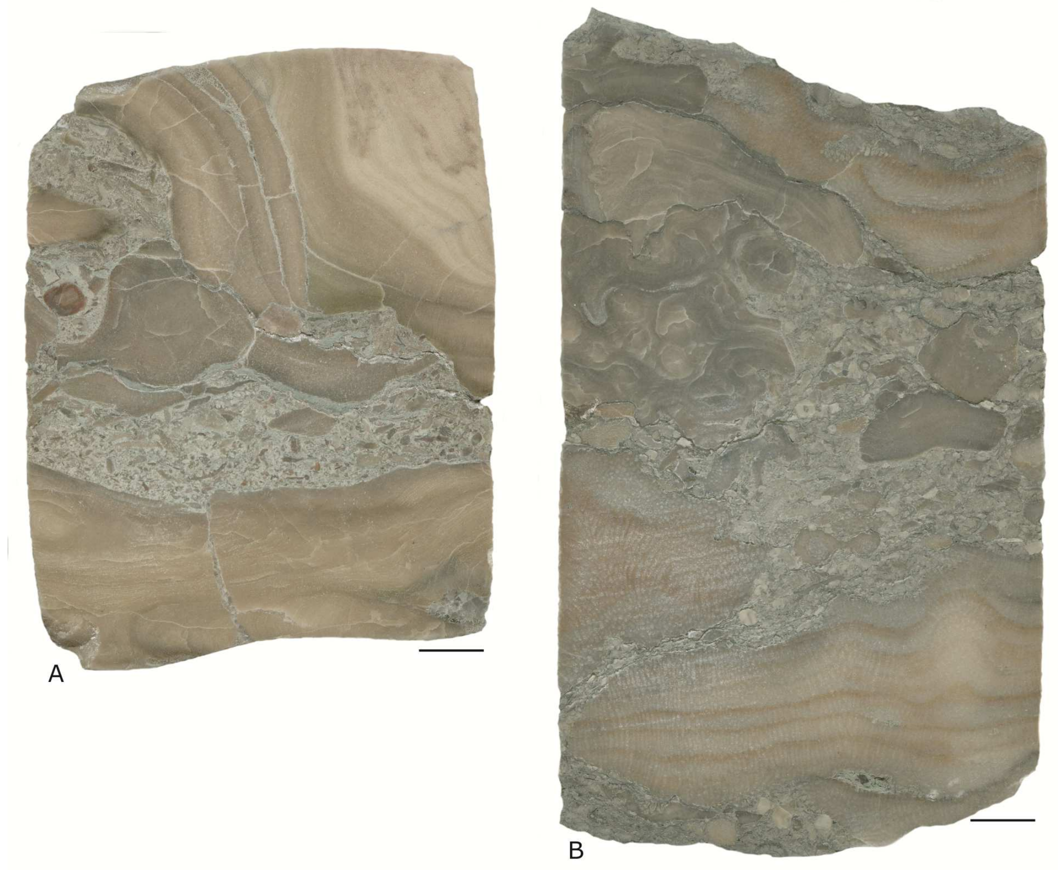


Fig. 2.3 A-slab photo from well Bliūdžiai 152 depth 946.1 m showing floatstone with very coarse and very fine fragments of the stromatoporoids; B-slab photo from well Bliūdžiai 156 depth 916.3 m showing floatstone with relatively small corals colonies with different size of stromatoporoid gains (scale bar 1 cm).

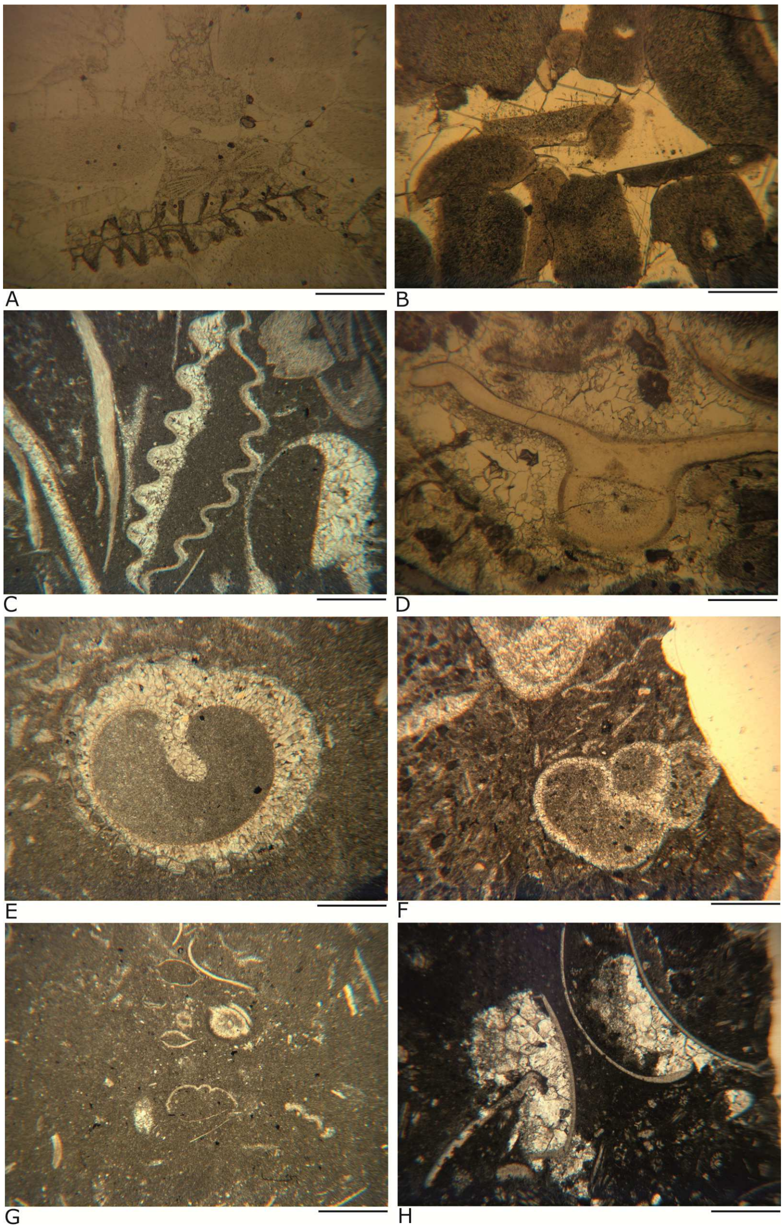


Fig. 2.4 Microphotographs of typical fauna groups which dominant in the study area (scale bar 1 mm): A-well Bliūdžiai 156 depth 911.9 m showing grainstone with bryozoan grain surrounding by crinoid grains; B-well Bliūdžiai 150 depth 942.7 m showing a grainstone composed entirely by loosely packed crinoid grains with different size of the syntaxial overgrowth cement; C-well Bebirva 111 depth 986.6 m showing wackestone with brachiopod shell filled by geopetal pattern. Note that both shells have different oriented geopetal mud fill; D-well Vilkaviškis 128 depth 669.2 m showing grainstone with trilobite shell with original texture preserved. Pores are filled by two generations of calcite cement; E-well Gargždai 1 depth 1402.2 m showing wackestone with gastropod grain (deep part of the basin). The original aragonite shell has been dissolved and filled by calcite cement; F-well Jakšiai 104 depth 683.3 m showing wackestone with gastropod shell (shallow part of the basin) and small shell debris; G-well Bebirva 111 depth 946.0 m showing wackestone with articulated and disarticulated ostracod shells (deep part of the basin); H-well Jakšiai 104 depth 669.9 m showing wackestone with ostracod shells (shallow part of the basin).

Table 2.1 Carbonate microfacies description in the Minija regional stage (Pridoli) of Lithuania based on the Dunham carbonates classification system (1962).

Microfacies	Grains	Grain size	Matrix	Fauna
Marly shale	Non or few bioclasts	<2mm	Dominated by carbonate mud (micrite) and terrigenic siliciclastic material	Brachiopods
Mudstone	Non or few bioclasts	<2mm	Dominant carbonate mud (micrite)	Crinoids, brachiopods, ostracods, bivalves
Brachiopod-crinoid wackestone	Bioclasts	<2mm	Dominated by carbonate mud (micrite) composed of calcite	Crinoids, brachiopods, trilobites, ostracods, bryozoans, gastropods, bivalves, pellets
Crinoid-brachiopod packstone	Bioclasts	<2mm	Minor admixture of carbonate mud (micrite)	Crinoids, brachiopods, trilobites, ostracods, bryozoa, pellets
Crinoid grainstone	Usually well rounded bioclasts	<2mm	Non	Crinoids, brachiopods, trilobites, ostracods, bryozoans
Stromatoporoid-crinoid or coral-crinoid rudstone	Different bioclast shapes from well-rounded to angular	Dominated by >2mm, but smaller ones also occur	Minor admixture of carbonate mud (micrite)	Stromatoporoids, tabulate and rugose corals, crinoids, brachiopods, bryozoa
Stromatoporoid-crinoid or coral-crinoid floatstone	Different bioclast shapes from well-rounded to angular	Variable size	Dominated by carbonate mud (micrite)	Stromatoporoids, tabulate and rugose corals, crinoids, brachiopods, bryozoa
Dolomudstone	Non or few badly preserved	<2mm	Dominated by carbonate mud (micrite) composed of dolomite	Bivalves, gastropods, algae

Of course, it is difficult to assess the exact shape of stromatoporoids from core samples and particularly from thin sections, but it is possible to determine that most of the stromatoporoids are relatively small, flat to bulbous or domical-shaped and more rarely laminar. Larger, cm to dm thick stromatoporoids are rare. Most of the stromatoporoids were not *in situ* but turned over and/or displaced and have angular or well-rounded shapes (Fig. 2.5 A and C). They were overturned or broken by waves and currents which were probably caused by occasional storm-induced currents. The angular shape of many of the stromatoporoids suggests that they were broken and transported over short distances, whereas well-rounded shapes indicate abrasion by transportation over longer distances. Moreover, no stromatoporoids were encountered attached to hard substrates were found, but instead appeared to have grown on soft substrates, i.e. muddy, fine-grained loose sediments. They were thus not bound together and did not build a rigid, stable framework. The stromatoporoids as well as corals are not attached to hard substrates and thus did not form a significant relief above the seafloor other than the height of a single individual or colony above the sea floor.

Bioturbation is intense in the mud-supported deposits and packstones (Fig. 2.5 B). Carbonate mud is abundant across all facies belts, much of the lithology being pack-wackestones. In packstones, the matrix was burrowed or infiltrated, the latter with geopetal accumulations (Fig. 2.5 C and Fig. 2.6 A). Micritization and microboring of skeletal grains are present (Fig. 2.6 B), but only to a minor degree. The intensive bioturbation suggests low net sedimentation rates and also suggest that in these, mud dominated, sediments remained soft and uncemented at or at shallow depth below the seafloor.

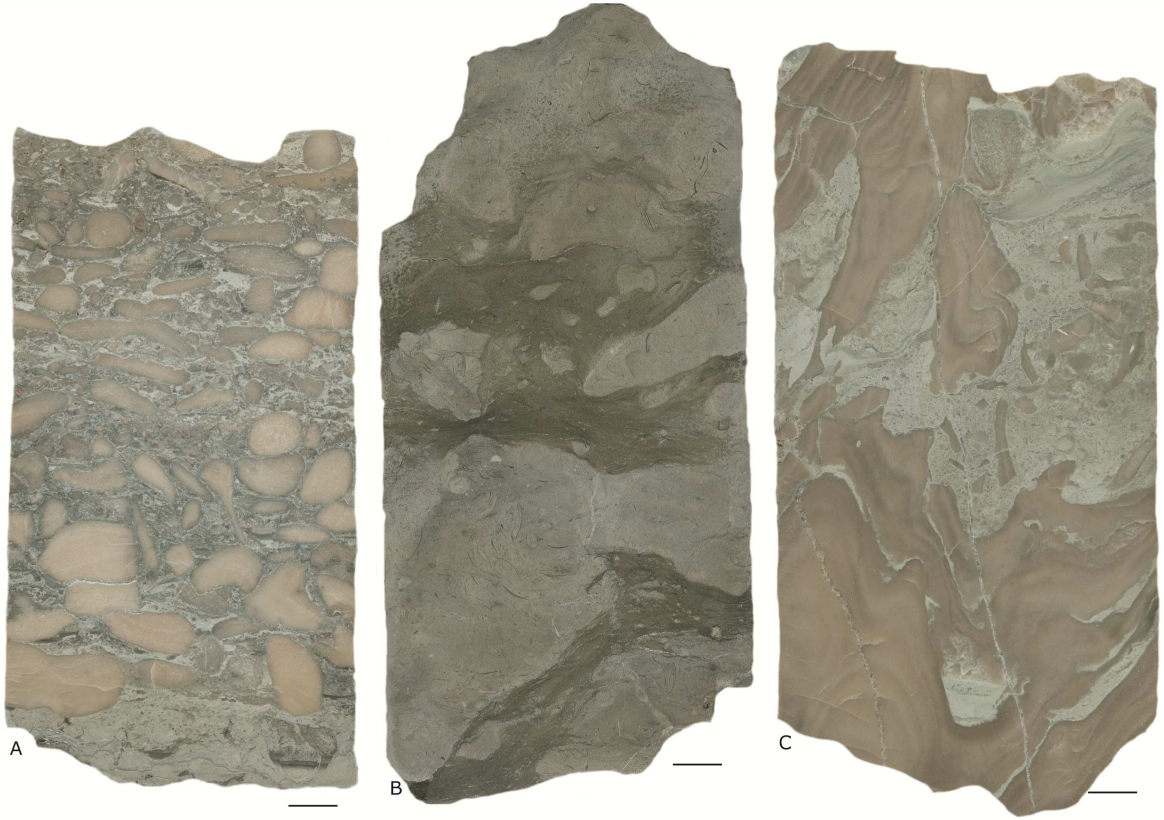
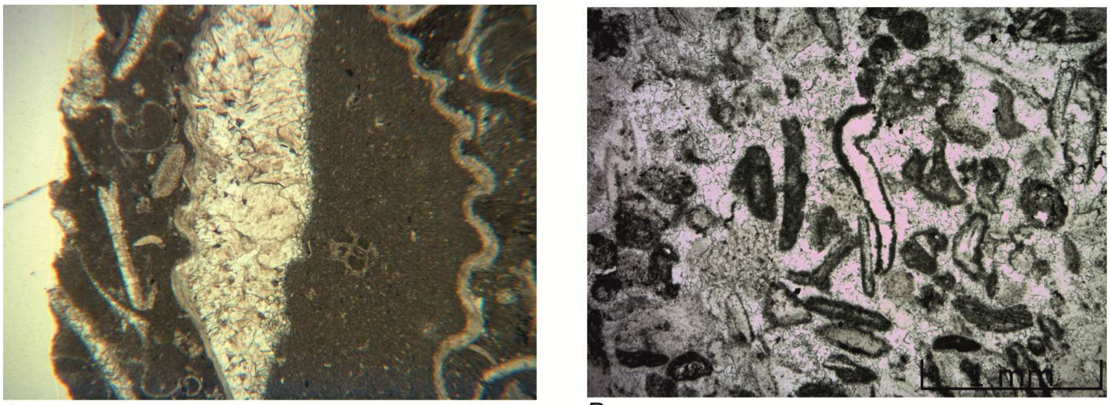


Fig. 2.5 A-core slab from well Bliūdžiai 152 depth 943.1 m, the rock showing well rounded different, but generally relative small size of stromatoporoid grains not in life position and surrounded by carbonate mud; B- core slab from well Bliūdžiai 158 depth 948.16 m, the rock showing intense bioturbations in the nodular carbonate mudstone-shale; C- core slab from well Bliūdžiai 156 depth 931.4 m, the rock showing different size and angular shape of stromatoporoid fragments with geopetal pattern in stromatoporoid. Note that in the geopetal pattern visible some laminations, which suggest that matrix infiltration has some stages and rest of the pore space, were occupied by calcite cement during further diagenesis period (scale bar 1 cm).



A B

Fig. 2.6 A-microphotograph from well Bebirva 111 depth 986.6 m, showing geopetal pattern in the brachiopod shell, which filled by micrite mud and calcite cement as well as with one algae fragment; B-microphotograph from well Bliūdžiai 151 depth 951.6 m showing intense micritization of the carbonate grains, some grains are converted to the cortoids (grains with micrite envelopes), whereas others completely micritized (scale bar is 1 mm).

Most of the macrofauna is present in sediments with mud-supported textures (wackestones) or contain mudmatrix. This suggests a generally low-energetic and muddy seafloor and high-production rates of carbonate mud-sized particles. And although carbonate mud is abundant throughout the system, grainstones are common in particular part (Mid ramp) of the basin. These grainstones usually are rich in crinoid remains, disarticulated, and also contain disarticulated brachiopods shells. The well-sorted nature of the coarse sand-sized material and the absence of micrite in some grainstone layers suggest an environment with occasionally high-energy and well-agitated water and/or in combination with high local grain productivity. Crinoids either were especially abundant and productive in high-energy environments or more likely, since they occur throughout the system including the more distal and deeper parts of the basin, they are easily reworked by currents and storms and selectively deposited in well-sorted grainstones. Post depositional matrix accumulation occurred either by mechanical infiltration in coarse-grained deposits, or actively through bioturbation and infaunal activity. This turned part of the grainstones and coarse-grained rudstones into packstones with pores partly filled with matrix.

Based on core macro description and distinguishing microfacies based on Dunham (1962) classification expand by Embry and Klovan (1971) the geological cross section was build (Fig. 2.7).

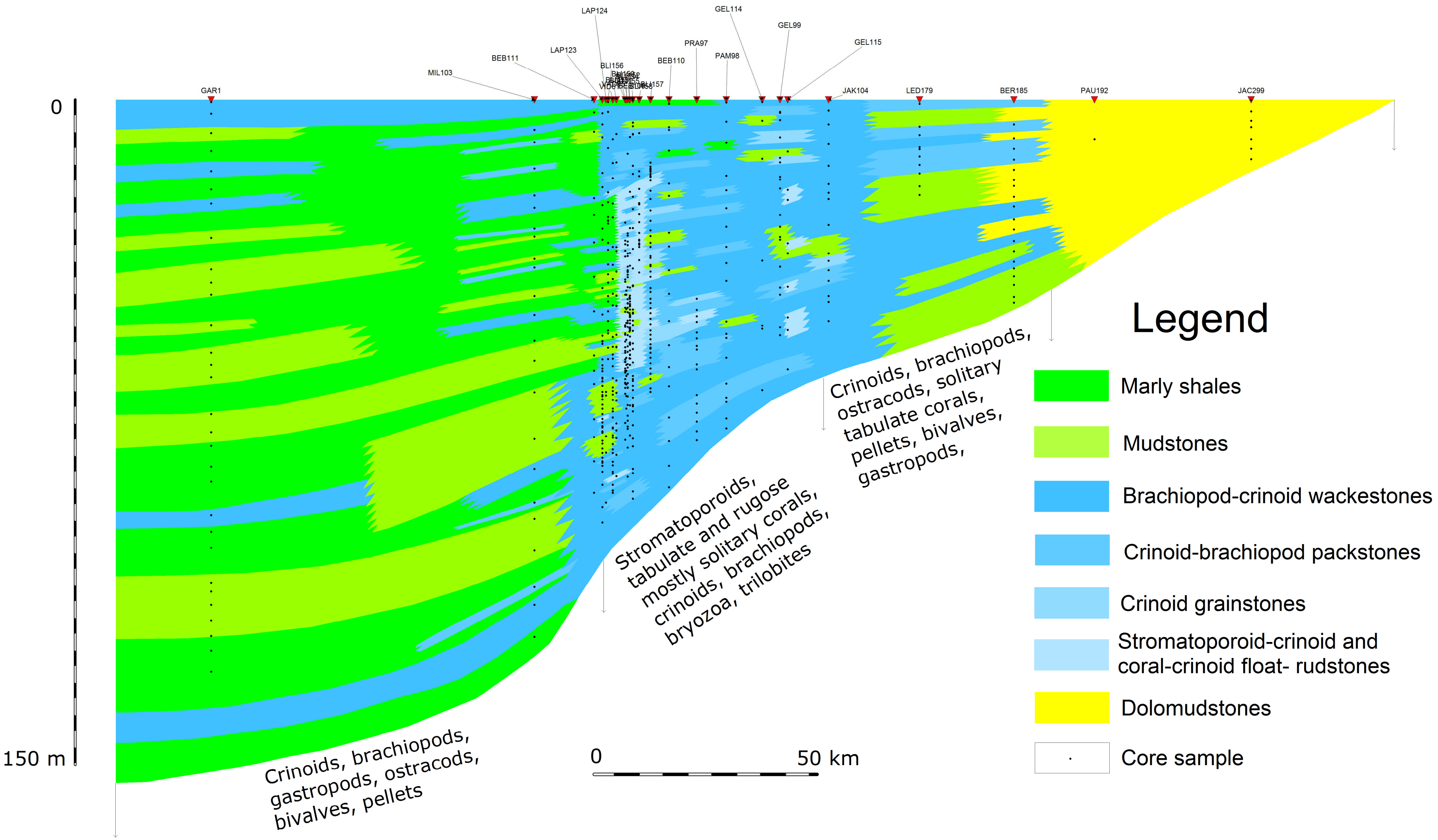


Fig. 2.7 Geological cross section (west-east direction) showing distribution of microfacies within Silurian Baltic basin.

Based on the microfacies, lithofacies and faunal distribution, a depositional model for the Minija regional stage carbonates was constructed (Fig. 2.8). The sedimentary system can be subdivided into five major, parallel depositional facies belts with typical lithofacies associations (Table. 2.2). From the proximal, near coastal to the distal, central basin these are: 1- a broad, near coastal facies belt with dolomudstones. Fauna is very rare in this facies belt, badly preserved and often dissolved; 2- a shallow facies with wackestones and mudstones with some coarse-grained bioclastic packstones, grainstones or rud- to floatstones. The fauna consists of bivalves, ostracods, gastropods, crinoids and brachiopods; 3- a central facies with coarse-grained bioclastic stromatoporoid - coral and crinoid deposits ranking from grainstones to rudstones and floatstones; 4- a deeper slope, fine-grained muddy facies belt with some thin intercalations of coarse-grained bioclastic packstones; 5- a distal, deepest slope facies with marls-shales and black shales. The depositional environments are briefly summarised in table 2.3. The central facies belt is the most fauna rich with respect to quantity and diversity of the whole system. This facies is composed mainly of floatstones and rudstones.

Table 2.2. Description of the lithology, classification and fossil content of the facies belts across the Pridolian carbonate ramp in Lithuania. This is based up on core descriptions, thin section petrography and the fauna distribution.

The main ramp facies	**Intertidal - subtidal shallow Inner-Ramp**	**Subtidal Inner Ramp**	**Mid Ramp**	**Outer Ramp**	**Basin floor**
Lithology	Dolostones	Limestones	Limestones	Limestones, marls and shales	Marls and shales
Dunham classification	Mudstones	Bioturbated Wackestones and mudstones with some coarser grained packstones and grainstones	Mostly rudstones and floatstones with grainstones, packstones, wackestones and mudstones	Bioturbated Mudstones and wackestones-packstones	Mudstones with wackestones (packstones)
Fossil content	Brachiopods, Bivalves?	Crinoids, brachiopods, ostracods, solitary tabulate corals, bivalves, gastropods	Stromatoporoids, crinoids, tabulate and rugose mostly solitary corals, brachiopods, bryozoans, trilobites	Crinoids, brachiopods, gastropods, ostracods, bivalves	Crinoids, brachiopods, ostracods,

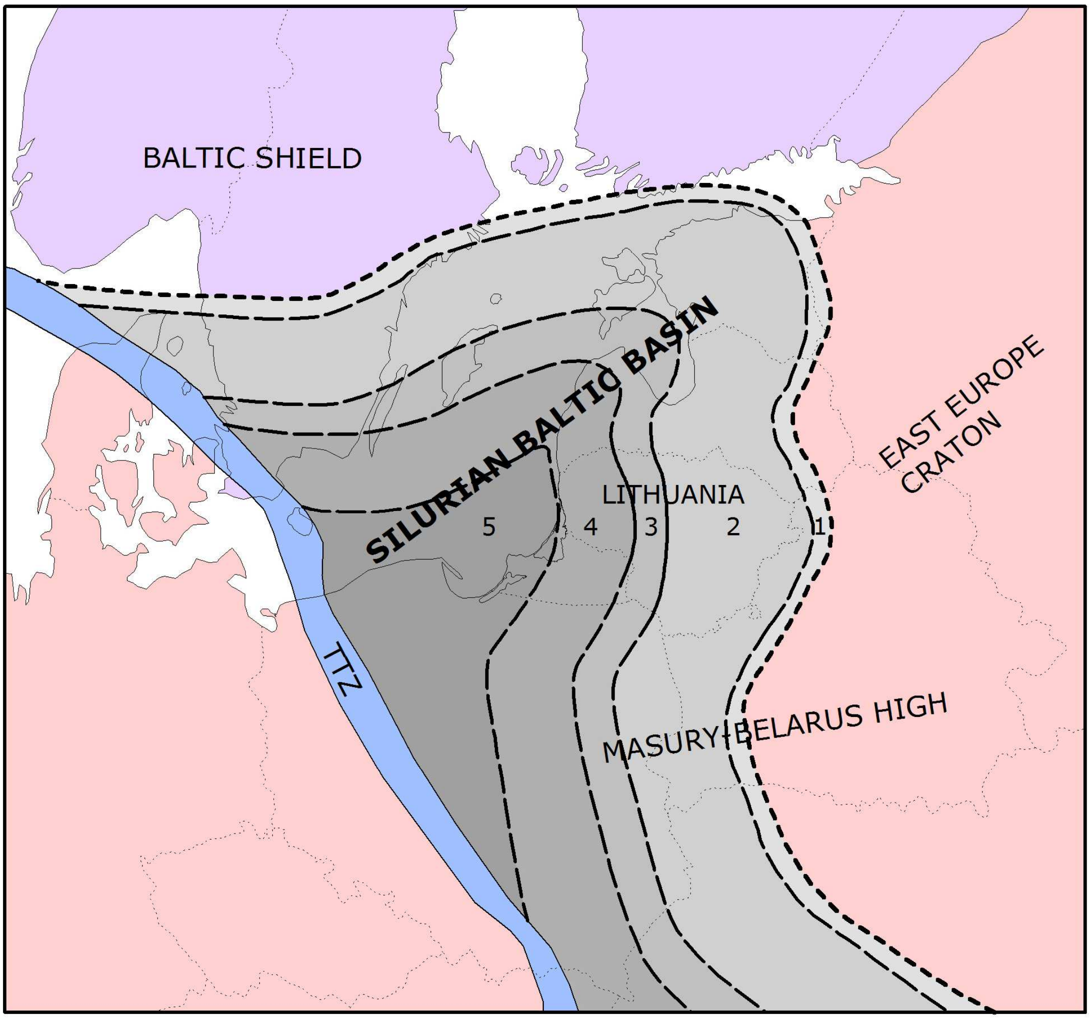


Fig. 2.8 Facies distribution in Silurian Baltic basin. The boundaries between facies within Lithuania territory (solid lines) are based on study data, the boundaries outside Lithuania territories (dashed lines) are extrapolated. 1 - sabkha; 2 - Inner shallow ramp; 3 - Mid ramp; 4 - Outer ramp; 5 - Basin floor.

Table 2.3. The main features of sediments in the various depositional facies belt.

lithofacies	**microfacies**	**dominant fauna**	**structures**	**depositional environment**	**ramp facies belt**
dolostones	dolomudstones, dolowackestones	ostracods, bivalves	laminated-bedded	intertidal to shallow subtidal deposition	inner-shallow ramp
limestones, some dolostones	mudstones, wackestones, packstones	crinoids, ostracods, bivalves, brachiopods, gastropods	bioturbated, bedded to thin bedded	Subtidal, well oxygenated	inner-shallow ramp
limestones	rudstones, floatstones, grainstones, packstones	stromatoporoids, tabulate and rugose corals, crinoids, bryozoans, brachiopods, trilobites	bioturbated, bedded, interbedded	below wave base, below photic zone, above fair weather storm base, storm reworking	mid ramp
limestones, marls, shales	mudstones, wackestones, packstones	crinoids, brachiopods, gastropods, graptolites	bioturbated, nodular bedded, interbedded	low energy, below wave base, pelagic and storm deposition	outer ramp
shales, marls	mudstones, wackestones	graptolites	bedded-laminated	occasional distal storm deposition, siliciclastic low energy deposition	lower ramp slope – deep basin

2.1. Stromatoporoids

A typical and abundant skeletal component in the central area is stromatoporoid, mostly fragments. Of course, it is difficult to assess the exact shape of stromatoporoids from core samples and particularly from thin sections, but it is possible to determine that most of the stromatoporoids are relatively small, flat to bulbous or domical-shaped and more rarely laminar. Larger, dm thick stromatoporoids are rare. Most of the stromatoporoids are not *in situ,* not in life position but displaced (Bičkauskas and Molenaar, 2008a). They are overturned and most are broken with angular or well-rounded shapes (Fig. 2.5 A and C). They were overturned or broken by waves and currents which were probably caused by occasional storm-induced currents. The angular shape of many of the stromatoporoids suggests that they were broken and transported over short distances, whereas well-rounded shapes indicate abrasion by transportation over longer distances. Moreover, no stromatoporoids were encountered attached to hard substrates, but instead appeared to have grown on soft substrates, i.e. muddy, fine-grained loose sediments that were not cemented but also on crinoidal packstones. The stromatoporoids were thus not bound together and did not build a rigid, stable framework. Such stable frameworks are typical for modern Cenozoic coral-red algal reefs. The stromatoporoids as well as the corals are not attached to hard skeletal substrates such as other large skeletal material including stromatoporoids. Calcareous red algae or calcimicrobial crusts are lacking. These bind skeletal coral material together during the Cenozoic and form large frameworks in modern coral-red algal reefs. The Silurian stromatoporoids instead appear individuals that they individuals loose from each other. Also, the eroded and displaced nature of most of the large skeletal material suggests that a form framework and early synsedimentary cementation was lacking.

Although most material is displaced and thus could be regarded as talus deposits from a reef, a reef talus composed of cemented reef/framework parts is absent. It may therefore be questioned if the stromatoporoids and corals formed anymore relief above the seafloor than the height of the living individuals or colony themselves.

2.2. The central facies belt: reefs or biostromes?

Traditionally the central facies belt is interpreted as a reef belt or barrier reef based up on the occurrence of stromatoporoid and/or coral remains (Laufeld, Bassett, 1981; Calner et al., 2004). One of the main questions to be answered is if these deposits are reefs (at least bioherms) or biostromes. The term 'reef' is often used very loosely in the literature, without giving clear definitions or adequate references defining the terminology. This implicitly leads to misunderstandings or wrong preconceptions about the nature of the sediments involved and the consequent interpretation of the depositional system and distribution of petrophysical properties. The terminology needs to be more strictly used, or the pertinent sediments need to be better described, allowing more useful interpretations of the depositional systems and their economic, i.e. oil, potential.

According to most of the literature, scientists tend to regard both terms as more or less synonymous and take the presence of larger colonial organisms as direct evidence for reefs. But taking a closer look at the definitions of the terminology it quickly becomes clear that both presumptions are not true. In appendix 1 a summary is presented of the definitions of the various terms such as 'reefs' and 'biostromes'. Indeed, most scientists claim that as soon as corals or stromatoporoids are present there is a reef but they also claim that this reef gives biostrome shape. First of all, the definition of a true '**reef**' is given according to this study. It implies a true coherent framework of calcareous skeletons from colonial organisms, lithified by early marine cements and with a clearly expressed morphology on a sea floor accompanied by talus deposits. Bioherms have a loose structure lacking a stable framework, whereas biostromes are lacking both framework components and any substantial seafloor relief. This definition of a reef is more or less the same as from a pure sedimentological point of view, that defines a reef as a structure having a stable and thus interconnected framework of sessile carbonate fossils, that distinctly arises above the sea floor, and that is early marine cemented and thus able to resist the action of waves and currents. This kind of structure should be accompanied with talus deposits in the front and back of the reef. In the study area, no such structures have been observed either in outcrops, cores or thin sections.

The limestones in the central facies belt, according to most of the literature (e.g. Kaljo, 1977; Paškevičius, 1997; Lapinskas, 2000), belong to a so-called reef belt, in the Silurian Baltic Basin are dominated by stromatoporoids with variable contents of tabulate and rugose corals, bryozoas and crinoids as main carbonate producing metazoan fauna elements. Occasionally corals are dominant. Rarely these deposits also contain calcareous encrusting organisms such as microbialites, calcimicrobes and calcareous algae.

Some recent studies of the central stromatoporoidal facies belt in Lithuania (Staškus, 2013) concluded that most of the central stromatoporoidal facies belt bodies appear as biostromes and has generally low relief. The same opinion was presented by Bičkauskas and Molenaar (2008 b).

For many decades, Gotland (Sweden) (Llandovery, Wenlock and Ludlow deposits) and Estonia (Llandovery-Pridoli deposits) were major research areas in Europe for Silurian reef-like carbonates, i.e., reefs in the implicit or explicit sense of biologically produced build-ups with relief in carbonate platform systems. In particular, there are numerous studies on the reefs of Gotland, some of them with excellent and comprehensive descriptions (e.g. Manten, 1962). Most of these studies are based on outcrops, which are common along the coastal cliffs around Gotland and the north of Estonia. Similar reef-like buildups recently have been interpreted from seismic data under the Baltic Sea (Flodén et al., 2001).

Several types of reefs in Baltic Silurian have been distinguished based upon their main fossil associations and also upon the dimensions but also various classifications and interpretations offered. Most of the reefs described from the Silurian in the Baltic Basin are of limited extension and thickness (Riding, 1981; Nestor, 1995). Some of the reefs are very small (Riding, 1981; Nestor, 1995; Kaljo, 1977) merely a few single colonies in a single bed, others are more extensive in the range of metres to tens of metres and thicker, but seldom more than a few metres of thickness. In particular, in Estonia most of the described reefs are small, usually only decimetres thick and few meters across (Kaljo, 1977). Kaljo (1977) described three different types of bioherms in Estonia based on their fossil association. A first type of bioherm mostly contains bryozoans, corals and algae. The second one consists mostly of corals and algae and a third type contains corals, stromatoporoids and algae. These bioherms are relatively small with a height varying from 1 to 6 m and a diameter between 4 and 50 m (Kaljo, 1977).

Kershaw (1993) regards the Silurian carbonates on Gotland containing mainly stromatoporoids or other autochthonous fauna like corals or algae as reefs. The size of these reefs varies from 0.5 to 12 m high and from 50 to 100 m width. One reef can have both biohermal and biostromal like phases such as the early Ludlow reefs in the Högklint and Kopparsvik formations in Gotland (Kershaw, 1993). To the contrary, the same Hogklint formation reefs are described by other authors as mere patch reefs up to 35 m thick and 100-150 m wide (Watts, Riding, 2000).

Kershaw and Mõtus (2016) described Ludllow series stromatoporoids and corals assemblage in Saaremaa and Gotland islands as bistromes with small (around 150 m wide), but dense fauna of stromatoporoids and corals appearances. Due to the short of information it was not possible to established controlling factors (i.e. environmental differences) on stromatoporoids and corals taxa in the different part of Silurian Baltic basin (Kershaw & Mõtus, 2016).

Stromatoporoid dominated deposits of the Ludlow Hemse group have dimensions of 0.5-5 m thickness and range from a few tens of meters to more than 1 km in lateral extension. Since some of these deposits have predominantly in situ fossils they are regarded as reefs (e.g., Sandström, Kershaw, 2002). A contradictory interpretation was given by Flodén et al. (2001) who investigated the Klinteberg-Hemse reef succession (Upper Wenlock-Lower Ludlow) and claimed that: '…the reef barriers are built up of biostromal limestone dominated by stromatoporoids in an argillaceous or crinoid limestone matrix with bryozoans and solitary corals'. Other authors interpret the same deposits as areas with patch reefs (Watts, Riding, 2000; Calner et al., 2004). Conflicting and contradictory statements and explanations are thus common.

Bjerkéus and Eriksson (2001) interpreted reef structures from seismic data. They found at least four reef barriers in Hemse sedimentary rocks in offshore area east of Gotland, which extend from the mainland of Gotland to the Estonian and Latvian mainland. They acknowledge that these are not, in the strict sense, true barrier reefs but rather composed of several vertically stacked flat biostromes (Bjerkéus, Eriksson, 2001).

From the available descriptions of reefs, it can be deduced that most are in fact biostromes and although they may be the main carbonate factory they have nothing to do with true reefs. However, the supposed presence of reefs tends to further misleading interpretations of the whole system.

It may raise a question what all this literature overview of Gotland Silurian has to do with current research. The answer could be as follow: the Silurian rock in the Gotland is a part of the same Silurian sedimentary basin as in Lithuania.

A number of researchers interpreted the Silurian Baltic basin as a platform depositional system because of the presence of reefs (Laufeld, Bassett, 1981; Calner et al., 2004). The argumentation for platform or ramp interpretation is not always clear and some authors even suggested that during the Silurian the systems are mainly platforms but ramps are also present (Sandström, Kershaw, 2002; Calner et al., 2004).

According to this study a carbonate ramp has a more or less uniformous depositional slope which gradually passes from a high-energy shore line into deeper muddier depositional environments. The steepness of the slope is merely a few degrees. A platform has a depositional slope which is not uniform and is rimmed in the middle part where a change profile from almost horizontal in the most shallow parts to a steep slope towards the basin centre. The rimmed middle part could from time to time rise above sea level. The shallow part behind the rim has often a restricted water circulation with the open sea.

According to the literature the central facies belt in Lithuania contains reefs or barrier reefs (Kaljo, 1977; Paškevičius, 1997; Lapinskas, 2000). Some oil shows have been found in deposits of this central facies belt. The vertical succession is arranged in more or less symmetrical depositional-lithological cycles that range from marls, nodular limestones to limestones that form the main lithology in this facies belt. The limestones are mainly packstones and grainstones, some of which are coarse grained and are better-called rudstones or floatstones, with few wackestones and mudstones. The coarse bioclastic material is mainly stromatoporoids, with bryozoans and some tabulate and rugose corals. The finer bioclastic material dominantly consists of crinoids, brachiopods, bryozoans and trilobites. The limestones are all well bedded.

Most of the rudstones and floatstones (Fig. 2.9) consist of coarse-grained calcareous fossils such as stromatoporoids and tabulate or rugose corals that are mostly displaced and not *in situ*. Matrix is dominant in floatstones, but in rudstones it occurs as well. Flat stromatoporoids are often arranged parallel to the bedding but have random stratigraphic facing, flattening accentuated by pressure solution and stylolitization during burial. These limestones are arranged in merely cm-dm thick beds. Most of the fauna is displaced, not in life position, re-orientated and transported for some distances.

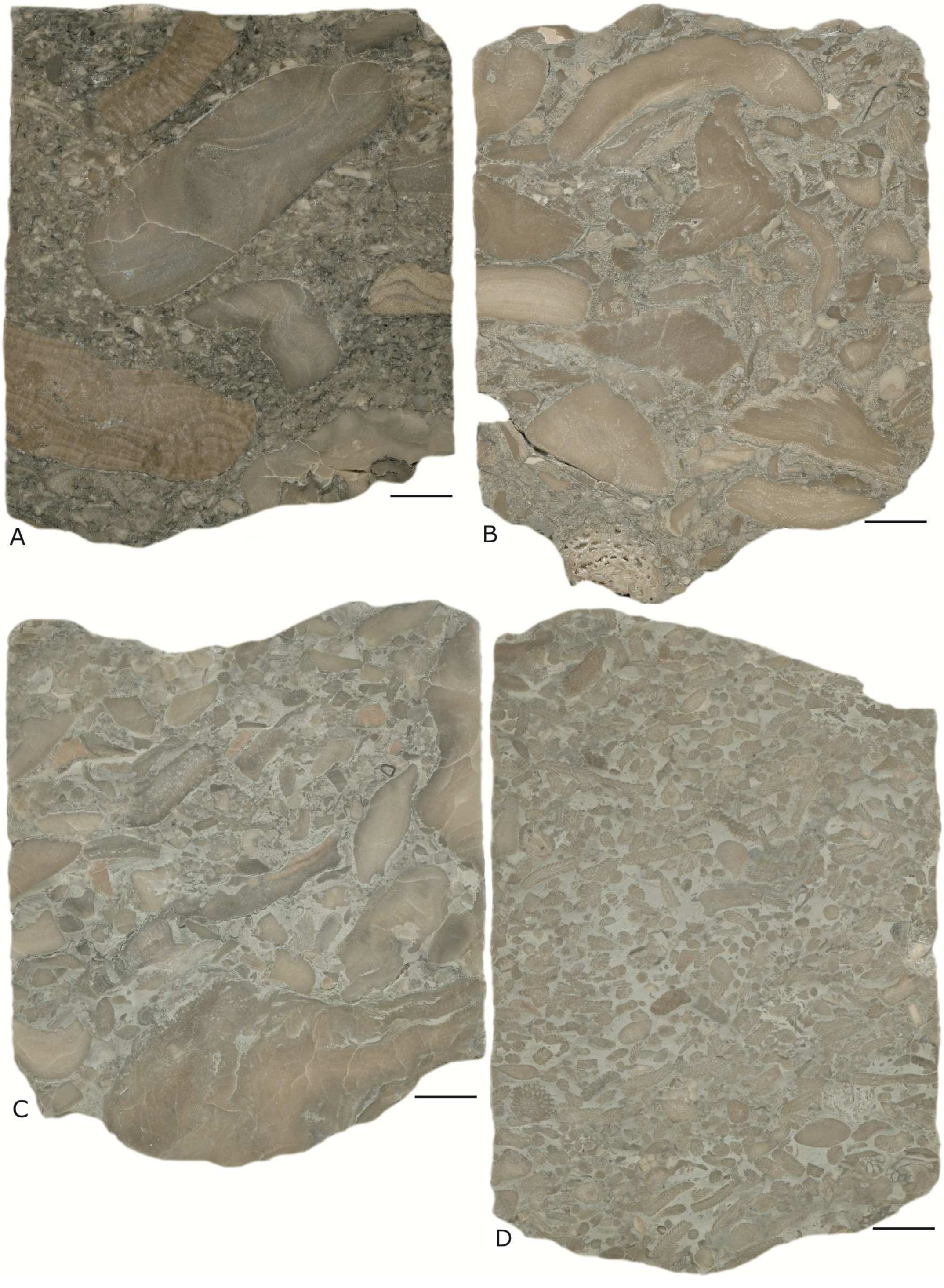


Fig. 2.9 A-core slab from well Bliūdžiai 150 depth 946.9 m showing rudstone of different size, but well-rounded coarse stromatoporoid and coral and smaller crinoid grains; B-core slab from well Bliūdžiai 152 depth 931.4 m showing rudstone of different size angular shape mostly stromatoporoid grains; C-core slab from well Bliūdžiai 156 depth 926.4 m showing floatstone of different size mostly angular shape stromatoporoids grains incorporated into mud supported sediments; D-core slab from well Bliūdžiai 156 depth 930.5 m showing floatstone of well-rounded stromatoporoid or coral grains in mud supported sediments. Note that all samples represent grains which are not *in situ* position, it suggests that the grains were transported for some distance (scale bar is 1 cm).

Floatstones and rudstones are generally assumed to be associated to the true reef facies forming the flanking talus deposits in front and backside of reefs. Intraclasts, i.e. cemented broken parts of a true synsedimentary lithified reef, are lacking completely in the studied area. In addition, evidence for synsedimentary marine cementation is also absent. Talus deposits are absent in most if not all the Silurian Baltic Basin (see the excellent descriptions of Manten, 1962). The observed floatstones and rudstones are no talus deposits, but instead form the biostromal facies proper that is characterized by a varying degree of displacement and redeposition by storm-induced currents (e.g., Sandström, Kershaw, 2002). However, these floatstones and rudstones are associated more to biostromes instead of reefs.

The presence of framework building skeletal remains may be clear in outcrops, but may be difficult to detect in cores. Similarly, *in situ* and life position of skeletal elements is a difficult and unclear criterion since much of the skeletal organism may be dislocated by storms, in particular in Mesozoic-Cainozoic reefs that grow in shallow water close to the sea level. However, encrusting organisms or remains of photosynthetic calcareous algae are easy to detect, also in core samples, and they have not been found in the study area.

The angular shape of many of the stromatoporoids suggests that they were transported for short distances, whereas well-rounded shapes point to transported over longer distances. Moreover, stromatoporoids have not been encountered attached to hard substrates but instead appear to have grown on soft substrates, i.e., muddy, fine-grained sediment. They were thus not bound together and did not build a rigid, stable framework (Bičkauskas and Molenaar, 2008a). Some research provided evidence that stromatoporoids alone are not able to produce stable framework. Evidence that stromatoporoids and Palaeozoic corals alone are not capable to build a framework was for instance presented by Nose et al. (2006). For a stable framework encrusting stromatoporoids, microbialites, calcimicrobes or calcareous red algae are needed (Meyer, Price, 1993; Nose et al., 2006), the latter indicating presence in the photic zone. However, it may be difficult to determine if the fossils are indeed in place and undisturbed or not, especially if the fauna did not build a framework (Sandström, Kershaw, 2002). Sandström and Kershaw (2002) presented the opinion that stromatoporoids did not fixate themselves to a hard substrate at all. Large ones are unstable and easily turned over, smaller and flat ones being more stable but potentially mobile. Kershaw (1998) and Sandström and Kershaw (2002) presented experimental evidence that currents could move stromatoporoids without being overturned. In the study area, a framework indeed has not been observed.

More recent research in Lithuania Silurian Baltic basin (wells Bliūdžiai157 and 158) in Minija regional stage also did not find any hard grounds in the basement of biostromes, just mud supported matrix (Jakaitė, 2010).

There is common saying or better calling it a priory assumption that when fauna considered typical for reefs is found in particular parts of the basin, and thus barriers or rims should be present, the whole carbonate system is considered to be a platform. In fact, thus the presence or absence of true reefs controls the nature of the carbonate depositional system: either a platform or a ramp. In table 2.4 summarizes the definitions of carbonate platform and ramp according to several authors. So far, the Silurian Baltic basin was usually interpreted as a carbonate platform (Kaljo, 1977; Lapinskas, 2000; Stentoft et al., 2003) with a central reef belt. Most of the platforms in the Palaeozoic are apparently accompanied by reef belts. Here we come again to the critical point what exactly is a ‘reef’? In platforms, as a result of the presence of reef barriers, lagoons develop behind the reefs with a more or less restricted water circulation. In the lagoons, the salinity therefore tends to be higher than normal marine, which results in decreased bioturbation and reduced or less diverse biota and biogenic activity. Lagoonal sediments therefore may be laminated. Besides, lagoonal deposits therefore often contain evaporitic minerals like gypsum, anhydrite, or halite. Any of these features have not been found in the research area.

Table 2.4. Some term such as ‘ramp’, ‘platform’ definitions based on literature.

Ramp	Platform	Reference
The term **carbonate ramp** was adopted to describe a gently sloping depositional surface which passes gradually without slope break from a shallow, high-energy environment to a deeper, low-energy environment.	The term **platform** described shallow-marine carbonate bodies with flat tops and steep flanks, formed by the accumulation of sediment on the shelf or in the ocean.	Erik Flügel (2004) Microfacies of carbonate rocks Analysis, interpretation and application.
	‘**Carbonate platform**’ is a general term. It is used to refer to carbonate sequences developed in a range of geotectonic settings and also to any depositional surface upon which shallow-water carbonate facies are deposited. It embraces a spectrum of depositional profiles between two end-member: homoclinal ramps and rimmed shelves.	Luis Pomar (2001) Types of carbonate platforms: a genetic approach.
A **carbonate ramp** is a gently sloping surface (generally less than 1°) on which near shore wave-agitated sandy facies pass offshore into deep-water, more muddy facies. Barrier reefs are generally absent, but mud mounds and pinnacle reefs are not uncommon on ramps.	**Carbonate platform** is used as a very general and loose term for a thick sequence of mostly shallow-water carbonates.	Maurice E. Tucker and V Paul Wright (1990) Carbonate sedimentology

For lagoon, depositional environment some depositional features should be present such as those indicating low energy depositional environments with (semi)closed connection with the open sea. However, such features were not observed. In all facies, apart from the most proximal dolomudstones, bioturbation is abundant and usually sedimentary structures resulting from tractive transport are absent. Evaporitic minerals or laminated structures indicating lack of oxygen is also absent. More important, there was no physical barrier that could close off lagoons from the open sea. A lagoon therefore was absent. Only the dolomudstone facies have laminated structures, pointing more to stromatolitic laminae origin with storm layers and inter- to supratidal conditions. Since this facies belt is broad, it suggests a very low and gradual depositional slope towards the centre of the basin.

Total carbon and organic carbon data shows (Fig. 2.10) that there are no big differences in carbon content in the different depositional facies. It means that most likely dark colours in so-called lagoon is caused not because of a lot of organic quantity but they are mudstones with disperse fine crystalline pyrite, which gives dark colour. During current studies, it was not found any sedimentological or geochemical clues for lagoon sedimentation environment.

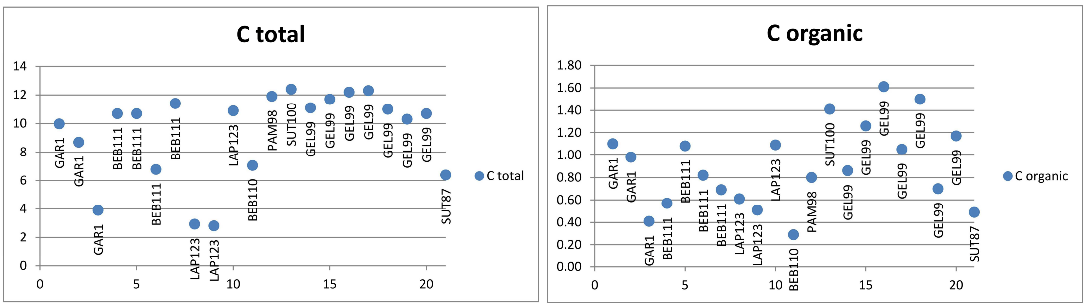


Fig. 2.10 Scatters show distribution of the total carbon (left) and organic carbon (right) content from the deepest to the shallowest (west-east direction) parts of the Silurian Baltic basin.

Basically, the major control on the facies in a ramp is the water energy, i.e. the depth of the fair-weather wave base and storm-wave base, variations in topography and depositional slope. The carbonate material is transported (or redeposited from the carbonate factories) by storms, waves and tides (e.g., Pomar, 2001; Flügel, 2004).

Most of the modern scleractinian corals, which build reefs, are colonial and fixated to hard substrates or (coarse grained) shelly carbonate sands and are prone to build rigid and stable frameworks through interconnected colonies. In contrast, Silurian corals like tabulate or rugosa are mostly solitary and occur in mud-rich sediments, i.e. grew on soft substrates, similar to stromatoporoids. Colonial tabulate do occur, but are a minor component with exception of some deposits described on Gotland. Some researchers (e.g., Scrutton, 1998; 1999) inferred that rugosa and tabulate corals lived on or even partly in soft sediments. Thus, all the above-mentioned features and the lack of positive indications suggest that in Minija regional stage reefs or even barrier reef do not occur, but production gave rise to biostromal shaped bodies. This may partly be the consequence of a fauna typically living on a soft substrate, but also partly due to periodic reworking of the sediment by storm induced current with variable transport basinward of both coarse-grained and fine-grained material. Besides most of the described stromatoporoid-rich sediments in Gotland are biostromes lacking talus deposits and thus lacking relief (Manten, 1962).

Based on depositional model and all observed sedimentological features and processes it is possible to interpret depositional environments from proximal to distal as: 1 Intertidal-subtidal Inner-shallow ramp; 2- Inner-shallow ramp; 3- Mid-ramp; 4- Outer ramp; 5- Lower Ramp slope - deep basin. Combined all collected material and observation it was constructed ramp model for the Silurian Baltic basin (Fig. 2.11).

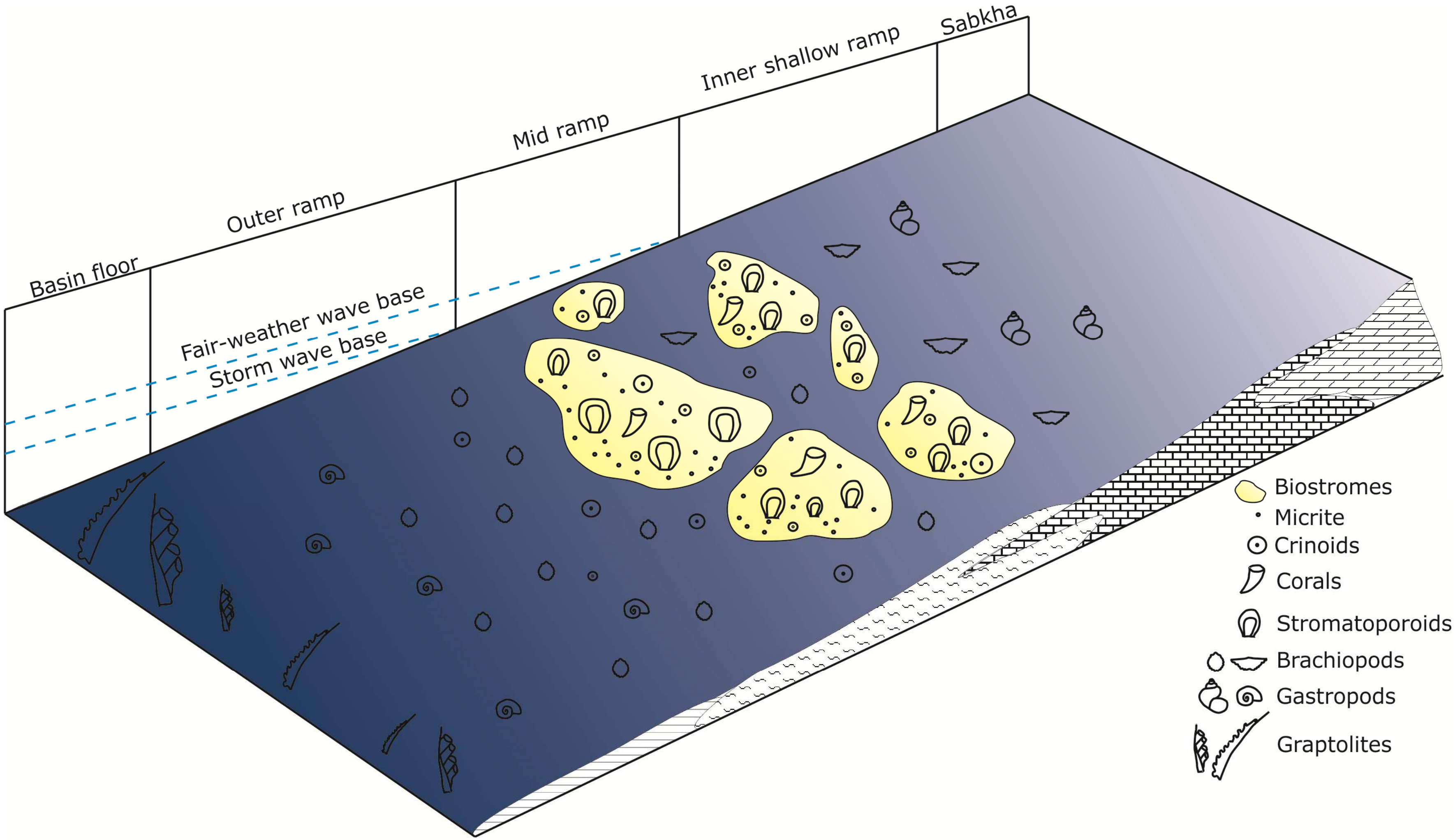


Fig. 2.11 Constructed ramp model in Silurian Baltic Basin.

CHAPTER 3

3. DIAGENESIS

This chapter is dedicated to diagenesis, which is particularly important for carbonates because of their high chemical reactivity. Diagenetic settings are often subdivided according to depth and to the possible interference between formation water and the overlying water column (sea water or meteoric water) into four parts (near-surface, shallow-burial, intermediate-burial and deep burial) according to Machel (2005), or two parts (near surface ‘early’ and subsurface ‘burial’) according to literature diagenesis includes all post-depositional processes until metamorphism (Adams & Mackenzie, 1998). In this chapter a distinction is made between syn- and post-depositional also called burial diagenetic processes. Syndepositional processes include bioturbation, microboring or micritization, and matrix infiltration. Postdepositional processes include cementation, pseudomorphous replacement or recrystallization, mechanical and chemical compaction, and fracturing and fracture filling. All these processes lead to changes of the original mineralogical composition and texture of the sediment and also of the original properties of the sediments and cause a continuous develop of porosity and permeability, which are the most important properties of hydrocarbons reservoirs.

Unfortunately, few data are available on the porosity of carbonate sediment up on or shortly after deposition, with exception of pelagic carbonates. The various deep sea drilling programs during the last decades did a lot of measurements on such deep-sea deposits. However, these are not relevant for the present study. The available data on shallow carbonates suggest that coarse-grained carbonate has an initial primary interparticle porosity around 40-45 % (Machel, 2005). According to the point counting results of this study the IGV (intergranular volume) in the coarse-grained sediments with a grain-supported framework is on average 42.8 percent (N=60).

Such porosities would be really promising for hydrocarbon reservoirs, but unfortunately, in most of the cases carbonates tend to lose their primary porosity quickly during progressive diagenesis, even more quickly than siliciclastic sediment (e.g., Ehrenberg and Nadeau, 2005). This may be expected because of the higher solubility of carbonate minerals. Silurian carbonates are not exceptional too. Pore space usually is lost during progressive mechanical and chemical compaction and cementation. Leaching of components and fracturing could lead to pervasive or local enhancement of porosity.

To understand the main petrophysical properties of carbonate reservoirs it is essential to know the diagenetic history of the sediments, because diagenesis is the main factor which tends to completely change pore systems occasionally in a positive and more often in a negative way.

X ray diffractometry (XRD) and electron micro probe (EMP) analyses revealed that all Silurian carbonates are exclusively composed of low-Mg calcite and much less by dolomite. However, a number of biogenic components and also early diagenetic components most likely were originally composed either of aragonite or high-Mg calcite. This is evident because such components were dissolved and voids filled or components replaced by low-Mg calcite often with complete or partial loss of original internal microstructures. XRD and EMP analyses also revealed that the insoluble residue is composed of minerals like quartz, pyrite and clay minerals including dominant illite, and some chlorite and kaolinite.

In general, only a few carbonate minerals are dominant in sediments, such as aragonite, calcite and dolomite. Calcite can be subdivided into low Mg-calcite and high Mg-calcite. Due to the specific reactions of these minerals to diagenesis (overburden pressure, temperature, solubility, fluid chemistry, etc.) aragonite and high Mg-calcite are not stable, in fact are often biogenically produced with the Mg content depending on the organism and environmental factors such as temperature and Ca/Mg ratio of the water, and during diagenesis are finally altered to low Mg-calcite which is stable under burial conditions (Ali et al., 2010). Much of the biogenic carbonate is originally aragonite or high-Mg calcite probably depending on when their lineage first developed carbonate skeletal parts during the Phanerozoic, either in periods with so-called calcite or aragonite seas. Such grains are not particularly stable partly because of their metastable mineralogical composition but also because of their internal structure with internal voids and pores that increases the reactive surface area. Skeletal mineralogy of some genera is well established, such as high-Mg calcite for echinodermata, low-Mg calcite for brachiopoda, but for other genera there is no conclusive evidence and the mineralogy might have varied during the Phanerozoic and across the various marine environments.

Microscopic investigations revealed that some of the biogenic grains were low-Mg calcite originally, such as brachiopod shells and ostracod shells since they retained their original microstructures and also contain still their original trace element content such as Sr. Other biogenic grains such as crinoids were high-Mg calcite and have been replaced by low-Mg calcite during diagenesis. Evidence for this is the inclusion of microdolomite crystals in these remains as well as in stromatoporoids, corals and bryozoa, and also their low Sr content. However, as mentioned before, the original mineralogical composition could have varied throughout the Phanerozoic and across the various marine environments.

3.1. Paragenetic succession

All diagenesis features, processes and their relatively timing are shown in table 3.1. This will be discussed in detail.

Table 3.1. Paragenetic succession of the Minija regional stage carbonates.

Features	Process	Relative timing
Burrows, random orientation of grains	Bioturbation	
Micrite rims	Microboring and micritization	
Infiltrated matrix in geopetal arrangement	Matrix infiltration (mechanical and through bioturbation)	
Fringing cement, overgrowth cement (bladed and fibrous)	Early marine high-Mg calcite cementation	
Loss of internal skeletal texture	Dissolution of aragonite or high-Mg calcite skeletal grains	
Dense grain packing, grain fractures, deformed ductile grains	Mechanical compaction	
Grain interpenetration, intergrain microstylolites, pervasive stylolites along shaly laminae	Chemical compaction (pressure dissolution - stylolitization)	
Low-Mg calcite composition of fringing-overgrowth cement and bioclast and partial loss of original internal texture	(Pseudomorphous) replacement of early marine cement and bioclasts	
Microdolomite crystals in bioclasts and cement	Precipitation of microdolomite during replacement	
Pore filling calcite cement (blocky)	Burial low-Mg calcite cementation	
Dolomite in remnant pores and along shaly laminae	Burial dolomite cementation	
Calcite - dolomite healed fractures	Fracturing and infilling by calcite and dolomite	

The table 3.1 shows the paragenetic succession of grainstones, rud/floatstones, packstones and partly wackestones. The lime- and dolo-mudstones are omitted due to the different sediment composition and paragenetic succession. In the case of mudstones, it is not possible to observe with simple ordinary microscopy the different between original particles, overgrowths and cements. It is evident that all mud was replaced by low-Mg calcite and original pore pace filled with low-Mg calcite micrite sized cement. The paragenetic succession was constructed based upon investigations of textural and spatial relationships between the various depositional and diagenetic features and components.

Bioturbation. It was observed in core slabs and thin sections that burrows are abundant and most of the carbonate grains are in random orientation. In another word, most of the sediment was highly bioturbated (Fig. 3.1 A) and any original depositional current induced structures were destroyed, which is common almost throughout the system. Bioturbation evidently is one of the first modifications of the sediment taking into account that biota activity is usually possible just during deposition or just after sedimentation, depending on net sediment accumulation rates.

Micritization. Micrite rims or also called micrite envelopes were found (Fig. 3.1 B) especially in the middle part of the ramp. These are the result of microsponges or micro-organisms, which are able to microbore into the outer margins of the bioclasts resulting in micritization of the original shell, mostly noted in brachiopod or bivalve shells. Microboring could also be one of the sources of micrite in the system but this feature is not common enough to have produced all micrite. According to the literature the widespread bioturbation and presence of microboring suggest normal oxygenated seawater (Berggren and van Couvering, 1984).

Matrix infiltration. Geopetal patterns of micrite accumulation were observed both macroscopically (Fig. 2.5 C) in core slabs and microscopically in thin sections (Fig. 3.1 C) pointing to the diagenetic process of matrix infiltration. Matrix can infiltrate through bioturbation or by mechanical infiltration into coarse grained sediment. During microscopic investigation geopetal pattern were observed in the intragranular and in the intergranular pores and next to bioclast grains either with or without micrite envelopes. This fact suggests that matrix infiltration could happen just after micritization. Most of the coarser grained sediment does contain some matrix dispersed in intergranular pores (i.e. packstones). In general, sediment consists of 36.8 percents of intergranular matrix and 0.7 intragranular matrix (within former voids of skeletal grains) according to point counting results.

Early marine high-Mg calcite cementation. Before describing the cements one fact should be taken into account: different biogenic grains react differently to the cementation, provide different nucleation sites, especially for the early cement. For instance, crinoid grains are very prone to develop syntaxial cement overgrowths. Probably this is related to their original high-Mg calcite composition and monocrystalline internal structures, which formed a most suitable nucleation surface for the high-Mg calcite cement. Brachiopod shells that originally had low-Mg calcite composition, but the shell layers were composed of fibrous calcite crystals, often have only thin cement fringes composed of bladed crystals and clearly were less favourite nucleation sites for the cement. Stromatoporoid, coral, bivalve, bryozoa, ostracod and trilobite grains reacted to the cementation similar like brachiopod shells. The mineralogical composition of the grains thus determined partly the susceptibility of the sediment for cementation (especially early) and also for compaction.

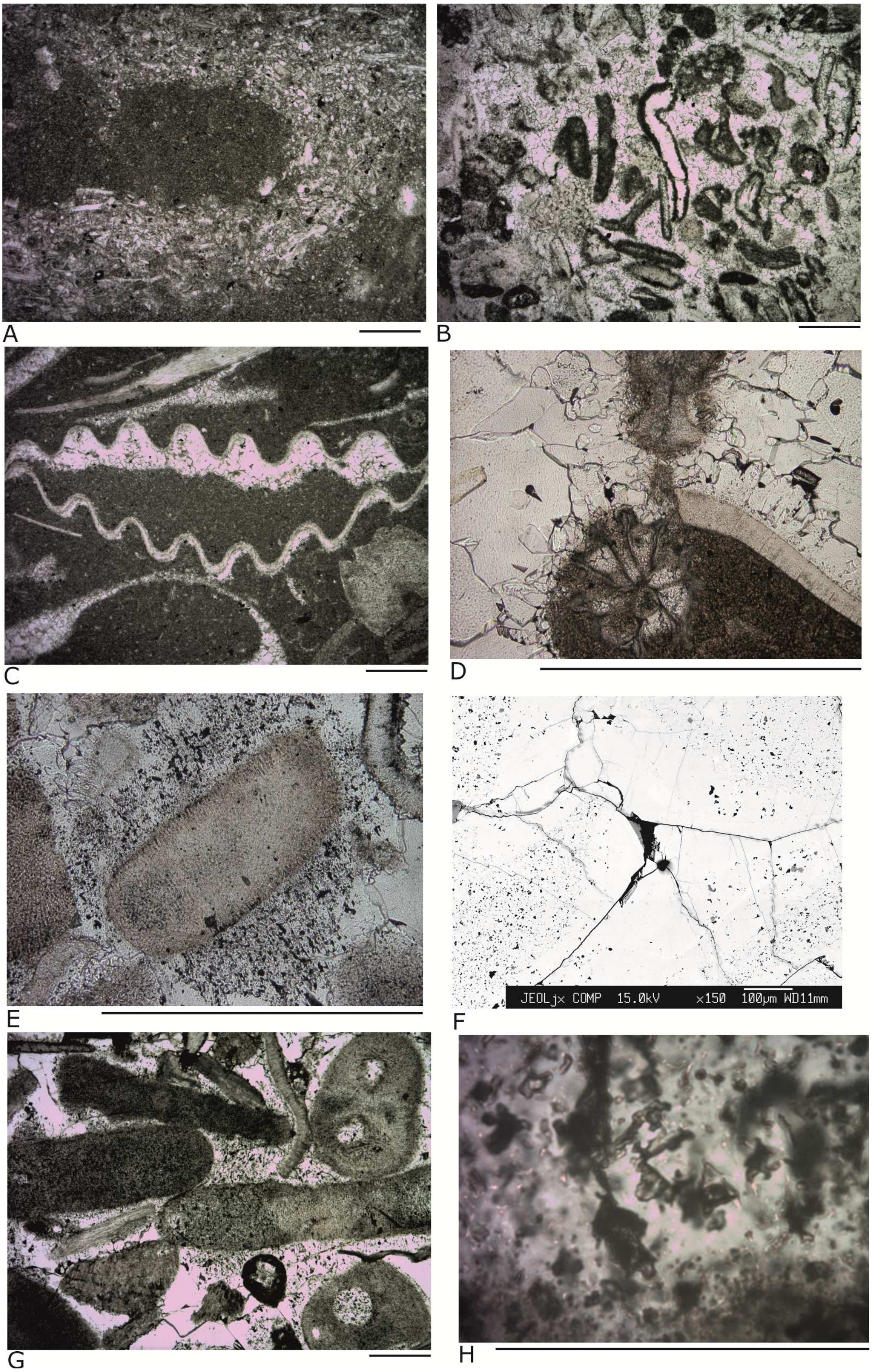

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Fig. 3.1 Microphotograph with different diagenetic features, scale bar is 1 mm: A-well Gargždai 1 depth 1402.2 m showing intense bioturbation in matrix supported mudstone; B-well Bliūdžiai 151 depth 951.6 m showing grains with micrite envelopes (cortoids) and some grains with complete micritization; C-well Bebirva 111 depth 986.6 m showing micro geopetal pattern (matrix infiltration) in the brachiopod and gastropod shell. The rest of the pore space in the brachiopod shell was occupied by calcite cement during diagenesis; D-well Bliūdžiai 152 depth 935.6 m showing trilobite, brachiopod and bryozoan grains which are overgrowth by bladed early calcite cement, which pass into equant calcite cement; E-well Bliūdžiai 150 depth 935.3 m showing crinoid grain with syntaxial overgrowth by early inclusions rich calcite cement; F- SEM microphotograph from well Bliūdžiai 152 depth 940.8 m showing syntaxial calcite cement on crinoid grains with inclusions and micro dolomite; G and H-well Bliūdžiai 152 depth 935.2 m showing inclusions and micro dolomite in early marine calcite cement.

Directly on bioclasts shells with or without micrite envelopes, fringing cement or cement overgrowths do occur. The fringing cements have fibrous or bladed crystal shapes Fig. 3.1 D and E. This cement in study area grow onto bioclasts such as brachiopods, bivalves or trilobites present as fibrous or bladed, which according to the literature is quite common shape for early marine cements (Flügel, 2004). Crystal shape of the cement, cold cathode microscope and geochemical data revealed that this cement is now calcite and microscope investigation confirms that this cement is common not everywhere in the research area. This cement is most common in the middle ramp and precipitated in intra- and/or intergranular pore space. Ordinary microscope and SEM investigation revealed that this cement is inclusion rich. The minerals study with scanning electron microscope reveal that in this cement there are smalls inclusions of dolomite Fig. 3.1 F. Point counting results show that the average percent of this calcite cement is about 7.1%. This calcite cement gives various colours under cold cathode microscopy: from dull or brightly luminescent to non-luminescent at all. According to the literature bladed and fibrous shape of the crystals and either aragonite or high-Mg calcite composition is common during early marine cementation (Flügel, 2004) According to the literature if low-Mg calcite cement is relatively rich in values of Sr, it means that most likely original mineralogical composition was aragonite (Flügel, 2004). Since in this low-Mg calcite cement was observed microdolomite (Fig. 3.1 G and H) it is possible to state that the early cement was a marine high-Mg calcite in origin. The environment of precipitation of early non-luminescent calcite cement is still under question in the scientific literature (Lavoie and Bourque, 1993). Some researchers claim that it is marine in origin (Kerans et al., 1986) and some of them that it is meteoric-phreatic (Meyers, 1978; Dorobek, 1987; Kaufman et al., 1988). This early marine high-Mg calcite cement played a significant role during diagenesis especially in the grain supported sediments, because after microscopic investigation it was observed that the grains which were surrounded by this cement were prevented of chemical compaction. Whereas the grains which were not surrounded by early marine high-Mg calcite cement were affected by pressure dissolution and stylolitization. During microscopic investigation, it was also observed that in some thin sections early cement is overlaid by stylolites (Fig. 3.2 A). It means that this cement was formed earlier than stylolitzation, pressure dissolution and chemical compaction did occur.

Electron microprobe (EMP) and X ray diffractometry (XRD) analyses revealed that all carbonate material consists mostly of low-Mg calcite and impurity of dolomite minerals. It means that whatever the original mineralogical composition was (aragonite or high-Mg calcite), it was altered or replaced by low-Mg calcite and/or dolomite. In case of the early marine cement, this replacement was partly pseudomorphous with preservation or partial preservation of the original crystal shapes. The EMP data shows that the chemical composition as expressed by the Mg/Ca ratio of the early cement have a log-normal distribution and consist of one major population and possibly a few sub-populations (Fig. 3.6 A). Most likely these differences are due to different original mineralogical compositions of the early cement. It could also well be that there are slight differences in Mg/Ca ratio that depended on the composition of the grains on which the cement nucleated. It is not possible to confirm this at this stage of the research.

Dissolution of aragonite or high-Mg calcite skeletal grains. Loss of internal skeletal texture or recrystallization of bioclasts like crinoids, bivalves, bryozoans and corals was observed too (Fig. 3.2 B). During progressive diagenesis dissolution of unstable minerals such as aragonite or high-Mg calcite caused the loss of internal skeletal texture. Dissolution gives evidence not just about diagenesis relatively timing but also bring to the thoughts about pristine or original skeletal composition. Scanning electron microscopy (SEM) reveals that in some bioclasts like crinoids, stromatoporoids, bryozoans and some corals was observed microdolomite, which is a strong argument that these bioclasts were originally composed of high-Mg calcite. According to some scientists this assumption could be confirmed (Flügel, 2004). The original composition of bioclasts is very important because dissolution of mineralogically unstable components influence the further character of diagenesis. Here should be noted that according to the literature it is known that original crinoid grain composition is high-Mg calcite (Flügel, 2004) and for some unknown reason during the recrystallization these grains are able to keep their original texture. Further discussion on this issue is behind the scope of this study.

Mechanical compaction. Dense grain packing, fractures and deformed ductile grains were observed in the sediments (Fig. 3.2 C), which gives evidence for mechanical compaction. According to the literature carbonate sediments can lose about one half of their original thickness due to the mechanical compaction (Choquette and James, 1987). Mechanical compaction is an important diagenetic process because it defines how further diagenesis will go. If mechanical compaction is low it means that in the system still exists a lot of pore volume and mass redistribution could go much further from the source but if the mechanical compaction is intense, it means that in the system we have less porosity and less permeability and therefore the mass redistribution will go not far from the source.

Chemical compaction. Grain interpenetration, intergrain microstylolites and pervasive stylolites along shaly laminae are common features (Fig. 3.2 D) in grainstones, packstones, floatstones, rudstones and wackestones, which were observed in thin sections and hand rock samples. The stylolitization is most common in the central part of the basin (biostrome). Crinoids and stromatoporoids are the main fauna, which are, involved to the grain interpenetration or microstylolitization, brachiopods somewhere are also involve to this.

To get better understanding about the effects of chemical compaction, crinoid grains affected by pressure dissolution it was selected for quantification. The original shape of crinoid grains in most cases is easy to define and can thus be used to identify which parts of the grain were lost due to pressure dissolution. Point counting results revealed that the crinoid grains which were involved into chemical compaction show a range in loss through dissolution from a minimum of 2.4 percent up to a maximum of 77.8 percent. On average the loss is 27.7 percent of the volume. This volume loss, and potential material for burial cementation, must be corrected for the internal porosity of such grains.

The main features indicating or giving evidence for chemical compaction are sutured contacts between grains and stylolites, which were formed during pressure dissolution that is caused by stress at the grain contacts, during increasing of overburden pressure. Stress increases mineral solubility. There are also other factors, which influence pressure dissolution like burial depth, temperature, chemical composition of pore water, grain mineralogy, and presence or absence of organic matter. Depending on these factors chemical compaction in carbonates is reported to start at a depth of 200-300m by some authors (Machel, 2005). But according to other scientists, pressure dissolution and stylolitization in low-Mg calcite (chalk) could start at a depth between 500-800m (Lind, 1993; Fabricius and Borre, 2007). It was observed in Ontong Java Plateu that pervasive stylolitization is more common in marly and shaly intervals where clay minerals are abundant, whereas grain stylolitization is more common in grain-supported sediments. The same was reported for the chalks from North Sea (Lind, 1993; Fabricius and Borre, 2007). If there are a lot of shaly intervals in the system probably already from beginning, there is source for early cementation and diagenesis is predicted and there is normal loss of porosity. Good porosity is exceptional. It looks like shale intervals somehow does trigger pervasive stylolitization but further discussion about this issue is behind the scope of this research. Coarse-grained sediments are presented thicker than shaly ones. In more shaly sediments processes like pressure dissolution started earlier than in grain-supported carbonates. It would thus take more time to fill primary pores in grain supported sediments because the processes yielding the cement mass are starting later and diffusion distance from the more shaly sediments is longer.

It was already mentioned before that during chemical compaction crinoid grains in sediments without early marine cement average lost around 27.7 percent of their volume. It means that in the diagenetic system was put extra material, which influence pore water chemistry. During chemical compaction, some volume of unstable carbonates minerals was dissolved and in some area, was observed insoluble residue accumulations, which are call stylolitic seams or just stylolites. These seams usually are orientated horizontally and this reduces the possibility for vertical movement or pore water.

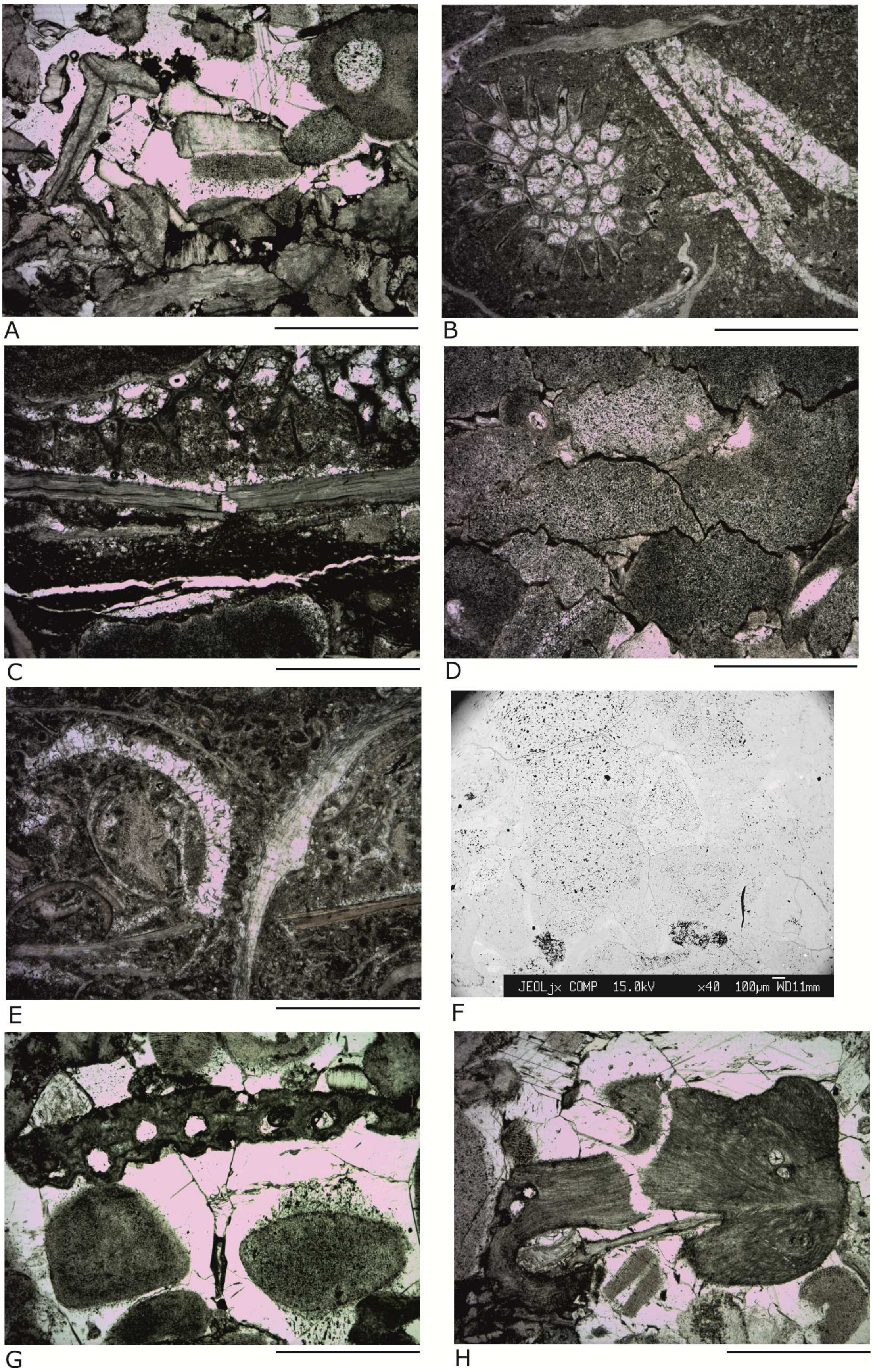
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Fig. 3.2 Microphotograph with different diagenetic features, scale bar is 1 mm: A-well Bliūdžiai 150 depth 935.2 m showing that early calcite cement is overlaid by stylolites; B-well Bebirva 111 depth 986.6 m showing partly loss of internal original structure of shell fragments; C-well Bliūdžiai 157 depth 895.2 m showing the evidence of mechanical compaction, which broke brachiopod shell; D-well Bliūdžiai 150 depth 942.7 m showing the evidence of chemical compaction, which represented here as suture lines between crinoid grains; E-well Gargždai 1 depth 1324.5 m showing the evidence of bioclast replacement by calcite crystals; F-well Bliūdžiai 156 depth 949.5 m showing inclusions and micro dolomite in crinoid grains; G-well Bliūdžiai 150 depth 935.2 m showing late burial calcite cement which filled most of the pore space during diagenesis; H-well Bliūdžiai 156 depth 917.5 m showing burial late calcite cement which fill the fractured brachiopod shell fragment and most of the pore space. This kind of evidence suggests that late calcite cement took place after mechanical compaction.

Replacement of early marine cement and bioclasts. After microscopical investigation it was observed low-Mg calcite composition of fringing – overgrowth cement and bioclast as well as partial loss of original internal texture (Fig. 3.2 E). It is well known that aragonite and high-Mg calcite are unstable during diagenesis leading to dissolution of such components and filling by cements and loss of former textures of bioclasts. Crinoids, tabulate and rugose corals are the main bioclasts which were involved into replacement because they were originally composed of high-Mg calcite. This type of replacement is common throughout the entire ramp. Only ostracod and brachiopod shells retained their original texture and composition. Bivalve shells (gastropods) were merely dissolved and voids filled by late calcite cement.

Precipitation of the micro dolomite during replacement. SEM (scanning electron microscope) analysis revealed that in low-Mg calcite composition of fringing – overgrowth cement and some kind of bioclasts like crinoids, ostracoda, bryozoa and coral present crystals of microdolomite (Fig. 3.2 F). Precipitation of the micro dolomite was triggered by pseudomorphous replacement of the original high-Mg calcite by the present low-Mg calcite that released Mg, which was bound by precipitation of the small dolomite crystals.

Burial low-Mg calcite cementation. Low-Mg calcite, equant shape, microsparite, sparite and macrosparite sized cement conformable, without any dissolution evidence or additional space, overlay bladed, fibrous or fringing calcite cement and fill most of the left pore space (Fig. 3.2 G). Point counting results show that average percent of low-Mg calcite cement is 12.3 percent. This cement do fill inter and the intra pores and all observed features basically are the same. It has generally dull luminescent colour with slightly variety in the shade, which was probable influence of variation of iron and manganese content in lattice of calcite (Adams & Mackenzie, 1998). In addition, somewhere between non luminescent replaced bladed or fibrous calcite cement and dull luminescent calcite cement present thin bright luminescent rim, somewhere do occur multi rims changing in dark and bright luminescent (Fig. 3.3 A). The changes in luminescent colours from non-luminescent to dull luminescent with thin layers of bright luminescent is well known for carbonates and it reflect progressive changing in burial depth (Adams & Mackenzie, 1998). This cement often has no obvious substrate or grows syntaxial overgrowths over the crinoid's grains. This cement is free of inclusions, which suggests of the original pore water chemistry composition reflected in this late low-Mg calcite. It was already mentioned several extra sources (dissolution of aragonite or high-Mg calcite skeletal gains, chemical compaction, pseudomorphous) material in the system itself which most likely trigger precipitation of pristine low-Mg calcite cement. During microscopic investigation, it was observed that in some fractures pore which appear in broken bioclasts surely after mechanical compaction low-Mg calcite fill the pores (Fig. 3.2 H), which mean that this cementation was surely not early. It was also observed some oil or bitumen occurrence on outer edge of low-Mg calcite cement. It means that oil infiltration was late after late calcite cementation. Beside that some scientists (Zdanavičiūtė and Lazauskienė, 2004; 2007) claim that the oil generation and migration in Baltic depression started in the end of Silurian and the major oil generation took place during Devonian and early Permian. This suggests that Silurian rocks were quickly buried and diagenesis progressed also very quickly also. The Mg/Ca shows that late low-Mg calcite cement is homogeneous and has normal geochemical distribution (Fig. 3.6 B).

In general Mg/Ca for all calcite, despite early or late calcite cement or whatever bioclasts grain is, shows that distribution of data is normal and homogeneous (Fig. 3.6 C). Here surely it possible to state that source for the calcite precipitation was one and most likely it was the carbonate system itself and there was no external influx, which could trigger diagenesis and all mass redistribution took place in the system itself. It could rise question why is it important? The answer would be that depend of that it is possible to predict diagenesis model which play major part for petrophysical properties. If the source for diagenesis would be external it would have specific chemical pattern. It is difficult to except that from different sources components like meteoric or marine ones would have exactly the same chemical composition. This is simply not possible.

Burial Dolomite cementation. Pervasive dolomitization is common only in most east part of the ramp, whereas in middle and deep ramp dolomite is less common (Fig. 3.5 C.) Usually in middle and deep part of the ramp dolomite occurs in remnant parts of the pores and along shaly laminae (Fig. 3.3 C, D, E, F.). Somewhere dolomite crystals present on the edge of sparry calcite cement. The size of dolomite crystals varies from sparry to macrosparry and gives equant shape. Somewhere was observed baroque or saddle dolomite crystals (Fig. 3.5 A and B), which according to the literature pointing more to the hydrothermal activity or deep burial diagenesis (Flügel, 2004). The CL investigation reveals that there is different in dolomite composition, mostly dolomite in middle part of the ramp is Fe-rich and non luminescent, with red luminescent dots (Fig. 3.3 G), whereas in eastern most part of the ramp dolomite is Fe free and give red luminescence colour (Fig. 3.3 A). Scanning electron microscopy (SEM) investigation also reveals that in some dolomite presents zonational overgrowth of the crystals, which was probably due to different ratio of Mn and Fe (Fig. 3.5 D) and reflects ration changes of these chemical elements in pore water. The precipitation of dolomite most likely was possible due to the increase volume of Mg in the system during late calcite compaction and which was not all consumed during precipitation of low-Mg calcite.

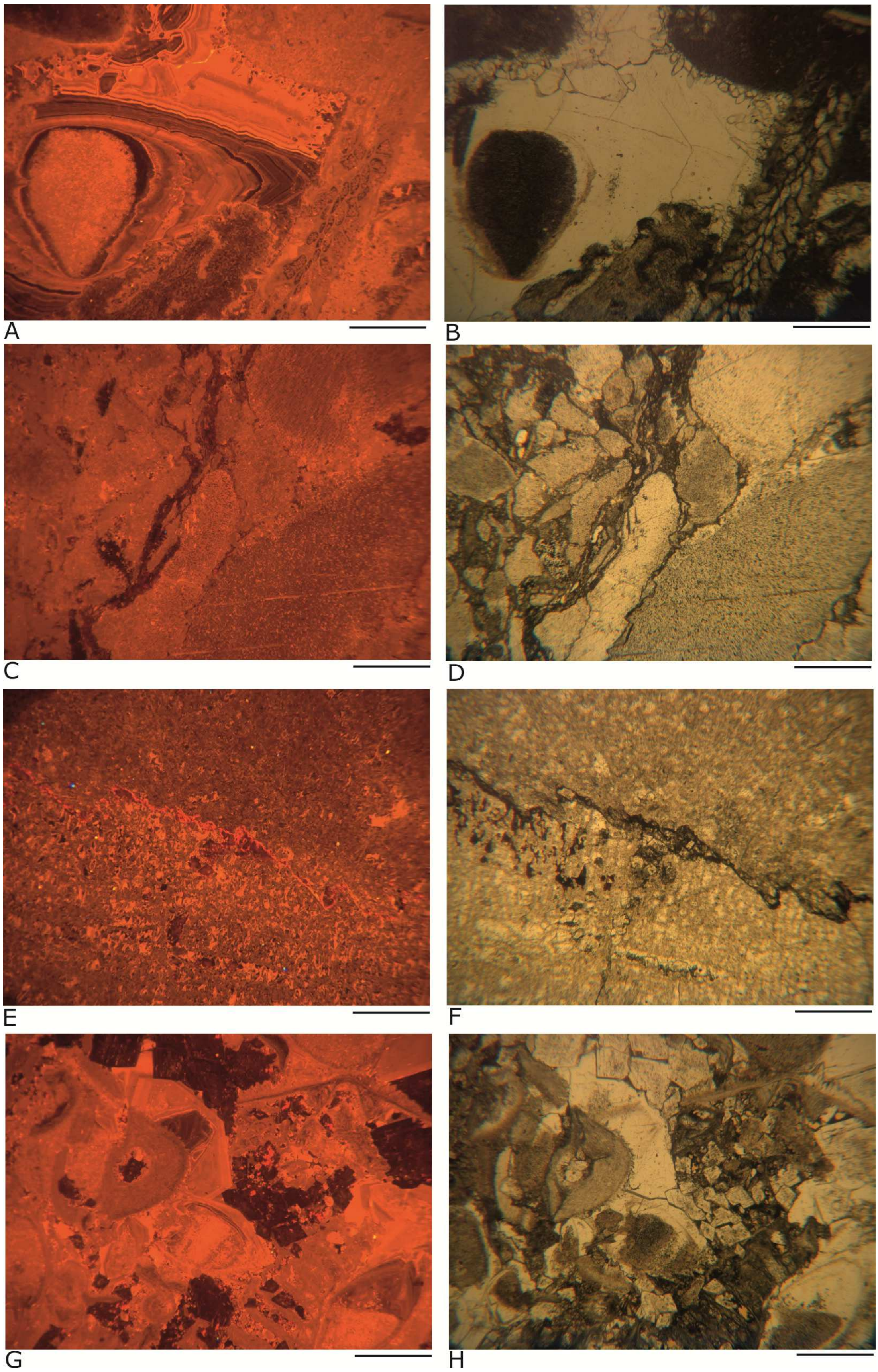
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Fig. 3.3 Microphotographs of CL (left) and plane polarize (right) microscopy, scale bar 1 mm,: A, B-well Bliūdžiai 152 depth 935.6 m showing the change of intense of luminesce in CL in the late burial calcite cement, which represents different iron and manganese ratio in the different parts of the late calcite cement, which suggest that late cementation took place in several stages; C, D, E, F-showing late burial dolomite in the middle and deeper ramp parts occur in the or close to stylolites. Note that CL microscopy helps to distinguished calcite from dolomite crystals because in CL the dolomite crystals shows black and/or red luminescence color (C, D- well Bliūdžiai 151 depth 953.6 m; E, F-well Sutkai 100 depth 731.3 m); G, H-well Bliūdžiai 152 depth 934.0 m showing late burial dolomite crystals. In most of the cases dolomite crystals in the middle and deeper ramp parts shows as non-luminescent (black in CL) dolomite with some red luminescence inclusions.

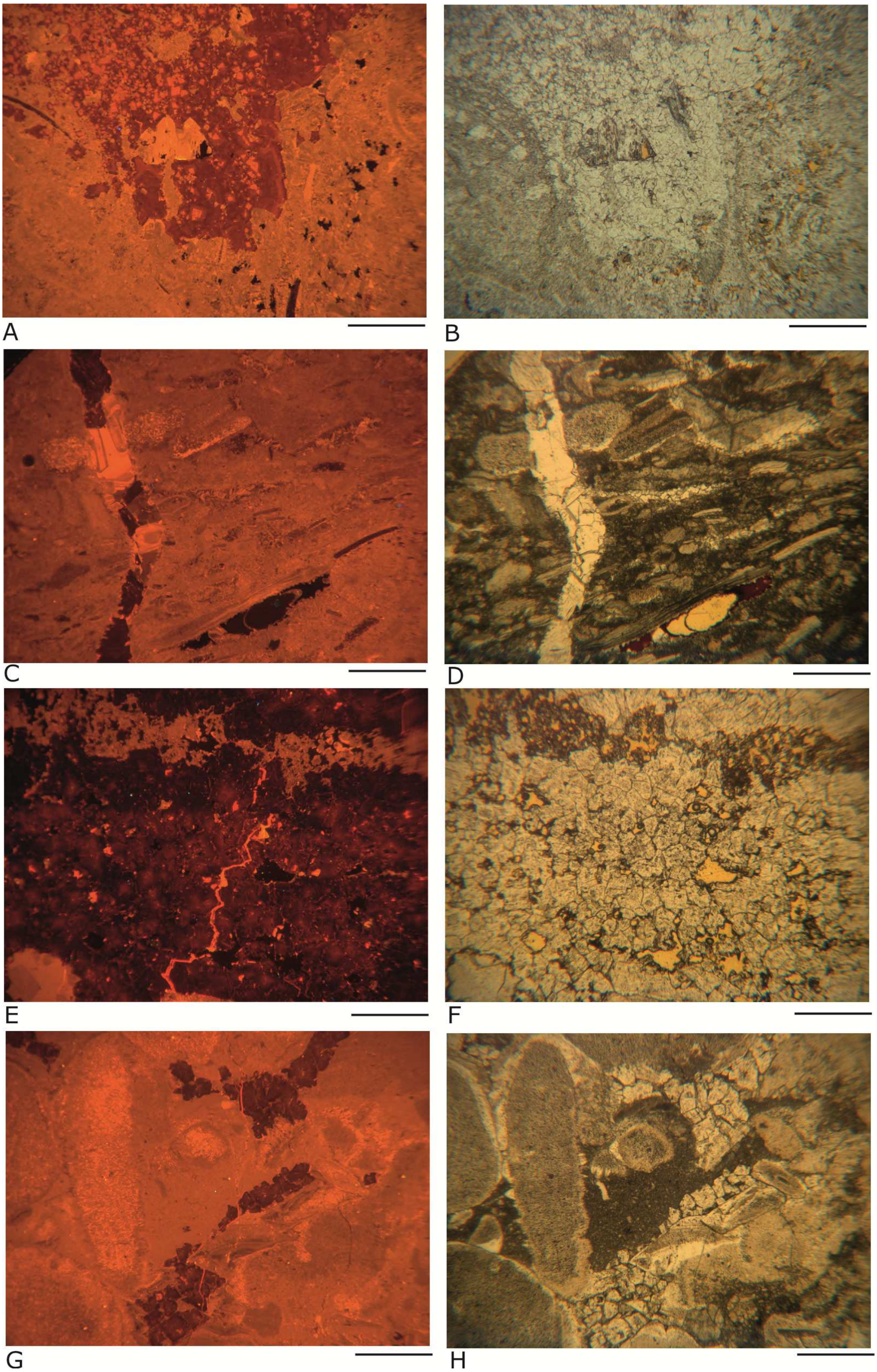
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Fig. 3.4 Microphotographs of CL (left) and plane polarize (right) microscopy, scale bar 1 mm, A, B- well Beržai 185 depth 407.8 m showing dolomite crystals which are much more discernible in CL microscopy and in the eastern (shallow) part of the ramp system with luminescence in different intense red colours, C, D- well Sutkai 100 depth 731.7 m showing fracture which filled by calcite and dolomite cement. Note that CL helps distinguishing the calcite and dolomite crystals; E, F, G, H- well Sutkai 100 depth 731.3 m showing 'hidden' fractures which is visible just under CL.

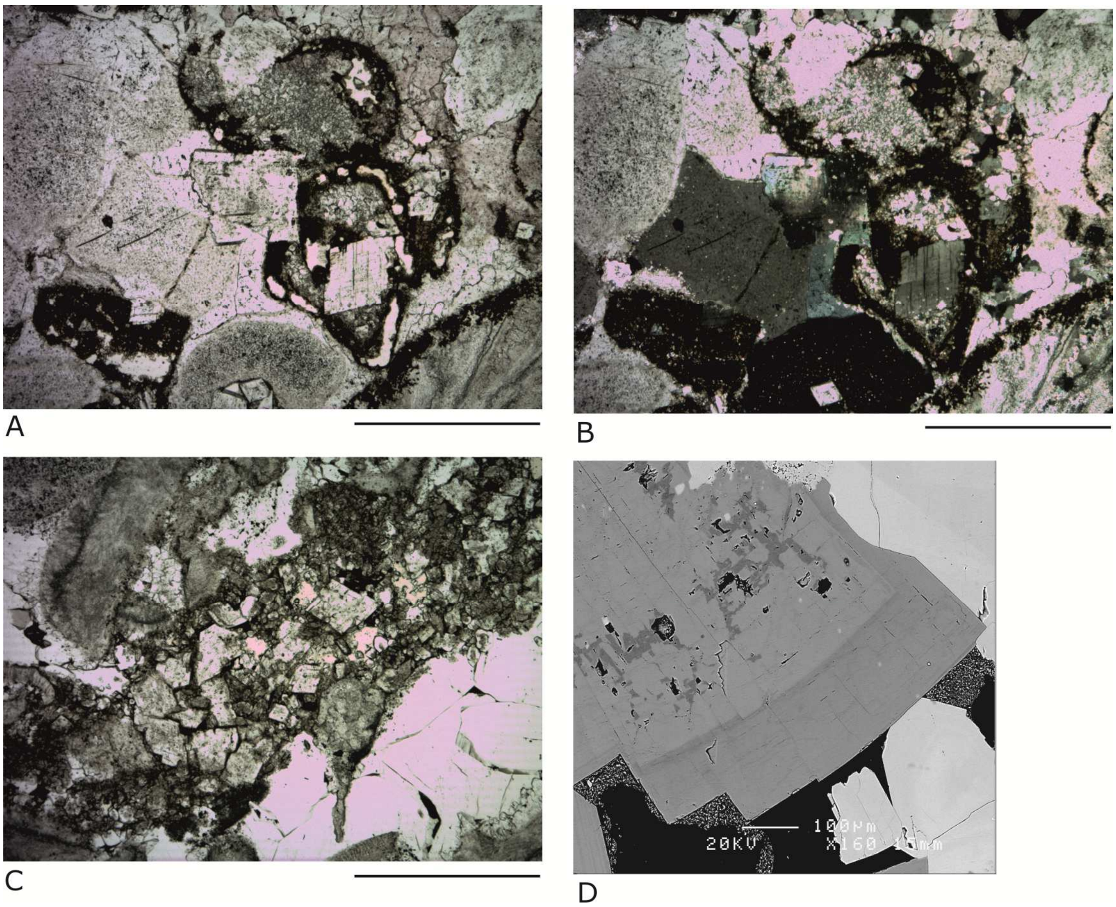


Fig. 3.5 A, B-well Sutkai 100 depth 728.5 m showing baroque or saddle late burial dolomite crystal, which is very rare in the study area, scale bars 1 mm; C- well Bliūdžiai 150 depth 953.6 m showing occurrences of burial dolomite cement. Most of the dolomite crystals are inclusion rich, scale bars 1 mm; D- SEM microphotograph from well Bliūdžiai 151 depth 951.6 m showing dolomite crystal zonation which is caused by different Mn and Fe ratio.

The histogram of Mg/Ca of all dolomite shows that there are three populations (Fig. 3.6 D). The highest ratio is related more to the shallow inner ramp. The lower values are related to the deeper parts of the system. The lowest ratio is mixture of all depositional facies, from shallow to deep.

Fracturing and infilling by calcite or dolomite. Fractures were observed which are completely or partly filled by calcite and/or dolomite (Fig. 3.4 C). Fracturing and infilling is not so common in the study area and present only in the middle part. Fractures cut all other components like grains early or late cements. Calcite and dolomite filling the fractures has a much higher content of iron pointing to different origin of the carbonate. CL investigation also reveals some micro fracturing in the late dolomite and in the whole rock sample, but this kind of the feature were not common (Fig. 3.4 E and G)

3.2. Causes of diagenesis

It is evident that the early marine cementation took place when the sediment was in contact with the overlying seawater and the material for the cement was simply carried by the seawater either through diffusion or flow through the uppermost permeable sediment in case of coarse-grained sediment. The seawater must have been oversaturated with respect to high-Mg calcite. It is less clear what causes the various diagenetic processes during burial. An important question is what the trigger for burial cementation and burial diagenesis in general was. There are two possibilities: either the system is mass conservative (or taking place essentially in a closed system with redistribution of already present materials) or otherwise triggered by external supply or influx of diagenetic fluids from outside (that could for instance be meteoric water during periods of uplift and erosion somewhere, or during period of seawater low stands). Also, faulting may provide at some stage in the history open pathways for fluid flow.

In the study area, there are lots of shales and marls (low permeable already from deposition) and a lot of muddy limestones (limestones with matrix or even matrix supported) also having relative low permeability from deposition. If we take into account that there were so many sources for cements precipitation and cementation reduce pore water circulation and the luminescence of the cement were vary from sample to sample and there were observed any systematic changes i.e. were no so-called cement stratigraphy it is possible to assumed that most likely the diagenesis was triggered by mass itself and the system is closed.

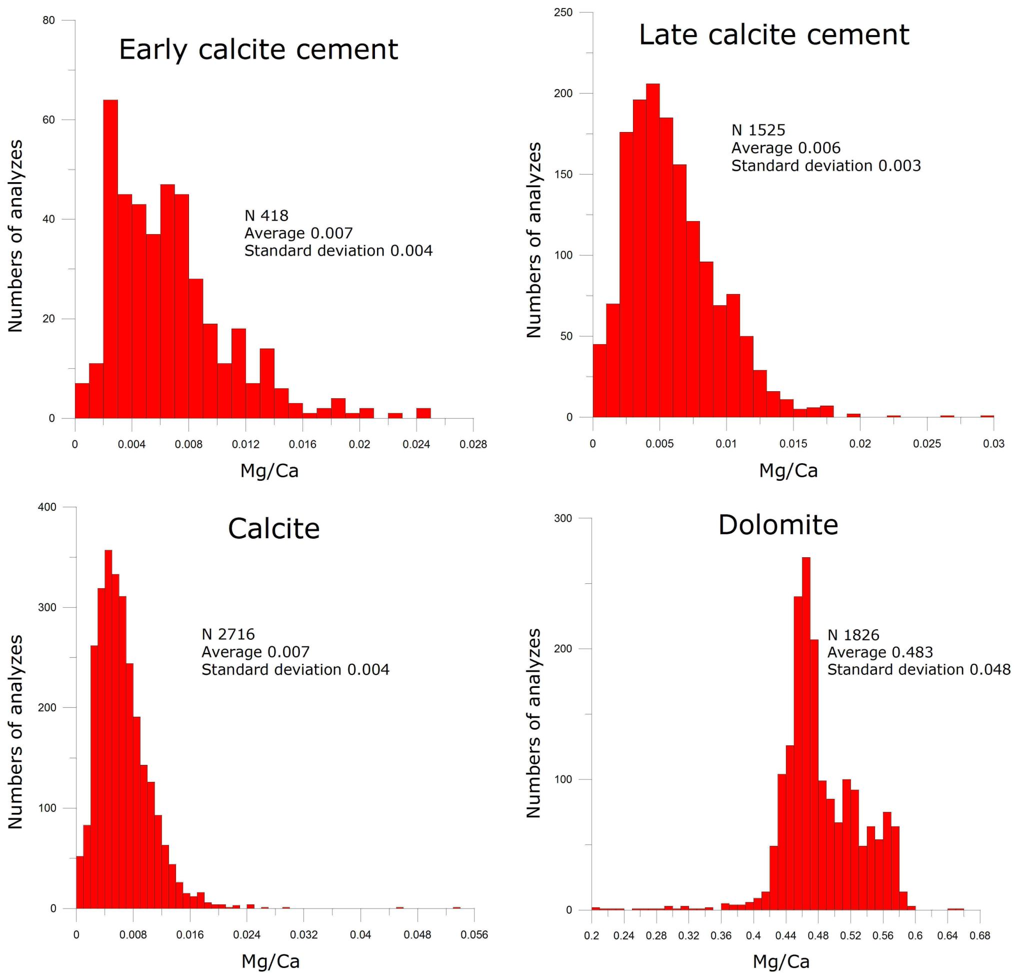


Fig. 3.6 A-histogram that shows Mg/Ca ratio distribution in the early calcite cement. It shows log normal distribution; B-histogram shows Ca/Mg ratio distribution in the late burial calcite cement. It shows log normal distribution; C-histogram shows the Mg/Ca ratio distribution in early and late calcite cement. It shows log normal distribution; D-histogram of Mg/Ca ratio in late burial dolomite cement with three different populations represented by different parts of the ramp.

One more important aspect is permeability. It was mentioned already that the system from very beginning of deposition is very rich in fine-grained matrix and matrix is abundant and common throughout all the system, with just few exceptions in the central part. The carbonates just from the beginning could reach about 50 percent or more in porosity (depending on the shape of the larger particles) but as was shown above as a result of the various diagenetic processes it now has a porosity of around 5 percent on average (see further). Moreover, the permeability is now in most cases below the equipment detection limit (of around 0.01 mD) (Fig. 3.7). Together with the relatively quick loss in porosity during initial burial of the system during the Devonian, it makes any large-scale flow through the system difficult to imagine.

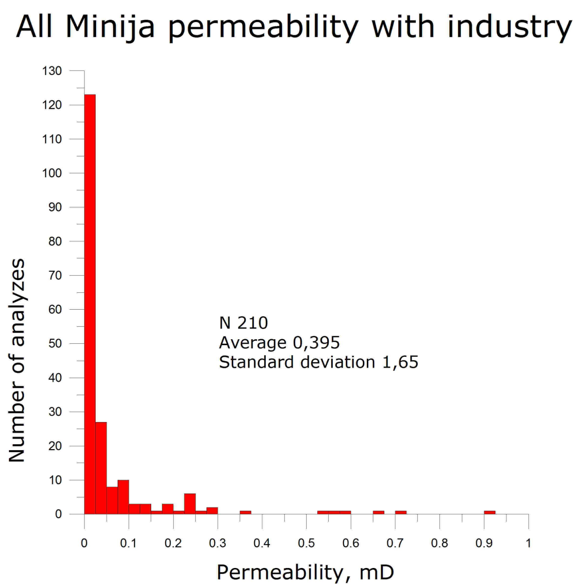


Fig. 3.7 The histogram of permeability in Minija regional stage.

A burial model has been constructed after Šliaupa (not published) (Fig. 3.8). This model shows rapid and progressive burial during much of the Devonian. After that depending on the location within the basin some uplift and repeated burial took place. Thereafter temperature slowly dropped. After this initial rapid burial in combination with dropping temperatures it can be expected that most diagenetic processes slowed down and maybe even stopped. The graph shows the timing of the major diagenetic processes within this burial model.

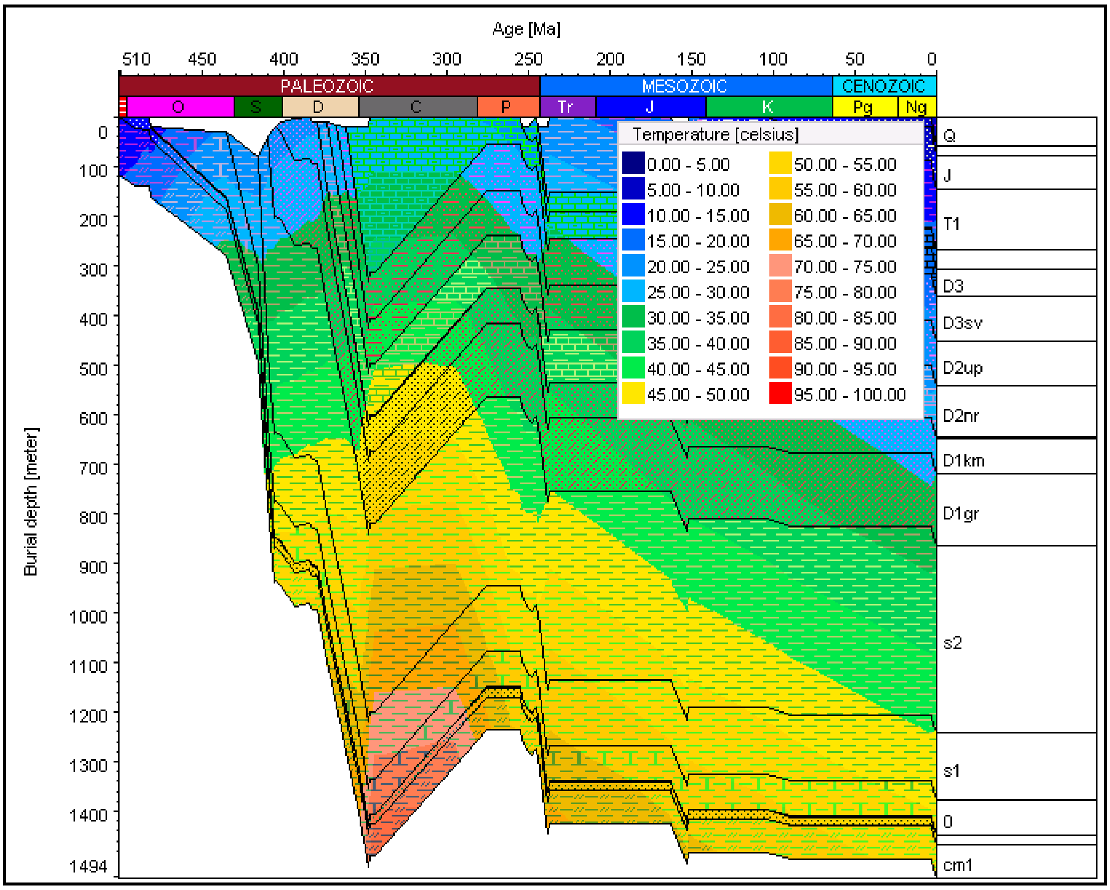


Fig. 3.8 The burial model of the well Vadžgiris95 constructed by S. Šliaupa.

Large scale externally induced flow through the system that would trigger diagenesis is doubtful if not impossible, even shortly after deposition within deposits dominated by fine-grained, low permeable carbonate mud. It is much more likely that the drives for diagenesis are the original mineralogical composition of the sediment in combination with increasing effective pressure (and maybe temperature) as a result of burial.

CHAPTER 4

4. RESERVOIR POTENTIAL

4.1. Porosity types

Petrophysical properties (porosity, permeability and grain density) of different carbonate facies have been measured and linked to the geometry of facies units and the main depositional and diagenetic features and textures. Also, petrophysical data from existing reports have been used. The assumption that will be tested is if the primary characteristics, comprising mineralogical and textural composition of grains, as well as sedimentary textures and depositional structures of the deposits, are correlation to porosity and permeability. These primary characteristics defined the diagenetic susceptibility of all carbonate components. This lead to specific reactions or reaction rates of diagenetic processes and thus also their effects on the petrophisical properties. The various microfacies were combined with core sample description and the measured petrophysical properties. It will be established if the expected correlation between microfacies and reservoir quality exists or not.

This chapter is focussed on the types of pores in the carbonates, the evolution of porosity and the link to facies.

In general, according to Tucker and Wright (1990) modified after Choquette and Pray (1970) all porosity types are subdivided into three parts 1) fabric selective; 2) not fabric selective; 3) fabric selective or not. To the first part belong intergranular, intragranular, intercrystalline, moldic, fenestral, shelter and framework porosity. To the second belong fracture, channel, vugs, cavern and stylolitic porosity. To the third one belong breccia, boring burrow and shrinkage (Tucker and Wright, 1990). More practical is the distinction between macro- and micropores, primary and secondary pores within grains and in between grains.

Primary macropores are intergranular pores within grain-supported frameworks when pores are not completely filled by calcite cements, micropores within carbonate mud matrix, and pores or voids within some bioclastic grains (intrapores) that were not completely filled by mud matrix and calcite cements. Porosity is mostly dominated by primary intergranular pores and these are common throughout all the system. Intragranular occurs in all the system, including mud and wackestones, but is less common. Intercrystalline porosity does occur just in the most shallow (Eastern) part of the system in dolostones.

Porosity is one of the most important parameter for the hydrocarbons reservoirs, moreover more than half Earth's hydrocarbon reserves are in carbonates, that is why it is important to describe them in crore or thin sections. Generally, porosity can be described as primary or secondary (Adams & MacKenzie, 1998). The primary porosity has been presented from deposition, whereas secondary developed during diagenesis. In the study area mostly prevails primary porosity whereas secondary do occur very rare. Porosity can be also described as fabric selective and not fabric selective (Adams & MacKenzie, 1998). Fabric selective porosity location is controlled by particular parts of rocks, whereas not fabric selective porosity cuts across of the rock. In the study area mostly prevail fabric selective porosity, whereas not fabric selective porosity does occur very rare.

Generally, it was observed in the study area two types of porosity: inter grain and intra grain pore space which are shown in the Fig. 4.1 A and B. It was found also inter crystalline porosity (Fig. 4.1 C, D, E, F), which is more common for the dolomite rather than calcite. Note that dolomite crystals vary in composition in the shallow part of the ramp and rest of the ramp.

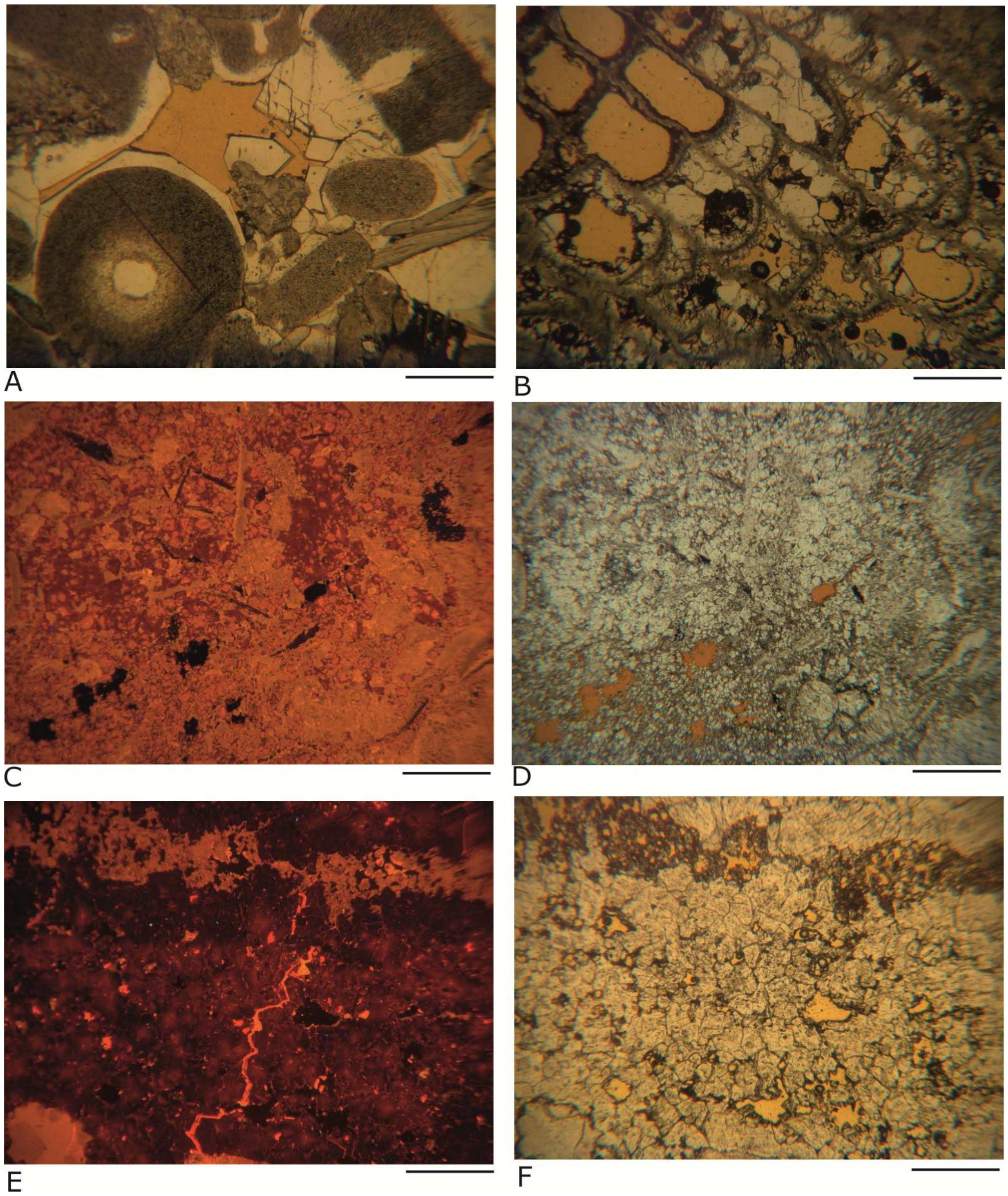


Fig. 4.1 A-microphotograph of plane polarize microscopy from well Bliūdžiai 150 depth 942.7 m showing crinoidal grainstone with primary interparticle pore space; B-microphotograph of plane polarize microscopy from well Bliūdžiai 158 depth 912.7 m showing coral primary intraparticle pore space; C, D-microphotographs of CL (C) and plane polarize (D) microscopy from well Beržai 185 depth 407.8 m showing inter crystalline pore space in the shallow part of the basin; E, F-microphotographs of CL (E) and plane polarize (F) microscopy from well Sutkai 100 depth 729.9 m showing inter crystalline pore space in dolomitized limestone. Scale bar 1 mm.

Based on the figure 4.2 it is possible to state that the highest porosity values are in the rocks with highest grain density in other word, that dolostone is more porous than limestone.

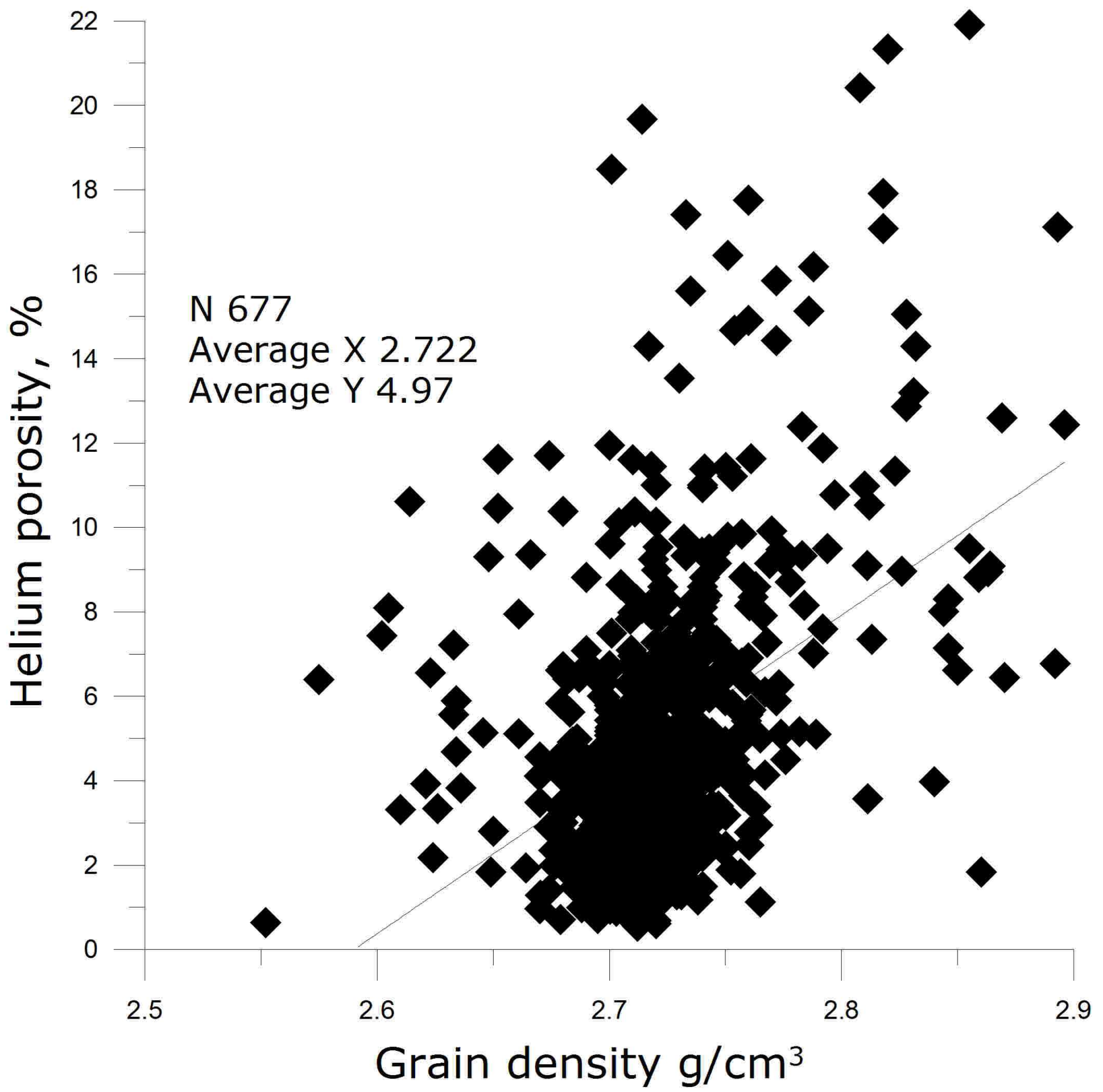


Fig. 4.2 The plot of grain density of the rock versus porosity.

The website of C&CReservoirs inc. describes 997 producing hydrocarbon reservoirs globally distributed, from which 66% are siliciclastic sediments and 34% are carbonate sediment amongst these several giant oilfields. From the carbonate reservoirs about 28% are in reefs or closely associated deposits, whereas this percentage is around 38% in for Palaeozoic reservoirs most of them in the Devonian.

A number of recent carbonate platforms is easily accessible and therefore has been studied intensively. These are often dominated by corals and calcareous red algae, and have been subjected to meteoric water influx during the Pleistocene glacial and interglacial periods and associated sea level fluctuations. The interpretation of carbonate sediments might thus be dominated by models derived from studies of these particular recent-subrecent carbonate platforms and reefs.

The difference is that Cainozoic reefs are constructed by organisms that have symbiotic algae and by algae themselves so they are only occurring in the photic zone close to the water level. As such they are prone to be exposed often maybe even during storms but surely as a result of sea level movements. In the Palaeozoic was a completely different situation. Most of the larger skeletal carbonate producers are not bound to the photic zone. Moreover, if they occur in biostromes and reefs on a sloping ramp, they are far less exposed to meteoric water influxes.

Despite that some authors built paragenetic succession with enhance secondary porosity in the Silurian (Stentoft et. al., 2003), whereas during this study no dissolutional secondary pores have been found in the studied Minija limestones.

Recent reefs and the surrounding lagoonal fine-grained sediments form evident potential stratigraphic traps. Together with the observation of dissolutional features related to sea level lowering and meteoric water influx lead to the assumption that the presence of ‘reef-like’ deposits, often by the shear presence of corals, automatically would mean the presence of reservoirs. But this almost automatic assumption is not a priory true for Palaeozoic carbonates.

In most of the Palaeozoic carbonates cases there are no organism which could produce build ups. It is often stated in the literature that particular fauna associations like either tabulate or rugose corals, stromatoporoids and bryozoans are reefs. But in most of the cases authors agree that the shape of so-called reef is simple biostrome and just some of them give biohermal shape.

Real reefs are probably restricted to the Mesozoic and in particular Cainozoic carbonate platform systems since the arrival of Scleractinian corals. This kind of corals is able to build structure which arise above the sea floor up to sea level and then in surrounding the space are filled with other material.

It is important to have good or better say correct interpretation of the system because the lithofacies distribution in both systems is different. It is essential to have comprehensive lithological model for reservoir engineers only in this case it is possible to build good reservoir model. The problem is that in most of the cases reservoirs are not homogeneous and it is influence by sediments and their properties. Misunderstandings between geologists and engineers leads to the misleading geological and reservoirs models, which is most important for oil reservoirs.

It is stated in a number of publications that Lithuanian Silurian carbonates could potentially form hydrocarbon reservoirs and that the most likely candidate is deposits in the Minija regional stage (Jacyna et al., 2004; Zdanavičiūtė and Lazauskienė, 2007).

Of course, it is not possible to exclude that there are no layers with high porosity and permeability. However, the very low average porosity and permeability actually measured in this study and understanding the effects of the various diagenetic processes on original porosity are not encouraging. If there are some higher porous and permeable layers or bodies, they are not interconnected. And the figure 4.3 shows that there is no direct correlation between porosity and permeability as it is more usual in the siliciclastic rocks. Due to the fact that there is no correlation it is not possible to predict permeability based on porosity data.

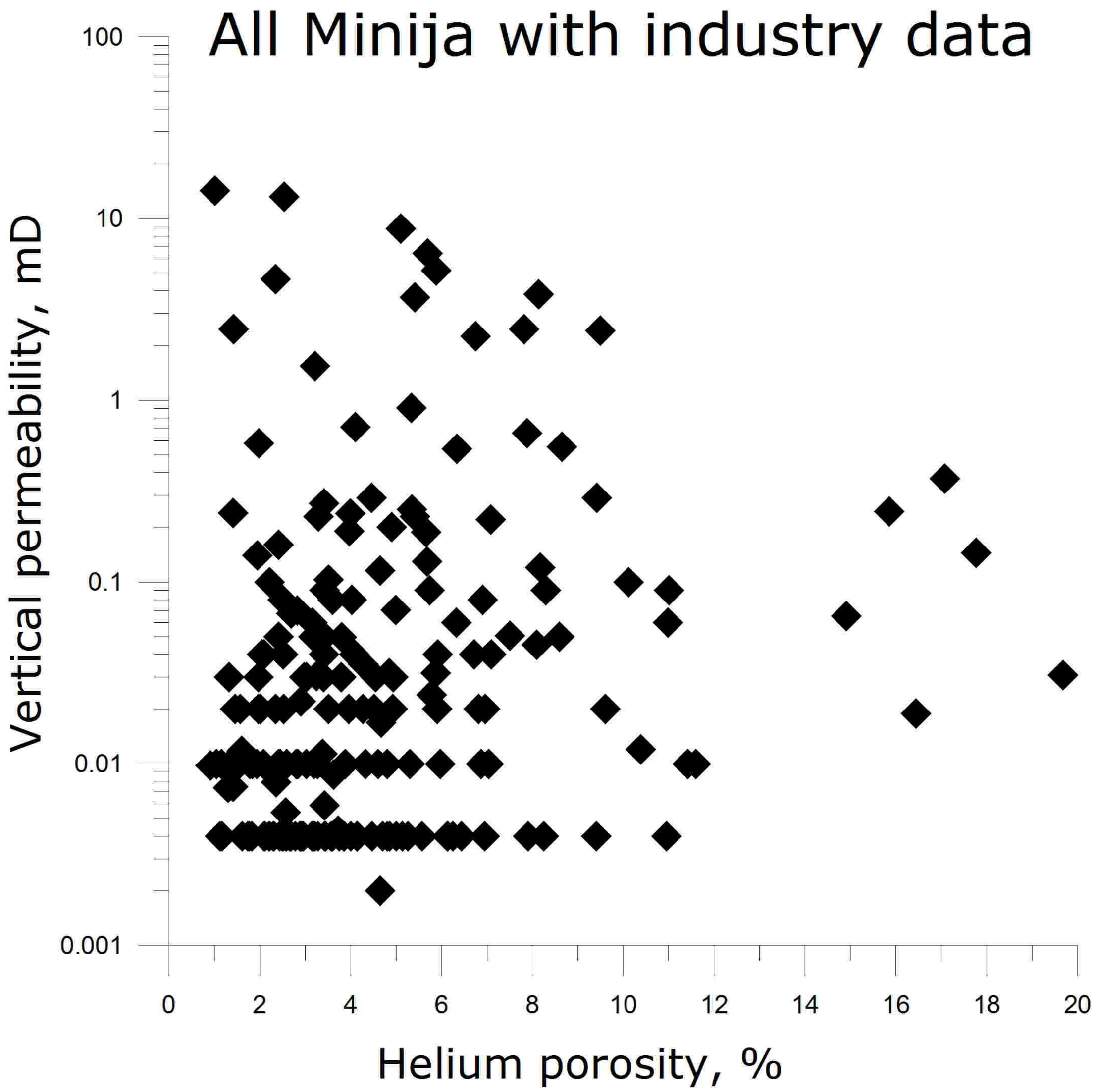


Fig. 4.3 Plot of porosity versus permeability distributions in the study area, which showing that there is no good correlation between these parameters.

Taking the various diagenetic processes into account it is evident that porosity has evolved during burial and depositional porosity strongly modified. Different types of pores can be recognized. According to the time of origin primary and secondary pores can be distinguished (Choquette and Pray, 1970). Usually carbonate rocks losing their porosity with time from 40-70 %, just deposited carbonate sediments to few percent, most of ancient limestones (Choquette and Pray, 1970; Lucia, 2007). According to the literature there are number of carbonate reservoirs which have as low as 5-10% porosity (Tucker and Wright, 1990) or porosity in carbonate reservoirs could range from 1 to

35% (Schmoker et al., 1985) and in the United States ranges from 9 to 17% in carbonates reservoir, averages 10% in dolostones reservoirs and 12% in limestones reservoirs (Schmoker et al., 1985) while most of the sandstones reservoirs have values of 15-30% (Tucker and Wright, 1990). But there are no rules without exceptions, most Cambrian sandstones reservoirs in Lithuania have porosity values of 7-11%. Here should be note that for both carbonates and sandstones reservoirs quality is more important permeability than porosity. Some scientists like Tucker and Wright also claim that 'the importance of a carbonate reservoir really depends more on its permeability, which controls the recovery of hydrocarbons, than its simple porosity. Some rocks are porous but have low permeability and so it is the effective porosity which is important (Tucker and Wright, 1990). Probably due to the fact that carbonates are more prone to diagenetic changes than sandstones, their porosity evolution is more prone to changes too. Broadly speaking porosity in carbonates is controlled by diagenesis and therefore it is difficult to predict reservoir quality, which will be controlled by the original facies types and later diagenetic processes. As it was mention before in most cases carbonates tend to loss of their initial porosity and the main player in this role belongs to diagenesis (Lucia, 2007). Lithuania Silurian carbonates are not exception, the main process, which influence of reduction of porosity is diagenesis. Diagenetic processes and their effect on porosity are shown in table 4.1. It is clear that the three-dimensional spatial distribution of petrophysical properties is initially controlled by patterns of depositional texture, it is also clear from reservoir studies that petrophysical properties found in carbonate reservoirs are significantly different from those of modern carbonate sediments (Lucia, 2007). Porosity evolution depend on diagenesis. Therefore, an understanding of diagenesis processes and patterns of their products is essential for carbonate reservoir description and reservoir model construction (Lucia, 2007).

The table 4.1 Diagenetic processes and their impact on porosity.

Diagenetic process	Effect on porosity	Remarks
Bioturbation	No effect	
Microboring and micritization	No effect	May have influenced the suitability of grain surfaces for nucleating cements
Matrix infiltration (mechanical and through bioturbation)	Decrease	Part of the pore spaces is filled with carbonate mud with originally microporosity
Marine high-Mg calcite cementation	Decrease	Fills or partly fills inter- and intraparticle pores and voids in grainstones, packstones and wackestones
Dissolution of aragonite or high-Mg calcite skeletal grains	Temporary increase	All of these pores and voids are later filled by calcite cement
Mechanical compaction	Significant decrease	Increase in grain packing density, deformation of ductile grains, brittle fracturing of elongated grains (shells)
Chemical compaction along shaly or marly laminae and beds (penetrative stylolitization)	decrease	Delivers carbonate for burial low-Mg calcite cementation
Chemical compaction by grain interpenetration (pressure dissolution)	decrease	Delivers carbonate for burial low-Mg calcite cementation
Burial low-Mg calcite cementation	Significant decrease	Filling of intra- and interparticle pores
Burial dolomite cementation	Slight decrease	
Fracturing and infilling by calcite and dolomite	No effect on the rock mass	Filling of fractures is strictly limited to the fractures without effect on the adjacent rock mass

The table 4.1 shows row of diagenetic processes which had any influence on porosity. Initial porosity range based on literature, other range based on point counting results from thin sections. Here should be noted that slightly different paragenetic succession prevail in the early dolostones in the shallow eastern part of the basin.

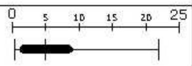
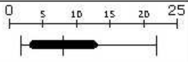
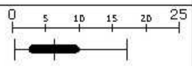
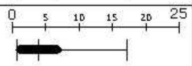
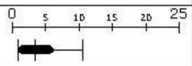
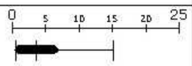
Carbonate type	Porosity %	Average	Min.	Max.	Standard Deviation	Number of analyses
Total		4.97	0.32	21.92	3.44	758
Mudstones		7.95	1.67	21.92	4.59	110
Wackestones		6.21	0.32	17.11	3.31	176
Packstones		3.93	0.63	17.12	2.89	100
Grainstones		3.45	0.90	10.46	2.15	46
Float/rudstones		3.62	0.55	15.04	2.70	76

Fig. 4.4 The distribution of porosity values in the different types of carbonate. Note that mudstone includes both lime- and dolomudstones. To determine the analytical precision two samples with distinctly different porosities (around 2 and 22%) were measured each 100 times. For the porosity values of 2% and 22% standard deviations of 0.061% and 0.209%, respectively, were obtained, indicating high precision of the equipment.

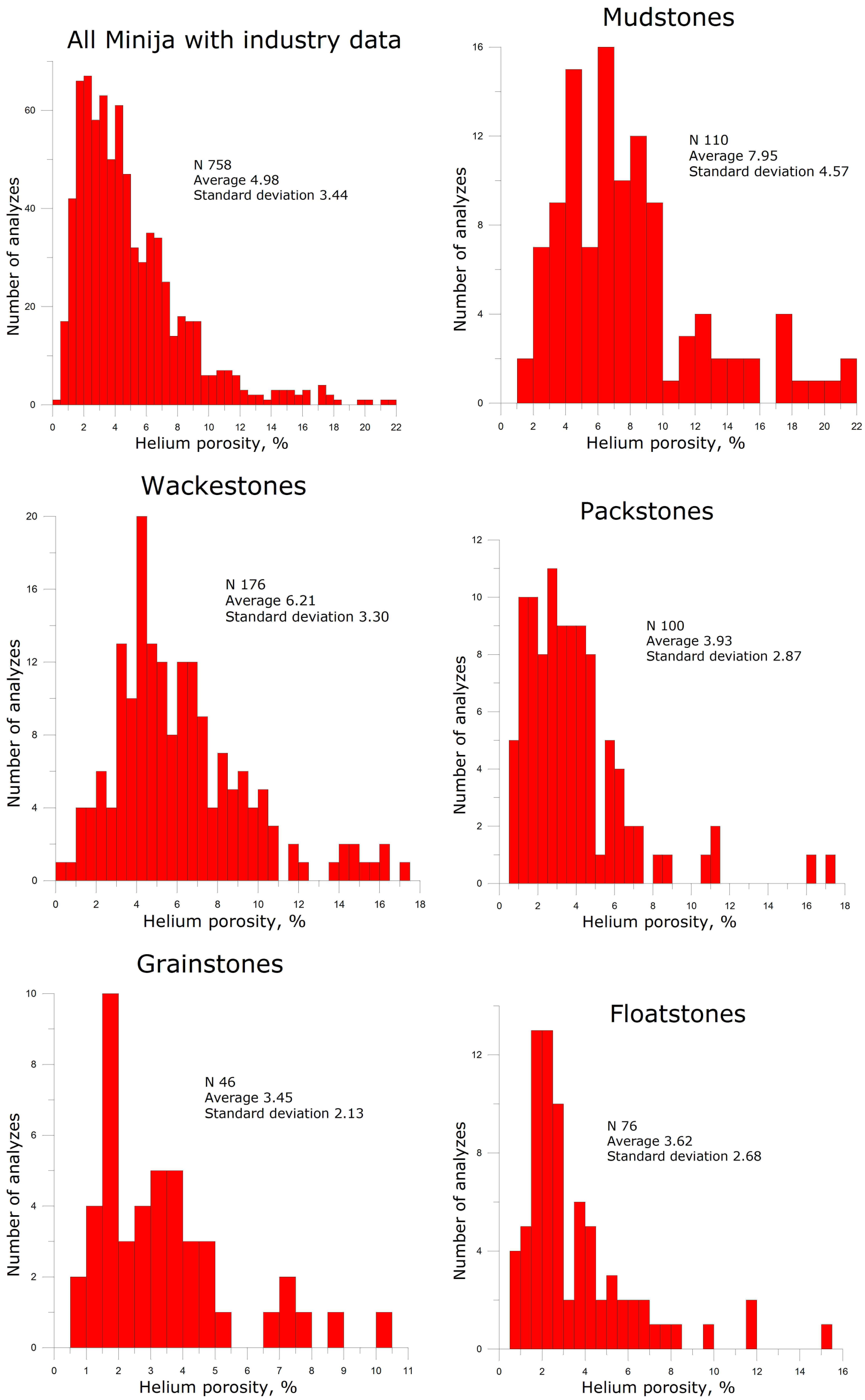


Fig. 4.5 The series of histograms of porosity distribution in the different types of carbonates shows that there is no clear pattern to certain type of carbonates. Note that highest average porosity show mudstone which includes most shallow facies of dolomudstones, which are early dolomitized. Rest of the carbonate types do not show higher average porosity than 5 %.

It appears from that most of the microfacies are mud dominated and have a matrix-supported fabric. Microporosity is dominant in such sediments and permeability is thus low. Only grainstones and to a lesser degree packstones had larger sized interparticle pores and thus initially appreciable permeability. The proximal dolostones are probably the resultant of early dolomitization processes related to the depositional environment and as such have appreciable mouldic porosity, from dissolved shells, and intercrystalline porosity. In figures 4.4 and 4.5 are summarized porosity histograms for different types of carbonates. In figure 4.6 are summarized porosity histograms or different part of the ramp.

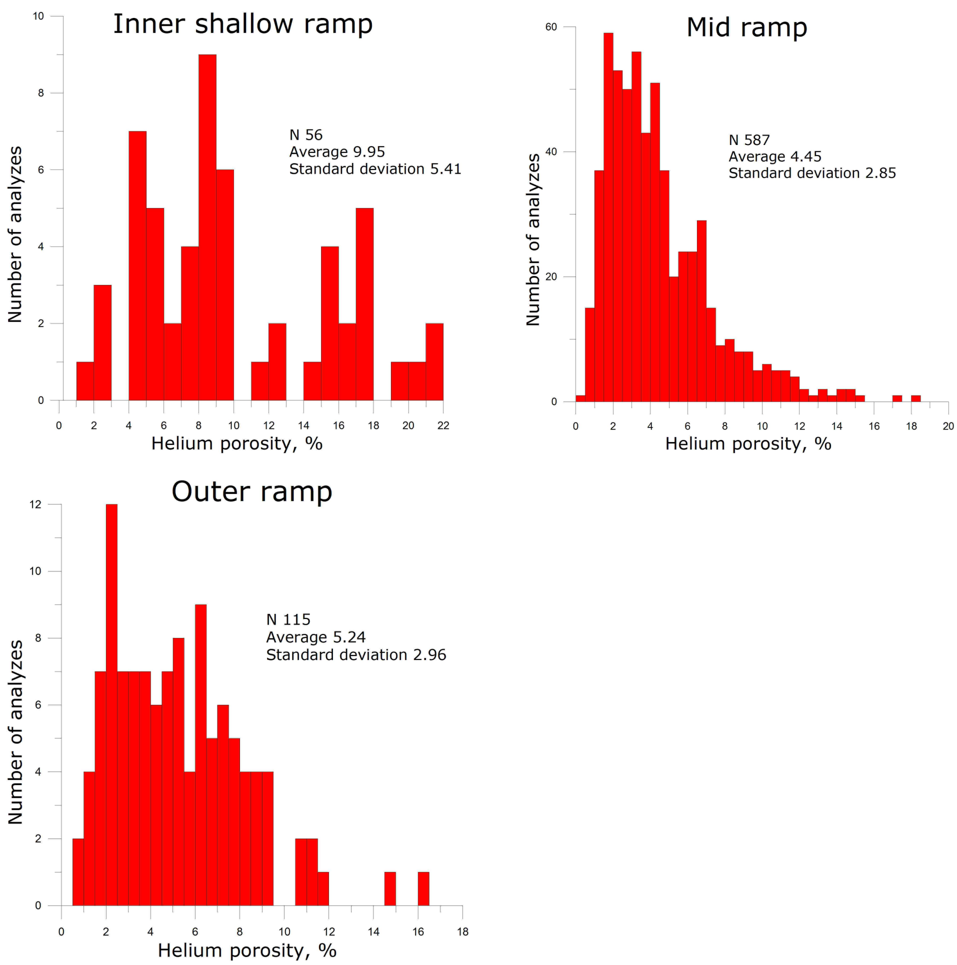


Fig. 4.6 The series histograms of porosity in different parts of the ramp shows that average porosity is highest in shallow part of the basin i.e. inner ramp. The most clear pattern of the porosity distribution shown in the mid ramp which has log normal distribution.

Most of the processes which were observed led to a loss of original porosity and often also a loss of permeability too. The first process that significantly reduced pore space was mechanical and biological matrix infiltration which according to the point count results took about 37 percent (there was matrix infiltrated or burrowed in packstones (a grainstone is per definition without matrix), and also in intrapores in wackestones?) of the total rock volume. Equivocal process was early marine cementation. From one point of view it occupied pore volume but from another point of view it helped to withstand to the progressive mechanical compaction. Loss of internal texture maybe did not play significantly straight to the porosity but it gave the source for the further cementation. Recrystallization or pseudomorphous replacement of metastable minerals like high Mg-calcite and aragonite generally has little effect on porosity and permeability development it was confirm by literature too e.g. Machel (2005). Most likely chemical compaction was the most harmful process which led to the loss of porosity. Pressure dissolution impacted in two way. First it leads to compaction itself and second it was the source for low-Mg calcite and maybe also for dolomite cements that precipitated during burial.

Usually in the system there are thin bedded layers which were formed by cyclic sedimentation, with a lot of matrix and porosity is predictably prone to be lost. If there would be thick layers of grain supported sediments it would be much more promising for reservoir. Thick layers of grainstones were no observed. Some layers with high intraporosity may occur, but this kind of layers has no permeability. Whereas layers with initial inter pores merely filled by matrix or different stages of cement. If there are in the study high pores and permeable layers or body, it is not interconnected and it is not possible to trace if from well to well.

In general, there are no layers with promising reservoir properties of reservoir in the system. Of course, it could be some layer with relatively high values of porosity but permeability is nearly always low. It is not possible to exclude bodies with suitable petrophysical properties (porosity and permeability) for reservoir but these bodies are not interconnected and it is not possible to trace them even from well to well. Most promising part for reservoir it was observed in most proximal part of the system in Inner shallow ramp where dolomudstones are dominated. These dolomudstones had high porosity from the beginning of deposition and also due to the early dolomitization preserved their porosity in high values. But that part of the basin has no proper sealing for reservoir and also there is no significant burial depth for oil maturation.

That oil is present in some thin (5-10cm thick) layers is a consequence of the heterogeneity. Some beds may have had still interconnected porosity whereas others were completely cemented. So, the heterogeneity and the different effects of diagenetic processes on porosity decline.

It was mentioned before that there are statements that in Silurian could be potential for reservoir and it could be in Minija regional stage. It is not excluded there could be layers with higher porosity and higher permeability but it was not find during the study. In general, it is possible to state that there was no observed hydrocarbon reservoir in the research area despite some statements that in Minija regional stage it could be.

CONCLUSIONS

- When using the term loosely, there were many reefs at the time of deposition. Tightening the definitions, these reefs most probably were mainly stromatoporoidal biostromes. These were continuously reworked by storm induced currents into widespread proximal skeletal rudstones to more distal packstones (that is distally from the main site of the reef).
- The entire carbonate system is likely to be a ramp instead of carbonate platform, because there is no reef in the system and the biostromes had little or no relief.
- The reservoir properties of all carbonates in the studied area are not good, with low porosity and low permeability. This is because of the intense diagenesis including early marine cementation of part of the coarser grained limestones (including grain- and packstones), mechanical compaction, chemical compaction and almost complete cementation by calcite during burial.
- The best reservoir properties are found in the dolostones in the eastern shallow parts of the basin

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Appendix1. Some term such as 'Reef', 'Biostrome' and 'Bioherm' definitions based on literature.

Reef	Biostrome	Bioherm	Remarks or Emblematic citations	Author and Reference
Reefs are here considered to form as the direct or indirect result of organic activity, developing due to the aggregation of sessile epibenthic marine organisms, with the resultant higher rate of in-situ carbonate production than in surrounding sediments			Except for some reefs built by cyanobacteria and calcified algae, many modern reefs are constructed by organisms that possess little inherent stability under agitated conditions and, being nonphotosynthetic, are not dependent upon light.	Rachel Wood (1998) The Ecological evolution of reefs.
The term **carbonate build-up** describes locally formed carbonate body that has a topographic relief. It is generally useful term, as there is no inference as to internal composition. The term **carbonate mass** is used for a carbonate body showing only slight relief and consisting of pure limestone. The terms **ecologic reef** and **stratigraphic reef** (Dunham, 1970) describe carbonate bodies that include both of the above-mentioned concepts. The **patch-reef** is characteristically an isolated circulararea of organic	The term bioherm should be separated from the term **biostrome**, which refers to purely bedded structures.	**Bioherm** is a very useful non-genetic term for a lens-like accumulation of the remains of mainly sedentary organisms.	The bioherms occur on the seaward side of the larger reef structures, on the biohermal slope. Patch-reefs also occur on the biohermal slope but they are more common on the landward (lagoon) side of the barriers. The first four facies belt formed a carbonate ramp or platform. The last two correspond to a deeper basin where fine-grained terrigenous sediments were deposited. They are not, in a strict sense, true barrier reefs but	Monica Bjerkéus and Maria Eriksson (2001) Late Silurian reef development in the Baltic Sea.

framework build-ups. The term **barrier reef** is used for a curvilinear offshore belt of an organic accumulation that is separated from the coast by a lagoon.			rather composed of several flat biostromes, which have growth on top of one another and successively been displaced towards the basin.	
Reefs are defined as calcareous deposits created by essentially in place sessile organisms. Lowenstam (1950) formulated **ecological reef** definition: 'a reef, in terms of ecologic principles, is a product of the actively building and sediment-binding biotic constituents, which, because of their potential wave-resistance, have the ability to erect rigid, wave-resistant topographic structures' Heckel (1974) defined **reef** as 'a buildup that displays: 1) evidence of a) potential wave-resistance or b) growth in turbulent water which implies wave-resistance; 2) evidence of control over the surrounding environment	Cumings (1932) added biostrome for 'distinctly bedded structures that do not swell into lens-like or reef-like form but…consist mainly or exclusively of the remains of organisms'	Cumings and Shrock (1928) proposed bioherm for 'a dome-like, lens-like or other circumscribed mass built exclusively or mainly by sedentary organisms and enclosed in normal rock of different lithological character'		Robert Riding (2002) Structure and composition of organic reefs and carbonate mud mounds: concepts and categories.
Reef is used in this paper for any biologically influenced buildup of carbonate sediment which affected		This reef definition is essentially the	This reef definition is essentially the same as that proposed by Heckel (1974),	Mark W. Longman (1981) A process approach to

deposition in adjacent areas (and thus differed to some degree from surrounding sediments), and stood topographically higher than surrounding sediments during deposition.		same as that proposed by Heckel (1974), as well as that proposed by Cumings (1932) for **bioherm**.	as well as that proposed by Cumings (1932) for bioherm, and has some major advantages over the others. First, it is basically the same as that used by most geologists, particularly those in the petroleum industry. Second, it avoids the problem of requiring reefs to have a rigid organic framework as required by the definitions of Lowenstam (1950) and Newell et al. (1953), or potential wave resistance as required by Walker (1974). Delicate or non-framework building organisms such as phylloid algae, rudists, rugose corals, bryozoans, Nummulites, and crinoids formed ancient carbonate buildups that are sometimes called reefs, but these structures are very different from modern reef complex.	recognizing facies of reef complexes.
We use term **reef** as a general term to describe any kind of biologically			According to our calculations of the	Tom Flodén, Monica Bjerkéus, Igor

influenced carbonate buildup, but we additionally use the term reef barrier for describing the laterally extensional topographic coast-following buildups that have a distinct control over the facies distribution in the surrounding basin.			palaeodepth conditions, the biohermal zone seems to have terminated rather abruptly at water depths between 40 and 60m. The reefs barriers are built up of biostromal limestones dominated by stromatoporoids in an argillaceous or crinoid limestone matrix with bryozoans and solitary corals.	Tuuling and Maria Eriksson (2001) A Silurian reefal succession in the Gotland area, Baltic sea.
Opinions on reef definitions differ, but on Gotland, bioherms and biostromes rich in stromatoporoids are abundant, and both are regarded here as **reefs**. Many of biostromes on Gotland are very stromatoporoid-rich and contain a large protion of autochhonous fossils, and so are most appropriately regarded as **reefs**.			Silurian stromatoporod-dominated reefs of Gotland, Sweden, are bioherms and biostromes formed during phases of reduced clastic supply. Most of Gotland's reefs appear to be biostromes.	Stephen Kershaw (1993) Sedimentation control on growth of stromatoporoid reefs in the Silurian of Gotland, Sweden.
Some biostromes have predominantly in-place fossils and are regarded as **reefs**.			Some biostromes have predominantly in-place fossils and are regarded as reefs, but lack rigid frameworks because of	Olof Sandström and Steve Kershaw (2002) Ludlow (Silurian) stromatoporoid biostromes from

			abundant low-profile non-framebuilding stromatoporoids; other biostromes consists of stromatoporoid-rich rudstones interpreted here as storm deposits. Biostromes are common on carbonate ramps (cf. Burchette & Wright, 1992), but may occur in a variety of settings in various water depths.	Gotland, Sweden: facies, depositional models and modern analogues.
			The strata on Gotland reflect a series of stacked carbonate platform generations. The minor dips indicate that individual platforms were of ramp type. However intermittent development of extensive stromatoporoid-coral reef barriers indicates that these ramps developed steeper gradients with time, and transformed into distally steepening ramps, or even rimmed shelfs, in their mature stages. Biohermal, biostromal and	Michael Calner, Lenart Jeppsson and Axel Munnecke (2004) The Silurian of Gotland – PartI: Review of the stratigraphic framework, event stratigraphy, and stable carbon and oxygen isotope development.

			shoals areas are characterized by stromatoporoid-coral reef complex, related coarse-grained skeletal float- and rudstone reef flank deposits and well sorted crinoidal/peloidal grainstones. The reefs on Gotland are mostly composed of pale boundstones, often with a micritic matrix.	
			The role of stromatoporoids increased in frame building towards the end of the Silurian. Shoal-barrier type reef tracts, developed at different stratigraphic levels, were situated in the middle part of a broad carbonate shelf (platform) on the SW margin of the Baltic.	Heldur Nestor (1995) Ordovician and Silurian reefs in the Baltic area.
			The patch reefs expand upwards from an initial bioherm phase with a small base to a laterally extensive biostrome phase	Nigel R. Watts and Robert Riding (2000) Growth of rigid high-relief patch reefs, Mid-Silurian, Gotland, Sweden.

Ecologic reef: An ancient reef interpreted as having been built by organisms into a rigid, wave resistant, topographic high on the sea floor (Dunham 1970) **Framework reef**: Built by organisms forming a rigid calcareous frame. **Reef**: Laterally confined biogenetic structures, developing due to the growt or activity of sessile benthic organisms and exhibiting topographic relief. This broad definition covers framework reefs, reef mounds, mud mounds as well as biostromes. **Reef mound**: Lenticular carbonate bodies consisting of bioclastic mud with minor accounts of organic biding. Skeletal organisms are common, but there is no evidence for a prominent in situ skeletal framework. Lime mud/carbonate cement and skeletal organisms are aboutequally important. Syndepositional relief. **Skeletal reef**: Corresponds to frameworks reefs with organisms, forming a rigid calcareous	**Biostrome**: Tabular rock body, usually a single bed of similar composition. Laterally extended, dense growth of skeletal organisms. No depositional relief. A rigid framework may or may not be present.	**Bioherm**: Mound or lens-shaped reefal buildup		Erik Flügel (2004) Microfacies of carbonate rocks Analysis, interpretation and application.

framework. **Stratigraphic reef**: A thick, laterally restricted mass of carbonate rock, without genetic connotations (Dunham 1970).				
	The facies described here are considered to be **biostromes** because of the abundance, grain size, growth form and organisation of stromatoporoids. Their compositions are similar or indentical to that found in bioherms or reefs, but arranged in layers or strata that do not attain a significant vertical relief above yhe sea			Anne-Christine Da Silva and Frederic Boulvain (2004) From palaeosols to carbonate mounds: facies and environments of the middle Frasnian platform in Belgium.

	floor.			
In this papaer I choose an open definition of **reefs**: skeletal mounds built above sea floor.				Peter M. Sheehan (1985) Reefs are not so different – They follow the evolutionary pattern of level-bottom communities.
In this paper '**reefs**' are defined in a very broad sedimentological and palaecological sense to encompass all facies with a significant component of macroepifaunal calcifying organisms, whether or not the facies has syn-depositional relief or was potentially wave resistant.	Where it is clear that the reefal unit had a sheet-like geometry and possesses very little syn-depositional relief the term '**biostrome**' (sensu Heckel, 1974) is used, which in this paper is understood to be a type of **reefs**.			Enzo Insalaco (1998) The descriptive nomenclature and classification of growth fabrics in fossil scleractinian reefs.
In this paper, the term '**reef**' is used in its broadest sense to include thick, stratigraphically restricted, shelf carbonate buildups as well as the familiar framework-built, ecologic reefs of today (Heckel,				George D. Stanley Jr. (1988) The history of early Mesozoic reef communities: a three-step process.

1974)				
Stromatoporoid biostromes are common in the middle Ludlow of Gotland, Sweden, and are striking for their densely packed reef builders. Here they are regarded as **reefs** because of the abundance of in-place reef-building skeletal biotas, and because in some places they grade vertically into bioherms.				Stephen Kershaw, Michael Keeling (1994) Factors controlling the growth of stromatoporoids biostromes in the Ludlow of Gotland, Sweden.
Biostrome and bioherm were described as term by Cumings (1932), and bioherm has become synonymous with **reef** because of the discrete mound or lens shape in vertical section. The phrase "**reefs** and biostromes" is common in the literature and emphasizes that biostromes are normally regarded explicitly as not reefal structures, because of the lack of topographic relief and common absence of a framework.		Cumings (1932: 333) used **bioherm** to describe '...reeflike, moundlike, lenslike or otherwise circumscribed structures of strictly organic origin, embedded in rocks of different lithology, and **biostromes** as organic features which		Stephen Kershaw (1994) Classification and geological significance of biostromes.

		are ‘... purely bedded structures ... not swelling into moundlike or lenslike forms’		
The term **reef** is used here simply to denote any biologically influenced carbonate accumulation which was large enough to have developed topographic relief above the sea floor.				Harold G. Reading (2004) Sedimentary environments: processes, facies and stratigraphy.
In simple terms two features characterize **reefs**. First, they are laterally restricted in some way, even though they may cover large areas and/or have significant relief. Secondly, they show evidence of the biological influence during growth, although this is not always clear in some ancient reefs, such as mud mounds. In the past the term reef has been used by some workers to describe any discrete carbonate buildup, but Dunham (1970) suggested a distinction be made between stratigraphic reefs, which are laterally restricted				Maurice E. Tucker and V Paul Wright (1999) Carbonate sedimentology.

carbonate buildups, perhaps composed of superimposed small reefs, and ecologic reefs which regarded as rigid, wave resistant, topographically distinct, and biogenically formed. In this chapter the term is used in a general sense for any biologically-influenced carbonate accumulation which was large enough during formation to have possessed some topographic relief. Recent useful definitions have been given by Longman (1981) and informally by James et al. (1985). It should be appreciated that a variety of organisms can build reefs, involving many different processes. As a result a wide spectrum of reefs can be formed, but broadly speaking two main types can be recognized: skeletal (frame-built) reefs and reef mounds.				
A major distinction between reefs (sensu stricto) and other kinds of buildups was highlighted by Lowenstam (1950): '**reefs** and '**ecological reefs**' of Dunham (1970) are organically produced				J. Javier Álvaro, Markus Aretz, Frédéric Boulvain, Axel Munnecke, Daniel Vachard and Emmanuelle Vennin

wave-resistant topographic structures'. This concept was further developed by Heckel (1974), in which he proposed that reefs are buildups which display evidence of potential wave resistance or growth in turbulent water and of control over the surrounding environment.				(2007) Palaeozoic reefs and Bioaccumulations Climatic and evolutionary controls.

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The lists of scientific publications:

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Presentations at conferences:

The eighth Baltic Stratigraphical conference 28-31 August 2011, Riga, Latvia 'Implications from stable ^{13}C isotope stratigraphy for closed system carbonate diagenesis; An example from the Upper Silurian Baltic Basin'.

The seventh Baltic Stratigraphical conference 15-22 May 2008, Tallinn, Estonia. 'Nature of the so-called 'reefs' in the Přidolian carbonate system of the Silurian Baltic Basin'

International conference, Geology in Vilnius University 2003 October 8-9. 'Lithological and petrophisical researches.'

Participation in projects:

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Specialist in project: 'Evolution of palaeogeographical conditions in Lithuania during postglacial period in the conjunction of Baltic sea and land' 2010-2011 LNMP project No. LEK-10005

Performer in project: ‘Petrophisical properties of Upper Silurian, Lithuania’ 2009. VMSF Registration No. T-09073. Contract No. T-79/09.

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Performer in budgeted topic: Vilnius University Faculty of Natural Sciences Department of geology and mineralogy: ‘Peculiarities of Evolution of Silurian Sedimentological Basin of Lithuania on the Data of Lithological, Paleontological, Geochemical and Geophysical‘ 2006-2010

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