From detached to attached carbonate buildup complexes - 3D seismic data from the Upper Palaeozoic, Finnmark Platform, southwestern Barents Sea

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Abstract

Carbonate buildups were abundant during the Palaeozoic. Three-dimensional seismic data from the Finnmark Platform, Barents Sea, has been used to reconstruct the evolution of laterally extensive carbonate buildup complexes in space and time. The results suggest that the location of Upper Palaeozoic warm- and cool-water carbonate buildups from the Finnmark Platform is controlled by faults and the sea floor morphology at the time of their growth. A fluctuating sea-level affected the growth of the carbonate buildups, but they also influenced their own environment by forming lagoons, atoll-like ridges and possibly areas with restricted circulation. Warm-water carbonate buildups, forming ridges and isolated mounds, occur in the Gipsdalen Group (latest Serpukhovian-mid-Sakmarian), where they initially grew in a detached platform setting. The carbonate buildups are several tens of kilometres long, up to 2.5 km wide and 300 m thick, and interpreted to consist of vertically stacked complexes of sub-seismic scale carbonate buildups. Evaporites were deposited and later subject to karstification, possibly during a period of sub-aerial exposure, before a transgression and the subsequent carbonate deposition and buildup growth bridged the detached platform with the attached platform. In the Bjarmeland Group (Lower Permian) 0.35-4.8 km wide, 1.5-27 km long and 60-420 m thick cool-water bryozoan-dominated straight, sinuous and continuous carbonate ridges or atoll-like ridges are located on top of the warm-water carbonate structures. Three-dimensional maps of Upper Palaeozoic carbonate buildups document their geomorphology, distribution and size through time. The lateral and vertical growth of carbonate buildups has been reconstructed, revealing how their distribution changed over time and with changing environmental settings.

Introduction

Isolated, mound-shaped carbonate buildups form a characteristic outcrop feature of many Carboniferous–Permian successions around the world, including the Muleshoe Mound in New Mexico (Pray 1961; Kirkby and Hunt 1996). Isolated buildups are also common in Artic Upper Carboniferous – Lower Permian outcrops (Beauchamp and Desrochers, 1997; Beauchamp and Olchowy 2003; Stemmerik, 1997, 2003; Samuelsberg and Pickard, 1999; Samuelsberg, 2000; Stemmerik et al., 1994; Kuznetsov, 2002; Vennin et al., 2002; Wahlman and Konovalova, 2002). Early studies, based on relatively sparse 2-D seismic data coverage of the southern Norwegian Barents Sea indicated the presence of numerous isolated buildups in the subsurface offshore Palaeozoic sections (e.g. Bugge et al., 1995; Blendinger et al, 1997; Ehrenberg et al., 1998;
Stemmerik et al. 1995, 1999). However, as more offshore data, particularly three dimensional (3D) seismic data have become available, our understanding of buildup geometries have changed dramatically, such that rather than being isolated mounds the buildups are now seen to form interconnected polygonal networks of laterally amalgamated and bifurcating ridges (Elvebakk et al., 2002; Samuelsberg et al., 2003; Colpaert et al., 2007).

The objective of this paper is to report on investigations into the evolution of the Late Palaeozoic carbonate buildups of the Finnmark Platform (Fig. 1), south-eastern Norwegian Barents Sea and explain the interaction between underlying structures, carbonate buildups, sea level and palaeo-environment. The growth of the Barents Sea carbonate buildups spans 35–40 Myr starting in the Moscovian and ending in the Artinskian (Larssen et al., 2005). During this period the Barents Sea area, as part of the northern Pangean shelf drifted northwards from a subtropical position at around 30ºN to a temperate position at approximately 45 °N (Stemmerik 2000). Also, during the Sakmarian the southern hemisphere Gondwana glaciation terminated and sea level fluctuations became less pronounced.

The study is based on 3D seismic data from the northern, more distal part of the Finnmark Platform which allows detailed facies mapping of several time intervals during the Late Palaeozoic. The seismic facies maps have been combined into four-dimensional maps (3D seismic maps with the variation in build-up growth through time as the fourth dimension) to visualise the changes over time in response to shifting environmental conditions. The seismic data set is one of several semi-regional industry 3D seismic surveys that have been designed to cover the prospective Upper Carboniferous – Lower Permian succession in the Barents Sea. The Upper Palaeozoic carbonates have significant reservoir potential and are an important play model in the Norwegian Barents Sea. The most prospective reservoir rocks are the Moscovian–Asselian exposure-capped shelf carbonates and buildups of the Gipsdalen Group (Stemmerik et al., 1999; Stemmerik and Worsley, 2005).

Data

The 3D seismic area is located on the Finnmark Platform, south-eastern Norwegian Barents Sea and covers an area of 519 km² (Fig. 1). During acquisition the bin size of the data, i.e. the inline by crossline distance was 18.75 m by 25 m. The interval velocities of the Upper Palaeozoic carbonates range from 4300-6500 m/s, although mainly between 5000 and 6000 m/s. An average velocity of 6000 m/s has been applied for the carbonates of the Carboniferous–Permian Gipsdalen and Bjarmeland groups when converting to depth. On seismic profiles and in
the text, scales in milliseconds represent two-way travel-time below sea level. With a dominating
frequency of around 25 Hz, the vertical seismic resolution in the Upper Palaeozoic succession is
around 50 m. The theoretical horizontal resolution is c. 50 m (1/4 \( \lambda \)) but the practical resolution
may be closer to 100 m (1/2 \( \lambda \)). The vertical and lateral resolution of the 3D seismic data has
been preserved through the interpretation and filtering processes so that detailed morphological
features are preserved in the final maps.

The seismic data set has been tied to exploration wells on the Finnmark Platform to
constrain the age of seismic reflectors and interpretation of seismic facies. Well 7229/11-1,
located close to the centre of the 3D area was terminated in the Upper Carboniferous Gipsdalen
Group at 4630 m Rig Kelly Bushing whereas the more southerly located wells 7128/6-1 and
7128/4-1 both penetrated the entire Upper Palaeozoic succession (Larssen et al., 2005). In
addition to correlation to well 7229/11-1, geomorphology, seismic amplitude, seismic signature
and seismic facies mapping has been used to interpret the depositional setting.

When using seismic data in carbonate buildup studies it is important to be aware that the
complexity of the carbonate facies results in heterogeneities at all scales. Using synthetic seismic
modeling, Nielsen et al., (2004) demonstrate how seismic images may be interference patterns
caused by numerous mounds, each with a size below seismic resolution.

Porous carbonate buildups may abruptly change laterally into tight buildup flank deposits
and finally into porous lagoonal deposits. Abrupt changes in carbonate facies may give rise to
artefacts such as pull-up effects and fake faults caused by abrupt lateral velocity changes. For
example, a 150 ms thick buildup (with velocities of 6000 m/s) surrounded by sediments with
lower velocities (around 5000 m/s) may account for a pull-up effect of up to 30 ms twoway
travel-time, and a rapid lateral velocity change from 6000 to 5000 m/s in a 50 ms thick bed may
cause fault-like artefacts with a throw of up to 10 ms two-way travel-time. For example, offshore
Ireland discontinuities related to carbonate mounds were initially interpreted as faults (Hovland
et al., 1994), but later studies based on 3D seismic data caused many of the inferred
discontinuities to be re-interpreted as artefacts (Bailey et al., 2003).

Geological setting

The study area on the Finnmark Platform formed part of a vast, roughly east-west
oriented Late Palaeozoic shelf stretching from the Sverdrup Basin (Arctic Canada) in the west,
across North Greenland and the Norwegian Barents Sea to Arctic Russia in the east. This
represents the northern margin of Pangaea (Stemmerik and Worsley, 2005). The Finnmark Platform (Fig. 1) formed a relatively stable and slowly subsiding block influenced by NE–SW (Caledonian) and NW–SE (Baikalian) trending structures during the Late Carboniferous and Permian (Gabrielsen et al., 1990; Alsgaard 1993). It is bounded to the north-west by the deep Harstad and Tromsø basins and to the north by the Hammerfest and Nordkapp basins. From the mid-Carboniferous and throughout the Permian, the platform formed a northerly dipping, distally steepening carbonate ramp with buildups (Samuelsberg et al. 2003). Towards the north-east, the outer part of the Finnmark Platform includes many examples of structurally controlled, detached Moscovian–Sakmarian carbonate platforms which became attached to the Finnmark Platform ramp during the Artinskian. The 3D seismic study area covers such a Moscovian–Sakmarian carbonate platform sitting on a mid-Carboniferous structural high. The Finnmark Platform was later modified by Jurassic tectonic movements along pre-existing faults and by differential Tertiary uplift (Samuelsberg et al., 2003).

The northern Pangaeans shelf, including the Norwegian Barents Sea drifted northwards at a rate of 2-3 mm per year from around 20° N to 45° N during the Carboniferous and Permian (Scotese and McKerrow, 1990; Golonka and Ford, 2000; Stemmerik and Worsley, 2005). This northward movement caused a gradual change in climate from tropical and humid in the Early Carboniferous to subtropical and dry in the Bashkirian – mid-Sakmarian, warm temperate in the late Sakmarian – Kungurian, and finally cool temperate in the Late Permian (Beauchamp 1994, Stemmerik, 2000). The northward drift of the area is reflected in the gross depositional patterns of the Carboniferous–Permian succession that form the basis for the lithostratigraphic subdivision of the succession into four groups (Fig. 2; Larssen et al., 2005). The dominantly non-marine Famennian – lower Serpukhovian Billefjorden Group is mainly composed of humid fluvial and lacustrine deposits. It is separated from the upper Serpukhovian – lower Sakmarian Gipsdalen Group by a regional unconformity (Stemmerik and Worsley, 1989, 2005). The basal, upper Serpukhovian – lower Bashkirian Ugle Formation consists mainly of alluvial red beds deposited in syn-rift half-grabens (Larssen et al., 2005). As regional subsidence started in the mid-Bashkirian, the region was gradually transgressed and the overlying Falk Formation consists of interbedded alluvial and shallow marine siliciclastics, carbonates and evaporites. The upper Ørn Formation consists of warm-water shelf carbonates, including phylloid algae and Palaeoaplysina buildups and minor shallow water anhydrite and reflects deposition over structural highs like the Finnmark and Bjarmeland platforms and the Loppa High. In the more
rapid subsiding Nordkapp, Ottar, Maud and Tromsø basins basinal evaporites were deposited (Breivik et al., 1995; Nilsen et al., 1995).

There is an abrupt and in many places unconformable transition from the Gipsdalen Group to the overlying mid Sakmarian – Artinskian (lowermost Kungurian?) Bjarmeland Group (Fig. 2). The transition reflects a change from warm-water to cool-water carbonates in the platform areas and from evaporite to fine-grained carbonate and shale deposition in the basins (Stemmerik and Worsley, 2005). The group is divided into three formations which interfinger laterally. The Isbjørn Formation is dominated by crinoid-, bryozoan- and brachiopod-rich packstones and grainstones and reflects deposition in inner shelf environments. Fine-grained carbonates and shales of the Ulv Formation were deposited in more distal settings, and the Polarrev Formation include large carbonate buildups with cores composed of bryozoan–*Tubiphytes* and microbial cementstone (Blendinger et al., 1997; Larssen et al., 2005). The youngest Permian sediments of the Tempelfjorden Group are separated from the Bjarmeland Group sediments by a sub-aerial exposure surface in the platform areas. The boundary represents a shift from cool-water carbonates to deposition of deeper water spiculites, shales and locally sandstones (Stemmerik and Worsley, 2005).

**Finnmark Platform**

The Moscovian – early Sakmarian warm-water carbonate platform shows a distally steepening ramp profile with isolated palaeoaplysinid – phylloid algal buildups in inner and middle ramp settings (Bruce and Toomey, 1993; Bugge et al., 1995; Stemmerik et al., 1995, 1999; Ehrenberg et al., 1998; Elvebakk et al., 2002; Larssen et al., 2005). The warm-water carbonates were deposited in an icehouse world with high frequency and high amplitude sea level fluctuations. The repeated subaerial exposure of the platform led to widespread dolomitization and leaching of metastable carbonate grains, and the Gipsdalen Group carbonates are generally porous and have significant reservoir potential (Stemmerik et al., 1999, Stemmerik and Worsley, 2005). Well 7229/11-1 penetrated almost 350 m of warm-water carbonates of the Ørn Formation from 4282–4630 m RKB (Larssen et al., 2005). The drilled succession consists mainly of alternating limestone, dolomite and anhydrite beds and includes dolomitized phylloid algal buildups. In the upper part of the formation subaqueous anhydrite beds occur at several levels. The velocities of the Gipsdalen Group range from 5000-6500 m/s with an average around 6000 m/s.
The warm water carbonates are separated from the overlying cool water carbonates of the Bjarmeland Group by the Top Gipsdalen seismic horizon. The Late Sakmarian – Artinskian cool-water platform shows a distally steepening ramp profile. Deposition in the southern, proximal platform areas (wells 7128/4-1 and 7128/6-1; Fig. 1) were dominated by bioclastic packstones and grainstones whereas the more distal parts of the platform towards the Nordkapp Basin were characterised by deposition of fine-grained carbonates and shale. In well 7229/11-1, the basal part of the Bjarmeland Group from 4046–4282 m consists of non-porous limestones of the Polarrev Formation. The Polarrev Formation buildup at this locality is dominated by bryozoan–Tubiphytes microbial buildup facies with abundant Stromatactis limestones (Blendinger et al., 1997). The penetrated buildup consists of repeated alternations of cement-dominated buildup core facies and flank deposits of crinoidal-rich grainstone. Deposition of the bryozoan-dominated buildup complex started in relatively deep water below storm wave base and grew upwards into shallower water close to storm wave base (Larssen et al., 2005). The buildup is overlain by cool-water crinoidal-bryozoan limestone of the Isbjørn Formation (3970–4046 m), the uppermost formation in the Bjarmeland Group at this locality (Larssen et al., 2005). The seismic velocity of the cool-water carbonates ranges from 5800-6200 m/s.

The Top Bjarmeland seismic horizon separates the platform carbonates from an upper Permian succession of chert-rich spiculitic mudstone and black shale of the overlying Tempelfjorden Group. The seismic velocity of these sediments ranges from 3800–6000 m/s with an average velocity for the Tempelfjorden Group of around 5000 m/s. The overlying Triassic succession has a velocity of around 4300 m/s.

Results

Pre-carbonate platform topography – Billefjorden Group

The study area is centred on an isolated, fault-controlled structural high that formed as the result of Early Carboniferous, syn-Billefjorden Group rifting (Fig. 3). Initially, the high was separated from the Finnmark Platform to the south by a fault-controlled basin (Fig. 3a), but over time a fault-controlled saddle area evolved towards the south forming a bridge to the Finnmark Platform. The topography of the top Billefjorden Group surface seems to have had a profound influence on the foundation and distribution of the overlying Gipsdalen Group carbonate buildups (Fig. 3c).

Warm-water carbonate platform - Gipsdalen Group
The Gipsdalen Group ranges in thickness from 414–864 m (138–288 ms), thinning locally towards the south whereas the larger-scale regional trend is a southward thickening (Samuelsberg et al., 2003). The boundary between the Billefjorden and Gipsdalen groups is a regional unconformity with local truncations of reflectors in the uppermost part of the Billefjorden Group. This event is probably linked to latest Serpukhovian – Bashkirian rifting of the western Barents Sea and Svalbard (Steel & Worsley, 1984, Stemmerik & Worsley, 2005). The basal part of the Gipsdalen Group represents a major transgressive event that allowed carbonate platforms with buildups to be established over topographic highs whereas deeper water deposits, characterized by parallel to sub-parallel low amplitude reflections with generally low continuity, surrounded and locally onlapped the high (Figure 3a).

As illustrated with yellow colours in Figure 4c, six main levels of carbonate buildups have been identified in the Gipsdalen Group. Buildup growth apparently initiated along the margins of the underlying palaeo-high (buildup 1, Fig. 4c), and following a period of lateral expansion (buildups 2 and 3) the buildups became confined to the edges of the palaeo-high where they stacked to form c. 300 m thick buildup complexes (buildups 2, 4, 6). In the basinal settings southeast of the palaeo-high, small mounds and ridges are limited to the upper part of the Gipsdalen Group where mounds and ridges, 100-3300 m long, 100-400 m wide and 20-120 m (6-40 ms) thick occur just below high-amplitude reflections (Fig. 5a, c, d). Over the palaeo-high itself, the buildup complexes form ridges up to 25 km long, 2.5 km wide and 300 m (100 ms) thick (Figs. 6 and 7, shown with yellow colour in Fig. 6b). The locations of the mounds and ridges are interpreted to have been controlled by the underlying topography (with siliciclastic-dominated sediments) which again is affected by faults (Figs. 3 and 6). Similar observations are reported from the Loppa High (Elvebakk et al. 2002). In our study area, the large buildups occur mainly along the edge of the palaeo-high and along the flanks of the saddle area in regions where the rate of subsidence allowed accommodation of expanded shallow marine carbonate successions (Figure 4c).

Based on their stratigraphic interval and seismic signature the mounds and ridges are interpreted as warm-water carbonate buildups (Figs. 6a and b). The buildups located in more basinal settings (Figs. 5a, c and d) clearly pre-date the high-amplitude evaporite reflector (see below) whereas the buildups located over the palaeo-high both pre- and post-date evaporite deposition. The buildups are age-equivalent to those described by Elvebakk et al. (2002) from the Loppa High area, and possible outcrop analogues are those in the Kapp Dunér Formation of Bjørnøya and the Wordiekammen Formation of Spitsbergen (Lønøy, 1988; Stemmerik and
Larssen, 1993; Stemmerik et al., 1994; Samuelsberg, 2000; Skaug et al., 1982). However, most exposed buildups are less than 10 m thick and only rarely are the buildups seen to stack to seismic scale buildup complexes (Stemmerik et al., 1994; Samuelsberg, 2000). This implies that the buildups described in this paper are more complex than the seismic data indicates, and that details (small faults, fractures, small karst features, etc.) are most likely to be present but below seismic resolution (50 m). It is important to be aware that features below seismic resolution can make interference patterns that hamper the seismic image (i.e. Nielsen et al., 2004).

Evaporites and karst - Gipsdalen Group

The overlying succession is characterised by parallel to sub-parallel high-amplitude reflections with medium to high continuity (Fig. 3a). Based on well data and seismic signature, the high amplitude reflectors are correlated to subaqueous anhydrite beds cored in the upper Gipsdalen Group in well 7229/11-1. The evaporites occur in the basinal parts of the study area and thicken towards the edge of the central palaeo-high (Figs. 8 and 9), before they rapidly thin beyond seismic resolution at the flanks of buildup 4 on the palaeo-high (Figs. 3a and 10). Based on well tie and regional correlation these evaporites are most likely of early Permian age and a lateral equivalent to halite deposits in the Nordkapp Basin (Larssen et al., 2005) and to widespread high amplitude anhydrite deposits in outer platform areas in the southwestern Barents Sea. The lack of seismic scale evaporites on the palaeo-high in our study area most likely reflects a lack of accommodation over the high due to subaerial exposure but could also reflect dissolution during later subaerial exposure at the Top Evaporite reflector time (Figs. 5b and 10c). The onlap of the evaporites towards the flanks of the buildups in the crestal area of the high suggests that they formed during rising sea-level following a sea level fall that resulted in subaerial exposure of the high. Thickening of the evaporite succession surrounding the palaeo-high (Figs. 8-10) is interpreted to have been caused by carbonate buildups formed below / within the evaporite succession and later draped by evaporites (Fig. 9). Possibly, differential compaction of evaporites and carbonate buildups further enhanced the apparent difference in thickness. The evaporites were probably gypsum that during burial dewatered and formed anhydrite, and thus may have compacted more than the rigid carbonate buildups. The slight down-bulge in Figure 9 may be a push-down effect caused by velocity difference between the evaporites and the carbonate buildups. Push-down is caused by deposits with a relatively slow sound velocity, of which the reflections reach the seismic receivers at the surface later than normal. Thus these strata appear in seismic time maps / profiles to be located deeper than they
actually are. The presence of mounded facies within the evaporite succession suggests that open marine conditions were established temporarily within the overall evaporitic basin, most likely during repeated higher-order sea level rises. Alternatively, the thickening of the evaporite succession could be due to a local over-deepening close to the palaeo highs (due to differential subsidence/loading and/or active faults), and thus reflects local variations in available accommodation. The existence of erosional bottom current scouring along the buildups cannot be excluded.

Several circular depressions, ranging in diameter from 410 to 870 m and 6 to 33 m in depth, occur at the top evaporite level (Figs. 5b, 10 and 11). The depressions are cone-shaped and deepest in the centre (Fig. 5b). There is a 1:1 correlation between the depressions on the top evaporite horizon (Fig. 5b) and the mound-shaped features just below the base evaporite horizon (Fig. 5a). Anhydrite is relatively brittle (compared to halite) and differential compaction may have caused fracturing of the evaporites above the mound-shaped carbonate buildups, increasing the permeability and allowing dissolution and karstification processes to escalate in these areas (compared to surrounding areas). The depressions are accordingly interpreted as karst sinkholes or dolinas (Rafaelsen, 2006), and may represent a prolonged event of subaerial exposure. However, the possibility of these features being submarine sinkholes similar to those described from the Straits of Florida (Land et al., 1995) cannot be excluded.

Cool-water carbonate platform – Bjarmeland Group

In the study area the Bjarmeland Group ranges in thickness from 45-435 m (15-145 ms) and is characterized by discontinuous low amplitude reflections, except in the southwest, where the reflection continuity is slightly improved. The group is dominated by large mounds and sinuous, straight and semi-circular ridges over the palaeohighs. The mounds and ridges exhibit a sub-parallel to chaotic or semi-transparent internal seismic facies with varying amplitude (Figs 3a, 6c, 7, 9 and 10c). The sinuous and straight ridges are 350-1500 m wide, more than 27 km long and have a relief of 60-325 m (20-108 ms) (Fig. 12). The semi-circular ridges are 1.3-4.8 km wide, 1.5-3.3 km long and up to 420 m thick. Without taking into account differential compaction, the relief measured on seismic time data from the ridge top to the surrounding palaeo-seafloor is 150-345 m (50-115 ms) whereas the relief down to the floor of the enclosed internal zones was 90-180 m (30-60 ms). The time-equivalent basinal succession is typically 120-240 m (40-80 ms) thick and may according to well 7229/11-1 consist of echinoderm-rich grainstones (Blendinger et al., 1997).
The ridges are interpreted as complexes of bryozoan-dominated buildups based on observations in well 7229/11-1 (Fig. 12). This well penetrates an approximately 240 m thick Bjarmeland Group mound complex dominated by bryozoan-\textit{Tubiphytes} grainstones and cementstones with \textit{Stromatactis} fabric (Blendinger et al. 1997). The buildups are assumed to have formed in an outer ramp setting below storm wave base (cf. Stemmerik 1997).

The initial location of the ridges was controlled by the position of the underlying Gipsdalen Group buildups, but as the Bjarmeland mounds continued to grow they expanded laterally beyond the location of the underlying buildups (Fig. 4). The largest mounds are located along the margins of underlying palaeohighs while mounds and ridges become smaller and less abundant towards the centre of the highs. Over time the differential growth of the marginal ridges transformed the central parts of the palaeohigh to a deep semi-enclosed basin with a floor 100 m or more below the crest of the ridges (not taking into account differential compaction).

The semi-circular, atoll-like ridges in Fig. 12 (number 1 and 2) are slightly asymmetric with the highest parts towards the open sea and the lowest parts in a more back-reef position. This most likely reflects optimal conditions for the reef builders along the seaward side margin whereas the back reef side of the ridge may have been characterised by poorer water circulation, possibly even dysoxic conditions.

Generally, most of the buildup complexes in the study area interpreted as having kept up with rise in relative sea level for a long period but they narrow significantly towards their top as if they were struggling in the latest stages of growth before finally being drowned (Figs 9, 11, 12). Buildups and ridges located in more updip positions often have rounded or flat tops and seem to have been able to migrate laterally eventually to fill central parts of the atoll-like structures (Fig. 12, number 3).

\textit{Post-carbonate platform deposition - Tempelfjorden Group}

Sediments of the overlying, Permian Tempelfjorden Group range from 37 to 200 m (15-80 ms) in thickness, but are generally 75-100 m (30-40 ms) thick in the study area (using 5000 m/s as an average velocity). The succession is dominated by high-amplitude reflections with high continuity and forms a relatively thin drape of chert-rich mudstone and shale on top of the older Bjarmeland Group topography (Figs. 12 and 13).

\textbf{Discussion}
The seismic data illustrate the evolution of a complex carbonate platform system over a timespan of more than 30 Myr, from the Moscovian to the Artinskian. During this time interval the southern Barents Sea drifted northwards from a Moscovian position at approximately 30°N to a position in the Artinskian of around 45°N, and depositional conditions shifted from subtropical warm-water to cool water (Beauchamp, 1994; Stemmerik, 2000). Over the same timespan, the climate changed from icehouse conditions in the late Carboniferous – mid-Sakmarian towards greenhouse conditions later in the Permian. The combined results have been documented in numerous studies of outcropping shelf sediments in Svalbard, North Greenland and the Sverdrup Basin, indicating arid warm water conditions during the Moscovian – early Sakmarian and cooler water conditions from the mid-Sakmarian and onwards (see Beauchamp 1994; Stemmerik 2000).

The Gipsdalen buildup complexes and time-equivalent platform and basinal successions were subjected to repeated high-frequency and high-amplitude sea-level fluctuations and in outcrop Moscovian–Asselian carbonate buildups complexes consist of stacked, 2–10 m thick *Palaeoaplysina* and phylloid algae buildups (e.g. Stemmerik et al, 1994; Stemmerik, 2003). The *Palaeoaplysina*–phylloid algal buildups generally occur in inner-platform settings, while the biogenic composition of the larger buildups downdip on the platforms and basin margins is more speculative; by comparison with the Sverdrup Basin they are likely to be dominated by bryozoans and phylloid algae (Beauchamp 1993).

In this study area, faults and the morphology of the top Billefjorden Group surface (Fig. 3) strongly affected later carbonate deposition and buildup growth. Gradual transgression of the palaeo-high initiated deposition of Gipsdalen Group carbonates and warm-water carbonate buildups, starting downflank and expanding over time to include the palaeo-high itself (Fig. 6). Time-equivalent buildups in outcrop, and those drilled in updip positions, are all composed of stacked sub-seismic scale units separated by subaerial exposure surfaces (e.g. Ehrenberg et al., 1998; Bugge et al., 1995). In our study, lateral growth towards the high was a response to increasing water depth which may have drowned the down-flank buildups. The buildup complexes observed in the 3D seismic area are therefore interpreted to consist of sub-seismic scale carbonate buildups stacked on top of each other, reaching cumulative heights of up to 300 m.

The first stage of carbonate buildup development was terminated by a prolonged event of widespread evaporite deposition. Well 7229/11-1, on top of a palaeo-high cored thin sub-aqueous anhydrites and the seismic data indicate considerably thickening of this unit away from
the high. In the deep Nordkapp Basin to the north, halite was deposited during this stage. Repeated events of high sea-level and better sea-water circulation apparently allowed small buildups to form temporarily on the palaeo-high but over time the evaporites gradually lapped onto and covered the buildups (Fig. 5a and c). The growth of the basinward buildups (Fig. 5a) probably ceased early, while the growth of the buildups at the edge of the palaeo-high ceased later. At the bathymetrically highest points, towards the centre of the palaeo-high, growth seems to have continued relatively undisturbed, possibly restricting evaporite deposition. A subsequent fall in sea-level may have led to subaerial exposure and allowed karst sinkholes to form at the top evaporite surface (Fig. 5b). This subaerial exposure event is believed to be a regional event which on the inner Finnmark Platform is recorded by thin sandstone at the transition between the Gipsdalen and Bjarmeland groups (Ehrenberg et al., 1998). The collapse pipes and V-structures from the gypsum palaeo-karst system in Central Spitsbergen are of Moscovian-Kazimovian age (Eliassen and Talbot, 2005) and may serve as a possible analogue to karst formation in relation to evaporites.

Large faults are observed in relation to the underlying carbonate buildups and smaller faults occur beneath and / or within the buildups (Fig. 14). Some of the large faults are interpreted to be of pre-Mid Carboniferous age, while some of the smaller probably are of Gzhelian / post Gzhelian age. This indicates that the formation of the carbonate mosaics was partly related to underlying tectonic elements in accordance with the regional pattern described by Larssen et al. (2005). The best developed buildup trends often coincide with pinch-out of evaporites in the underlying Gipsdalen Group, where the basinal evaporites pass laterally into Gipsdalen Group buildups (Gèrard and Bührig, 1990; Fig. 10). This fits well with the observed thinning of evaporites in the study area.

The second stage of carbonate buildup growth took place in times of more subdued global sea-level changes. Age-equivalent buildups have been drilled by several wells in the Norwegian Barents Sea, all indicating that they are dominated by bryozoans and containing large amounts of early marine cement (Blendinger et al., 1997; Stemmerik, 1997). Formation of the carbonate buildups took place below wave base and, judging from the aggradational nature of the ridges, during rapid rise in sea level or increased nutrient supply. The Bjarmeland Group buildups nucleated on top of the Gipsdalen Group buildups at the centre of the palaeo-high, but later prograded laterally, over the evaporites, towards the palaeo-edge of the palaeo-high and finally experienced a strong vertical growth. The buildups formed significant topographic features on the sea floor and may have influenced circulation in the surrounding environments. The result is
protected environments occurring behind the straight and sinuous ridges, in between the mosaics of buildups and enclosed inside the semi-circular atoll-like ridges (Fig. 12). The largest buildups are located on the edge of the palaeo-topographical high and the size of the buildups diminishes towards the centre, implying that subsidence – and thereby creation of accommodation – strongly influenced their growth.

Conclusions

- The geomorphology, extent and size of Upper Palaeozoic warm- and cool-water carbonate buildups from the Finnmark Platform reveal that their location is controlled by the underlying bathymetry and/or pre-Carboniferous – Permian faults
- Gipsdalen Group evaporite deposition interrupted the growth of warm-water carbonates, and the evaporites were later most likely subaerially exposed, allowing formation of karst
- 4D maps of the carbonate ridge growth pattern reveal that the cool-water Bjarmeland Group carbonate buildups grew on top of older Gipsdalen Group buildups
- A four-dimensional image of the extent and distribution of the Upper Palaeozoic carbonate buildups through time demonstrates how they tended to prefer the palaeo-edge of the topographical high, where not restricted by evaporite deposition (Fig. 4).
- As shown from the Loppa High (Elvebakk et al., 2002) and the Finnmark Platform (Samuelsberg et al., 2003; Colpaert et al., 2007), continuous ridge-like carbonate buildups may be more common in the Upper Palaeozoic than previously assumed.

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References


sequences of central Spitsbergen, Arctic Norway. Geological Journal 34, 393-411.


Figure captions

**Figure 1.** Map of the southwestern Barents Sea with location of the studied 3D seismic area (grey box) and superimposed main structural elements (after Gabrielsen et al. 1990). FB: Fugløybanken; TF: Tromsøflaket; BT: Bear Island Trough; I: Ingøydijupet and NB: Nordkappbanken.

**Figure 2.** Overview of the age, groups, formations (from Dallmann 1999; Larssen et al., 2005), climate (Beauchamp and Desrochers 1997) and lithostratigraphy (modified from Stemmerik & Worsley, 2005) from the Barents Sea and Svalbard. Seismic sequences (SS; Samuelsberg et al., 2003) and seismic units (Su; Colpaert et al., 2007) from the Finnmark Platform are shown to the far right.

**Figure 3.** (a) WNW-ESE seismic profile crossing the palaeo-high located in the centre of the 3D area. Location shown in b and c. (b) Time-structure map of the ?intra Billefjorden horizon display how pre-Permian faults (black lines) relate to the palaeo-high. (c) Time-structure map from the ?top Billefjorden Group horizon. Location of well 7229/11-1 is shown as white circle.

**Figure 4.** (a) Illuminated time-structure map of Top Bjarmeland horizon. The vertical exaggeration on the figure is 8x. (b) Map of Upper Palaeozoic carbonate buildups showing their growth pattern through time. Note that the cold-water carbonates of the Bjarmeland Group grow on top of the pre-evaporite warm-water carbonate buildups. (c) Seismic profile displaying karst depressions (far right) located above a pre-evaporite carbonate buildup, as well as up to 7 generations (numbered 1-7) of carbonate buildups and their relation to the palaeo-high, underlying faults and the evaporite deposits.

**Figure 5.** (a and b) Illuminated time-structure maps of horizon Base Evaporites (left) and Top Evaporites (right) in the south-eastern part of the 3D area. For location see inset map in upper left corner. Base Evaporites display circular and oblong mounds while Top Evaporites display circular depressions interpreted as sinkholes (dolinas). Note the lateral amplitude variation in relation to the positive features below Base Evaporites. The vertical exaggeration on the figure is 8x. (c) Vertical seismic profile with yellow arrows pointing out mounds below base evaporites. Inset the high amplitudes have been given yellow and green colours to enhance the lateral amplitude variation in relation to the pre-evaporite mound. (d) Vertical seismic profile with a yellow arrow pointing out a pre-evaporite mound and a depression directly above in the top evaporites. The positive feature in b is also visible on the seismic profile south of the mound. Locations of the seismic profiles are shown in a and b.

**Figure 6.** (a) Illuminated time-structure map of pre Evaporites horizon (equal to base evaporites in areas where evaporites occur on seismic scale). The vertical exaggeration on the figure is 8x. (b) Palaeogeographic map of a, illustrating the size and extent of carbonate buildups formed just before the evaporite deposition. Note that smaller buildups occur basinward. Yellow: buildup. Grayish shade: basinal/lagoonal deposits. (c) Seismic profile displaying carbonate buildups beneath, within, and above the evaporite succession and their relation to the palaeo-high and pre-Permian faults.
Figure 7. (a) Seismic profile from the seismic amplitude cube. (b) Vertical seismic profile from the post-stack low-cut (26 Hz) frequency filtered seismic profile. The seismic amplitude is weaker in (b) due to removal of the lower frequencies, but discontinuities are easier to detect. The apparent resolution is better than in (a), revealing that a cool-water carbonate buildup complex formed on top of stacked warm-water carbonate buildups. Note how thickening of the evaporite succession is related to the location of the Gipsdalen Group carbonate buildups. Inset map shows the location of the seismic profile.

Figure 8. Isotime map between Top Evaporites and Base Evaporites. Note how the evaporites thicken towards the areas with carbonate buildups (red). The black rectangle represents the area shown in Fig. 5a and 5b.

Figure 9. (a) Vertical profile from the seismic amplitude cube. For location see inset map in the upper right corner. (b) Post-stack low-cut (26 Hz) frequency filtered seismic profile. The seismic amplitude is weaker in (b) due to removal of the lower frequencies, but discontinuities are easier to detect. Note how thickening of the evaporite succession is related to the overlying Bjarmeland Group carbonate buildups. Also note the asymmetric shape with steep side to the left of the Bjarmeland Group buildups. (c) Sketch of the seismic profile in (a).

Figure 10. (a) Illuminated time-structure map of horizon Top Evaporites. The vertical exaggeration on the figure is 8x. (b) Palaeo-geographic facies map of (a), illustrating the extent of the evaporites, areas where evaporites are not present or below seismic resolution, carbonate buildups within the evaporite succession and karst depressions located above the basinward carbonate buildups from Fig. 5a. (c) Seismic profile displaying carbonate buildups below, within, next to and above the evaporite succession and their relation to the palaeo-high and prominent faults. (d) Sketch of the seismic profile in (c).

Figure 11. Illuminated time-structure map of Top Evaporites horizon, with seismic profile in the background. Note the circular depressions and rounded rectangle. See black rectangle on inset map for location.

Figure 12. Illuminated time-structure map of Top Bjarmeland horizon, displaying carbonate buildup ridges and basins. The vertical exaggeration on the figure is 8x. White line shows the location of seismic profile in Figure 3a. Yellow circles indicate atoll-shaped ridges.

Figure 13. Illuminated time-structure map of Near Top Tempelfjorden horizon. The topography is dominantly caused by Lower Permian carbonate buildups (compare with Fig. 12) which are draped by Tempelfjorden Group deposits. The vertical exaggeration on the figure is 8x. The location of the 3D area is shown in Fig. 1. The line I to II illustrates the location of the profile in Fig. 14.

Figure 14. (a) Seismic profile from the seismic amplitude cube. (b) Vertical seismic profile from the variance cube. The discontinuities related to the carbonate buildups are more readily detectable in the variance cube. Additionally, details of the internal configuration of the carbonate buildups, not visible in the seismic amplitude cube, are revealed in the correlation (variance) cube. The location of the profiles is indicated on Fig. 13.
Fig. 1
Fig. 2
Fig. 3.
Fig. 4.
Fig. 5.
Fig. 6.
Fig. 7.
Fig. 8.

- *Palaeo-high*
- *Thin spots*
- Thickening of evaporites towards carbonate build-ups

5 km
Fig. 9.
Fig. 10.
Fig. 11.
Fig. 12.
Fig. 13.
Fig. 14.