From isolated buildups to buildup mosaics: 3D seismic sheds new light on upper Carboniferous–Permian fault controlled carbonate buildups, Norwegian Barents Sea

Geir Elvebakk a, David W. Hunt b,1, Lars Stemmerik c,*

a Norsk Hydro Production AS, N-9480 Harstad, Norway
b Department of Earth Sciences, University of Manchester, Oxford Road, Manchester, M13 9PL, UK
c Geological Survey of Denmark and Greenland, Øster Voldgade 10, DK-1350 Copenhagen, NV, Denmark

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Abstract

Carbonate buildups are a common feature of many ancient carbonate platforms, and were especially abundant during the Palaeozoic. Our present understanding of buildup distribution, and the ability to better predict their location, is however hampered by the fact that maps of buildups rarely show evidence of widespread spatial organisation and indeed their distribution often appears chaotic. A previously unrecognized pattern of buildup distribution has been revealed by three-dimensional (3D) seismic data recently acquired from the Loppa High, Norwegian Barents Sea. Here, syn-rift Carboniferous–Permian buildups are not isolated but are instead linked into a mosaic of laterally extensive ridges. The buildups’ location is controlled by the intersection of three trends of syndepositional faults. Systematic organisation of buildup height, width, density and external form across the study area appears to have been controlled by changes in accommodation space driven by differential subsidence. The buildups were remarkably long-lived and developed over an interval of 35 Ma. Despite this longevity, buildup location remained relatively static and true to the underlying pattern of basement faults, indicating that their progradation was likely restricted by a combination of factors including limited highstand production, their depositional relief <420 m, steep flanks and/or differential subsidence. Study of the buildups’ internal seismic geometries, and analogy to well-exposed onshore buildups, indicates that they are composite features, developed through the repeated recolonization of antecedent bathymetric seafloor highs following hiatuses related to both subaerial exposure and drowning. The picture of interconnected buildup mosaics described for the first time here provides important new insights as to the spatial and internal organisation of carbonate buildups and has potentially far-reaching implications for the interpretation of buildups in areas where good 3D control is poor or unavailable.

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1. Introduction

One of the greatest challenges in sedimentology is to explain the spatial distribution of isolated buildups on ancient carbonate platforms. This is because in
map-view, buildups, seldom show obvious widespread organisation in terms of their location, spacing, areal extent, elongation or preferred orientation. More often, maps of buildup distribution reveal little obvious order, and indeed frequently appear chaotic (e.g. Hurst, 1980). By way of contrast, dip section buildups are known to show systematic down slope organisation in terms of their vertical relief, external form, internal stacking patterns, facies and fauna (e.g. Beauchamp, 1993). Such variation attests to the control of water depth and accommodation on buildup location and development. Given the importance of these controls, and that of tectonically generated or depositional slope breaks on buildup location (e.g. Nilsen et al., 1993; Kirkby and Hunt, 1996; Rankey et al., 1999; James et al., 2000), the general absence of widespread map-view trends and order in buildup distribution is rather perplexing.

Carboniferous–Permian rift-related buildups of the Loppa High, Norwegian Barents Sea, present a well-constrained example of such a situation (Fig. 1A,B). Seismic sections reveal both systematic down ramp changes in the size, external form and internal geometries of the buildups, and a clear relationship between syndepositional faulting and carbonate buildup location (e.g. Fig. 1C; Stemmerik et al., 1999). However, mapping the buildups over 5000 km² from a 1×1 km to 2×2 km spaced two-dimensional (2D) seismic grid has revealed a picture of several hundred isolated buildups that is mostly devoid of obvious spatial organisation (Fig. 1B). Only in the SE of the area are there obvious NNE–SSW trends of buildups that can be related to the control of syndepositional faults on their location.

On the Loppa High, it seems paradoxical that although in seismic section, more than 40% of the

Fig. 1. (A) Position of the Loppa High in the Norwegian Barents Sea. (B) Palaeogeography of the Loppa High during the Gzelian–Asselian. The distribution of the buildups appears to be largely devoid of obvious spatial organisation, except in the SE of the area where there are NNE–SSW buildups trends. The map also shows the location of the 3D seismic data that covers the Obelix Structure, and the approximate location of (C) and Fig. 3. (C) Schematic dip section through the Loppa High illustrating the inferred fault control on buildup location, a pattern generally not reflected by the mapped distribution of buildups from the 2D seismic data set (e.g. (B)).
buildups show evidence of fault control on their location, most of the area mapped from the 2D data shows little in the way of buildup organisation or preferred orientation (Fig. 1B). Prior to the arrival of 3D data, we considered that Late Carboniferous–Early Permian high frequency, high amplitude sea level changes (e.g. Crowell, 1978; Sohregan and Giles, 1999) might offer an explanation for the paucity of buildup organisation apparent in Fig. 1B. High frequency, high amplitude sea level changes would have repeatedly shifted the optimum depth window for carbonate production up and down ramp, and so could have facilitated buildup initiation and growth in locations aside from the areas of fault controlled relief. It was thought that in sufficient numbers, the growth of such buildups might have obscured the linear trends expected from the widespread control of faulting on buildup location across the high (e.g. Fig. 1C).

The arrival of a new 3D seismic survey acquired from some 967 km² of the Loppa High has, however, radically altered previous understanding of the distribution, external form and connectivity of the buildups. To our complete surprise, the large isolated carbonate buildups interpreted from the 2D data (e.g. Fig. 1B) and so well known from many other late Palaeozoic carbonate platforms (e.g. Wilson, 1975; Davies et al., 1989) do not exist. Instead, the buildups are laterally linked into a mosaic of ridges that bifurcate and amalgamate along strike. The mosaic of buildups is related to their initiation and growth over a network of three intersecting trends of syndepositional faults. The highly organised picture of laterally linked carbonate buildup ridges revealed here could not be more different to the seemingly chaotic distribution of isolated buildups interpreted from the 2D data. The results of this study have important implications for the interpretation of buildup distribution and connectivity on ancient carbonate platforms, especially those where

Fig. 2. Relief map of the Obelix Structure for the Gzelian seismic reflector from the 3D seismic dataset as located in Fig. 1B. Note the division of the easterly and southerly dipping ramp into several fault blocks by NE–SW trending faults (F1–4). Across the area, there are systematic changes in the density and the relief of the buildup ridges and the polygonal intraplatform basins/lagoons that they enclose from N to S and W to E. The location of the buildups illustrated in Figs. 4 and 5 is also marked. I-M: Inner-middle ramp; O: outer ramp; cross-hatched area: Evaporite basins.
good 3D control is absent. It is also worth noting that two other nearby 3D surveys covering the easternmost part of the Loppa High/westernmost part of the Bjarmeland Platform and a third 3D survey from the Finnmark Platform (Fig. 1A) also show laterally linked buildup ridges and associated polygonal lagoon patterns. Clearly, the laterally linked buildup ridges are not a local phenomenon, but have a more regional distribution.

2. Regional setting

The Loppa High, located in the westernmost Barents Sea (Fig. 1A), is positioned at the intersection between the Caledonian, Franklinian and Baikalian structural trends that were formed during Precambrian–Early Palaeozoic orogenesis. These basement fabrics are considered to have controlled the orientation of the three main rift-related NE–SW, N–S and NW–SE trends of the Carboniferous–Permian fault systems (e.g. Ziegler, 1982; Gabrielsen et al., 1990; Alsgaard, 1993; Gudlaugsson et al., 1998). Of these, the NE–SW Caledonian trend that parallels the Nordkapp, Hammerfest and Tromsø basins is most important (Fig. 1A,B). During Upper Carboniferous–Permian rifting, NE–SW oriented hinge faults controlled the gradual tilting of the fault block to form an overall eastward dipping carbonate ramp. This ramp was distally steepened and is divided into several ramp segments by N–S and NW–SE trending faults (e.g. faults F1–4, Figs. 2 and 3). The N–S directed faults parallel the main fault systems in Svalbard and North Greenland and are related to the Arctic rift system located between Svalbard and North Greenland (Gudlaugsson et al., 1998). The NW–SE oriented faults are most important in the northern fault block covered by the 3D data (Figs. 2 and 3) and may represent reactivated Baikalian lineaments (Alsgaard, 1993).

During the Late Carboniferous and Permian, the Barents Sea was a part of a huge segmented shelf system running along the northern margin of Pangea from the Sverdrup Basin of Arctic Canada, through North Greenland and Svalbard to the Timan–Pechora basin in Arctic Russia (Watkins and Wilson, 1989; Golonka et al., 1994; Stemmerik and Worsley, 1989; Stemmerik, 2000). During the late Bashkirian–Sakmarian (mid-Carboniferous–Early Permian), this area was located in the northern semi-arid climatic belt. Ramp sedimentation was dominated by warm water carbonates with deep basinal areas filled by evaporites (e.g. Fig. 1B; Stemmerik, 2000).

![Seismic line and SG9810-6501](image-url)
During rifting, the Loppa High was positioned close to the eastern margin of a Late Palaeozoic Arctic rift system located between North Greenland and Svalbard (Gudlaugsson et al., 1998). It experienced three distinct late Palaeozoic rift phases; Early Carboniferous, Bashkirian–Moscovian (late Carboniferous) and mid–late Permian. Across the Loppa High, these phases resulted in overall gradual eastward tilting, faulting and differential subsidence (e.g. Stemmerik et al., 1999). Well data show initially high rates of siliciclastic sedimentation during the initial phase of Bashkirian rifting but that siliciclastic supply had ceased by the mid-Moscovian as the high was flooded (Stemmerik et al., 1999; Elvebakk et al., in preparation).

3. Data

In 1998, 3D seismic data covering a large structural high, known as the Obelix Structure in the central area of the Loppa High, were acquired (Figs. 1B and 2). The area was selected on the basis of seismic mapping of 2D data of various vintages that established the overall structural framework and palaeogeography across approximately 5000 km². Interpretation of the 2D data showed several hundred scattered isolated buildups on an easterly dipping carbonate ramp that gradually passed eastward into an evaporite basin (Fig. 1B), and this picture is consistent with the regional palaeogeographic framework established by Stemmerik et al. (1999) and Stemmerik (2000).

4. Results

Detailed seismic facies mapping of the Upper Carboniferous–Lower Permian interval from the 3D data shows that the carbonate ramp on the Obelix Structure is cut by four major NE–SW oriented hinge faults (F1–4, Figs. 2 and 3). They define areas with different subsidence histories and accordingly different palaeogeography. Displacement on the NE–SW faults typical increases to the east and south resulting in low-angle ramp development on each fault block with the greatest subsidence in the east. Based on seismic facies mapping, the more rapidly subsiding northern fault block 1 is believed to represent mainly outer ramp environments, while fault blocks 2–4 show well-developed inner ramp and middle ramp environments passing out into outer ramp and basinal environments (Fig. 2). The platform on the southernmost fault block shows the same general pattern but with a much narrower middle shelf. Rough estimates of subsidence rates based on thickness variations indicate that on the outer ramp, subsidence was at least double that experienced by the inner ramp areas (ca. 40 m/Ma compared to ca. 17 m/Ma).

4.1. Linked mosaic buildup ridges: external form and internal characteristics

Regional correlation with existing seismic, well and biostratigraphic data indicate that the seismic buildups were established in the early Moscovian and that their growth lasted until the early Sakmarian (ca. 35 Ma). The buildups range from 350 to 1200 m thick and in seismic section the majority appear to be almost stationary, especially in outer ramp environments (Figs. 3 and 4). However, mapping of the buildups has shown that they are not isolated, as was previously thought from extensive study of the 2D data (e.g. Fig. 2). Instead, they form well-defined and continuous but somewhat sinuous ridges, many of which can be traced over distances of 45 km (Fig. 3). The main orientations of the buildup ridge are NE–SW, N–S and NW–SE; the latter being typical of the northernmost fault block. There is good agreement between the location and orientation of the buildup ridges and the mapped position of basement controlled syndepositional faults (e.g. Figs. 4 and 5).

In cross-section, the width of the buildups that comprise the ridges is typically 0.5–1.5 km, with a maximum of approximately 3 km. Buildup density varies from inner to outer ramp settings. In the inner ramp, the buildups are most extensive and can cover <65% of the area whereas in outer ramp settings, the figure is nearer 35% (Fig. 2). At the resolution of seismic data (ca. 30–40 m), the external form of the buildups appears to be rather smooth but is frequently somewhat asymmetric. The steeper flanks preferentially face seaward, towards the east and south (Fig. 2). The buildups’ flanks dip from a few degrees up to 50° and the outer ramp buildups tend to have steeper slopes than those in inner and middle settings, as the former developed greater seafloor relief (Figs. 4 and
5). The steepest slopes occur in buildups affected by syn-sedimentary faulting.

Internally, the buildups show some complex stacking patterns within third-order seismic sequences that are typically in the order of 50–100-m thick (Figs. 4 and 5). The buildups typically display low relief undulations of up to 50 m along their length. The creation of random orientation seismic lines from the 3D data, specifically positioned to view lateral variability along the length of the buildup mosaics, indicates that the undulating relief is related to lateral progradation of the buildups along the ridges outward from individual growth centres.

4.2. Semi-enclosed basins/lagoons

The buildup ridges form mosaics that enclose polygonal basins or lagoons <6 km across (Figs.
3–5). They are predominantly filled by parallel to subparallel seismic reflectors that often thicken towards the buildups’ flanks (Figs. 4 and 5). Mapping reveals that as buildup density changes from the inner to outer ramp so does the area and depositional relief of these polygonal semi-enclosed basins or lagoons (Figs. 2, 4 and 5). In outer ramp settings, the buildups attained a maximum depositional relief of approximately 350 m (e.g. 120 ms two-way travel time (TWT) given average seismic velocity of 6000 m/s). These large outer ramp buildup ridges enclose polygonal basins/lagoons typically 2–3 km across but up to 6.25 km wide (Fig. 4). After restoration for structural dip, the measured depth of the outer ramp lagoons is normally between 225 and 300 m (e.g. 75 and 100 ms TWT at 6000 m/s) with a maximum of 420 m (e.g. 140 ms TWT, 6000 m/s). Internally, the floors of these larger lagoons tend to be subdivided by lower relief buildups into 1.5–3 km wide polygonal subbasins/lagoons (Fig. 4).

In contrast, updip in inner ramp settings, the buildups tend to range in width from 0.5 to 1 km and enclosed polygonal lagoons with a typical width of 1–2.5 km, one 4-km wide being an extreme (Figs.
In the inner ramp setting, spit-like morphologic features are quite commonly resolved in the lagoons, and are normally located adjacent to bends in the buildup ridges. Locally, these spit-like features are observed to have prograded to fill the lagoons, ultimately to create mound-shaped polygonal buildups.

5. Discussion

5.1. Buildup growth and the controls of faulting and differential subsidence

A mosaic of build-up ridges and semi-enclosed polygonal basins/lagoons form the dominant morphological elements of the Bashkirian–Sakmarian carbonate ramp systems developed on the Obelix Structure, Loppa High (Figs. 2–5). The buildups and lagoons show distinct inner ramp to outer ramp variation of their spacing, vertical size, width, depositional relief and external form (Figs. 2–5). However, no variation in the overall shape of the lagoons and orientation of the buildups is observed (Fig. 2). The 3D seismic data reveal a direct correlation between the distribution and orientation of sea floor bathymetry controlled by underlying pre- and syn-sedimentary faults and buildup location (Figs. 2, 4 and 5). The buildups are typically located along the down dip margins of the underlying footwall blocks (Figs. 4 and 5). Those areas of the Obelix Structure with no or few faults, as in a down dip part of the inner ramp environment of fault block 2 (e.g. area Y in Fig. 2), demonstrate the importance of fault controlled bathymetry on buildup locations, as here, the sea floor appears as a rather smooth, slightly undulating surface virtually devoid of buildups and obvious pattern. Across the Obelix structural high, the growth of the buildups is thought to have initiated in inner ramp environments during the mid-Carboniferous, with initial buildup location and spacing controlled by the underlying fault pattern (Figs. 3–5). Through time, the inner ramp environments were displaced updip (west) to the slowly subsiding updip areas of the high. Thus, middle and outer ramp environments dominated across most of the study area. The down ramp variability observed in buildup density, external form, thickness and internal stacking, and also in the dimensions of the polygonal lagoons, is considered to be related to both local variations in fault density and most importantly, to tectonically driven east–west variations in accommodation development (Fig. 2).

In the updip more gently subsiding western parts of the study area, inner ramp environments are considered to have continued to dominate during the Late Carboniferous and Early Permian. However, even here the fault controlled pattern of buildups is retained despite the fact that a significant number of the buildups show periodic episodes of progradation in updip areas of the high of up to 450 m. The reason for the longevity of the basement controlled pattern of buildups in the updip areas must be because of continued subsidence related to active faulting and/or differential compaction. For this is the only mechanism that would act to reestablish the pattern of buildup location in areas where they were able to prograde laterally.

In contrast, the eastern down dip areas of the ramp experienced greater rates of tilting and subsidence. As a consequence, it is thought that inner ramp environments progressively retreated updip to be replaced by deeper water outer ramp conditions after the initial growth of the buildups during the Moscovian. Here, the thickest and steepest buildups enclose the largest polygonal lagoons (Figs. 3 and 4). These larger lagoons are thought to have formed through the selective drowning of some of the buildup ridges, possibly at times when increased rates of subsidence and high rates of glacio-eustatic sea level rise were coincident. Subsequent reorganisation of the system created lagoons of greater width divided into sublagoons by the crests of the drowned antecedent buildups.

5.2. Buildup growth and sea level changes

The 350–1200 m thick seismic buildups shown here were incredibly long-lived and grew in overall warm and dry palaeoclimatic conditions over a time interval of approximately 35 Ma. The internal seismic geometries of the third-order buildup sequences suggest that during sea level rises carbonate sedimentation retreated to small pinnacle-like growth centres as large parts of the ridges periodically drowned (Elvebakk et al., in preparation). These pinnacles are typically developed at the intersection of different
trending ridges and are interpreted to have developed on bathymetric highs. During the subsequent highstand/fall in sea level active buildup development shifted laterally along the ridges, extending along and downlapping onto parts of the buildup mosaics that were previously drowned. This pattern of growth is evident from the arrangement of oblique and toplapping clinoforms that dip away from the superimposed pinnacle structures interpreted to have formed along the buildup ridges during overall transgression and sea level highstand. However, little progradation off of the buildup ridges occurred.

Comparison to time-equivalent buildups exposed on the island of Bjørnoya, Spitsbergen, North Greenland and Arctic Canada (Beauchamp, 1993; Stemmerik et al., 1994; Stemmerik, 1996; Pickard et al., 1996; Samuelsberg and Pickard, 1999), and the subsurface of the Barents Sea (Bugge et al., 1995; Stemmerik et al., 1995; Ehrenberg et al., 1998) indicates that the third-order seismic buildup sequences are comprised of stacked subseismic buildup sequences. The subseismic buildups are typically 5–10 m thick and are normally bounded by composite exposure/flooding surfaces (e.g. Beauchamp, 1993; Stemmerik et al., 1994; Stemmerik, 1996; Pickard et al., 1996; Samuelsberg and Pickard, 1999). They represent transgressive-highstand deposits of fourth- and fifth-order sequences thought to have formed as a consequence of high amplitude/frequency glacio-eustatically driven sea level fluctuations.

Thus, despite the fact that high amplitude sea level changes during the late Carboniferous and earliest Permian would have shifted the optimum depth window for carbonate growth, considerable distances up and down ramp buildup growth was repeatedly limited to relatively narrow zones over long time spans to form the seismic scale buildups (e.g. Figs. 3–5). Thus, it appears that either highstand production and progradation of the carbonate systems was very limited and/or that differential subsidence continued during buildup development to limit lateral growth. The latter situation must have been important in those parts of the inner ramp where buildups periodically prograded to fill the interridge basins/lagoons, yet the basement controlled pattern of buildup distribution was maintained. It is therefore most likely that the pattern of buildup distribution inherited from the basement structure was controlled by continued faulting and/or subsidence driven by differential compaction acting in concert with limited highstand production.

6. Summary and conclusions

Previous study of an extensive closely spaced 2D grid of seismic data from the Loppa High revealed a fault controlled distally steepened ramp covered by several hundred isolated carbonate buildups (e.g. Figs. 1B and 3). Although the pattern of buildups mapped from the 2D data did not largely appear to reflect the known control of faulting on their location, it seemed to present a realistic depiction of buildup distribution that was consistent with existing knowledge of buildup distribution on other Palaeozoic platforms. The pattern of buildup development apparent from the 3D seismic data is without precedent, and has provided a picture of buildup distribution that could hardly be more different to that produced from the 2D data.

There is a direct relationship between active faults and the location of the interconnected mosaic of buildups. Systematic down ramp changes in the density, height, width and external form of the buildups appear to be related to regional accommodation gradients resulting from fault block tilting. The remarkable picture of buildups on the Loppa High has far-reaching implications for the interpretation of buildups in areas where good 3D control is poor or unavailable. It may well be the case that comparable morphologic patterns also exist on other ancient carbonate platforms, but require exceptional 3D data to be revealed. Clearly, any increase in the lateral extent and connectivity of buildups also has potential economic importance as many hydrocarbon reservoirs are located in carbonate buildups.

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References


