Polygonal mounds in the Barents Sea reveal sustained organic productivity towards the P-T boundary

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Abstract

Three-dimensional (3D) seismic-reflection data from the Barents Sea show geometric similarities between Permian cool-water mounds and older carbonate build-ups. In detail, the Samson Dome area records the development of polygonal mounds in Upper Permian strata, at the same time a gradual drowning event took place in the Barents Sea. The presence of these polygonal mounds is interpreted to reflect: i) shallower conditions around the Samson Dome when compared to other parts of the Barents Sea; ii) earlier drowning of Upper Permian mounds towards the west and northwest into the Ottar Basin. Based on the recognition of mounds ~20 metres below the Permian-Triassic stratigraphic boundary, this paper proposes for the first time that shallow areas of the Barents Sea, such as the Samson Dome, witnessed sustained organic productivity until the onset of the P-T extinction event.

Keywords: Pangaea; Barents Sea; carbonate build-ups; Upper Permian mounds; P-T boundary.

Introduction

Continental margins of the Arctic Sea were affected by multiple tectonic events during rifting and subsequent break-up of the Pangaea supercontinent (Faleide et al., 1984; 1993; Glørstad-Clark...
et al., 2010). As a result, polygonal carbonate build-ups grew on active structural highs of the
Barents Sea prior to the development of isolated (cool-water) reefs in the latest Palaeozoic
(Elvebakk et al., 2002; Colpaert et al., 2007) (Fig. 1). This shift from warm- to cool-water
conditions was accompanied by important lithological changes. Carboniferous-Lower Permian
build-ups are carbonate-rich and alternate with evaporites and dolomitic sediments (Blendinger et
at, 1997; Rafaelsen et al., 2008). In contrast, Upper Permian sediments comprise a mixture of
siliciclastics, cherts and carbonates accumulated during a long term sea-level rise (Nøttvedt et al.,
1993).

On Svalbard, detrital banks of locally derived limestones with bryozoan-echinoderm-spicule
fragmental debris, crinoids, sponges and brachiopods, comprise the majority of the Upper Permian
Kapp Starostin Formation (Blendinger et al., 1997; Ehrenberg et al., 2001). Lacking the sediment-
baffling or binding mode of accumulation typical of the Upper Carboniferous-Lower Permian build-
ups (Malkowski and Hoffman, 1979; Wignall et al., 1998; Ehrenberg et al., 2001; 2010), regional
seismic and borehole data nevertheless showed these detrital banks as capable of forming reliefs of
10s of metres on the Permian seafloor (Ehrenberg et al., 1998). They are intercalated with siliceous
shales and more marginal carbonates and clastics (Nilson et al., 1996). Further south on the
Finnmark Platform, Mid-Upper Permian build-ups are locally developed and interpreted as similar
to those formed in Upper Permian strata of East Greenland (Gérard & Buhrig, 1990). Their
geometries and extent in the Barents Sea, however, have not been investigated using a combination
of high-quality 3D seismic and borehole data.

This paper focuses on a region ~150 km to the northwest of Finnmark, Northern Norway (Figs.
1a and 1b). It documents, for the first time, the generation of ~150m-thick polygonal mounds in the
Central Barents Sea during the Late Permian. These mounds grew away from the more sheltered
Finnmark Platform and are that are geometrically similar to older Carboniferous build-ups (Fig. 1a).
Their identification suggests sustained organic productivity in shallow parts of the Barents Sea until
very close to the P-T extinction event (252 Ma; Shen et al., 2011).
**Data and methods**

This work uses three-dimensional (3D) seismic data and regional 2D profiles across 1160 km² of the Barents Sea (Figs 1a and 1b). The dataset images a salt anticline, the Samson Dome, of yet undetermined age (Figs. 1a and 1b). The 3D seismic volume has a bin spacing of 12.5 x 25 m, a 4 ms vertical sampling window, and was acquired by a 10 x 6000 m array of streamers. Data processing included signal resampling, TAU-P linear noise attenuation, TAU-P domain deconvolution and zero-phase conversions. Pre-stack time migration used the Kirchhoff algorithm. As a result, any velocity-derived seismic artefacts were processed out of the seismic volume. Time-depth conversions were undertaken using a $V_p$-wave velocity of 5800 m/s for Upper Permian mounds, and 6600 m/s for Carboniferous-Lower Permian strata, based on wells 7121/1-1 R and 7124/3-1 (Figs. 1a and 2). Vertical seismic resolution approaches 60 m.

Regional 2D profiles were used to tie stratigraphic data from two exploration wells to the 3D seismic volume (Figs. 1a and 2). Well 7124/3-1 is located 36 km to the south of the 3D seismic volume. Well 7121/1-1 R is located on the Loppa High c. 105 km to the west of the Samson Dome (Figs. 1a, 2a and 2b). Well 7224/7-1 was drilled on the Samson Dome without crossing Permian strata.

Biostratigraphy constraints are robust for the Carboniferous-Early Permian, but information for Upper Permian strata are based on sparser outcrop and borehole data (Larsen et al., 2002). Nevertheless, Ehrenberg et al. (1998) and Glørstad-Clark et al. (2010) identified a maximum-flooding surface (MFS) at the top of Permian strata in the Barents Sea (Glørstad-Clark et al., 2010) (Figs. 2, 3 and 4). The MFS was used by Ehrenberg et al. (2001) to correlate outcrops in Svalbard with wells 7128/6-1 and 7128/4-1 on the Finnmark Platform. Over the Samson Dome, the top Permian MFS is a negative to transparent continuous reflection observed ~10 ms (25-30 m) above Horizon 1 (Figs. 3 and 4).
Regional geological setting

On the Loppa High, Carboniferous build-ups were long-lived (~35 Ma), polygonal, and of high depositional relief (< 420 m) (Elvebakk et al., 2002) (Fig. 1a). They were also relatively static, changing laterally into evaporites and dolomites in adjacent basin depocentres (Ehrenberg et al., 1998) (Fig. 1c). In contrast to the Carboniferous, large isolated carbonate build-ups of Early Permian (Artinskian) age became detached from shelf areas on the Finnmark Platform (Colpaert et al., 2007), but not on the Loppa High where they preserved a polygonal mosaic of laterally extensive ridges (Elvebakk et al., 2002). Isolated build-ups on the Finnmark Platform record a change from photozoan assemblages below the Artinskian (unit L-7), to heterozoan biota above (unit L-8) due to a shift from warm- to cool-water conditions (Beauchamp and Desrochers, 1997; Stemmerik, 1997; Ehrenberg et al., 1998; Beauchamp and Baud, 2002) (Table 1). Significantly, rapid flooding of isolated carbonate build-ups occurred after the Kungurian throughout the Barents Sea, in contrast to the regression recorded in global sea-level curves, and at the top of the Upper Permian interval analysed in this paper (Fig. 3).

Upper Permian detrital banks formed by locally derived bryozoan-echinoderm-spicule fragmental debris have thus been identified on Finnmark and Svalbard (Ehrenberg et al., 1998; 2010). They are ?Kungurian to Late Permian in age, and comprise cold-water 'hyalosponge-bryonoderm' assemblages part of unit L-9 (Beauchamp, 1993; 1994) (Fig. 3 and Table 1). At a regional scale, this same L-9 unit marks the closure of the Uralian seaway, which extended as far south as the tropical regions of the Pre-Caspian basin.

On the Samson Dome, well 7224/7-1 crossed a thick (~600 m) succession of Lower Triassic strata above a Top Permian maximum-flooding surface (MFS) (Fig. 2a). On the Loppa High, well 7121/1-1 R drilled a 2007 m thick Palaeozoic section of silicified limestones, limestones, dolomitic limestones and dolomites, with minor amounts of chert, siltstones and anhydrites (Larsen et al.,
2002) (Figs. 2 and 4). As a comparison, well 7124/3-1 drilled only 604 m of Palaeozoic strata (Figs. 2a, 2b and 4). Upper Permian strata in well 7124/3-1 comprise limestone, spiculitic (chert-dominated) and shaley intervals.

The contact between Upper Permian strata and overlying shales is apparently conformable and occurs ~20 m below a sharp increase in gamma-ray values as the top Permian MFS is crossed (Figs. 4 and 5). The P-T boundary per se occurs near the base of the high gamma-ray interval shown in Fig. 4. On Svalbard, the top of Upper Permian spiculites was suggested by Wignall et al. (1998) and Mørk et al. (1999) to precede the Permian-Triassic (P-T) boundary by ~ 10 m.

Geometry of Carboniferous polygonal build-ups

Carboniferous polygonal build-ups have long and short ridges, and show a predominant northwest strike for the longest ridges in Horizon 5 (Figs. 6 and 7). In cross-section, their width is typically 250–750 m for a length of < 3.0 km. More distal facies are interpreted northwest of the Samson Dome where build-ups are scarce (Figs. 7a and 7b).

Polygonal build-ups change their geometry from smooth to steep, asymmetric features near the Carboniferous-Permian boundary i.e., below Horizon 4 (Figs. 5, 6 and 7b). Similarly to the Loppa High, the steeper flanks of Carboniferous build-ups identified on the Samson Dome face seawards to the northwest (Fig. 7b). However, build-ups change orientation from Horizon 6 to Horizon 4 (Fig. 7). Horizon 4 shows a series of linear build-ups around the Samson Dome and small isolated build-ups to the southeast and east (Fig. 7b). In cross-section, the width of these linear build-ups is typically 200-300 m, with a maximum of ~1.5 km (Fig. 5). Small isolated build-ups are observed together with irregular polygonal features (Figs. 6 and 7c). These features are interpreted as small patches of isolated build-ups that continued their development in risen parts of older carbonate edifices.
Isolated build-ups of Early Permian age

A major change in geometry is recorded above Horizon 4 with the appearance of isolated (cool-water) build-ups (Fig. 8a). This change was interpreted by Ehrenberg et al. (1998) as marking a shift from photozoan (sunlight-dependent) to heterozoan (mainly sunlight-independent) biota at the L-7/L-8 boundary (Table 1). In Figure 8a, a two-way time (TWT) structural map for Horizon 3 demonstrates the wide distribution of isolated build-ups in the study area. Using velocity ($V_p$) data from well 7121/1-1 R, an average thickness of ~575 m was calculated for the isolated build-ups. A maximum thickness of ~739 m was observed to the southeast of the Samson Dome (Figs. 8a and 9a).

Blendinger et al. (1997) and Ehrenberg et al. (1998) showed Lower Permian build-ups to comprise carbonate cements and bryozoan-echinoderm wackestones to grainstones. The associated change in biota across the L-7/L-8 boundary resulted from a decrease in water temperature, but with the recognised caveat that biota and lithologies very similar to L-8 occur in thin, transgressive intervals in L-7 and L-6 (Ehrenberg et al., 1998). Alternatively, the latter authors explain the biotic change at the L-7/L-8 boundary as relating to a relative rise in sea level, which would have eliminated barriers to oceanic circulation promoting the establishment of cool-water currents across the Finnmark platform. Details of typical depositional environments in L-7 and L-8 are provided in Table 1.

Upper Permian polygonal mounds

The main difference between the study area, the Finnmark Platform and the Loppa High, is the return of mounds with polygonal geometries in the Late Permian, this time with a characteristic distribution to the east and southeast of the Samson Dome (Figs. 5, 6 and 8b). Morphological data show that Upper Permian polygonal mounds are ~151-m thick on average (Fig. 9a). Upper Permian
mounds show low-amplitude, parallel to sub-parallel seismic reflections with moderate thickening towards their flanks (Figs. 5 and 6). This character suggests the presence of interbedded shales in the successions imaged around the Samson Dome, with polygonal features comprising localised spiculitic-carbonate mounds and detrital banks similar to those documented on Svalbard (Ehrenberg et al., 2001) (Figs. 5, 8b and 8c).

The maps in Figs. 9b and 9c highlight the shifts in the position of carbonate build-ups and Upper Permian mounds. The early settlement of carbonate build-ups above Horizon 6 was followed by the drowning of some 90% of these same edifices at Horizon 4, with linear build-ups forming on the margins of the Samson Dome. This same event coincides with a highstand period that drowned most of the polygonal build-ups generated in the Late Carboniferous. However, some surviving pinnacle-like build-ups were kept over the large edifices observed in Horizon 4 (Figs. 6 and 7c). These pinnacle build-ups later formed the base for Lower Permian mounds, which shifted location by a few 100's of metres to <1 km in regressive sea-level conditions (Figs. 9b and 9c). Upper Permian mounds also show lateral shifts of 100's of metres, being concentrated in the region to the southeast of the Samson Dome as we cross Horizon H1 into the top Permian MFS (Figs. 6 and 9c).

Discussion and conclusions

The interpreted data favours two explanations for sustained organic productivity into the P-T boundary. The first explanation takes into account a combination of halokinesis and late Variscan tectonics, necessary to maintain a relatively shallow seafloor over the Samson Dome. The main tectonic event affecting the Barents Sea during the Late Carboniferous-Permian is recorded in the form of a regional Kungurian unconformity (Fig. 3). However, this unconformity is not identified on the Samson Dome, with polygonal mounds occurring above Horizon 2 until the top Permian MFS (~20 m above Horizon 1) drowned all carbonate edifices (Figs. 4 and 5). Regardless of the importance of tectonics as a controlling factor on Late Permian deposition, Schlager and Purkis
(2015) suggested as primary cause for the generation of polygonal features on carbonate platforms a tendency for biotic self-organization. The link between karst morphology and overlying reef patterns was deemed unconvincing for a significant number of examples, particularly those on a substrate of tower karst with high relief. Instead, an alternative pathway to reticulate reefs may be the colonization of reticulate hydrodynamic bedforms by reef builders (Schlager and Purkis, 2015).

This latter postulate is supported in this work, with Upper Permian mounds around the Samson Dome forming polygonal patterns on an irregular seafloor, which they were able to colonise in an organised way (Figs. 9b, 9c and 10).

Ehrenberg et al. (1998) showed that Upper Permian strata comprise detrital banks of calcareous spiculite and subordinate mudstone with nodular to lensoid fabrics and abundant laminations. Detrital banks formed biostromes and, lacking the binding mode characteristic of the older Carboniferous build-ups, they are assumed to have nucleated in a spicule-covered seabed in areas of favourable topography and nutrient supply, after which enhanced carbonate production was reinforced by bioherm relief (Ehrenberg et al., 1998). As the 3D seismic data interpreted in this work has been processed to exclude velocity artefacts, and Upper Permian mounds have a significant relief (151 m on average), they are interpreted to comprise authochtonous carbonate mounds developed in quiet, and relatively deep waters with variable contribution from baffled, bound or trapped spiculitic grains (see Pratt, 2000 and Wood, 2001). In addition, mounded structures with bright amplitude seen on seismic at top Permian level are likely to be porosity anomalies within spiculitic sediment, enhancing any biologically constructed build-ups and banks with ~150-m relief (Figs. 5, 8b and 8c).

A second explanation assumes an established balance between relative sea-level, accommodation space and tectonic movements for a period of time as long as 55-60 Ma. In this case, the presence of relative thick evaporites above the Variscan structures resulted in a smoother seafloor, hindering a closer control of basement faults upon mound growth - a setting that is markedly distinct from the Loppa High (e.g. Elvebakk et al., 2002). As the interpreted mounds
present depositional thickening relative to adjacent strata that is typical of carbonate build-ups and
mounds in multiple geological settings (Bosence and Bridges 1995; Burgess et al., 2013), this paper
proposes the region to the southeast of the Samson Dome to have been shallow enough to support
the growth of polygonal mounds until the Late Permian. As suggested by Gérard and Buhrig
(1990), the polygonal mounds appear to rest on top of a silicified seafloor, anticipating the sudden
arrival of Triassic clastic material to the Barents Sea. In such a setting, the persistence of self-
organised carbonate mounds beyond the Kungurian unconformity proves that organic productivity
was maintained, albeit at a local scale, on the northern margin of Pangea. The Permian mounds
interpreted in this work also demonstrate the extent of carbonate deposition beyond the Finnmark
Platform above persistent structural highs. As a corollary, it is suggested that structures similar to
the Samson Dome prevented exposure, or drowning, of Upper Permian mounds in the Barents Sea
until very close to the P-T boundary.

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**Figure Captions**

Figure 1 – (a) Map of the Barents Sea depicting the location of geological features mentioned in the text and the interpreted 3D seismic volume. (b) Two-way time (TWT) structure of the Mid Jurassic Major Sequence Boundary (MSB) highlighting the geometry of the Samson Dome, the locations of selected profiles shown in the paper and the locations of wells 7124/3-1 and 7224/7-1. (c) Schematic dip section across the Loppa High illustrating the control of basement structures on buildup location as inferred by Elvebakk et al. (2002). tA - top Artinskian; iK - intra-Kasimovian; IM - intra-Moscovian; IB - intra-Basement. The regional map in (a) is modified from Faleide et al. (2008), Gudlaugsson et al. (1998) and Glørstad-Clark et al. (2010).

Figure 2 – a) North-South 2D seismic profile crossing the Samson Dome showing the main structural features in the study area and interpreted seismic stratigraphic intervals. b) Composite 2D seismic profile crossing the region south of the Samson Dome and Loppa High illustrating the main seismic-stratigraphic boundaries interpreted in the Barents Sea. The location of the 2D profiles and wells is shown in Figure 1a.

Figure 3 - Correlation panel amongst the interpreted seismic units, stratigraphic information from Larsen et al. (2002), Glørstad-Clark et al. (2010) and published global sea-level curves for the Late Devonian-Early Tertiary time periods (Haq and Schutter, 2008). See Figure 1a for the location of
the two seismic sections. Well data is courtesy of the Norwegian Petroleum Directorate (NPD).

Vertical exaggeration approaches 10x on the seismic sections.

Figure 4 - a) Correlation panel between stratigraphic units in the study area, and wells 7121/1-1 R and 7124/3-1. Main seismic surfaces (Horizons H1 to H6) interpreted in this work are highlighted in the panel. The abbreviations used to describe borehole lithologies are based on the Shell Exploration and Production (1995) standard borehole legend.

Figure 5 - a) and b) Zoomed seismic sections across Carboniferous-Permian units in the Samson Dome area. The sections highlight the acoustic character of the P-T boundary and Upper Permian mounds. Note the vertical scale of 100 ms shown next to the imaged mounds (see insets). Figure 1b shows the location of the seismic sections. Vertical exaggeration = 5x.

Figure 6 – North-South seismic section highlighting the geometry of isolated build-ups and mound systems across the study area. a) Uninterpreted seismic section imaging Carboniferous-Lower Triassic strata in the study area. b) Interpreted seismic section highlighting the main seismic-stratigraphic boundaries (and units) observed across the Samson Dome area. Note the tabular to pinnacle-like shapes of Late Carboniferous build-ups and their different sizes in Horizons 3 to 6. Vertical exaggeration = 10x.

Figure 7 – TWT structure maps highlighting the geometry of carbonate build-ups from Horizon H6 to H4. a) Reveals the onset of polygonal build-ups at the base of the Falk Formation, with deeper basins being devoid of build-ups. b) Shows sets of developed polygonal build-ups at the base of the Ørn Formation, Late Carboniferous. c) Reflects the drowning and demise of polygonal build-ups at the start of the Permian. Vertical exaggeration = 30x.
Figure 8 – TWT structure maps highlighting the geometry of spiculitic edifices from Horizon H3 to H1. a) Highlights the geometry of isolated (cool-water) build-ups in the Polarrev Formation (Early Permian). b) Denotes the presence of polygonal mounds in the Upper Permian (Røye Formation). c) Highlights the presence of polygonal mounds in Horizon H1, 50-100 ms below the P-T boundary. The maps have a 30x vertical exaggeration.

Figure 9 - Relevant statistical data for the interpreted carbonate build-ups and mounds. a) Plot of thickness vs. interpreted seismic horizons highlighting the variations in the thickness of build-ups and mounds across the study area. Note the thickness maximum for isolated (cool-water) build-ups in the Polarrev Formation and the relatively small variations in thickness recorded by Upper Permian mounds. b) Overlay of the position of build-ups and mounds from H3 to H1, highlighting the marked shifts in their location. c) Overlay of the position of build-ups from H6 to H4, showing once again marked variations in the location of Late Carboniferous build-ups. These changes in the position of the carbonate build-ups and Si-rich mounds are likely to result from a combination of early halokinesis and regional (late Variscan) tectonics.

Figure 10 - Coherence maps highlighting the change in the geometry of Permian build-ups and mounds in the Samson Dome area. a) Coherence slice at Z=3316 ms showing the geometry of isolated carbonate build-ups near the top of the Polarrev Formation (Early Permian). Compare with the time-structural map in Fig. 8a. b) Coherence slice at Z=2996 ms highlighting the existence of mounds ~ 20 m (50-100 ms) below the P-T boundary. The same mounds are shown on the time-structural map in Fig. 8c.
Figure 2

a) 

b)
Figure 3

Lithology key
- Continental clay and silt
- Marine sand
- Limestone
- Chert (spiculite)
- Anhydrite
- Continental sand
- Marine shale and silt
- Coal
- Marine kerogen

Time extent of carbonate growth

Sea Level Curve (Haq and Schutter, 2008)

Early Induan

Top Induan

Top Permian MFS

Early Ladinian

Basement

L-9

L-8

L-7

L-6

L-5

L-4

L-3

L-2

L-1

L-100

L-50

L-0

H1

H2

H3

H4

H5

H6
Figure 5
Figure 6

Isolated Artinskian build-ups

Polygonal build-ups

Top Permian MFS

Basement
Pinnacle-like build-ups formed during highstand conditions.

Linear build-ups around the Samson Dome.

Deeper basin to NW.

Developed polygonal build-up systems to the NE and SE.

Incipient polygonal build-ups in the Early-Mid Carboniferous.

Deeper basin separating the N and S flanks of the Samson Dome.

Figure 7
Isolated cool-water build-ups more developed to the SE and NE.

No large Artinskian build-ups to the NW of the Samson Dome.

Smaller polygonal mounds to the NE.

No mounds to the NW of the Samson Dome into the Nordkapp Basin.

No mounds to the NE.

Figure 8
a) Overlay of Top Polarrev (H3) to Top Ørret (Top Permian MFS) Formations

- H3 - Top Polarrev Formation
- H2 - Top Roye Formation
- H1 - Top Ørret Formation (Top Permian MFS)

b) Overlay of Base Falk (H6) to Top Ørn Formations (H4)

- H6 - Near Base Falk Formation
- H5 - Near base Ørn Formation
- H4 - Top Ørn Formation

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Figure 9

- Thickness (m)
- Topmost Horizon
- Isolated build-ups (Polarrev Formation)
- Late Permian mounds
- Late Carboniferous mounds
- Early-Mid Carboniferous mounds
- Late Carboniferous buildups

- Samson Dome
- 7224/7-1

- 5 km

Isolated build-ups

n=120

7224/7-1
Isolated build-ups near the top of the Polarrev Formation

Polygonal mounds immediately below the Top Permian MFS

Coherence slice at Z=3316 ms

Isolated build-ups near the top of the Polarrev Formation

Coherence slice at Z=2996 ms

Polygonal mounds immediately below the Top Permian MFS

Figure 10
<table>
<thead>
<tr>
<th>Unit</th>
<th>Depositional setting and lithology</th>
<th>Age</th>
<th>Average Thickness (m)</th>
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<tbody>
<tr>
<td>L-9</td>
<td>Deep-water spiculite, limestone and spiculitic mud</td>
<td>?Kungurian-Late Permian</td>
<td>129</td>
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<tr>
<td>L-8</td>
<td>Open-shelf limestone</td>
<td>Late Sakmarian-late Artinskian</td>
<td>97</td>
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<td>L-7</td>
<td>Offshore to lower-shoreface shale and shallow-water limestone</td>
<td>early Sakmarian</td>
<td>30</td>
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<td>L-6</td>
<td>Shallow-shelf limestone</td>
<td>middle Asselian-early Sakmarian</td>
<td>19</td>
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<tr>
<td>L-5</td>
<td>Lagoon/sabkha dolomitic mudstone and shallow-water packstone</td>
<td>middle Asselian</td>
<td>34</td>
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<td>L-4</td>
<td>Shallow-water wackestone and buildups (partly dolomitised)</td>
<td>late Gzhelian-early Asselian</td>
<td>76</td>
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<tr>
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<td>Lagoon/sabkha dolomitic mudstone</td>
<td>middle-late Gzhelian</td>
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<tr>
<td>L-1</td>
<td>Shallow-water sandstone (partly dolomitised) and limestone</td>
<td>late Moscovian</td>
<td>35</td>
</tr>
</tbody>
</table>

Table 1