

Seismic Stratigraphic Framework of an Early Cretaceous Sand Lobe at the Slope of Southern Loppa High, Barents Sea, Norway*

Nauman Sattar¹, Christopher Juhlin¹, and Nadeem Ahmad²

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¹Dept. of Earth Sciences, Geocentrum, Uppsala University, Sweden (sattarnauman@gmail.com)

²BG Group Plc., Reading, UK (Current Address: Pakistan Petroleum Ltd., Islamabad, Pakistan) (ah_nadeem@ppl.com.pk)

Abstract

The Hammerfest Basin was formed through downfaulting in the Late Jurassic-Early Cretaceous, allowing the deposition and preservation of Jurassic sediments which were later covered by thick Cretaceous sequences filling the basin. As a result of the Loppa High uplift and subaerial erosion, thick Jurassic sediments have been eroded and deposited along the slope of Loppa High in the form of fans. This study has been conducted along the southern margin of the Loppa High to develop a complete sequence stratigraphic framework and to map one such turbidite lobe along the slope of the high, in the Early Cretaceous Knurr Formation. Three wells drilled along the southern margin of the Loppa High have proved small amounts of oil are present, with an oil discovery in Shell's 7120/1-2 well. Thick, massive sandstones of Early Cretaceous age (Valanginian-Hauterivian) display very good reservoir quality gravity flow (turbidite) sands in wells 7120/1-2 and 7122/2-1.

One regional seismic profile has been selected as a type section for interpretation along the southern margin of the Loppa High. A complete sequence stratigraphic framework has been developed to mark the major surfaces (Sequence Boundary, MFS) by geologic characterization of high-resolution seismic reflection geometries (truncation patterns; onlap, downlap, toplap and sigmoidal reflections) and seismic facies using the coarsening-up, fining up and blocky gamma ray (GR) log motifs from both the offset wells and the well located on the seismic section. The whole sedimentary package is divided into various sequences and system tracts. In addition to a detailed sequence stratigraphic analysis to investigate the hydrocarbon prospectivity, an Early Cretaceous turbidite sand lobe has been mapped (LHSG- 84-428) using seismic stratigraphy.

Introduction

The Barents Shelf is a large epicontinental platform within the Arctic Circle. Water depths within the area are generally greater than 200 m, in some parts reaching 400 m. The Barents Shelf is bounded on all sides by distinct physiographic elements: to the south by the Fennoscandian Shield and to the North by the Arctic Ocean. To the west it is bounded by the present-day passive Atlantic continental margin and to the east by the Urals Fold Belt (Novaya Zemlya). The NE-SW trending Hammerfest Basin lies between the Loppa high in the North and Troms-Finnmark Platform in the south and the much deeper Tromsø Basin to the west ([Figure 1](#)) The boundary between the Hammerfest Basin and the Loppa High is the Southern Loppa High Fault Complex. The original westerly extension of the Hammerfest Basin was possibly far beyond its present limits. A north-south-trending zone of easterly-rotated fault-blocks, the Ringvassøy-Loppa Fault Complex marks the western boundary. A possible westerly extension of the Hammerfest Basin is buried under the thick Cretaceous sediments of the Tromsø Basin.

Seismic data in the Barents Sea was first acquired in 1970 and made available to companies in 1977. Exploration drilling started in 1980, when limited areas in the southwestern part of the Barents Sea were awarded to groups with Norwegian companies as operators. The Askeladd Field was the first significant find made by Statoil in late 1981 with well 7120/8-1. The largest field in the southwest Barents Sea is the Snøhvit Field that is comprised mainly of gas with a thin oil leg below. The only oil field is the Goliath that is operated by ENI Norge and is in the development stage.

Despite much early optimism in correlating Hammerfest Basin to the Norwegian Sea and looking for similar traps, it has proved to be a mostly gas prone province and the reservoir quality was worse than expected for the type of reservoir and depth of burial. The average porosity and permeability of these sandstones are low at 15% and 100-500 mD, respectively, for the average burial depths of 2000-2500 m. This was initially thought to be due to exceptionally severe diagenesis resulting perhaps from higher-than-normal geothermal gradients (Mitchum, et al., 1977). Now, it is generally believed that the reservoirs were buried more deeply, and subsequently uplifted during the Tertiary as much as 1000-1500 m of sediments were stripped off due to uplift. This uplift has an adverse effect on reservoir quality but also on hydrocarbon retention since many traps were dry, having been breached by faulting to the surface.

Throughout most of Cretaceous times the Loppa High was a topographic high, uplifted and eroded due to several reactivations along the main fault zones. On the southern part of the Loppa High, Cretaceous sediments are present as coastal onlap sequences onlapping and filling in erosional valley cuts into Triassic sequences. Cretaceous sediments presumably covered major parts of the western Barents Shelf. However, a late Cretaceous uplift with subsequent erosion affected most of the area (Berglund et al., 1986). During Upper Cretaceous, the Tromsø Basin was the major depocenter for sedimentation (Våagnes and Gudlaugsson, 1993a). Paleocene-Eocene sedimentation was followed by an uplift of the western Barents Shelf. This uplift, which was related to an early phase of sea-

floor spreading, was followed by continuous Eocene-Oligocene sedimentation with westerly progradation. In the Hammerfest Basin, exposure and erosion lasted into Late Pliocene time when the entire shelf was transgressed. A thin blanket of Upper Pliocene and Pleistocene sediments cover the entire Hammerfest Basin. Due to loading from ice sheets, these uppermost sediments are highly compacted and cause a strong sea-bottom reflector on seismic.

Upper Jurassic shales (equivalent to Kimmeridgian age) are the main source rock interval in the Hammerfest Basin, hence oil shows are very common in underlying Jurassic and overlying Lower Cretaceous strata. The major part of the reserves in the Hammerfest Basin are in the Sto Formation of Early to Middle Jurassic age. The formation is dominated by clean, medium- to fine-grained sandstones exhibiting large-scale cross bedding, marine body fossils and trace fossils indicating deposition along a high-energy shallow-marine shoreline including shoreface and tidal delta environments (Helland-Hansen and Martinsen, 1996; Richards et al., 1998). The main cap rock to these Jurassic reservoirs is the regionally developed Upper Jurassic shale of the Fuglen and Hekkingen formations. Together these formations comprise a seal of more than 100 m (Worsley et al., 1988). A lithostratigraphic scheme is shown in the [Figure 2](#).

The importance of submarine fans as hydrocarbon reservoirs has been highlighted by large discoveries in the Frigg (Hersey, 1965) and Forties (Carman and Young, 1981) fields in the North Sea, as well as older fields such as Wilmington (Olsen and Hansen, 1987). Present study focuses on the Early Cretaceous Knurr sandstone lobes which are lying at the toe of the slope fans along the southern margin of the Loppa High. These lobes are very prominent features on seismic sections and attract many petroleum company eyes as secondary targets after the giant Jurassic closures (Snohvit) in Barents Shelf. These turbidity lobes were formed during the Loppa High uplift, which caused subaerial erosion and incision of thick Jurassic sediments and deposited these sediments in the form of turbidity lobes along the Loppa High slope. This erosion occurred during the post-rift stage in the Cretaceous when the Loppa High was sub-aerially exposed. These lobes are deposited above the Hekkingen shales (typically 200 - 300 mg HC/g; TOC in the range of 2-13%), a regional source rock and in the oil window in the Southern Loppa High area. One such lobe has been drilled and encountered a massive Knurr sandstone turbidite sequence (1831-1954 m), but was entirely water bearing. One such Early Cretaceous (Valanginian/Hauterivian) wedge has been drilled by Shell and proved to be an oil discovery. This is an analogue for the area to be in the oil window.

Dataset and Methodology

The data studied consisted of conventional multichannel seismic reflection (MCS) profiles supplemented by conventional well log data. Data were provided by the Norwegian Petroleum Directorate (NPD) for research at Uppsala University, Sweden. In addition to seismic data, eight in-line and offset wells were selected for seismic to well correlation and generation of synthetic seismograms. The location of these wells is also marked on [Figure 1](#).

Although seismic coverage is good in the Northern Hammerfest Basin, data quality is still a major issue. Most of the old surveys are low frequency with significant noise (multiples) (Surveys NPD-TR-82, NH8306). We have chosen seismic lines from “survey LHSG-89” for seismic stratigraphic interpretation because of its higher frequency content and good signal to noise ratio. This survey covering part of southern Loppa High and it is easy to mark shelf break on seismic. Based on the seismic data quality and good signal to noise ratio, one type section was selected for a complete sequence stratigraphic interpretation ([Figure 2](#)).

Interpretation Strategy

First of all, synthetic logs were generated using sonic and density logs and major seismic surfaces (reflectors) were marked. Structural interpretation was done to mark the Southern Loppa High Fault Complex. A complete Seismic Stratigraphic scheme was developed to recognize major surfaces (SB, MFS, etc.), stacking patterns (progradational, aggradational, and retrogradational) and system tracts (LST, HST, LST and FSST). Geological characterization of the high resolution seismic geometries (truncation patterns, sigmoidal reflections), and seismic facies using the coarsening-up and fining-up GR log motifs was done from the offset wells or from the wells located on the seismic lines. Then a detailed seismic stratigraphic interpretation was carried out. Seismic facies analysis is done based on reflection geometry, continuity, amplitude and frequency, as well as the external form (lobate, mound, etc.) and three dimensional associations of group of reflections.

To integrate this, we have identified the flooding surfaces, potentially sand-prone intervals represented by brightening and dimming (of amplitude) of seismic events and coarsening-up, fining-up and blocky log motifs in the offset wells. An interpretation scheme has been developed along regionally dip oriented NE-SW line from the Base Cretaceous Unconformity (BCU) up to the Pliocene-Pleistocene sediments (2nd order cycles, > 20 My), three seismic sequences have been recognized and mapped based on their seismic character and reflection geometry. Location of the seismic profile is shown in [Figure 1](#).

Interpretation for Seismic Profile LHSG-89-430

In order to obtain a regional picture of the area, a NE-SW oriented line was picked along the Loppa High slope and the first major through-going surfaces have been marked ([Figure 3](#) and [Figure 4](#)). Various system tracts were recognized on the basis of bounded surfaces and internal stratigraphic patterns. After seismic stratigraphic interpretation, three seismic sequences (SS1-SS3) and three Maximum Flooding Surfaces were marked on the seismic. An explanation of the seismic reflection geometry and terminology used in this study is shown in [Figure 5](#).

Seismic Sequence SS1

Seismic sequence SS1 is interpreted as a lowstand system tract (LST) and bounded at its base by a sequence boundary (Figure 5). This SB has been recognized on the basis of truncation of seismic reflections as a result of subaerial exposure with erosion in the proximal direction and a downward shift in coastal onlap along the Loppa High slope in the distal part. Sediments have been eroded from the previous highstand (Jurassic topsets) and deposited in the form of basin floor fans during relative sea-level fall, Barremian sediments infill as a lowstand wedge above the Valanginian/Hauterivian lobe fan. Within SS1 a transgressive surface has also been recognized which formed as a result of deepening and filling of the accommodation space. The basin floor fan and the LSW together are interpreted as an LST, bounded at its top by a maximum flooding surface (MFS). Above the MFS the system tract has been interpreted as a HST.

Seismic Sequence SS2

The Aptian seismic sequence SS2 is bounded at its base by a MFS. This MFS is recognized based on downlaps on it and is easy to mark on the seismic section (Figure 5). The overlying sequence above the MFS is marked as HST. Just above the maximum flooding zone, the chaotic seismic response may represent a potential transgressive lag or healing phase deposits formed during a sea-level standstill. In the proximal direction towards Loppa High, sediments are onlapping older Triassic units. The onlapping nature of this facies, together with its tendency to selectively fill lows in the depositional topography, suggests deposition by gravity controlled flow (turbidity currents) along the sea bottom (Hersey, 1965). A seismic pattern forms discontinuous reflections that show an increased rate of thickening into topographic lows. These deposits probably contain discontinuous beds and reflect a less uniform and possibly high velocity mode of transportation and deposition. Turbidity current flow seems to be the most likely origin for this facies. Discontinuous and irregular patterns with minor mounding probably represent deposits formed by higher velocity turbidity currents, possibly capable of transporting sands if sands were available at the source.

Seismic Sequence SS3

Seismic sequence SS3 is interpreted to be a HST and is bounded at its base by a MFS which is interpreted by constant downlaps on a through-going surface (Figure 5). Within this sequence, sediments are aggrading to prograding towards the Hammerfest Basin. The shoreline trajectory for this unit is building upward and outward. This unit is bounded at its top by a very condensed lower Cretaceous section which is recognized as a sequence boundary. This surface just overlying the SS3 is also recognized as the BT unconformity (Base Tertiary SB) (Berglund et al., 1986; Faleide et al., 1993a). On the southern part of the Loppa High, Cretaceous sediments are present as coastal onlap sequences onlapping and filling-in erosional valley cuts into older Triassic sequences. In the proximal part,

some high amplitude reflections can be interpreted as potential prograding shelf sands that appear to be prograding clinoform sets downlapping on the MFS.

Seismic Lobe Facies

A closer zoom in picture of the lobe can help to recognize some of the internal features. Within the lobe the seismic amplitude is strong to weak, downlapping in the distal part and onlapping with the slope in proximal direction ([Figure 6](#)). The reflection configuration is sigmoidal oblique, characteristic of sandy facies. In the distal portion, breakup of the lobe internal reflections may represent channels running into the basin. Above the lobe the chaotic discontinuous seismic pattern may suggest some kind of plastic lithology (uncompacted sediments) deposited in a variable, relatively high-energy setting, or as initially continuous strata which have been deformed so as to disrupt continuity.

Feeder System

The feeder system for these lower Cretaceous wedges are the incised valleys along the southern margin of the Loppa High. These canyons are several hundred meters deep and wide and pass through the intensely faulted Loppa High margin. This shows that these canyons are controlled by the fault complex along the zone of weakness. Reflections that characterize these facies are horizontal to gently tilted, parallel to divergent onlapping/truncating with the canyon walls. Reflection continuity varies from good to poor, amplitude is variable, and spacing is non-uniform. These canyons are eroded through the Jurassic sediments of the Loppa High and may be up to Triassic in age and filled with recent Paleocene-Eocene muds. Probable interfluvial of Early Jurassic sediments have been preserved. At some places, canyon wall failure can be marked due to over steepening of the canyon walls ([Figure 7](#)).

Prospectivity

The Late Jurassic organic-rich Hekkingen shales represent a regional flooding event throughout the Arctic during which organic-rich shales were deposited (Kimmeridgian, Hekkingen, Spec, Agardfjellet) over a wide spread area. Hekkingen shales are organic rich and one oil discovery in well 7120/1-2 by Norske Shell in these early Cretaceous sandy wedges shows that the area is in the oil window and a petroleum system exists in the area ([Figure 8](#)). During the Early Cretaceous Loppa High uplift, subaerial exposure caused deeply incised valleys and erosion of Jurassic sequences from the high, which were deposited in the form of turbidity lobes along the slope. These lobes have good reservoir quality sands (well 7122/2-1; permeability 726 mD) and covered by transgressive shales, acting as a top seal. Such lobes can prove to be potential stratigraphic traps in the future.

Summary and Conclusions

A thick Cretaceous sedimentary succession along the southern slopes of the Loppa High is divided into various sequences and system tracts (HST, TST and LST) by using seismic stratigraphic techniques through integrated use of well logs and seismic. A complete sequence stratigraphic framework has been developed to mark major surfaces (SB, MFS, TS). This was done by geologic characterization of high-resolution seismic reflection geometries (truncation patterns, sigmoidal reflections). The following conclusion can be drawn:

- An Early Cretaceous uplift on Loppa High accompanied by a relative sea-level fall and subaerial exposure caused deeply eroded incised valleys. These valleys provided feeder systems for the Knurr Sandstone turbidite lobes deposited as slope-to-basin floor fans (line LHSg-89-430) in the Hammerfest Basin.
- Proximity of the Knurr turbidites to the feeders, overlying transgressive marine shales above these Knurr lobes and directly underlying organic-rich Hekkingen shales make this play a promising target for future exploration.
- Seal failure, thief sands on the slope towards north and preferential hydrocarbon migration towards the nearby Snøhvit Gas Field in south are the geological uncertainties and key exploration risks related to this play. Also, undoubtedly the late Oligocene uplift and erosion of almost 1000 m of sediments throughout the Hammerfest Basin has its implications on the preservation of any hydrocarbon accumulations and temperature gradients which in turn control porosity and permeability.
- Oil discovery in well 7120/1-2 in the neighboring area through one such Early Cretaceous wedge provides an analogue for the presence of a petroleum system and confirm that the play works at the toe-of-slope of the Loppa High.

On the basis of the above results we can conclude that seismic/sequence stratigraphic techniques can help in predicting the stratigraphic traps in the Southern Hammerfest Basin. De-risking of key geological uncertainties highlighted above through 3D seismic acquisition and integrated use of high-resolution sequence stratigraphy, attribute maps and 3D seismic geomorphology maps can be a winning exploration strategy for targeting stratigraphic traps in the region.

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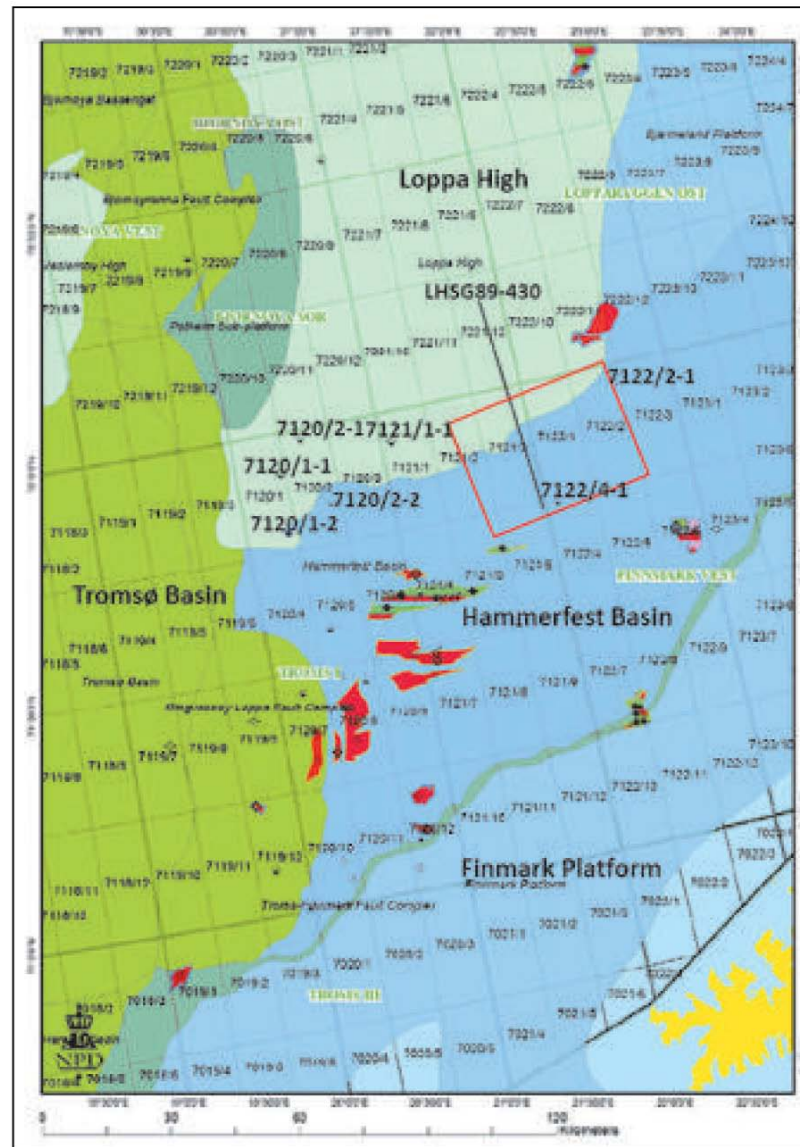


Figure 1. Map showing study area location and major structural elements of Barents Sea.

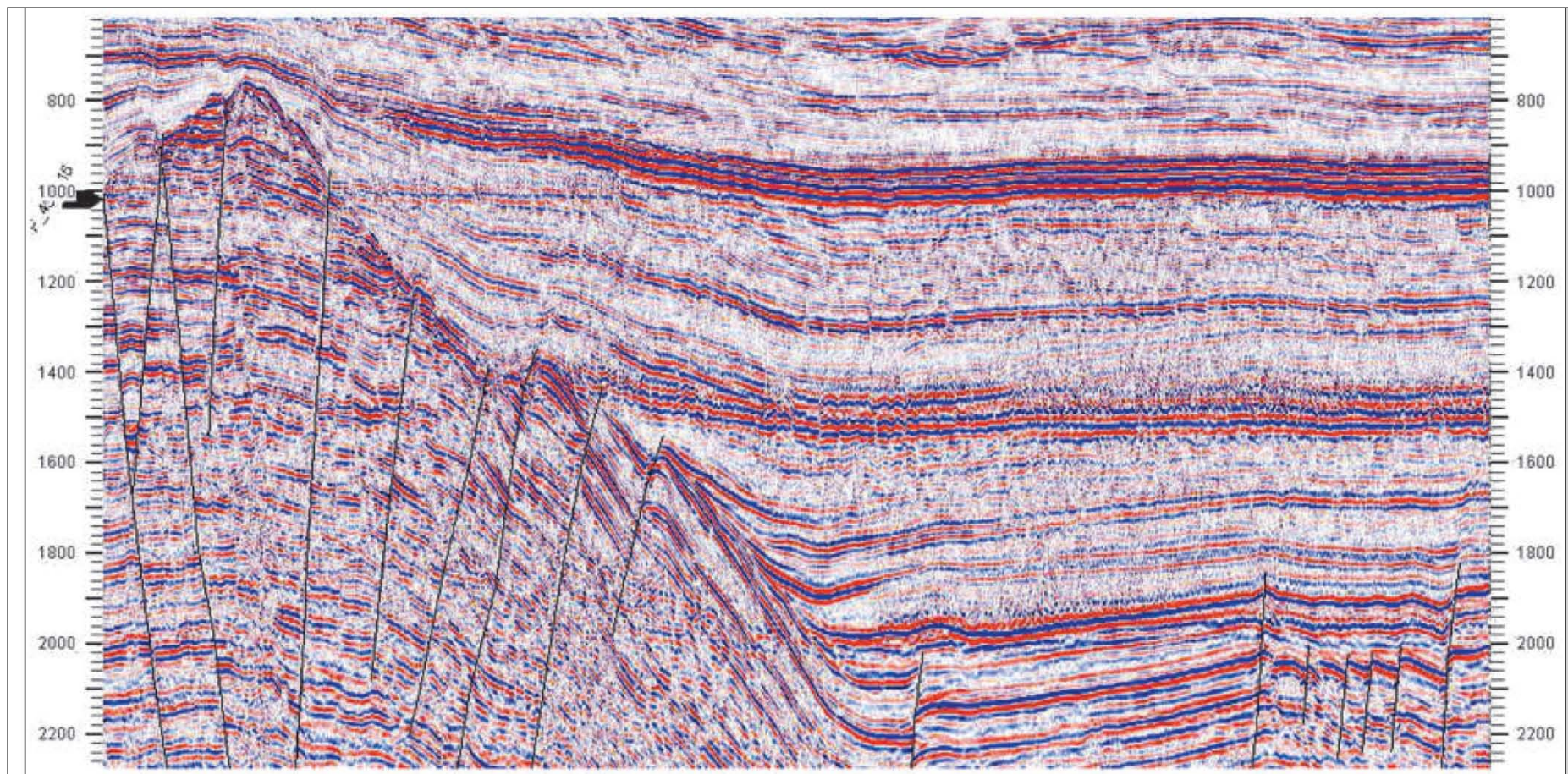


Figure 3. Uninterpreted seismic section LHSG 89-430 along the slope of Loppa High (28 km long section).

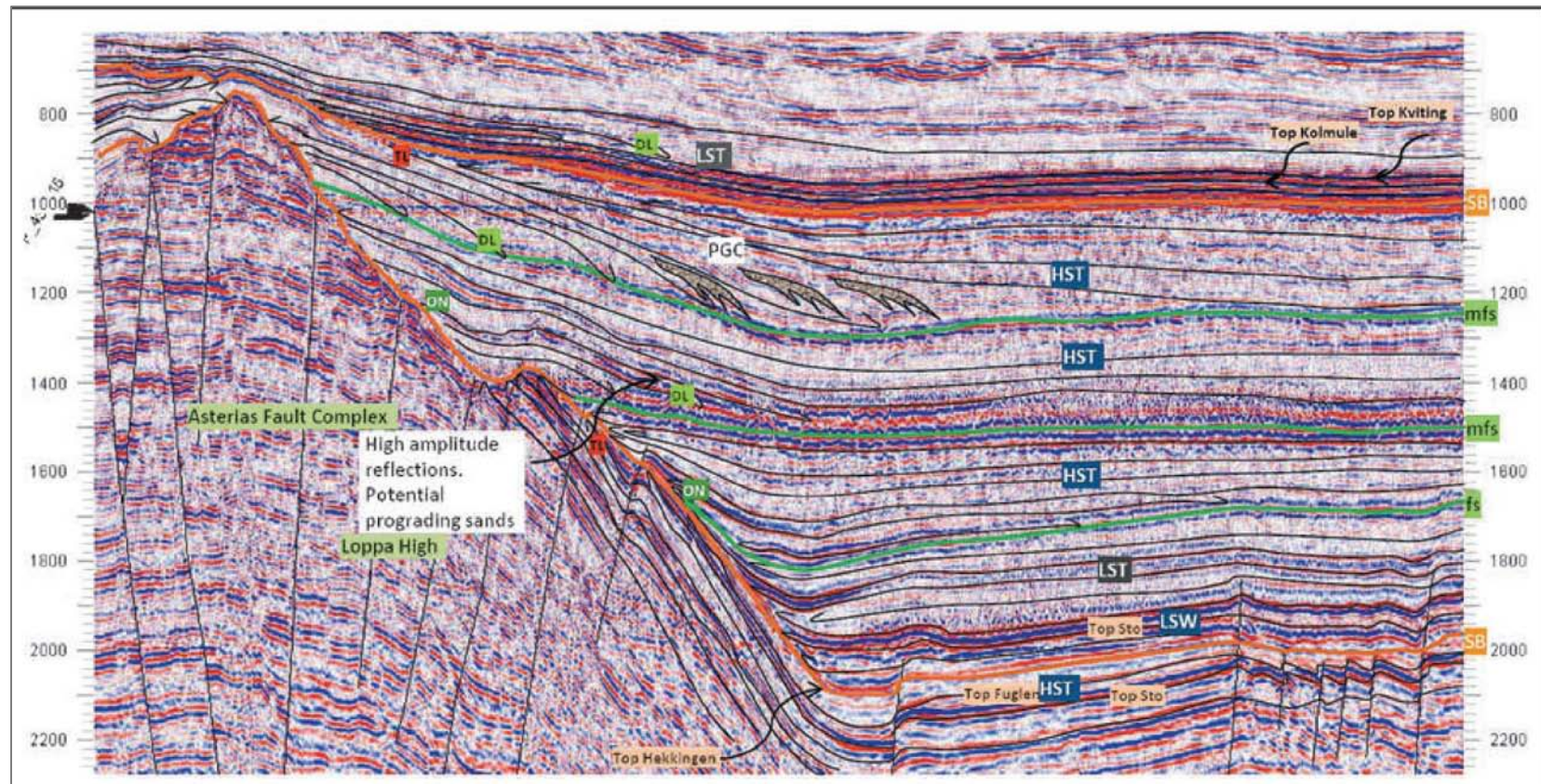


Figure 4. Interpreted seismic section LHSg 89-430 with major thought-going surfaces has been recognized by identifying the seismic reflection geometry and truncation patterns.

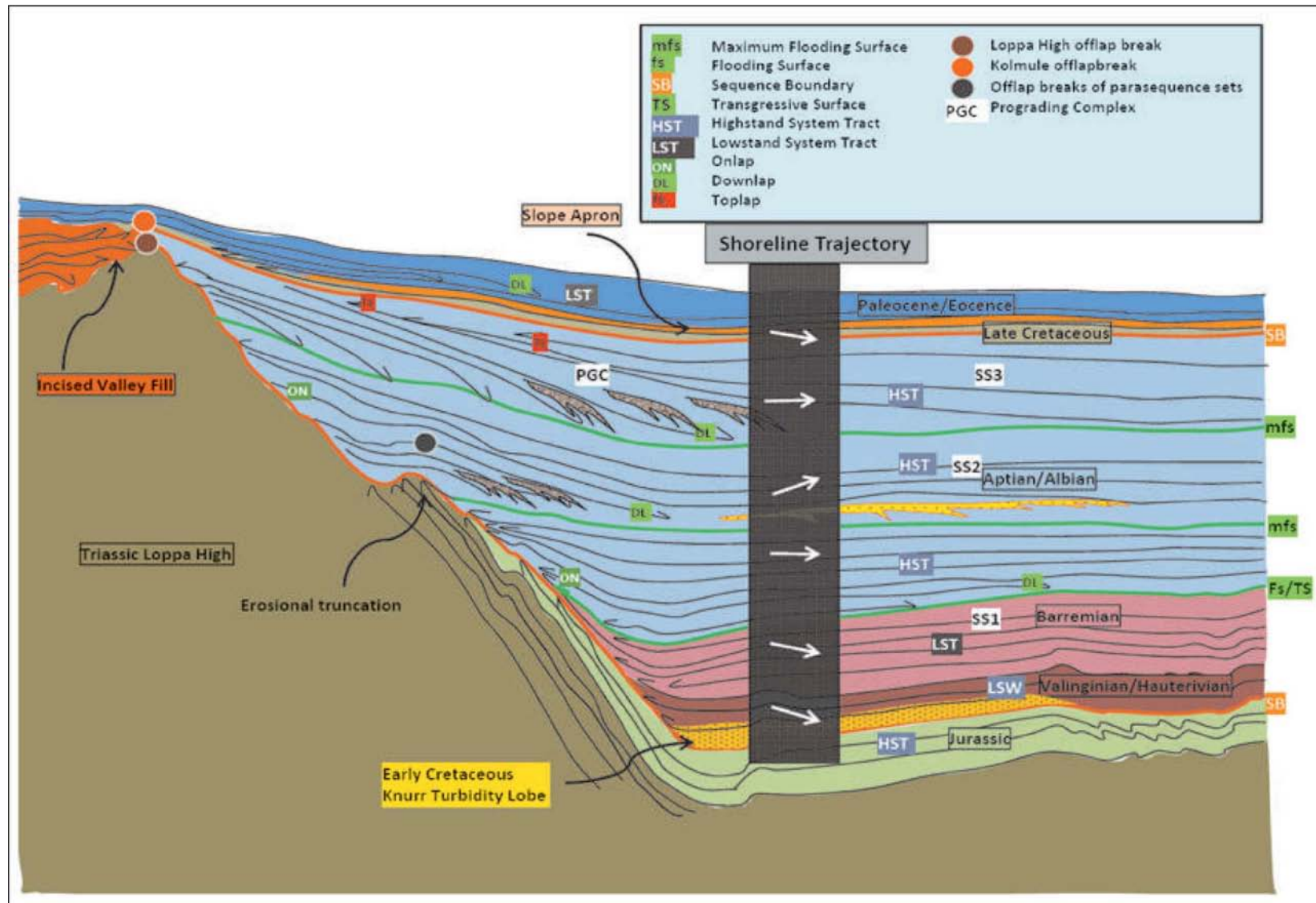


Figure 5. Interpreted seismic section showing the seismic facies interpreted based on reflection configuration. Kunrr turbidity lobe is also marked in this schematic section.

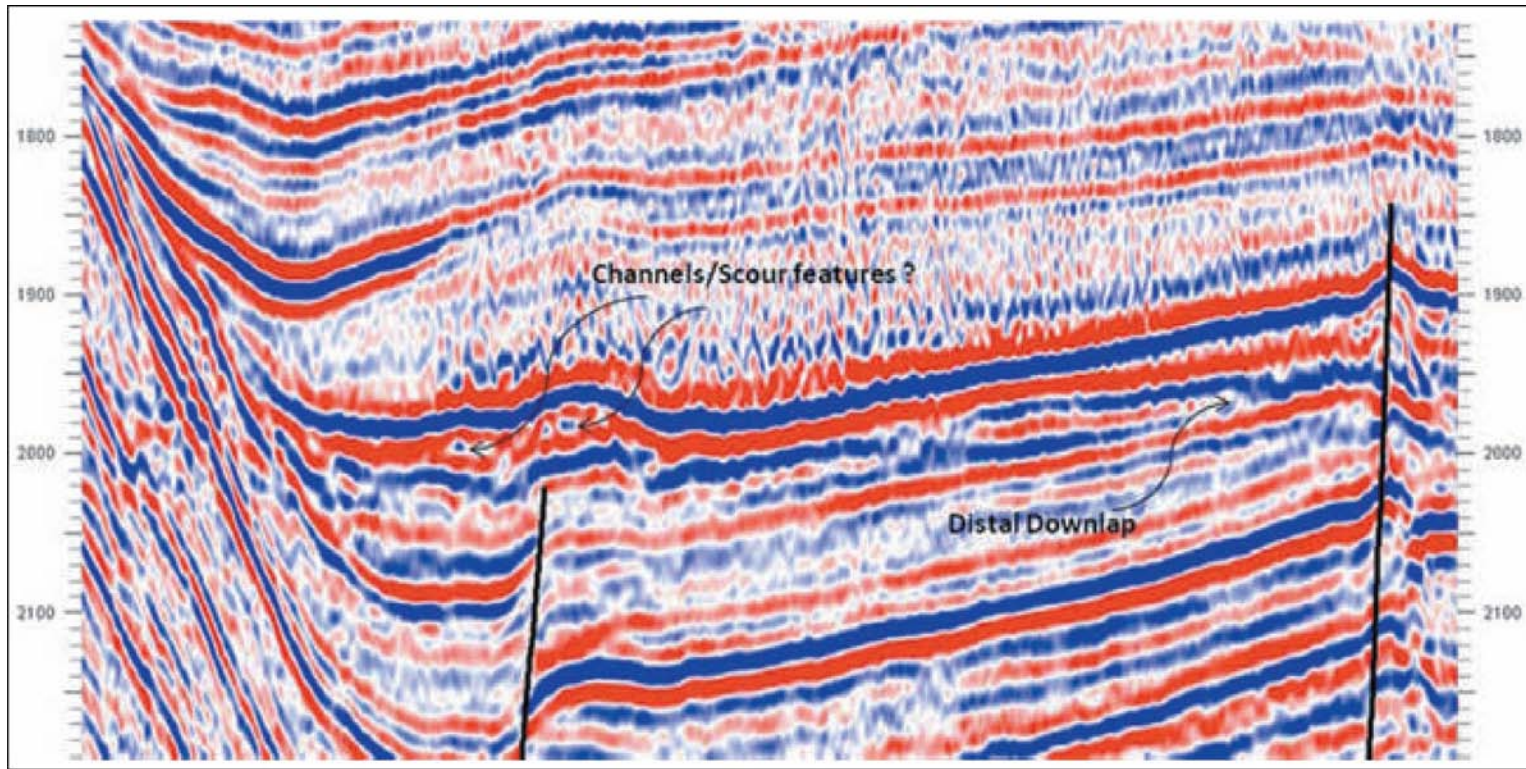


Figure 6. Seismic lobe and internal seismic character. Breaking reflections within the lobe may be potential channels meandering in the basin during early Cretaceous (12 km long section).

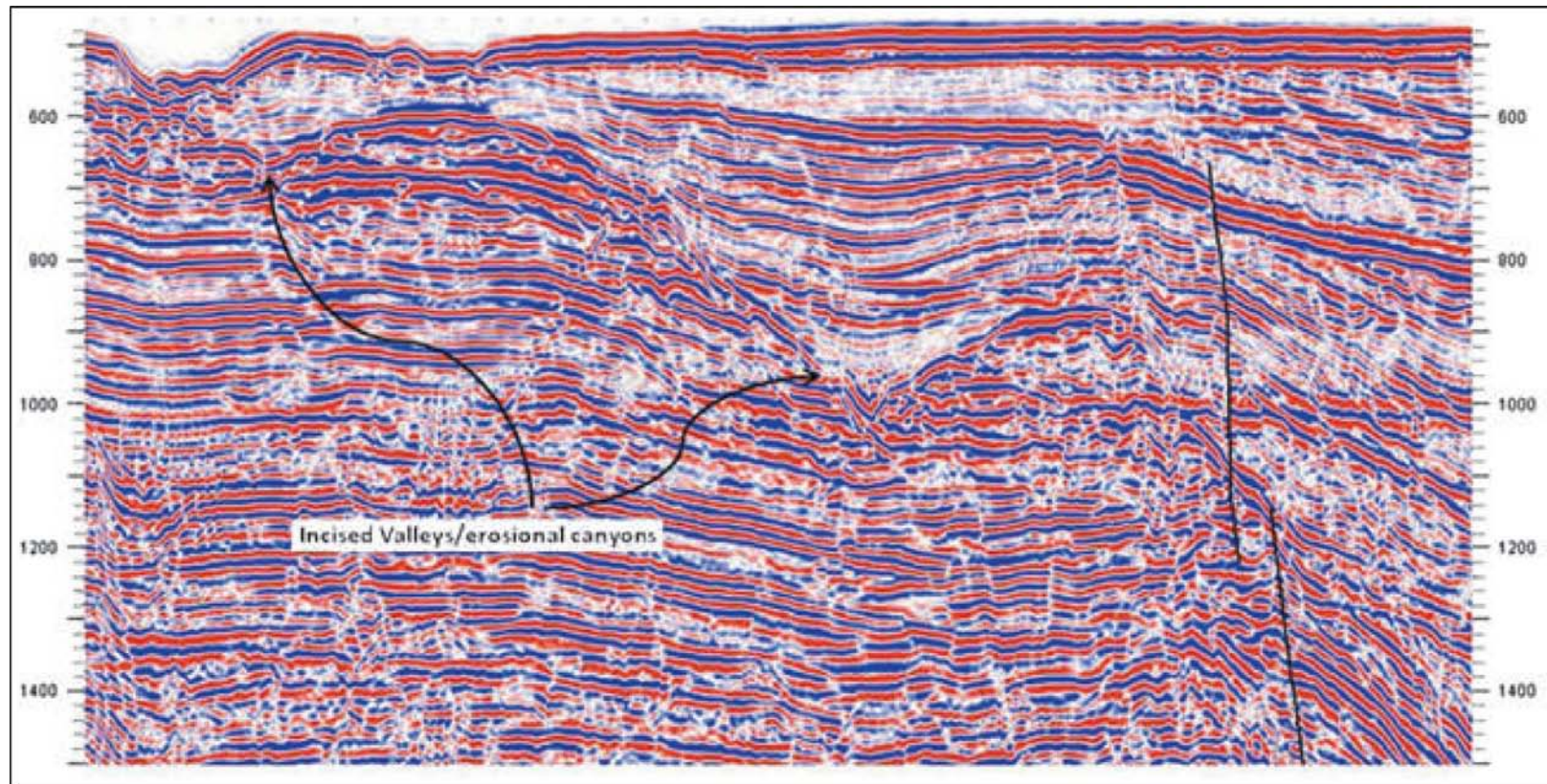


Figure 7. Early Cretaceous incised valleys which are the feeder channels of the Knurr lobes along the Southern Loppa High Margin (14 km long section).

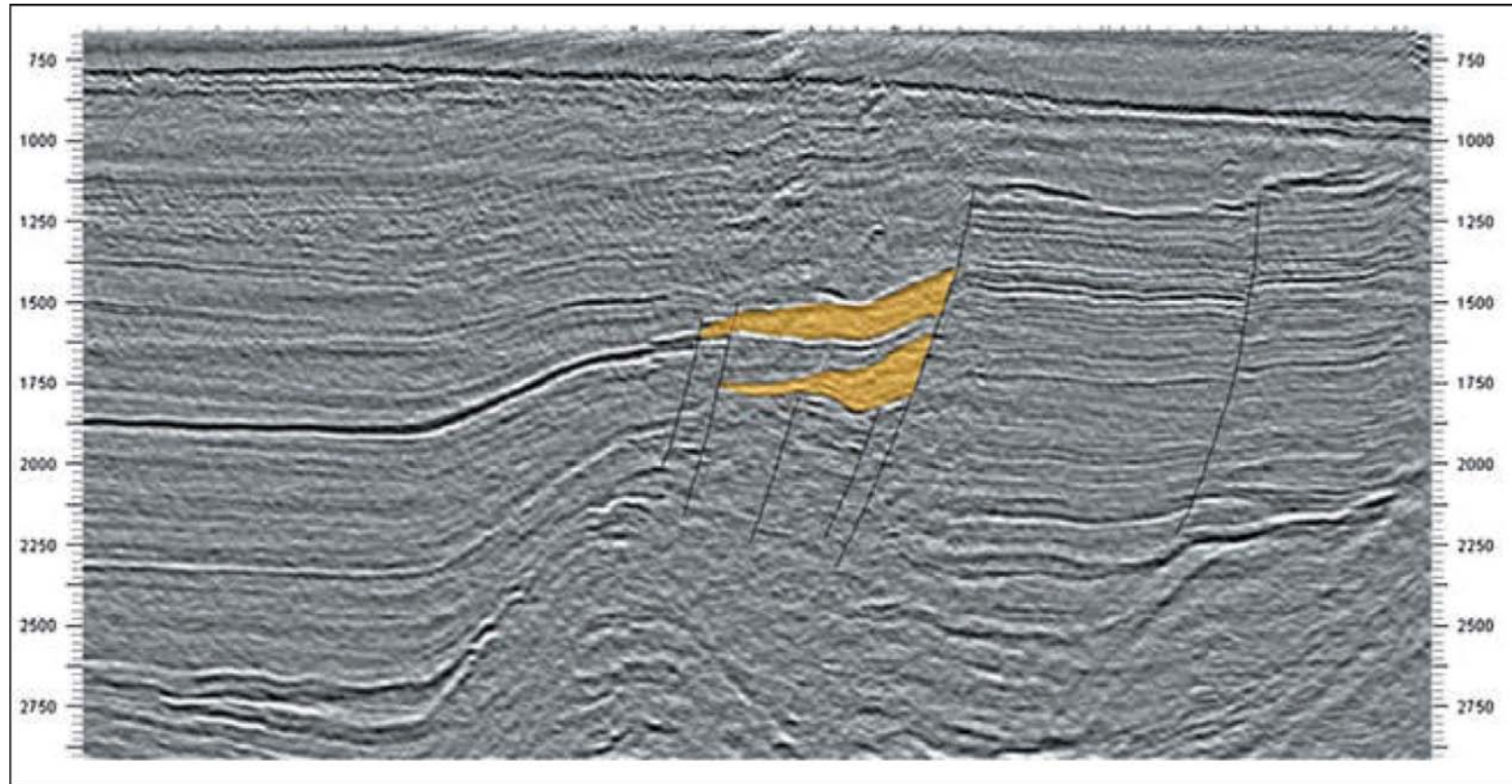


Figure 8. Seismic section showing two seismostratigraphically-defined wedges in a fault-bound closure along the Loppa High. This was a discovery, lower hydrocarbon-bearing wedge contains two units of latest Ryazanian /Early Valanginian of the Cretaceous wedge drilled by well 7120/1-2 (24 km long section).