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Abstract

A 3D seismic cube combined with well data from ten exploration wells are used to form a model of the tectono-stratigraphic evolution of the Greater Mandal High Area, Southern North Sea, Norway. The data defines the crystalline Mandal High as an elongated, s-shaped, SE-NW trending horst. The first sub aerial exposure of the horst was in the Triassic, lasting up until the Upper Cretaceous flooding. Deformations and lineaments dating back to the Caledonian orogeny are identified. The two main lineaments have a near N-S and NE-SW orientation.

Seven chronostratigraphic sequences have been defined: The Lower Permian with rifting, doming and volcanic activity in a continental environment, flooding in the Upper Permian and subsequent deposition of the Zechstein salt, rifting in a continental setting of the Triassic, uplift and erosion in the Middle Jurassic leading to deposition in shallow marine and delta environments, rifting and transgression in a deep marine environment during the Upper Jurassic, a post rift phase in a marine environment of the Lower Cretaceous and lastly; flooding, deposition of chalk groups and inversion in the Upper Cretaceous.

Three fault families consisting of Lower Permian normal faults families are defined with the following orientation: Fault family 1 – near N-S, fault family 2 – NE-SW, fault family 3 – W-E. These faults inherit the structural grain first established by the Caledonian folding. In addition, fault family 4 consisting of NW-SE oriented normal faults, with large displacements are associated with the Upper Jurassic rifting. They were reactivated in the Upper Cretaceous as reverse fault, creating inverted structures. Fault family 5 is observed in all sequences above the Upper Permian, has various orientations and is associated with salt tectonics.

Salt mobilized during three phases: The Triassic, Upper Jurassic and Upper Cretaceous, and served as an important structural and stratigraphic control. Salt bodies were created on weakness zones first established during the Caledonian folding, and deformed above layers

By serving as an analogue to the Utsira High, the Mandal High might comprise a set of petroleum plays, including fractured crystalline basement and shallow marine systems evolving around the high. A source rock kitchen is proven to the west in the Feda Graben, and the south in the Danish Feda Graben. Hydrocarbons may migrate from these areas into the Greater Mandal High Area, but migration is further complicated by the possibility of both the Mandal High and the salt structures acting as migration barriers.

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I wish to express my gratitude towards Dr. Alejandro Escalona for supporting my through my studies and the work with this thesis. His faith, persistence and dedication in guiding me has been a big inspiration. I also wish to thank Nexen Exploration Norge AS for providing me the data, facilities, assistance and ideas that made this thesis possible. The support and encouragement I received from the people at Nexen were admirable.

I greatly appreciate the dedication, keen interest, scientific input and last but not least; friendship of Rinn Rolfsen.

Lastly, I thank the unconditional support provided by my family during my studies and work with the thesis.

University of Stavanger, June 2011

Anders Rossland

Introduction

The southern North Sea has been actively explored by the oil industry since the 1960's, resulting in discoveries ranging from the giant Ekofisk and Valhall Fields in Norway to the Siri and South Arne Fields in Denmark (Fig 1, 2). As observed in figure 2, hydrocarbon accumulation seems to follow a N-S Cretaceous trend in Norway, a N-S Cretaceous and Jurassic trend in Denmark, and an E-W Paleocene trend in Denmark. However, the field trends seem to stop at the political borders. The majority of the fields are drilled on structural highs. Currently, the basin is in a more mature exploration stage, and is focused on more subtle stratigraphic and combination structural-stratigraphic traps, which require a detailed understanding of local and regional sediment provenance and basin fill.

The Greater Mandal High area is to the east of the Central Graben, north of the Norwegian-Danish border (Fig 2). It is an area where several exploration wells has been drilled, but few have been discoveries.

Recent hydrocarbon discoveries in the Utsira High open a new geological model for similar highs in the North Sea. The Mandal High is one of these cases where so far exploration has been unsuccessful, and there is no clear understanding of the region. Particularly, the region lacked full 3D seismic coverage until the first quarter of 2011.

In this study, we use the new 3D seismic cube CGR2010FT (fast track) with a total of 8 Norwegian and 2 Danish wells. Interpretation and analysis of the subsurface data aim to fulfill the objectives listed below.

Objectives

- Create a detailed tectono-stratigraphic framework for rocks from Permian to Cretaceous in age, based on interpretation of the newly acquired 3D seismic dataset and the wells.
- Understand how the crystalline basement structural grain controls the development of the basin.
- Study and propose a model for the structural evolution of the crystalline basement of the Mandal High, based on vertical seismic sections and time slices.
- Propose possible hydrocarbon plays in the underexplored mature basin.

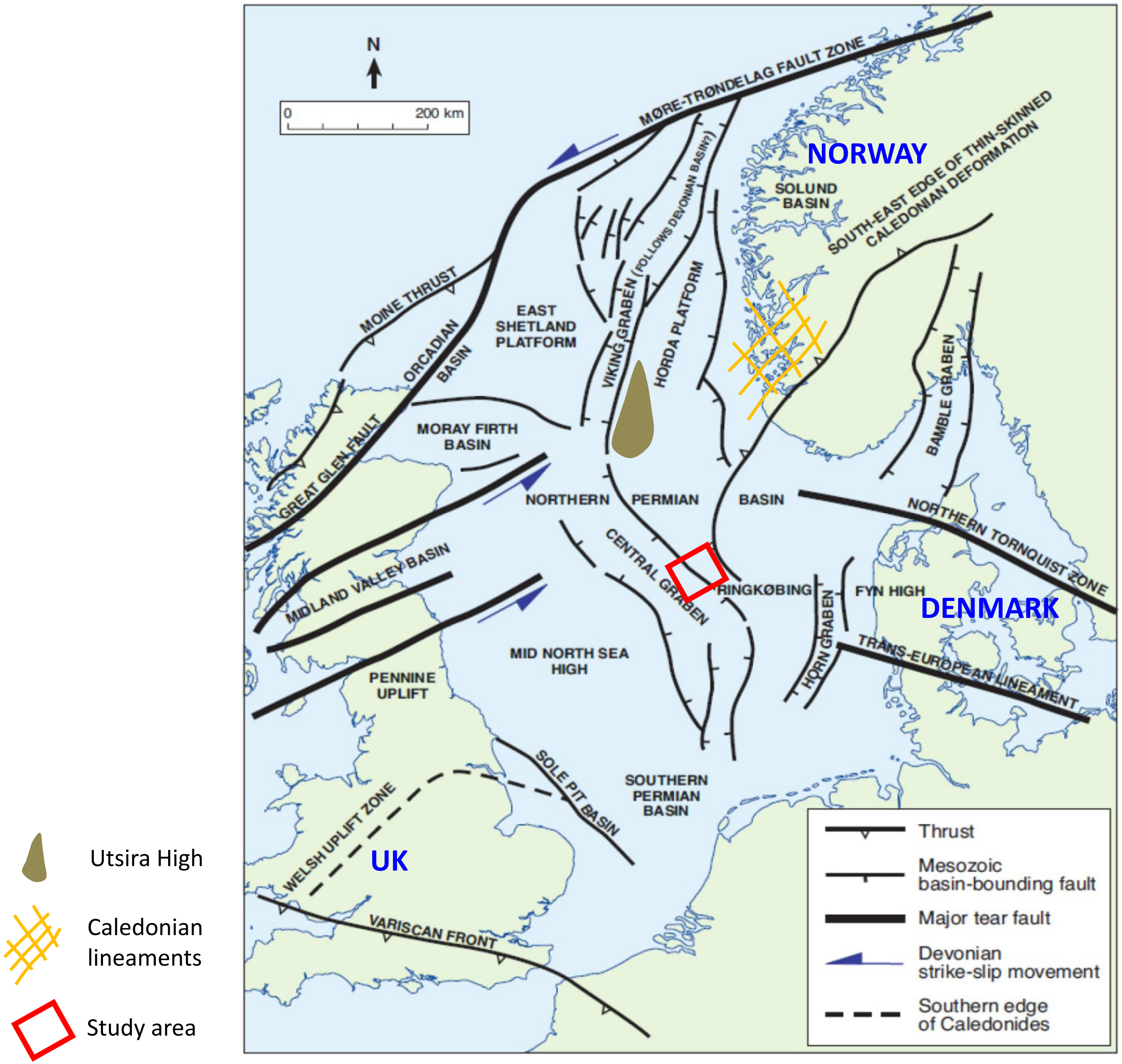

Figure 1: Geographic location of the study area and the structural grain of North-West Europe (Armour 2003). The Utsira High is also shown.

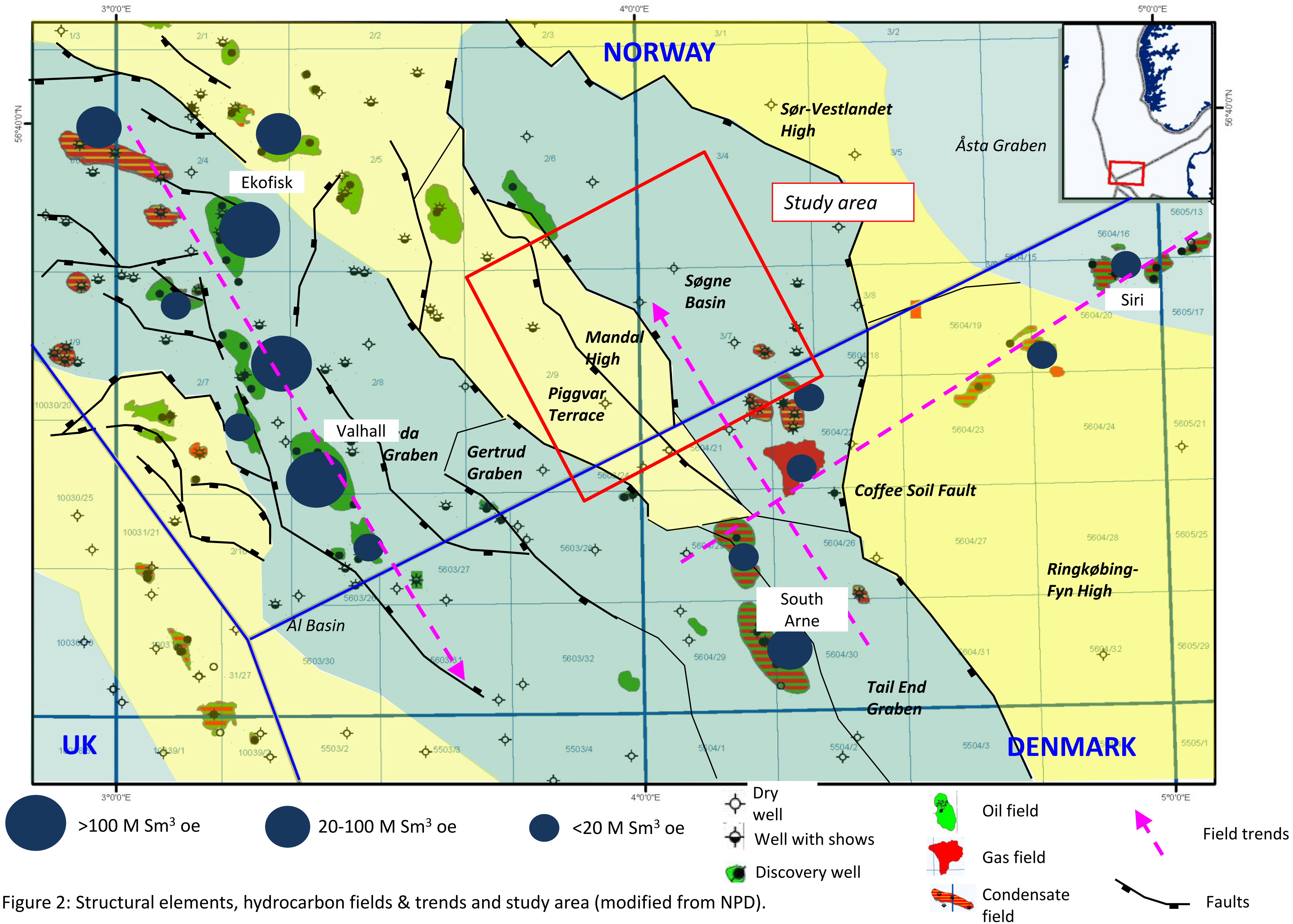

Figure 2: Structural elements, hydrocarbon fields & trends and study area (modified from NPD).

Geological setting

Regional evolution

The southern North Sea has undergone several tectonic events such as the Permo-Triassic rifting, and the Upper Jurassic-Lower Cretaceous rifting episodes (Fig 3, 4) (Gowers & Sæbøe 1985, Ziegler 1990).

Caledonian orogeny

The regional evolution of Pre-Permian crystalline rocks is based on observations of outcrops onland Northern Europe (Ziegler 1990). Few wells have been drilled into Pre-Permian crystalline rocks in the North Sea, and seismic resolution is generally poor. The crystalline basement underlying the southern North Sea area became consolidated during the Caledonian orogenic cycle commencing from the Late Cambrian to Early Devonian. The Caledonian fold in the central North Sea is probably characterized by a north-south trending structural grain, into a south-west to north-east trend on mainland Norway (Ziegler 1990). These lineaments of the Caledonian folding are shown in Figure 1 (Armour et al. 2003, NGU).

Permian early rifting, volcanics & pre-rift salt deposits

By early Permian time, the North Sea area was characterized by a mature continental crust with an average thickness of 35 km (Ziegler 1990). The widespread occurrence of Permo-Carboniferous volcanics and intrusives suggests that large parts of the lithosphere of the North Sea were thermally destabilized (Fig 4a). The northern and southern Permian basins extend in an east-west direction across the central North Sea (Fig 4a) (Ziegler 1990).Thick sand bodies of Early Permian age are deposited as aeolian dunes in a continental environment in the two basins (Fig 3, 4a) (Deegan & Skull 1977). The southern and northern basins are separated by the W-E oriented Mid-North Sea-Ringkøbing-Fyn-Møns trend of highs (Ziegler 1990). Evidence for the timing of the initial formation of the rifts in the Central Graben is difficult to find, although many have assumed an Early Permian age (Gowers & Sæbøe 1985). At the transition from Lower and Middle Permian to the Late Permian, the Zechstein Sea advanced from the Norwegian-Greenland Sea rift southward and flooded the Permian basins of north-west Europe (Fig 4a). Repeated glacio-eustatic sea level fluctuation governed the accumulation of the highly cyclical Zechstein carbonate, sulphate and halite series. The present thickness distribution of the Zechstein Group is highly variable due to salt diapirism and erosion at the base of the mid-Jurassic unconformity. As there is little evidence for Late Permian rifting governing Zechstein facies patterns in the North Sea, the Zechstein Group is considered to form part of a pre-rift sequence (Fig 3) (Ziegler 1990).

Triassic rifting

At the transition from the Permian to the Triassic, rifting accelerated in the Norwegian-Greenland Sea area and in the Tethys domain (Ziegler 1990). By Early Triassic time, north-west and central Europe as a whole were subjected to regional tensional stresses causing the differential subsidence of a complex set of multidirectional grabens and troughs (Fig 4b). In the northern and central North Sea, the Triassic is developed as a continental red bed facies Lower and Middle Triassic shales and sandstones are overlain by more sandy units which was mainly derived from the tectonically active Fenno-Scandian Shield (Fig 3, 4b) (Ziegler 1990). Fine grained clastics of the Triassic represent a range of distal continental environments. Sands are deposited in a coalescing and prograding system of alluvial fans along the eastern and southern flanks of a structurally controlled basin (Deegan & Skull 1977). In the central North Sea, accumulation of the Triassic series and syndepositional faulting triggered diapiric deformation of the Zechstein salts during the Middle and Late Triassic, largely controlling the distribution of Triassic sediments in the southern North Sea (Gowers & Sæbøe 1985).

Lower-Middle Jurassic uplift & erosion

At the transition from the Early-Middle Jurassic the central North Sea area became uplifted and formed a broad arch that was transected by the Central Graben, causing the formation of the central North Sea Dome (Fig 4c). Within the Central Graben, sediments deposited under continental to lacustrine conditions (Fig 3, 4c) (Ziegler 1990). Fluviatile, deltaic, swamp or even shallow marine facies were developed (Gowers & Sæbøe, 1985). During the Bathonian, increased subsidence of the Central Graben combined with a relative rise in sea level caused the first marine transgressions. This may reflect the onset of collapse of the North Sea dome (Ziegler 1990). Eventually, the subsidence led to the deposition of sandstones, in a marine to shallow marine environment (Vollset & Dore 1984).

Upper Jurassic rifting

By Oxfordian and Kimmeridgian time, the rift shoulders of the Central Graben became gradually inundated, and during the Kimmeridgian to Berriasian/Valanginian, the rate of crustal extension across the North Sea rift system apparently accelerated. The reader is referred to Errat et al. 1999 for discussion on different models of the Upper Jurassic rifting. The Upper Jurassic tectonic phases created a NW-SE structural orientation of the Central Trough, aligning with many of the structural elements of the southern North Sea (Fig 4d). The Søgne Basin, however, became relatively inactive in the Upper Jurassic compared to the Feda and Tail End Graben (Gowers & Sæbøe 1985). Oxfordian-Ryazanian sands are locally present around structural highs in the Central Graben, and are deposited in a shallow marine environment, probably before the Upper Jurassic transgression reached its full potential (Vollset & Dore 1984) (Fig 3, 4d). Following the transgression, shales, often carbonaceous and calcareous, with frequent thin sandstone interbeds and sands of probable turbiditic origin deposited in a shallow or deep marine, low energy environment (Vollset & Dore 1984). During the Oxfordian and Kimmeridgian, deeper water anaerobic conditions were established in the Central Graben, developing shales in a kerogenous source rock facies; though their thickness and richness are very variable (Fig 3) (Ziegler 1990).

Cretaceous post rift & inversion

Following the late-Kimmeridgian rifting pulse, the rate of crustal extension across the North Sea Graben system diminished gradually, and faded out upward into the Lower Cretaceous (Gowers & Sæbøe 1985). During the Early Cretaceous, continued differential subsidence of this graben system was accompanied by the gradual infilling of its relief with deep-water shales and minor pelagic carbonates, ranging in age from Berriasian to Albian (Fig 3, 4e). Deposition was in an open marine environment with generally low energy (Isaksen & Tonstad 1989).

Compression events from the Barremian-Aptian into the Tertiary resulted from the closure of the Tethys Ocean, and included phases of orogeny in the continental landmass south of the North Sea (Oakman & Partington 1998). Throughout the Cretaceous, intraplate push-pull stresses created a pattern of structures that were oblique to pre-existing lines of weakness; the pull, or transtension, in an east-west direction, and the push, or transpression, directed from the south (Oakman & Partington 1998). These stresses reactivated faults of Mesozoic grabens and troughs (Ziegler 1990). Several Cretaceous compressive events created a wide range of structures throughout the North Sea Basin, seen as inversions of variable magnitude and areal extent, complex fault tectonics and a range of NE-SW to NW-SE folds of variable size. Strike slip and oblique-slip movements along reactivated Jurassic faults were extremely common during the Cretaceous (Oakman & Partington 1998).

In the southern North Sea, the boundary between the Early and Upper Cretaceous are marked by the entry of the Cretaceous Sea and subsequent deposition of the Upper Cretaceous Chalk Group in clear water conditions which prevailed until Danian times (Fig 3) (Ziegler 1990). The chalk is deposited regionally in the southern North Sea, but thickness variations can occur due to major subsidence patterns, salt diapir growth, facies changes, intra chalk erosions, structural inversion and variation in original depositional thickness (Gowers & Sæbøe 1985).

Tertiary basin subsidence

During the Tertiary the Central Trough continued to subside as a broad elongate downwarp. Apart from this regional subsidence, significant halokinetic activity persisted throughout the Tertiary and some continuation of the Cretaceous inversion trends in the early Tertiary (Gowers & Sæbøe 1985). From the Eocene, the North Sea basin became tectonically quiescent; its subsequent evolution was essentially governed by thermal relaxation of the lithosphere and its loading by sediments. The clear water conditions and regional sea level rise of the Cretaceous ended in the Tertiary, and clastic sedimentation has dominated the North Sea basin up to present day (Fig 3). Sediment nature and distribution was controlled by the onset of the Atlantic Sea rifting, changes in sea level, uplift and erosion of basin margins (Ziegler 1990, Bowman 1998).

Structural elements

The structural relief seen at present day is a result of several tectonic events of extension, uplift, tectonic quiescence, inversion and salt mobilization. Figure 2 shows an overview of the main structural elements in the area. The crystalline basement of the Mandal High represents the eastern boundary of the Central Graben, separating it from the Søgne Basin, with the Tail End Graben to the south.

The Piggvar Terrace is a N-S trending terrace bounded by major basement faults off the Mandal High to the east, and the Feda Graben to the west (Fig 2, 5). The Jurassic-Triassic sediments are broken into a large number of small rotated fault blocks, detached from the crystalline basement, concentrated in a zone in the centre of the Piggvar Terrace, and aligned WNW to coincide with the trend of the northern edge of the Feda Graben (Gowers et al. 1993).

The Mandal High is a crystalline NNW-SEE trending eastward rotated high (Rønnevik et al. 1975), dated to 435 Ma by well 3/7-1 (Renard 1974). Cretaceous sediments are resting directly on the Devonian basement. Gowers & Sæbøe (1985) restricted the definition of the Mandal High to only refer to the central horst of crystalline basement shown in figure 2 and 5 (hereafter termed the Mandal High). Gowers et al. (1993) developed on the 1985 definition, suggesting the Mandal High to be the eroded tip of the Søgne Basin fault block. In common with the Søgne Basin, the high is interpreted to be little influenced by the various tectonic phases which are present in the rest of the Norwegian Central Trough (Gowers et al. 1993).

The Søgne Basin is a large rotated easterly dipping fault block limited to the east by the major basement fault; the Coffee Soil Fault (Fig 2, 5) (Gowers et al. 1993). Cartwright (1991) suggested that basement faulting of the Coffee Soil fault commenced at least as early as the beginning of the Triassic, possibly at the latest of Permian, based on differences in depositional patterns seen in the southern Danish analogue of the Søgne Basin; the Tail End Graben. The Søgne Basin is divided into a northern and southern half by an east-west-trending fracture, the southern half showing greater fault block rotation than the northern half. The Søgne Basin shows evidence of extensive Triassic salt tectonics, with a more or less continuous line of salt highs along its southwestern edge, several diapirs in the centre, and several salt highs and salt swells along the Coffee Soil Fault (Fig 5) (Gowers et al. 1993).

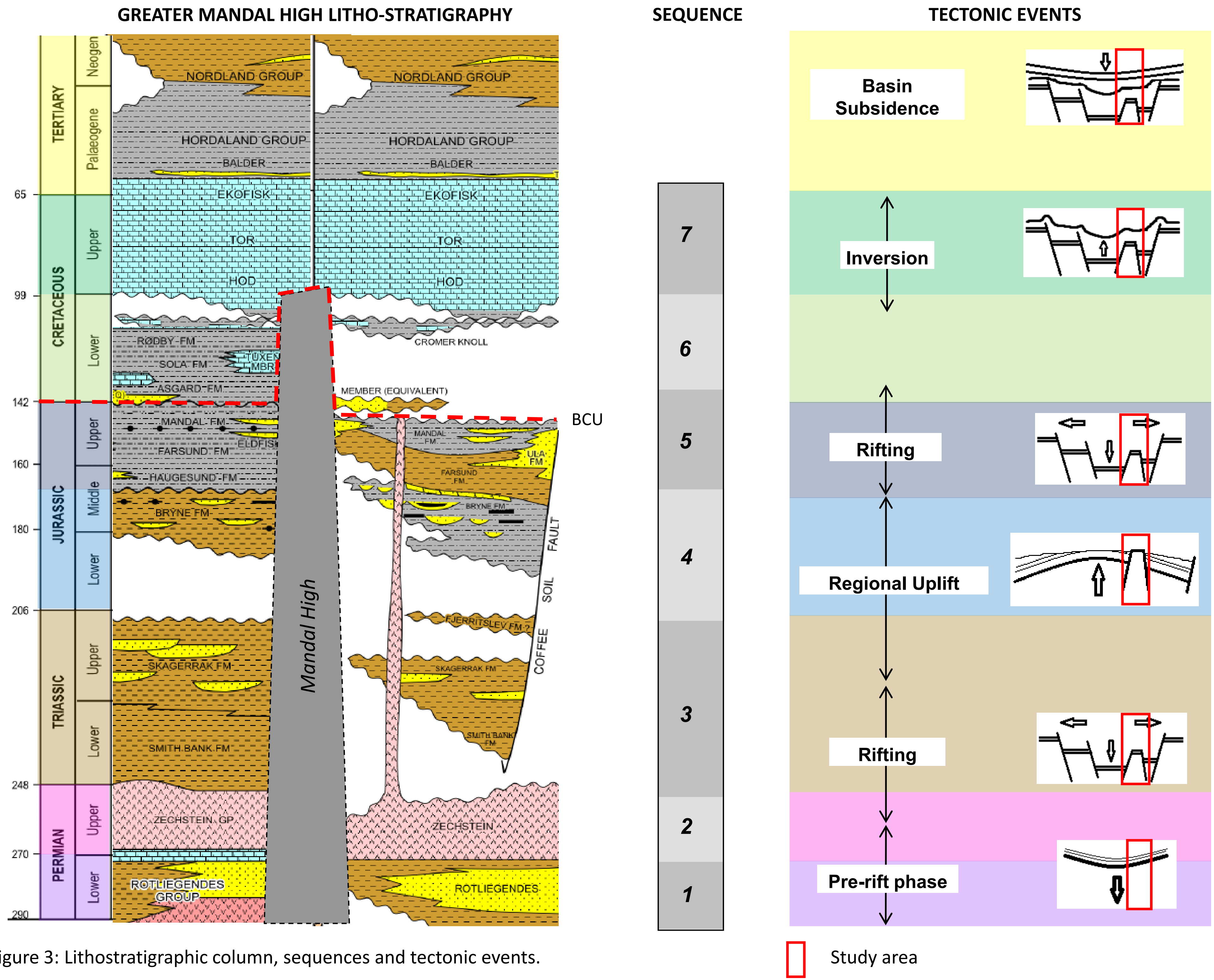

Figure 3: Lithostratigraphic column, sequences and tectonic events.

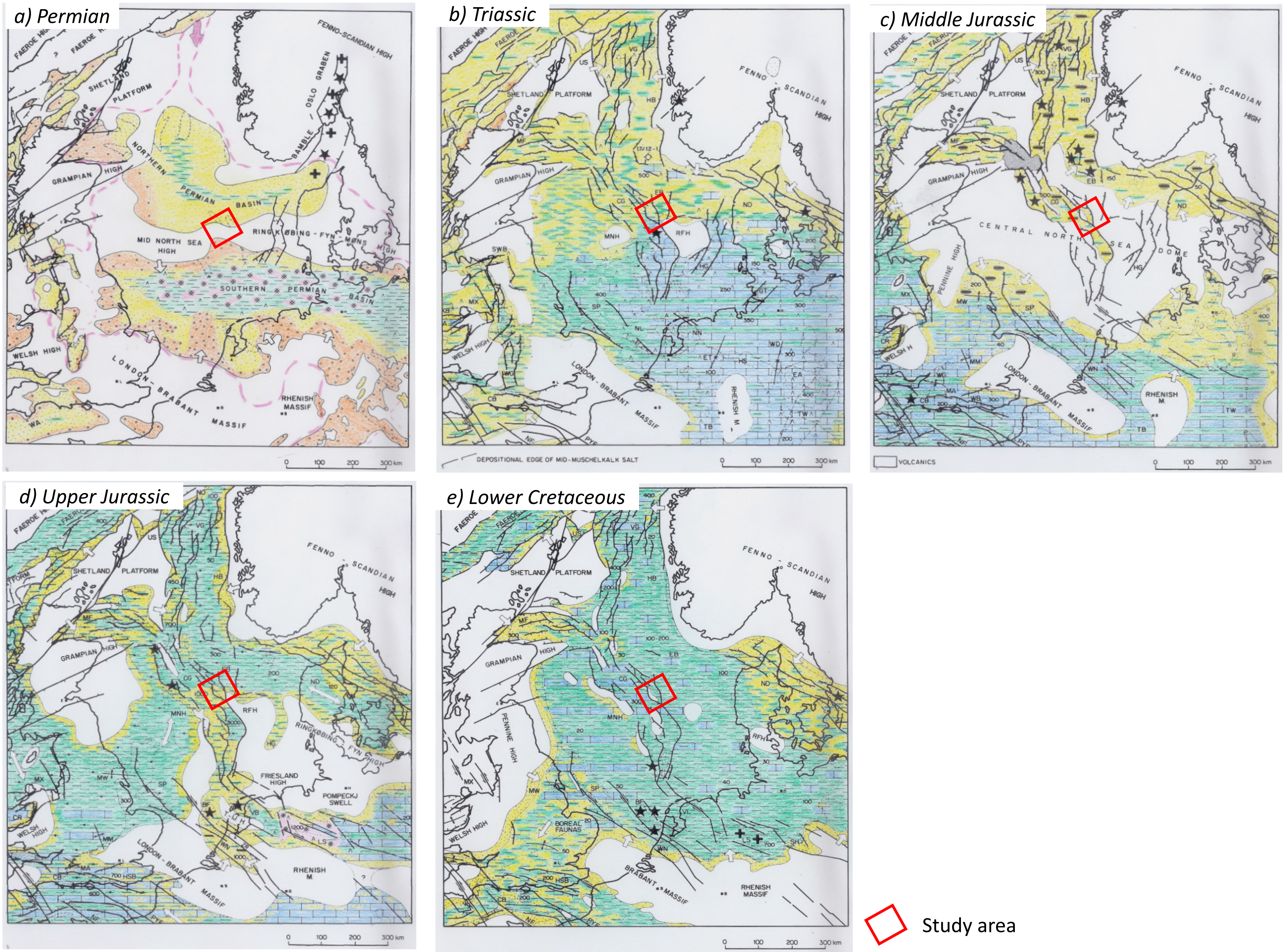

Figure 4a-e: Paleogeographic maps (modified from Ziegler 1990). a) Permian b) Triassic c) Middle Jurassic d) Upper Jurassic e) Lower Cretaceous

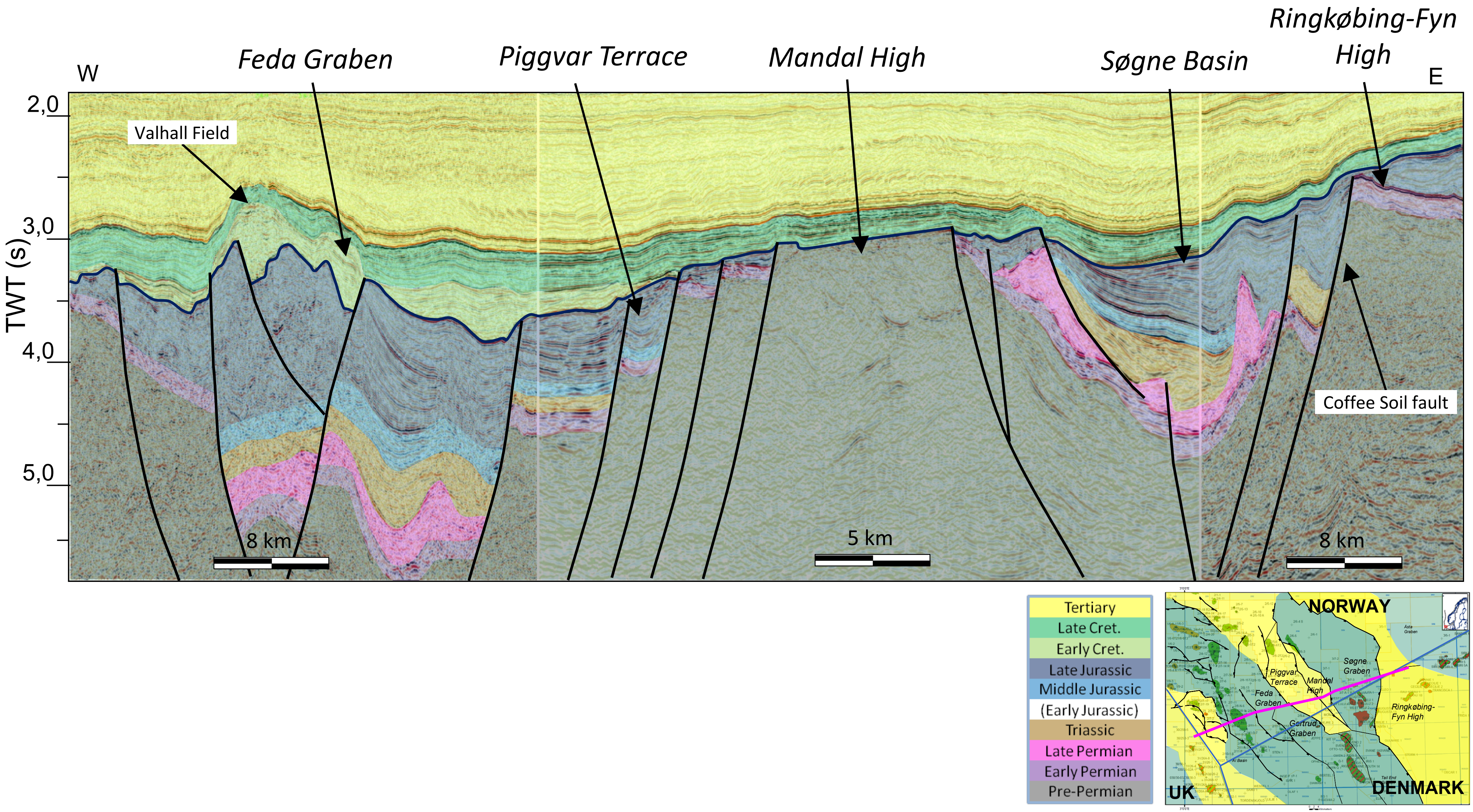

Figure 5: W-E Regional seismic-cross section across the southern North Sea, Norway.

Data and Methodology

A fast track of a 3D seismic cube acquired in 2010 and processed in 2011 was used for the seismic interpretation (CGR2010FT). The survey was shot by PGS for Nexen Exploration Norway, together with other companies, and covers a total area of 943 km^2. The outline of the survey is shown in figure 6. The data is sampled with the PGS GeoStreamer® technology.

Data details:

Sample Rate: 4,0 msec
Trace length: 7000 ms
Data type: Final full offset stack
Polarity: Zero phase, reverse polarity (trough=hard kick red , peak=soft kick on black)
Inlines: 1030-2655, 18,75 m bin size
Xlines: 2870-5350, 12,5 m bin size

Well log information from 8 Norwegian wells and 2 Danish wells were used (Table 1). Well data consists of well logs. For the Norwegian wells, well data sheets from the Norwegian Petroleum Directorate (NPD) providing geochemical information, stratigraphic tops and geological reports were used. The stratigraphic tops were QC'ed with interpretation and used as a basis for well correlations.

Well	**Year**	**TD (MD) [m]**	**Oldest rocks penetrated**	**Discovery**	**Reservoir**
2/6-3	1982	4060	Pre-Devonian	No	N/A
2/9-2	1979	4367	Early Permian	No	N/A
2/9-3	1989	4859	Early Permian	No	N/A
3/7-1	1973	3227	Pre-Devonian	No	N/A
3/7-2	1981	4330	Early Permian	No	N/A
3/7-3	1981	3540	Late Permian	No	N/A
3/7-4	1989	3723	Late Permian	Yes (G/Cond.)	Middle Jurassic sands
3/7-7	2008	3930	Late Jurassic	No	N/A
5604/21-02 (DK)	1983	4825	Early Permian	No	N/A
5604/21-05 (DK)	1985	3859	Triassic	Yes (O/G)	Middle Jurassic sands

Table 1: Well information

Time depth tables from all wells were available. They were used together with density and sonic logs to create synthetic seismograms. Different wavelets were applied to get the best match for the seismic. In most cases, a zero phase Ricker wavelet of 28 Hz and reverse polarity gave a good match. Otherwise, a wavelet was extracted from the seismic data close to the well using the SeisWell® application of Landmark's SynTool® suite. This was further matched with seismic to give improved time depth tables, with two strong seismic markers as reference picks; the top chalk and Base Cretaceous Unconformity events.

With the basis in the well-seismic correlation, conventional seismic interpretation of 7 chronostratigraphic sequences was carried out (Lower Permian, Upper Permian, Triassic, Middle Jurassic, Upper Jurassic, Lower Cretaceous and Upper Cretaceous (Fig 3)). The seismic quality was good to-excellent down to basement level across the study area. The extensive distribution of large salt structures provided a challenge for interpretation close to these structures, as in particular the flanks of salt bodies are hard to map. The interpretations made a basis for the seismic stratigraphy and sequences to define lap relationships and patterns. Two additional intervals; pre-Permian and the Tertiary are also mentioned, but are not the key focus of this study.

The interpretation of the horizons was carried out in intervals of every 20th line and trace using Landmark Openworks® software from Landmark Graphic Corporation (LGC). An interpolation tool was used to create structural maps, and by subtracting the structural maps, isochrone maps were created. Attributes such as edge detection, coherency and reflector amplitudes were used to identify subtle faults not visible on structural maps. To fully utilize the 3D seismic cube, time slices of key time intervals were interpreted and used in much the same manner as surface geological maps (Fig 7). This allowed for a detailed interpretation in between the seismic reflectors, possibly revealing a more detailed structural profile of the area. By doing this, structural features such as faults, dip directions of the reflectors and anticlines & synclines can be mapped.

Furthermore, the isochrone maps together with well logs and CPI logs provided a basis for a discussion on depositional environment and evolution of the different sequences in the study area. Net to gross ratios in paleogeographic maps are calculated by dividing an estimate of the net sand thickness divided by gross rock thickness.

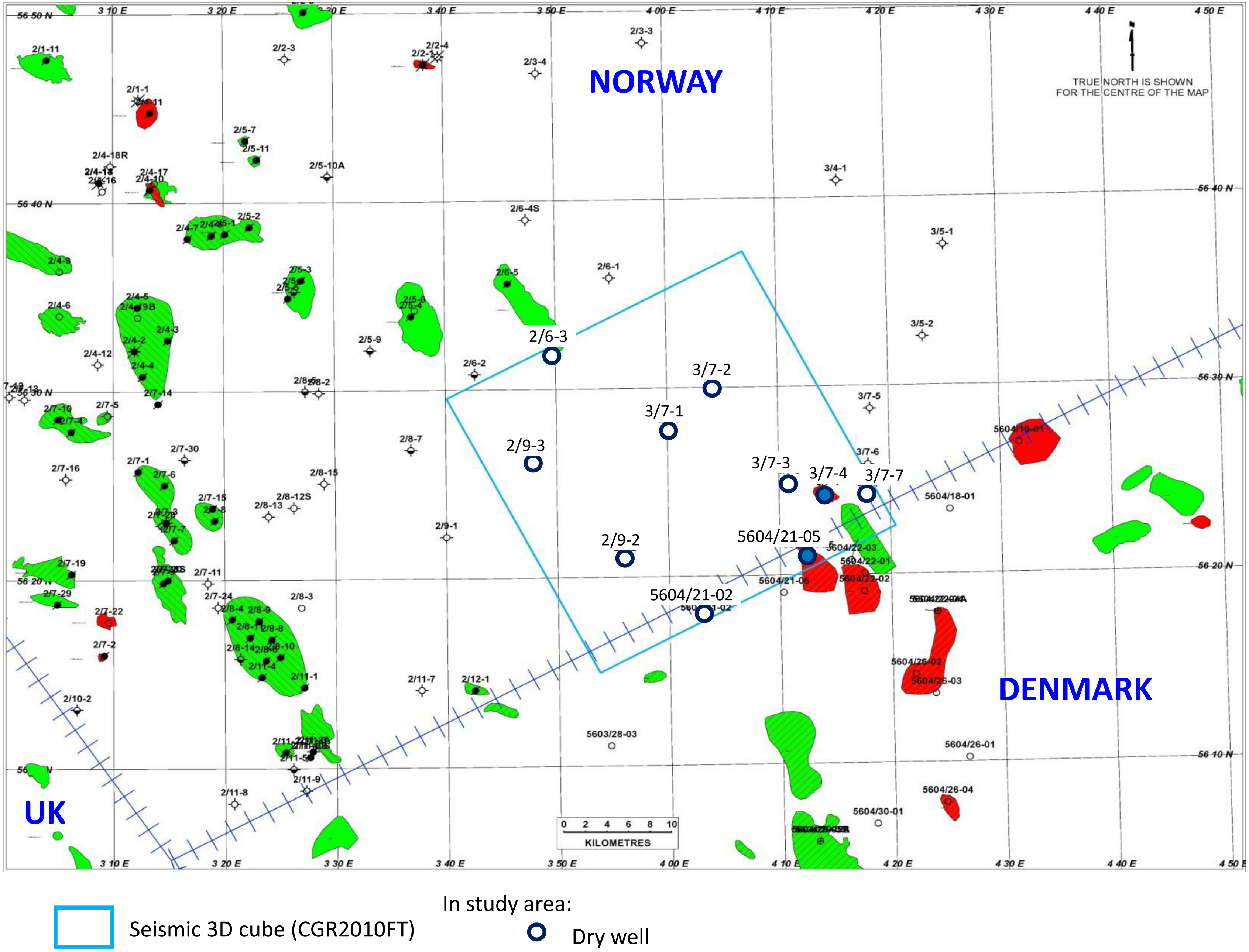

Figure 6: Outline of seismic survey CGR2010FT and key wells.

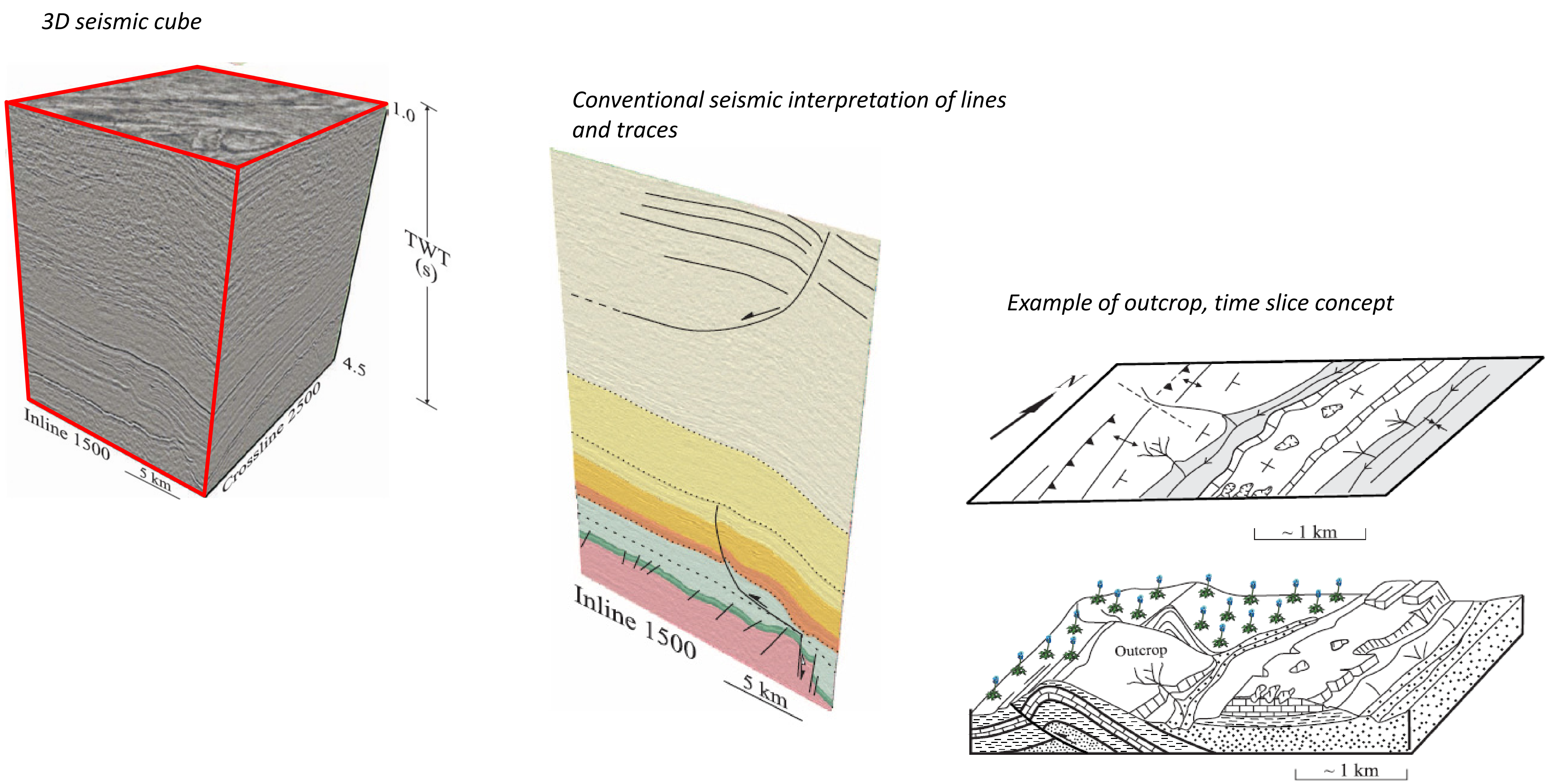

Figure 7: Methods of interpretation on a 3D cube used in the study (Castillo et al. 2006).

Observations

Stratigraphic framework

The stratigraphy of the study area, and terminology used in this study, is based on definitions of stratigraphic units made by previous authors, including Deegan & Scull (1977), Vollset & Dore (1984) and Isaksen and Tonstad (1988). The nomenclature established and compiled by these authors is broadly accepted and referred to as a fundamental stratigraphic overview. The seven key sequences are described below, followed by a description of the pre-Permian and Tertiary intervals. Lastly, three time slices are interpreted.

Sequence 1 - Lower Permian

Well character

The log character of the Lower Permian is highly variable in the study area. Volcanic sediments penetrated by several wells (2/9-2, 5604/21-02, 3/7-2) are usually observed in the logs by an increase in density and resistivity, and a decrease in the gamma ray, as opposed to the shales that often interbed the volcanics (Fig 8, 9). Sands are only visible in well 2/9-3, and have a low, clean gamma ray response and in general high resistivity readings probably caused by compaction. Lower density readings identify the sands from the volcanics, which can have similar gamma ray and resistivity values (Fig 9). Completion log descriptions of well 2/9-2 states the volcanics as being weathered, with abundant hematite, basaltic hornblende and rhyolite. A general trend in the area seems to be higher clastic input towards the north, with volcanics dominating towards the south.

Seismic character

The top of the Lower Permian is identified by strong increase in acoustic impedance, identified and correlated in several wells with synthetics as a trough (Fig 9, 10). The pick is considered to be of high confidence. The unit is widely distributed around the Mandal High, wrapping around the high itself. The base is considered to represent an increase in acoustic impedance upon entering the Pre-Permian basement, but confidence on the pick is lower, and only the 2/6-3 has penetrated through the Permian into the basement. Internally, the unit consists of several non-parallel, noisy and strong reflectors making internal configuration hard to identify (Fig 10). The interpretation is complicated by the formation of thick salt pillars on large faults, possibly causing pull-up effects of the seismic. However, faulting is still observed.

Structural configuration

The structural map of the Top Lower Permian is where most fault families can be studied, as the seismic resolution is high and imprints of all the latter tectonic events are interpreted (Fig 11A). It is the basis for definition of four fault families, chronologically numbered from 1-4. These normal faults have generally low throws and high dips.

- Fault family 1, a set of near N-S faults observed in the Søgne Basin, where the unit dips steeply, and along the boundary of the Mandal High (Fig 11A). In the isochrone map (Fig 11B), growth strata can be observed.

- Fault family 2, NE-SW oriented and present to the north-east part of the area in the Søgne Basin (Fig 11A). They appear as a cluster of faults downdip and crosscutting into a terrace observed on the structural map. Minor evidence of growth strata is also observed along these faults (Fig 11B).

- Fault family 3, near E-W oriented and located to the north-east part of the area in the Søgne Basin, downdip of the terrace (Fig 11A). A large W-E fault separating the northern and southern regime in the Søgne Basin is probably a part of this fault family. It develops out from the Mandal High, displacing the northern terrace from the steeper, southern terrace. It shows evidence of growth strata (Fig 11B). No significant growth strata are observed in other members of this fault family.

- Fault family 4, a set of NW-SE faults, developing on the Piggvar Terrace, with particular large displacements to the south-west of the study area (Fig 11A).

In general, the Top Lower Permian surface dips towards the Søgne Basin along the eastern flank of the Mandal High to the south-east (Fig 11A, 12, 13). To the north, a fault bounded terrace grows out from the Mandal High, before the sequence dips down into the Søgne Basin (Fig 11A). To the south, dips are much steeper and the top Lower Permian plunge into the deeper parts of the Søgne Graben (Fig 12). The sequence is faulted down from the Mandal High, and is juxtaposed against the basement along the boundary faults of the high itself (Fig 13). To the west of the Mandal High, a pronounced triangle shaped terrace is interpreted (Fig 11A, 13). It is bounded by the boundary fault of Mandal High to the east, a N-S fault to the west, and a NNW-SSE fault to the south. On the Piggvar Terrace, the unit is dipping gently to the SW, except in the south-west part of the area, where large displacements occur across faults (Fig 11A, 12). No difference in dip direction and angle is seen internally in parallel reflectors.

The unit shows relatively small variations in thickness across the study area. In general however, the unit is thicker and more developed in the Søgne Basin, east of Mandal High, compared to the west (Fig 12-14). The sequence shows no evidence of thinning up towards the Mandal High itself, with minor thickening towards the far south-east corner of the study area, into the basinal areas. At the terrace on seismic inline 2050, the unit is considerably thin (Fig 13).

To the southern and northern edges of the Mandal High, the unit is truncating and eroded by the BCU reflector (Fig 12).

Sequence 2 - Upper Permian (Salt)

Well character

Well 3/7-2 penetrates a thick body of salt (Fig 8). Gamma ray log character is highly dependent on the mineral composition. Halite gives a low response, while potassium salt gives a high response. In well 3/7-2, a block of potassium gives a drastic increase and subsequent decrease in gamma ray log response. Furthermore, the evaporites show a decrease in travel time, decrease in density and increase in resistivity compared to above layers (Fig 15). Due to the mobilization and internal deformation of the salt, little information can be derived from log interpretation.

Seismic character

The top salt is picked on a trough, representing a general increase in acoustic impedance, seen in synthetics and seismic (Fig 10, 15). Interpretation shows a variety of salt structures formed by salt mobilization and withdrawal. On top of the structures, the seismic reflector gives a strong response (Fig 10), while the same amplitude strength is not seen in the pods (Fig 14). The flanks of the salt bodies are often poorly imaged on seismic data due to the steep dip of the structures, making interpretation difficult and speculative. Pick confidence ranges from high to low. A possible polarity reversal may occur between pods and intrapods, due to the large variation of overlying sediments, but interpretation is maintained on a trough for continuity. Internal reflector nature of the Zechstein salt is chaotic, with random layering seen in certain areas, possibly due to sediment blocks suspended and floating in the salt (Fig 10).

Structural configuration

The structural map of the top Zechstein salt surface maps out the salt as being present only in the Søgne Basin (Fig 16A). The previously defined faults of fault families 1-4 are not seen, although salt structures seem to develop on these (Fig 12-14). In particular, salt bodies seem to form on faults of fault families 1-3. Clear structures are observed (Fig 16A-B). To the south, a thin salt wall can be seen, curving in towards Mandal High in a SSE-NNW trend similar to the high. It shows little or no deformation on sequences above the Upper Jurassic (Fig 14, 16B). When it reaches the previously defined W-E fault seen in Lower Permian intervals, it splits, moves away from the Mandal High towards the NE, before curving back up again towards the NW (Fig 16B). The middle diapir in figure 14 is small compared to other structures, and later rocks seem to slide along the salt body itself, controlled by a listric fault developing on the salt flank. This diapir is developed on top of the W-E fault. A large diapir is formed along the SSE-NNW trend, drilled by well 3/7-2 and deforms layers up into the Tertiary (Fig 10).

To the south-east, the unit dips steeply further into the Søgne Basin, while in the northern regime, contours are more flat (Fig 16A). Synclines are seen to the north and south of the W-E fault, and form major depocenters caused by salt withdrawal into the observed salt structures. In the depocenters, the salt is observed to be very thin (Fig 16A).

Sequence 3 - Triassic

Well character

The well character of the penetrated intervals in the wells show medium stable, high gamma ray readings, consistent with shales (Fig 8, 9). Furthermore, descriptions of cuttings and cores from well reports (NPD) identify sub-aerially exposed shales of brown-red colours. No sandstones are identified in the wells (Fig 8).

Seismic character

The Triassic is tied with synthetics and is picked on a trough, representing a general increase in acoustic impedance (Fig 9, 10). The impedance contrast between the Triassic and Middle Jurassic makes the pick confident to the east of Mandal High. To the west, thin units and weak contrasts complicates the interpretation (Fig 10). Internal layering is observed in the Søgne Basin, including cross-bedded reflectors, channel geometries and shift in depositional direction (Fig 12). In the Søgne

Basin, the pick is of high confidence, on the Piggvar Terrace the unit is thinner, and pick is of low confidence.

Structural configuration
The scattered distribution of sequence 3 can be seen on a structural map (Fig 17A). To the west, a few faults of fault family 4 can be seen. In the Søgne Graben, faults of a different fault family are observed. They belong to a new fault family; fault family 5.

- Fault family 5, seen developing on salt structures. They have various orientations.

To the west of the high, the sequence is more or less flat lying on the Piggvar Terrace (Fig 17A). Distribution seems to concentrate in the north-western part of the terrace. In the Søgne Basin, the unit is seen dipping in towards the southern and north depocenter, and to the far south plunging into the Søgne Basin (Fig 17A). Over salt structures, the sequence is absent, except across the salt diapir drilled by well 3/7-2, where the sequence is present although thin (Fig 17B). Sediments onlap the salt structures (Fig 13, 14). The isochrone map (Fig 17B) show in general that sequence 3 is thin on the Piggvar Terrace. In the northern regime in the Søgne Basin, the sequence is relatively thin where present, with a thickening to the NE of the curved salt wall. To the south, the sequence is massive towards the south-east corner, east of the salt structures (Fig 12). The sequence is thicker in the southern depocenter compared to the northern one (Fig 17B).

Sequence 4 - Middle Jurassic

Well character
Complete well sections of the Middle Jurassic are not found in the study area. However, a general trend seems to be coarsening upwards of the gamma log (Fig 8, 15). Coal stringers are normal, particularly in the well 5604/21-05. They are identified by a significant drop in density and interval travel time, and an increase in resistivity. The coal layers are not more than a few meters thick. Otherwise, the unit takes on a highly heterogeneous shaly sand signature in logs, reflecting the interplay of shallow marine and deltaic facies (Fig 8).

Seismic character
An increase in acoustic impedance is observed in synthetic seismograms, and correlated with penetrating wells (Fig 9, 10). The horizon is picked on a strong trough, picked and correlated with high confidence in the Søgne Basin (Fig 10). In the Piggvar Terrace, the reflector is more dimmed, and is of low confidence. The top of the unit is normally correlated by the entrance of Middle Jurassic sands from Upper Jurassic shales, giving rise to the amplitude response (Fig 9, 15). To the west of Mandal High, the unit is thin, and seismic interpretation is of low confidence as no clear seismic marker is seen. Internally, reflectors are semi-parallel, and the complex internal structure seen in the Triassic sequence is not observed here (Fig 12, 14).

Structural configuration
In the structure and isochrone map, several faults are seen (Fig 18A, B). In the Piggvar Terrace, these are interpreted to belong to fault family 4. They show no evidence of growth strata. In the Søgne Basin, the faults follow closely the salt structures, and belong to fault family 5.

Middle Jurassic sediments are in general flat and thin on Piggvar Terrace, with low dip, except on rotated fault blocks (Fig 12). In the Søgne Basin, the distribution of the sequence is heavily controlled by salt structures, with onlaps on the structures, or thinning above (Fig 14). The relief of the northern depocenter in the Søgne Basin is observed. The southern depocenter is not clearly defined, a continuous dip towards the east is seen in this area (Fig 18A, B). In the Søgne Basin, the sequence thickens in the northern depocenter, and towards the south-east of the basin (Fig 18B). It is flanking up towards the Mandal High, flooding more of the study area than sediments of the Triassic. The unit is onlapping the Triassic sequence in figure 14, towards the north.

Sequence 5 - Upper Jurassic

Well character
The high value gamma ray often underlying the Base Cretaceous Unconformity (called BCU) is not observed in the study area (Fig 8). The top Upper Jurassic is however marked by a strong increase in gamma ray values and a decrease in density and velocity logs upon entering shales from the overlying chalky units (Fig 9, 15). To the west, on the Piggvar Terrace, the unit has significant thickness, and pulses of regression and transgression are interpreted on gamma logs, together with thin sand stringers (Fig 8, 9). Well reports state presence of minerals helping to restrain depositional environment (NPD). Some intervals have pyritic presence, indications of low energy marine environments. Other intervals have glauconite, indicating marine conditions with water levels no more than 200 m.

Seismic character
The top of the Upper Jurassic, when present, is interpreted on the diachronous surface the BCU (Fig 10). Throughout the study area, this surface gives a strong negative response correlated on a peak moving from fast velocity chalk to lower velocity shales of the Upper Jurassic (Fig 9-10, 15). The surface is a regional unconformity and a pick of high confidence across the area. The BCU was used as a reference surface when synthetic seismograms were created and correlated with seismic (Fig 9, 15). The Upper Jurassic sequence is interpreted to be present over the entire study area, except on top of the structural relief of the Mandal High (Fig 10). Internally, the unit consists of parallel reflectors, truncations against the BCU and unconformities (Fig 10, 12-14). In certain areas, in particular to the southeast and northeast area towards the Mandal High, the unit is chaotic internally (Fig 12, 14).

Structural configuration
The correlating surface for sequence 4 is the BCU, and represents the top of the Upper Jurassic except on the Mandal High. The relief of the Mandal High stands out as a structural high point in the map, and reveals the structure of the basement high (Fig 19A). In the structure map, we see the faults of fault family 4. Furthermore, faults of fault family 5 relating to salt mobilization is seen over and along the flanks of salt structures, developing growth strata. The boundary faults of the Mandal High are also assumed observed at this level.

On the Piggvar Terrace, the sequence is observed to develop heavy syn-rift sedimentation on faults of fault family 4, creating large thickness variations (Fig 19B). This is particularly visible to the south-west corner, where fault blocks are tilted (Fig 12). In the Søgne Basin, sediments fill the northern and southern depocenters (Fig 15). Internal reflectors onlap towards the south in the northern depocenter, opposite of the Middle Jurassic northwards onlap on the Triassic. Adversely, the unit thin over the diapirs, and develops more thickness down towards the Søgne Basin to the south-east (Fig 19B). Towards the Mandal High, Upper Jurassic wedges are either juxtaposed and downfaulted to the basement, or pinching out (Fig 12, 13). The BCU erodes into the Upper Jurassic, particularly in the Søgne Basin, where salt movement seems to have deformed and uplifted layers, causing truncation against the BCU (Fig 14). The unit is thin across the previously defined triangle shaped terrace to the west (Fig 19B). A sub-basin seems to develop south of the triangle shaped terrace. On Piggvar Terrace, the unit shows growth strata along the boundary of the Mandal High, while it pinches out towards the Mandal High in the Søgne Basin. The Mandal High dips gently to the south-west (Fig 19A).

Sequence 6 - Lower Cretaceous

Well character

The top is normally indicated by an increase in gamma ray log values upon leaving the chalk sequence (Fig 8). Gamma ray response is largely controlled by the amount of limestone present; with lower values indicating more calcareous material, and higher values indicating clastic dominated intervals. Density and velocity is low compared to the overlying chalk (Fig 9, 15).

Seismic character

The sequence is correlated on synthetic seismic to correspond to a drop in acoustic impedance, resulting in a negative response on seismic, interpreted on a peak (Fig 9, 15). The pick is of relatively high confidence, because, where present, it corresponds to the base chalk surface. To the east however, the unit is occasionally so thin that it only corresponds to a single loop on the seismic, making interpretation more challenging. The internal structure consists of clear parallel layers where the sequence takes on considerably thickness (Fig 12).

Structural configuration

The structure and isochrone map reveals two visible fault families at this level; fault family 4 and 5 (Fig 20A, B). Growth strata develops along faults of fault family 4. In the south-west corner of the study area, they are reactivated and seen to create large inversion structures (Fig 12).

The salt bodies and associated faults seem to control the structural dip of the sequence in the Søgne Basin. The unit dip towards the deepest point of the depocenters, and away from the salt bodies (Fig 20A). It is deposited in re-entrants in towards the Mandal High, overlying Upper Jurassic sediments within one or two seismic loops (Fig 14, 20B). The unit is very thin, and is deposited irregularly. A gentle thickening across the northern depocenter is seen. In the Piggvar Terrace, the formation gently dips towards the W-SW, and thins up towards the Mandal High (Fig 20A). Faults of fault family 4 seems to be an important structural control on the dips to the south-west of the area, where the unit steepens near the hanging wall (Fig 20A). Possible marine incursions are observed springing out from the Mandal High towards the west (Fig 20B).

Sequence 7 - Upper Cretaceous

Well character

Generally, the chalk formations have a consistent, homogenous, low gamma ray response (Fig 8). Velocity logs show fast velocities and high density (Fig 9, 15). The top and base of the chalk is easily identified by a strong increase in gamma log response. From well reports of well 3/7-1, the chalk is reported to be tight on top of the Mandal High (NPD).

Seismic character

In the synthetic seismograms, the top of this sequence is identified by a sharp increase in acoustic impedance upon entering the chalk layers (Fig 9, 15). This is correlated with a strong amplitude contrast picked on a trough on seismic (Fig 10). The sequence is deposited regionally across the study area, and the pick is of high confidence throughout the dataset due to the strong response. Internally, the sequence consists of high amplitude parallel reflectors. Little internal sedimentary structure is seen, reflecting the pelagic open water depositional conditions. Local thickness variations are seen across structural highs, salt structures and inverted structures (Fig 10).

Structural configuration

Sequence 7 is seen on the structure map to be deposited regionally (Fig 21A). The first flooding of the Mandal High is observed, as the sequence deposits across the high. Faults associated with fault family 5 develop all along the salt trend, faulting the brittle chalk layers of this sequence. Faults associated with the Mandal High boundary faults are also seen at this level (Fig 21A).

Dip directions on Piggvar Terrace are towards the basinal areas of the Central Graben (Fig 13, 21A). A clear relief is observed where the Mandal High is located, together with the triangle shaped terrace. In the Søgne Basin, the structure of the salt wall can be seen. In particular, the diapir where well 3/7-2 is located, deforms and uplift this sequence (Fig 21A). Synclines associated with the two depocenters are seen. Sequence 7 is thinning on structurally elevated areas like the Mandal High, salt structures and inverted structures (Fig 12-14, 21B). In general, the unit is thinner in the Søgne Basin as opposed to the Piggvar Terrace . A sub-basin can be seen to the south of the study area, where the sequence seems to thicken significantly.

Pre Permian

Well character

Two wells, 2/6-3 and 3/7-1, have drilled into the crystalline basement of the Mandal High. The gamma ray values of this interval are in general high and spiky (Fig 8). In the geological completion report of well 2/6-3, drilled on the north-western flank of the high, the pre-Permian interval is thoroughly described (Minsaas 1984). A layer of foliated shale with muscovite, free quartz and red shale to clay is identified between the Permian sediments and the "true" metamorphic basement. Small scale foliations in phyllites have a ENE-WSW structural orientation. In well 3/7-1, core description from well reports tells of lithology comprising foliated gneiss, with numerous vertical fractures of chloritic infill (Minsaas 1984).

Seismic character
The top basement usually gives high velocities upon entering metamorphic rocks. However, no confident tie is made in the two well penetrating the basement. Top basement is therefore picked where Lower Permian high amplitude layers cease to exist, and internal reflectors become chaotic (Fig 10). This transition is usually marked by a clear trough event in the basins around the Mandal High. This reflector has low frequency, and is considered to be of low confidence. On the Mandal High, the same response is not observed (Fig13). A polarity reversal is possible due to the overlying high velocity compacted chalk group.

Structural configuration
Some internal, non-continuous basement structures is observed in the seismic sections (Fig 10, 13). Otherwise, this sequence displays little observable geometrical features. Basement faults in the Mandal High are observed. The crystalline basement of the Mandal High is appears as a fault bounded, horst-like structure in seismic sections. The boundary faults are nearly vertical, and can be seen deep into the basement (Fig 13). In the Søgne Basin, the basement dips steeply towards the east, and pull-ups is observed underlying salt structures (Fig 12). On Figure 14, a slight southward dip is also observed, with minor fault block rotation.

Tertiary
The Tertiary sequence has not been studied in detail for this thesis. However, from sections it is observed that the Tertiary is characterized by thick sediment infill across the study area. Reflectors are parallel, and internal reflectors are common (Fig 10, 12-14). The dip of the reflectors seem to follow the structural relief below. In particular, the relief of salt pods and intrapods are visible, with some salt structures deforming Tertiary strata (Fig 13, 14). Across the Mandal High, the sequence is uplifted slightly, before dipping down into the Søgne Basin and Piggvar Terrace (Fig 10, 10). No major faults are observed, however, faults of fault family 5 occasionally goes up into the Tertiary interval. A set of minor, polygonal faults are observed, but not interpreted.

Time slices

3200ms
On this time slice, we observe that the basement level covers large parts of the area (Fig 22). Lower Permian sediments are seen on either side of the high. In the Piggvar Terrace, Upper Jurassic sediments are seen in syn-rift packages. As the rocks dip down towards the west, we see Lower Cretaceous sediments. The incised valley structures observed earlier are clearly seen. In the Søgne Basin, the geometry of the salt structures at this level is revealed. Triassic sediments are seen on the flanks of the salt, before we enter the Jurassic interval in the four depocenters seen. On the Piggvar Terrace, we observe faults of fault family 4, in addition to the large, undefined NE-SW trending fault. To the east of the basement, faults of fault family 1 can be seen at Permian level. Faults of fault family 5 are visible in younger intervals.

3020ms

A time slice at 3020 ms reveals the structure of the Mandal High itself (Fig 23). The 3D horizon interpretation of the top salt can be seen cross-cutting the time slice in red at well 3/7-2. The structure of the Mandal High stands out as an s-shape. At this level, Upper Cretaceous chalk develops out from the high. Internal structure of the high is clearly visible. By looking at vertical sections, internal deformations and low-angle faults are seen (Fig 13). They are deep basement faults, terminating against the BCU reflector. In the time slice, the lineaments of these faults can be observed and interpreted, with the strike of the faults concentrating in two directions; near N-S and NE-SW. Jurassic sediments are squeezed up against the flanks of the fault, creating depositional and structural trends for these sequences. The geometry of an inverted structure and the two depocenters can be observed. The earlier defined W-E fault separating the Søgne Basin into two regimes is present on the Mandal High as well (Fig 11A, 23). The fault seems to create a displacement in the salt structures and subsequently the orientation of the sequences around the salt.

2800ms

In this time slice, we observe that most of the area cut through Tertiary sediments, and the previously mentioned polygonal fault pattern is seen on the Piggvar Terrace (Fig 24). Upper Cretaceous sediments are present at this level on top of uplifted structural reliefs such as the Mandal High and the salt structures to the east. The Mandal High dips to the south-west. Faults of fault family 5 are observed in sequence 7. In addition, the reliefs of the two depocenters stand out from syncline structures, even up to the Tertiary interval.

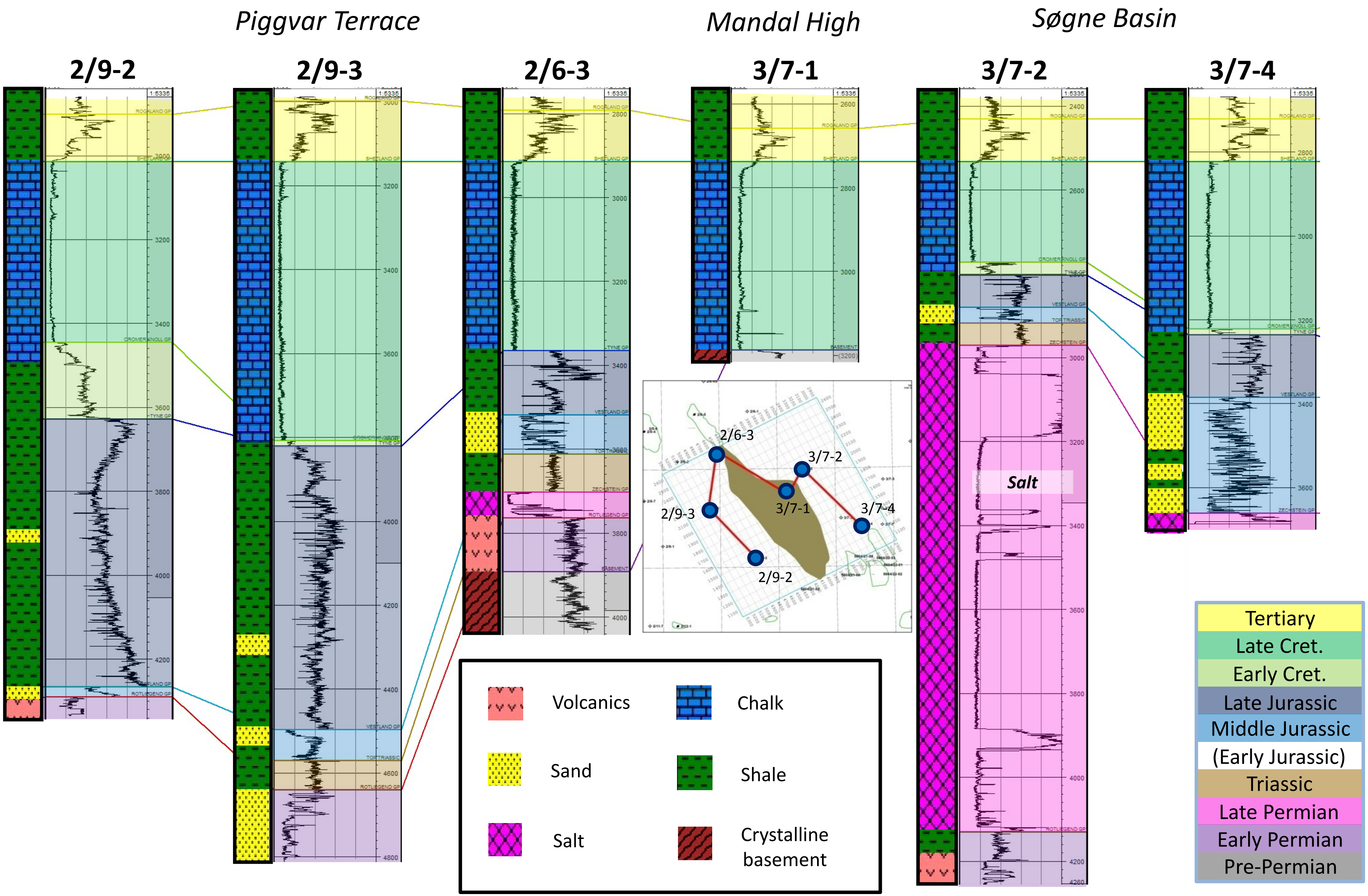

Figure 8: Well correlation diagram across the study area, with GR log, lithostratigraphy and chronostratigraphy displayed.

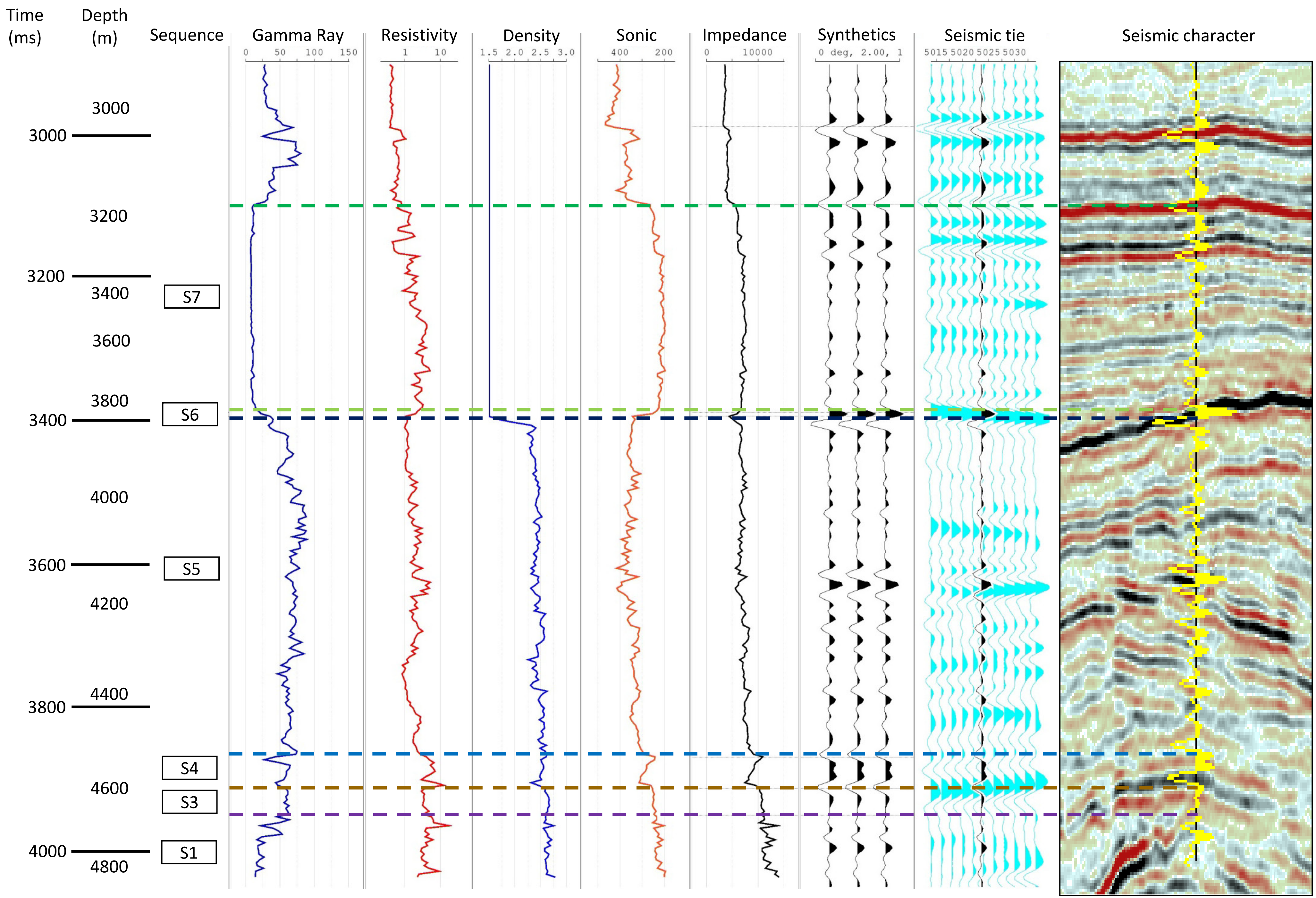

Figure 9: Logs, synthetics and seismic characters of well 2/9-3.

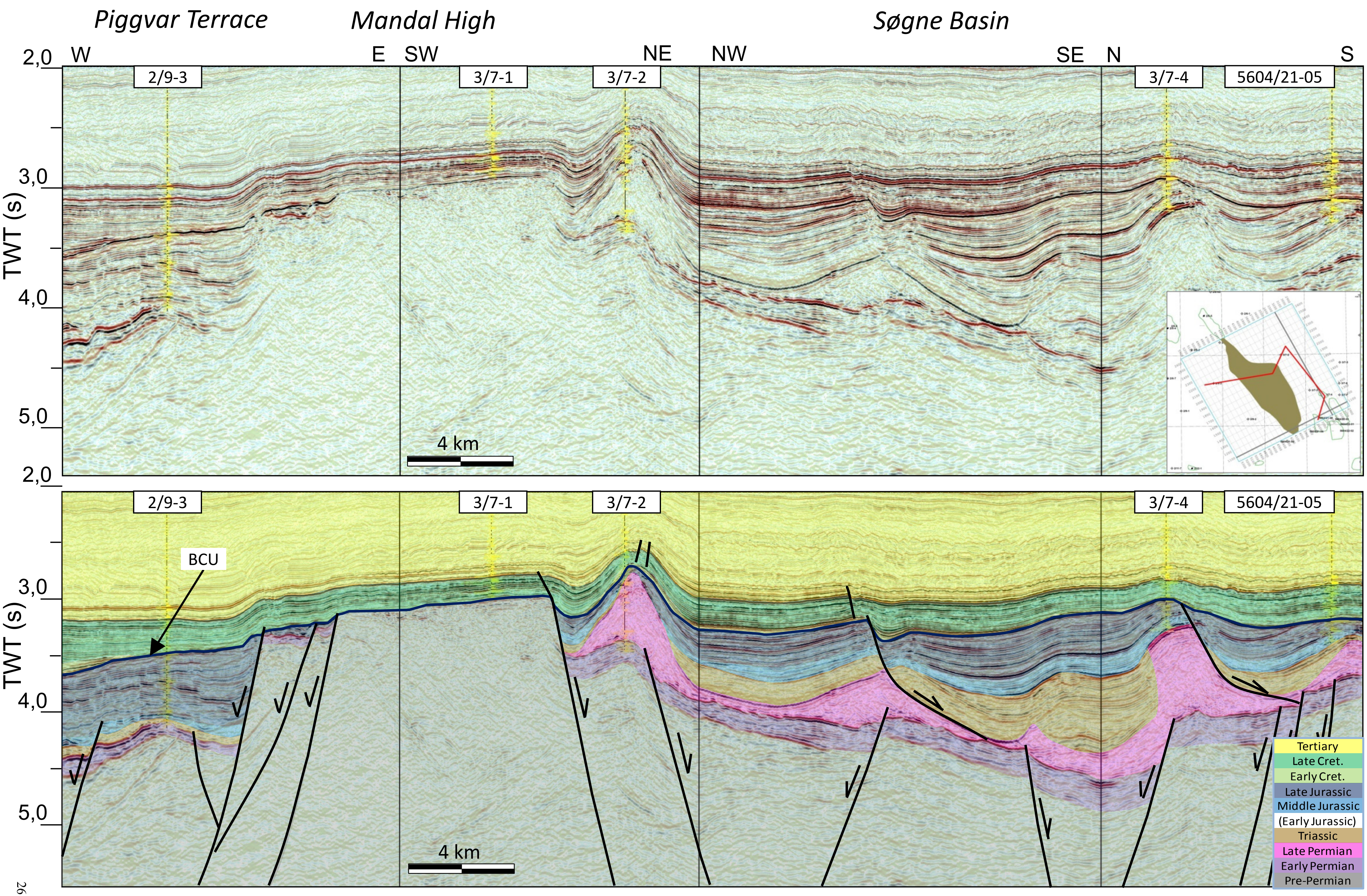

Figure 10: Seismic cross-section across the study area, with and without interpretation.

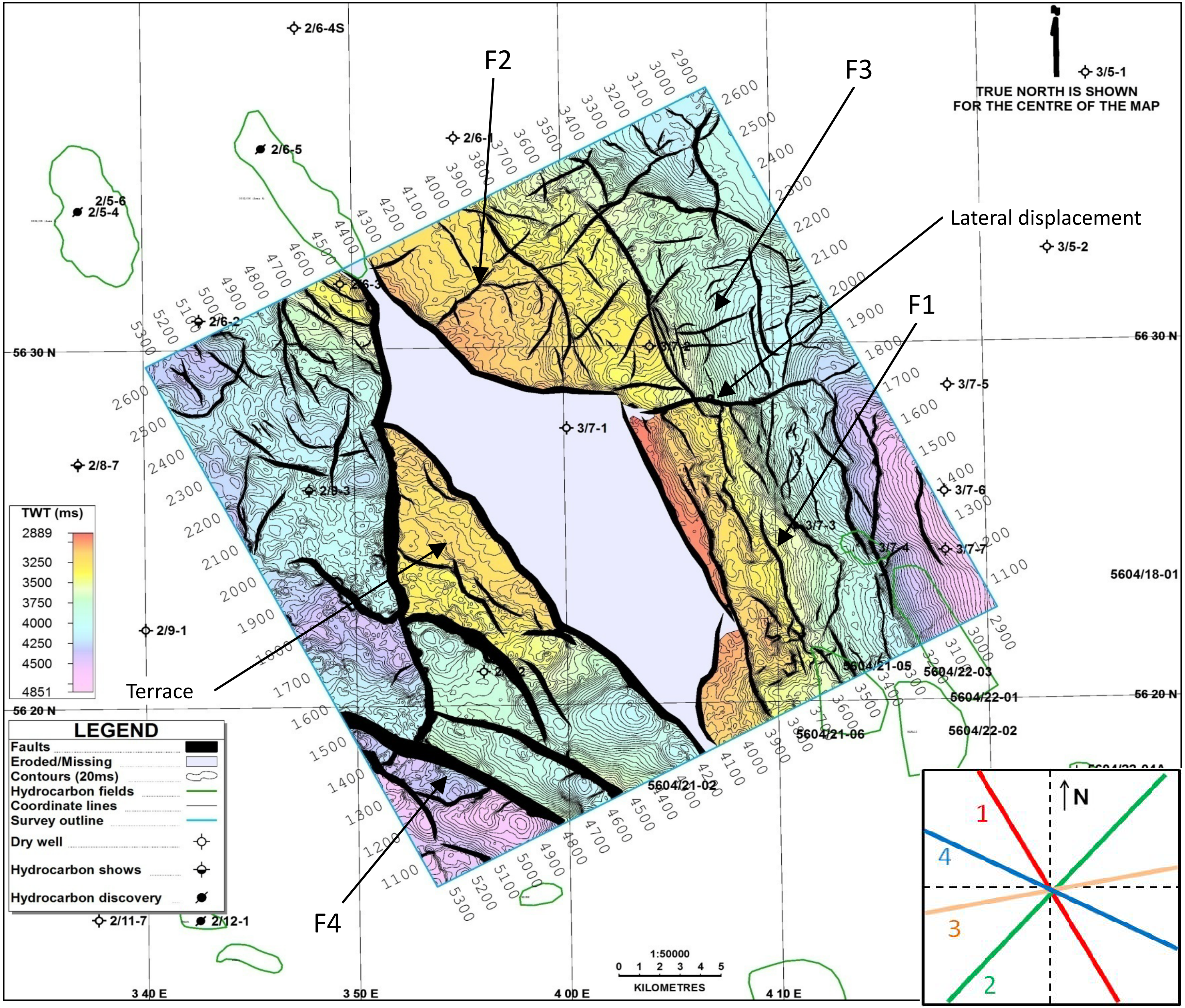

Figure 11A: Structural time map (TWT) of Top Lower Permian (sequence 1), with fault families 1-4 defined.

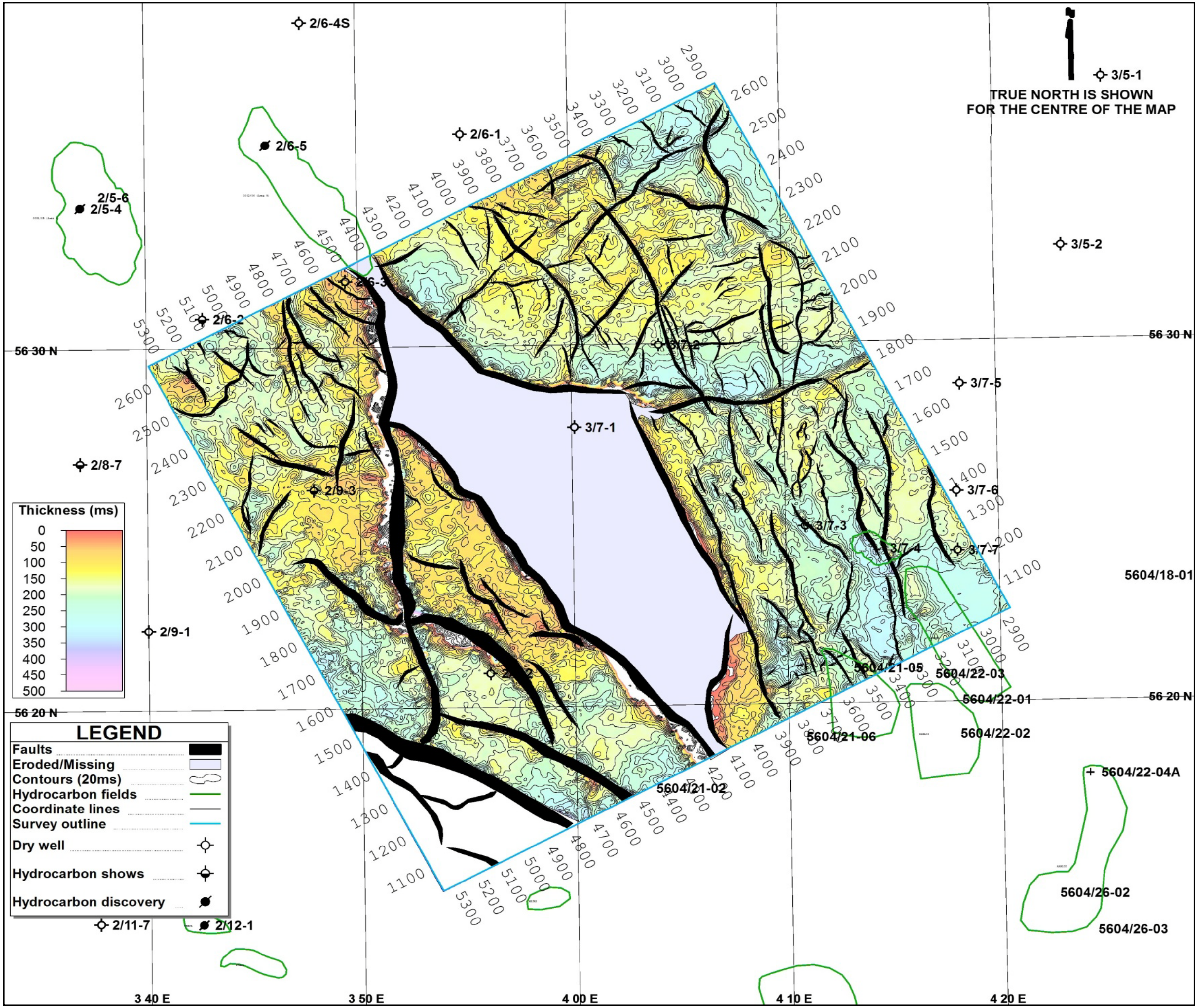

Figure 11B: Isochrone map (TWT) of Lower Permian (sequence 1).

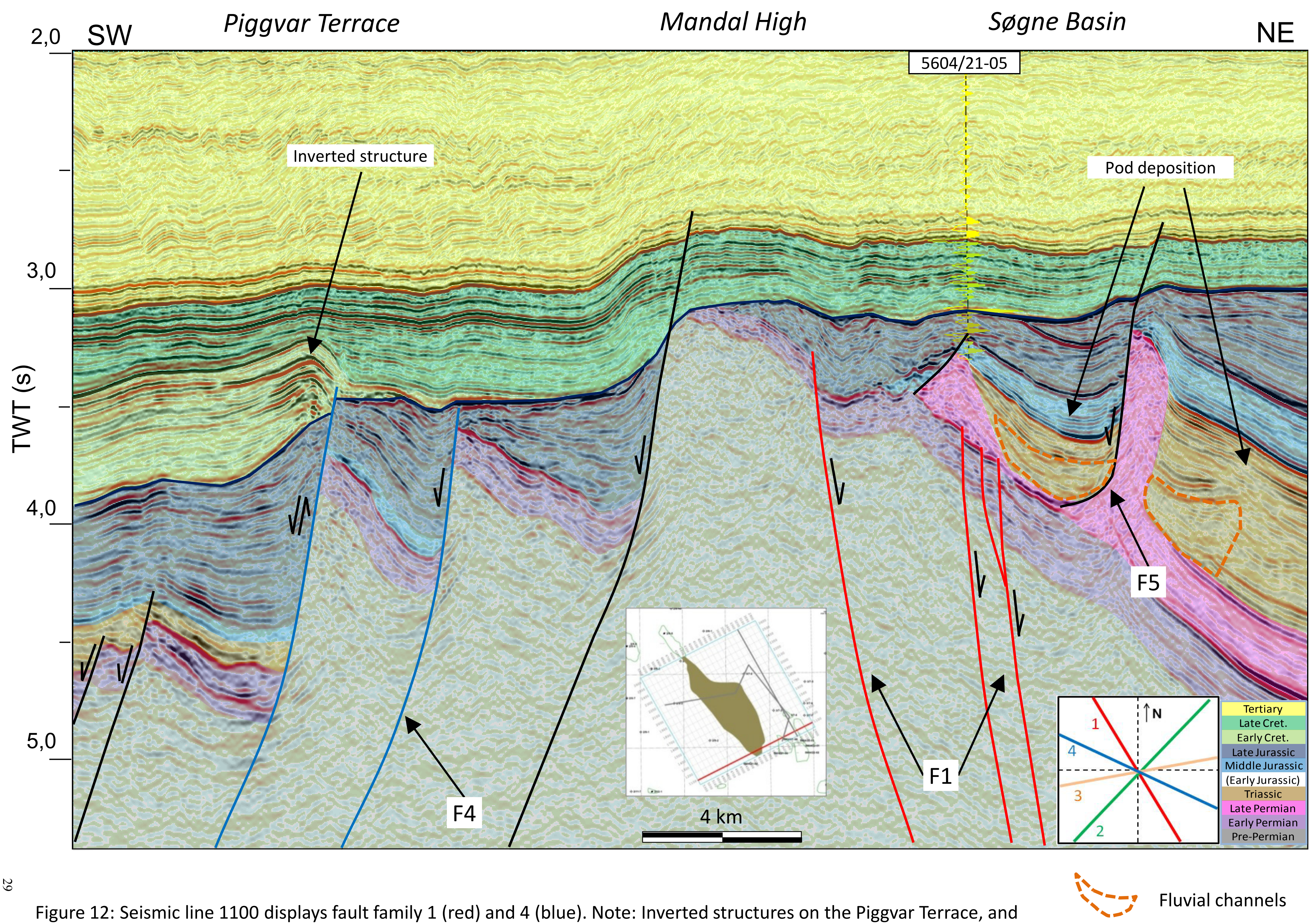

Figure 12: Seismic line 1100 displays fault family 1 (red) and 4 (blue). Note: Inverted structures on the Piggvar Terrace, and pod deposits in the Triassic and Middle Jurassic in the Søgne Graben.

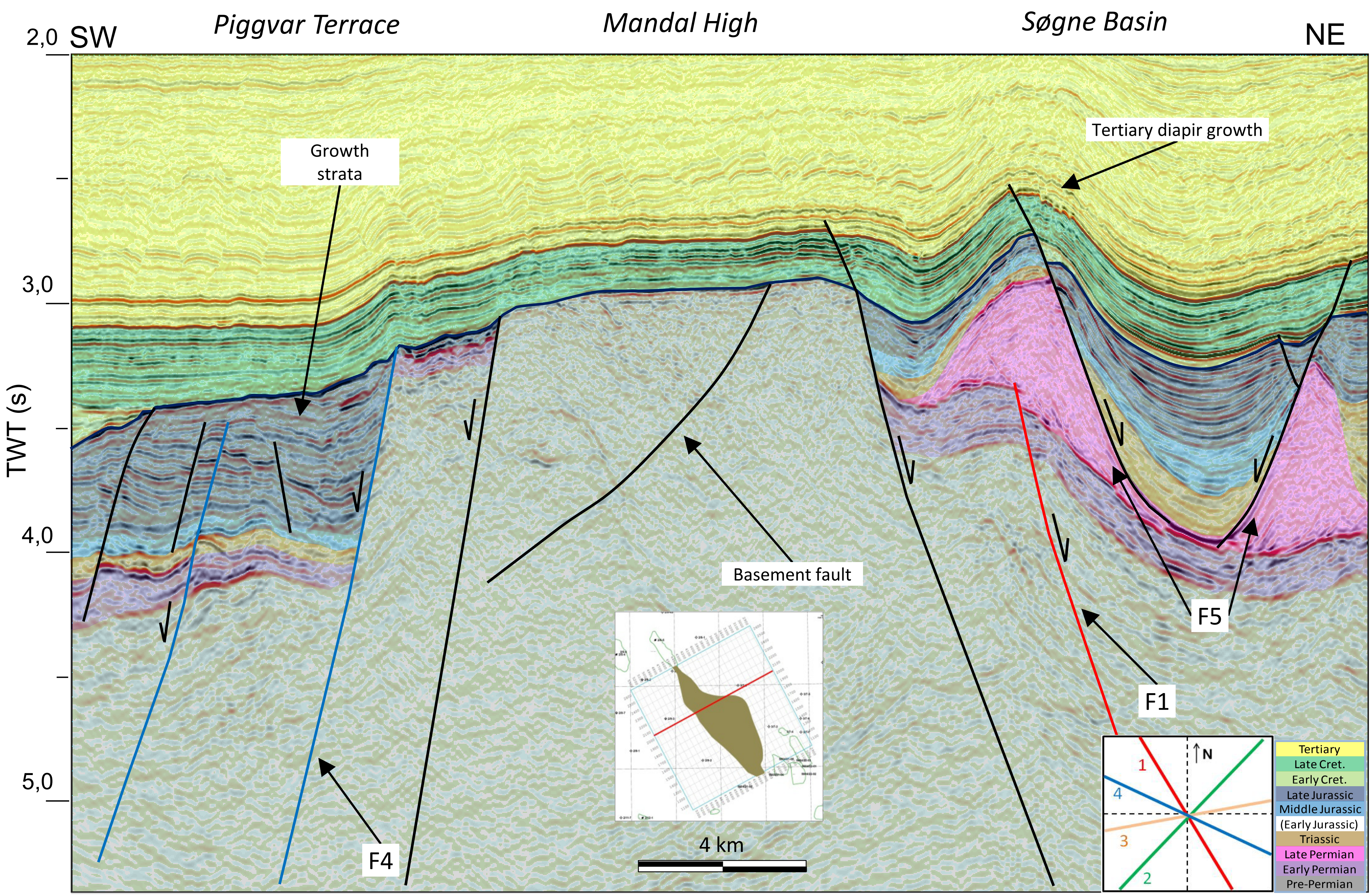

Figure 13: Seismic line 2050 displays fault family 1 (red), fault family 2 (blue) and fault family 5. Note: Growth strata of the Upper Jurassic, Tertiary salt diapir growth and basement faulting.

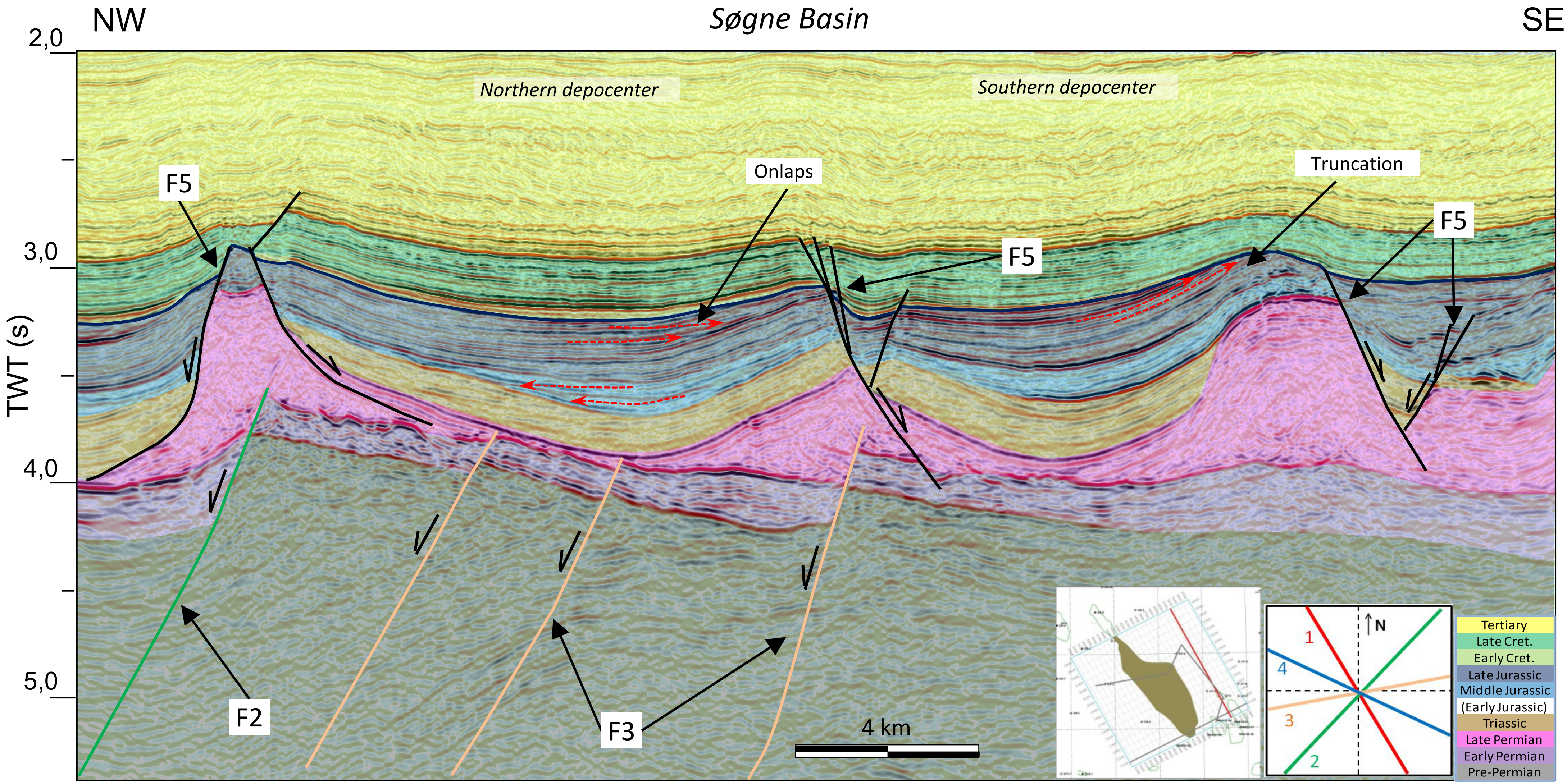

Figure 14: Seismic trace 3250 displays fault family 2 (green), fault family 3 (beige) and fault family 5. Note: Northern and southern depocenter, onlaps in the northern depocenter and truncation of internal Upper Jurassic towards the BCU to the South-East.

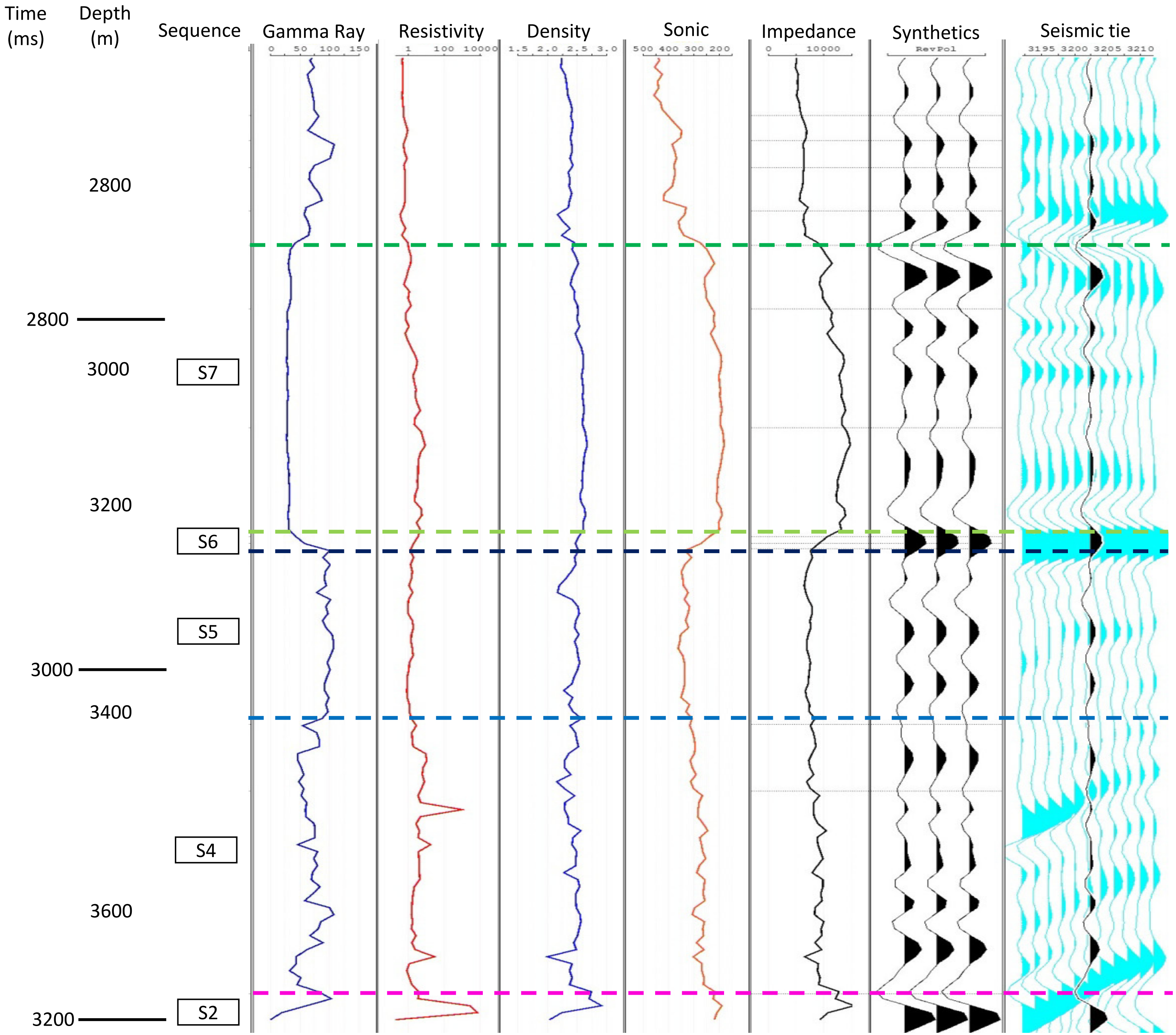

Figure 15: Logs and synthetics of well 3/7-4.

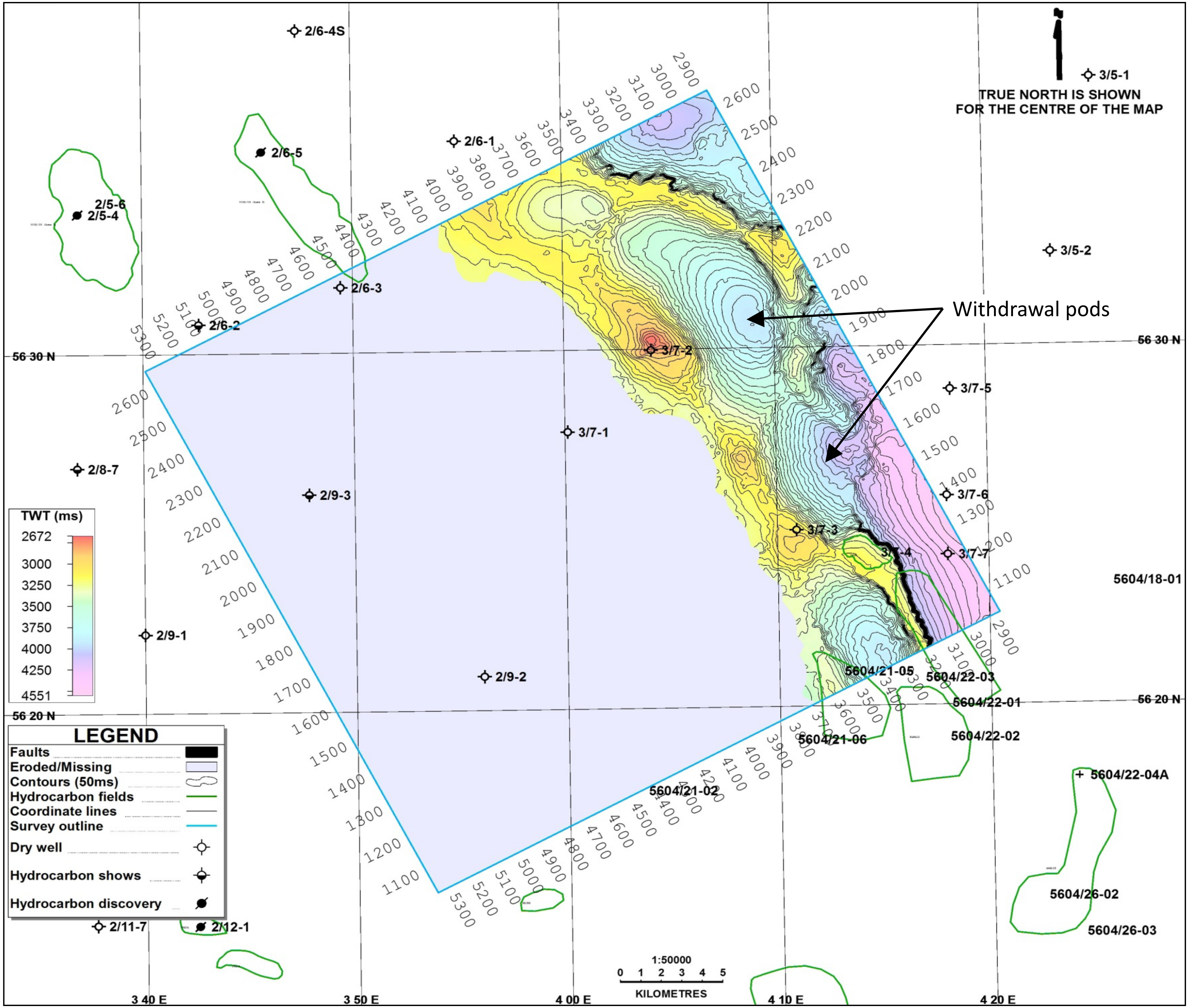

Figure 16A: Structural time map (TWT) of Top Upper Permian salt (sequence 2), with withdrawal pods marked.

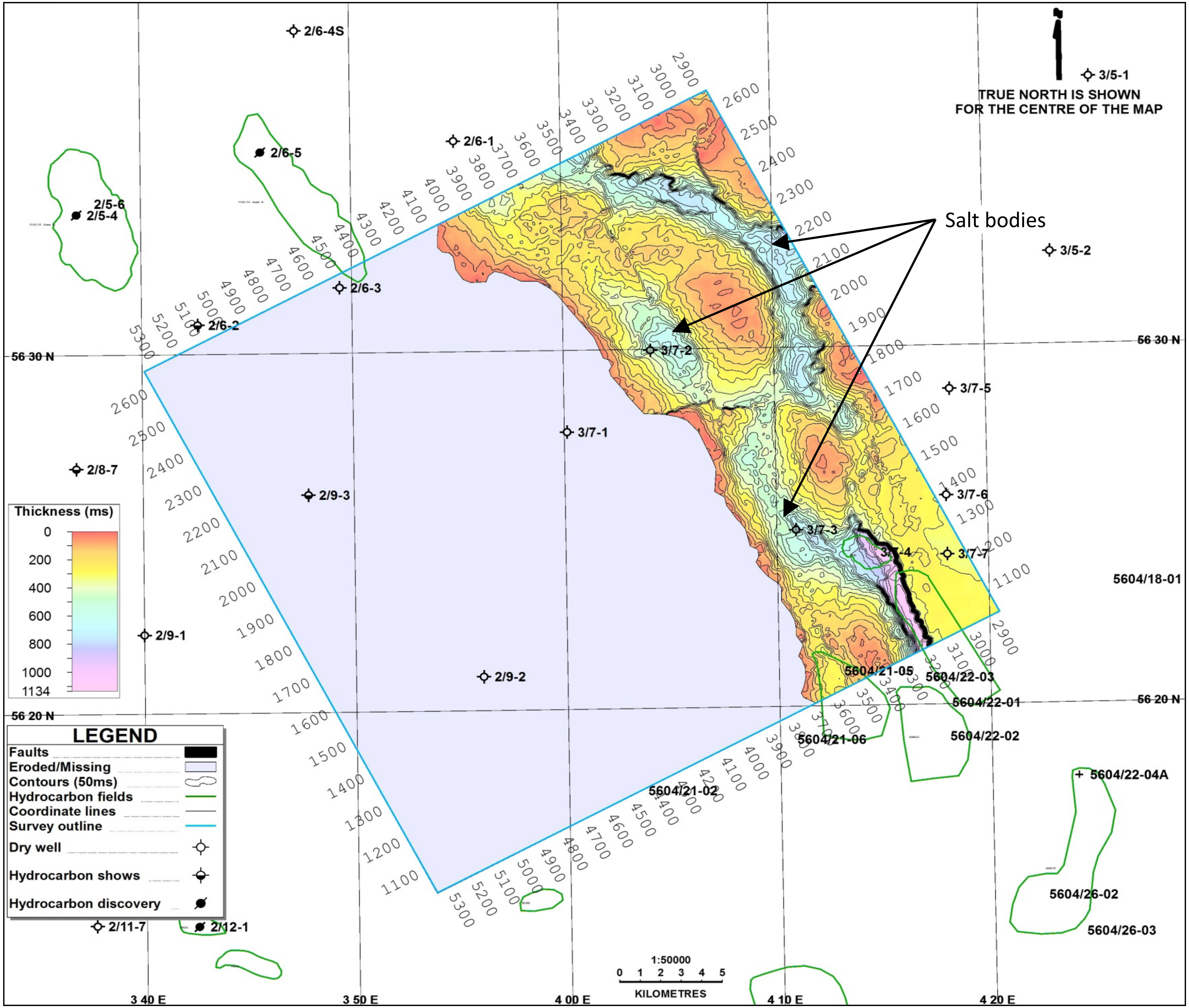

Figure 16B: Isochrone map (TWT) of Top Upper Permian salt (sequence 2), with the salt bodies marked.

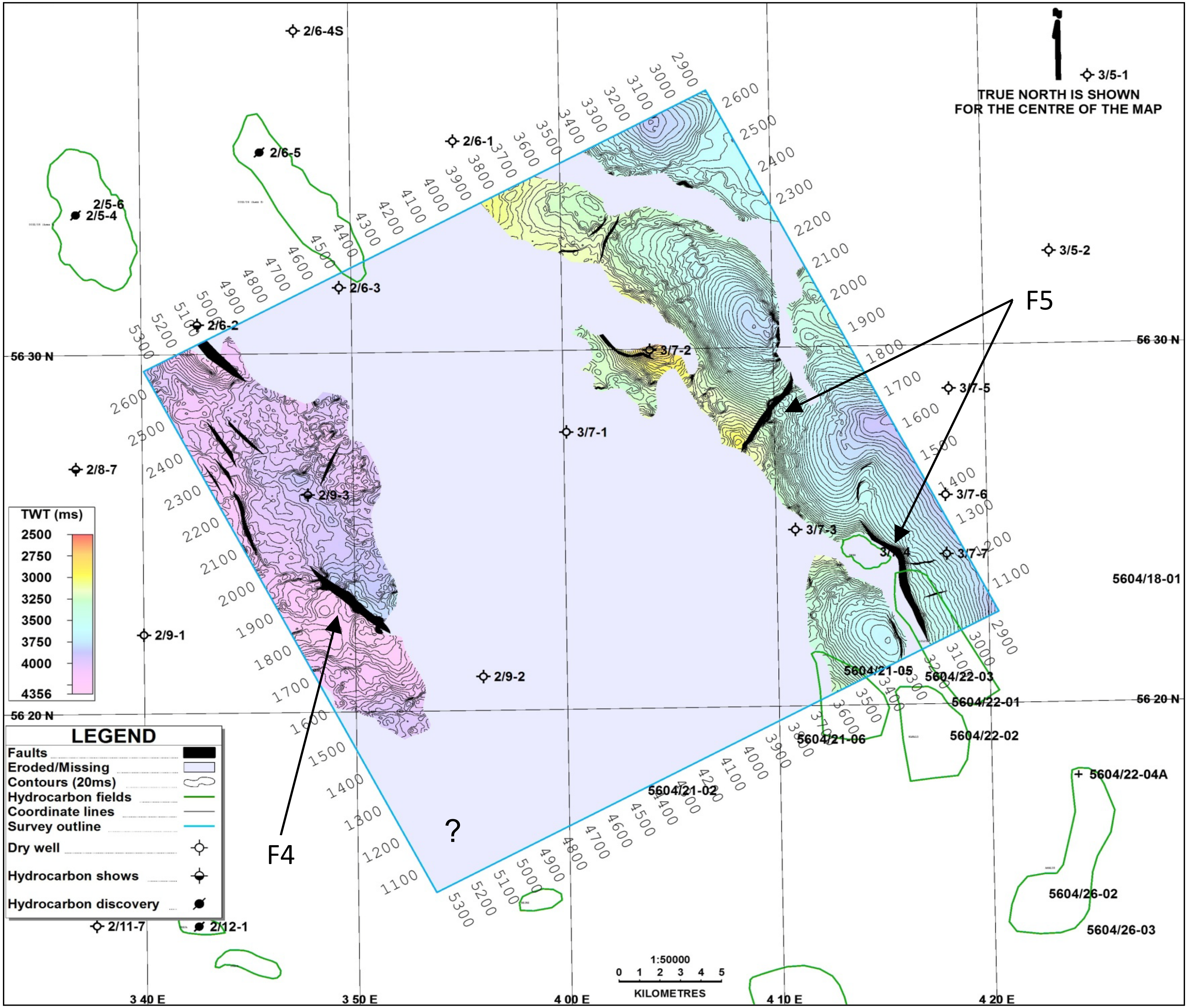

Figure 17A: Structural time map (TWT) of Top Triassic (sequence 3), with fault families 4 and 5.

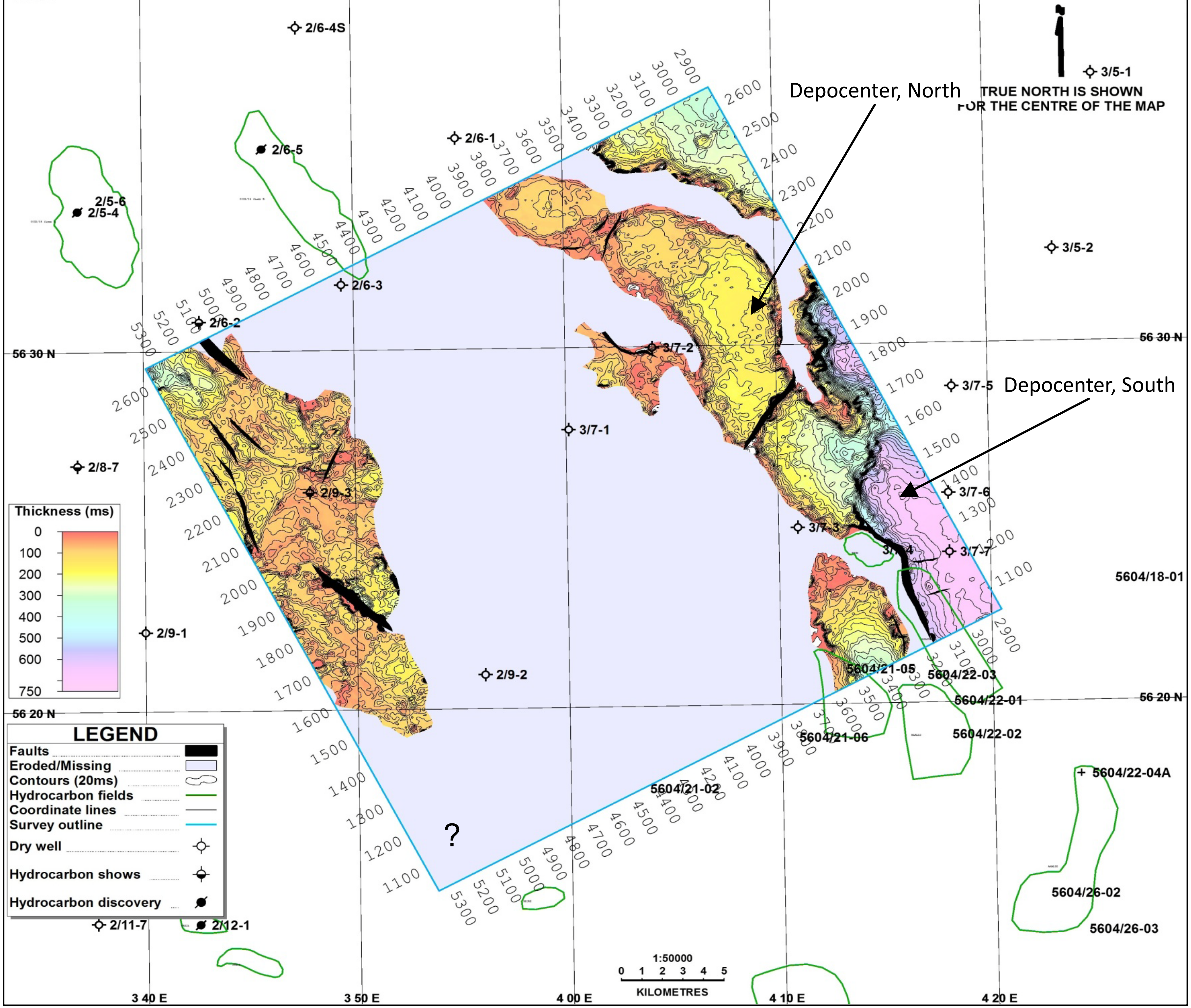

Figure 17B: Isochrone map (TWT) of Top Triassic (sequence 3), with the two depocenters marked out. Note: Salt structural control on salt thickness.

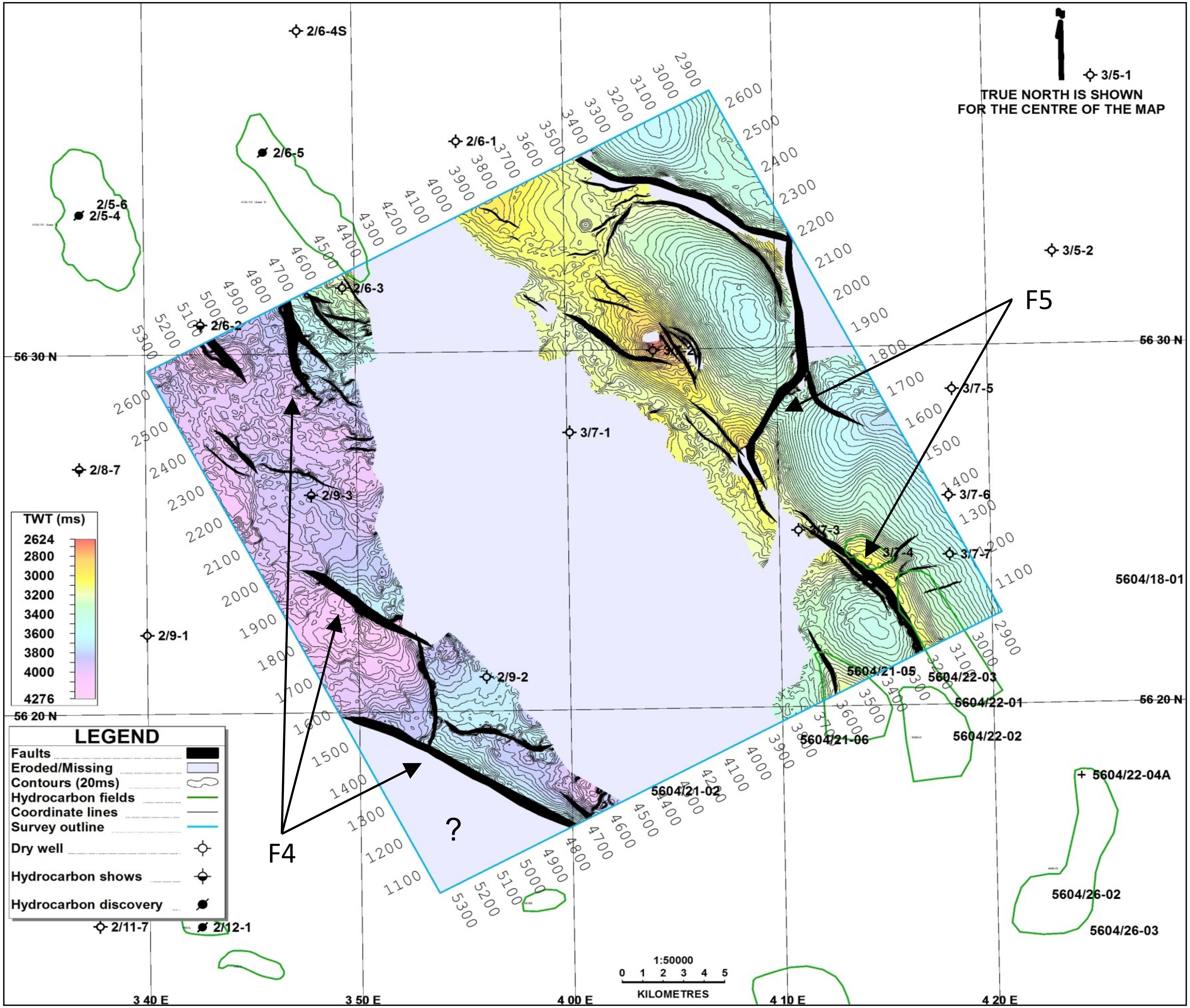

Figure 18A: Structural time map (TWT) of Top Middle Jurassic (sequence 4), with fault families 4 and 5.

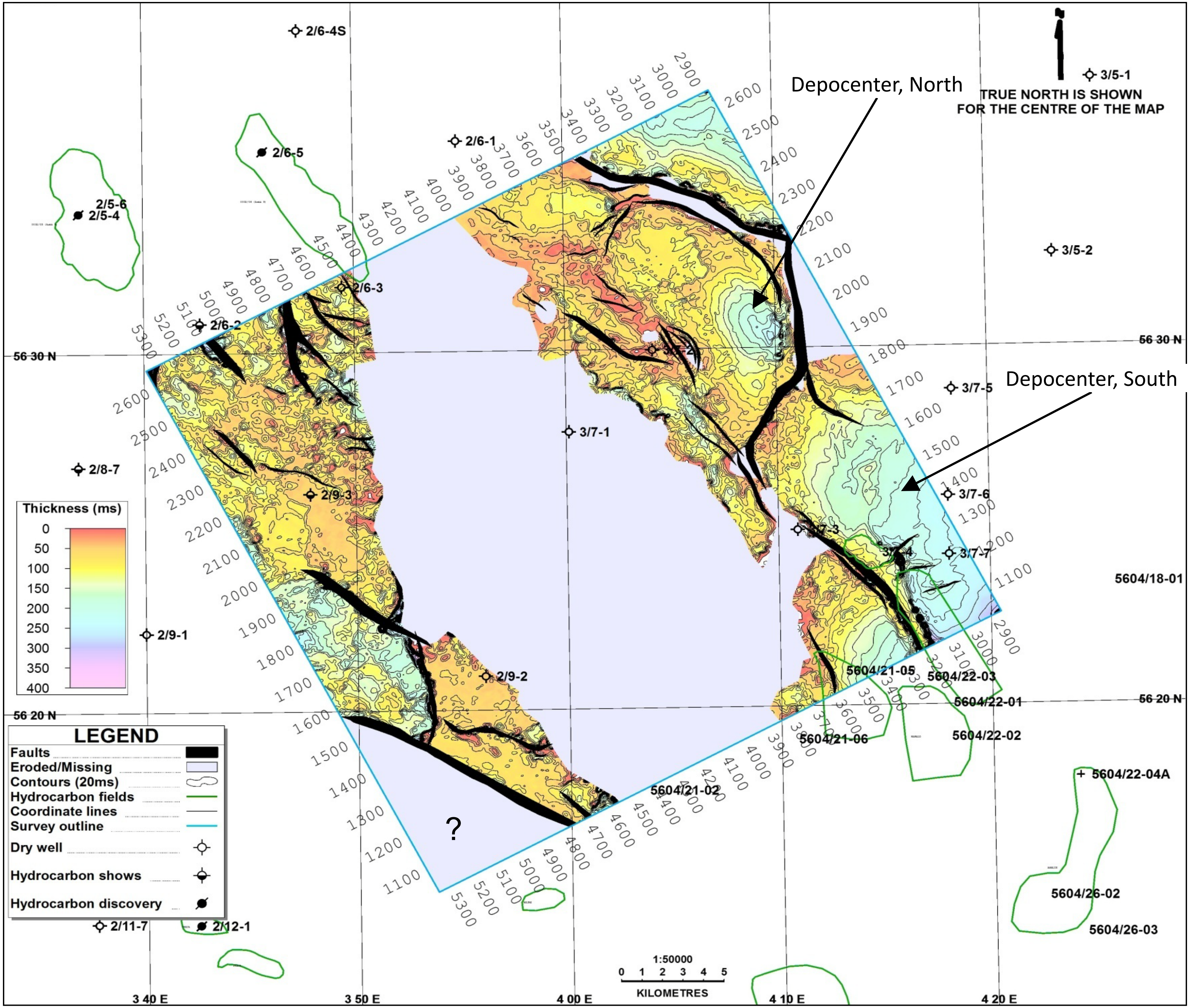

Figure 18B: Isochrone map (TWT) of Top Middle Jurassic (sequence 4), with the northern and southern depocenter. Note: Thickness variations in the depocenters.

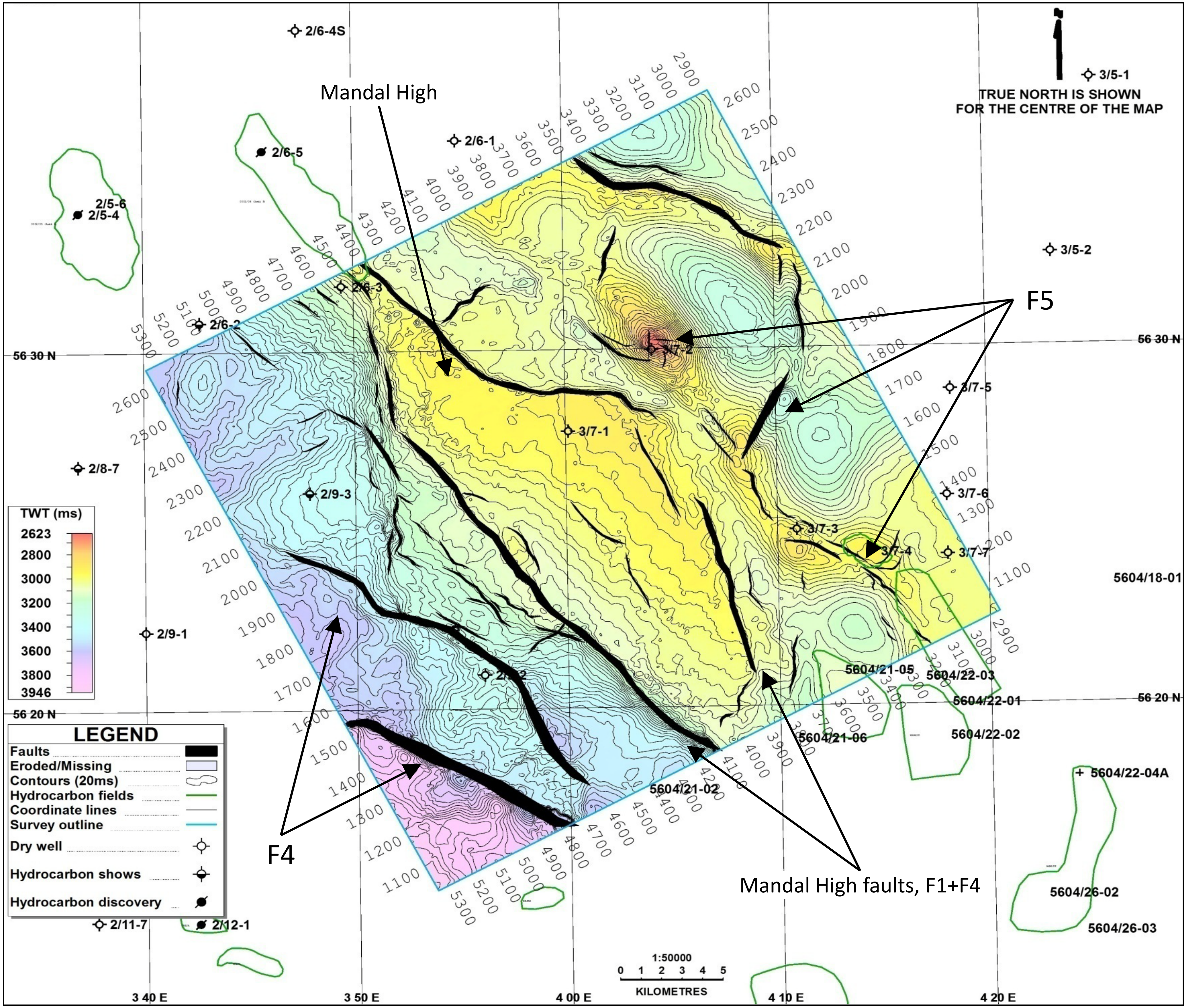

Figure 19A: Structural time map (TWT) of the BCU(sequence 5), with fault families 4 and 5. Note: The outline of the Mandal High, together with the boundary faults.

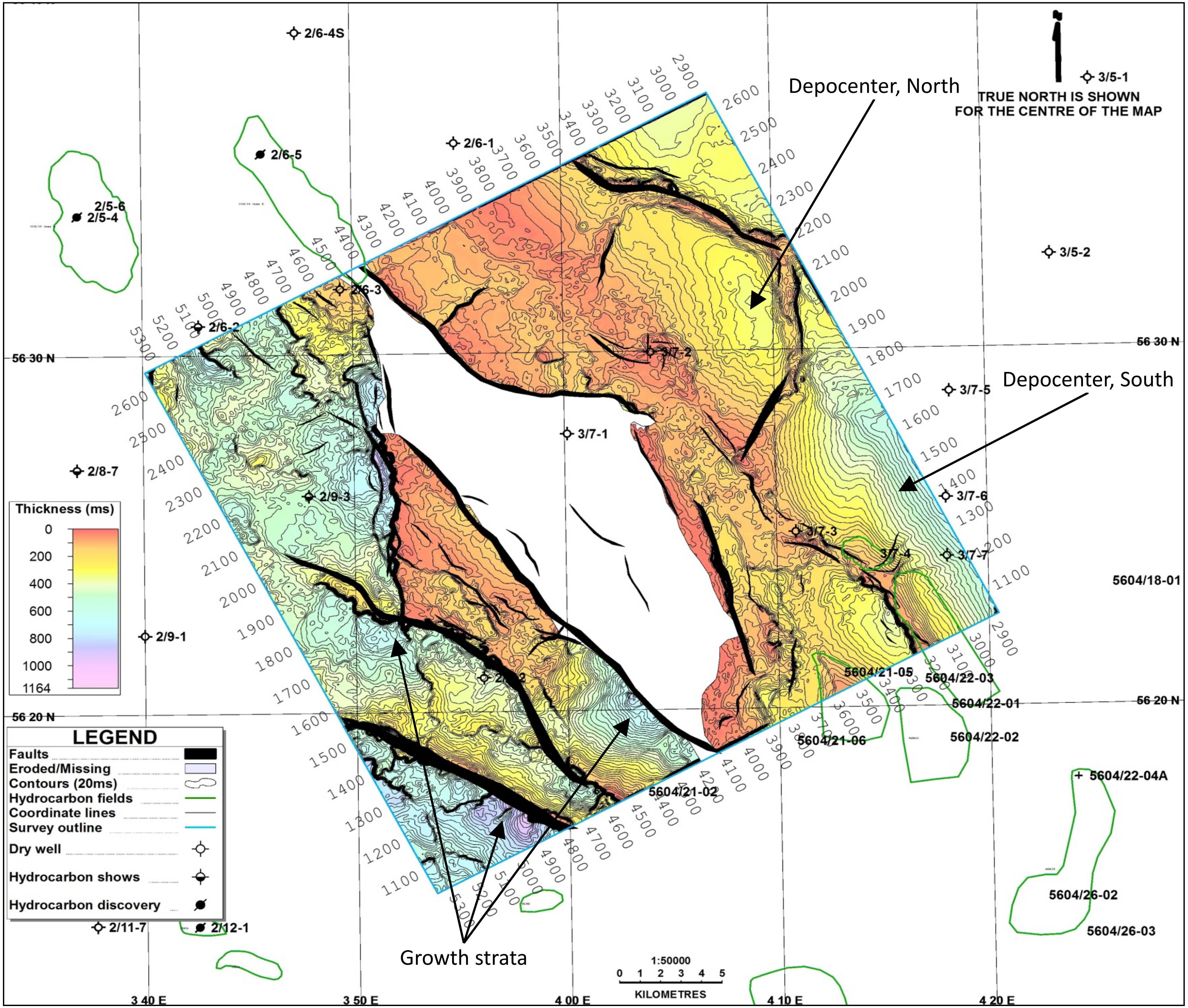

Figure 19B: Isochrone map (TWT) of Top Upper Jurassic (sequence 5), with the northern and southern depocenter. Note: Growth strata on the Piggvar Terrace.

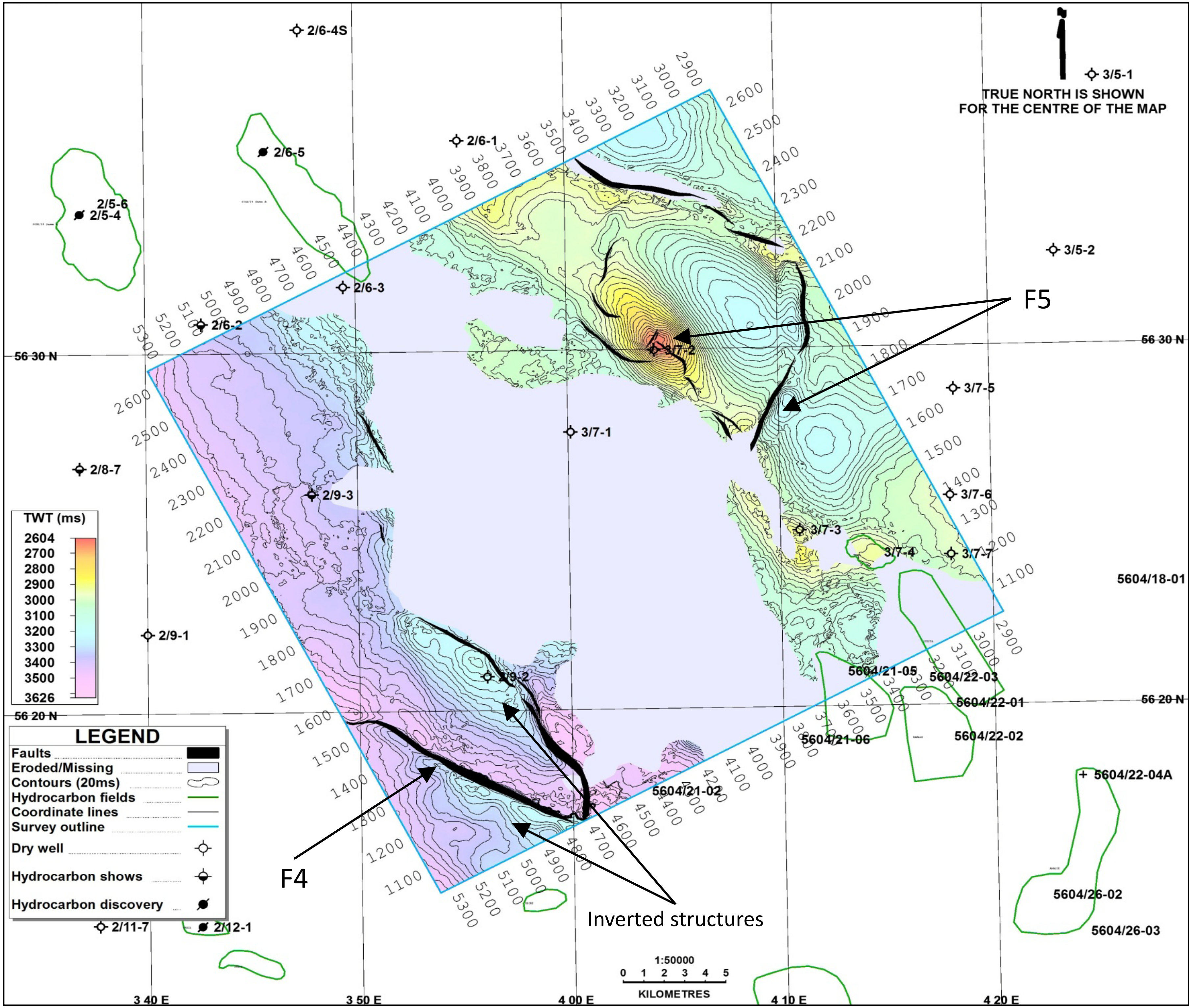

Figure 20A: Structural time map (TWT) of the Top Lower Cretaceous (sequence 6), with fault families 4 and 5. Note: Inverted

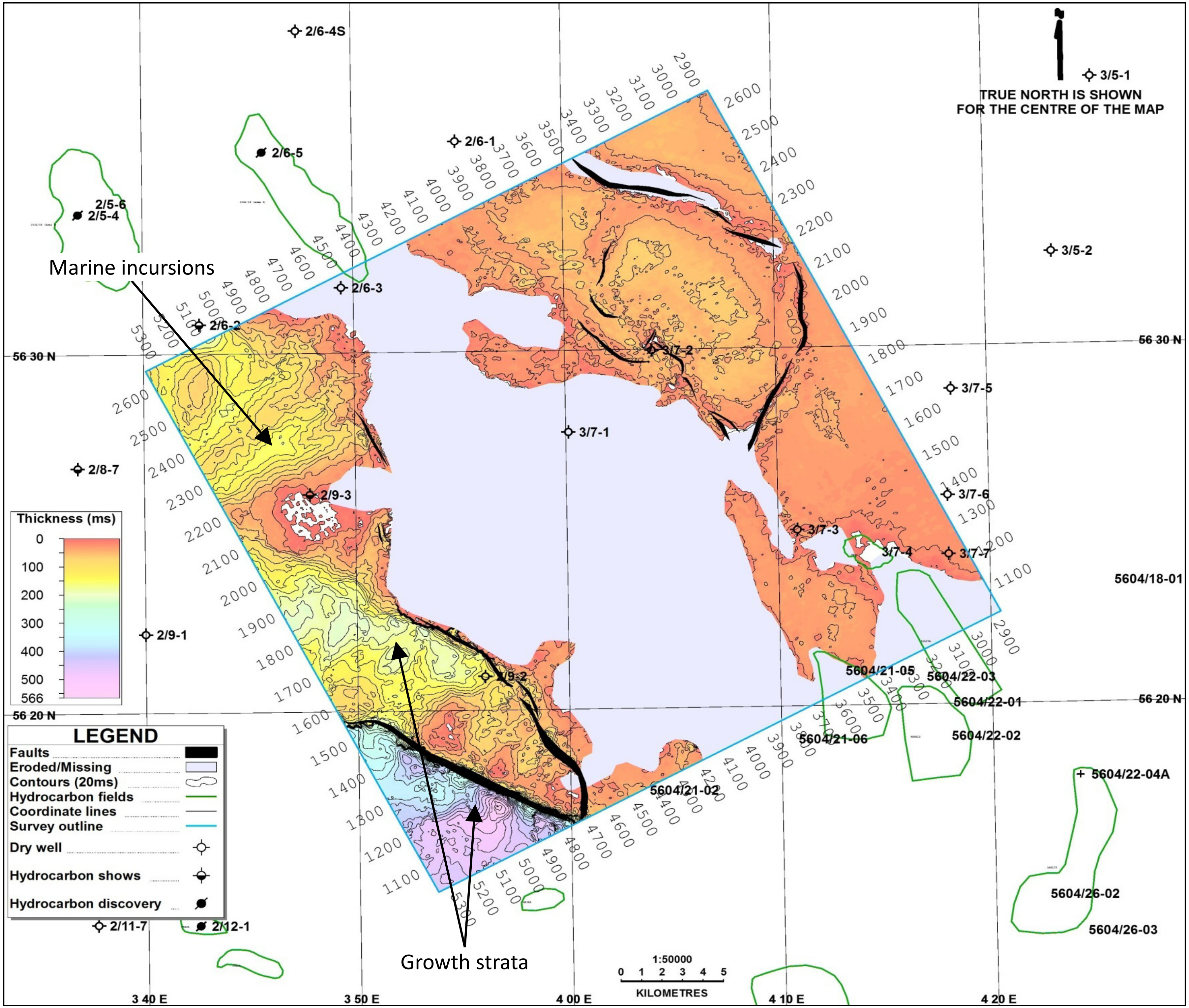

Figure 20B: Isochrone map (TWT) of Top Lower Cretaceous (sequence 6). Note: Growth strata on the Piggvar Terrace and marine incursions.

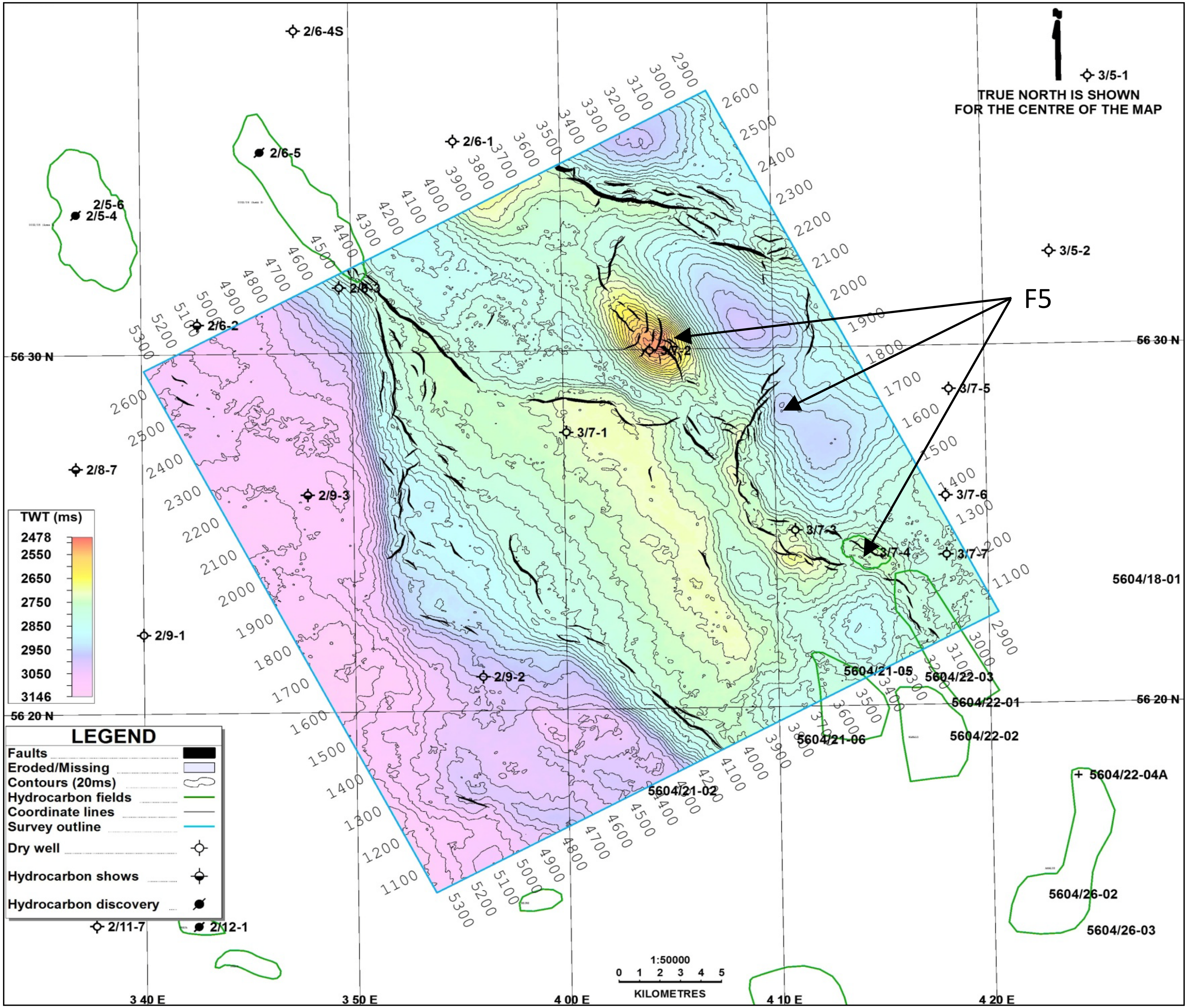

Figure 21A: Structural time map (TWT) of the Top Upper Cretaceous (sequence 7), with fault family 5.

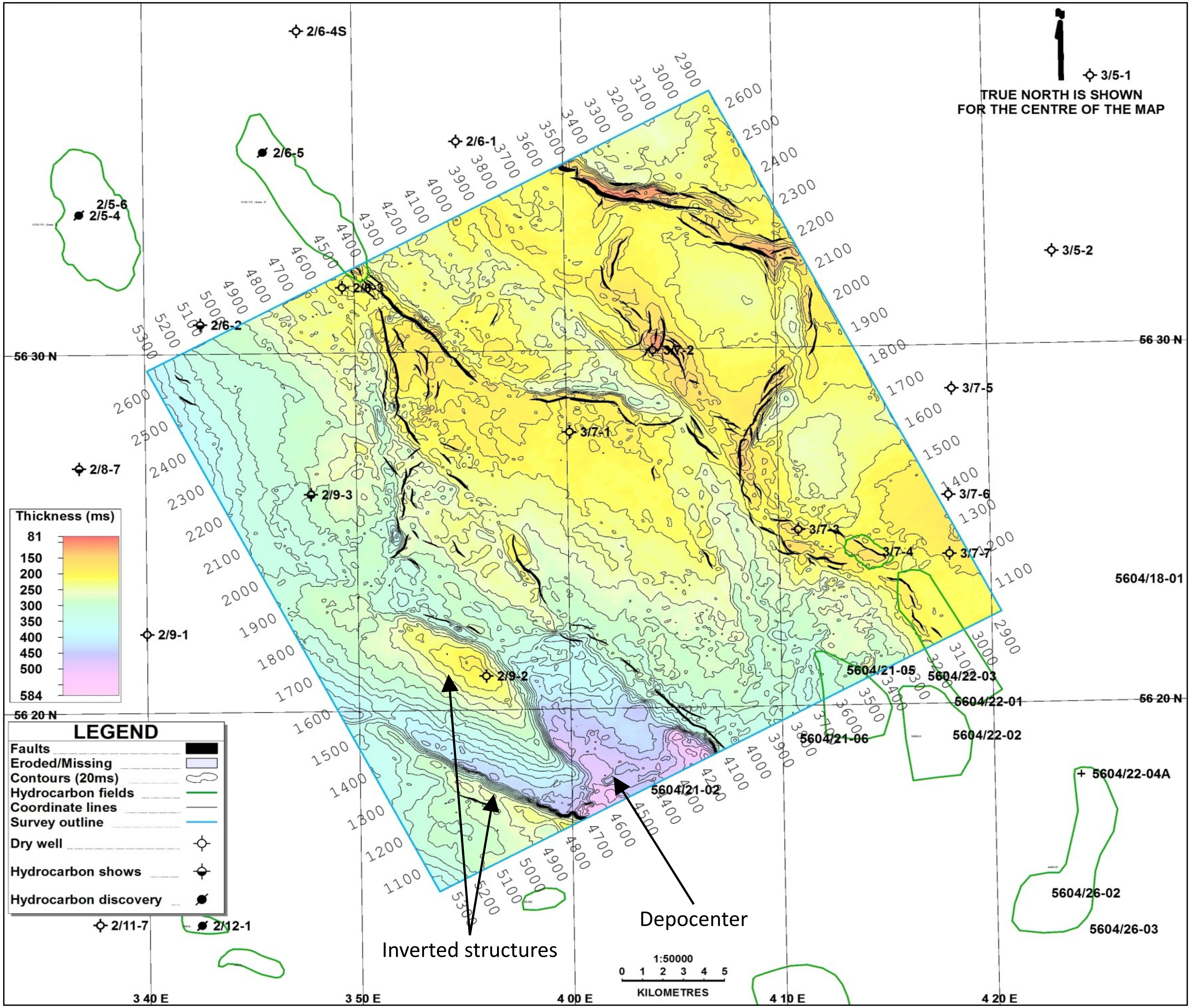

Figure 21B: Isochrone map (TWT) of Top Upper Cretaceous (sequence 7). Note: Thinning/thickening over inverted structures, depocenter on the Piggvar Terrace.

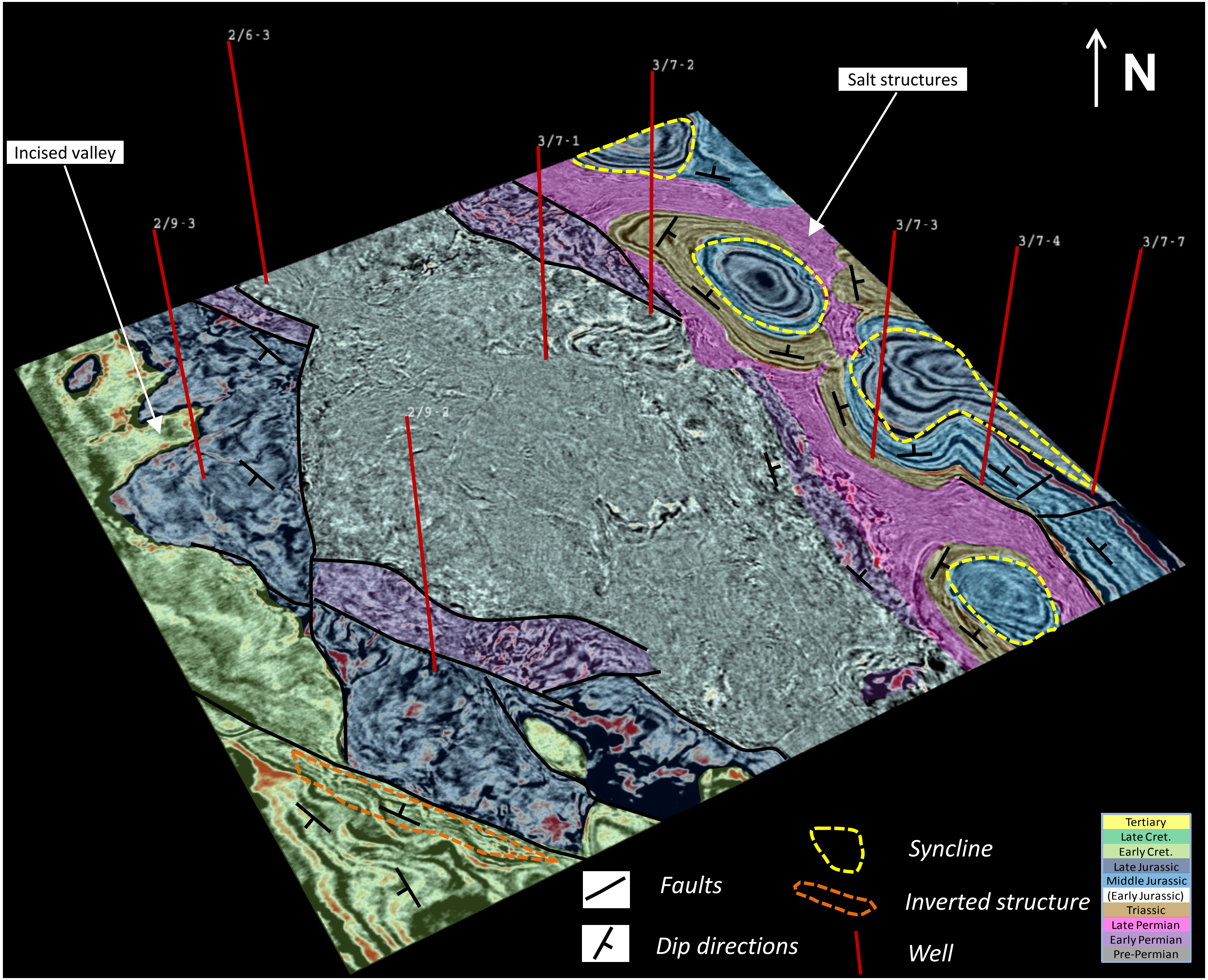

Figure 22: Time slice at 3200ms (TWT). Note: Incised valleys of the Early Cretaceous and salt structures.

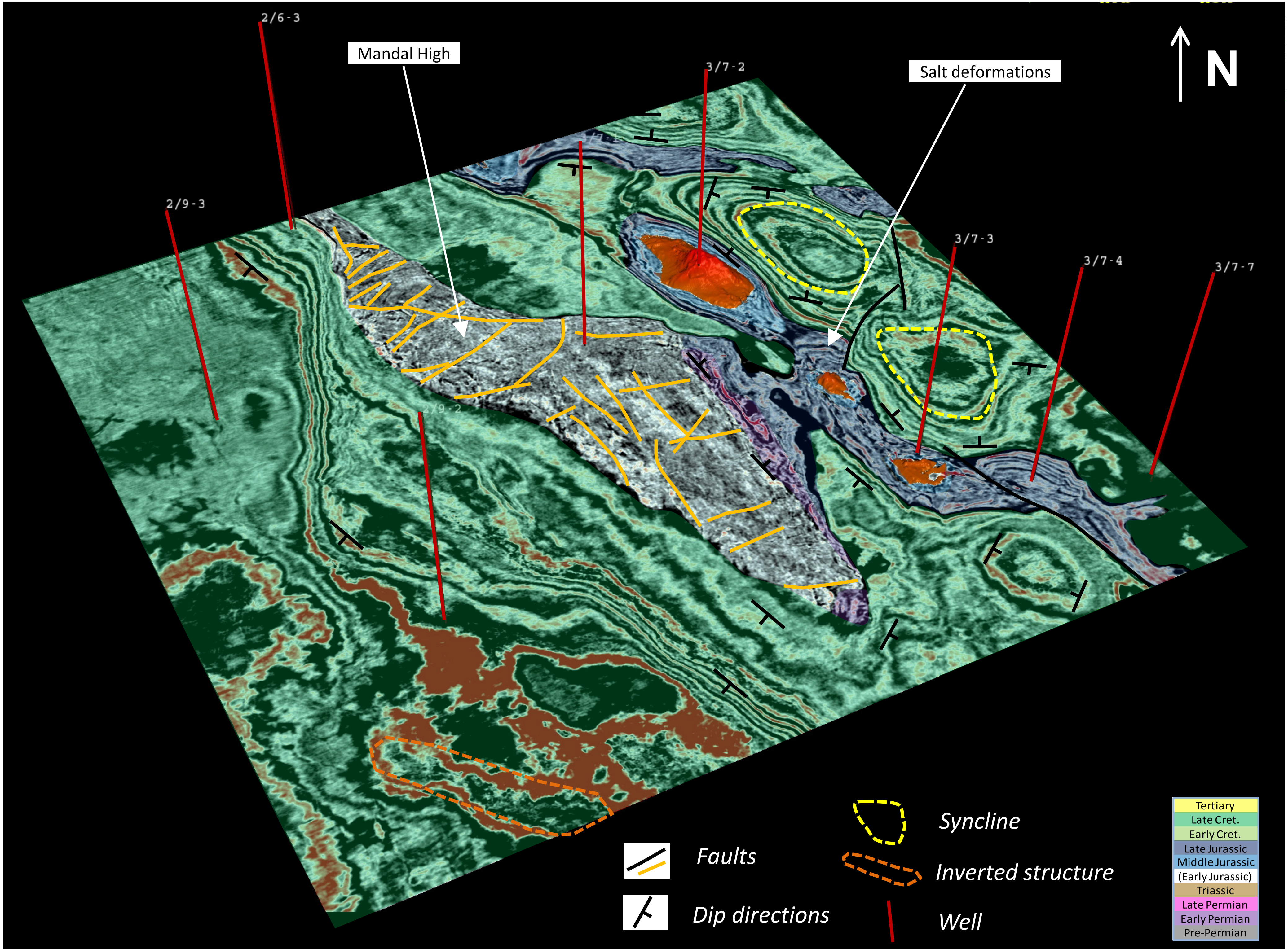

Figure 23: Time slice of 3020ms (TWT). Note: The Mandal High and salt deformations along an s-shaped structure

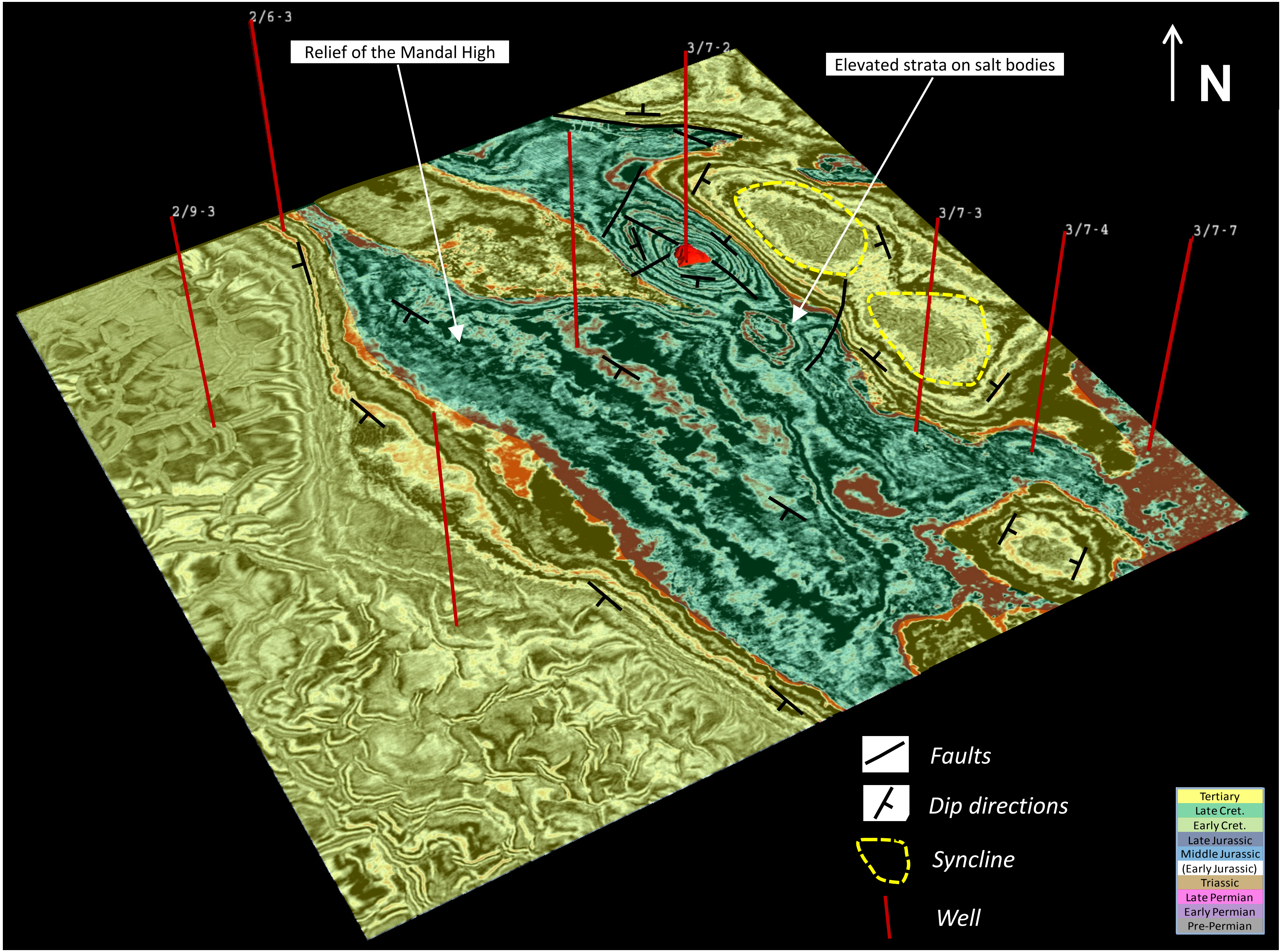

Figure 24: Time slice at 2800ms (TWT). Note: The outline of the Mandal High elevated, with the salt trends.

Discussion
From the observations, it is clear that the Greater Mandal High Area has undergone several phases of tectonics, including salt tectonics, resulting in a complex structural image. The tectonic phases have had various impacts on sediment distribution and depositional patters. It is evident that the Mandal High is centerpoint for the borderline between two tectonic regimes; the Søgne Basin and the Central Graben. The distribution of the fault families on either side of the high indicates this. In addition, the Søgne Basin seems to divide in two sub-regimes within the study area. A proposed evolutionary model for the Greater Mandal High Area will take into account the tectonic and stratigraphic evolution to explain the observations seen in subsurface data, including the role of salt mobilization, the evolution of the Mandal Basement High, and possible implications for the petroleum system.

Evolutionary model of the study area

Volcanic activity early rifting & doming
The Greater Mandal High area is located in the border region between the Northern Permian Basin and the Mid North Sea High. This is clearly indicated by the drilled Lower Permian sequence in the study area which shows more volcanic influence towards the south. This is the basis for the depositionary model presented in Figure 25. The extensive clastic sediments of wells 2/9-2 and 3/7-2 support a W-E boundary between the northern Permian Basin and the Mid North Sea high. The Mandal High was probably not yet defined as a structural high, and sediments of this sequence was deposited across the high and eroded later. Indications to support this idea are derived from the following observations:

- The dip of the Lower Permian sequence seems to closely follow the dip of the crystalline basement
- The sequence is downfaulted and juxtaposed to the Mandal High, with no growth strata evolving along the boundary faults of the high
- To the south, the sequence is deposited across the Mandal High, truncating against the Base Cretaceous Unconformity

Faults of fault families 1 & 2 closely follow the lineations (near N-S and NE-SW) of the faults of the Mandal Basement High (Fig 26). The faults are normal faults with low throws (Fig 27). The faults may therefore indicate rifting systems of the Lower Permian as suggested by Gowers & Sæbøe (1985). We suggest that the rifts are formed upon older weakness zones ultimately controlled by the basement structural grain established in the Caledonian orogeny. However, data covering a larger area is needed to confirm this theory. Fault family 3 has the same W-E orientation as the Mid North Sea dome. The origin of these faults is probably related to the extensive volcanic activity induced by the Mid North Sea dome, but may very well be controlled by the same structural grain as well. The faults of these three fault families had minor control on sediment distribution in the study area.

Pre-rift salt deposition

During the transition from Middle Permian to Late Permian, the Zechstein Sea advanced from the Norwegian-Greenland Sea rift southward and flooded the Permian basins (Fig 27) (Ziegler 1990). The Søgne Basin began to subside and separate from the Ringkøbing-Fyn High. This was related to movements of the Coffee Soil Fault (Cartwright 1991). This is supported by the observations that Zechstein salt is deposited in the Søgne Basin and not on the Piggvar Terrace (Fig 27). A western limit of Zechstein salt towards the Mandal High is observed from the structure map (16A). This is explained by the Piggvar Terrace being a part of a sub aerially exposed high. The Zechstein salt deposition is regarded as a pre-rift sequence before the Permo-Triassic rifting event, due to the lack of growth strata. This is also supported by Ziegler (1990). It should however, be taken into account that conclusions are hard to derive due to the later mobilization of the salt.

Rifting & salt mobilization

Entering the Triassic, the Søgne Basin was still subsiding as a response to movements of the Coffee Soil fault (Cartwright 1991). The Mandal High was probably formed as a horst structure during the Permo-Triassic rifting event (Fig 27). The near N-S orientations of fault family 1 is similar to the orientation of the Mandal High, and the faults were probably reactivated during this phase. A withdrawal of the Zechstein Sea was followed by continental deposits of the Triassic. A suggested environment of deposition of the Triassic is seen in Figure 28. The two wells that have drilled the Triassic show low net to gross ratios (N/G). It is likely that distal continental facies with fine gained deposits dominate on the Piggvar Terrace due to the lack of seismic geometries indicating fluvial deposits. The only well penetrating the interval in the Søgne Basin has low N/G ratio, but it is drilled through a thin sequence over a salt diapir. It is clear that thick Triassic sequences develop in between salt structures (though sequences of this thickness has not been drilled), in particular in the southern regime of the Søgne Basin (Fig 28). Salt mobilization was initiated during the Triassic and provides a strict control on sediment distribution. Possible development of sheet flood and fluvial facies are interpreted, suggested by internal geometries observed in seismic sections (although no evidence exists in the study area from well data).

Mid North Sea Dome - Uplift and erosion

The Middle Jurassic sequence was deposited during the last stages of the Mid-North Sea dome. The first marine transgressions occurred in the Bathonian (Ziegler 1990). Figure 29 suggests a model for the depositional environment. The N/G ratio in the western part of the area seems to increase towards the Mandal High. CPI logs show evidence of coal deposits, especially in the lower part of the sequence. In the Søgne Basin, the drilled intervals seem to have low N/G around 0,3-0,4. The Mandal High might act as a minor sediment source during this time, with the Middle Jurassic relief outlined. The earlier established SW dip of the structure suggests major sediment input in this direction, possibly explaining the higher N/G ratios seen in the logs to the west (Fig 29). Possible minor delta and shallow marine systems might evolve around the high. The Mid-North Sea dome may have been a prominent sediment source.

Continued subsidence of the Søgne Basin related to normal fault movement of the Coffee Soil fault is assumed based on the general thickening of the unit to the east and south-east (Fig 29). Salt is a major control on sediment distribution at this time, possible directing sediments along the salt structures (Fig 27). However, the same pronounced syn-depositional patterns seen to the south in the Triassic sequence is not observed. This is probably related to a lower intensity in salt mobilization, causing the salt to have a less strict control on sediment distribution.

Rifting & marine transgressions

The Upper Jurassic rifting event caused major subsidence in the Central Graben area (Piggvar Terrace in the study area). Fault family 4 is pronounced on the Piggvar Terrace. The faults are normal with large throws, growth strata and fault block rotation (Fig 27). Fault family 4 is there assumed to originate from the rifting event. In the Søgne Basin, fault family 4 is not observed. The rifting event had less impact here. However, a thickening to the east suggests continued subsidence of the Søgne Basin due to continuous movement of the Coffee Soil fault. In response, the basin acts as a half graben (Cartwright 1991). It is likely that the stresses caused by the rifting event reactivated salt mobilization, increasing the intensity of salt movements. Diapirs, salt walls and depocenters were formed and reactivated. The salt had a major control on deposition. Internal reflectors of the Upper Jurassic onlapping to the south had a shift in depositional direction in the northern depocenter. The onlap is probably related to the growth of the middle diapir seen in Figure 14. Listric faults of fault family 5 formed along salt bodies creating further accommodation space for Upper Jurassic sediments. Marine and deep marine shales were deposited during a transgression (though little or no anoxic conditions seem to develop in the study area) (Fig 30). N/G ratios over the study area are close to zero, only disrupted by occasional thin sands. Towards the end of the Upper Jurassic, more coarse grained clastics were deposited as observed by N/G ratios in the wells 3/7-7 and 3/7-3. Dip directions of the Upper Jurassic sands of well 3/7-3 suggests sediments being sourced from the Mandal High. A shallow marine system may have evolved around the Mandal High towards the end of the Upper Jurassic (Fig 30). The south west dipping Mandal High was probably a sediment source for these systems focusing deposition towards the southern Piggvar Terrace. The thin Upper Jurassic sequence formed on the previously defined triangle shaped terrace to the west can be an example for such a system. No wells have been drilled close to the Mandal High to prove this.

Late stage rifting & post rift sedimentation

During the Lower Cretaceous, thick sequences to the south-west of the study area suggest deposition during the late stage of the rifting (Fig 27) (Gowers & Sæbøe 1985). Faults of fault family 4 are assumed to die out during the early stages of this sequence. The observations show no growth strata along salt bodies, suggesting that salt movement ceased by this time (Fig 27, 31). Salt was probably less of a structural control than before, as no significant thinning and thickening are observed on the seismic sections across salt bodies and depocenters (Fig 31). E-W channels, probably marine incursions are interpretated west of the Mandal High (Fig 31). They are identified by a thickening of the contours on the isochrone map, and appear to be sourced from the Mandal High. N/G ratios are close to 0 in most wells. The subsidence in the Søgne Graben seems to have ceased, and only thin sheets of marine marls and shales are deposited. However, Lower Cretaceous sands are recorded in well 3/7-3, and dip-meter studies indicate that they may be sourced from the eastern Ringkøbing-Fyn High, and possible turbiditic in origin. A northern embayment is observed to the north east of the

Mandal High. This may represent a shallow marine system, provided that the high acts as a sediment source, which is indeed indicated by the western marine incursions.

Flooding & inversion

During the Upper Cretaceous regional flooding was caused by the entry of the Cretaceous Sea This led to the deposition of the chalk group (Ziegler 1990). Faults of fault family 4 were reactivated during the Upper Cretaceous. This is evident by the inverted structures previously observed, and particularly visible in the Lower Cretaceous sequence (Fig 27).

During the Cretaceous the Thethys Ocean closed to the south on what is today continental Europe occurred (Fig 32). This event created a S-N compressional pulse causing reactivation of older faults in the southern North Sea (Oakman & Partington 1998). By taking a closer look at the implications of the compression in the study area, I suggest how this affected the fault families. A stress ellipsoid overlies the Lower Cretaceous structure map in the south-west corner of the study area (Fig 32). The inversion structures are clearly observed. The stress field suggests a possible oblique strike-slip reactivation of fault family 1. In particular, it might include the Mandal High boundary faults. However, the motion is probably subtle as no effects are observable on the seismic. The N-S pulse seems to have reactivated faults of fault family 4 in an oblique reverse movement (Fig 32). This resulted in the inverted structures. No reactivation is observed on faults of fault family 2 and 3. However, they are only observed to the north east of the Mandal High. The high itself may have acted as a backstop for the stress field, and together with the massive salt bodies in the area, caused stresses to diverge.

A reactivation of salt movements in the Upper Cretaceous created extensive deformations. Faults of fault family 5 were active at this time (Fig 27). The sequence thins over diapirs and salt structures, illustrating the salt control on the deposition.

Evolution & impact of salt mobilization

The importance of the salt calls for a broader discussion on its evolution and impact. It was established previously that salt movement seemed to concentrate around three pulses:

1. Triassic - Initiation of salt mobilization, connected with the Permo-Triassic rifting
2. Upper Jurassic - Reactivation of salt movement during Upper Jurassic-Lower Cretaceous rifting
3. Upper Cretaceous-Tertiary - Last pulse of salt mobilization, with the diapir where well 3/7-2 is drilled being active into the Tertiary

Based on the observations, the first salt mobilizations created a NNW-SSE trending salt wall. In the northern regime of the Søgne Basin this curves to the east before curving back up to the North West again (Fig 33). Observations on deformed layers indicate that this salt wall had its major movement in pulse 1 and 2, with minor mobilization in the Upper Cretaceous. Salt was probably migrating from the southern depocenter, and possible from a western depocenter outside the coverage of the seismic cube. The salt body where well 3/7-2 is drilled however, uplifts layers all the way up to Tertiary. This is probably related to the movement of salt from the northern depocenter.

The salt structures seem follow the lineations of fault family 1, 2 and 3 (Fig 33). Combining this with the observation that salt seems to develop on faults of Lower Permian age suggests a strong basement structural grain control on salt evolution in the study area. Furthermore, we observe how salt controls the depositional patterns of the overlying sequences. In the southern regime, this is particularly visible in the deposition of Triassic sediments. In the northern regime, salt seems to gain importance on the Jurassic intervals, acting more or less as a structural relief directing sediment flow. The viscous nature of the salt caused listric faults of fault family 5 to evolve throughout the sequences. Continuous movements of the faults up to the Upper Cretaceous (at least) created a new set of faults, cracking and deforming the brittle chalk (Fig 27). It is clear that the salt deformation provides the dominant structural control in the Søgne Basin, with the pulses being ultimately related to regional tectonic events and changes in the stress field.

The Mandal High

Structure

The Mandal High appears on seismic to be a south-west dipping crystalline basement horst. The structural relief of the high has a NW-SE orientation to the south, except for a slight bend to the west in the northern part of the study area (Fig 26). The triangle shaped basement structure to the west on the Piggvar Terrace is not part of the Mandal High today, but may have been up until the Upper Jurassic. The same applies to the northern Permian terrace. The eastern boundary fault of the Mandal High seems to have been active from Late Permian-Triassic to the Upper Jurassic (Fig 26). This fault probably relates to the continuous subsidence of the Søgne Basin half graben as a response to movement in the Coffee Soil fault area. The Mandal High was probably acting as a stable basement high with little or no subsidence. To the west, the high may have had a larger extent during the Triassic and Middle Jurassic (Fig 28, 29), before the Upper Jurassic rifting properly defined the Piggvar Terrace as separate structural element.

Evolution

Gowers et al. (1993) suggests the formation of the Mandal High to be of Middle Jurassic age. However, this study indicates that the high might have acted as a sub aerially exposed structure from Late-Permian - Triassic (Fig 27). The crystalline basement structure of the high is previously observed to have several internal structures and faults seen on vertical seismic sections and time slices (Fig 26). The lineaments of these deformations follow closely the proposed lineaments of the Caledonian orogeny. The Søgne Basin began to subside during the Late Permian, allowing Zechstein salt to accumulate up to a certain level towards the Mandal High (Fig 27). Furthermore, the high was probably defined during the N-S oriented Permo-Triassic rifting. Triassic sediments are thick in the Søgne Basin, thin towards the Mandal High, and are in general thin on the Piggvar Terrace (Fig 28). They are overlain by Middle Jurassic sediments, suggesting that an Upper Jurassic erosion (as proposed by Gowers et al. 1993) of these sediments did not occur towards the Mandal High, as they were probably never here. N/G ratios increasing towards the high suggests that it acted as a sediment source during the Middle Jurassic.. Upper Jurassic wedges towards the high to the east and west supports a sub aerial exposure during this time. During the Upper Cretaceous, the high was flooded with subsequent deposition of the chalk groups (Fig 27).

Structural controls

The Mandal High is also seen to separate to tectonic regimes; the Central Graben and the Søgne Basin. The difference observed in tectonic evolution cannot be explained sufficiently without introducing the Mandal High as a basement boundary for the tectonic regimes from the Permo-Triassic.

It is also clear from this study that the basement grain visible on the Mandal High had importance for the latter tectonic evolution of fault families 1-3 and salt structures. To summarize the discussion of the key points regarding the Mandal High found in this study, we can say that:

- The basement grain and lineations of the Caledonian orogeny is clearly observed in the Mandal High, comprising two directions: Near N-S and NE-SW, matching with fault family 1 and 2, possibly also fault family 3.
- The high was a tectonically stable element, with no internal deformation caused by post-Permian tectonics.
- The high was probably formed during the Permo-Triassic rifting, and was partly or completely sub aerially exposed up until the Early Cretaceous.

The high probably acted as a backstop for stress fields for the Upper Jurassic rifting and Upper Cretaceous inversion.

Implications on the petroleum system

Crystalline basement highs like the Utsira High and the Mandal High are becoming a part of new re-exploration strategies in the mature petroleum provinces of the North Sea. In particular, the Utsira High area has proven a successful petroleum system the latter years. This study has proven similarities between the Utsira High and the Mandal High: Both are weathered basement highs, with rocks deformed during the Caledonian orogeny, and possible clastic systems forming in and around the highs (Lie et al. 2011).

Source rock & migration

The Upper Jurassic source rock is well established as a good source rock in the Central Graben, filling fields of the fields along trends in Norway and Denmark (Fig 34). In the Norwegian Feda Graben, and the Danish Tail End Graben, this source rock seems more widely distributed and deeper buried than in the Søgne Basin. Following elements regarding source rock and migration are discussed:

1. Through regional well studies, it is assumed that the Upper Jurassic source rock is mature and (partly) present in the Feda Graben

2. The same source rock is probably immature in most areas of the Søgne Graben due to shallow burial depths

3. Migration from the Feda Graben may occur to the west or east, filling up fields along the chalk trend or traps at Piggvar Terrace up against the Mandal High

4. The Mandal Basement High is likely to act as a migration barrier for hydrocarbons migrating from the Feda Graben and into the Søgne Basin. A possible route might exist wrapping around the southern tip of the high, but basin modeling with a 3D component may be needed to better understand

5. Another possibility is that hydrocarbons migrating from the Tail End Graben filling Danish fields to the south of the study area have travelled further into the Søgne Graben. Salt may play an important structural control on the migration fairway. No wells have been drilled to the west of the salt wall observed in the Søgne Graben, up against the Mandal High

Traps & plays

The wide range of different tectonic and stratigraphic events in the study area provides a basis for suggesting possible hydrocarbon traps and plays in the area. The following have been identified from this study and illustrated in Figure 35.

1. Shallow marine systems of Jurassic age, wedging up against salt bodies and the Mandal High

2. Structural closures induced by salt movement. An important factor for this play to work is the timing of the salt mobilization. The trap may form after migration and escape faults caused by late salt mobilization can provide an escape route for hydrocarbons

3. Stratigraphic traps are possible, as sand distribution seems irregular (seen in some wells at certain sequences, others not). Turbiditic flows originating from the Mandal High or Ringkøbing-Fyn High are an example of this.

4. Cretaceous inverted structures may form an efficient structural trap, sealed by overlying chalk. However, sand distribution is a high risk, and the well 2/9-3 has been drilled on an inverted structure with no sands encountered in the Lower Cretaceous sequence.

5. Fractured basement rocks as a reservoir may exist, especially considering the recent successes at the analogue basement high; the Utsira High. Well 3/7-1 drilled into the Mandal High, but this well was drilled on the most elevated point of the basement. Amplitude values and reflector nature may suggest weathered and fractured basement at the southern edge of the Mandal High.

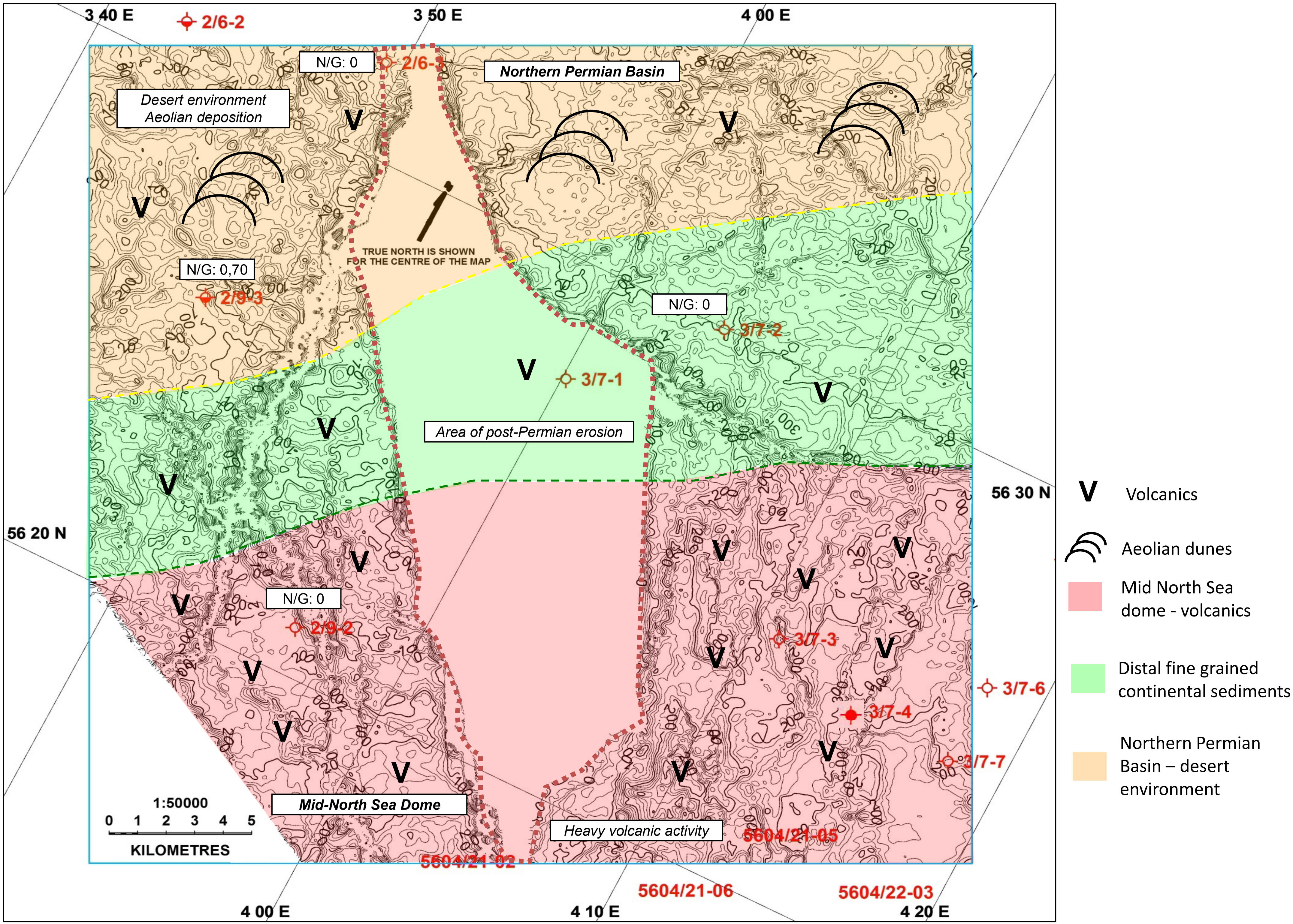

Figure 25: Paleogeographic map of Lower Permian (sequence 1).

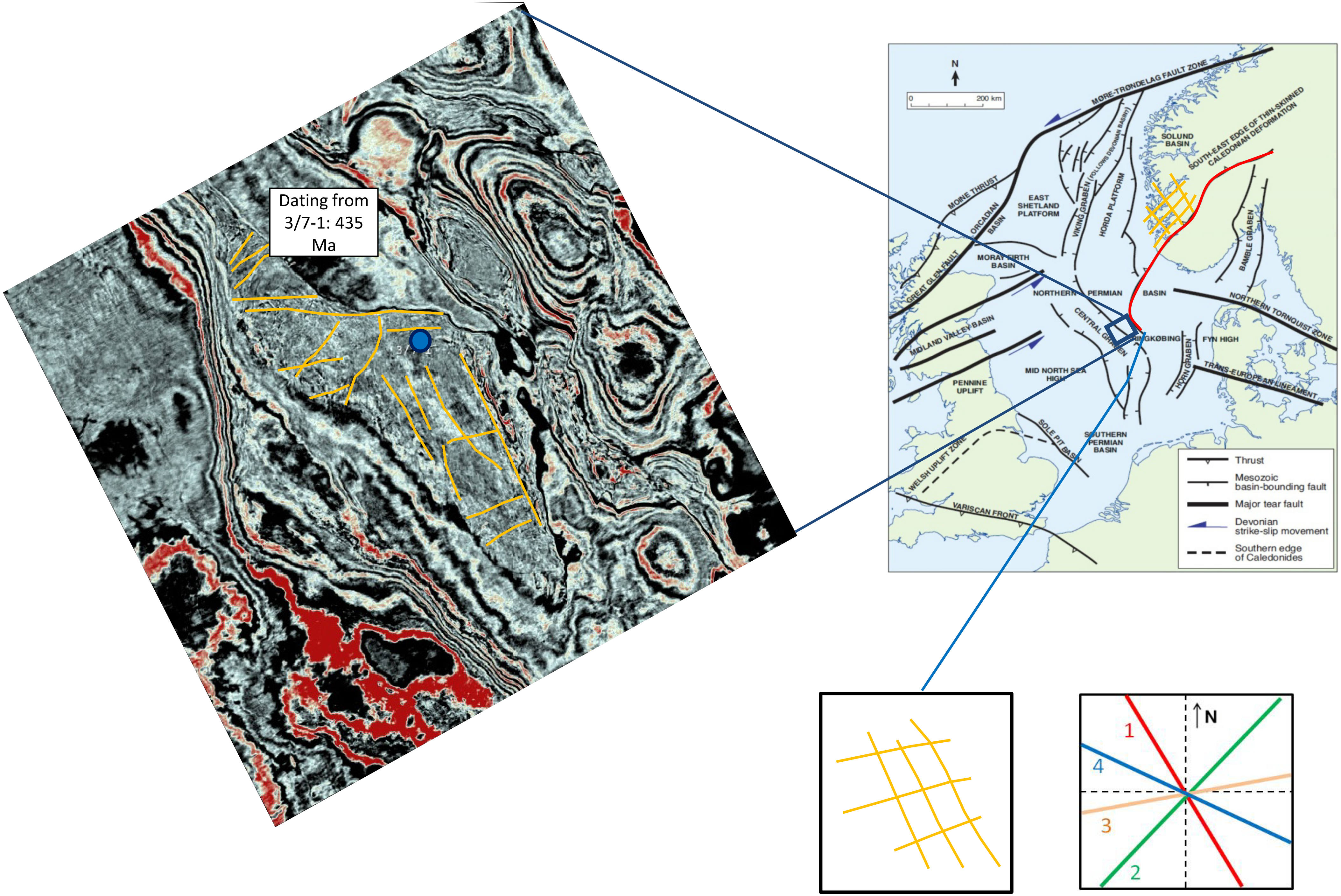

Figure 26: Time slice of Mandal High showing lineaments of basements faults together with structural grain of the Caledonian folding and fault families.

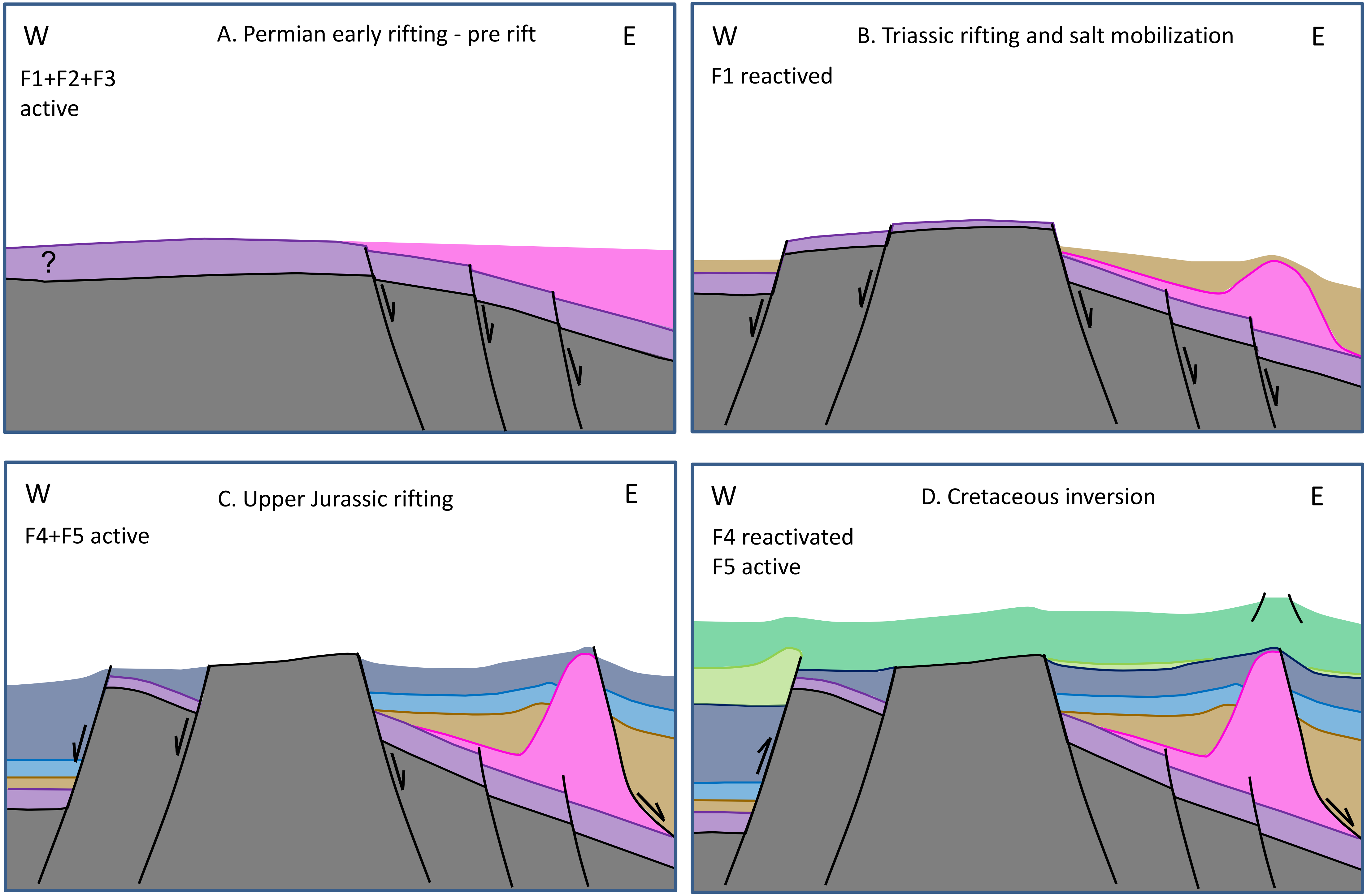

Figure 27: Idealized W-E cross-section of structural evolution of the Greater Mandal High area. Arrows indicate active faults.

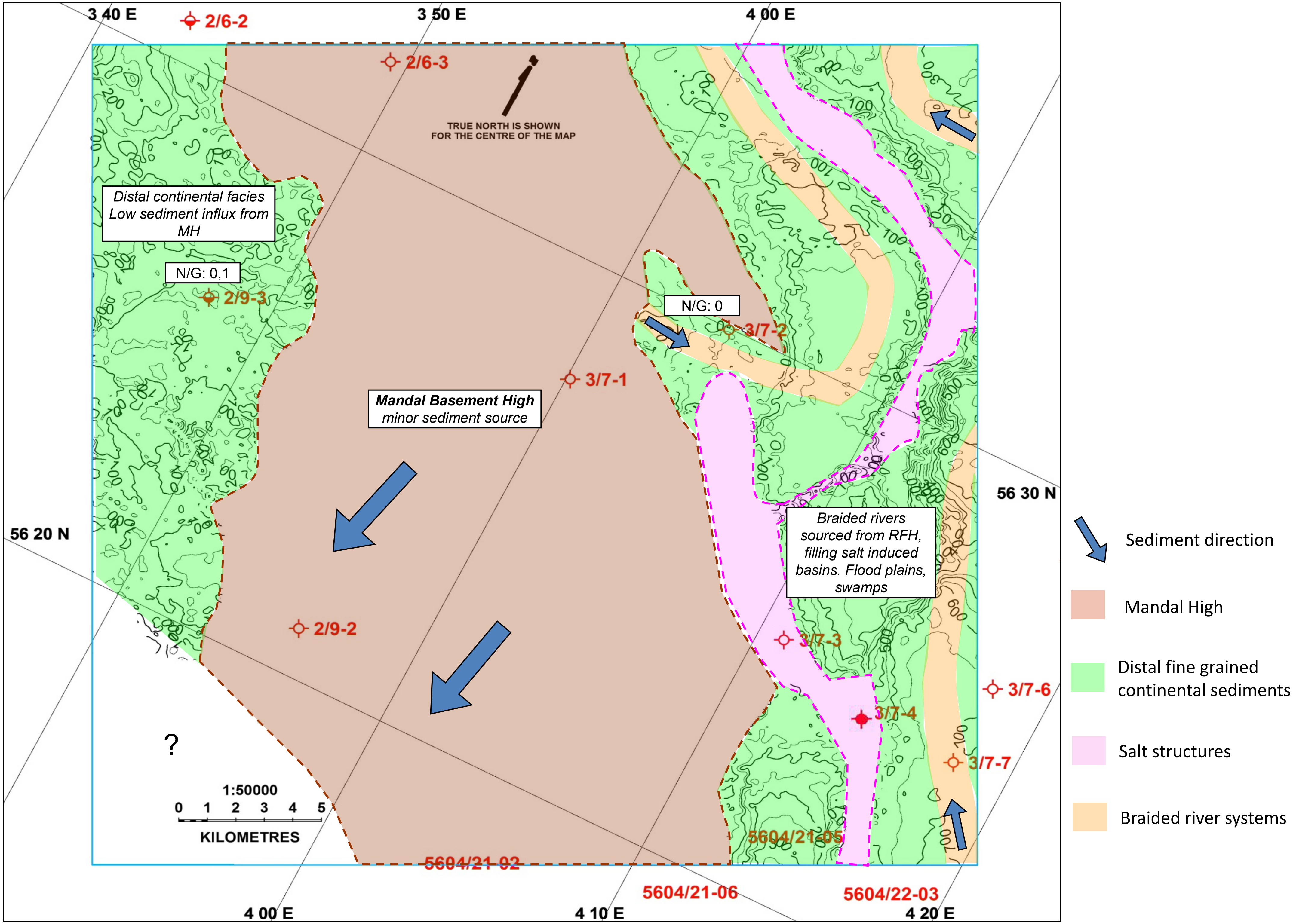

Figure 28: Paleogeographic map of the Triassic (sequence 3).

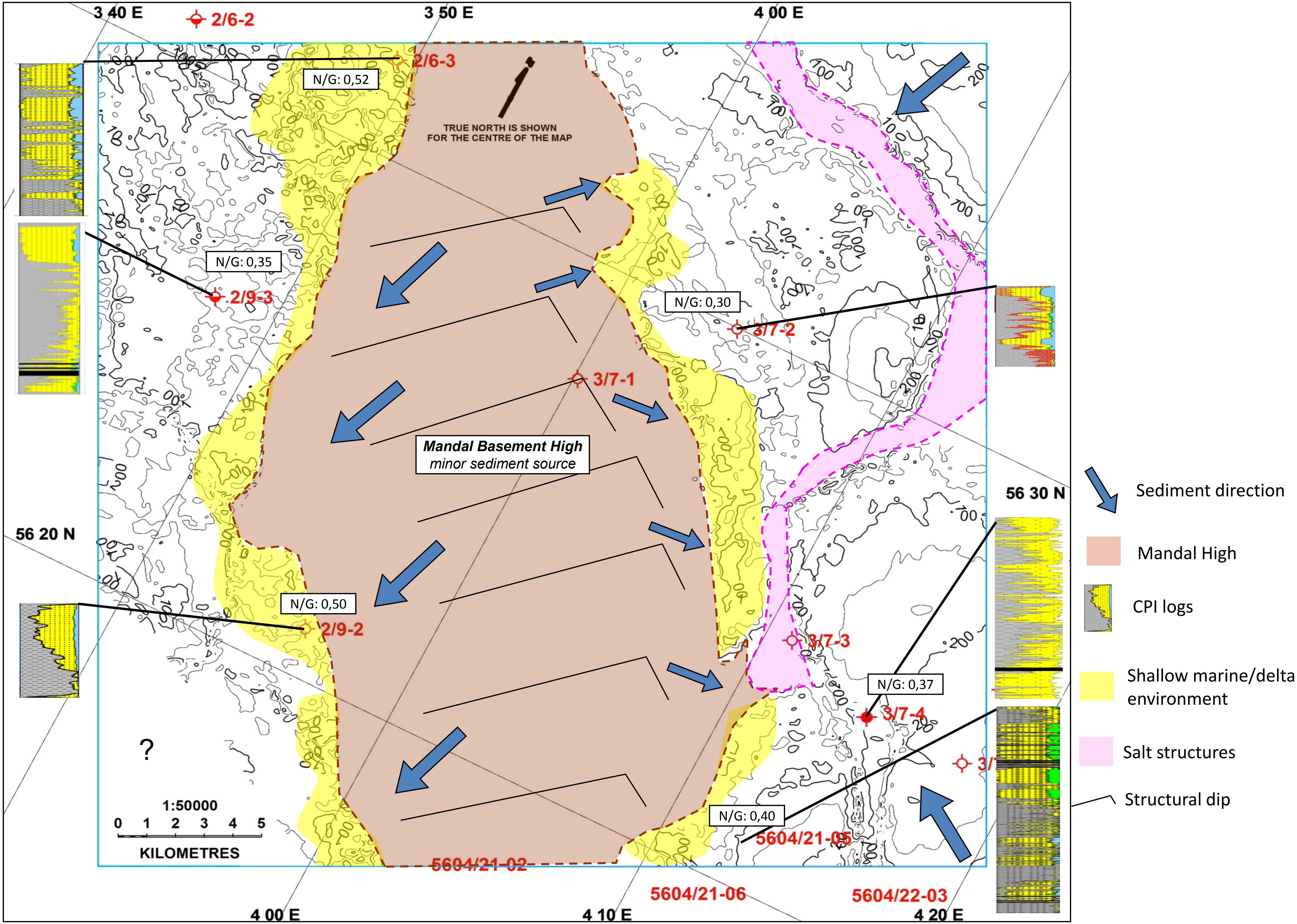

Figure 29: Paleogeographic map of the Middle Jurassic (sequence 4). Increasing net to gross towards the Mandal High.

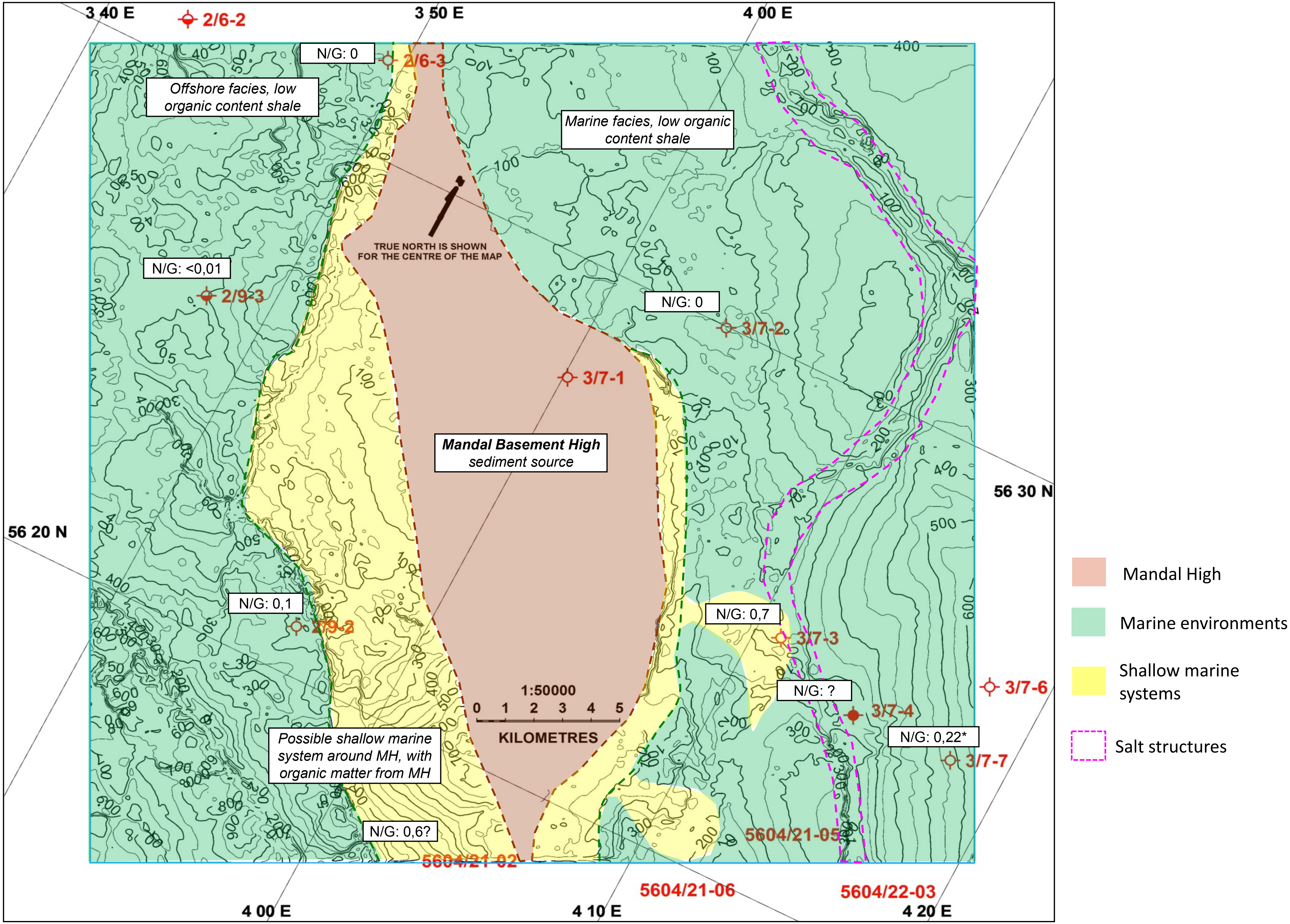

Figure 30: Paleogeographic map of the Upper Jurassic (sequence 5).

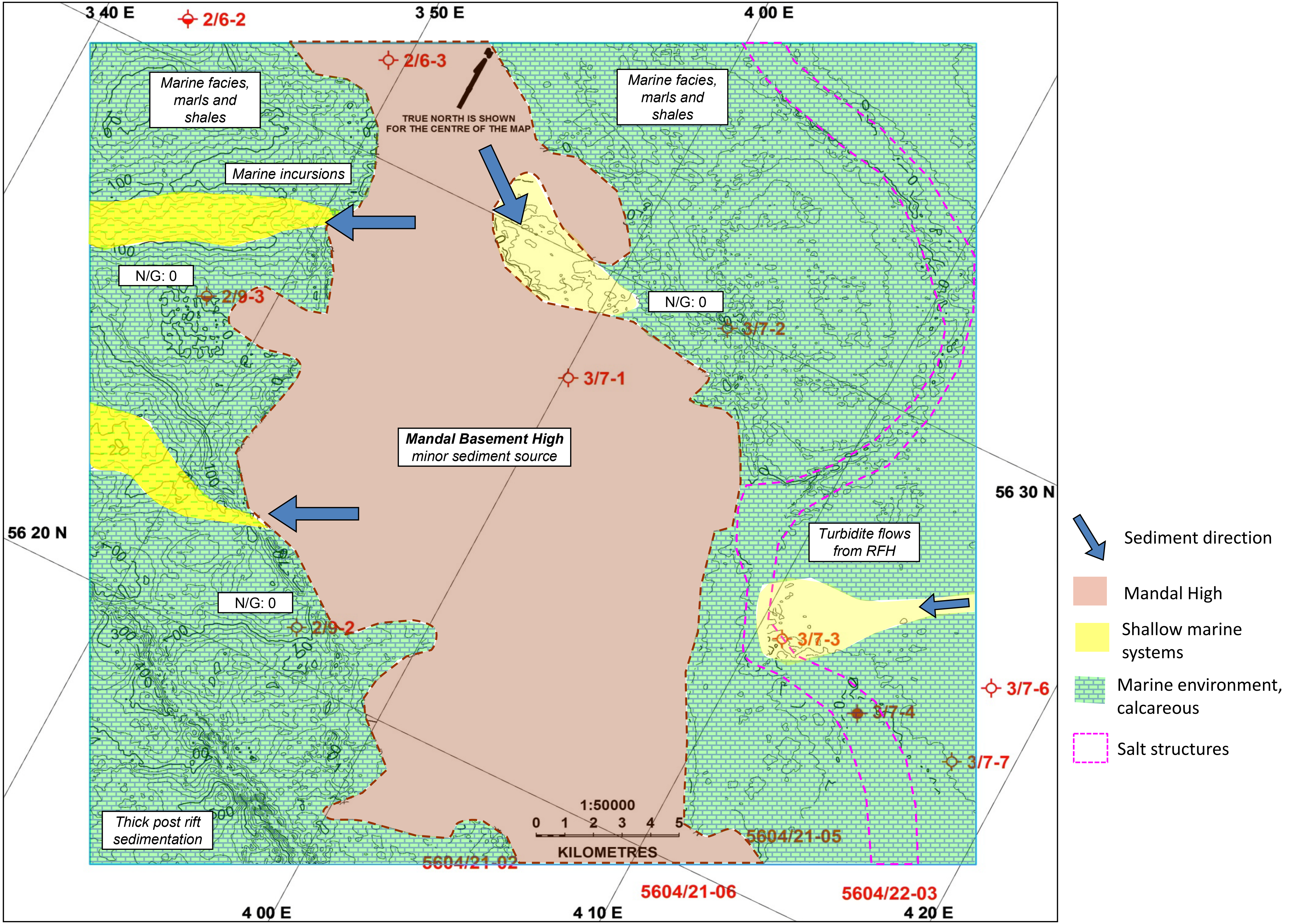

Figure 31: Paleogeographic map of the Lower Cretaceous (sequence 6).

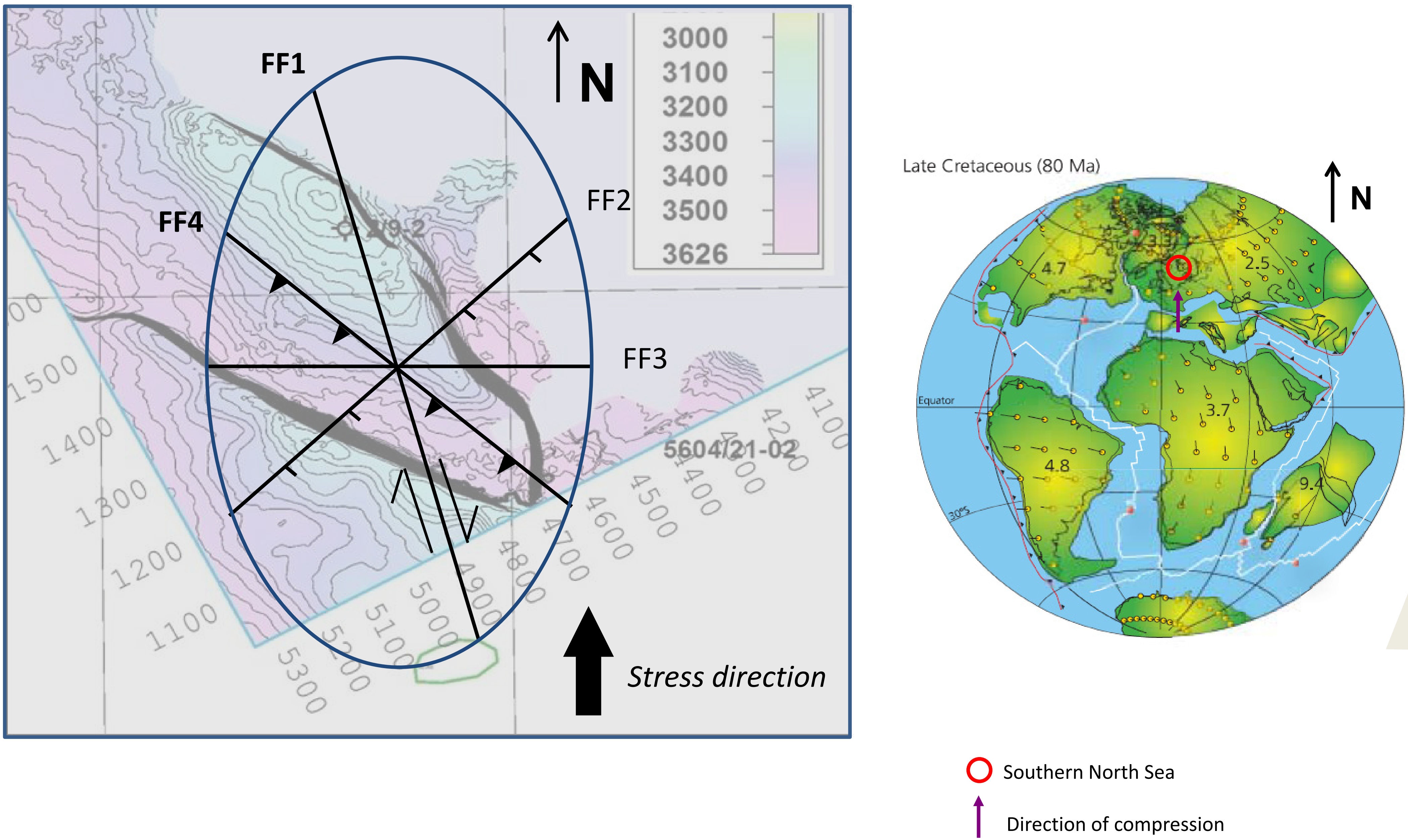

Figure 32: Top Lower Cretaceous structure TWT map overlain by a stress ellipsoid with fault families 1-4. Stress direction towards the north. To the right: Plate reconstruction at Cretaceous times, with study area outlined in red, and compressional direction by purple arrow (Torsvik et al. 2002).

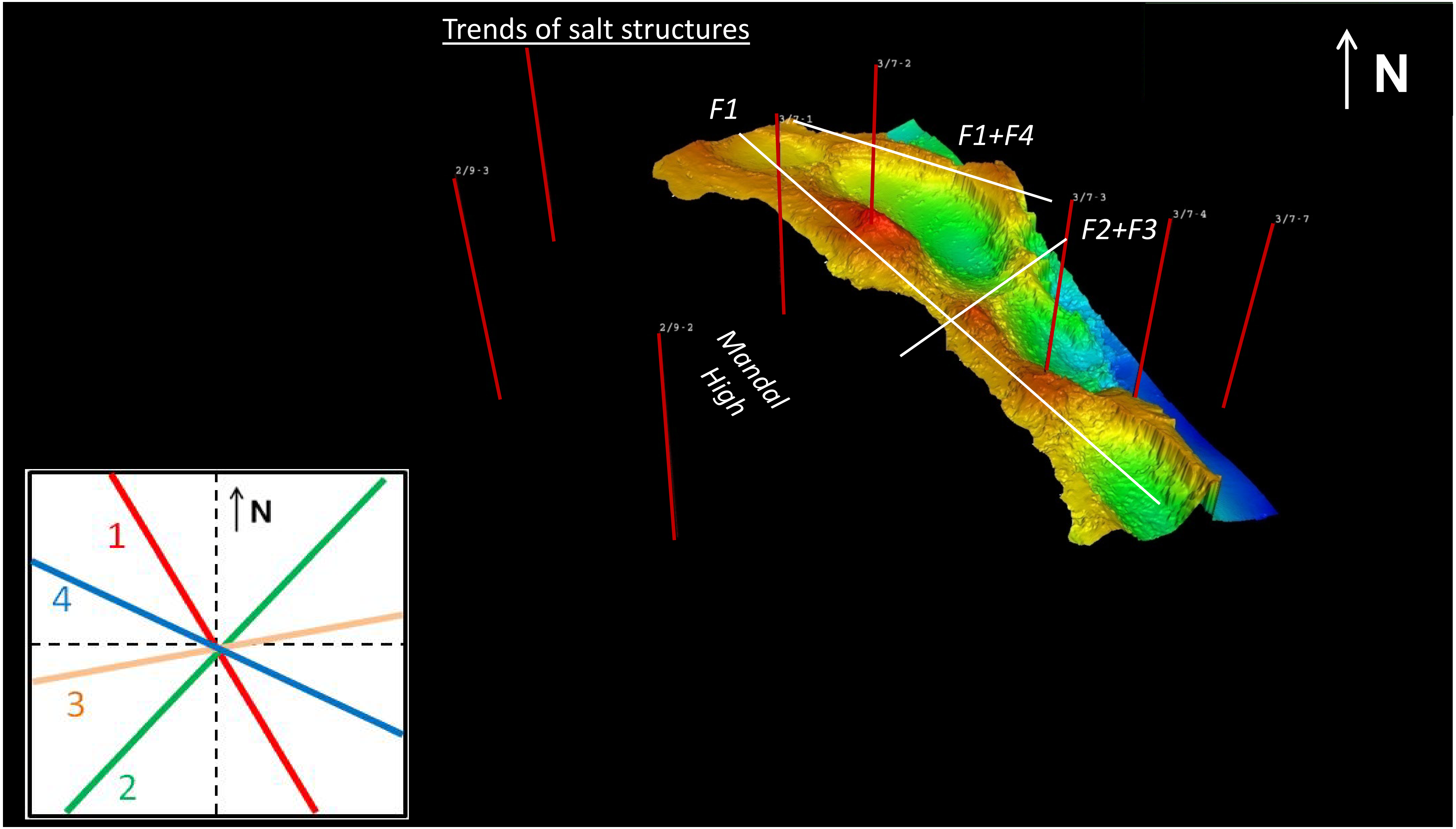

Figure 33: Structure TWT map of Top Zechstein Salt, 3D view, with lineaments and relation to fault families.

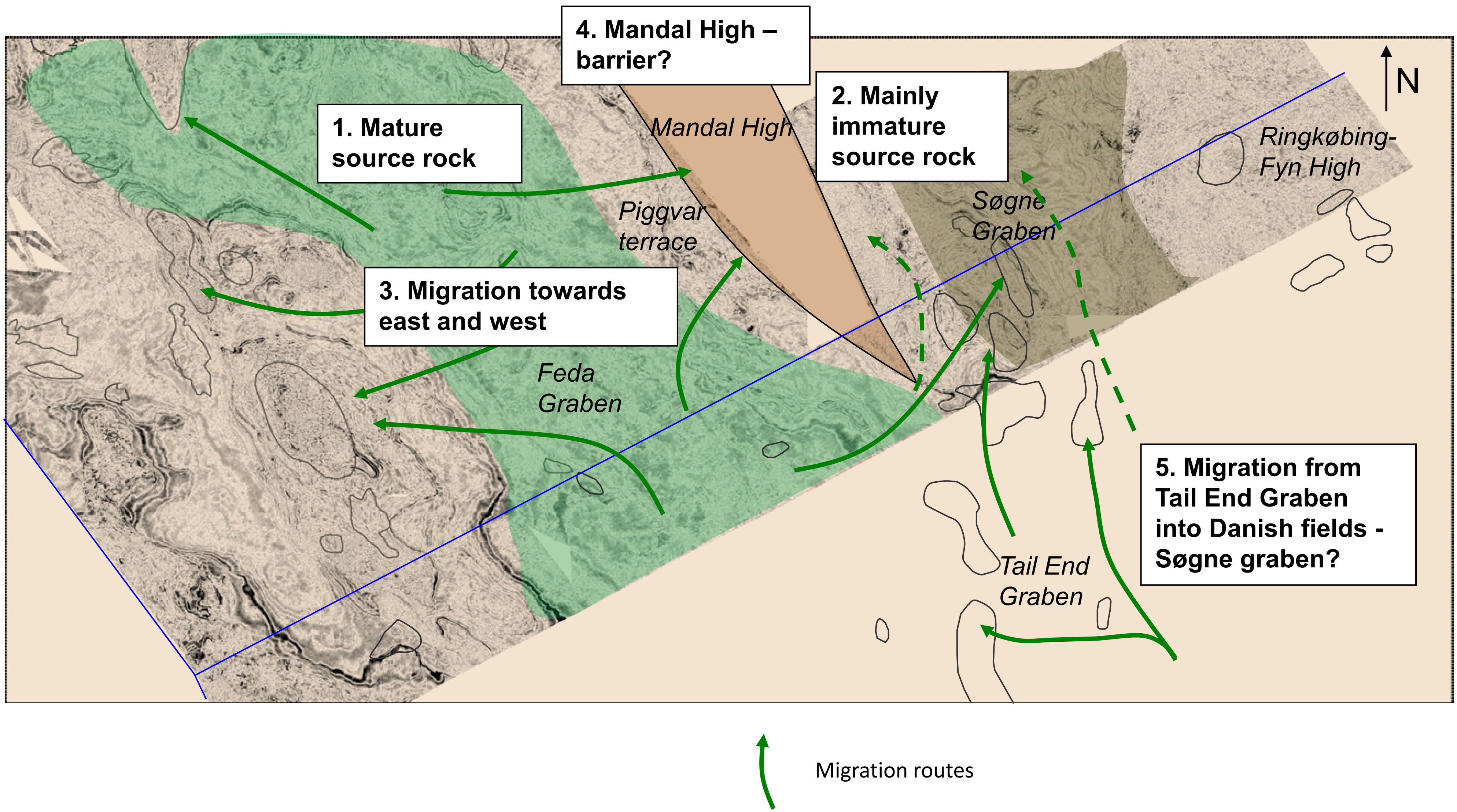

Figure 34: Regional evaluation of source rock and migration.

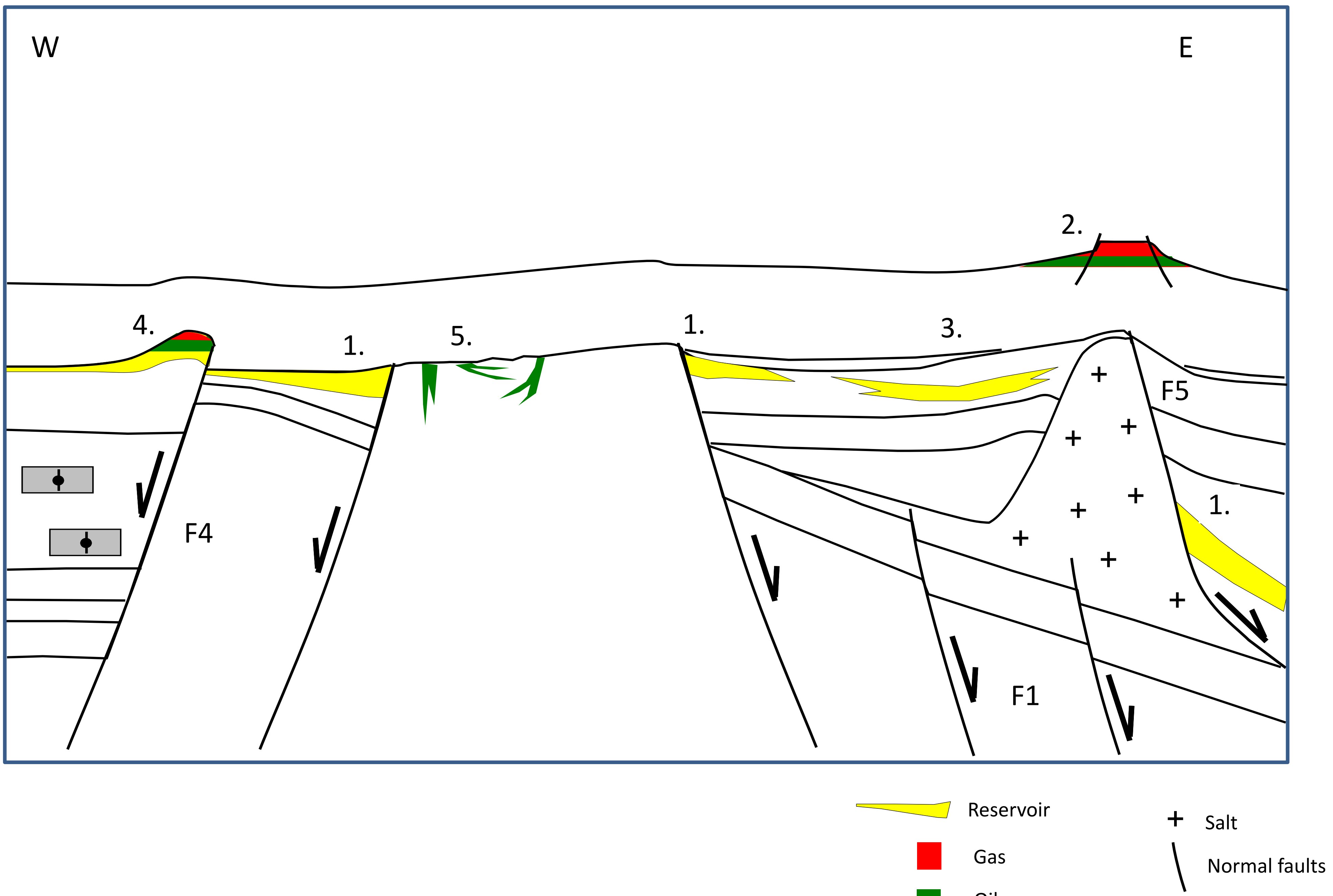

Figure 35: Proposed hydrocarbon trap and reservoir distribution in the Greater Mandal High area.

Conclusions

A new 3D seismic cube (PGS GeoStreamer technology) covering the Mandal High for the first time has been the basis for this study. With the focus on different seismic interpretation techniques (i.e. Conventional 2D seismic interpretation, time slice interpretation and attribute maps), a detailed study of the geological evolution and petroleum system has lead to the following conclusions:

The Mandal High is a crystalline basement high shaped as NW-SE trending horst. The high was initially formed as a sub aerial exposed high during the Triassic. The high was not flooded until the Upper Cretaceous. Lineaments of faults in the crystalline basement of the Mandal High include mainly two directions: near N-S and NE-SW. We propose that they follow the lineaments of a structural grain established in the Caledonian orogeny.

Five fault families, ordered chronologically, have been identified. Originally, all the faults formed as normal faults. Fault family 1 and 2, oriented near N-S and NNE-SSW respectively, suggests Lower Permian rifting controlled by the inherited Caledonian structural grain. The W-E oriented faults of fault family 3 may also be traced back to Lower Permian rifting. Another possibility is that they are a response to the heavy volcanic activity induced by the W-E oriented Permian Mid North Sea Dome. Fault family 4 is present on the Piggvar Terrace and show a set of large displacement normal faults with a NW-SE orientation. It is associated with the Upper Jurassic rifting event, reactivated as reverse faults in the Upper Cretaceous, creating inversion structures. The last and fifth fault family has various orientations and is associated with deformations induced by salt movements.

Volcanic and continental clastic rocks were deposited in the Lower Permian. Flooding and subsidence led to salt deposition in the Søgne Basin in the Upper Permian. In the Triassic fine grained clastics and fluvial sediments were deposited in a continental setting. The onset of the Mid North Sea Dome created delta and shallow marine systems in the Middle Jurassic, possibly also evolving around the exposed Mandal High. Upper Jurassic transgression caused the deposition of low energy marine and deep marine sediments. Shallow marine system may have evolved around the Mandal High. Lower Cretaceous shales with carbonates deposited in a marine environment. Regional flooding in the Upper Cretaceous led to the deposition of the chalk groups. In the Tertiary, basin subsidence caused the deposition of marine clastic sediments

Salt structures and mobilization in the Søgne Basin have served as an important structural and depositional control. The salt structures formed upon faults of fault family 1, 2 and 3, inheriting the Caledonian structural grain controlling these faults. Salt mobilization occurred in three pulses: The Triassic, Upper Jurassic and Upper Cretaceous-Tertiary. Movements of the salt resulted in a complex set of salt structures and depocenters, and deformed layers above.

The petroleum system of the Mandal High is considered to be an analogue to the successfully explored Utsira High. Several plays have been identified. Shallow marine plays around the highs together with fractured basement plays have never been drilled, but assumed to exist based on observations of this study. A proven mature source rock exists in the western Feda Graben and the southern Tail End Graben, but uncertainty exists with regards to migration.

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