LINKING ONSHORE AND OFFSHORE CRUSTAL FEATURES, INTEGRATING SEISMIC AND BOREHOLE DATA IN THE GAMTOOS BASIN.

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Submitted in fulfilment of the requirements of a Masters degree in Geology at the Department of Geosciences & AEON, Nelson Mandela University,

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DECLARATION:

I declare that **LINKING ONSHORE AND OFFSHORE CRUSTAL FEATURES, INTEGRATING SEISMIC AND BOREHOLE DATA IN THE GAMTOOS BASIN** is my own work, that it has not been submitted before for any degree or examination in any other university, and that all the sources I have used or quoted have been indicated and acknowledged by means of complete references.

Signature  Date: 13 July 2020

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ABSTRACT

The margin of the Southern Africa continent harbours the history about the fragmentation and separation of Gondwana in its basins. The integration of onshore and offshore geology is of primordial importance to understand the complete geological history and evolution of the southern African border. The study focuses on the Gamtoos Basin, where the sediment deposits on the onshore portion are generally unfossiliferous and therefore difficult to correlate with the offshore portion of the basin. In an attempt to do this, several datasets were integrated such as old 2-D seismic reflection data and borehole wells. This data, acquired by SOEKER in the 1970s was purchased from the Petroleum Agency of South Africa (PASA). Some data reprocessing involved digitization and conversion of the old seismic data from TIF format to SEG-Y format. Conventional seismic stratigraphic method (Mitchum, JR, et al., 1977) was used to identify seismic discontinuities and remarkable stratigraphic surfaces and units based on reflection configurations and facies characteristics, and ages of these surfaces were provided by well data. Seismic interpretation was first done on printed seismogram papers, and then integrated into the ‘Kingdom Suite’ software to ensure coherency at all crossing lines. Isochron and Isopach maps (using QGIS, Mirone and tools such as GMT) were created. The first results, allow us to estimate for the first time a precise age calibration of onshore deposit. Furthermore, the delimitation in 5 second-order seismic sequences along the Gamtoos Basin suggest a link between different basin filling dynamics and kinematic phases related to the opening of the Indian and Atlantic Oceans along the southern Africa margins. The study shows that the Gamtoos Basin is an essential area linking the geological histories of both East and Western parts of the Southern Africa continent.

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INTRODUCTION

The studying of the Gamtoos basin which lies along the passive margin of the Southern Africa continent is of key importance to the understanding to the fragmentation and separation of Gondwana during the Mesozoic and Cenozoic Era.

Investigations have been undertaken by several authors to study the geological processes involved in the offshore portion of the basin and its outlier (e.g Paton and Underhill, 2004; Dingle et al., 1983). The outlier is less well-known because the stratigraphy is poorly understood. The lithofacies (predominantly continental and fluviatile) onshore are sparsely fossiliferous and cannot be dated making it is difficult to correlate on a regional basis due to the absence of chronostratigraphic markers (Dingle et., 1983). The basin thus remains poorly understood because linking onshore-offshore processes remains a challenge (Linol, et al., 2016). Secondly, the depositional sequences within the Gamtoos Basin have not been constrained by rifting associated with the separation of the continents during the Mesozoic Era.

The purpose of this study therefore is to do a correlation of the stratigraphy onshore and offshore to determine whether the offshore portion of the basin is a continuation to the onshore outlier. Additionally, to link the basin sedimentary episodes to kinematic phases within Mesozoic. The objectives to understand and reconstruct the geodynamic evolution of this domain will thus be met. The Petroleum Agency of South Africa (PASA) has made available 2D seismic reflection and borehole datasets that will enable an integrated onshore-offshore interpretation using the seismic stratigraphy method and standard industry software such as Kingdom Suite and QGIS.

CHAPTER 1

1.1 Geographic Location of the Study Area

The Agulhas Bank is between 0-500 below sea level, lying along the south and south east coasts of the South Africa continent. It is flanked to the east by the Agulhas-Falkland Transform Zone (AFFZ). In the SE, lies several rift basins, including the Gamtoos Basin *(Figure 1)*. The basin has an area of 5,0.38km^2, drained by the 645 km long Gamtoos River and bounded to the south by the Gamtoos Fault and shelf break. It is not known how far sediments extend in the abyssal plain. The South African continent forms the southern tip of Africa, with a coastline along the Southern Oceans that stretches more than 2,850 kilometres from its western to eastern border. The topography is characterised by a 1000-3000m relief from the Cape Karoo Mountains. The relief decreases to 0-300m along the coastal region. The continent is covered by a vast river drainage network, which contribute depositing sediments offshore onto the 240 km wide Agulhas Bank.

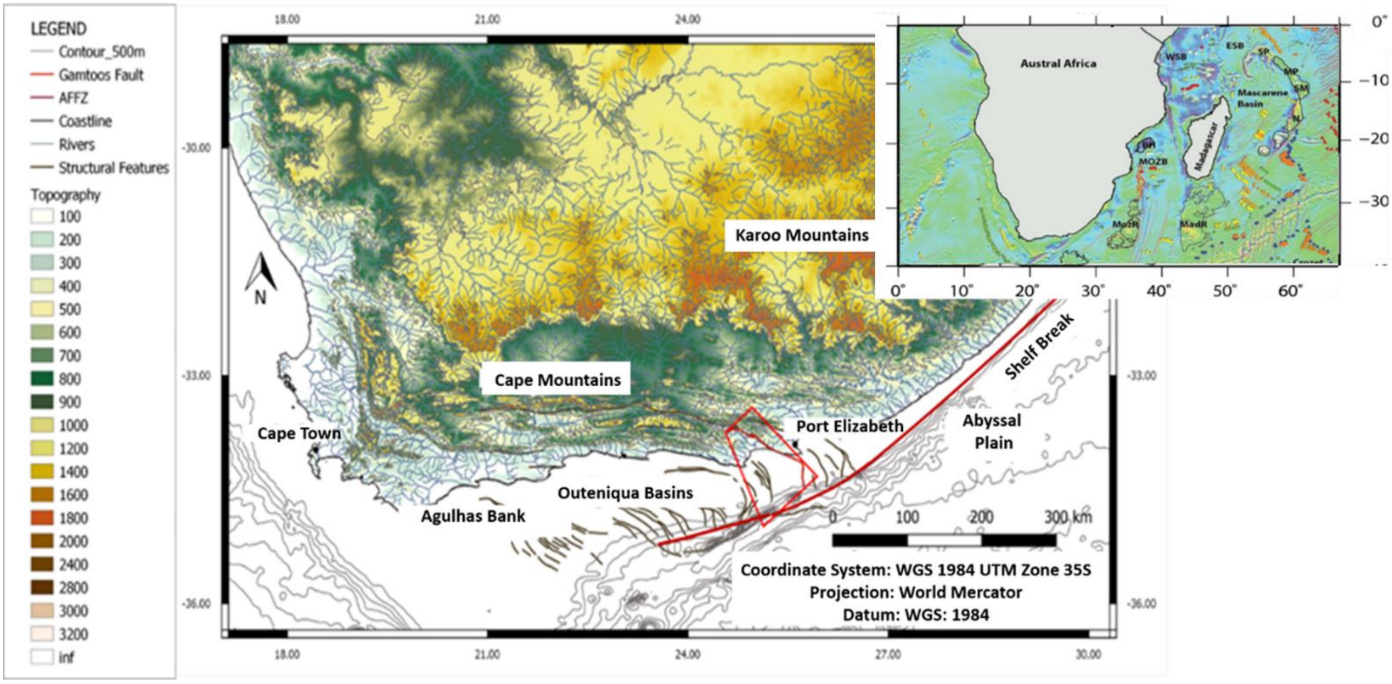

Figure 1: Location map of the Gamtoos Basin within the physical geography of Southern Africa margins. The location of the study area is outlined by the red block.

1.2 Data Description and Location

For this study, data collected, and reports compiled by SOEKER in the 1970s in the Gamtoos Basin were made available by the Petroleum Agency of South Africa. Different datasets were integrated *(figure 2)*. A total of 5 2-D seismic reflection lines and 3 boreholes were used. In the offshore part of the Gamtoos Basin, 4 seismic lines with 1 borehole were provided and in the onshore part, archival data comprised of 1 seismic profile was made available in TIF format (Tagged Image File) including 2 boreholes. The old seismic profiles were digitized and converted to the standard SEG-Y format. In addition to this, fieldwork was conducted onshore, in the Hankey and Patensie Towns situated in the Gamtoos Basin.

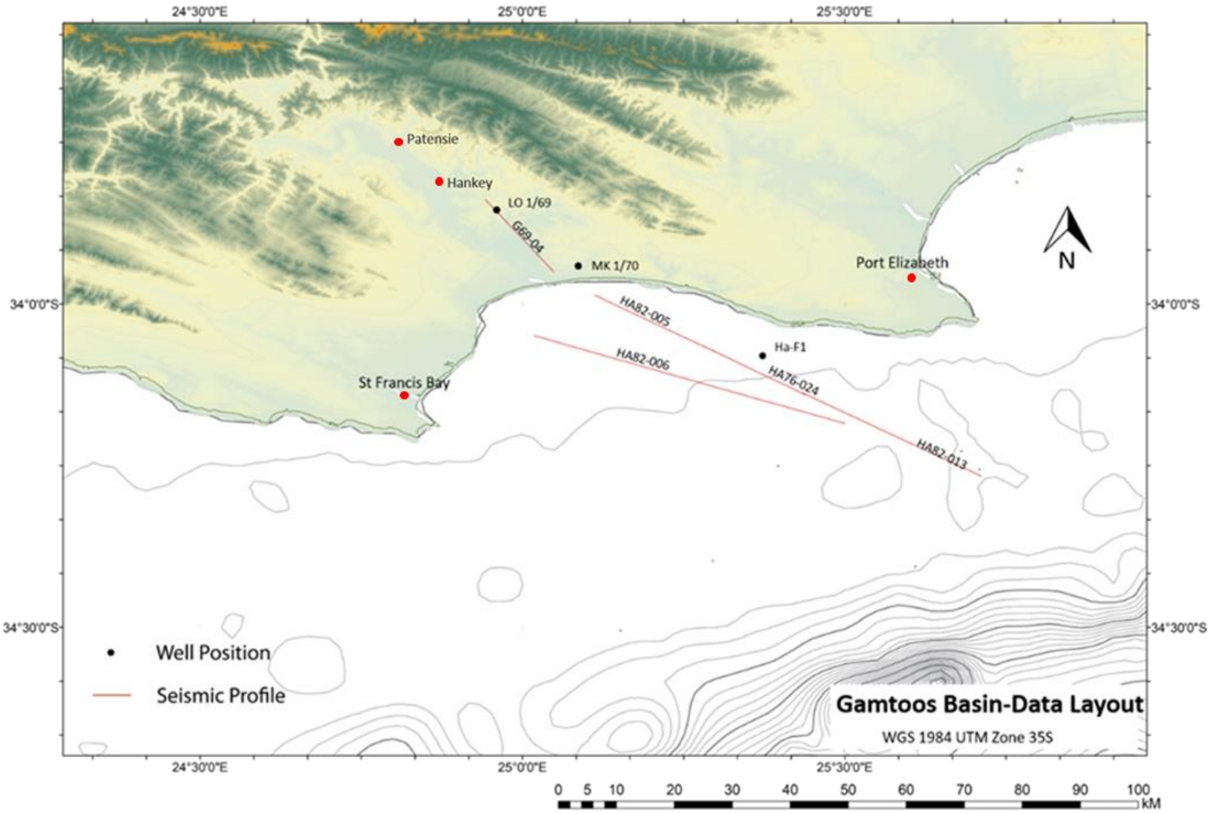

Figure 2: Map showing the location of borehole and seismic reflection data in the Gamtoos Basin used in this study. Borehole = black dot, Seismic Line = red line.

CHAPTER 2 – GEOLOGICAL AND TECTONIC SETTING

2.1 Gondwana Break-up and Evolution

2.1.1 The history of separation of Africa from the Gondwana Supercontinent

The history of Gondwana break-up is recorded in its margins. The southern Africa margins formed as a result of the break-up and separation of East Gondwana from West Gondwana and then the break-up of Southern America from Africa *(figure 3)* (McMillan et al., 1997; Tuck-Martin, 2004). Along the western margin are features evident of a volcanic rifted margin whilst the south-east coast is a transform margin that formed as result of the relative motion of Africa and South America along the Agulhas-Falkland Transform Zone (AFFZ). The margin experienced shearing as a consequence of dextral strike-slip motion during the Cretaceous (145 Ma) (Stankiewicz, et al., 2008). The southern part of Africa is the emplacement of voluminous basaltic lava flows and intrusive gabbro of the Karoo Large Igneous Province. The Mesozoic sedimentation is contemporaneous with the separation of Madagascar and India from Africa, and of Africa and South America (Dingle et al., 1983; McMillan et al., 1997; Linol et al., 2016). On the southern African margins, the sediments generally record a history of initial continental rifting during the Middle-Late Jurassic to latest Valanginian, followed by a drifting episode from (Early Aptian to present day) (McMillan et al., 1997). Subsequent to the break-up of Gondwana, occurring contemporaneously with the rifting of the South Atlantic Ocean, the Cape Fold Belt underwent a tectonic inversion and basement resetting (de Wit and Ransome, 1992).

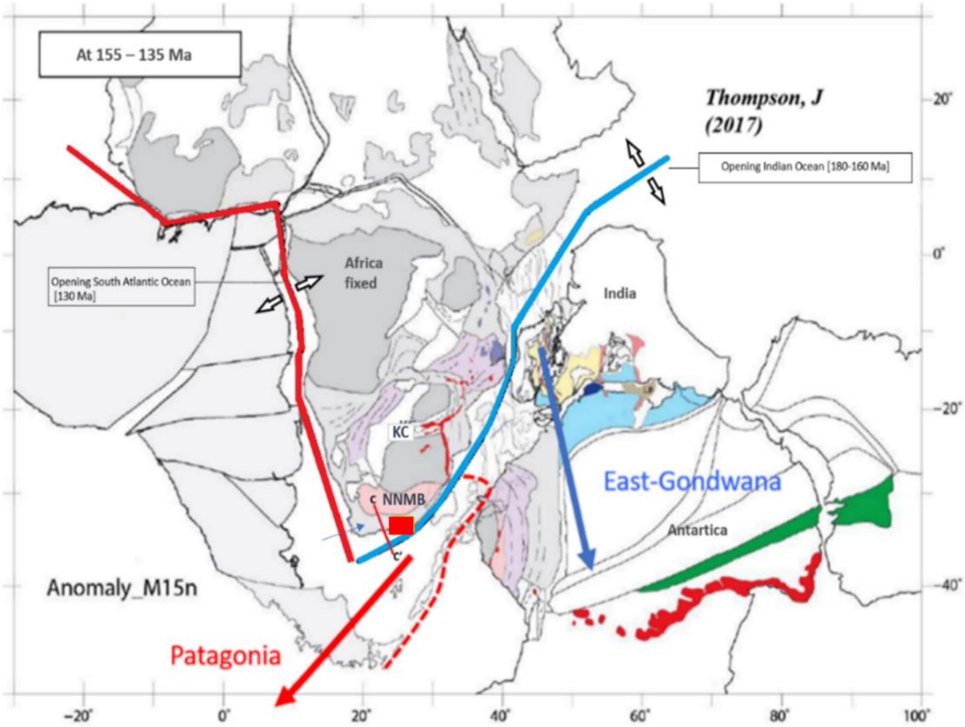

Figure 3: Gondwana reconstruction showing separation of East Gondwana from the African plate during mid-Jurassic (155Ma) age and movement of Patagonia and South America during the Cretaceous (135 Ma). Also shown is the location of the study area (red block). KC=Kaapvaal Craton, Transect c-c'= Agulhas – Karoo Geoscience Transect (Modified from Thompson et al, 2019).

2.1.2 Crustal Structure of the South African Margin

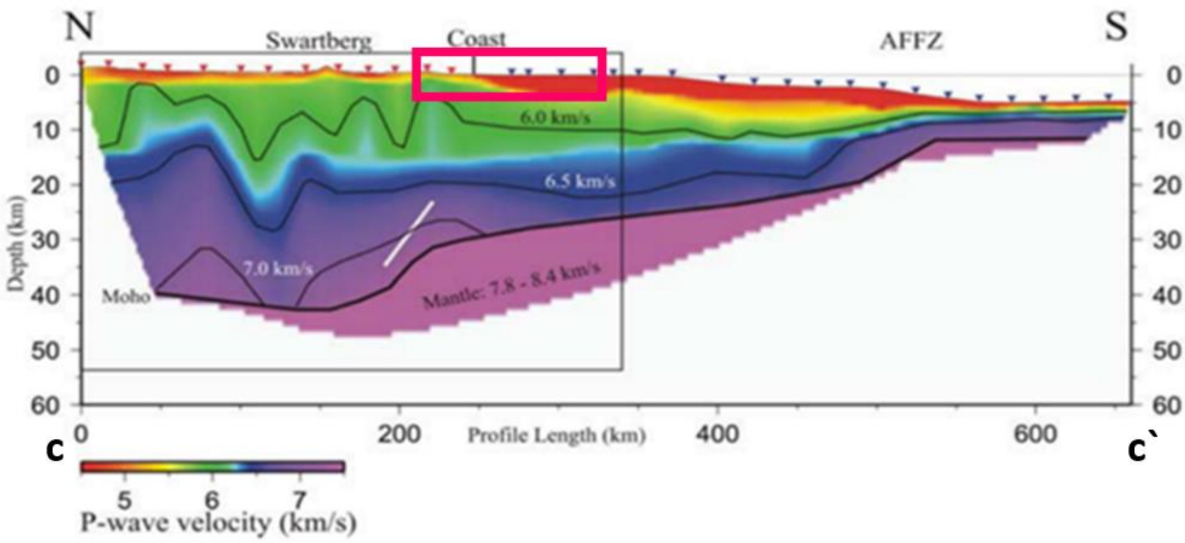

Figure 4: P-wave velocity model of the Agulhas - Karoo Geoscience Transect extending from the Agulhas Plateau across the Agulhas - Falkland Fracture Zone (AFFZ) and inland as far as the southern boundary of the Kaapvaal Craton (see figure 3 for location). Velocity contours between 6.0 and 7.0 km/s in the upper crust show an abrupt decrease in the coastal area and offshore towards the Agulhas-Falkland Fracture Zone. The studied area is shown with a red box (modified from Stankiewicz, 2008).

The Kaapvaal Craton is comprised of eastern (3.5 Ga) and western domains (3.2 Ga), whilst the Namaqua-Natal Mobile Belt (NNMB- 1.4 -1.0 Ga) is of metabasic lithologies with possible mafic intrusions added to the base of the crust by younger Mesoproterozoic magmatism *(figure 3).* A previous wide-angle seismic study shows a variation in thickness of the continental crust of the southern Africa margin. The Agulhas-Karoo Geoscience Transect, which extends from the Agulhas Plateau, across the CFB and up to the boundary between the NNMB and the Kaapvaal Craton *(figure 3),* shows an abrupt change in the crust thickness from 20-40 km *(figure 4).* In the region, the abruptly decreasing Moho depth corresponds to where the boundary between the NNMB and the CFB where crustal P-wave velocities up to 7.4 km/s are observed. This refraction seismic profile also shows that the Moho depth decreases rapidly from over 40 km inland to around 30 km at the present coast before gently thinning out toward the AFFZ. The location of the study area *(figure 4)* is lying directly above (at length 190 -220 km) the region of abrupt change in crust thickness considered to be the first necking zone from a depth of 35 km to 23 km. The depth is consistent with values obtained from an older east-west reflection profile, which runs approximately 10 kilometres south of the coast (Stankiewicz, 2008; Durrheim, 1987). Farther south, the crust thins more gradually for another 250 km underneath the Agulhas Bank, Outeniqua Rift Basins and the Diaz Marginal Ridge until it reaches the AFFZ. The depth of 11-12 kilometres for the Moho (i.e., 6-7 kilometres of crust under 5 kilometres of ocean) is observed in the Agulhas Passage, where the southernmost 130 kilometres of the profile stretches (Stankiewicz, et al., 2008).

2.1.3 Inversion of the Cape Fold Belt

Along the southern coastlines and to the south of the NNMB is the 1300 km long Cape Mountains, which trend in an east-west direction (Blewett & Phillips, 2016). The belt comprises thick, folded sequences of Palaeozoic sandstones and shales of the Cape Supergroup (Stankiewicz, et al., 2008). The Cape Mountains underwent two inversion events. The first positive inversion event occurred during the Cape Orogeny (252 Ma). Subsequent to this was a negative inversion event in Middle to Late Jurassic times (180-155Ma). During this event the Permo-Triassic thrusts were reactivated as normal faults. Large depocenters in the form of E-W to NNW-SSE orientated half-grabens were formed along the Agulhas Bank (de Wit and Ransome, 1992; Gresse, 1992; Baby et al., 2018). These are evident in the present-day Agulhas

Bank as four offshore marginal basins, bounded by south-dipping normal faults and named the Outeniqua Rift Basins *(Figure 5).*

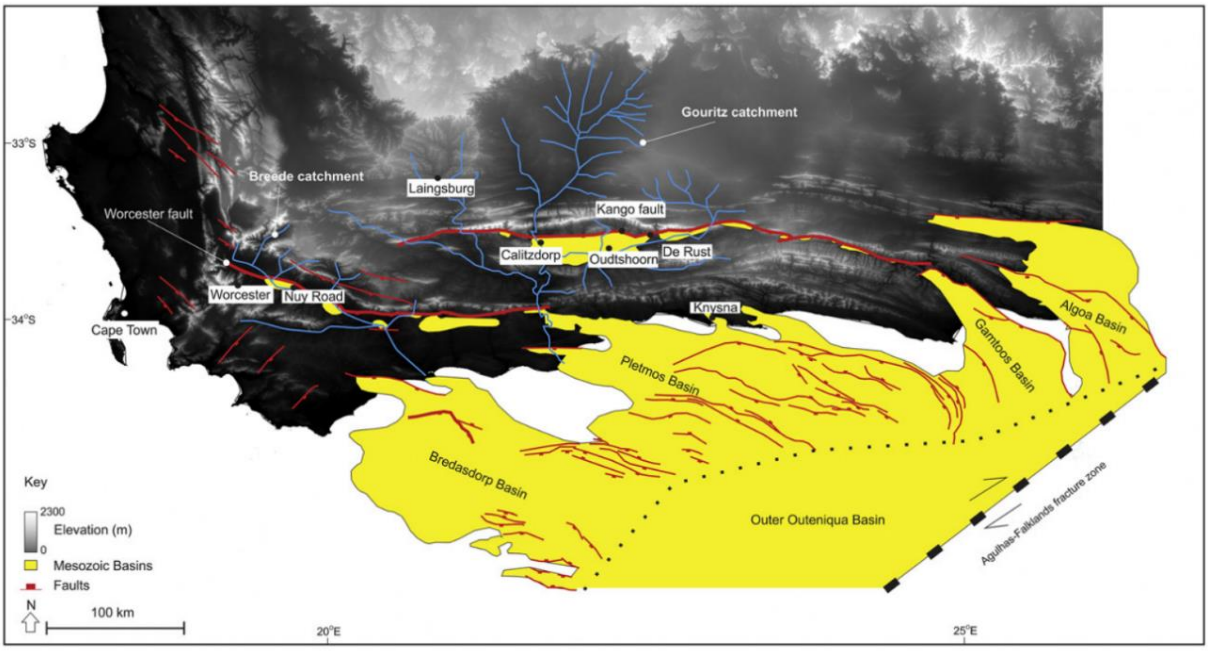

Figure 5: Map showing the four Outeniqua Rift Basins of Southern Africa, adapted from Richardson et al (2017).

2.1.4 Formation of the Outeniqua Rift Basins

Along the Agulhas Bank the Outeniqua Rift Basins are named from the west to east: the Bredasdorp, Pletmos, Gamtoos and Algoa Basins which are separated by fault-bounded basement arches composed of the Cape Supergroup meta-sediments. To the west, the basins are bounded by the Columbine-Agulhas Arch, to the east by the Port Alfred Arch and to the south by the Diaz Marginal Ridge (DMR) (Johnson et al., 2006; Stankiewicz, 2008). The rift basins exhibit a variety of structural styles showing extension and inversion, which could have been possibly inherited from the strike-slip deformation along the AFFZ (Thomas, 1999). The oldest datable sediments drilled in the Outeniqua Rift Basins are of Kimmeridgian/Oxfordian (155-160 Ma) (Dingle et al., 1983; Thomson, 1999).

2.2 Geology of the Gamtoos Basin

2.2.1 Fault Geometry

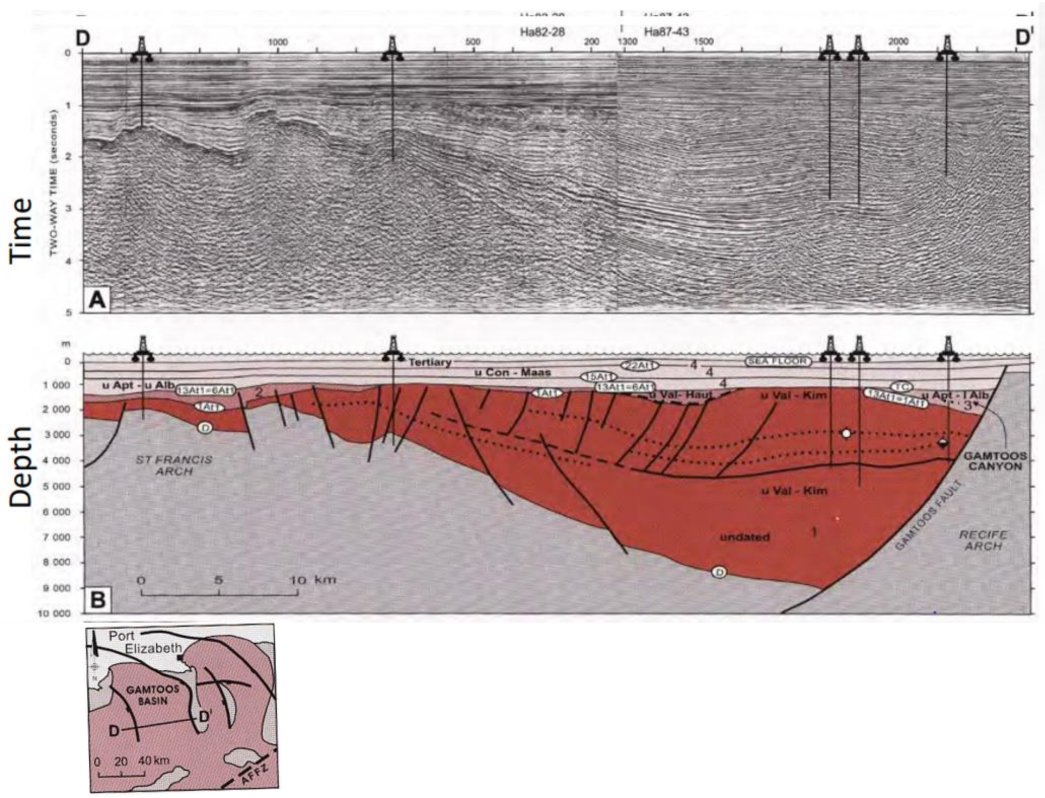

Figure 6: A seismic and interpreted geological profile D-D' across the Gamtoos Basin, illustrating the structural style and vertical extension of the listric Gamtoos fault (Broad et al., 2006).

Bounding the Gamtoos half-graben to the north-east, is the 490 km-long Gamtoos Fault *(figure 6b)*, trending from a ESE-WNW strike onshore N-S strike offshore *(figure 7b)* (Thomson, 1999). Onshore the Gamtoos Fault has a downthrow of about 3 km. Offshore the fault plane can be traced on reflection seismic data to a depth of approximately 12 km (5.5 seconds two-way travel-time). The seismic profiles across the fault reveal a listric nature *(Figure 6b)*. The fault likely formed as a result of the break-up of Gondwana and established its length very early in its syn-rift phase. In the offshore portion the fault makes an almost 90°bend (Paton & Underhill, 2004). The change in fault strike has been interpreted to be as a result of the Cape Fold Belt and the influence of its flat-lying thrust sheets affecting the listric nature of the Gamtoos Fault (Thomson, 1999). In contrast, Ben-Avraham, Hartnady and Malan (1993) attribute this change to the movement of the Patagonia plate along the AFFZ during the break-up of Gondwana. McMillan et al. (1997) mentions that in the Gamtoos Basin, there are additional major faults in the basin that occur on the eastern flanks of the shallow St. Francis Arch (*figure 6*).

2.2.2 Stratigraphic Framework of the Jurassic-Cretaceous Sequences

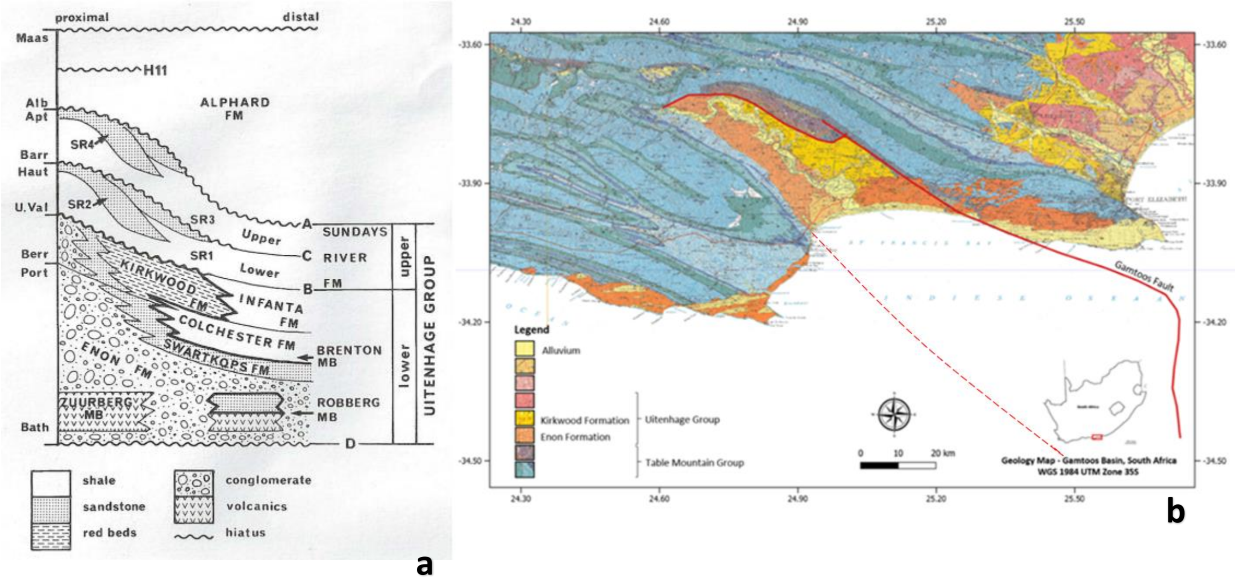

Figure 7 (a-b): General stratigraphy of the Uitenhage Group in the Outeniqua Rift Basins (Modified from Dingle et al., 1983). (a) a cross-section showing the stratigraphic and proximal-distal relationship between Jurassic and Cretaceous deposits in the Outeniqua Rift Basins (b) A map of the Gamtoos Basin (study area) showing the arrangement of the formations onshore.

The Zuurberg Member

The Zuurberg Member *(figure 7a)* unconformably overlies folded and eroded rocks of the Witteberg Group (Cape Supergroup) and Dwyka Group (Karoo Supergroup). It is overlain by sandstones and conglomerates of the Upper Jurassic Enon Formation. The Zuurberg Member comprises a lower clastic package of breccia, conglomerate, shale, sandstone and volcaniclastic deposits overlain by a sequence of pahoehoe flows of tholeiitic basalt (Linol et al., 2016).

The Robberg Member

Deposited at distal parts within the Enon Formation is the Robberg Member. This deposit is described as silicified conglomerate, slightly modified conglomerates of the Enon Formation. The conglomerates are abundant in fauna.

Swartkops Formation

The formation is a distal vertical and lateral facies equivalent of the Enon Formation. It is comprised of medium to fine-grained, poorly-sorted angular to sub-angular quartzitic sandstones. The sandstones are interbedded with minor brownish and dark grey shales suggested to be of Upper Jurassic or older. There have been no fossils recorded in the formation. The Swartkops Formation is not mapped in the Gamtoos Basin.

Colchester Formation

The Colchester Formation underlies the Kirkwood Formation at distal parts in the Outeniqua Rift Basin. The formation is interpreted to be of Upper Jurassic in age. It is comprised of grey sandstones and clays, and sandy limestones which locally contain estuarine and shallow marine invertebrate fauna, as well as vertebrate bones and plant fragments. The Colchester Formation is not found in the Gamtoos Basin (Dingle et al., 1983b).

Infanta Formation

The Infanta Formation occupies a similar position with the Kirkwood Formation in the succession and is its distal facies equivalent. The formation is described as a thick sequence of light grey to medium grey (occasionally dark grey) siltstones, clays and shales which are known only from boreholes in the Outeniqua Rift Basins. This formation is not recorded in the Gamtoos Basin (Dingle et al., 1983). The Infanta Formation in the Outeniqua Basin shows a paucity of sandstone, a lack of lithologic differentiation and a poorly fossiliferous and stratified character. This indicates that the Infanta Formation was deposited in a low-energy environment, under limited marine influence such as prevails in a lagoon, estuary or epi-continental sea (Du Toit, 1995).

Sundays River Formation

The Sundays River Formation appears to grade laterally into more proximal Kirkwood Formation deposits. It consists of thin, grey sandstones, siltstones and mud rocks. The sandstones are fine to medium grained and often contain an abundance of shell fragments and associated carbonate cement. Small scale trough and planar cross-bedding occur in the sandstones. Interbedded sandstones and mud rock unit exhibit wavy, flaser and lenticular bedding. Wave-ripple and load structures are common. The Sundays River Formation has high fossil content, and coquinoidal sandstones with invertebrate shells and cemented with calcite. Plant remains, vertebrate fragments and microfossils are also common. The faunal association points to a shallow-marine depositional environment which may have encompassed estuarine, lagoonal and even shallow shelf settings. The sediments are possibly of Upper Valanginian to Hauterivian (140 – 130 Ma) (McLachlan and McMillan, 1976). The Sundays River Formation is not mapped in the Gamtoos Basin.

Cenozoic Deposits

Cenozoic deposits of nearshore marine, estuarine, fluvial, lacustrine and aeolian origin are developed along the Gamtoos Basin. The offshore Cenozoic strata are well developed around the entire coastline of the subcontinent. The thickest accumulations occur on the outer shelf and continental slope, extending to the deep-sea basin on the east coast. Sandstones and mud rocks are the main lithologies, although limestones and marls feature prominently on the east coast on the continental shelves (Johnson et al., 2006).

2.2.3 Outcropping Sedimentary Rocks and Depositional Environments

The Gamtoos Basin is comprised of the siliclastic deposits of Mesozoic to Cenozoic ages. Bounding the basin as prominent arches and underlying the Late Mesozoic sediments as the basement are the rocks of the Ordovician-Devonian Cape Supergroup (McMillan et al., 1997). Along the south-east coast, sediments of Middle-Jurassic to Late Cretaceous age were deposited in the basins. At Present, the thickest and most extensive Cretaceous and Jurassic sequences are found in the continental shelf, slope and rise offshore in the Gamtoos Basin. Tinker (2008) has shown that the timing of increased sediment accumulation closely matches the timing of increased onshore denudation. Great volumes of material were transported from source to sink during two distinct Cretaceous episodes; the early Cretaceous (136-130 Ma) and mid-late Cretaceous (93-67 Ma). Denudation decreased by an order of magnitude during the Cenozoic. This explains the decrease in stratigraphy thickness towards the onshore portion of the basin. The sedimentary cover displays a thickness of up to 8 km in the Gamtoos Basin offshore corresponding to 5.000 ms (TWT) from collected seismic data onshore. The Uitenhage Group makes up most of the sediment cover in the Gamtoos basin. The deposits of the Enon Formation lie unconformably on the quartzite basement. Overlying the Enon Formation is the Kirkwood Formation of Cretaceous age (135 Ma). This is followed by the Sundays River Formation which is not mapped in the study area; but outcrops in the Algoa Basin. Overlying these Mesozoic sediments are Cenozoic deposits.

Enon Formation

The sequence is described as closely packed, poorly sorted, generally unstratified conglomerates with silt/ sandy to clayey matrix which are intercalated with sandstone beds (McLachlan and McMillan, 1976; Shone, 2006). It is generally unfossiliferous (Dingle et al., 1983) though minor amounts of shale, quartz veins, fossil woods occur. The size of the clasts ranges from large quartzite pebbles to boulders and consists of sandstone *(figure 8)* derived from the Cape Supergroup. The quartzite boulders are laminated with percussion marks. This large-sized conglomerate is indicative of a high-energy environment is a possibly a marine (Hjulstrom-Type) fan delta (Rigassi and Dixon, 1972; Hill, 1972; Winter, 1973). The current

of sediment flow is toward north-east, toward the main fault.

Figure 8: At location 33° 45' 31.3" S 024° 41' 24.5" E in Hankey Area. A 30m thick bed of poorly sorted conglomerate of the Enon Formation.

<u>Kirkwood Formation</u>

The Kirkwood Formation is an alternation of sandstones with silty mudstones *(figure 9a).* Diverse assemblages of vertebrate, invertebrate and plant fossils of Mid-Late Valanginian (Early Cretaceous) age have been found. Wood trunks up to 6m long and 45 cm in diameter have been found at various localities (Engelbrecht et al.,1962; Gomez et al., 2002; Choiniere et al., 2012).

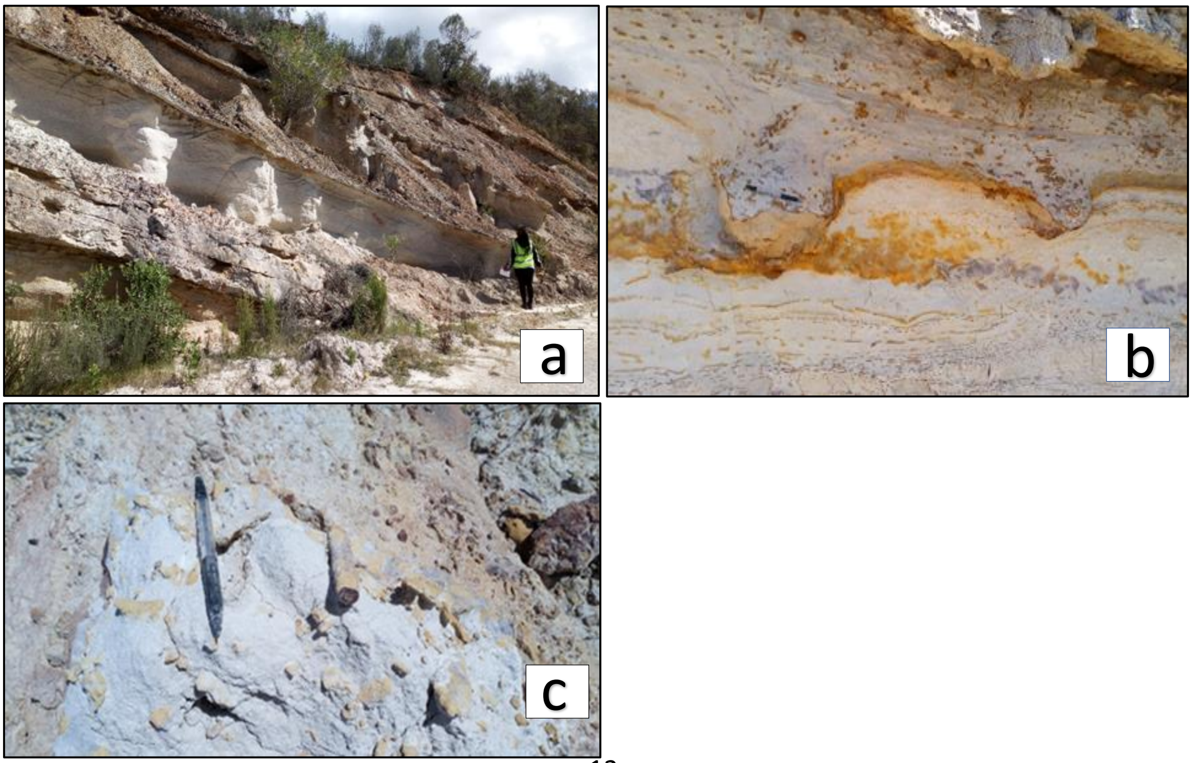

Figure 9: A north-east dipping outcrop of the Kirkwood Formation at location 33° 49' 55.3" S 024° 58' 37.0" E in the Hankey Area (figure 10 for location) (a) Alternating 1 m sandstone and 4 m mudstone beds characteristic of sediment deposition in an environment of high and low energy (b) Oxidized mudstone with deposition of very fine-grained particles in a quiet marine environment, typical of a channel. Concave-up structures possibly formed as a result of sting-ray burrowing in a marine environment; (c) Ophiomorpha, an evidence of bioturbation in near-shore environments.

2.2.4 Current Basin Model Evolution

Recent studies of the Gamtoos Basin show that sedimentation occurred during two rifting phases (Figure 10; Paton and Underhill, 2004). Prior to rifting, the Gamtoos basin was a terrestrial environment with sediment deposits of Palaeozoic age forming as the basement.

- Principal Syn-Rift Phase

Though the oldest dated sediments in the Gamtoos Basin are Oxfordian (160 Ma) in age, the model assigns rifting initiation to Kimmeridgian age (~155Ma) (Paton and Underhill, 2004; Baby et al., 2018). During this age, taphrogenic tectonics accompanied by the full establishment of the fault led to a radical shift in depocenters along the edges of the old cratonic blocks. There was a west-east extension of fault portion offshore where sedimentation accumulation occurred in a single depocenter, along the fault trace in deep anoxic environment (Dingle et al., 1983). Around Portlandinian to Early Valanginian (152-135 Ma), the Gamtoos Fault was displaced without an increase in length. The faults on the basement "switched off". Along with this displacement, was a SW-NE extension of the fault portion offshore, the depocenter gradually shifted from a slope to an outer shelf environment.

- Late Rift Phase

At Late Valanginian (~135 Ma), around the period of opening of the South Atlantic Ocean and the movement along the AFFZ, the depocenter continued to gradually shallow to a middle shelf environment with a continuous extension of the fault portion in the east-west portion. Maximum accommodation was in the east-west fault portion. Until the top Aptian, the movement (/drift) of the Falkland Malvinas Plateau along the Agulhas Falkland Fracture Zone (AFFZ) which induced uplift and subsidence controlled the structural and sedimentary evolution of the margin (Bate and Malan, 1992; McMillan et al., 1997; McMillan, 2003; Paton and Underhill, 2004).

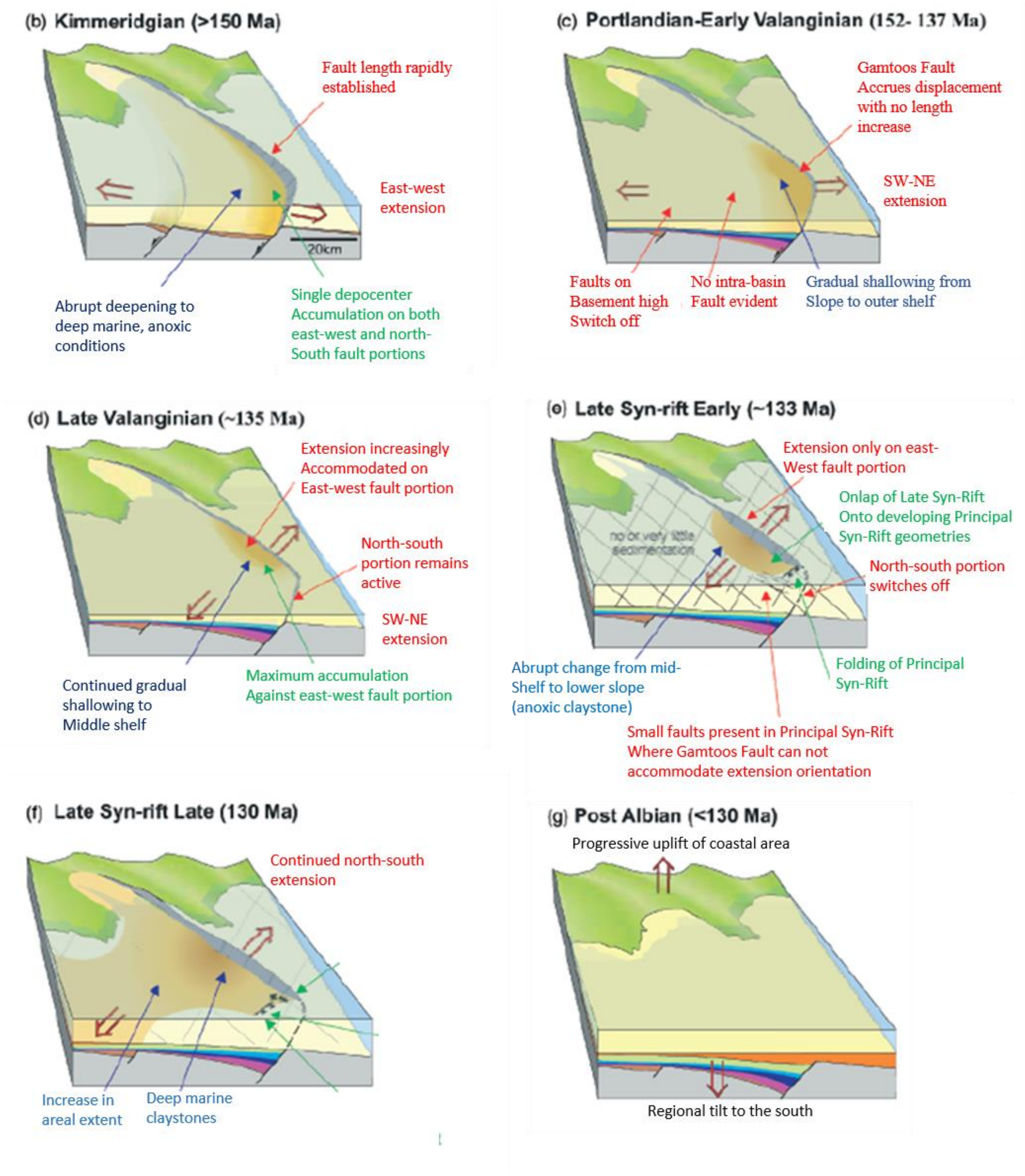

Figure 10: A model showing rifting stages of the Gamtoos Basin (Paton and Underhill, 2004).

CHAPTER 3: METHODOLOGY

1.1 Dataset

The datasets that have been used have already been processed in the 1970s by PASA. Digital seismic data processing is carried out for the purpose of attenuating noise and increasing the signal to noise ratio. When data is recorded in the field *(figure 11)*, unwanted energy from seismic data recording instruments, humans and other outside sources are recorded as part of the seismic signal thus affecting the quality of the data and interpretation. This noise recorded is classified into two categories, namely; random and coherent noise. Random noise has no phase relationship between adjacent traces, whereas coherent noise shows continuity in phase between adjacent traces. Therefore, for the purpose of quality seismic data imaging several stages of processing are conducted to attenuate this kind of noise.

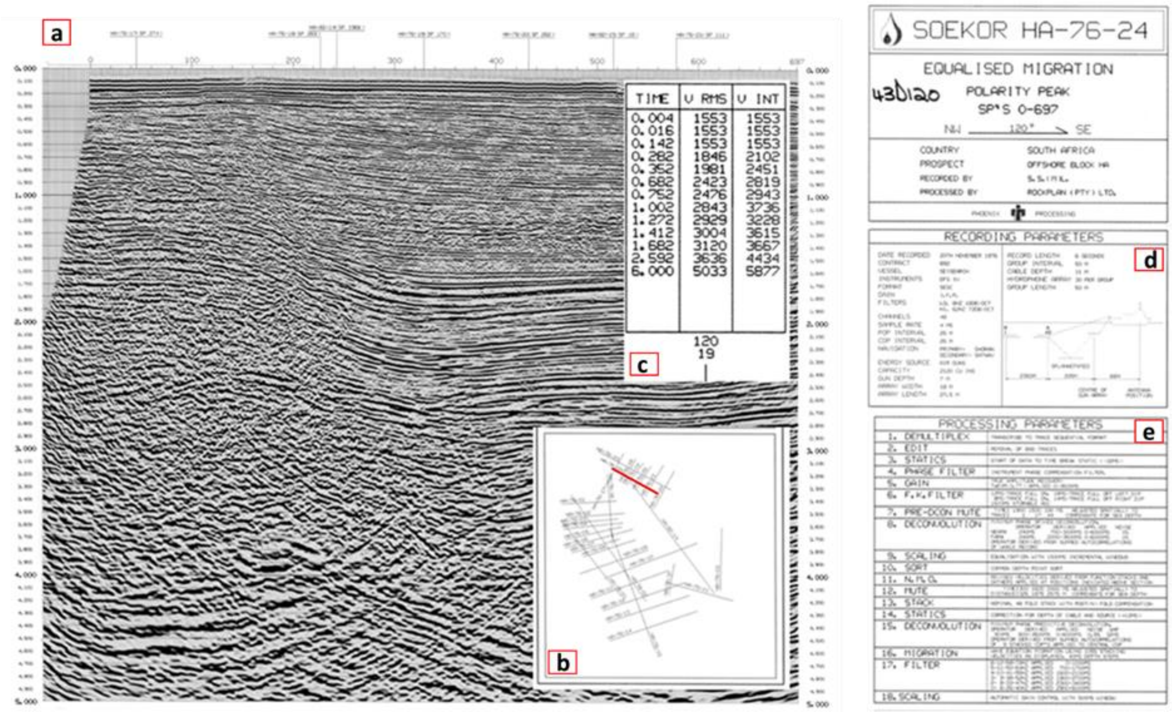

Figure 11 (a-e): An example of a processed 2D seismic reflection section shot at zero-offset with a trace spacing of 100m in the Gamtoos Basin (a) seismogram of HA76-24 (b) a map showing the location of the profile in the Gamtoos Basin (HA76-24 profile in red line) (c) table listing recorded two-way travel time data and their corresponding interval and root-mean square velocities (d) recording parameters of 2D seismic reflection data, offshore (e) processing parameters used in digital processing of the HA76-24.

The standard digital signal processing steps aimed at improving seismic resolution are listed (Mousa, 2011):

a. Filtering
b. Common mid-point sorting

c. Velocity analysis

d. Normal move-out correction

e. Stacking

Furthermore, the data is de-convolved by the application of spiking and predictive deconvolution *(Appendix, Figure A1).* To improve the temporal resolution, the seismic wavelet is collapsed to approximately a zero-phase spike of zero width thus suppressing reverberations and short period multiples of the data. Following this is the application of a filter to predict systematic noise of an input series. At acquiring the seismic lines in processed format, the dataset is then interpreted manually and by using softwares.

3.1.1 Seismic Database Building

Initially, the data was organized in printed seismograms because interpretation of seismic profiles are visualized better on paper in wiggle trace display format. The scale and size parameters of the seismic profile were adjusted before printing. The vertical scale used was 1.000 millisecond = 5 centimetres according to the ISO 216 standard and the horizontal scale was 5km = 2.5 cm. Following this, a database was created in Kingdom Software, an industry standard software.

3.1.2 Seismic trace and navigation data integration

The first step in creating a database involved merging of the navigation data with seismic line records in Kingdom Software. The SEGY Viewer plug-in was used to view the Header, its trace data and to extract shot-point details necessary for importing data *(figure 12).* The data was then imported into Kingdom Suite and set to UTM Projection System WGS84. The shot-point position of both datasets was defined and merged. The data could then be interpreted.

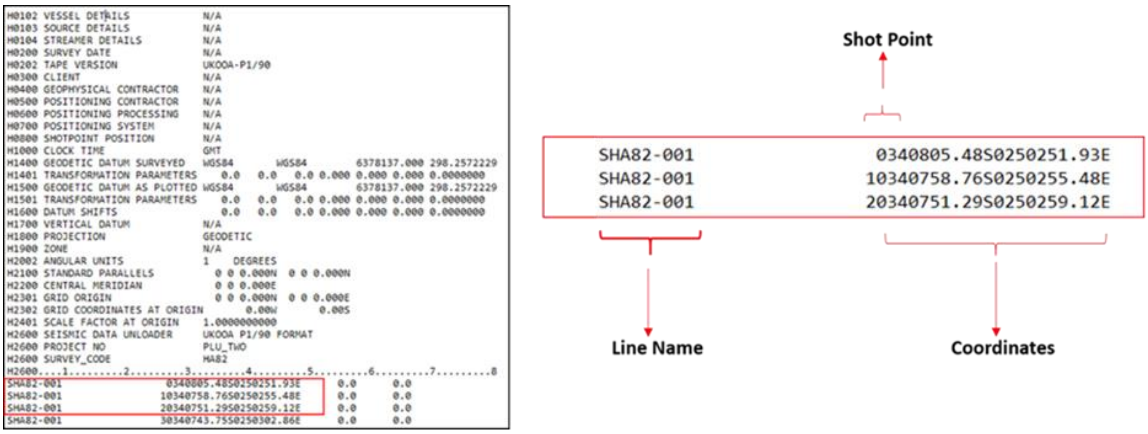

Figure 12:The structure of the seismic data viewed using the Seismic Viewer Package. The values in each trace are uniquely related to shot and receiver positions on the surface of the earth.

3.2 Seismic Stratigraphy Interpretation

3.2.1 Seismic Reflector and Unit Characterization

For interpretation, the stratal termination technique was used. The technique entails delineation of geometric relationships between strata and stratigraphic surface against which they terminate *(Figure 13)*. Four stratal terminations were used to identify surfaces and seismic units, two occurring above a surface (onlap and toplap), two occurring below the surface *(Figure 13; Snedden 2008)*. The offlap break was used as a key identifier of stratal stacking pattern. This is because it affords the recognition of forced regressions and the delineation of subaerial unconformities and their correlative conformities.

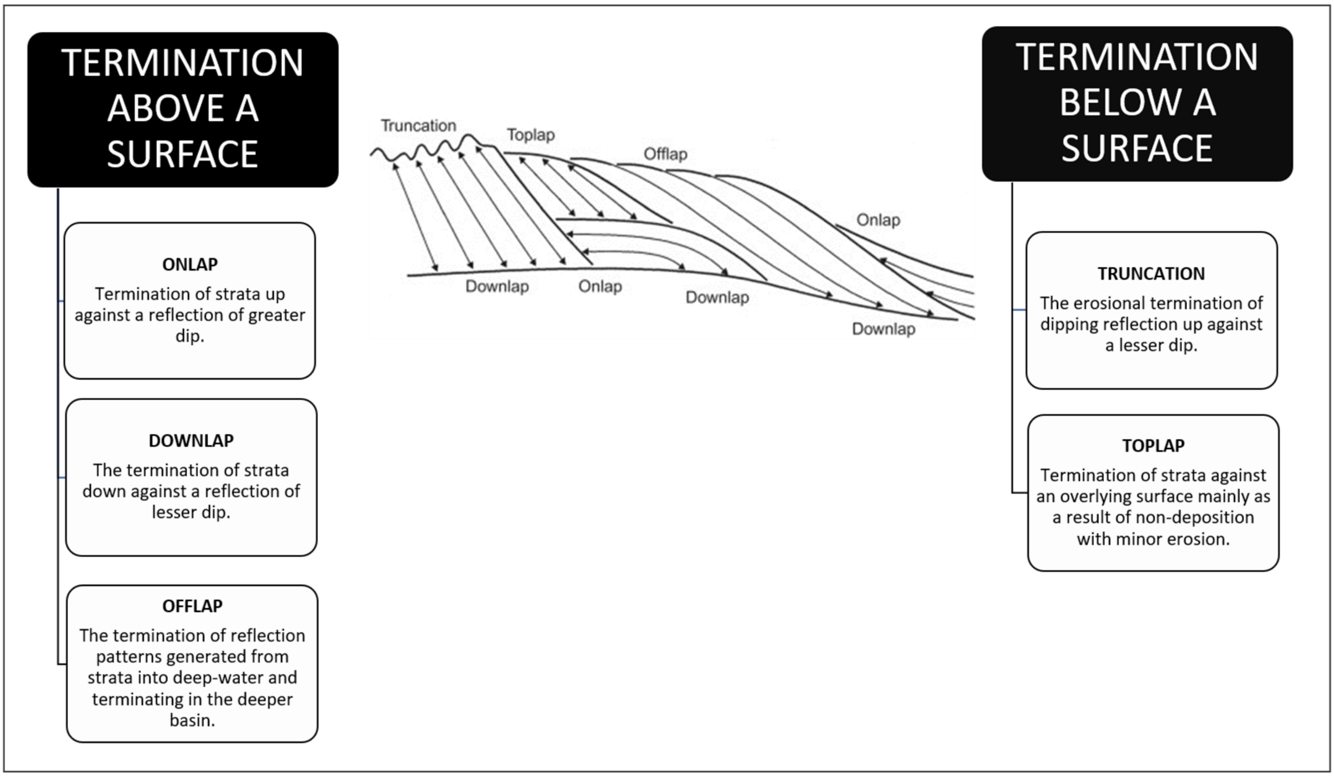

Figure 13: A diagram showing the different reflector terminations to identify surfaces (Modified from Mitchum, 1977).

The sedimentary reflections mimic mainly bedding planes that represent conformable changes in the depositional regime. The reflectors can be characterized on the basis of:

a) lithology
b) energy level
c) input source
d) termination

Reflectors were further defined by describing the amplitude, continuity, frequency and the geometry *(Figure 14)* defined by Mitchum. (1977):

AMPLITUDE: is proportional to the velocity-density contrast (Veeken, 2014). Amplitude measures the properties between two layers. It measures the reflection strength, lithological contrast, bedding spacing and fluid contents. From the data, relative impedance can be calculated and the relative change of the rock property impedance which is equivalent to a measure in rock hardness from one layer to the next can be measured. The property contrast between rock varies with factors such as depth of burial, compaction, porosity and lithological composition. The amplitude range is from high to low. From the magnitude of the amplitude, the impedance contrast which defines significant stratal surfaces can be determined, bed spacing/ tuning litho-facies as well fluid content in the sediment packages.

CONTINUITY: determines the lateral stratal continuity of reflectors (Snedden, 2008). The continuity of reflectors is explained as the level of coherency between two seismic traces. A trace correlated with its series that gives a coherency equal to 1 has a high probability of continuity of the reflector and a coherency with values less than one (<1) will show less continuity.

FREQUENCY: is the rate at which a signal can be sampled, with the Nyquist Frequency being the highest frequency that can be reliably restored from recorded seismic time sample dataset. It is defined as "the minimum rate at which a signal can be sampled without introducing errors, which is twice the highest frequency present in the signal." Seismic reflection data ranges normally between 10 – 65 Hz. The frequency of a reflection is determined by: (1) the natural frequency absorption profile of the earth (2) the signature of the reflected wavelet (3) actual sharpness in the velocity-density contrast. From the characterization of the frequency range the bed thickness can be estimated and fluid content can be determined.

GEOMETRY: defines how the reflector are configured. The reflectors are described and classified into three groups which are: reflection free within the seismic data, stratified and chaotic reflectors. From the geometry of the reflectors, the depositional processes and the energy at which sedimentation occurred can be defined.

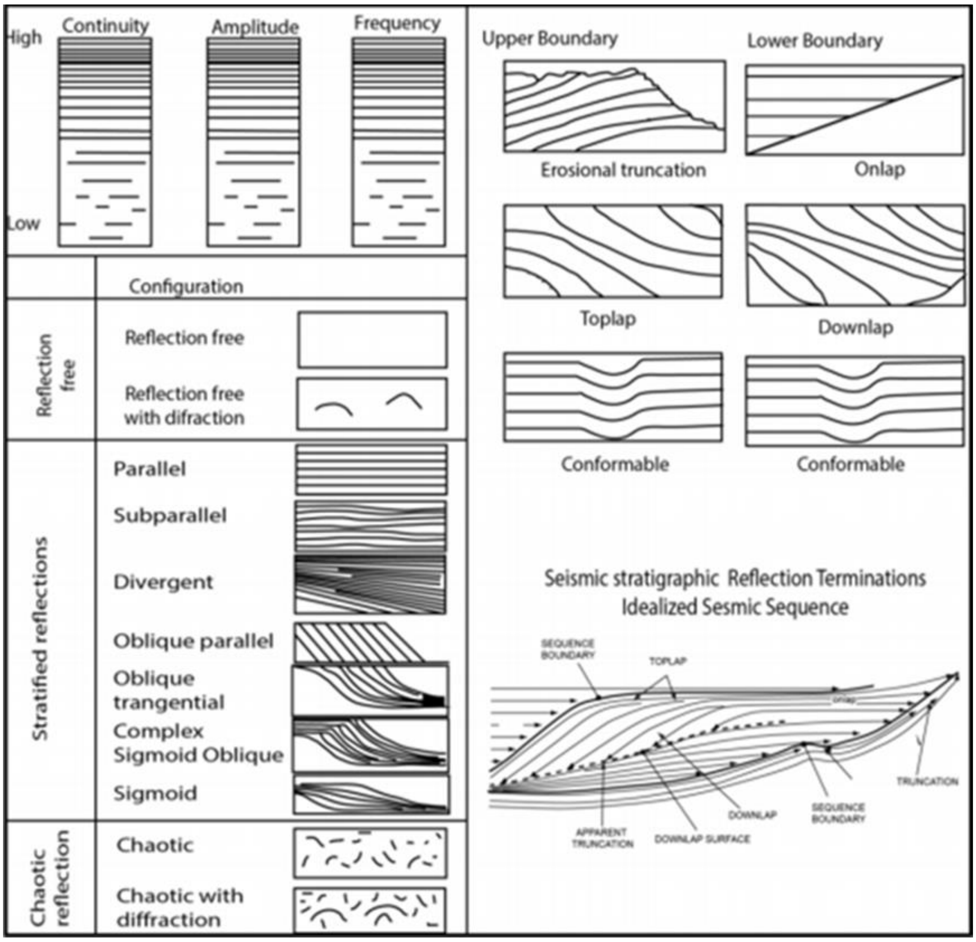

Figure 14: Image illustrating different stages in interpreting seismic reflection sections (Mitchum et al., 1977a; b).

<u>Depositional Sequences</u>

On broader scale, from the application of seismic stratigraphy method, genetically related packages with a thickness of hundreds of meters (depending on the resolution of the seismic profile) grouped together can be defined. These packages are termed depositional sequences and are generally defined as a stratigraphic unit composed of a relatively conformable succession of genetically related strata *(figure 14)*, and bounded at its top and base by unconformities or their correlative conformities (Mitchum, JR, et al., 1977). The criterion used to determine a depositional sequence is determined by the physical relations of the strata. The depositional sequence is deposited during a given interval of geologic time limited by ages of the sequence boundaries, where the boundaries are conformities; however, the age of the strata within the sequence may differ from place to place where the boundaries are unconformities. To define and correlate a depositional sequence accurately, the sequence boundaries must be defined and traced precisely based on mapping of lap-out terminations. Discordance of strata is the main criterion used in the determination of sequence boundaries, and the type of discordant relation is the best indicator of whether and unconformity results from erosion or non-deposition.

With the parameters defined, the stratigraphic relationships and depositional environments can be determined from subsurface seismic data.

a) Seismic – Well Tie

The best multi-disciplinary approach to meeting the targets of seismic stratigraphic studies is to extract relevant information from all available datasets: outcrop, borehole and geophysical measurements. Calibrated datasets served as a reference or guide for the interpretation of less well-calibrated datasets.

3.3 Borehole Data Calibration

Borehole data and wireline logs were used to calibrate borehole data on the seismic section in two-way travel time (sTWT). The well data from reports provided by PASA were used to construct lithostratigraphic sections. Wireline logs were provided in Log ASCII Standard (LAS) format and could be displayed using Las File Viewer and uploaded in Kingdom Suite. The process of borehole data calibration involves conversion of seismic (TWT) to depth. This was achieved in the Microsoft Excel Spreadsheet. The depth in metres is calculated using the formula:

$$d = v*t/2 \qquad (1)$$

Where v is the root mean square velocity, t is two-way travel time (TWT) in seconds, and d is distance in metres.

In the Kingdom software workspace, time-depth data in text file format were imported. The calculated time-depth data was uploaded as Seismic True Vertical Depth (STVD). The Kelly Bushing reference datum is fixed reference point of operation in the process of drilling and the WGS84 datum with minimum datum shift from the Kelly Bushing was used as an approximate definition of sea level. Subsequently, the well data from reports provided by PASA was then used to construct lithostratigraphic sections and extract depth at which there was a stratigraphic break to constrain the units of the calibrated logs to their depositional ages *(figure 15).*

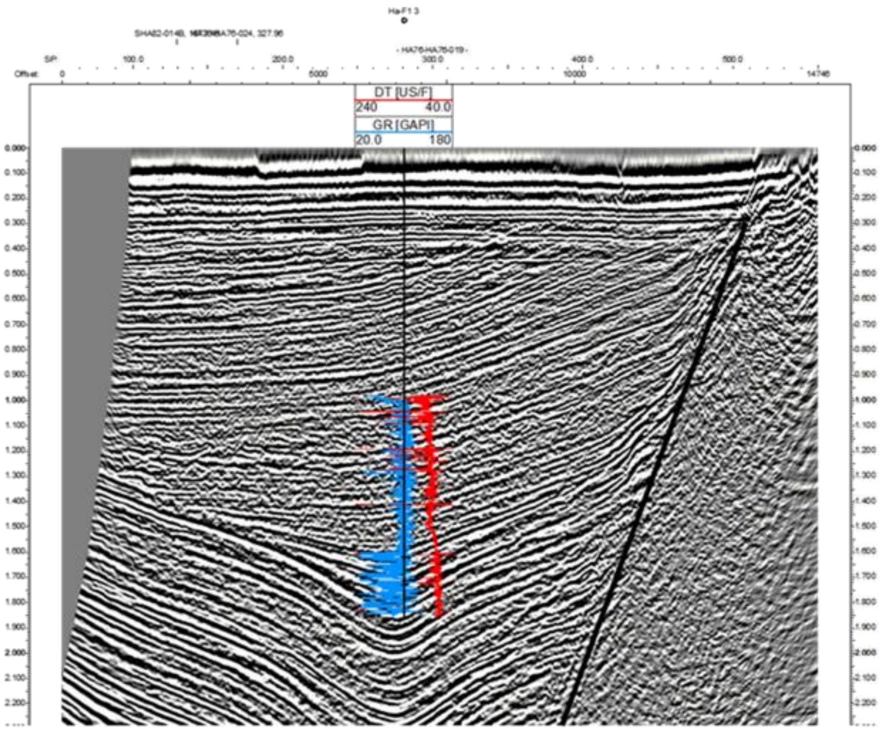

Figure 15: Image displaying HA-F1 successfully tied to seismic section HA76-019 (screenshot from Kingdom Suite).

a) <u>Wireline Logs</u>

Available gamma-ray wireline logs in Log ASCII Standard (LAS) format were tied to the calibrated boreholes. The gamma ray log measures the total natural gamma radiation emanating from a formation (Olayiwola et al., 2019). This radiation originates from Potassium-40 and the isotopes of the Uranium-Radium and Thorium series which are mostly found in shaly units. The radiation level in carbonates and sands is normally less than that in shale rocks. Different lithologies were determined through interpretation of the variations in log response *(figure 16).*

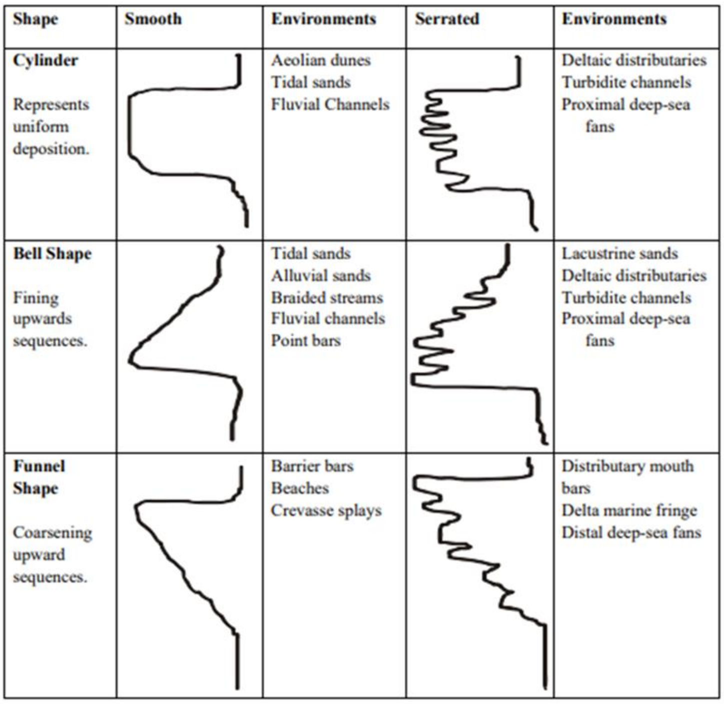

Figure 16: Illustration of varying gamma ray log response linked to possible different depositional environment (Olayiwola et al., 2019).

3.4 Seismic Stratigraphic Method

Seismic Stratigraphy is explained as the science of using subsurface seismic data to interpret stratigraphic relationships and depositional environments. Interpretation includes delineation of lithofacies, unconformities, making chronostratigraphic time correlations and determining the depositional history of basins. According to Veeken (2013), the seismic stratigraphic method is a widely accepted method and is nowadays standard practice for interpreting seismic datasets. It can be applied for the purpose of investigation of the earth's crustal structure within a depth of up to 100 kilometres. Furthermore, Veeken (2013), states that the advantage of the method for geological studies lies in the fact that the method combines different scales of observation. Large scale seismic data and high resolution well logging or outcrop approach provides a robust means to make less erroneous interpolations when doing correlations.

3.5 Seismic Stratigraphic Interpretation – Procedural Steps

Interpretation of seismic profiles was initially carried out manually on paper as seismograms are visualized better on paper in wiggle trace display format. Preparation of the data before interpretation involved adjusting scale and size parameters of the seismic section before printing. The vertical scale that was used is 1.000 millisecond = 5 centimetres according to the ISO 216 standard. The horizontal scale that was used is 5 km = 2.5 cm.

Colours were then assigned to the different stratigraphic terminations as defined in *(figure 19b).* As an initial step, two seismic profiles HA82-43 (figure 29) and HA82-045 *(figure 30)* that were interpreted by Paton and Underhill (2004) are used. A loop was done by propagating the identified key stratigraphic surfaces through profiles that intersect each other in the offshore portion of the basin. This is a useful way of reducing variations among interpreters, the two profiles were used as a starting point for interpretation. After key horizons are identified and looped, only limited significant alterations can be done.

Subsequent to this, areas of major structural deformation and data artifacts on the seismic sections were identified. This is to help have a general idea of the tectonic style, presence of structural decollements, depositional environments and key deformational events.

In the results chapter, I am presenting the results:

- Boreholes
- Seismic Profiles
- Borehole-seismic connection

CHAPTERS 4: RESULTS AND DISCUSSIONS

Using the seismic database created for the Gamtoos Basin from available PASA datasets, I describe 3 boreholes and 3 seismic lines both onshore and offshore. The studied boreholes are located near Hankey (LO 1/69) along the coastline (MK 1/70) and HA-F1 about 40 km offshore. They were drilled between 2.3 and 3.0 km in depth. The seismic lines are almost continuous along the basin axis, close to (10-20 km) the fault, from onshore to offshore, with a gap of 91 km *(figure 17)*. All the seismic data have maximum recording values of either 5000 or 6000 sTWT. Included as part of the seismic database for my master's project, a total of 20 seismic lines were interpreted *(figure 23)*. This allowed me to create thickness maps and propose hypotheses about processes leading to the formation, and filling dynamic of the Gamtoos Basin. This chapter is discussed in 2 parts dealing with 1) possible processes controlling the first order geological evolution and the depocenter evolution through time along the Gamtoos Basin, 2) onshore – offshore connection of the Gamtoos Basin.

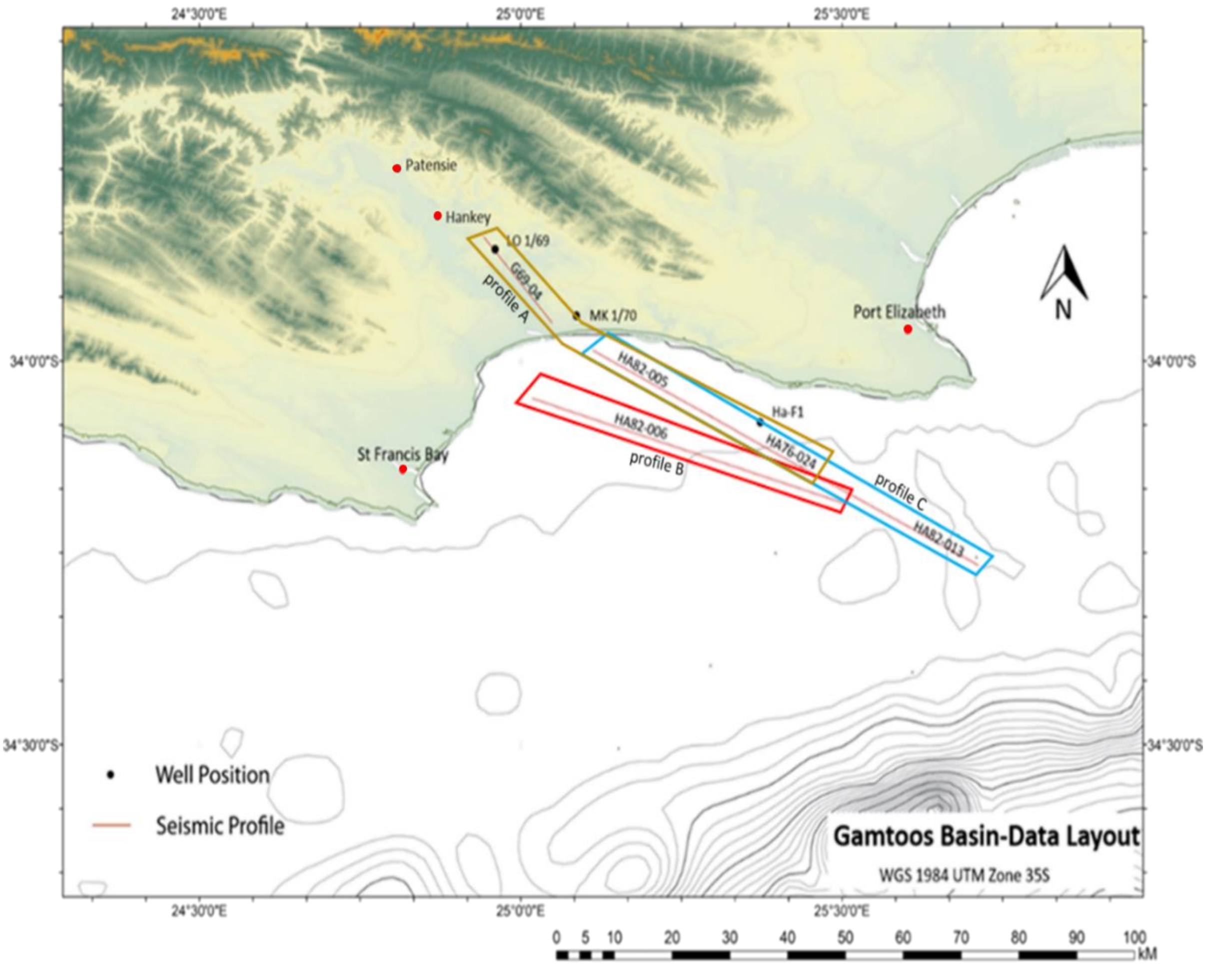

Figure 17: A map showing the layout of the 3 seismic profiles and boreholes used for the purpose of this study in the Gamtoos Basin. Profile D is comprised of 3 seismic lines merged into 1 profile.

4.1 Borehole Description

The onshore borehole (LO 1/69) is mainly comprised of conglomerate. The conglomerate deposit has no fossils making it unable to date directly. Borehole MK 1/70 situated along the coast dominant of conglomerates and is overlain by the Wood Bed Formation whereas offshore the Gamtoos Basin is dominated by claystone's dominant of fossils and shell fragments *(see figure 18a)*. The ages of the formations in HA-F1 were determined based on palaeontology data and were correlation to the Enon conglomerates of MK 1/70 and LO 1/69.

4.1.1 L0 1/69

The borehole (*figure 18a*) has been drilled to a total depth of 2291 m. However, lithostratigraphic sections were created based on available data which extends up to only 1350 m in depth. The lithology is mainly a thick, white bed of boulder and pebble sized conglomerate with minor coarse-grained sandstone and siltstone. These lithological units are possibly of the Enon Formation. At 957 m quartzite pebbles were recovered. Between depth 1100 – 1350 m no samples were recovered, thus the lithology is not known.

4.1.2 MK 1/70

MK 1/70 *(figure 18a)* shows a gradual transition from conglomerates to medium grained sandstone and fine-grained claystone's, generating a fining upward succession. The claystone units are dominated by fossil fragments. The conglomerates are interpreted to be of the Enon Formation whereas the sandstones and claystone's are of the deposits of the Kirkwood Formation.

4.1.3 HA-F1

The sandstones and claystone's shows fining upward successions and the sediment deposits are dominated by fossils and shell fragments. The base of the borehole is observed at 2796 m with late Valanginian sediment. The ages of the formations in HA-F1 *(figure 18c)* are of Late Valanginian (~135 Ma) to Hauterivian (~132 Ma) in age. The ages were determined based on palaeontology data and were correlated to the Enon conglomerates in MK 1/70 and LO 1/69. The Sundays River Formation has been shown to be within the Valanginian to Hauterivian stratigraphic range (McMillan, 2003).

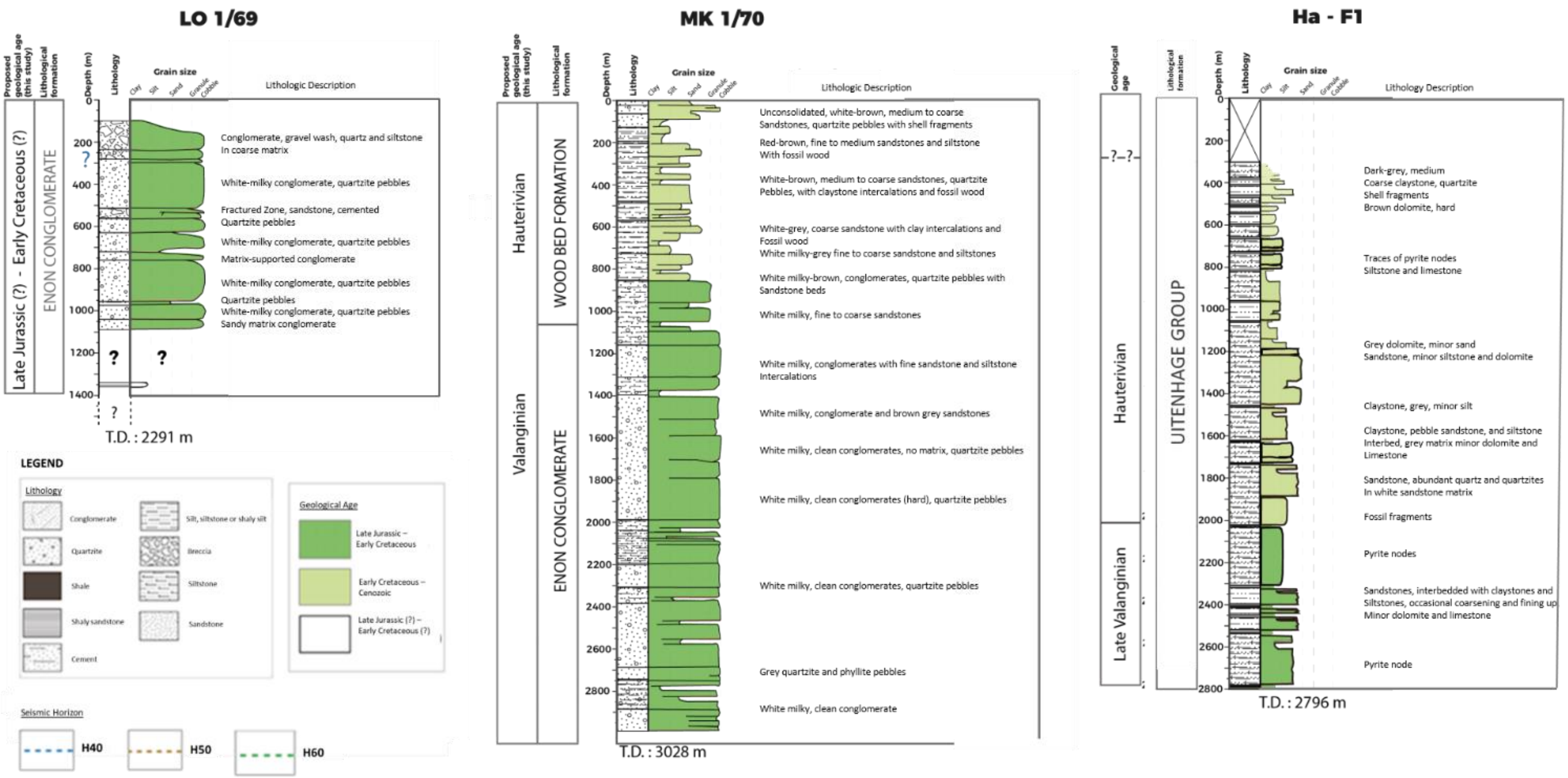

Figure 18a: Reconstructed lithostratigraphic units of boreholes situated both onshore (LO1/69) and offshore (MK 1/70 and HA-F1) in the Gamtoos Basin.

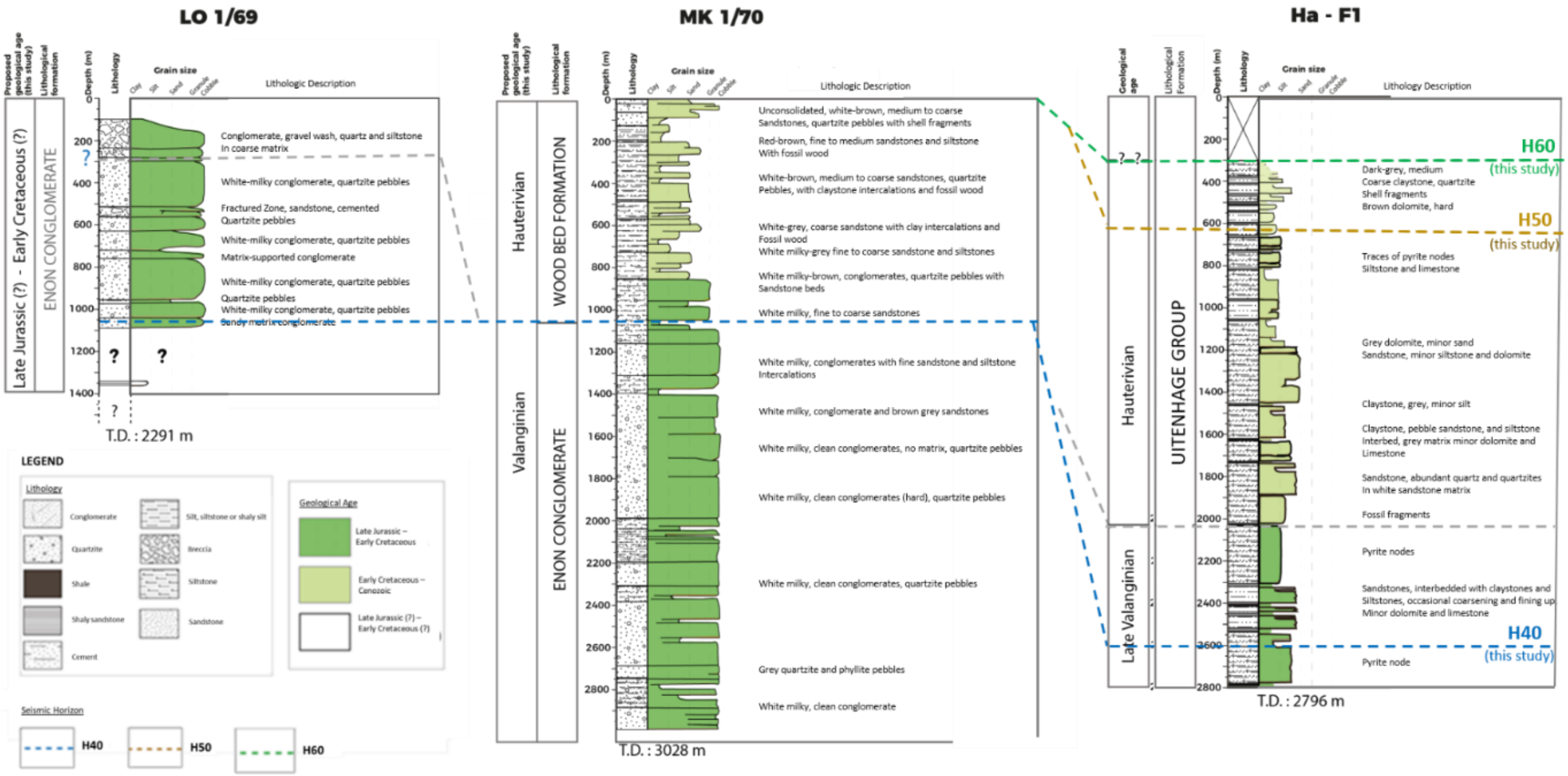

Figure 18b: Correlation of onshore (LO 1/69) and offshore (MK 1/70 and HA-F1) boreholes in the Gamtoos Basin based on seismic stratigraphy interpretation with mention of the lithology. One major Late Valanginian unconformity is present and accounts for much of overlying Hauterivian sediment deposits above the erosional truncation. H40=Late Valanginian (unconformity), H50=Top Hauterivian, H60=Cenozoic sediments.

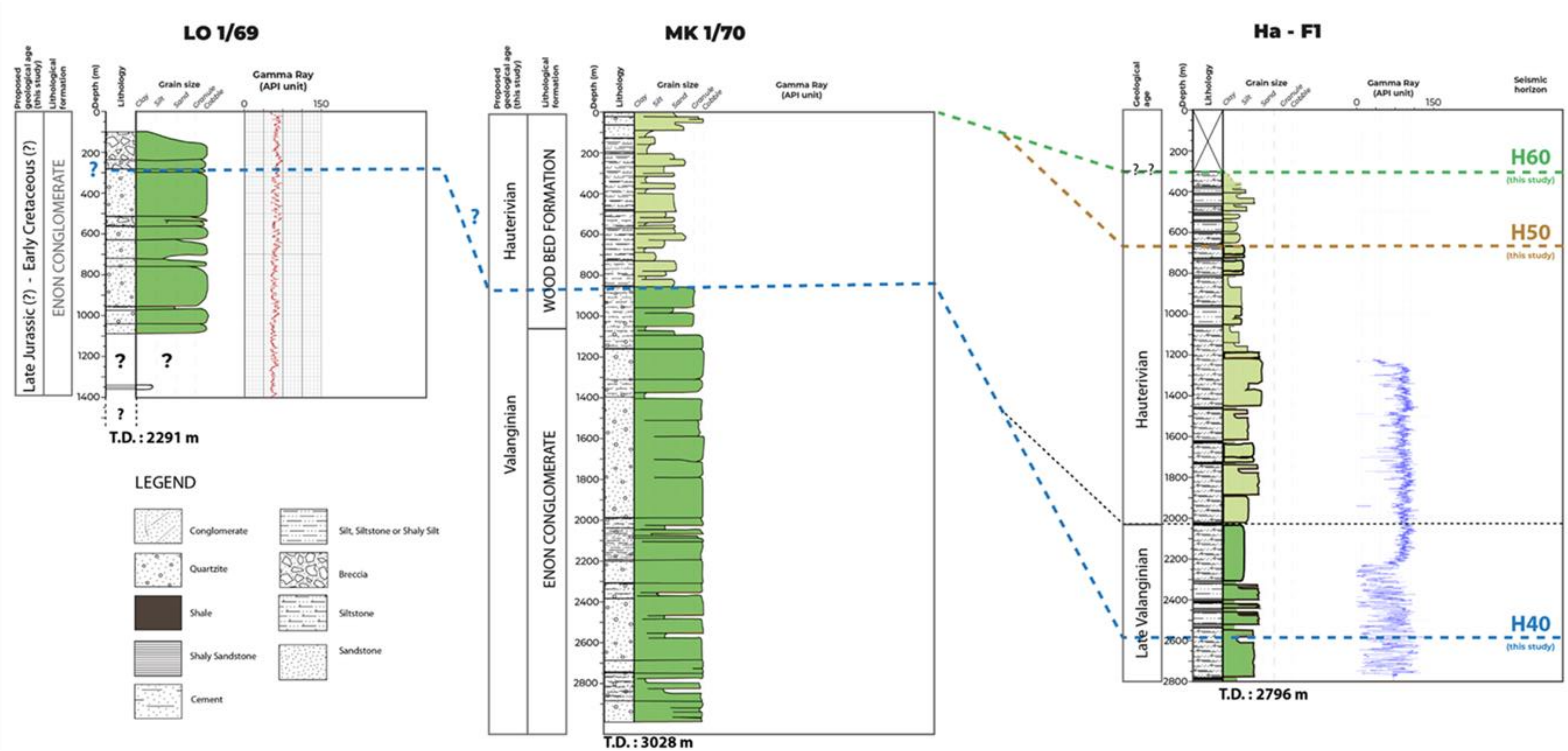

Figure 18c: A correlation of reconstructed lithostratigraphic boreholes in the Gamtoos Basin with gamma ray logs tied to boreholes LO 1/69 (onshore) and HA-F1 (offshore). The gamma ray logs have a scale of 0-150 API units.

Geophysical Information from boreholes

The gamma ray log *(figure 18c)* values for LO 1/69 show a value of 37-75 API units and is constant throughout the log. The log response shows a cylindrical shape and reflects a cleanliness (lack of clays) in the formation. The gamma ray reading is consistent with the lithology of the borehole which is the mainly the conglomerates of the Enon Formation which is Jurassic in age. Borehole HA-F1 shows a sharp change in the curve shape at 2200 metres. The sharp change corresponds to a change in lithology, from conglomerate to silt units. Between 1200 to 2200 metres the gamma ray readings show a serrated bell curve signature ranging between 0 – 20 API units and between 2200 to 2796 metres the curve shows sharp peaks with a maximum of 75 API unit.

Data Limitations

The identification of lithologic contacts from borehole *(figure 18c)* and surface boundaries in archive seismic profiles *(figure 19)* hold inherent uncertainties. The identification and connection of lithologic contacts from surface boundaries in archive seismic profile G69-04 holds inherent uncertainties. Matching two-way travel time (TWT) in the archive seismic profile *(figure 15)* to the borehole depths requires a detailed velocity model. The model is used to convert TWT of reflectors in the archive seismic data to accurate depths and match it with the borehole logs. Root-Mean Square velocities *(figure 11c)* from seismic data processing were used to calculate and convert TWT to depth. Interpretation of data using this calculated depth has minor inaccuracies, the position of the horizon mapped can differ (up to 100 metres; which could be equivalent of 2 to 3 reflectors). Another uncertainty related to the number of boreholes drilled onshore, the depth of the borehole and the distance between them. Regional variations in dip and thickness variations of strata between two boreholes makes an accurate match unlikely, thus limiting the interpretation to a best fit solution (Lindeque et al., 2010). Poorly documented criteria were used to define the stratigraphy at the time of logging the boreholes. Thus, the lithostratigraphic contacts from old well data have limited reliability in a regional correlation. Despite these uncertainties, boreholes LO 1/69 and MK 1/70 are still considered for stratigraphic control. The integration of different data sets aided in minimizing inaccuracies during interpretation.

4.2 Seismic Profile Description

To define the Gamtoos Basin fill evolution, interpretation of the 3 seismic profiles was achieved by mapping the seismic discontinuities and surface boundaries based on the configuration of reflections and characterization of facies. Names were assigned to different seismic boundaries mapped with H-value=Horizon (offshore), S-value=Horizon (onshore). The reflectors were further grouped based on 4 seismic units. From the base (reflector S00 to reflector H60: the BLUE, GREEN, YELLOW, ORANGE units. Beginning at H60 to the sea floor, the most recent unit has no colour assigned to it (COLOURLESS).

South-East in the Gamtoos Basin, the Gamtoos Fault extends up to 6 TWT in seconds (s) and the maximum length is not known beyond recording time. The fault bounds the BLUE and GREEN sequences at the region of the fault bend offshore. Profile B *(figure 20b)* shows a gradual increase in the amplitude of reflectors with depth. The beds above S00 show a high frequency and continuity. The sedimentary infilling shows a wedge-shape geometry onlapping and thickening towards the hanging-wall of the Gamtoos Fault. Offshore there is a shelf break of seismic units at 55km (1.5-4.0 s).

4.2.1 BASEMENT

S00 is the first bottom horizon that is mappable *(figure 19b)* in the seismic data. The reflectors below the S00 are mainly high amplitude and show low continuity. S00 is interpreted as the top basement horizon of a non-depositional hiatus.

4.2.2 BLUE SEQUENCE

The base of the BLUE sequence is marked by a few reflectors onlapping onto to S00 and is interpreted to be Kimmeridgian age(155Ma). To the top the sequence is bounded by the H05 seismic horizon which is possibly Early Valanginian age (134 Ma). Both the interpretations are based on previously interpreted seismic data and borehole data (Paton and Underhill, 2004). The depocenter of the BLUE sequence *(figure 23e)* is located along the Gamtoos fault following a NW-SE axis, where sediment thickness ranges from 1.25-1.75 s at a 5 km radius. At 6 s, 45km from zero offset position and towards the fault, the north-eastern extension is difficult to identify due to bad quality data thus the extent of the BLUE sequence is not known. Both the BLUE and GREEN sequences diverge from the north-west part of the basin toward the Gamtoos Fault in the proximal offshore portion of the Gamtoos Basin *(figure 19b).* The BLUE sequence is characterised by high frequency reflectors with a medium amplitude and low continuity imaging. The sediments deposited at 2.0-2.5 s *(figure 19b)* in depth, north-west in proximal distance to the onshore portion of the Gamtoos Basin have a small bed thickness and gradually doubles in thickness at a depth 4.5 -6 s, south- east in the distal offshore part of the basin.

4.2.3 GREEN SEQUENCE

The GREEN sequence *(figure 23d)* overlies the BLUE sequence and is bounded at the top by H30 terminating at H40. The strong reflector-H40 was delineated *(figure 19b)* based on apparent top-laps identified. It is interpreted as an erosional truncation possibly of Late Valanginian (~135 Ma) times based on previously interpreted profiles (Paton & Underhill, 2004). The GREEN sequence occurs throughout the offshore Gamtoos basin with a maximum thickness value of 2.75 s. Sediment thickness decreases slowly radially (between 1.25-1.75 s thick) from the main depocenter. At the base of the GREEN sequence (reflector H05 – H10) between 2.5 – 3.5 s, the reflectors are less continuous, in contrast, the top sequence shows high reflection coherency and frequency which suggests less bed-spacing and thickness. The seismic facies are dramatically changing at the base of the yellow reflector H20, and are corresponding to the deepening of the basin. The seismic unit represented by reflectors between H20 -H30 is interpreted as possible channelled systems. The GREEN sequence shows folding throughout the extent of the seismogram *(figure 19).* The sediment deposits are interpreted to be of Portlandinian to Berrisian age based on previously interpreted profiles (Paton and Underhill, 2004). The sediments at this age have the highest coverage and thickness throughout the offshore portion. The Gamtoos Basin sediment fill evolution *(figure 23)* shows a clear progression from deep water sediments (offshore) to shelf, deltaic and ultimately fluvial sediments.

4.2.4 YELLOW SEQUENCE

The YELLOW sequence lies unconformably onto the Green sequence and is bounded to the top by H50 which is interpreted to be possibly of Late Hauterivian (131 Ma) age based on drilled borehole data. The depocenter of the YELLOW sequence is located along the syn-rift hanging-wall of the Gamtoos fault up to 2500 m (Baby et al., 2018). In the fault region (75km), the reflectors onlap onto the erosional truncation (H50) and pinches out at 0.7 s. The bottom YELLOW sequence is interpreted to be a possible mass deposits eroded during Late Valanginian (H40). The overlying reflectors of the YELLOW seismic unit do not conform to the folding of the GREEN sequence. This suggests that folding occurred at Late Valanginian times (~135Ma) *(figure 25).* In the YELLOW sequence, the reflectors are chaotic with few beds which are interpreted as eroded sandstones and siltstone deposits. To the top of the YELLOW sequence the beds are more distinct and show high frequency and coherency. The stratum are possibly siltstone and claystone beds. This sequence terminates against H60 *(figure 20).*

4.2.5 ORANGE SEQUENCE

Overlying the Yellow sequence are the deposits of the Orange sequence. The ORANGE sequence has no main depocenter, low sediment deposits with a seismic time thickness ranging between 0.25 – 1s covers the two parts in the basin; the region of the fault bend north-east of the basin and further south-west in the basin. Between these two low sediment cover regions is a non-deposition zone, however, the maximum sequence thickness of the ORANGE sequence *(figure 23b)* ranges between 0.3 – 0.5 s close to the Gamtoos fault and SW of the Gamtoos basin and the St Francis structural high (Pletmos basin), with a more prominent depocenter that is 0.5 -0.75s thick. The sequence is confined to 15- 75 km within the Gamtoos Basin (figure 19). Forming as the youngest deposit is the ORANGE sequence which is confined to km 20 – 58 *(Figure 20).* The stratal patterns of the sequence conform to those of the YELLOW sequence and toplap onto the high amplitude reflector H60.

4.2.6 COLOURLESS SEQUENCE

The COLOURLESS sequence is the youngest bed and is thin. The depocenter of the COLOURLESS sequence (131 Ma – present) *(figure 23a)* is mostly located along the southern border of the Gamtoos Basin following a SW-NE axis, which correspond to the present-day shelf break axis. The deposits are mainly restricted to 55 -77 km south-east of the basin. Evident as strong reflectors top-lapping onto the seafloor, the sequence rapidly thins out at 42 km, maintaining a constant thickness from 40 km to zero offset north-west towards the onshore portion of the Gamtoos Basin. The COLOURLESS is characterised by medium amplitude and frequency. The reflectors have a medium to low continuity.

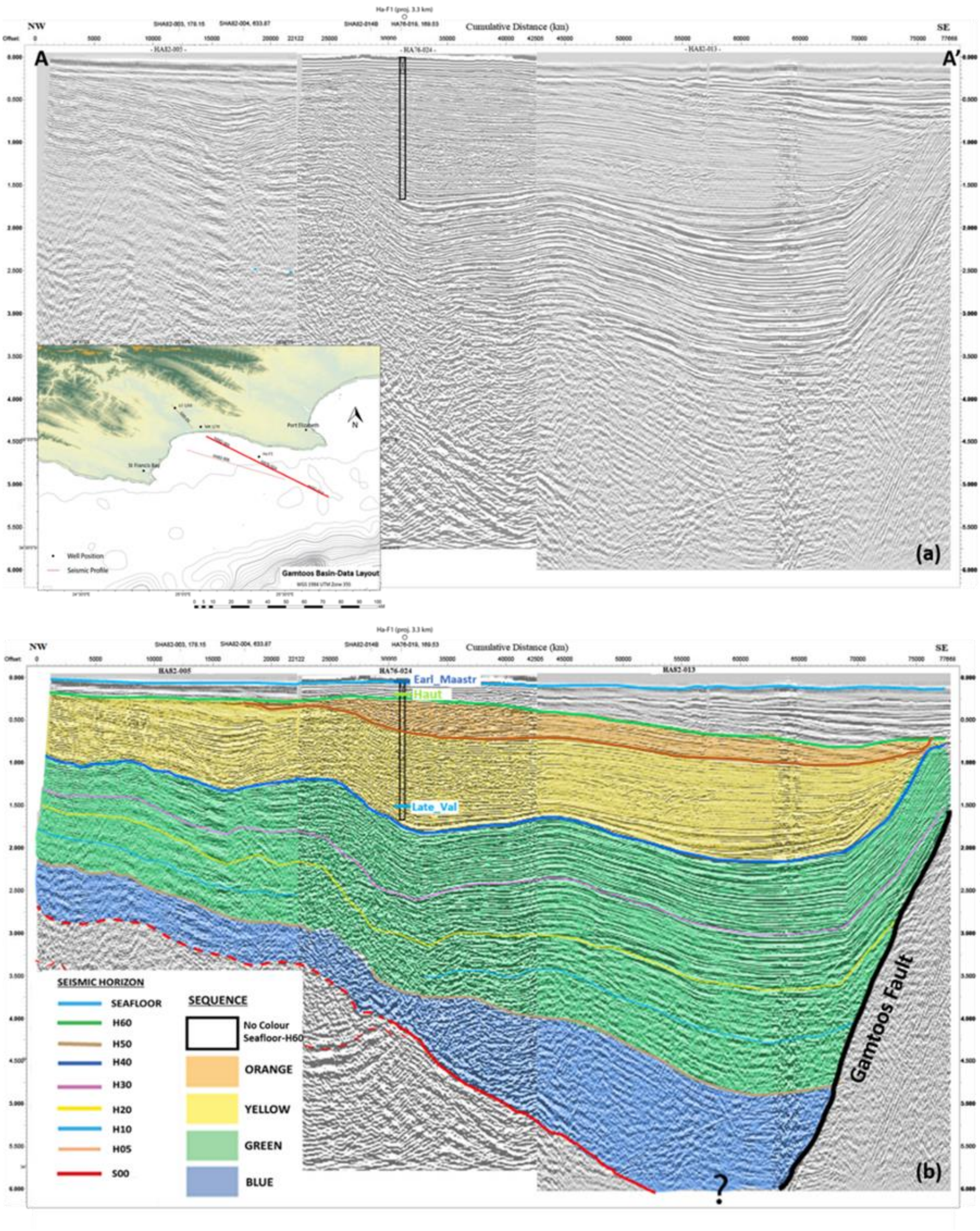

Figure 19(a-b): A seismogram of the uninterpreted seismic profile A (b) an interpreted geologic profile A based on seismic interpretation and borehole data. Profile A has a cumulative distance (horizontal axis) of 77 km from zero and a maximum (vertical axis) depth of 6.000 s. Borehole HA-F1 is projected onto profile A at 3.3 km.

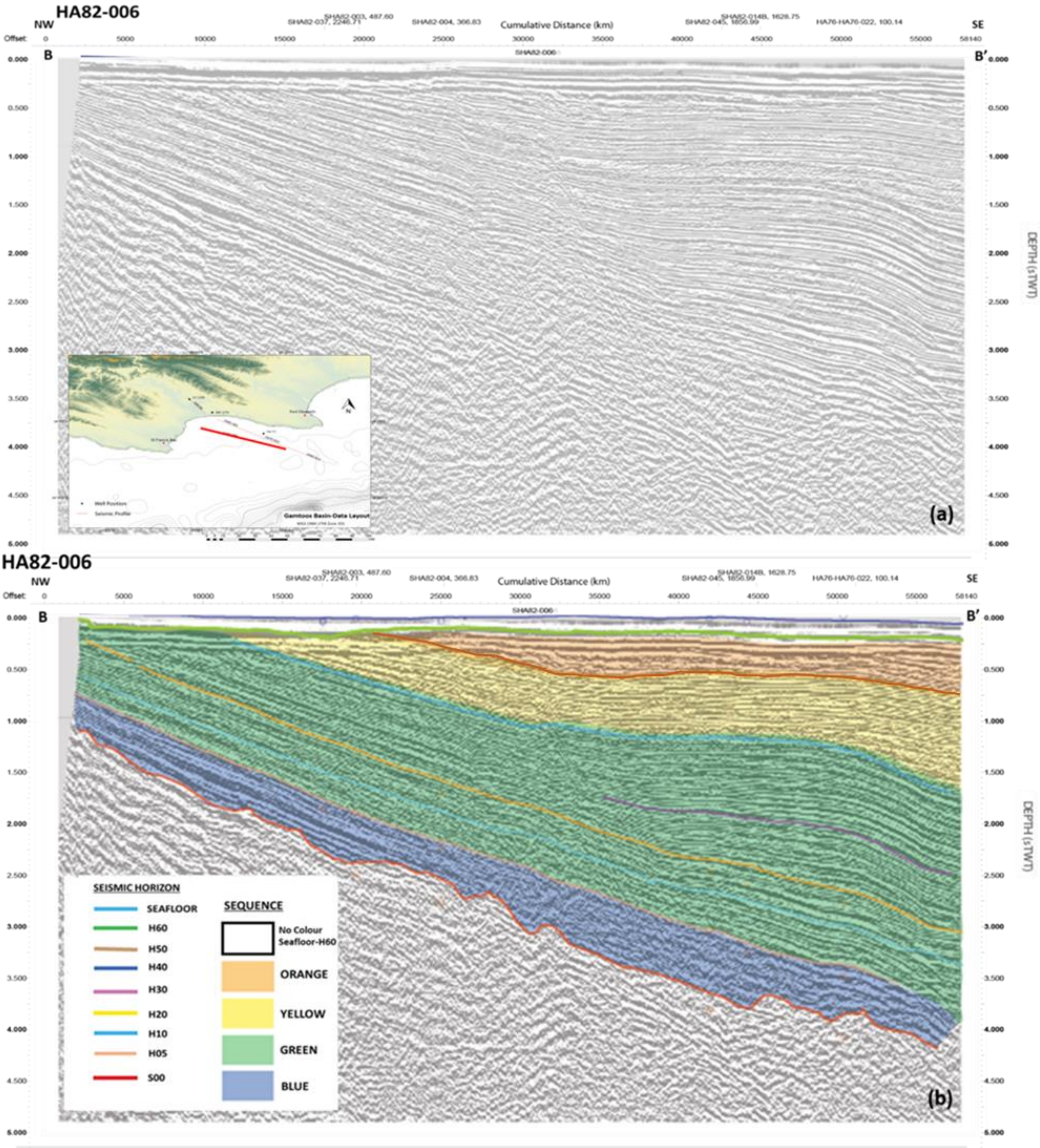

Figure 20(a-b): A seismogram of the uninterpreted seismic profile B (b) an interpreted geological profile B based on seismic interpretation and borehole data.

Onshore Profile

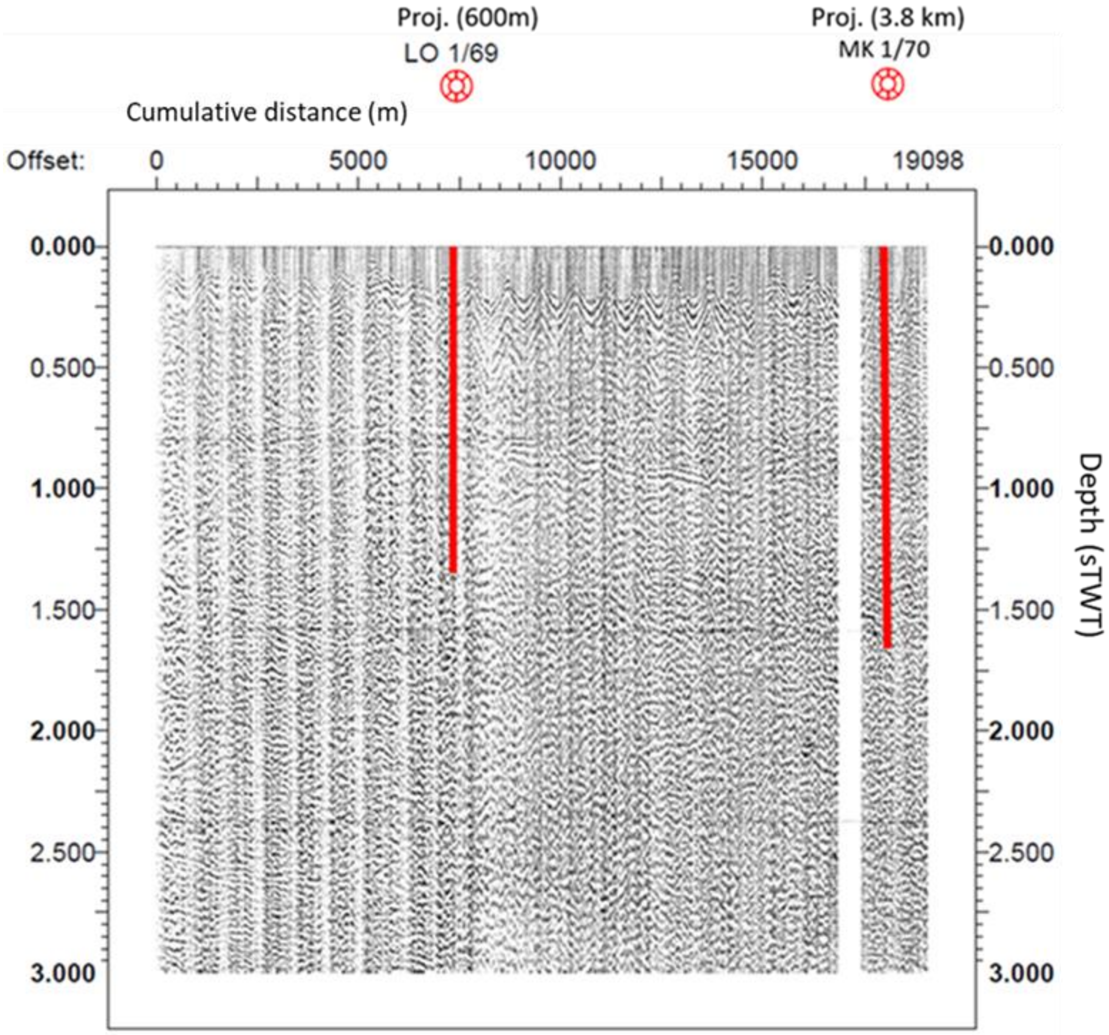

Figure 21: A representation of the onshore seismic line G69-04. The old seismogram shows poor quality data with low coherency in reflections.

G69-04 is situated in the onshore portion of the Gamtoos Basin where horizons S05 and S10 were mapped. The reflection event assigned to S10 at 0.75 s corresponds to a depth range of about 1050 m and is proposed as the top basement horizon. The reflector has a medium frequency range, is fragmented showing low continuity. Below S10, the reflectors are chaotic and there is low coherency between traces. At 0.55 s is mapped horizon S05.

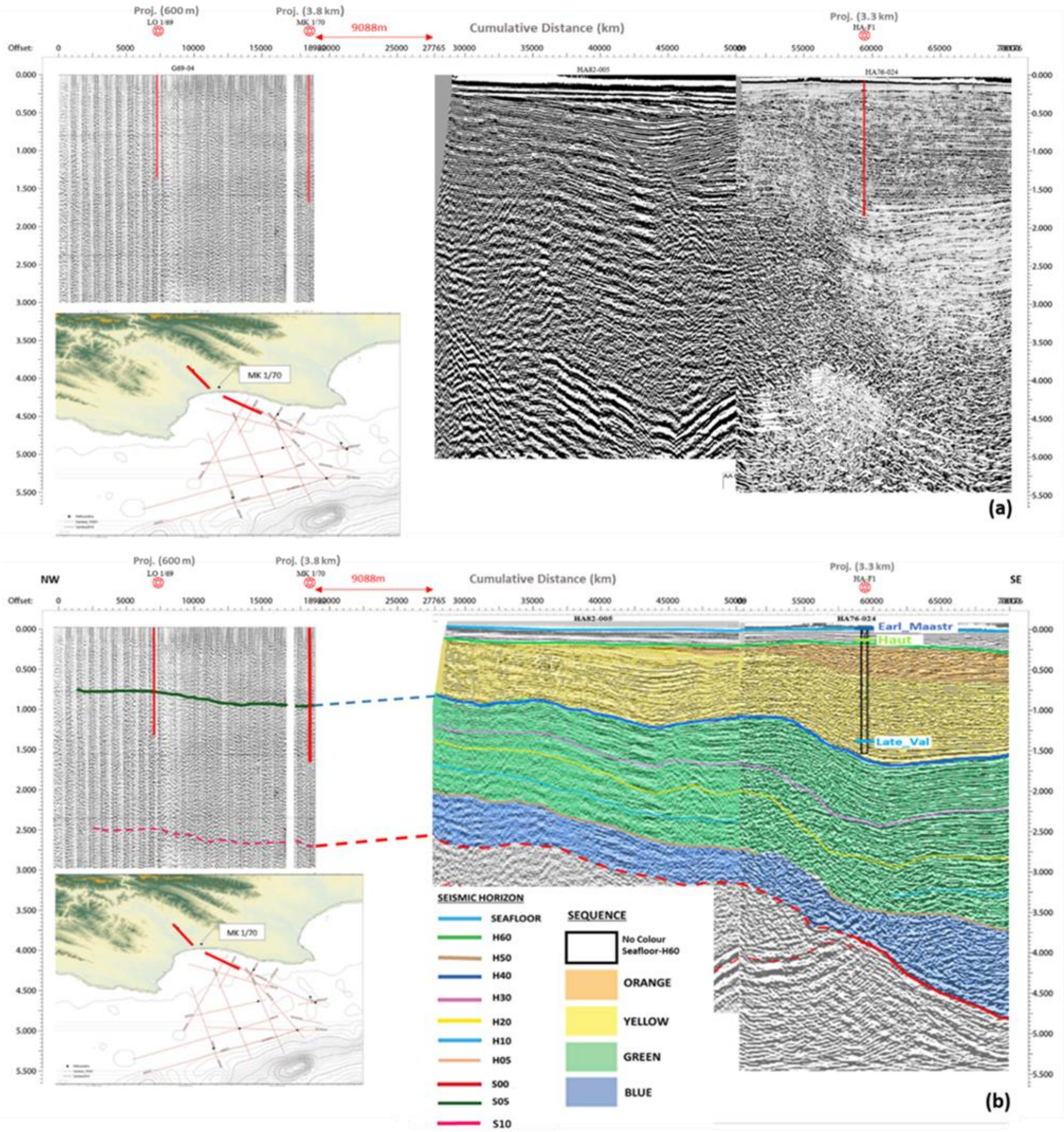

Figure 22: Onshore profile (G69-04) and offshore part of profile A. Borehole LO 1/69 and MK 1/70 are respectively projected onto the onshore seismic line at 600 m and at 3.8 km. Offshore, borehole HA-F1 intersects HA76-24 at 60 km from zero offset and is projected at 3.3 km onto profile A. The distance between the onshore and the offshore profile (G69-04 and HA82-005: HA76-24) is 9088 m.

4.3 Onshore – Offshore Connection

Two horizons have been mapped along the onshore profile and named: S10 (red) and S05 (green) *(figure 22).* S10 is the proposed basement on G69-04 at 2.5 s and was extended as horizon S00 of the profile A, offshore. The reflector cannot be easily traced throughout profile G69-04. At 0.75 s, the mapped horizon S05 is interpreted to be a continuation of H40 on profile A. The sequence bounded by horizons S10 (to the bottom) and S05 (to the top) shows reflectors as chaotic with a low coherency and frequency response. The sequence shows sediment deposits of the thick bed conglomerates of the Enon Formation *(figure 22)*. Profile A *(figure 22)* shows a gradual change in the type of lithology from conglomerates overlying the basement to sandstones alternating with siltstone and shale beds at shallower depths in the Gamtoos Basin offshore. Based on interpretation of the 3 boreholes and 3 seismic profiles situated in the extent of the onshore and offshore parts of the Gamtoos Basin, the facies show a gradual lateral change in the lithology, from conglomerates dominating the onshore part of the Gamtoos Basin to a finer claystone deposits in the deeper anoxic environments offshore (Paton & Underhill, 2004).

Based on the results and interpretation of the profiles, the geometry of the sediment infilling in the Gamtoos Basin, both onshore and offshore shows wedge-shaped sediment sequences thickening towards the hanging-wall of the bounding Gamtoos Fault. Much of the sediment deposits in the Gamtoos Basin lie in the offshore portion of the basin. The timing of increased sediment accumulation closely matches the timing of increased onshore denudation. Great volumes of material were transported from source to sink during the two distinct Cretaceous episodes (mentioned in chapter 1). This accounts for a decrease in stratigraphy thickness towards the onshore portion in the basin (Tinker, 2007). The sediment cover displays a thickness of up to 8km from interpreted seismic data *(figure 19a).* Onshore, the Gamtoos Basin preserves siliclastic deposits of the Uitenhage Group *(figure 7a)*. The reflector characteristics of the seismic facies for profile G69-04 (*figure 22*) and their stratigraphic position above the basement on the seismic line including the drill data (*fig 18a*) show that these seismic facies could be correlated to the poorly sorted conglomerates observed onshore and described as Enon Formation (Paton and Underhill, 2004). The geometry and characteristics of reflections bounded by horizon S10 (from the bottom) and S05 (from the top) are typical of thick bed conglomerates which lack continuity in reflection and consistence in amplitude and frequency response in a sequence. The lithostratigraphic section LO 1/69 tied to seismic section G69-04 shows a lithology of mainly conglomerate with minor coarse-grained sandstone and siltstone and therefore is consistence with interpretation of results seismic section. The facies onshore show a gradual lateral change in lithology from conglomerates dominating the proximal parts *(figure 7a)* of the basin, medium grained to pebbly sandstones and finer grained sediments in distal part of the basin, closer to the Gamtoos Fault. Offshore the oldest sedimentation onlapping onto the basement reflector interpreted to be the top basement of Cape Supergroup rocks are sandstones and conglomerates of Oxfordian / Kimmeridgian age penetrated by boreholes HA-H1 and HA-J1 (Paton & Underhill, 2004). The interpreted results suggest that the conglomerates onshore are a continuation of the Kimmeridgian high amplitude conglomerates grading into sandstones and finer sediments offshore and therefore the onshore and offshore in the Gamtoos Basin are connected.

4.4 Depocenter Migration Along the Gamtoos Basin

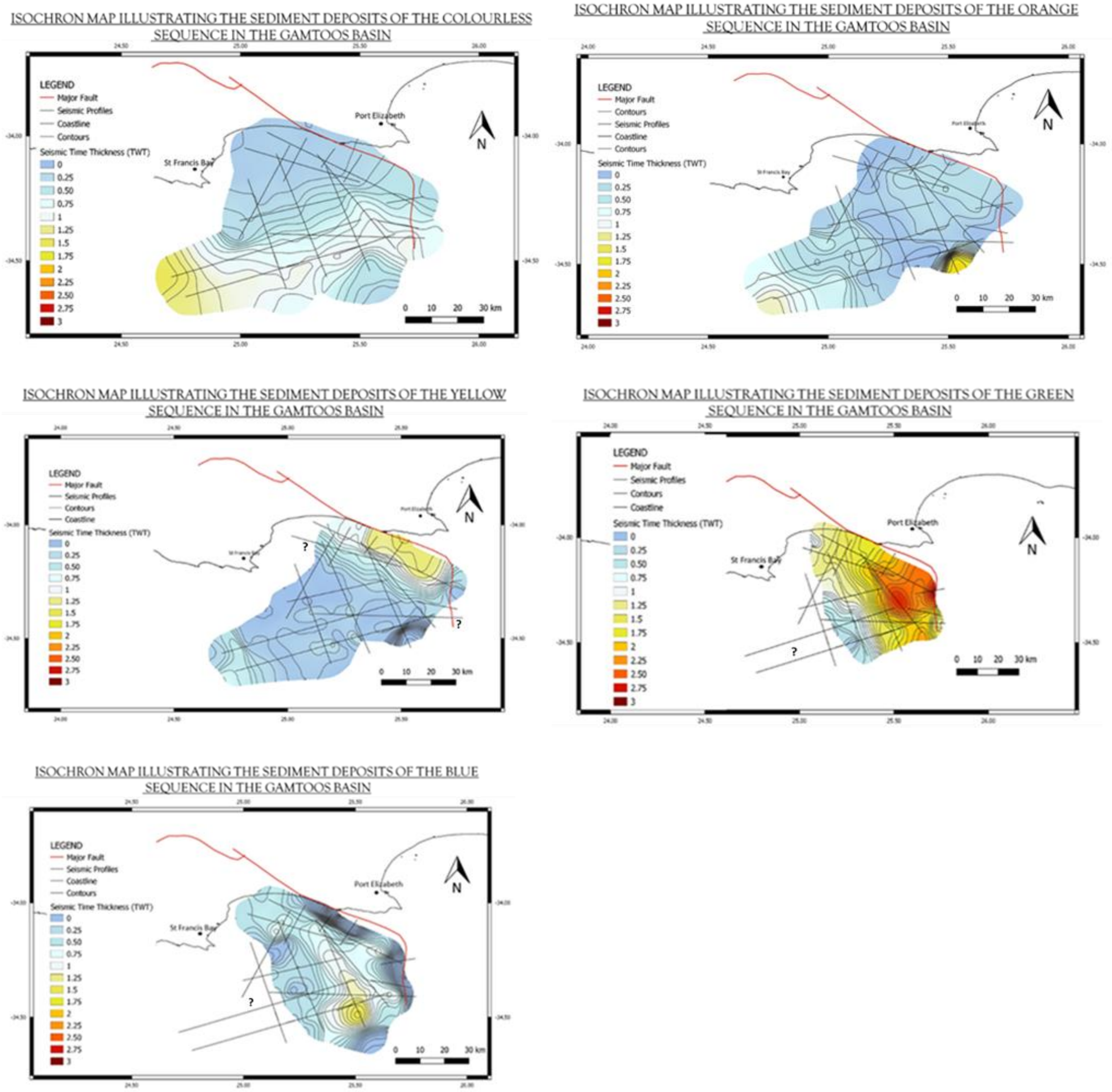

Figure 23(a-e): Isochron maps illustrating the time thickness variations of 5 stratigraphic units. Each sequence is calculated at the time difference between two surfaces. the intervals for calculated sequences represented as thickness maps (displayed in the hsv colour model) are as follows: (a) no colour sequence: seafloor-H60 (b) Orange: H60-H50 (c) Yellow: H50-H40 (d) Green: H40-H05 (e) Blue: H05-S00. Each sequence has a maximum of 3s.

4.4.1 Gamtoos Basin Evolution and Kinematic Phases

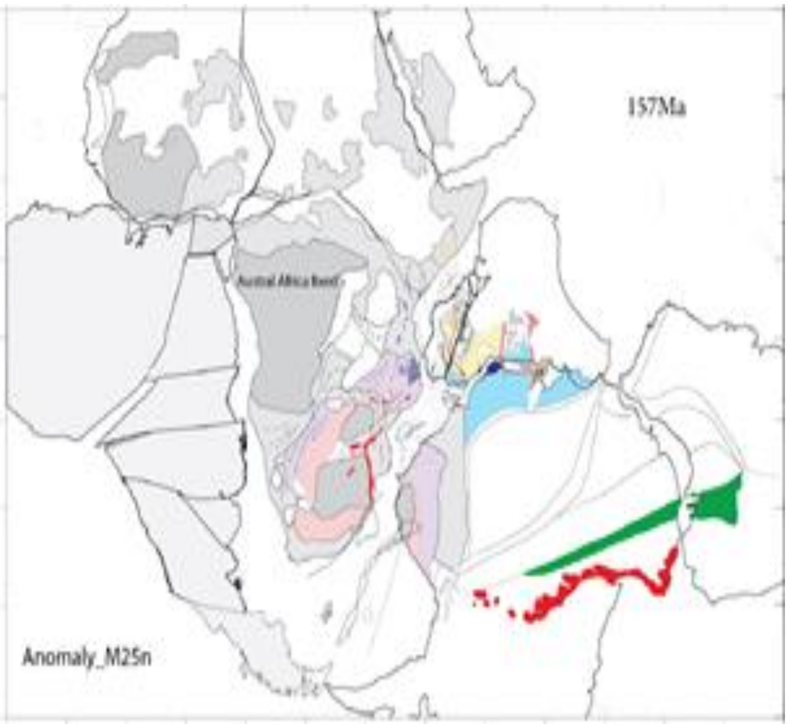

Figure 24: The separation of East - West Gondwana during mid-late Jurassic. New oceanic crust from seafloor spreading at M25 (157 Ma) was formed when the Western Somalia and Mozambique separated. I. B: Elan Bank (Mercator projection) (Thompson et al, 2019).

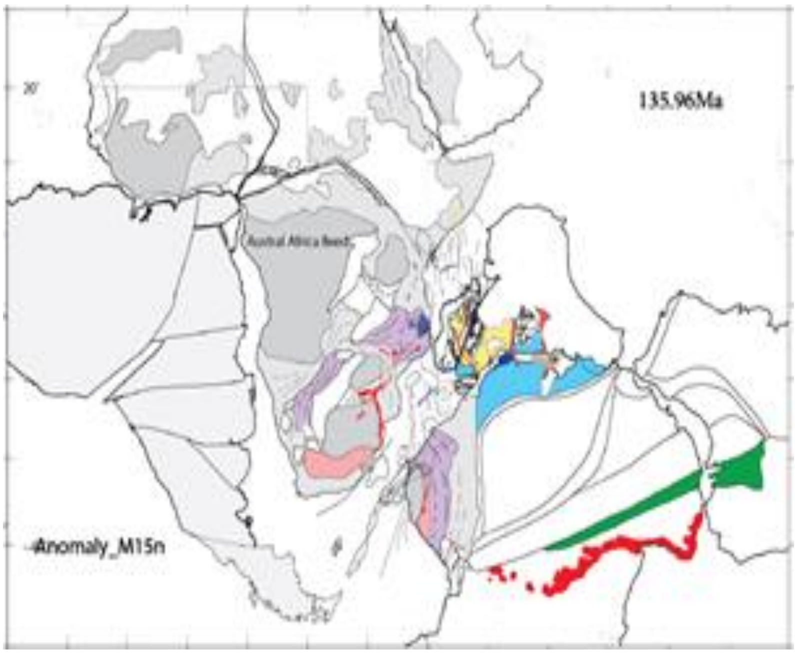

Figure 25: A diagram showing the reconstruction of the Indian Ocean at anomaly M15 (135 Ma). (Mercator projection) (Thompson et al, 2019).

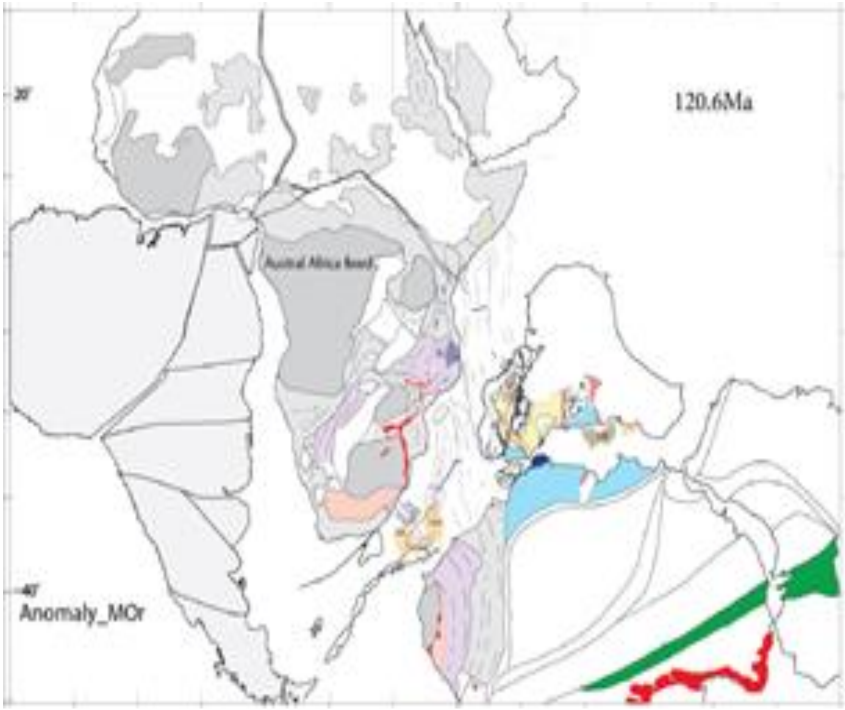

Figure 26: A diagram showing the Indian Ocean reconstructed at anomaly M0r (120.6 Ma). At anomaly M0 the Madagascar - Greater India Sri Lanka block stopped its southward drift from Africa. The South Mozambique Ridge, Maud Rise, Agulhas Plateau, and northern part of the Astrid Ridge these four ridges overlap at the Southern Mozambique Ridge at M0, which means they may have emplaced during the time, possibly due to anomalous volcanism. The North Kerguelen Plateau may have been initiated around this time (Mercator projection) (Thompson et al, 2019).

Along the continental margins onshore and offshore geological and geophysical data were integrated and interpreted to constrain the evolution of the tectonic plates (Thompson et al, 2019). In the Gamtoos Basin is preserved the oldest dated sediments of the Indian Ocean which are crucial to our understanding of the basin evolution relative to the kinematic phases during the Jurassic time. The infill evolution of the Gamtoos Basin comprises several sedimentary sequences as in interpreted in chapter 4 (Results and Interpretation), the interpreted sequences are namely from oldest to youngest *(figure 22):* BLUE, GREEN, YELLOW, ORANGE and COLOURLESS. The sequences are mainly composed of continental passing laterally to a shallow marine environment.

Sediment deposition in the Gamtoos Basin occurred during two different spreading regimes from Kimmeridgian to Valanginian (155-134 Ma) times. The two spreading regimes were termed by the Principal and Late Syn-rift phase (Paton & Underhill, 2004). The Principal syn-rift phase is contemporaneous with the opening of the Indian Ocean at Kimmeridgian (155Ma) times. From interpreted seismic data (Chapter 4), the oldest sediments deposited during this phase are conglomerates and sandstones represented by the BLUE and GREEN sequence. The seismic unit is bounded at the bottom by a strong reflector S00 and interpreted as top boundary for underlying Palaeozoic age deposits. Here the age of the initial rifting stage is associated with the oldest Mesozoic magnetic anomaly (M25n) *(figure 24),* the formation of new oceanic crust in the Indian Ocean. The rifting event marks the successful breakup and initial rifting at Kimmeridgian times in the Indian Ocean (Thompson et al., 2019).

Overlying the BLUE sequence are the younger GREEN sequence siltstone and claystone units *(figure 18c).* The Late Kimmeridgian/Early Valanginian boundary shows evidences of growth strata indicating syn-rifting deposition characterised by a reflector geometry thickening seaward and towards the Gamtoos fault, with sub-parallel reflectors onlapping onto the reflector H05. At this phase, the Patagonia moved southwards, away from the African continents *(figure 26),* opening the Atlantic Ocean. Sediment deposition during the Syn-Rift stage ended at Late Valanginian (134Ma) and is represented by the strong reflector H40 *(figure 22b).* The Principal syn-rifting event ends at Late Valanginian (134 Ma) times contrary to the Late Hauterivian age (H60) proposed by Paton and Underhill (2004).

The Hauterivian age deposits (H40- H60) *(figure 22b)* are possibly Late Valanginian (135 Ma) sediments eroded and deposited after the Principal Syn-rift event ceased. The folding and major unconformity represented by H40 accounts for the overlying Hauterivian age sediment deposits.

The sedimentary evolution of the Gamtoos Basin is thus connected to the two rifting events which occurred in the Mesozoic Era. The first rifting event being linked to the opening of the Indian Ocean and the second rifting event linked to the opening of the Atlantic Ocean.

CHAPTER 6: CONCLUSIONS

The study proves that the onshore and offshore crustal features of the Gamtoos Basin are linked. High amplitude horizon surfaces traced from seismic reflection data in the offshore portion of the basin could be extended to the onshore portion of the basin. Furthermore, by successfully identifying five second-order seismic depositional sequences and their bounding surfaces/ discontinuities, the study also presents a new basin fill evolution of the Gamtoos Basin. The new model indicates that infilling started during the Kimmeridgian age (~155Ma) which marks the initial syn-rift stage with the formation of the first oceanic crust along the Indian Ocean. Subsequently, the Patagonia moved south-west relative to the African plate, opening the Atlantic Ocean at Valanginian (~135Ma) age. For a more comprehensive insight on the connection of the onshore portion with the offshore portion of the Gamtoos Basin as well as the basin fill evolution, I recommend that more seismic data acquisition and borehole drilling be conducted in the Gamtoos Basin.

A1. Stages of the spiking and the predictive deconvolution filters

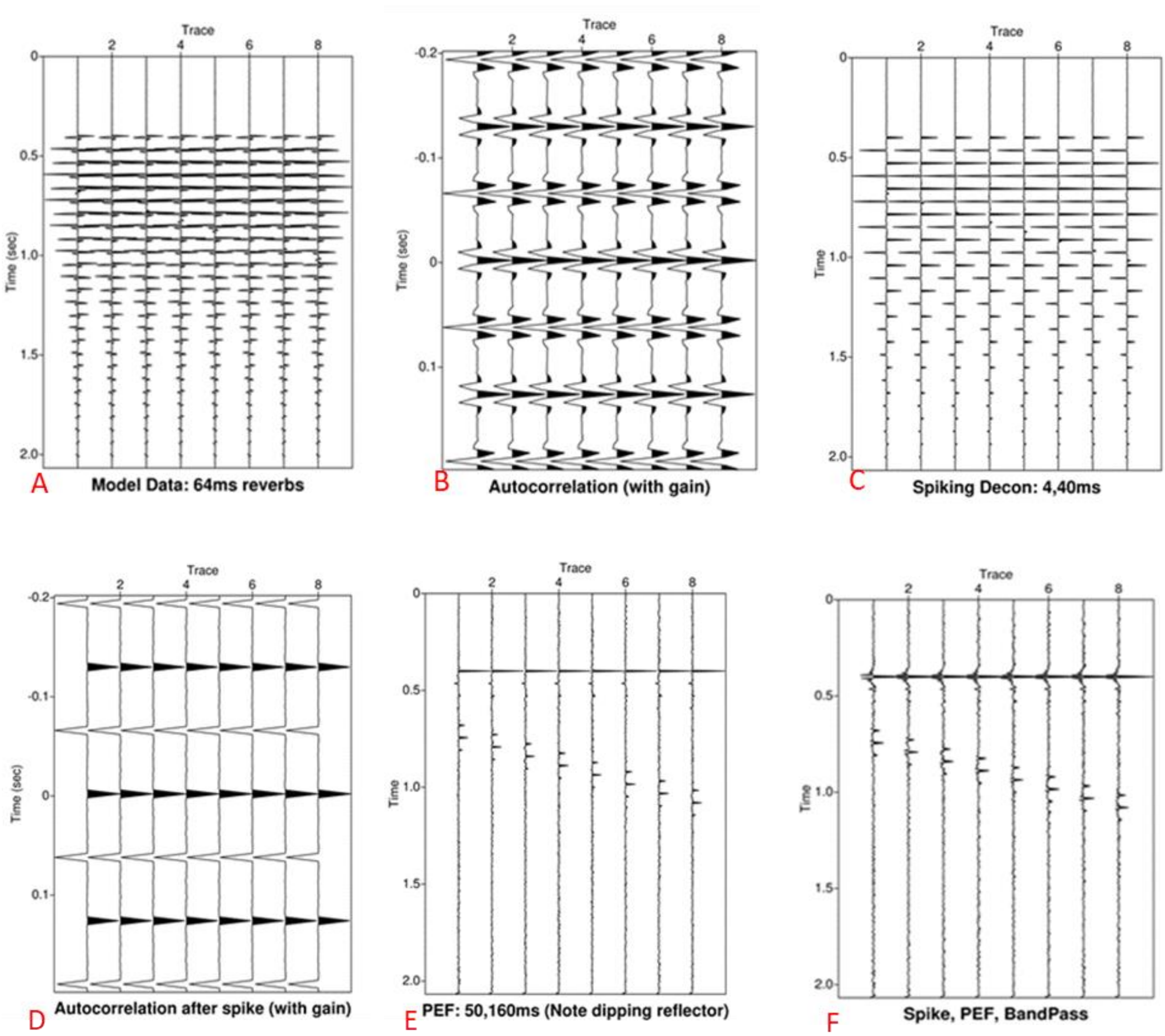

Figure A1: Stages of the spiking and the predictive deconvolution filters (a) Original data. (b) autocorrelated trace. (c) application of spiking deconvolution on the original data with a Wiener filter of 40 ms in length and 4 ms gap (d) autocorrelation after the application of the spiking deconvolution (e) application of predictive deconvolution on the spiked data with a Wiener filter of 160 ms in length and 50 ms gap. The dipping reflector which is the noise free record is enhanced (f) final output of the data after 5-15-80-100 bandpass filter.

A2. 2D seismic reflection lines interpreted for the purpose of isochron map creation

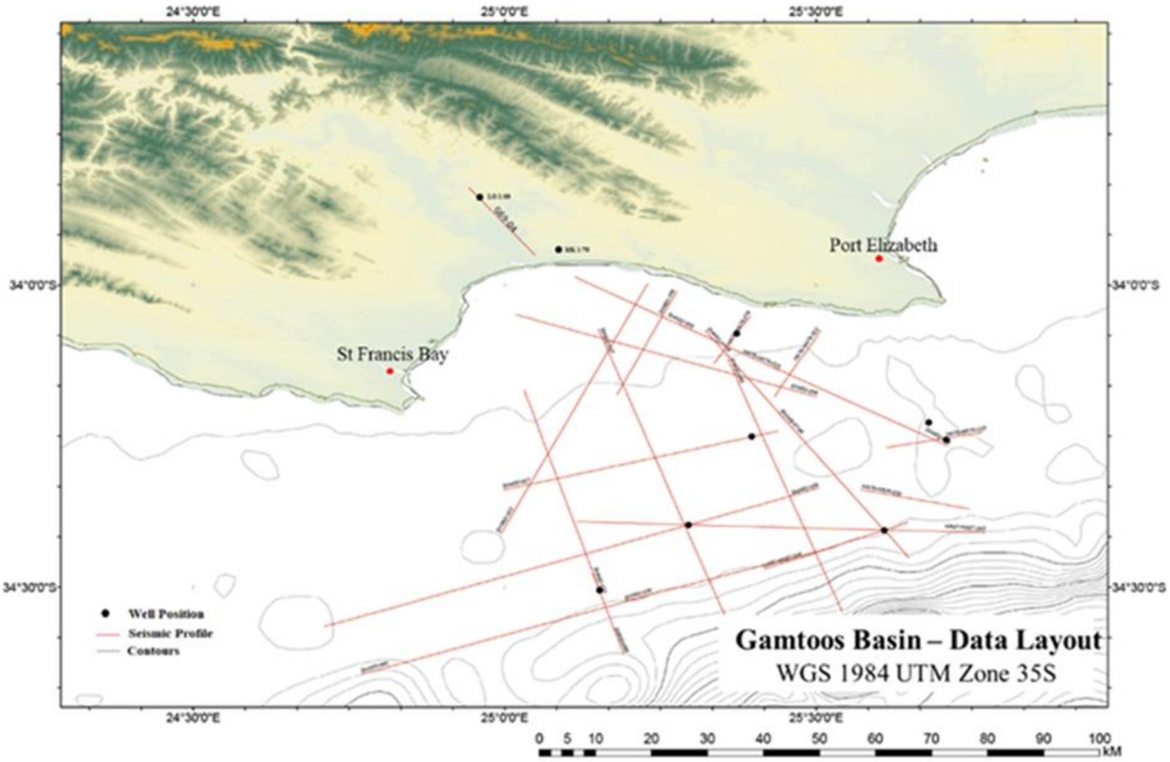

Figure A2: Map showing a total number of 16 2D seismic reflection data that was interpreted for the purpose of isochron map creation and 1 seismic profile onshore. A total of 9 boreholes were made available (marked in black dots). Only 3 boreholes were used namely; L0 1/69, MK 1/70 and HA-F1.

A3. Seismic profile HA87-043

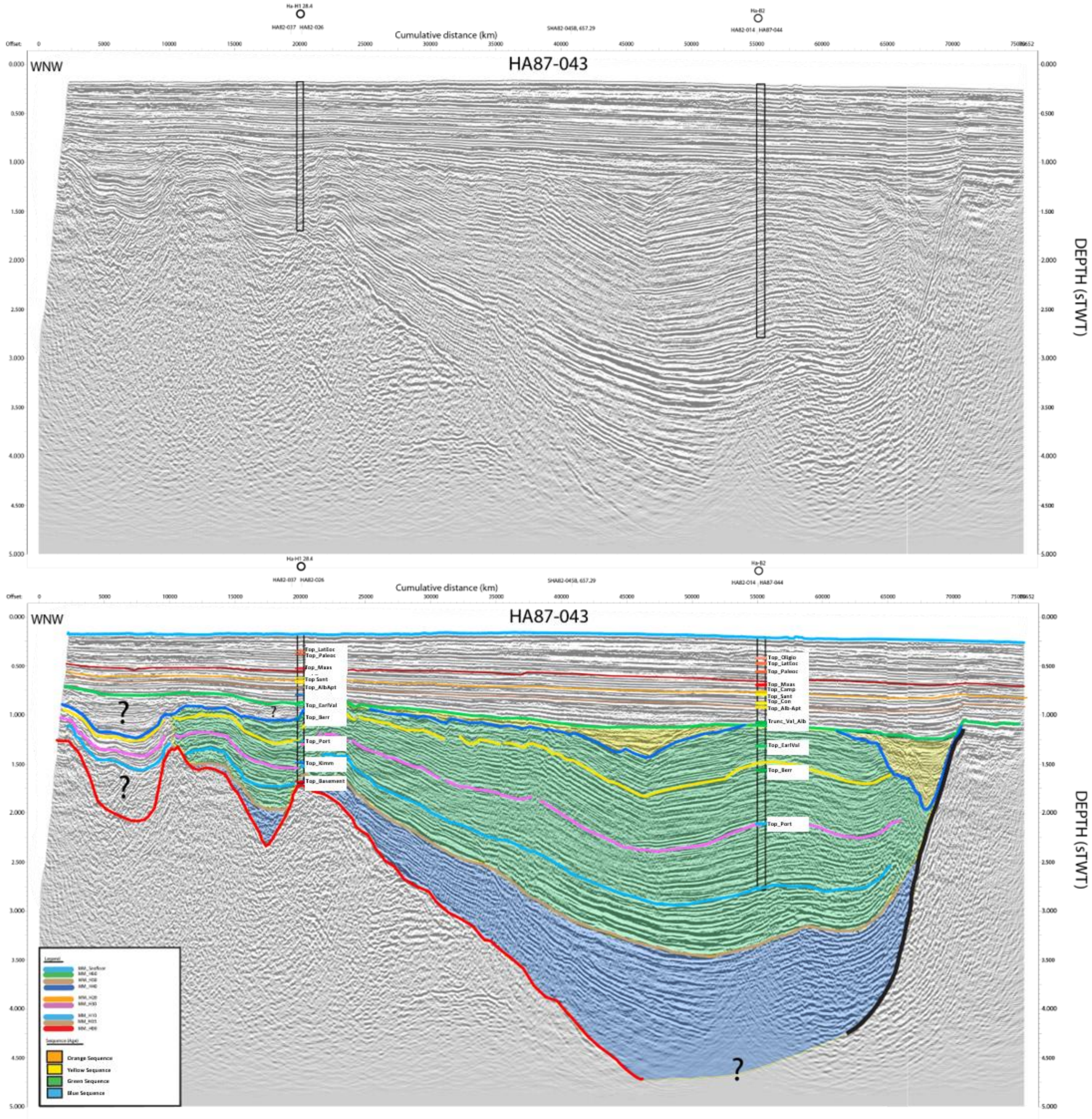

Figure A3: (a) Seismogram HA87-043 selected as one of the profiles from which interpretation was propagated to the rest of the available profiles for the purpose of the study in the Gamtoos Basin (b) Interpreted seismic section showing the different seismic horizons and sequences.

A4. Seismic profile HA82-045

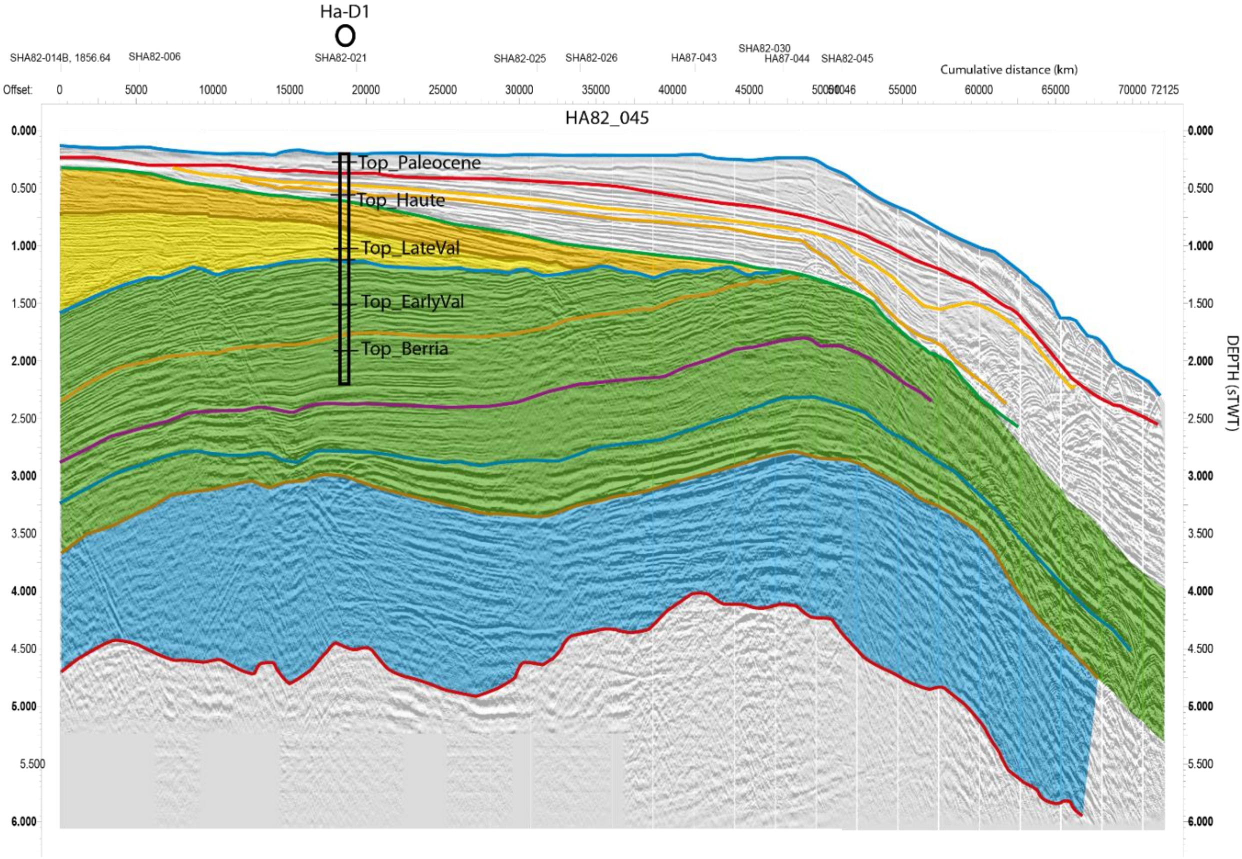

Figure A4: Interpreted seismic section of profile HA82-045 situated offshore. The profile cross-cuts HA87-043 around 40 km.

A5. SCRIPTS

General Mapping Tools (GMT) Script

Pro-Grid:

```
#!/bin/bash                           %script should always be run in bash shell
####PARAMETERS
#General parameters for the script
LIMIT=24.5/26/-35/-33.85              %geographic area for the study-west/east/south/north
SCALE=m7c                             %scale of the displayed map
NAME=MM_H40-Grid
INPUTFILE=$NAME.xyz
GRDMEAN=Mean$NAME.grd
GRDNEAR=Near$NAME.grd
GRDINTERM1=1INTERM$NAME.grd           %intermediate Grid
GRDFINAL=GRDH40.grd
#Grid internal parameters:
I=-10.05m                             %sample scale
S=S1k                                 %sample interpolation outside data (km)
F=-Fm0.05m                            %median filter
####GRID CREATION
#Simple grid creation:
#xyz2grd$NAME -GNAME.grd -R$LIMITES $I -Vv
#Complex
blockmean NAME.xyz  -R$LIMIT  $I  -V  |  surface -G$GRDMEAN - R$LIMIT $I -V
nearneighbor NAME.xyz -GNear$NAME.grd -R$LIMIT $I -V -N3 $S
grdmath -V Mean$NAME.grd Near$NAME.grd OR =$GRDINTERM1
grdfilter 1INTERM$NAME.grd -D0 $F -G$GRDFINAL -V
```

Prog_Isopach:

```
#!/bin/bash          %corresponds to the correct header for a bash script (general to all script
#### PARAMETER
LIMIT=24.5/26/-35/-33.85
SCALE=m7c

#Name of the file for gridding and processing (02: UpperGrid/ 01: LowerGrid)
NAME=THICKNESS_H50-H40
#Inputfile=NAME.xyz
```

```
GRDFILE02=GRDFINAL                          %upper Grid
GRDFILE01=GRDFINAL                          %lower Grid
GRDFINAL=$NAME.grd
XYZFINAL=$NAME.xyz
FICHPS=$NAME.ps                             %Output Postscript
FICHCPT=paletteColour2.cpt
#Internal parameters for interpolation (specify increment (m: nautical mile); Sk=Interpolation
Outside the grid (k=kilometre); F: low-pass filter type and full diameter filter-width)
F=-Fm0.05m
```

<u>Prog_Isobath:</u>

```
#!/bin/bash
#general limits
#LIMITS=0/5/38/43
#limit Ebre -1/6/38/44                      %Ebre?
LIMITS=24.5/26/-35/-33.85
ECHELLE=m1.5c                               %Intermediate? Interpolation?
LIMECH="-R$LIMITS -J$ECHELLE" %limech?
####Input Parameters:
NAME=HorizonFICHXYZNET=$NAME.xyz
GRDMEAN=Mean$NAME.grd
GRDNEAR=Near$NAME.grd
FICHCPT=echellecouler.cpt
GRDINTERM1=1INTERM$NAME.grd
GRDFINAL=$NAME.grd
FICHPS=Carte_$NAME.ps #Set output survey
#set FICHSURVEY=Survey.nxy
#Internal parameters of grids
#I=-I0.05m
#S=-S4k
#F=-Fm0.05m
###INTERPOLATION
#blockmean $FICHXYZNET -R$LIMITS $I -V | surface -G$GRDMEAN -R$LIMITS $I
#-V
#Nearneighbor $FICHXYZNET -G$GRDNEAR -R$LIMITS $I -V -N3 $S
#grdmath -V $GRDMEAN $GRDNEAR OR =$GRDINTERM1
#grdfilter $GRDINTERM1 -D0 $F -G$GRDFINAL -V
```

```
###DISPLAY GRID THICKNESS
#psbasemap -R$LIMITS -J$ECHELLE -Bg20a20:.”’’:WSenS -V -K -Y4c -P > $FICHPS
#grd2cpt $EPGRDFINAL1 -Z -Crainbow -L-200/200 -S-200/200/10 -V >$FICHCPT
#grdimage Filename.grd -R$LIMITS -J$ECHELLE -CPALET Filename.cpt -Q -O -K
#-V >>$FICHPS
#grdcontour Filename.grd -R$LIMITS -L-200/200 -C20 -Gdl -W0.1, black -J$ECHELLE
#-O -K -P >> $FICHPS
#grdcontour Filename.grd -R$LIMITS -L-200/200 -C100 -Gdl -W0.8, black -J$ECHELLE
#-O -K -P >> $FICHPS
#pscoast -R$LIMITS -J$ECHELLE -W2 -Df -Ir/blue -Ia/blue -Tf6/43.4/1c -Ggrey -O -K
#-V -P >> $FICHPS
#psscale -D12c/5c/6c/0.5c/ -Cechellecouleur.cpt -O -V -P >> $FICHPS
    #gs $FICHPS
```

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