Seismic Sequence Stratigraphic Sub-Division Using Well Logs and Seismic Data of Taranaki Basin, New Zealand

Abd Al-Salam Al-Masgari 1,2,*, Mohamed Elsaadany 1, Abdul Halim Abdul Latiff 1, Maman Hermana 1, Umair Bin Hamzah 3, Ismail Alwali Babikir 1, Teslim Adeleke 1, Qazi Sohail Imran 1 and Mohammed Ali Mohammed Al-Bared 1,2

1 Centre for Subsurface Imaging, Department of Geosciences, Universiti Teknologi Petronas, Seri Iskandar 32610, Perak, Malaysia; mohamed.elsaadany@utp.edu.my (M.E.); abdulhalim.alatif@utp.edu.my (A.H.A.L.); maman.harman@utp.edu.my (M.H.); ismailalwali-19011556@utp.edu.my (I.B.); teslim-180003571@utp.edu.my (T.A.); qazi-17007558@utp.edu.my (Q.S.I.); mohammed_17005214@utp.edu.my (M.A.M.A.-B.)
2 Department of Geology and Environment, Faculty of Applied Science, Thamar University, Dhamar 124401, Yemen
3 Department of Geology, School of Environmental Science and Natural Resources, National University of Malaysia, Bangi 43600, Selangor, Malaysia; hashe053@gmail.com

* Correspondence: almasgari@gmail.com

Abstract: This study focuses on the sequence stratigraphy and the dominated seismic facies in the Central Taranaki basin. Four regional seismic sequences namely SEQ4 to SEQ1 from bottom to top and four boundaries representing unconformities namely H4 to H1 from bottom to top have been traced based on the reflection terminations. This was validated using well logs information. An onlapping feature on the seismic section indicates a new perspective surface separated between the upper and lower Giant formation, which indicates a period of seawater encroachment. This study focused extensively on deposition units from SEQ4 to SEQ1. The seismic facies, isochron map, and depositional environment were determined, and the system tract was established. This study was also able to propose a new perspective sequence stratigraphy framework of the basin and probable hydrocarbon accumulations and from the general geological aspect, SA-Middle Giant Formation (SEQ3) could act as potential traps.

Keywords: Taranaki basin; seismic sequence stratigraphy; seismic facies classification; and isochron maps

1. Introduction

Seismic stratigraphy is a basic geological approach relating to the interpretation of stratigraphy and depositional facies from the seismic data [1]. Sequence stratigraphy is also considered as a study of sediments and sedimentary rocks in order to define geometrically connected sedimentary facies [2]. The importance of the seismic methods is evident from the fact that these methods are now extensively employed for the exploration of hydrocarbons [3].

The seismic techniques can directly detect some hydrocarbon accumulations in the seismic section [4] using the seismic geometries. The seismic methods involve the measurement of two-way travel time (TWT) of the seismic waves that are transmitted across the geological layers from the surface and reflected to the surface after passing through the interface between contrasting geological layers [5]. Due to the contrast in acoustic impedance at an interface, the reflections are caused due to the transmitted energy produced by the seismic velocity and density between these layers. Primary seismic reflections are generated by the last defense in the physical properties of the rock surfaces [6]. Seismic reflections represent mainly the stratal surfaces and unconformities with velocity and density contrasts. A seismic section can be considered as a record of chronostratigraphic, structural, and lithostratigraphy [7]. Seismic reflections that contain chronostratigraphic information...
can use the geometry of seismic reflections to interpret the stratigraphy, post-depositional distortion form, burial history depositional units, topography, and reliefs of unconformities. Seismic reflection can also be used to interpret paleo bathymetry and paleogeography. Nevertheless, the type of rocks and lithofacies could not be directly recognized from the geometry of reflection patterns [8].

Seismic sequence analysis is usually constructed for identifying the stratigraphic components of a genetically conformable sequence of linked strata known as a depositional sequence [9]. The lower and upper borders of depositional units are identified as unconformities. The depositional sequence boundaries on 2D and 3D seismic data can be observed by identifying the reflection termination, such as onlap, downlap, toplap, and erosional truncation [10]. Seismic configuration, well tops, and well tie are usually utilized in order to establish a seismic sequence stratigraphy framework. Moreover, the 2D seismic section and well logs data are used for completing seismic stratigraphic interpretation.

The importance of this present study can be due to considering Taranaki basin as one of the most economically significant elements of New Zealand nation with the addition of the hydrocarbon production from this basin that is considered as an essential component of New Zealand energy requirements [11]. In the Taranaki basin, early work on geology mainly involved investigation and regional mapping, which was carried out for Petroleum exploration. Taranaki petroleum geology had an early assessment with other New Zealand basins as highlighted by Hans and Katz [12] (Hans R. Katz (2) 1971), Sprigg [13], Stern and Davey [14], Katz [15], and Beggs [16].

Related geology was governed by the oil industry, where it was responsible for most unpublished notes of literature and lodged with the Ministry of Commerce as Petroleum Reports, of which about 1200 reports are related to the Taranaki basin. Interpretations of seismic reflection profiles were primarily the source used to delineate the regional basin structure that has been done by Kamp and others [17]. Knox [18] described the morphology of the southern Taranaki basin and its location on the Australian Plate, with a large scale from an in-depth seismic reflection profile. Not only that but also the Taranaki Peninsula was described using deep seismic reflection profiling [19].

To the author’s knowledge, few studies were conducted in the Taranaki basin and were limited to classifying the Giant Forest Formation that is considered very wide (approximately 800 m) and divided into two sequences only; upper and lower different intervals. The lower sequence formation (Lower Giant formation) extended from H3 to H1, while the upper sequence formation (Upper Giant Formation) began from H1 to the seafloor. In the current study, the classification of the Giant Forest Formation was identified using the method of the seismic interpretation principles and identified a a new horizon between H3 and H1 which was named H2, this subdivision resulted in a new proposed classification with new sequence named (Salam Middle Giant Formation) (SA-SEQ3).

2. Study Area

The study area was chosen to be in the Taranaki basin as this area is still considered a virgin and a major resource for hydrocarbon accumulation. The total area investigated in this study was approximately 214 km². The significant geological formation was found to be a series of adjacent and interlocked Cretaceous-Cenozoic sedimentary basins that outspread along the western boundary of New Zealand [18]. Primarily, the basin subsurface configuration lies offshore underneath the continental shelf, but it is also comprised of the Taranaki Peninsula at the northern coastal areas and in the northwestern south part. Several tectonic events have been occurred which reformed and modified the basin. Thus, it is challenging to define and classify the basin style or the geographic area individually. The Taranaki Basin remained open towards the sea from the west and north parts, whereas the fluctuated depositional area distinguished the east and south parts under the influence of eustatic and tectonic events. Besides, the Taranaki basin was separated into two structural regions; the steady western platform and the eastern movable belt as shown in Figure 1.
The movement of the eastern movable region of the basin started to slow down since the Cretaceous times and was categorized as a layered cake.

This was followed by a progradation deposition on an un-faulted, sub-horizontal, and locally subsided seafloor [21]. The eastern movable belt also showed a complex morphology due to the tectonics associated with the Neogene Kaikoura Orogeny [17]. Figure 1 also shows the study area of the Taranaki basin, the most important structural features, and the well location. To obtain a complete geological interpretation, several stages of analysis must be carried out such as analysis of seismic sequence, seismic facies, and relative changes of sea-level investigation.

3. Former Exploration History

In Taranaki Basin, an early work on geology mainly involved investigation and regional mapping was carried out for Petroleum exploration. Taranaki petroleum geology had an early assessment with other New Zealand basins as published by Sprigg et al. [13], Katz [22], and Urusk [23].

The majority of reports on Taranaki Basin petroleum and related geology were governed by the oil industry, where it is responsible for most unpublished literature and lodged with the Ministry of Commerce as Petroleum Reports, of which about 1200 are related to Taranaki Basin.

Geologically, previous examinations of surface geology relevant to Taranaki Basin Cretaceous-Cenozoic sedimentary stratigraphy were carried out mainly in the Taranaki coastal region north of the peninsula, and in the northern South Island coastal regions. The earliest geological studies in Taranaki were carried out in the 1860s. Oozing petroleum alongside the beach near Moturoa led to the drilling of the first oil well in New Zealand in 1865. Bell (1909) look over the signs of petroleum in the New Plymouth area. References to these earliest inquiries are given in Henry [24], Clarke [25], Morgan and Gibson [26], and Adams et al. [27].

In the early 1900s, the Geological Survey of New Zealand concentrated a significant regional mapping work in Taranaki Basin (Clark [25], Kamp [17] and Morgan and Gibson [26]. This effort provided the groundwork for onshore stratigraphic subdivision and terminology, afterward combined in Hay’s (1967) [28] 1:250,000 scale map.
In the late 1950s, the recent oil exploration period was started where numerous stratigraphic and mapping surveys of onshore zones nearby to the Taranaki Basin was done by many geologists from several companies such as Shell, BP, and Todd consortium (Glennie 1956 [29], Arnold 1957 [30], and van der Sijp [31]. This introductory stage of exploration started in conjunction with a seismic reflection investigation on the Taranaki Peninsula that was reviewed by McBeath 1977 [32]. After the drilling of first few wells, a reassessment was done on the petroleum geology of the subsurface Taranaki Basin and adjacent Wanganui Basin Cope 1965 [33].

In terms of the subsurface geology and geophysics studies, Cope and Reed (1967) have only recently referred the Taranaki Basin in a published literature. The basin had been recognized by those in the oil industry [33] Cope 1965, but it was not until the industry data and interpretations were first published that the existence and nature of this primarily subsurface basin became more widely known, Several case histories of the Kapuni and Maui gas-condensate discoveries have also been published in McBeath 1977 [32]. Above the last period of petroleum exploration in Taranaki, an ever-growing quantity of subsurface information (mainly from reflection seismic and well data) has become freely available, resulting in many published papers confirming findings in the number of unpublished industry and government reports on the Taranaki Basin.

Interpretations of seismic reflection profiles were primarily the source used to delineate the regional basin structure that has been done by Thrasher and Cahill 1990 [34]. Stern and Davey 1990 [35] described the morphology of southern Taranaki Basin and its situation on the Australian Plate, with a comprehensive scale from a deep seismic reflection profiles.

The mainstream of modern Taranaki Basin papers involving numerous of those listed above, have also published in proceedings volumes for 1990, 1992, 1994, and 1996 New Zealand Oil Exploration conferences, published by the Ministry of Commerce, and in Petroleum Exploration in New Zealand News, a quarterly magazine issued by the Ministry of Commerce. These papers cover topics including structure, reservoir quality, and the distribution of seismic reflection mapping and sequence stratigraphy, basin evolution and tectonic setting, petroleum habitats, exploration plays, and hydrocarbon geochemistry King and Thrasher 1996 [36].

4. Methodology

The adopted methodology in this study is shown in Figure 2, at which the first stage of the research started by obtaining the 2D seismic and well log data. The data contained 2D seismic lines, GR, Sonic, Density, Neutron, Resistivity logs and geological reports. These data come in a form of digital files with SGY format of the seismic data and LAS or ASCII files format of the well logs. These data were obtained from the New Zealand petroleum and minerals online exploration database store. In the second stage, the data integrated, analyzed, and interpreted to highlight the geological features of the study area. A detailed description of each step in the methodology is outlined in the following sub-sections.

However, the main methodology consists of two main steps, first is the well log analysis which includes tying the well to the seismic data by generating the synthetic seismogram and matching the major events - utilizing the stretch and squeeze function in the used software - in the wells to the main reflectors in the seismic sections. The second step conducted the conventional seismic interpretation, this step initiated after the well tie was performed by integrating the well and seismic information and then identify the interested sequence boundaries into the 3rd order based on the newly obtained synthetic seismogram, seismic facies, reflection terminations, and other well logs curves shapes. The seismic facies which are genetically related deposited units and their boundaries have been in turn classified. The fault sticks over the available seismic sections have been traced and established the structural framework.
Figure 2. Layout shows the adopted methodology in this study.

The internal reflection configurations were utilized to predict and classify the associated seismic facies for every deposit unit. Stacking patterns and parasequences were established as well for the interested zone. System tract for these units has been also performed utilizing the GR and the seismic reflection terminations. More explanations for each step are as follows.

4.1. The Seismic Sequences Stratigraphy

The synthetic seismogram is a computer-generated seismic response computed from well data and is most frequently used to correlate geologic information from well logs with seismic data. Seismic data mainly provides time values, while synthetics provide time and depth values that are used to verify reflection events. The components of the generated synthetics produced in this research are time-depth charts, reflection coefficient, seismic trace, the new generated synthetic picked horizons, and the new finding of top formation which are all shown in Figure 3.
The first step in this study has been carried out by tying the seismic data to the well data. The sequence boundary determination, seismic facies, stacking patterns, para sequences and system tract analysis were respectively delineated. The usual way to tie well information to seismic data in depth is to convert them to time and reconvert them back to depth [37]. In the well tie technique, the synthetic seismogram was generated by integrating density and sonic logs to estimate the seismic impedance \(Z\) of each subsurface layer. The reflection coefficient \(R\) at boundaries between these layers was then determined with the Zoepretz equation \(R = (Z_2 - Z_1)/(Z_2 + Z_1)\). The series of reflection coefficients were then convolved with a Ricker wavelet of 28 Hz frequency to produce the synthetic seismogram using Witiore-1 well. Reflection coefficient curve, seismic traces near the well and formation tops in-depth domain have been displayed side by side for comparison as displayed in Figure 3. A good match between the formation tops from Witiore-1 well and the generated synthetic seismogram.
Ten 2D seismic profiles covering an area of 217 km$^2$ and logs from Witiora-1 well exploration were used in this analysis. The sequence boundaries were interpreted based on reflection configuration, reflection termination, and well log information, this interpretation was confirmed by a synthetic seismogram. The seismic facies were identified based on the internal seismic reflection patterns and reflection terminations.

4.2. Structural Interpretation

The raw data was processed into seismic sections which each section is an image of the subsurface structure. The adopted method involves structural interpretation as apart from this study. Generally, it is preferred to pick these faults prior to any horizons picking to avoid miss leading by the auto horizons picking or non clear reflectors. The faults were picked on the 2D vertical display to produce a pick, and the line between two picks (points) which two more of these points forms one fault segment. A fault line is a collection of one or more digitized fault segments. Continue picking on successive vertical displays as required on all over the seismic lines affected by faults [38]. The fault segments for each fault were traced over the available seismic sections which are automatically triangulated in used software to give a fault surfaces. The sharp offsets in the amplitude seismic reflection sections have been utilized to pick such kinds of faults.

The interested horizon (SA-SEQ3) is slightly affected by one of these faults at the bottom of this unit as shown in Figure 10. The study area, in general, is distinguished by anticline with few faults in the southeast of the studied area. Based on the available seismic data, Variance seismic attribute for the 2D seismic sections has been generated and utilized in tracing the fault extension over the seismic data.

4.3. Seismic Facies Analysis

The adopted methodology of this study conducted the internal and external seismic reflection interpretation by using the seismic stratigraphic concepts. The procedures involved seismic sequence stratigraphy and seismic facies analysis in distinguishing the stratigraphy and depositional environment of the study interval. Seismic sequence stratigraphy analysis subdivided the seismic section into a package of consistent reflections, which was separated by unconformities that were also identified by the reflection terminations. These consistent seismic packages were interpreted as depositional sequences consisting of genetically associated layers that were bounded at their bottom and top by unconformities or their related conformities, as explained by Roksandic [39], Catuneanu and others [40], and Mitchum and others [41].

Figure 4 shows the seismic facies analysis that included the delineation of the internal reflection geometry, continuity, frequency, and internal velocity. The internal reflections indicate the deposition history of a unit, while the external reflection termination such as the onlaps, onlaps, and downlap can indicate the facies boundaries and limitations.

Seismic facies analysis is employed in this study to predict the lithology distribution and the classification of the sequences using the internal and external patterns of the targeted deposited unit. A reasonable assumption of the seismic facies can be made directly by looking at the seismic section. In this study, the seismic facies parameters that were utilized included the amplitude, continuity, frequency, phase, and geometric configurations as demonstrated in Table 1.
Figure 4. Reflection configurations of the seismic facies in the Taranaki Basin.

Table 1. Seismic reflection parameters and their associated characteristics [42].

| Parameters | Characteristic |
|------------|----------------|
| Amplitude  | Strong or weak  |
| Continuity | Good continuity to discontinuous |
| Frequency  | High to low     |
| Phase change | Peak changes to a trough (or vice versa) |
| Geometry   | Chaotic, laminated, draped, noisy zone, etc. |
| The flat spot | It is incompatible with the nearby structure’s |

4.4. Parasequences and Stacking Patterns Analysis

A parasequence is a relatively conformable, genetically related succession of beds and bed sets bounded by marine flooding surfaces and their correlative surfaces. The flooding surfaces bounding parasequences are not of the same scale as the regional transgressive
surface that is associated with a sequence boundary. The parasequences are separated into stacking patterns such as aggregational, progradation, and retrogradation. Each stacking pattern gives different information on the behavior of accommodation space and the depositional process [43].

Figure 5 shows the interpreting concept of GR logs according to the values of GR within strata units along Witiora-1 well. Lithostratigraphy defines rock units based on lithology, often irrespective of the depositional environment [44].

![Figure 5](https://via.placeholder.com/150)

**Figure 5.** Lithostratigraphic and sequence stratigraphic interpretations of Gamma-Ray (GR) log, modified after Reference [44].

Sequence stratigraphy represents rock units based on the event importance of their bounding surfaces. The stacking patterns, and consequently, parasequence is identified using the GR log by indicating minerals ratio variation [45]. A GR record is a handy tool for discrimination of different lithologies, but it cannot uniquely define any lithology. GR provides valuable information when combined with information obtained from other logs. Its primary use is the discrimination of shales by their high radioactivity. In this research, GR has been utilized to establish the stacking patterns based on the GR curve trajectory whither fining or crossing upward [46]. The system tracts have been established in turn.

### 4.5. Isochron Maps

Isochron map is a sort of time interval known as a contour map of equal values of seismic travel time between two different events. It shows the variation in time between two seismic reflections. In addition, isochron maps are the seismic equivalent of isochore maps that are anticipated to obtain thickness information from the seismic data [47]. Isochroning between seismic reflections below and above a pay horizon, for instance, would guesstimate the thickness pay of the target reservoir. Morton and Woods [48] have introduced an excellent case history of utilizing isochron and time-structure maps to produce isopach and elevation-structure maps. Their isochron-isopach approach outlined reef trends for additional drilling development and used well penetrations beyond a shallow horizon for depth control on a deeper horizon.

The time interval of isochron maps is usually utilized for interpreting variations in thickness between interpreted horizons [49]. The isochron maps in this study were analyzed using Kingdom 8.8 and Petrel software. The difference in the two-way time between two horizons were calculated in order to map the targeted zone (H2). These isochron maps have been introduced after the sequence borders (horizon H) for each survey line have been determined and traced using Kingdom 8.8 and Petrel software. The isochron map in this research has been performed to show the subsurface morphology of the targeted zone. Both 2D and 3D isochron maps have been generated as shows in
Figure 12A,B of SA-Middle Giant Formation as a new sequence between the upper and lower Giant Formation to show the sediment transport direction.

5. Results

5.1. Seismic Sequences Interpretation

The third-order sequences, system tract, environments, ages, and sequence boundaries from the Witiora-1 well logs and the seismic sections across the study area have been interpreted in detail. This interpretation has been done by analyzing the well log GR curves, the shapes of the GR (stacking patterns) within the four depositional packages (H4-H1) associated with the changes of sand and clay ratio.

Figure 6 shows a detailed description of the horizons in-depth domain, lithological types, depositional environments, and ages of each sequence separated by horizons. Four sequences; SEQ4 to SEQ1 from bottom to top have been detected between horizons H4 to H1. The fourth sequence (SEQ4) is Pliocene age deposits, which overlies the Miocene age deposited during the increasing sea-level environment. SEQ4 indicated a transgressive system tract (TST) and its environment can be described from upper slope neritic water mass to mid outer shelf and outer neritic water mass. Whereas SA-SEQ3 is considered as early Pliocene age deposits and indicated lower stand system tract (LST) with coastal to inner environments. It is overlaid by HST with coastal argillaceous abundant foraminifera in the marine sediments of the Late Pliocene-Middle Giant formation depositional environment. This was overlaid by a TST of middle to outer neritic environments.

The upper part of SA-SEQ3 represented a high stand system tract (HST) with the inner neritic depositional environment. Besides, SA-SEQ3 is a newly discovered depositional sequence in this study that can be related to the late Mangapahanian Plio-Pleistocene age deposits. This package was characterized by high and continuously seismic amplitude that represented the seismic facies of this interval. This stacking pattern was interpreted as a mid to outer neritic environment. These parameters indicated a progradation stage during the regression phase resulted in HST. The upper part of the new sequence (SA-SEQ3) represents an interval characterized by a noticeable low GR record, low and discontinuously seismic amplitude, and several downlaps across the seismic data. This new depositional sequence was part of SEQ4.

However, due to the different seismic facies and reflection termination, SA-SEQ3 is considered as a new sequence separated from SEQ4. This proofed that the new subdivision surface of the Giant deposition packages was entirely accurate. The new SA-Middle Giant Formation sequence (SA-SEQ3) has been identified based on the standard seismic sequence stratigraphic principles. The principles used included reflection terminations, seismic facies variations, seismic original amplitude patterns, and confirmed by the synthetic seismogram as shown in Figures 3–6. The Upper Giant formation is the youngest sequence among all that is underlain by the seafloor of SEQ1 which was deposited during the Pliocene-Pleistocene age as shown in Figure 6. This sequence consisted of two system tracts cycles; TST that formed the bottom part with middle to outer neritic depositional environment and HST that formed the upper part of this sequence with the coastal depositional environment.
5.2. Seismic Facies Analysis

Seismic facies interpretation is conducted based on the diversity of the characteristics resulted from reflections shape, amplitude, frequency, and continuity that existed in a particular sequence [39]. This process involved picking and determining the nature and orientation of the reflections within each sequence and the internal strata patterns. This analysis is fundamental in determining the sequence of sediments by the diversity in the seismic patterns that can usually be shown in the studied seismic sections.

Facies analysis identified and represented the depositional geological environments in the study interval as shown in Figure 8. This analysis was also carried out to confirm the depositional environment of the sequences, its lithofacies, stratification, and the direction of sediment transportation. Figure 7 reveals the dominant types of detected facies in the interval zones. Several seismic facies have been identified within the whole interval. The dominant seismic facies found were characterized by parallel, semi-parallel, continuous to sub-continuous, local chaotic, fully chaotic, complex, divergent, discontinuous, and free seismic facies.
Figure 7. Layout of the dominant seismic facies were detected of the studied intervals.

Figure 8 represents the dominant seismic facies of the Middle, Lower, and Upper Giant Formations within the chosen seismic line number ST03-317. Figure 8 part A shows clinoform reflections that are comprised of an essential class of seismic facies patterns. Those patterns are particularly common on continental margins, where they commonly represent prograde deltaic or continental-slope outgrowth. Variations in clinoform architecture reflect different combinations of depositional energy, subsidence rates, sediment supply, water depth, and sea-level position as discussed by Miall [50]. Sigmoidal clinoforms tend to have low depositional dips, typically less than 1°, whereas oblique clinoforms may show depositional dips up to 10°. Parallel-oblique clinoform patterns show no top sets. This usually reflects shallow water depths with a wave or current and sediment bypass to deeper water, perhaps down a submarine canyon that may be revealed on an adjacent seismic cross-section. Many seismic sequences show complex off-lapping reflections which is a complicated sigmoid-oblique clinoform pattern as shown by the work done by Kamp and others [51].

Figure 8 part B shows divergent facies with continuous and high amplitude reflections becoming thin towards the seaward. The lowermost Lower Giant Formation towards the sea in Figure 8 part C reveals sub-parallel facies with continuous high amplitude reflections associated with hummocky facies with low amplitude reflections. These hummocky facies represent delta plain and coals deposits with high amplitudes in the right direction towards the land. These facies might be interpreted as carbonate deposits in a relatively quick depositional environment in the platform.

Figure 8 part D illustrates some chaotic seismic facies representing channel fill towards the sea. Meanwhile, the results of this analysis were combined with other geological information obtained from the same well (Witiora-1) such as borehole data and regional geology. Most of the seismic facies are best seen in sections parallel to depositional dips. Whereas, parallel and subparallel reflections indicate uniform rates of deposition, and the divergent reflections resulted from subsidence rates such as half-graben or across a shelf-margin hinge zone.
Figure 8. The Middle and Lower Giant Formation facies.

5.3. Parasequences Interpretation

Parasequence and parasequence sets are explained as a relatively conformable genetically related succession of beds and bed sets bounded by marine flooding surfaces and their correlative surfaces (Van Wagoner and Mitchum 2003). The parasequences analysis of the stratal geometries started from the top formation (Surficial Formation) which shows regular beds with sharp tops and bases deposited in shallow water as a result of clastic sediment aggradation.

Figure 9 shows the GR logs with different colors relevant to the response of GR to the radioactivity lithology elements within the layers along the borehole of the Witiora-1 well. The lower part of the sequence was represented by a symmetrical shape GR pattern that is interpreted as retrogradation activity during the TST as shown in Figure 9. Furthermore, the Upper Giant Formation shows a gradual upward decrease or coarsening upward in GR response. This tendency was interpreted as a transformation from shale-rich into sand-rich lithology and an upward increase in depositional energy with shallowing upward and coarsening. This resulted in a bell shape that represents tidal sand, alluvial sand and fluvial channel deposits. The lower part of this sequence showed a sharp change in GR response interbedded with some beds of small GR value. This definite pattern represents alternating activity between aggrading and prograding within the sequence as also shown in Figure 9.

The new discovered SA-Middle Giant Formation displayed a full cycle of systems tract. These stacking patterns of this sequence started with LST overlaid by TST and end up with HST. In general, this sequence is dominated by the serrated shape, but within the whole interval, many other configurations are ranging from the funnel, bell, symmetrical and serrated shapes. In addition, there is no significant changes in the lithology except some fluctuated changes in GR readings as shown in Figure 9. Table 2 summarized the information of the unconformities (horizons) with the depositional sequences from SEQ4 to SEQ1, depths in meter and the reading of two-way time in millisecond that started from bottom to top with 1444 ms of H4 to H1 at 282 ms.
Figure 9. The parasequence system tracts from Surficial Formation to Lower Giant formation.
**Table 2.** Boundaries summary for the depositional sequences of Witiora-1 well.

| Unconformities | Depositional Sequence | Depth in Meter | Two-Way Time (TWT) in ms |
|----------------|----------------------|----------------|--------------------------|
| H4             | SEQ4                 | 1460           | 1444                     |
| H3             | SEQ3                 | 935            | 1083                     |
| H2             | SEQ2                 | 713            | 780                      |
| H1             | SEQ1                 | 263            | 282                      |

Figure 10 shows the full chronostratigraphic seismic sequences of the study interval that was subdivided into sub-packages bounded by the unconformities and the seismic reflection terminations. This investigated interval was subdivided into four seismic sequence units from bottom to top starting from SEQ4 to SEQ1. These successions packages were interpreted depending on the apparent unconformities represented subsequently by the horizons from H4 to H1 (from bottom to top across the section).

Figure 11 reveals the seismic section of line STO3-317 with all details highlighting the newfound boundary of sequence SA-SEQ2 emphasized by the reflection terminations. This sequence is extended from the SW to NE with a length of 28 km along the seismic line. Moreover, SEQ1 was deposited during the Pilo-Pleistocene, especially in the late Mangapanian. It is characterized by continuous, high amplitude, and low-frequency seismic reflection patterns. This sequence is underlined by horizon H1 which is represented by the presence of a few on-laps indicating TST deposit as shown in Figure 11A,B. The sequence consisted of shelf sediments that were deposited in a glacial environment. This was controlled by the fluctuations in the sea level with some deposits of soft silty mud, and some shelly sand interbeds. The interpretation was based on the data obtained from Witiora-1 well starting from 1444 ms of horizon H4 to 282 ms to horizon H1.
5.4. Isochron Maps

The isochron maps generated in this study after the sequence border (horizon H2) for the seismic lines have been determined and traced using Kingdom 8.8 and Petrel softwares. In this sub-section, the isochron maps were described in a 2D and 3D perspective showing the contour maps of the newly identified SA-Middle Giant Formation (SA-SEQ3). These maps provide valuable information about the geologic aspects such as subsurface morphology, depositional pathways and location of depocenters. SA-SEQ3 represents the interval between the surface, and horizon H2. This interval is considered more significant than the Lower Giant Formation and it is distributed all over the study area. Figure 12A reveals the 2D map depocenters of SA-SEQ3 layer with blue color in the northwest direction towards the sea with maximum time exceeding 1320 ms. While the shallowest value displayed in red color was in the southeast of the study area with a time of about 600 ms.

Figure 12B shows a 3D view of the time variation along the new SA-SEQ3 surface of horizon H2. The time interval is gradually decreasing towards the land in the southeast. The red color represents the shallowest points, this map displays a new sequence between the upper and lower formations to show the sediment transport direction.

**Figure 11.** Interpreted seismic section showing the position of the newly identified Sequence, namely SA-SEQ2. A shows the onlapping reflection terminations over the new identified horizon, B shows the down lapping reflection terminations of the picked horizon H3.
Figure 12. A-shows the A) 2D isochron map of SA-Middle Giant Formation, B- shows the 3D isochron map of SA-Middle Giant Formation.
6. Discussion

There was a correlation between the seismic reflection data and the geology of the studied area. The geological history of sediment deposition can be correlated with the sea-level change by seismic sequence and seismic facies analysis. The deposition of sediments during the rise and fall of sea-level determines the unconformities resulted after the erosion had taken place during the geological ages.

SA-Middle Giant Formation has been identified as a new seismic sequence bounded by H2 from top and H3 from the bottom and mapped to show the sediment transport direction oriented dominantly to the N/NW based on the 2D seismic data. This succession showed general trends and subdivided the large Giant Formation into upper and lower parts only, which reflected small to large scale features of the Giant Formation [52].

In this study, the first aim of seismic sequence stratigraphy was to break down the Giant succession into units called seismic sequences and system tracts based on sequence stratigraphic principles such as the reflection terminations on a seismic section. This was based on reflection patterns, seismic configurations, and well log data. These surfaces were designated as horizons from H4 to H1 over the picked unconformities on the whole seismic sections from the oldest to youngest.

This study was focused on the interval from H4 to H1. These sequences are believed to represent bodies of sediments that were deposited within a particular period. They included rocks deposited in different environments from terrestrial to the deep sea, but they were all connected in one continuous body [18]. Previous literature did not explain the Upper Giant Formation in detail as it is performed in this study.

The Upper Giant Formation was subdivided into two parts; Upper and SA-Middle Giant Formation based on the reflection terminations, seismic facies, and confirmed by a synthetic seismogram. The Giant formation was entirely subdivided and a new sequence boundary was discovered named SA-Middle Gian formation based on the seismic sequence stratigraphic principles. SA-Middle Giant formation represents a different depositional process and thus, a different lithofacies and depositional environment.

This new interpreted interval would help to predict the source rock, reservoir, seal, and even the hydrocarbons movement trajectory. The difference of the seismic facies in the SA-Giant middle Formation revealed some chaotic facies symbolizing the channel fill towards the sea. The findings of this assessment were merged with other geological evidence such as borehole data, regional geology, and other geological reports. Most of these facies are best seen in sections parallel to depositional dip, parallel or subparallel reflections suggest consistent rates of deposition, divergent reflections outcome from differential subsidence rates, such as in a half-graben or across a shelf-margin hinge zone. Clinoform reflections consisted of an essential class of seismic facies patterns that were common on continental margins, where they commonly represent prograded deltaic or continental-slope outgrowth. Variations in Clinoform architecture reflect different combinations of depositional energy, subsidence rates, sediment supply, water depth, and sea-level position. Sigmoidal clinoforms tend to have low depositional dips, typically less than 1°, whereas oblique clinoforms may show depositional dips up to 10°. Parallel-oblique clinoform patterns showed no top sets, which would be a good reservoir. Not only that but also seismic sequence interpretation was applied to improve the chances of discovering significant resources in less explored basins by offering a new investigation.

Moreover, the study of these layers by the seismic technique could be used in further prospective studies in different areas. This usually implies shallow water depths with a wave or current scour and sediment bypass to deeper water, perhaps down a submarine canyon that may be revealed on an adjacent seismic cross-section. Many seismic sequences showed complex off-lapping stratigraphy, which is the intricate sigmoid-oblique clinoform pattern.

The parasequences and system tracts have been addressed and identified based on the GR and the reflection terminations on the seismic sections. The newly identified SA-Middle Giant Formation has been summarized into LST reflecting a coastal to inner neritic
depositional environment. The lower LST was overlaid by TST inferring a middle to outer neritic depositional environment. The upper part of the new SA-SEQ3 was interpreted as an HST with an inner neritic depositional environment. Eventually, the isochrone map of the new SA-SEQ3 has been generated to display the sub-morphology of this succession.

7. Conclusions

The main aim of this study was to detect the sequence boundaries and seismic facies in the Central Taranaki basin. Four regional seismic sequences with their unconformities have been identified and named as SEQ4 to SEQ1, while the unconformities were designated as H4 to H1 within the late Paleocene to Pleistocene sediments. The four boundaries represented sequences that included Lower Giant Formation, SA-Middle Giant Formation, Upper Giant Formation, and Surficial Formation.

This study discovered a new sequence between the Upper and lower Giant Formation named as SA-Middle Giant Formation. This new sequence has been traced all over the seismic grid of the study area. Seismic facies interpretation helped to identify the geological features of the sequences such as channels, submarine canyon, incised valleys, chaotic, parallel, subparallel, hummocky, free reflection, and Clinoform seismic facies. The dominant seismic facies of the four sequences were characterized in order to discover the presence of the potential petroleum accumulation. Chaotic, channels, submarine canyon, and incised valleys were the essential seismic facies that were identified in the Lower and Middle Giant Formation and interpreted as a potential reservoir for hydrocarbon accumulations.

In general, the depositional facies in the study area consisted of inner shelf, marine inner neritic, slope, Clinoform, a complex sigmoid, and oblique Clinoform progradation facies, chaotic, hummocky, free reflection, fluvial channels environments facies. The Isochron maps were generated to illustrate the location of the depocenters of the sediments and other geomorphological features.

Author Contributions: Conceptualization, A.A.-S.A.-M. and U.B.H.; methodology, A.A.-S.A.-M.; software, A.A.-S.A.-M.; validation, A.A.-S.A.-M., M.E., I.B., and M.E.; formal analysis, A.A.-S.A.-M.; investigation, A.A.-S.A.-M.; resources, A.A.-S.A.-M.; data curation, A.A.-S.A.-M., I.B., and Q.S.I.; writing–original draft preparation, A.A.-S.A.-M. and U.B.H.; writing–review and editing, A.A.-S.A.-M., and M.A.M.A.-B.; visualization, A.A.-S.A.-M.; supervision, M.E.; project administration, A.H.A.L.; funding acquisition, A.H.A.L. and M.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported through three projects: 1. Centre of Seismic Imaging with cost center (0153C1-027), 2. Artificial intelligence on seismic attributes with cost center (015MD0-057), 3. Incorporating Anisotropy Effect in AVO Analysis for Hydrocarbon Prediction with cost center (015LCO-224).

Acknowledgments: The authors are so grateful to Universiti Teknologi Petronas, and Centre for Subsurface Imaging (CSI), Malaysia, for providing the required data for this research. We would like to express our admiration to the Centre of Seismic Imaging and Geoscience department Universiti Teknologi PETRONAS colleagues for supporting us during conducting this research. Great gratitude to the utilized research grants with cost centres (0153C1-027), (015MD0-057) and (015LCO-224) for granting this research. We acknowledge Schlumberger and IHS Markit Companies for providing Petrel and Kingdom Suite 2016 software licenses.

Conflicts of Interest: The authors declare no conflict of interest.
Abbreviations

The following abbreviations are used in this manuscript:

SEQ  Sequence boundary
H    Horizon
SA-SEQ3 Salam Middle Giant Formation
RC   Reflection coefficient
TST  Transgressive System Tract
HST  High System Tract
LST  Low System Tract

References

1. Steel, R.J.; Felt, V.; Johansson, E.; Mathieu, C. *Sequence Stratigraphy on the Northwest European Margin*; Elsevier: Amsterdam, The Netherlands, 1995.
2. Christie-Blick, N.; Driscoll, N.W. Sequence stratigraphy. *Ann. Rev. Earth Planet. Sci.* 1995, 23, 451–478. [CrossRef]
3. Hansen, R.J.; Kamp, P.J. An integrated biostratigraphy and seismic stratigraphy for the late Neogene continental margin succession in northern Taranaki Basin, New Zealand. *N. Z. J. Geol. Geophys.* 2006, 49, 39–56. [CrossRef]
4. Amedjoe, C.G.; Adjovu, I.T. Application of the mobile metal ion geochemical technique in the location of buried gold mineralization in Essaye Concession, Eastern Region, Ghana. *J. Geol. Mining Res.* 2013, 5, 147–160. [CrossRef]
5. Catuneanu, O. *Principles of Sequence Stratigraphy*; Elsevier: Amsterdam, The Netherlands, 2006.
6. Russell, B.; Hampson, D.; Todorov, T.; Lines, L. Combining geostatistics and multi-attribute transforms: A channel sand case study, Blackfoot oilfield (Alberta). *J. Pet. Geol.* 2002, 25, 97–117. [CrossRef]
7. Kumar, B.; Kishore, M. Electrofacies classification—A critical approach. In *Proceedings of the 6th International Conference and Exposition on Geophysics*, Kolkata, India, 25 October 2006; pp. 822–825.
8. Neal, J.; Risch, D.; Vail, P. Sequence stratigraphy—A global theory for local success. *Oilfield Rev.* 1993, 2, 51–62.
9. De Batist, M.; Henriet, J.P. Seismic sequence stratigraphy of the Palaeogene offshore of Belgium, southern North Sea. *J. Geol. Soc.* 1995, 152, 27–40. [CrossRef]
10. Vail, P.R. *Seismic Stratigraphy Interpretation Using Sequence Stratigraphy: Part 1: Seismic Stratigraphy Interpretation Procedure*; American Association of Petroleum Geologists (AAPG): Houston, TX, USA, 1987.
11. Grant, G.; Seffon, J.; Patterson, M.; Naish, T.; Dunbar, G.B.; Hayward, B.; Morgans, H.; Alloway, B.V.; Seward, D.; Tapia, C.; et al. Mid-to late Pliocene (3.3–2.6 Ma) global sea-level fluctuations recorded on a continental shelf transect, Whanganui Basin, New Zealand. *Quat. Sci. Rev.* 2018, 201, 241–260. [CrossRef]
12. Katz, H.R. Petroleum developments in New Zealand during 1971. *AAPG Bull.* 1972, 56, 1846–1850.
13. Sprigg, R.; Braithwaite, J.; Yakunin, A.; Wilson, R. Oil and gas prospects of southern Taranaki Bight, New Zealand. *AAPG Bull.* 1969, 53, 1956–1977.
14. Okaya, G.; Seffon, J.; Patterson, M.; Naish, T.; Dunbar, G.B.; Hayward, B.; Morgans, H.; Alloway, B.V.; Seward, D.; Tapia, C.; et al. Mid-to late Pliocene (3.3–2.6 Ma) global sea-level fluctuations recorded on a continental shelf transect, Whanganui Basin, New Zealand. *Quat. Sci. Rev.* 2018, 201, 241–260. [CrossRef]
15. Katz, H. Wanganui and East Coast Basins—Two of New Zealand’s Little Explored Sedimentary Basins. *Energy Explor. Exploit.* 1998, 6, 281–304. [CrossRef]
16. Beggs, J. Seismic stratigraphy of the Plio-Pleistocene giant foresets, western platform, Taranaki Basin. In *Proceedings of the 1989 New Zealand Oil Exploration Conference, Ministry of Commerce, Queenstown, New Zealand*, 11–14 September 1989; pp. 201–207.
17. Kamp, P.J.; Vonk, A.J.; Bland, K.J.; Hansen, R.J.; Hendy, A.J.; McIntyre, A.P.; Ngatai, M.; Cartwright, S.J.; Hayton, S.; Nelson, C.S. Neogene stratigraphic architecture and tectonic evolution of Wanganui, King Country, and eastern Taranaki Basins, New Zealand. *N. Z. J. Geol. Geophys.* 2004, 47, 625–644. [CrossRef]
18. Knox, G. Taranaki Basin, structural style and tectonic setting. *N. Z. J. Geol. Geophys.* 1982, 25, 125–140. [CrossRef]
19. Ravens, J.; O’Connor, R.; Zhu, H.; Anderson, H. Deep seismic reflection profiling in east Taranaki using standard oil-industry acquisition parameters. *N. Z. J. Geol. Geophys.* 1993, 36, 69–75. [CrossRef]
20. Steinshouer, D.W.; Qiang, J.; McCabe, P.; Ryder, R.T. Maps Showing Geology, Oil and Gas Fields, and Geological Provinces of the Asia Pacific Region; U.S. Geological Survey: Reston, VA, USA, 1997; pp. 97–470.
21. Packham, G. Cenozoic SE Asia: Reconstructing its aggregation and reorganization. *Geol. Soc. Lond. Spec. Publ.* 1996, 106, 123–152. [CrossRef]
22. Katz, H.R. Oil exploration in New Zealand—Past and future trends. *APPEA J. CSIRO* 1971, 11, 35–42. [CrossRef]
23. Uruski, C.; Wood, R. A new look at the New Caledonia Basin, an Extension of the Taranaki Basin, offshore North Island, New Zealand; *In Marine and Petroleum Geology; Elsevier*: New York, NY, USA, 1991; Volume 8, pp. 379–391.
24. Henry, J.D. Oil Fields of New Zealand: With Some Critical Notes on the Colonial Oil Situation of To-Day; Bradbury, Agnew & Co.: London, UK, 1911.
25. Clarke, E.C. *The Geology of the New Plymouth Subdivision, Taranaki Division*; Forgotten Books; FB and C Limited: London, UK, 28 October 2017.
