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A GUIDELINE FOR SEISMIC SEQUENCE STRATIGRAPHY INTERPRETATION

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ABSTRACT

Geologists use the concept of seismic and sequence stratigraphy during hydrocarbon exploration and production stages at different scales. While seismic stratigraphy is applied at the exploration scale, sequence stratigraphy, on the other hand, following the concept of chronostratigraphy, is applied at the production scale using the vail concepts in relation to cores, wireline logs, and outcrops. In other words, seismic stratigraphy involves the interpretation of seismic reflection data by extracting geologic and stratigraphic information. Seismic sequence stratigraphy, therefore, can be further subdivided and in order to analyze a seismic sequence and depositional time units that are separated on the basis of identifying unconformities or seismic pattern changes. In contrast, seismic facies involve the delineation of depositional environments from the characteristics of seismic reflection data. This is achieved by examining reflection events or series of events through their lateral variations to identify changes in stratigraphy and the nature of such changes. The fundamental tool used for this analysis is modeling, which begins with well tie and seismic logs studies. Moreover, understanding the deep-water reservoir architecture is essential in improving reservoir production performance. Sequence stratigraphy underlines relationships between facies and stratal structure in a chronological context. Due to its widespread use, the stratigraphy sequence must still be even involved in the stratigraphic code or guide. The lack of consistency illustrates different methods (or models) and the presence of ambiguous or even contradictory concepts. Standardizing sequence stratigraphy necessitates defining the basic model-independent definitions, groups, bounding surfaces, and layout that illustrate the technique's framework. A standardized methodology must be expansive enough to cover all possible solution options, instead of just a standard frame or model. The stratigraphic sequence comprises genetic units resulted from multifaceted exchanges of accommodation and sedimentation such as (highstand ordinary regressive, low standing, transgressive, and forced regressive), all these intervals must be bounded by sequence stratigraphic surfaces either unconformity, maximum flooding surfaces, or correlative conformity surfaces. Every Single genetic unit can be characterized by certain patterns of stratal stacking and surface boundaries and contains a correlatable depositional systems tract. The system tracts and stratigraphic sequence surfaces mappability rely on the setting of the deposition and data set used for the interpretation. This article presents a quick guidelines for the seismic sequence stratigraphy, these steps been discussed in details in the body text and involved; Generating the synthetic seismogram, reflection termination identification, locating the sequence boundaries, subdividing the seismic section into seismic sequences, seismic facies, and seismic sequence shape or geometries.

Keywords: seismic sequence stratigraphy, seismic facies, system tracts, seismic geometries.

INTRODUCTION

Geologists use the concept of seismic and sequence stratigraphy during hydrocarbon exploration and production stages at different scales (Gates, 2003; Williams and A. Dobb, 1993). While seismic stratigraphy is applied at the exploration scale, sequence stratigraphy on the other hand, following the concept of chronostratigraphy, is applied at the production scale using the vail concepts concerning cores, wireline logs and outcrops (Vail, 1987; Miall, 1994). In other words, seismic stratigraphy involves the interpretation of seismic reflection data by extracting geologic and stratigraphic information (Lin, 1977).

Seismic sequence stratigraphy, therefore, can be further subdivided to subunits to analyze a seismic sequence, time depositional units are separated based on identifying unconformities or seismic pattern changes. In contrast, seismic facies involves the delineation of depositional environments from the reflection characteristics of the seismic data (O. Catuneanu *et al.*, 2009). This is achieved by examining reflection events or series of events through their lateral variations to identify changes in stratigraphy and the nature of such changes. The fundamental tool used for this analysis is modeling which begins with well tie and seismic logs analyses (Vail, 1987). Moreover, (Hampton *et al.*, 2006) showed that understanding deep water reservoir architecture is essential in improving reservoir production performance.

The stratigraphy can be considered as the study of layered rocks and their origin. These rocks could be sedimentary, igneous, metamorphic, or volcanic (Emery and Myers, 2009). The layering in sedimentary rocks are indicated by the geometry and complexities of wide range of sedimentary facies. One of the divisions of sedimentary stratigraphy is sequence stratigraphy, which involves the order or sequence of layering of time-rock units (which are

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depositionally associated stratal successions) in what is known as space or accommodation (Posarnentier and George P Allen, 1999).

Through geologic time, one can access the chronostratigraphy of sedimentary rocks as their character changes, which can be expressed in the graphical form either as chronostratigraphic correlation charts and/or geologic cross-sections or as (Wheeler, 1958) diagrams which is different from their geologic age or geochronology. Sequence stratigraphy uses as an impressive means to comprehend the source of sediment deposition together with the prediction of lithofacies, their extent, heterogeneity, and character. Two frameworks guide this approach: (1) the depositional and erosional surfaces surrounding these successions of strata. (2) The geometry of successive contemporaneous layers upon accumulation (Donselaar and Overeem, 2008).

The depositional sequence is the basic stratal unit for sequence stratigraphy (Miall, 1996). A sequence (Figure-1) is thus commonly associated with a nearly consistent succession of normally connected layers, surrounded at their upper and lower surfaces by unconformities or correlatives conformities (Vail, 1987; Mitchum, 1977; Van Wagoner, 1991). This sequence includes system tracts (a series of genetically connected deposition systems) deposited during eustatic-fall variation segments (Posamentier and Vail, 1988). These sequences and system tracts are further split by "key" surfaces that surround discrete geometric bodies of the deposit. They are defined by some thresholds depicting changes in the depositional regime across that boundary (Almasgari and Hamzah, 2016a). On this basis, a deposition sequence can be defined as a comparatively consistent sequence of the genetically related strata bordered at its top and base by unconformities or their correlative conformities as shown in Figure-1 (Mitchum *et al.*, 1977; Vail, 1987; Van Wagoner *et al.*, 1990; Van Wagoner and Bertram, 1995).

Figure-1 shows the details of the depositional sequence. The first parts in Figure-1-A show a relatively conformable succession of genetically related strata, which means there is a package of sedimentary rocks that are representing a geological period. Depositional sequences are usually associated with a geological period in the order of three to ten million years as shown in Figure-1. The second part of the sequence deposition model in Figure-2-B shows that it is bounded at its bottom by an unconformity, which is labeled as layers A, B, C, D, and E with downlaps terminations. The third part showed the correlative conformities as shown in Figure-1-C along with A unit and the top part that overlaying the unconformity. The definition also explains that the depositional sequence is bounded at its top by an unconformity, as shown in figure-1-D with the green arrows heads at Z, Y, X, F, and E layers, so these three places of unconformities were the geometries of the strata reflecting that there is a significant break in deposition or unconformity, while the rest of the top surface where have no evidence based on the geometry of the strata for breaking deposition that would be the correlative conformity as shown in Figure-1-C.

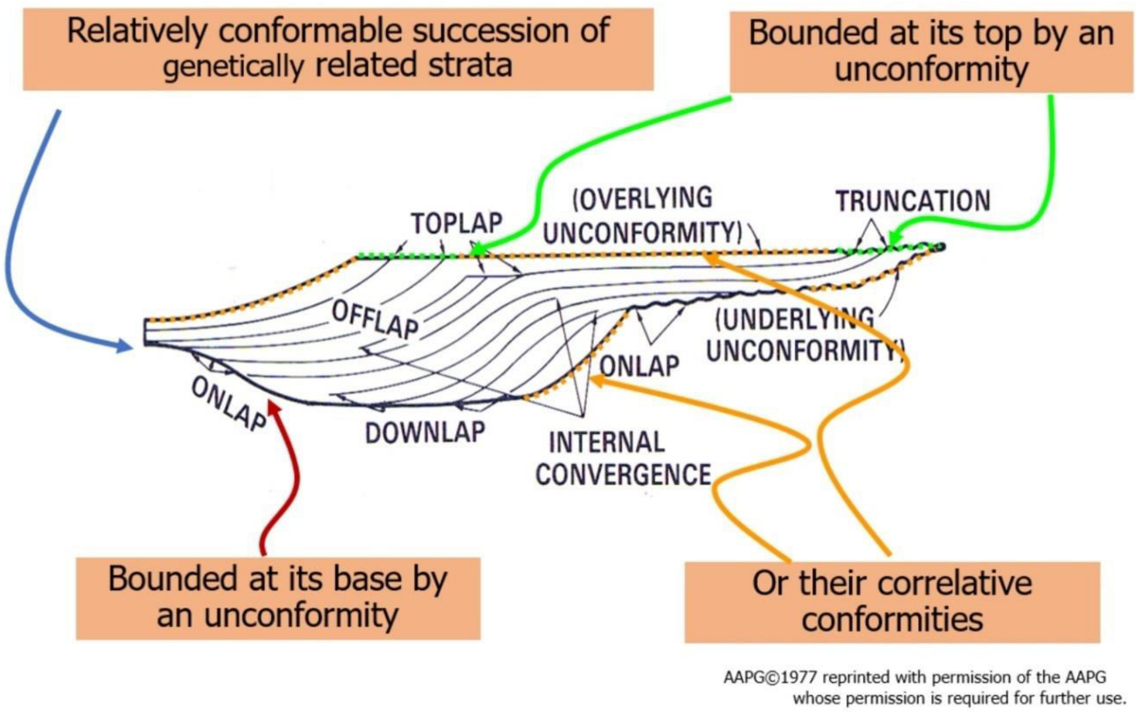

Figure-1. A detailed model of the depositional sequence edited after (Vail *et al.*, 1977b).

Sequences are subdivided by the system tracts, which contain sediments and related sedimentary depositional systems that were active during the episodes of base-level changes (Wei Chen *et al.*, 2015). These system tract sediments are therefore, sedimentary units that have mappable but synchronous deposition typified by

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continuous surfaces that extend from sub-aerial to sub-aqueous environments (Hunt and Tucker, 1995).

The ideal system tracts formed after sediment deposition can be assembled into (1) lowstand systems tract (E-LST)- Early-phase, (2) low stand systems tract (L-LST)- Late phase, (3) Transgressive systems tract (TST), (4) High stand systems tract (HST) (Lin, 1977; White *et al.,* 2012).

The lithostratigraphy Hierarchy

The rocks are mostly formed in strata or layers, and their sequence can be compared between different locations. Such various rock sequences are used to assess the evolving geological environments and historical geology of any region over time. Lithostratigraphy (rock stratigraphy) is the name, explanation, and interpretation of the rock units. Depending on the type of accessible information, the strata can also be represented in other ways; for example, the fossil can be used in biostratigraphy analysis (life stratigraphy) for establishing a chronostratigraphic framework.

Lithostratigraphy is essential for most geological investigations. Rock units are defined using their total lithological features and are labeled in a proper hierarchy, referring to their perceived level. The hierarchy of the stratal units (packages) that extends from local, Thin Lamina, Limina Sets, Bed, Bed Sets, Parasequences, Parasequence Sets, Sequences, Sequence Sets, to regional, thick depositional Group and Supergroup

The units generally are labeled after such a geographical location, normally the position of the first mention of exposures. Such formal ranks are often attached to the dictionary names. For mapping purposes, the formation is the basic rock structure. A Supergroup is an assemblage of more than one group. A group is an accumulation of associated and neighboring formations. One group can b subdivided into Sequence Sets, while some sequences can form sequence sets, and all these can be identified from the seismic data. Some Para sequences form the Parasequence Sets, while the assemblage of bed sets forms the one sequence. An assemblage of more than one bed can be forms the Bed Sets, which they can be identified from the well logs. The Lamina Sets is the basic unit of the Bed. Several of the Lamina forms the Lamina Sets. Some possible Statal hierarchy relationships are shown schematically below in Figure-2.

The Stratigraphic Hierarchy

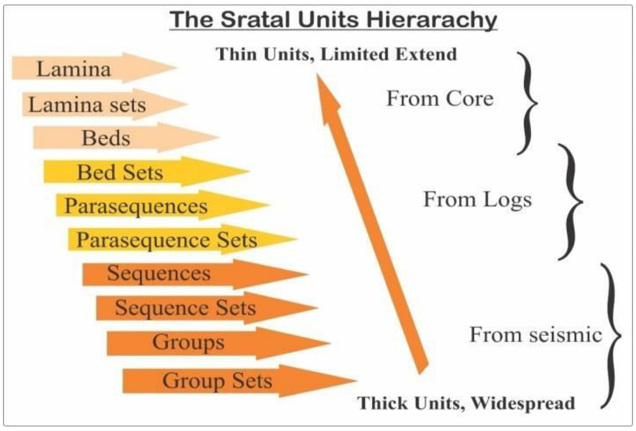

Figure-2. Stratigraphic units hierarchy classification and their associated data sets.

The fundamentals of stratigraphy come from the modern deposits and sedimentary outcrops study, it could be used as analogies for the offshore deposits. The more information we can use for the stratigraphic study investigation, the more accurate the interpretation image we can get.

Figure-3. Different resources data, including outcrops & modern deposits that contribute to establishing a reliable stratigraphy framework.

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Not only can the outcrops support our subsurface stratigraphic interpretation, but the well log, including the core and well logs, are very critical tools to illustrate the thin beds and beds in a very high-resolution scale.

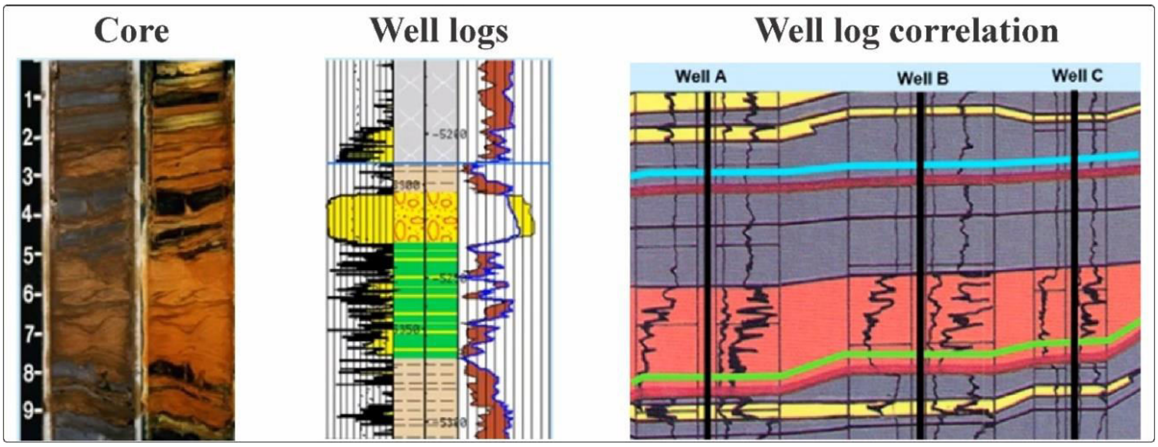

Figure-4. Stratigraphy core and well data for the stratigraphic correlation.

For regional studies, the seismic reflection data are suitable means that can show the geomorphological features, such as in Figure-5. A seismic sequence is a depositional sequence identified in a seismic section (Mitchum *et al.*, 1977). By definition, they are bounded at least in part, by unconformities. Thus, we look for evidence for unconformities and use these surfaces to identify the boundaries between depositional sequences of seismic sequences. The goal of Seismic Stratigraphy is to identify the location of rocks that will serve as sources, reservoirs, seals, and migration pathways, and the rock properties associated with these stratigraphic units. These units are commonly recognized by the seismic reflection terminations at these sequences' boundaries. The first goal is to get a geologic framework to prospecting (Exploration) by determining most of the significant fault planes, most of the significant stratigraphic surfaces, and proper horizon-fault and fault-fault intersections. During a stratigraphic analysis, we would be interpreting and mapping: erosional unconformities, packages of on lapping sediments, the geometries of reflections, the seismic attributes, such as horizon reflection amplitude, and other types of stratigraphic signatures. We also need to know the depositional environments for key sedimentary units. We want to define present-day stratigraphy, especially as it relates to present-day reservoirs, seals, source intervals, and traps. In addition, we will also want to understand how the basin filled with sediment over geologic time. During the stratigraphic analysis to construct a geologic framework, reflection terminations that mark unconformities and define seismic sequences will be utilized in addition to some individual seismic sequences such as clinoforms and the geomorphological feature that might expose by the seismic attributes and horizon slices Figure-6.

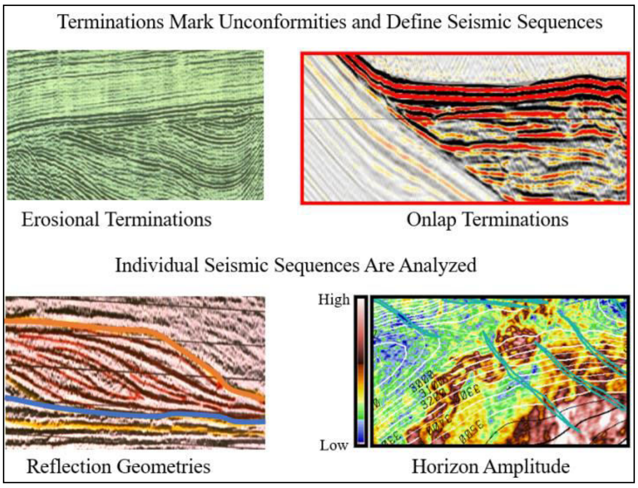

Figure-5. The key elements for sequence stratigraphy analysis.

Seismic stratigraphy subdivides the package of sediments visible on the seismic section into stratigraphic units representing rocks formed in one episode of sedimentation and attempts to work out the depositional environment of each from its shape and internal structures (Catuneanu, 2006). Seismic stratigraphy used to be known as seismic sequence stratigraphy until its principles were developed and extended to other geological data such as wireline log interpretation. The whole discipline then became known as sequence stratigraphy, with seismic stratigraphy remaining the branch applied to seismic data (Zeng *et al.*, 2012). The term 'sequence stratigraphy' is often used interchangeably with the more precise 'seismic stratigraphy (P.R. VAIL, 2003).

Stratigraphic interpretation is the examination of seismic data to identify the nature of the rock types present and the manner of their deposition (Lin, 1977). It requires better quality seismic data (Broadband seismic data) than traditional structural interpretation and has developed significantly only since the 1970s. The subject is divided

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broadly into two parts, seismic stratigraphy, and reflection character analysis.

Reflection character analysis is the detailed study of individual reflections or small packages of reflections from reservoir horizons. It compares the observed variations with the changes predicted by models of the reservoir using a range of reservoir parameters such as porosity and fluid content. For billions of years, the stratigraphic record considers the primary source of information about the geological history of sub-surfaces (Roksandić, 1978).

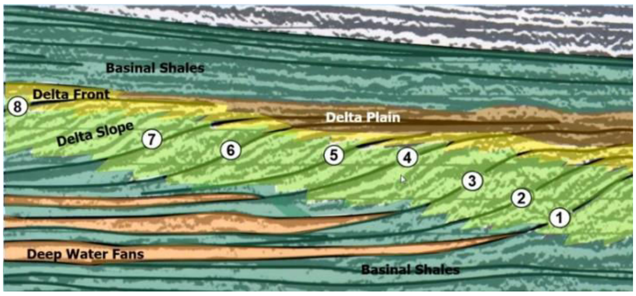

Figure-6. The stratigraphy from the seismic data.

A number of these stratigraphic studies were anchored on the history of plate tectonics, including paleogeography, past climates, and evolution in the quest to find fossil-fuel resources (Miall, 2016). Sequence stratigraphy, therefore, has become a powerful tool for facies analyses relevant to both the oil and gas industry as well as academia (Zeng *et al.,* 2012).

Sequence Stratigraphy Definition

Sequence stratigraphy provides a framework for describing the elements in any depositional setting, including reconstruction of the paleogeography and prediction of facies and lithologies away from control points (O Catuneanu *et al.,* 2009). This framework ties variations observed in stratal packages in relation to varying accommodation and sediment supply through time. The stratal stacking patterns reveal the order of stratal deposition, including their geometry and architecture. The stratigraphic sequence framework also provides the context within which to interpret the evolution of depositional systems through space and time (Catuneanu *et al.*, 2011). The primary tool used in sequence stratigraphic analysis is the stacking pattern of strata and the key surfaces that bound series defined by different stratal stacking patterns. These stacking patterns are sedimentary cycles that display persistent trends in thickness and facies composition and can be grouped into the following four types:

a) Aggradationis the vertical build-up of a sedimentary system. Usually occurs when there is a comparative rise in sea level produced by subsidence and eustatic sea-level rise, and the rate of sediment inflow is adequate to preserve the depositional surface at or close sea level (i.e., carbonate keep-up in an HST [highstand systems tract] or clastic HST). Happens when sediment flux=rate of sea-level rise. Produces aggradational stacking patterns in parasequences when the patterns of facies at the top of each parasequence are mostly the same Figure-7. (Wagoner *et al.*, 1988; Emery and Myers, 1996; Naish and Kamp, 1997; Posarnentier and George P Allen, 1999). In the figure below, each successively younger parasequence is deposited above one another with no significant lateral shifts when the rate of accommodation approximates the rate of deposition.

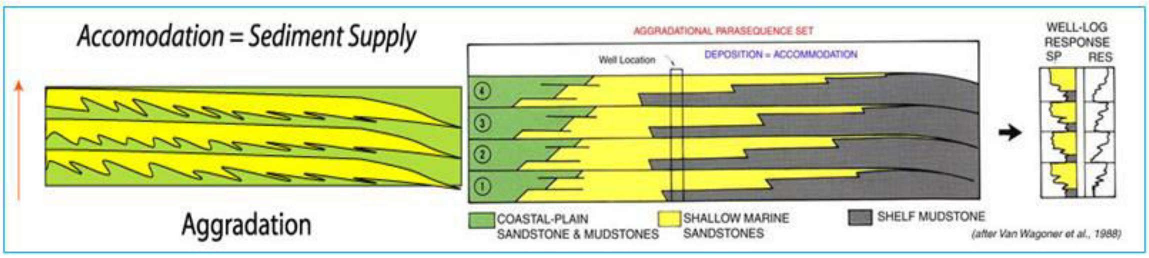

Figure-7. Showing the aggradation and the aggradation set. After (Wagoner *et al.,* 1988).

b) Retro-gradation is the effort of coastline land-ward in reaction to a transgression. This can happen during a sea-level rise with low sediment flux. Retrogradational stacking patterns of parasequences relate to patterns in which facies display progressively more distal when traced upward vertically (Posamentier and Vail, 1988; Emery and Myers, 1996; Wilgus *et al*., 1988). In the figure below, each successively younger parasequence is deposited farther landward in a backstepping pattern when the rate of deposition is less than the rate of accommodation, and a transgression of the sea occurs.

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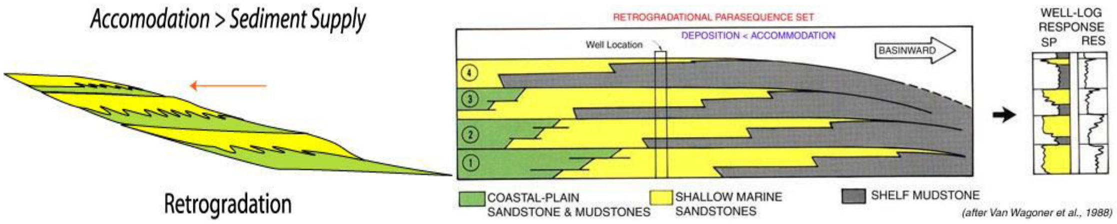

Figure-8. Retro gradation and Retro gradation set. After Van Wagoner *et al*., 1988.

c) Progradation, it is the lateral outbuilding of strata in a seaward track. Progradation can occur as a consequence of a sea-level increase followed by a high sediment flux (producing a regression). This latter customarily happens during the late stages of the evolution of a highstand systems tract and a falling phase systems tract. A progradational stacking pattern of parasequences belongs to the mode in which facies at the top of each parasequence converts progressively more proximal (Posamentier and Vail, 1988; Emery and Myers, 1996; Wilgus *et al*., 1988). As in the figure below, each successively younger parasequence is deposited faraway basinward when the amount of deposition is larger than the rate of accommodation (regression).

d) Degradation refers to the lowering of a fluvial surface, such as a stream bed or floodplain, through erosional processes. Degradation is the opposite of aggradation. A stratigraphic sequence framework may contain three dissimilar kinds of sequence stratigraphic elements, namely sequences, systems tracts, and parasequences. Each kind of unit would be defined by specific stratal stacking patterns and bounding surfaces. The definition of these units is independent of temporal and spatial scales, and the mechanism of formation. The next figure is showing the three main stacking patterns (Plint, 1995; Plint and Nummedal, 2000).

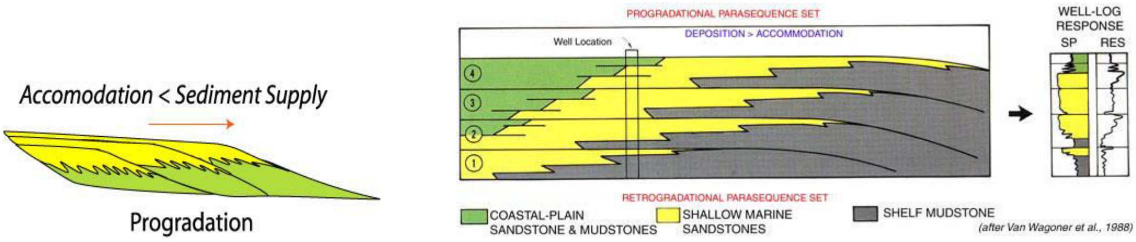

Figure-9. Progradation and progradation set. After Van Wagoner *et al*., 1988.

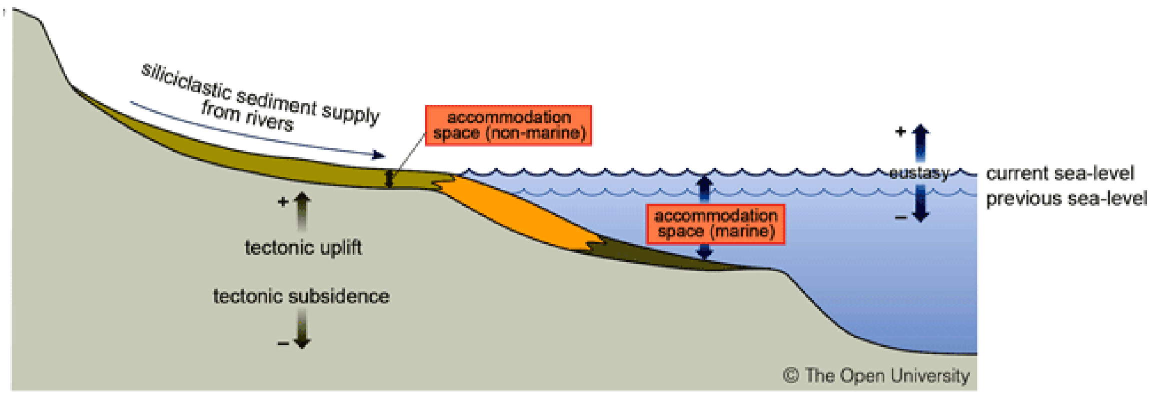

Figure-10. Represent the accommodation space in the marine and non-marine and the relationship between the tectonic movement and the sea-level change, after Van Wagoner *et al*., 1988.

Accommodation space according to (Jervey, 1988) refers to the space available for potential sediment accumulation and is controlled by the relative movement of the following factors including (1) The surface of the sea where the global sea level is measured from a datum (e.g. earth's center), (2) The seafloor (tectonics), (3) Changes in rates of sediment accumulation. (Posamentier *et al*., 1988) also affirmed that the significant controls on accommodation are changes in relative sea level (eustasy and tectonic movement). At the same time, and many other authors confirmed that the sedimentation rate is directly related to accommodation. As shown in the figure above, transgressions and regressions occurred in the accommodation space created due to the imbalance in the rate of sediment accumulation.

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The Importance of Stratigraphy

Stratigraphy plays a crucial role in geology and earth science, and this has been affirmed by several authors. For example, (Ochs and Godwin, 1978) gave reasons why with a reliable geological time scale, stratigraphy can provide information about: (1) Reliable basin history including tectonic processes and rates of sedimentation (2) Geological and geophysical events correlation including tectonic and eustatic events; (3) Epeirogenic movements (4) Extinctions of unrelated animal and plant groups (5) Information about era boundaries (6) Historical record of catastrophes in the earth localized or widespread and (7) Information regarding if boundaries existed in the geologic succession(Miall, 2016).

(Doyle and Bennett, 1998) stated that "Stratigraphy is really the best way to understand earth, its elements, architecture, and former events," he said. This contains all that has occurred in the world's history. It encompasses everything that has happened in the history of the planet.This statement reinforces the knowledge that the record of earth's historyincludes the stratigraphic history of layered sedimentary rocks preserved on the continents, oceans, and floors. This is the only branch of geology that can provide this information. (Jervey, 1988; Posamentier *et al*., 1988; Posamentier and Vail, 1988; Van Wagoner *et al.,* 1990) in their publications formalized a new, high resolution, reservoir scale sequence stratigraphy and many other scholars are considering the sequence stratigraphy of the latest theoretical uprisings in the comprehensive field of sedimentary geology (Miall, 1996) as well as refurbishing the methodology of stratigraphic analysis (Catuneanu *et al.*, 2009). In sequence stratigraphy, conformable or non-conformable surfaces can be identified through careful observation of reflection terminations. These terminations could be to the top or bottom of any depositional sequence and can be classified as on lap, down-lap, top-lap or erosional truncations in all seismic sections (Catuneanu, 2006). Sequence stratigraphy is thus primarily intended to analyze facial changes and geometric characteristics of strata and to highlight the major surfaces that govern the chronological cycle of basin filling and erosion steps. Stratal stacking characteristics correspond to the interactions of sediment and base-level changes and represent groupings of depositional trends which include programming. Every stratal pattern of stacking defines a particular genetic class of deposit like (transgressive, regular and forced regressive) with a complex shape and style of preservation of faces (Galloway, 1989).

Seismic Sequence Stratigraphy Interpretation

A seismic sequence is a depositional sequence identified in a seismic section (Vail *et al*., 1977a). The reflection terminations are the key to breaking up the seismic sequences by identifying their unconformities and their correlative conformities. The first aim of seismic sequence stratigraphy is to break up the succession of reflections on a seismic section into units called seismic sequences. These are assumed to depict bodies of sediment which were deposited down within a season. They may combine rocks deposited in diverse environments from earthly to the deep sea, but they are all joined in one continuous body. The sequences are isolated from each other by boundaries, which are, at most limited in places, unconformities showing an angular discordance between the reflections on either side. The boundaries between sequences interpret depositional breaks, times of non-deposition, between the periods of deposition represented by the sequences below and above.

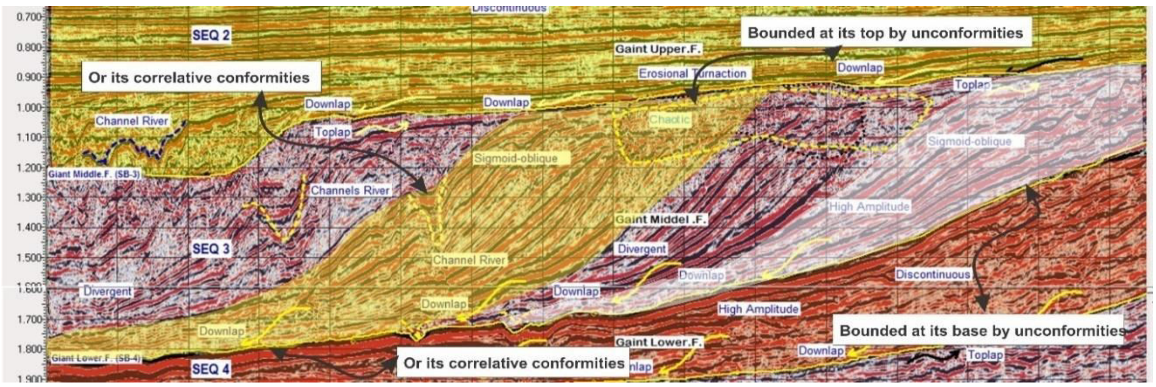

Figure-11. The sequence boundaries at the tops and bottoms as unconformities and their correlative conformities. Edited after (Almasgari and Hamzah, 2016b).

The sequence boundaries identification procedure begins by picking out the angular unconformities, nonconformities, disconformities, and paraconformities, which can then be traced laterally into areas where they are conformable. Figure-12 shows some of these unconformities. The technique of seismic sequence stratigraphic produces optimized performance when multi-data set information including outcrop, seismic, core samples, biostratographic, geochemical, and well log data in addition previouse interpretation of many professionals is needed (O. Catuneanu *et al.*, 2009). Figure-13 explains the ideal seismic sequence stratigraphy interpretation integrated with multiple data sets to get the best and most accurate results. Figure-14 shows the normal regressive, forced regressive, transgressive individual prograding lobes).

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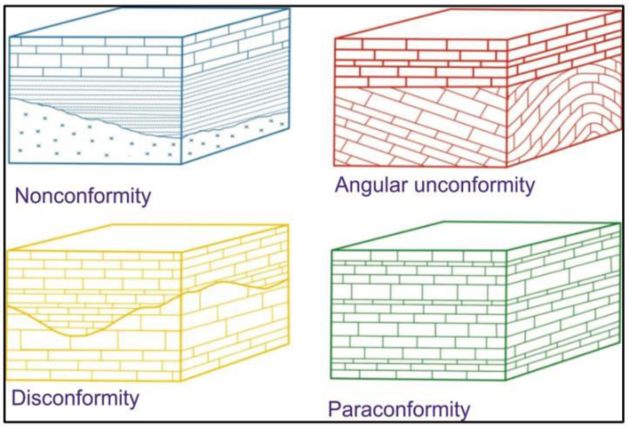

Figure-12. Different types of unconformities (Dunbar and Rodgers., 1957).

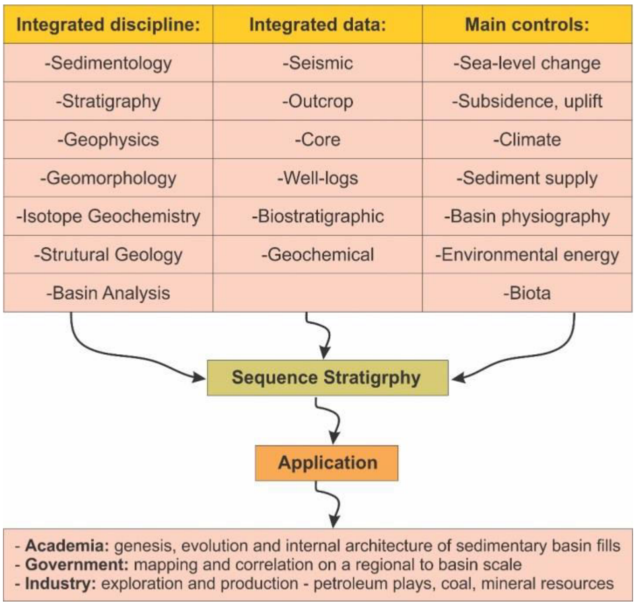

Figure-13. Stratigraphy sequence in the sense of interdisciplinary research. (O. Catuneanu *et al.*, 2009).

The chart shows potential shoreline pathway types on the base level throughout changes (rise or fall). In the meantime, the shoreline may be subject to sediment-driven progradation (regular regression, even the top set is replaced by top lap), erosion, or no movement. However, because of the sophistication of particularistic factors which interact to control changes in base levels, it is extraordinary to preserve circumstances for a long time (O. Catuneanu *et al.*, 2009).

It must use more than one evidence for marketing the boundaries of the sequences to assure and confirm the sequences subdividing. Nevertheless, not all these types of data are accessible in every case study, which could limit the' resolution' of the stratigraphic sequence model.

The integration of these sets of data is essential because each data set would contribute different insights regarding the recognition of depositional trends and strata stacking patterns, as shown in Figures-13. Seismic data can cover relatively large areas but not the vertical resolution. At the same time, the outcrops, core, and well logs can provide high-resolution details in a vertical diminution but limited to a specific location only.

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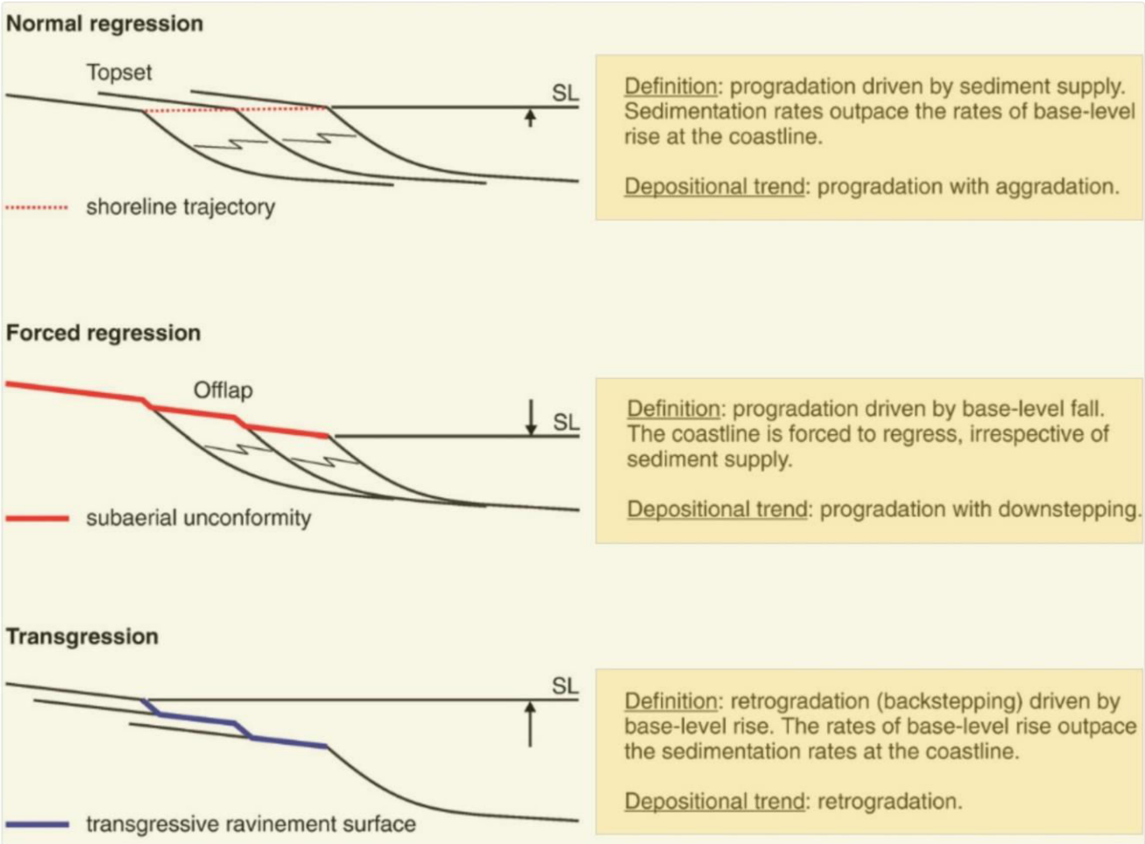

Figure-14. Shows the genetic kinds of deposits at the coastline direction throughout base level changes (rise or fall).

According to (Ghosh *et al.*, 2010; Reijenstein *et al.*, 2011) the resolution that can be obtained from the seismic data (using seismic inversion) would be reached to 5 meters. Therefore seismic data on one side and core, outcrop, and well logs on the other side are completing each other and would be calibrated against each other to come out with excellent visualization of the study area Figures 15 and 16. Cooperative calibration is necessary because there can be some partiality in the interpretation of any data set. The limitations involved in interpreting any types of data need to be understood and acknowledged. Hence, linking the G&G or gathering the interpretation of the geophysical and geological principles is one of the geologists and geophysicists' critical duties for getting a comprehensive and accurate image of the subsurface elements.

In most cases, such as our study case in the Malay Basin, the available data are including seismic, well logs, and core data. These data would be enough for a seismic sequence stratigraphic study. This investigation started with tie all wells data to the seismic data to have an accurate and reliable starting point from the top formations at the wells sites; these tops must be confirmed by a new generated synthetic seismogram, reflection terminations, and seismic facies in order to locate the right position for every sequence boundaries (Embry, 2009). However, having more evidence of the sequence boundaries, reducing the uncertainty, and getting a better estimation of the right position for all sequence stratigraphy in any basin, implementing these evidence goes through some complicated stages starting as following:-

A. Generating the Synthetic Seismogram:

Based on the well logs data such as density, sonic, top formations, and check shot, tying the seismic lines to well data is the first step carries out in any seismic sequence interpretation study, followed by sequence boundary determination, seismic facies classification, system tracts and stacking patterns analysis. The usual method to tie well information to seismic data in depth is to convert them to time and reconvert them back to depth (Bui et al. 2010). In the well tie procedure, synthetic seismograms can be generated by incorporating density and sonic logs to estimate the seismic impedance (Z) of each subsurface layer. Reflection coefficient (R) at boundaries between the layers can then determined usingthe Zoepretz equation ($R= Z_2-Z_1 / Z_2+Z_1$). The series of reflection coefficients will be convolved with a standard wavelet or extracted wavelet of particular Hz frequency value to produce both positive and negative synthetic seismograms. The synthetic seismogram is a simulated seismic response computed from well data 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 a synthetic are a time-depth chart, velocity log, density log, and wavelet generation (IHS 2012).

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Key: √√√ Good, √√ Fair, √ Poor	Rock Data			Geophysical Data		
	Outcrops		Core	Well logs	Seismic data	
	Large- scale	Small-scale			2D	3D
Tectonic seting	√√	√	√	√√	√√√	√√√
Facies	√√√	√√√	√√√	√√	√	√√
Nature of contacts	√√√	√√√	√√√	√√	√√	√√
Stratal terminations	√√√	√	√	√	√√√	√√√
Depositional trends	√√√	√√	√√	√√	√√	√√√
Startal geometries	√√	√	√	√	√√√	√√√
Depositional elements	√√√	√√	√√	√√	√	√√√
Depositional Systems	√√√	√√	√√	√√	√	√√√

Figure-15. The usefulness of various data sets for the creation of a stratigraphic sequence structure (modified after (Catuneanu 2006). Seismic and wide-scale outcrop data offer consistent surface and subsurface detail, respectively. In contrast, small outcrops, core and well logs provide light data from disconnected positions in the basin.

Data set	Main applications/ contributions to sequence stratigraphic analysis
Seismic data	Continuous subsurface imaging; structural styles; lapout relationships; strata stacking patterns; imaging of depositional elements ; geomorphology; stratal geometries
Well log data	Vertical stacking patterns; grading trends;depositional elements; depositional systems; petrophysics ; calibration of seismic data.
Core data	Facies; textures and sedimentary structures; nature of stratigraphic contacts; physical rock proporties; paleocurrents in oriented core; calibration of well log and seismic data
Outcrop data	3-D control on facies architecture; insights into process sedimentology; facies; depositional elements; depositioinal system; all other applications afforded by core data

Figure-16. A various data sets participating in the interpretation process of sequence stratigraphic (edited after Catuneanu, 2006). The emergence of multiple sets of data is the secret to an accurate and consistent stratigraphic sequence model.

A synthetic seismogram showing an excellent fit with the seismic section at a well site gives us a firm hold on the time/depth relationship and enables us to identify with seismic confidence reflectors which intersect the well. However, there will be differences between synthetic and actual seismic traces due to the presence of random noise on the latter, because the horizons intersected in the hole are usually regarded as horizontal for convolution and because the convolution is not usually extended to allow for the generation of multiples. Figure-17 shows an example of the result of the generated synthetic seismogram. This example shows a measured depth, reflection coefficient, seismic section penetrated by the well, a sample seismic trace, residual synthetic log, and the new synthetic seismogram based on it compared with a seismic line passing through the well location. In this case, a good match has been achieved used in shifting and squeezing tools. In restricted reservoir analyses where an understanding is needed down the resolution of the vertical seismic, the stratigraphic structure for higher frequency sequences can be addressed with core and well logs, and the synthetic seismogram would be enough to position the boundaries between the thin layers till the fifth and sixth orders.

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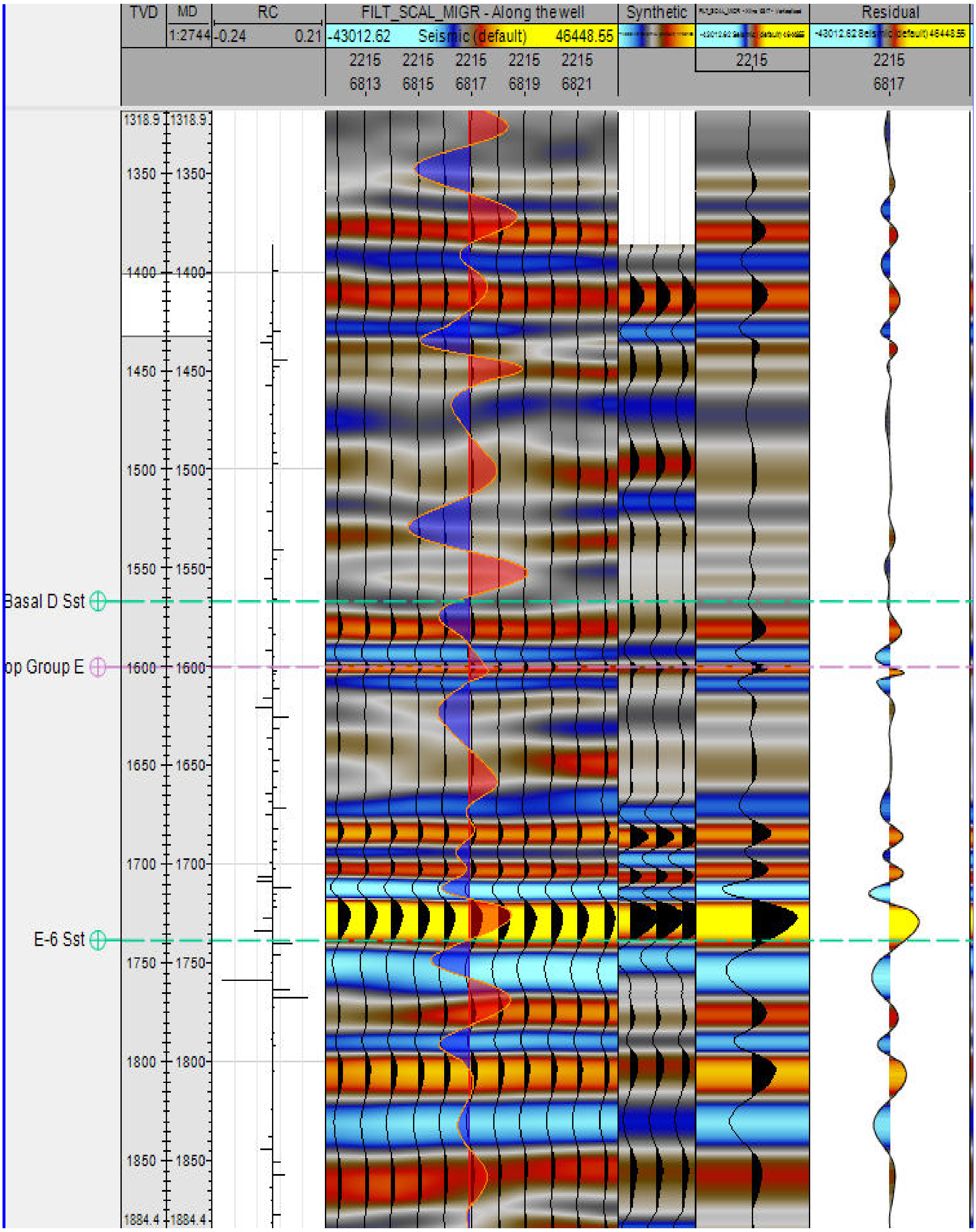

Figure-17. An example of the synthetic seismogram in the Malay Basin. Petrel 2018.

B. Subdividing the Seismic Section into Units:

The second stage after generating the synthetic seismogram is to transfer these conformed markers from the well site to all over the seismic section. These markers are indicating the sequence boundaries between the deposited units. These boundaries must be check and confirmed by looking to the other seismic, biostratigraphic, core, and outcrop data evidence. However, the synthetic considered as the starting point for picking the interesting horizon (sequences) at the well site.

The picking process must start at the well site and goes in a closed loop around the synthetics been created previously. Tying loops are included in consecutive steps in the interpretation procedures, where it started at the well location and moved to the next loop, and the horizons would be traced around a rectangle of lines (cube in 3D) which is known as the tying loop Figure-18.

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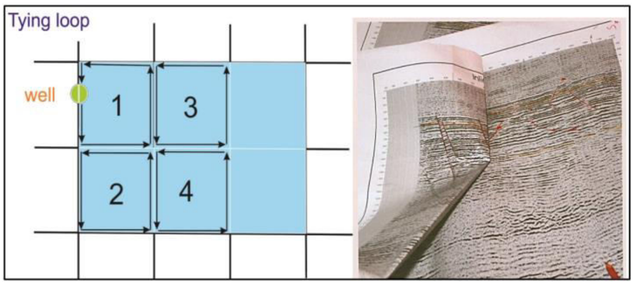

Figure-18. The process of tying the loop of seismic lines (www.fugro·robertson.com).

In petrel 2018, it is preferred to use the 3D seeded auto-tracking locally (not the whole cube in once), but not advised to run the common 3D auto-tracking for the whole cube due to the misleading might be caused. The more QC would be used for the picked horizons, the more accuracy would be achieved, and reasonable geological events would be found. All horizons should be traced as far as they intersect with another seismic line. The increment of going through the seismic cube should not be more than ten lines in the continuous reflectors, and not more than two lines in the poor reflectors to avoid misleading would happen using 3D auto-tracking. The second step is to transfer the horizons from these lines to other lines by using the neighbor dotted navigator displayed on the neighbor sections. A reasonable and colored event should be seen after picked the whole horizon, faults, folds, and high and low elevation of the picked horizon must be recognized directly from the picked horizon.

C. Reflection Terminations Identification:

The module shown in Figure-19 will concentrate on the methodology for analyzing a seismic sequence. The first step of the process is to sub-divide the seismic data into stratigraphic intervals by identifying and interpreting the reflectors comprising the sequence. The reflectors are analyzed in two keyways, by looking at their terminations and by assessing the character of the reflectors within a sequence. It is essential to note the relationship of the reflectors within a sequence to the boundaries at the top and bottom.

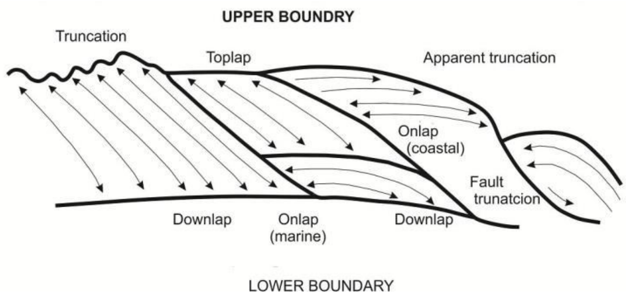

Figure-19. Illustration of reflection terminations at a lower and an upper boundary (Emery & Myers, 1996).

Reflectors commonly terminate against another reflector, and this can be marked using arrow notation. Multiple reflectors terminate consistently against a line on the section, and then a seismic surface can be identified. The number of seismic surfaces identified will depend upon the complexity, scale, and resolution of the seismic data.

The marking of the reflector terminations results in the division of the interval into depositional packages, which are relatively conformable. The reflectors may be concordant, that is parallel to the boundary, or they may terminate against it. At the top surface, the reflector may have been cut off by erosional truncation (Loucks and Sarg, 1993). They might also terminate at the top of the sequence by toplap, in which case the reflector has not been eroded but instead merges with the boundary. Termination against the base of the sequence is called baselap, this subdivided into onlap when the boundary dips more steeply than the reflectors and downlap when the reflectors dip more steeply. The appearance of new reflectors between others within sequences is called internal convergence. According to that, here are some of the significant reflection terminations that can be summarized as follow; (toplaps, downlaps, onlaps, and truncation). Figure-19 explains some of these reflection terminations; these reflection terminations are reliable for positioning the sequence boundaries in case we do not have well log data. The seismic data could be enough to position the boundaries of the sequence between the sequences based on the reflection terminations and the seismic facies; this evidence can help to subdivide the seismic section into the third order of any hierarchy (Boggs.Jr., 2006).

D. Identification Boundaries of Key Boundaries:

The boundary surfaces subdividing the main systems tracts can be identified on the seismic section through the interpretation of the seismic surfaces. Sequence boundaries can be interpreted on seismic through the identification of a downward shift in coastal onlap, or the development of a high relief truncation surface. Coastal onlap is identified as the proximal onlap of topset reflections, so a downward or basinward shift suggests a fall in relative sea level. Reflectors overlying the sequence boundary will onlap onto the sequence boundary. If a high relief truncation surface is developed, erosion of the underlying reflectors is commonly seen on seismic, with an uneven surface if well developed. The transgressive surface marks the onset of transgression and is seen on seismic as the boundary between topset/Clinoform packages and topset only packages (Embry, 2002). Although not all downlapping surfaces are an MFS, care must be taken in the identification of an MFS in seismic as it is essential not to confuse it with the top of a low stand fan. Erosional truncation is often expressed as the termination of strata against an overlying erosional surface. Truncation may exist as a result of erosional relief or the development of angular relief. Erosional truncation may exist within marine environments (e.g., the base of submarine canyons, turbidite channels or significant scour surface) and non-marine environments (e.g., sequence boundaries). Onlap is recognized on seismic data by the termination of low-

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angle reflections against a steeper seismic surface. Marine onlap and non-marine onlap have both been documented within global stratigraphic records. Downlap is often observed at the base of prograding clinoforms and usually represents the progradation of a basin-margin slope system into deep water. Downlap features are indicative of a change in depositional environment from marine slope deposition to marine condensation or non-deposition.

Internal convergence stratal patterns are often due to rising relative sea levels. This rise causes a retreat of the facies belts towards the proximal part of the basin. Careful analysis should ensure that this is not confused with fault activity. Figure-20 shows the reflection terminations assistance in locating the sequence boundaries between two different units to recognized even the system tracts from the seismic section. Seismic facies were classified based on the seismic configuration into different seismic facies, which represent different depositional environments.

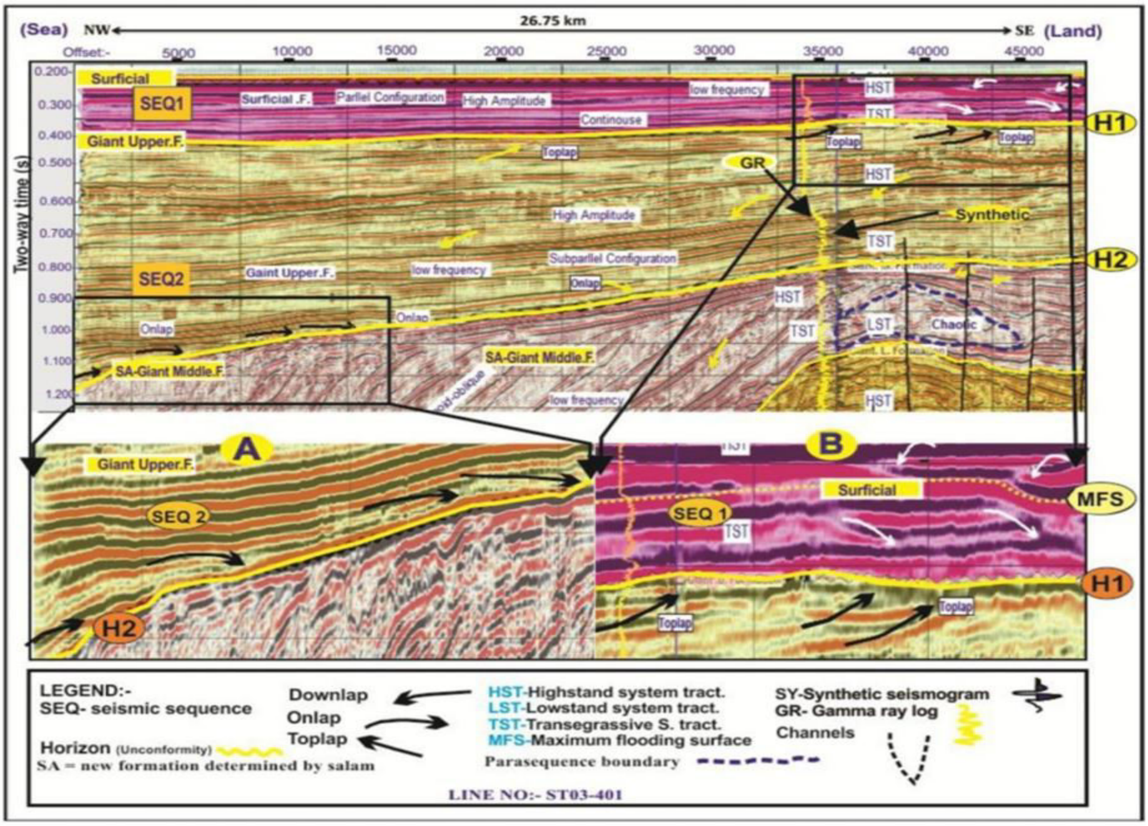

Figure-20. Reflection terminations and seismic facies used as evidence for the seismic sequences' classification. Almasgari 2017.

Therefore, most of the geologic features would be revealed using the seismic data, as can be seen in Figure-20. The sequence boundary (unconformity), fault, channels, and lithology can easily imagine using the seismic technique. For these reasons, geophysics and seismic techniques are playing a vital role in the geology study and widening the vision of the geological features in a major and a minor scale. Figure-21 shows another example of the sequence recognition boundary and geological features, in which the onlapping reflectors are marking well-developed sequence boundaries. Locally the underlying reflectors are eroded, indicating exposure at the sequence boundary.

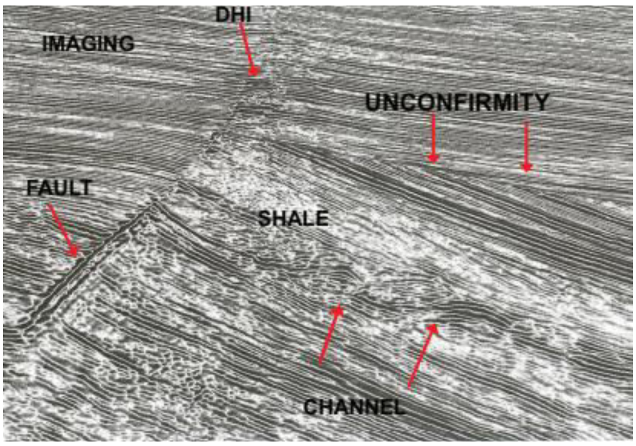

Figure-21. Geological features delineate by the seismic data. (Sajid *et al*., 2011).

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In case if well logs, paleontology, image log, and core sections are available, all hierarchical orders ('low' versus 'high') would be easily identified and be traced all over the study area. Seismic data contains several indexes that might lead to subdivide the seismic section for any study area up to the third-order based on reflection terminations, seismic facies, and configuration patterns. This sort of classification is good and acceptable for the global and regional investigations, while fourth and fifth orders are needed for the detail's studies and reservoir characterization in Figure-22. Because percentages of sediment collection and areas of accommodation space diversify, thickness and areal extent is of little use in establishing the order of depositional cycles (O Catuneanu *et al.,* 2009). Most cycle hierarchies are based on duration. Determining the period of a sequence is difficult because of problems in the high-resolution dating of rocks. However, with careful work, an estimation can be made using seismic data to subdivide the seismic section into subunits until the third order only. Another solution can reveal more details in case of using seismic inversion and would expose until the fifth order, as shown in Figure-22.A sequence can be divided up into system tracts that contain strata packages that corresponds to a specific genetic sediment types such as (transgressive high-standing, lowstand or regular regressive, forced regressive). A sequence may be subdivided into component systems tracts, which consist of packages of strata that correspond to specific genetic types of deposit (i.e., forced regressive, lowstand, or highstand normal regressive, transgressive (Catuneanu *et al.,* 2011).

By examining the reflection (or timeline), patterns, conclusions can be made regarding the depositional environment and lithology. Seismic reflection terminations are used to delimit stratification and depositional sequences. Seismic facies analysis is used to predict lithology distribution. A combination of the above analysis leads to systems tract definition, which is the building blocks of Sequence Stratigraphy.

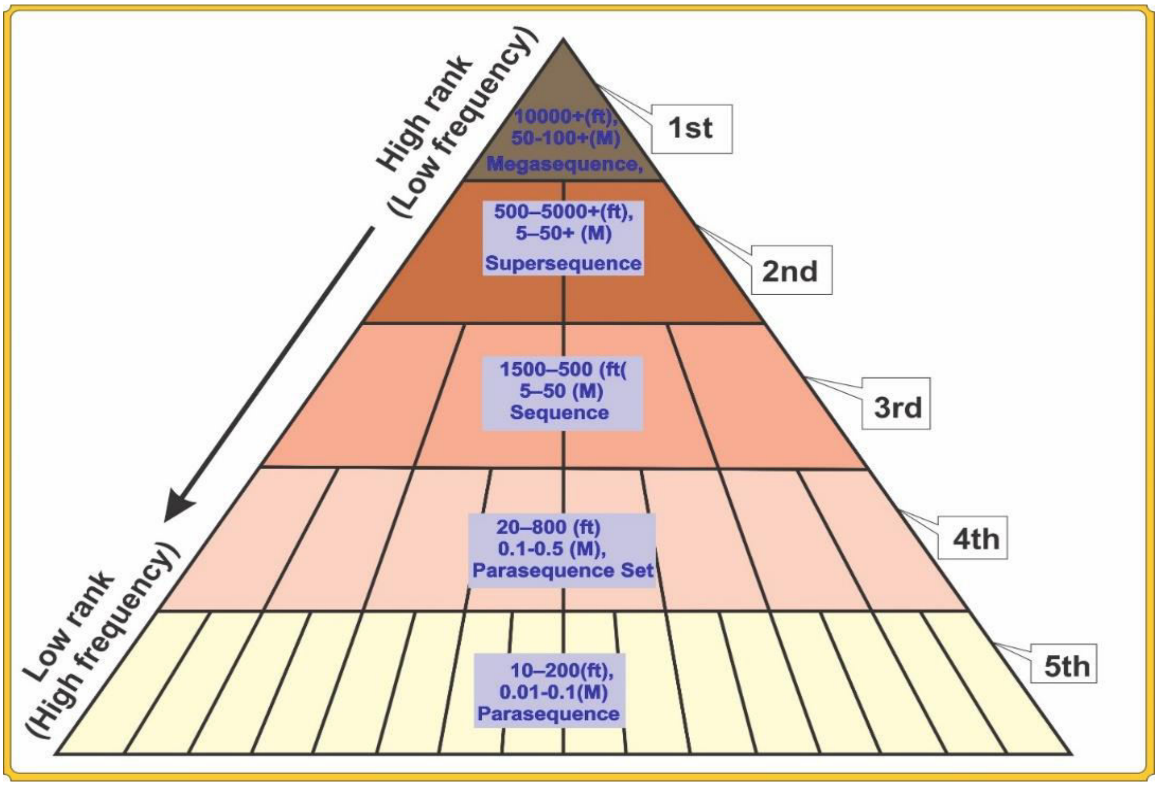

Figure-22. Schematic representation of the hierarchical concept. The terms 'high rank' versus 'low rank' refers to the location of the cycle within the hierarchy pyramid. This diagram is also showing the age, the thickness, and the hierarchy names. It was modified after (O Catuneanu *et al.*, 2009; Van Wagoner *et al.*, 1990).

E. Seismic Facies Analysis:

Seismic facies analysis attempts to formalize seismic stratigraphy ideas by extracting all the relevant information from the seismic data. These include the external shape of the seismic sequence and the relationship of the internal reflections to the boundaries to assign which kind of geological environment the rocks been formed. Seismic facies also used to predict lithology distribution. Seismic characteristics infer many of the geological interpretations, such as bedding patterns, depositional processes, erosion and palaeotopography, fluid contacts, and bed thickness. These facies parameters include reflection configuration, reflection continuity, reflection amplitude, reflection frequency, interval velocity, and external form Figure-23.

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Seismic Characteristics	
Seismic Facies Parameters	**Geological Interpretation**
Reflection Configuration	•Bedding pattems •Depositional processes •Erosion and palaeotopography •Fluid contacts •Depositional processes
Reflection Continuity	• Bedding continuity • Depositional processes
Reflection Amplitude	• Velocity and density contrasts • Bed spacing • Fluid content
Reflection Frequency	• Bed thickness • Fluid conten
Interval Velocity	• Estimation of lithology • Estimation of porosity • Fluid content
External form or aerial association of seismic facies	• Gross depositional environment • Sediment source • Geological setting

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Figure-23. Seismic facies parameters and their geological interpretations Edited after Fugro 2011.

F. Seismic Sequence Shapes:

The seismic geobodies which can extract the geological information for the sub geological elements by examined the seismic data, this information including the internal and external shape of the sequence interval and identified the internal reflectors relationships. Figure-24 represents some of these shapes, which gave an excellent understanding to locate the prospects area for drilling. The third step in seismic stratigraphy investigation is to characterize the external shape form of the sediment bodies. This investigation can be achieved in 2-D, but it is more accurate in 3-D by using several intersecting seismic lines.

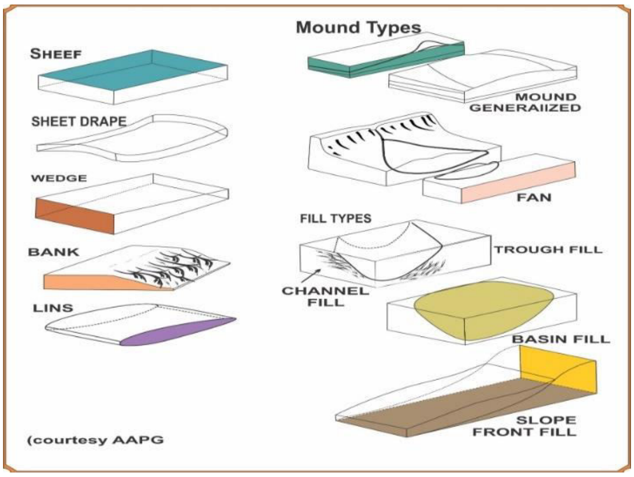

Figure-24. The external shapes of the sequence stratigraphic and their relationship of internal reflectors can be extracted from the seismic data.

The shape of a sediment package can give significant information on the depositional environment, such as mounds forming on the basin floor or shelf margin in carbonate systems, lowstand channels. In the Malay basin, an excellent geobodies could be identified directly from the seismic data using multi-seismic attributes; for example, curvature quantifies how ‘bent’ a curve is at a point. The curvature is defined as the rate of change of direction of the curve. It is closely related to the second derivative of a curve and derived in this case from volumetric estimates of reflector dip and azimuth.

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Upward-facing anticlines have positive curvature; upward-facing synclines negative curvature, dipping, or horizontal planar horizons have zero curvature. Curvature is accepted as a promising attribute to predict fracture distribution. Most positive and most negative curvatures are often the most valuable in conventional interpretation workflows and can be used to highlight the hanging wall and footwall cut-offs of faults (or the smearing in the Fresnel zone around faults). Curvature can provide good images of subtle flexures, folds, and collapse features. Several authors have shown a strong correlation between Gaussian curvature, dip curvature, and strike curvature and the presence of open fractures. Figure-25 showing an example of the curvatures that could be seen from the seismic data and reveals how the curvature can help.

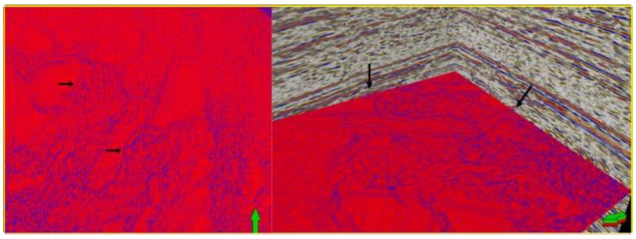

Figure-25. The curvature attribute reveals the rate of change of direction of the curve.

General spectral decomposition and Iso-spectral decomposition used to generate the RGB blending attribute from three different spectrally decomposed volumes at 15 Hz, 25 Hz, and 35 Hz, respectively, clearly highlighting the geomorphology features in an excellent manner across a seismic section in Malay basin(Almasgari *et al.*, 2020). This attribute usually generates by three different frequencies values and been mixed with the blender tool in Petrel 2019 software to reveal fantastic geological features as they are shown in Figure-26 and represented the major channel and some minor channels, faults, edges, horst, and graben in Malay basin.

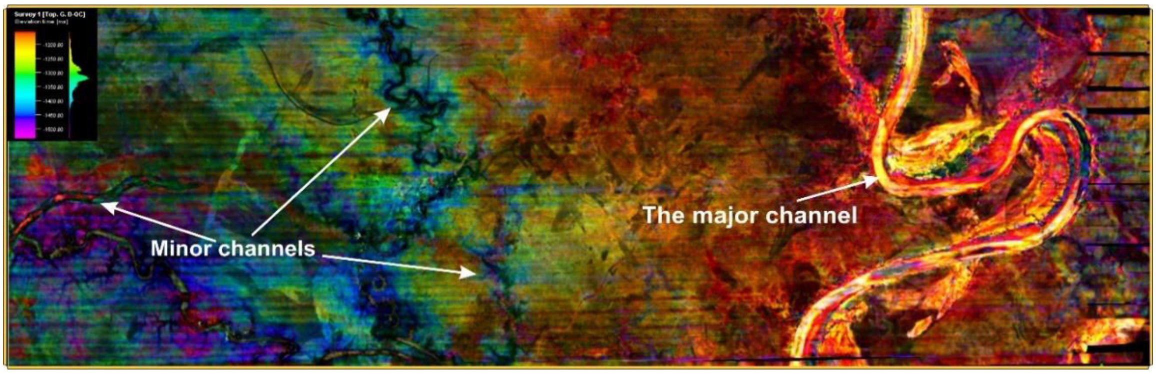

Figure-26. The RGB blending of the three spectrally decomposed volumes at 15 Hz, 25 Hz, and 35 Hz, respectively, clearly highlighting the detailed geomorphology geobodies across a seismic section in Malay basin.

Not only that, but also seismic stratigraphic spectral analysis attributes isnew excellent seismic attributes, which would help a lot to show several of the geological bodies in 3D visualization as never before, such as major and minor channels, faults, anticlines, and synclines, horst and graben. The sequences stratigraphy analysis can utilize some of the attributes such as decomposition and Iso-spectral decomposition and integrate them with fully picked horizons to map their outlines and thicknesses Figure-27. A further step that may be taken after all the seismic sequences on a section that has been identified is to construct a chronostratigraphic chart. This has time as a vertical scale and shows the distribution of the seismic sequences in time and distance along the line. The vertical time scale is not calibrated, but the chart does show the advance and retreat of sedimentation towards the edge, this may allow us to assign ages to the seismic sequences.

Figure-27. Seismic stratigraphic spectral analysis for a picked horizon reveals the most important geological features with a touchable map-view.

CONCLUSIONS

Uniformity of sequence stratigraphy demands that personal beliefs be taken apart from what may be included in stratigraphic standards or guidelines in implementing one stratigraphic stabilization clauses over another. Just the mutual interest of all methods will give an impartial normalization approach. That is means that

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the sequence stratigraphy must be distinguished among model-independent and model-dependent aspects. In such instances, system tact subdivision can utilize the normal regressive, forced regressive, including the (lowstand and highstand), and transgressive deposits. Such sequences, however, lack a genetic relationship to the shoreline, and thus cannot define their interior structuring of conventional system tracts. Such sequences may be divided up into eccentric systems tracts on the foundation ofthe percentage between the various depositional features that may form in those settings. The optimum method to sequence stratigraphy is defined as the integration of outcrop, core, log, and seismic data sets. Each provides different insights into the identification of stratal stacking patterns and sequence stratigraphic surfaces, and mutual corroboration is important to reduce the uncertainty of the interpretations. In each case study, not all data sets can be accessible, a variable that can restrict the "resolution" of the stratigraphic sequence analysis. At the same time, not all types of data are suitable for the detection of all sequence stratigraphic surfaces and systems tracts, and not all sequence stratigraphic surfaces form in every depositional setting. The high level of variation in the accurate representation for the stratigraphic units and surface boundaries necessitates the implementation of a satisfactorily flexible approach to familiarize the variety of rational expressions. The' resolution' of the sequence stratigraphic interpretation might be limited by lack of the information from one or another data set above; the more data set we could use in the analysis, the more resolution accuracy we can achieve. A consistent methodology of stratigraphic sequence interpretation requires identification, all genetic units and surface boundaries that can be theoretically explained at the chosen observational scale in a stratigraphic section. The development of a model structure of genetic units and surface boundaries demonstrates the stunning success of the stratigraphic sequence process. In addition, the interpreter will initiate a framework model decision concerning any surface of the stratigraphic sequences that would be up and be chosen as the boundary of the sequences. In reality, the sequence frequently determines which surfaces are most suitable explained and has the highest value in identifying sequence limits and near-chronostratigraphic units. The sequence stratigraphic and systems tracts surface terminologies can somewhat be considered as model-dependent, but formal term sets are suggested to simplify the interaction between all specialists. The dynamic, geomorphic, and tectonic settings have a strong impact on the way in which the variations in accommodation are demonstrated or conserved. Therefore, there are numerous variations, of what sequence in terms of element system tract can preserve, so that no single framework could provide an alternative for any situation. However, the common characteristic of all research articles here is that every sequence with a coastline pathway shifts comprises of one or both of the same genetic kinds of sediment such as (lowstand and highstand normal regressive, transgressive, and forced regressive). However, thesequence stratigraphic analysis standardized workflow highlights the classification of deposits genetic kinds and sequence stratigraphic surfaces, which can be used to divide the stratigraphic section up into element systems tracts. Further than this model-independent framework of genetic units and bonding surfaces, the choice from which surface(s) to a sequence boundary can vary with the method, deposition, and observational scale.

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