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A review of the application of sequence stratigraphy in the petroleum industry

Gargi Sen*
Digital and Integration Division, Schlumberger, Kuala Lumpur, Malaysia 50250
*Corresponding author: gsen@slb.com

Abstract: The concept of sequence stratigraphy has evolved in the last 40 years, and it has been used as a powerful tool for predicting the geographic and temporal distribution of reservoir, source, and seal rocks at both exploration and reservoir scales since its inception in the late 1970s. In the context of petroleum exploration, this article reviews the concept of sequence stratigraphy in several geological settings, including clastics, carbonates, and salt-related tectonics. In addition, the practical and realistic portrayal of sequence stratigraphy, as well as its relevance in the petroleum industry is discussed.
Keywords: Sequence stratigraphy, clastics, carbonates, salt tectonics, petroleum system element.

Introduction

The significant factors that impact the development of depositional sequences are the accommodation space and the changes in relative sea level (RSL) irrespective of the depositional environment or other associated complexities. The principles of sequence stratigraphy were first defined in passive continental settings and they have mostly been applied to understand the depositional architecture of clastic sequences. Although the principles and concepts are similar in carbonate settings, the manifestation of carbonate deposits in response to relative sea-level variations differs from clastics. This is due to the fact that, unlike clastics, carbonate sediments are frequently formed in situ. Because both carbonate and clastic reservoirs are equally prevalent in the petroleum business, the major differences in the sequence stratigraphic framework of clastics and carbonates have been emphasized in the following section. Many petroliferous basins have hydrocarbon reservoirs in the mini-basins associated with salt tectonics; a brief review on this topic is also given.

Resolution: Order of Sequences Suitable for Petroleum Exploration

Petroleum geologists work with seismic and well data; the seismic records arrive in two-way time (TWT in milliseconds) and the well data arrives in depth (meters or feet), and their resolution varies greatly. The seismic data resolution is on a ten-of-meter scale, commonly 25m or higher, but the logs are in centimeter-to-meter scale recordings. The lower-order seismic sequence stratigraphy can only interpret 3rd to 4th-order geometry, but the essential elements of the petroleum system, such as the reservoir, source, and seal, can be mapped in higher-order sequences of 4th to 5th-order. These higher-order sequences or parasequences (specific to 5th-order cycles) can be deciphered by integrating well logs, core, and analog outcrops (if exposure is available). During the petroleum exploration phase, the sequence stratigraphic interpretation of 3rd to 4th-order cycles is more precise with the analysis of seismic profiles, whenever the well data are limited. Subsequently, after the success of the exploration stage, when the hydrocarbon field moves into development and production, a larger number of wells are drilled and high-resolution sequence stratigraphic interpretation of 4th to 5th order is performed at this stage to predict the reservoir continuity and connectivity in- between baffles.

Petroleum System Element in the Context of Sequence Stratigraphy

The source, reservoir, trap, and seal rocks, as well as the key processes of generation, migration, and accumulation, are critical aspects of the petroleum system; relative timing of formation of these elements and processes are necessary for hydrocarbons to accumulate and be preserved. A brief description of the relevance of sequence stratigraphic interpretation in the context of these elements is provided here. The popular “Exxon” model (Vail et al., 1977; Wagoner et al., 1988) is widely used for clastic deposits which are transported frequently by channels and deposited in basins. Because of the huge sedimentary budget and the intraformational shales typically acting as a seal rock, highstand systems tract deposits in coastal and shallow marine environments are potentially attractive reservoir rocks. While the low stand deposits have the potential to be good reservoir rocks, they hardly have any potential for source and sealing capacity. The fine-grained shelf or pelagic sediments that are deposited in the overlying transgressive systems tract tend to have high organic content to form the source rock and act as a sealing rock.Thus, siliciclastic sequence stratigraphic models can forecast a wide range of reservoir occurrences, and varied successes have been recorded in turbidite systems in the lowstand systems tract (Fig. 1A-E) and incised valley fills in either the lowstand or transgressive systems tracts (Bowen et al., 1993).

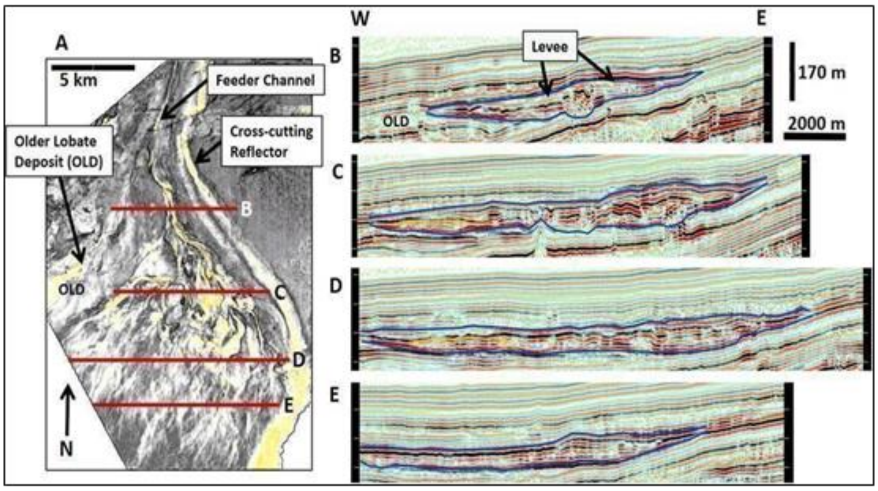

Fig. 1. A turbiditic channel system revealed in the seismic from offshore Nigeria, a deep-water clastic deposit that forms the current trend of exploration. (A). Map view of Root Mean Square amplitude extracted along the midway between the upper and lower bounding surfaces marked in blue in the cross-section displays. (B-E). Various cross-sections from the proximal to the distal part show the profile of the channel complex (after McHargue et al., 2021).

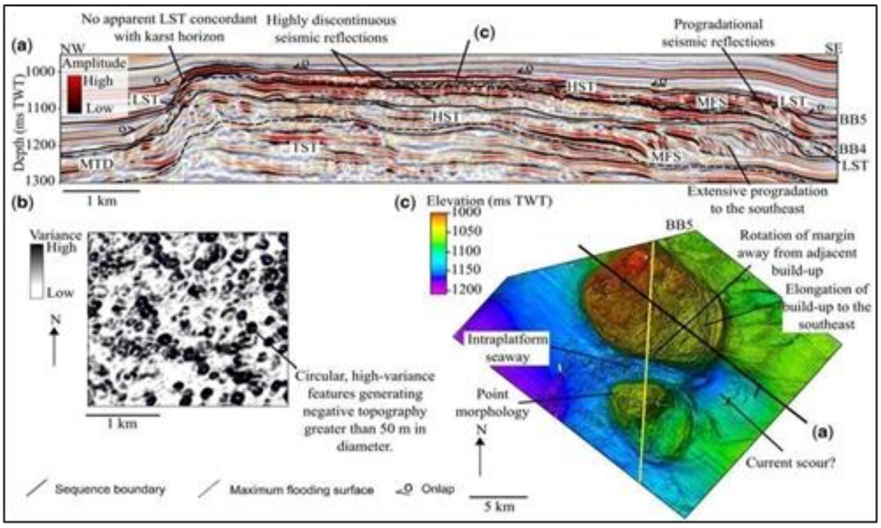

Fig. 2. Example of sophisticated interpretation of carbonate architecture, depositional processes, and sequence stratigraphic interpretation that can be performed using 3D seismic data from Miocene isolated platform from the Browse Basin, offshore NW Australia (after Van Tuyl et al., 2019). (a) Interpreted seismic profile showing the final stages of carbonate build-up growth in the Browse Basin. There are several phases of carbonate growth having aggradational to progradational stacking patterns, the upper limit of the final phase is marked by BB5, which is characterized by highly discontinuous seismic reflections suggestive of karsts, with the topmost seismic reflection showing some small subtle topography. It can be noted that transgressive systems tract (TST) is marked by aggradational to progradational stacking patterns and has overall a greater thickness compared to the highstand systems tract (HST) section, which is the contrast with the conventional clastic deposits. (b) A variance slice through BB5 showing this sequence boundary as comprising high-variance circular to dendritic features with diameters of 60 m. These correlate with highly discontinuous seismic reflections and are interpreted as karsts. (c) TWT structure map of BB5 showing the platform geomorphology and it is influenced by ocean currents. LST=low stand systems tract; MFS= maximum flooding surface; MTD = mass transport deposit.

The sequence stratigraphic architecture is different in carbonates because of the various geological factors:
(1) With moderate rise in RSL, the carbonate factory often keeps up the pace and expands, resulting in substantially thicker transgressive systems tracts in carbonate environments than in siliciclastic rocks.
(2) With further rise in relative sea level, the carbonate factory shuts down production and forms the condensed hard ground. In comparison to siliciclastic deposits, the highstand systems tract in carbonates is substantially thinner.
(3) The subaerial exposure of the carbonates results in more chemical erosion than the mechanical erosion that clastic rocks experience. Depending on the length of the exposure, the subsequent dissolution displays

karstification features such as caves and caverns, collapsed breccia, grain dissolution, etc. Carbonates of the lowstand and transgressive systems tracts have a higher potential for being good reservoir rocks as they are prone to be dominated by reefal bodies than siliciclastics, but carbonates are much more difficult to predict than siliciclastics due to their susceptibility to severe diagenesis. Seismic characteristics can disclose several elements that can help analyse the sequence stratigraphic architecture and provide information into the growth periods of the carbonate (Fig. 2).

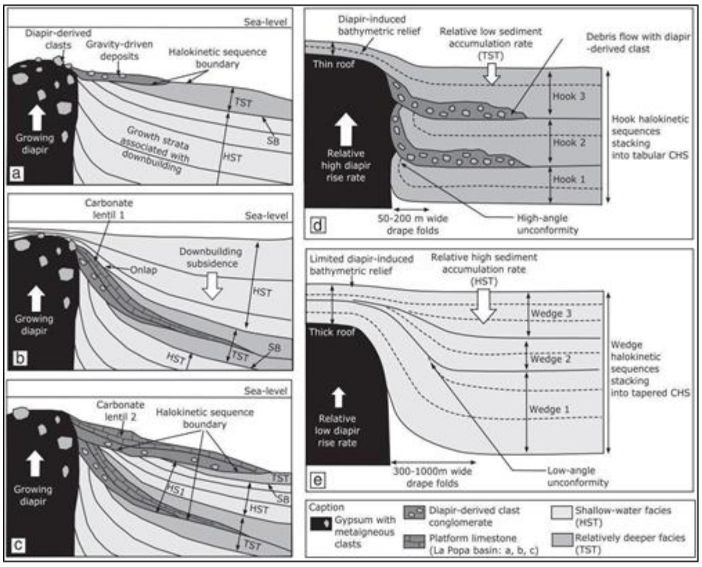

Fig. 3. The HS model from the La Popa Basin, Mexico. (a) Diapir rise is active, gravity-driven sediments define angular unconformity. (b)Sedimentationrateishigh, diapers buried, sediment slap on stable flanks. (c)Repetition of (a) and (b) leads to creation of new HS. (d) Hook HSs stack into tabular CHSs, commonly form during transgressive systems tracts. (e) Wedge HSs stack into tapered CHSs, commonly form during highstand system tracts. HSs stack into CHSs, which are currently considered to be at the scale of 3rd-order systems tracts (d and e) (after Yohann et al., 2016).

Sequence Stratigraphy in Salt Tectonics

There is a tremendous interest in salt tectonics in the petroleum industry because many of the world's largest hydrocarbon discoveries have occurred in salt basins like the Gulf of Mexico, Campos Basin, Persian Gulf, Congo Basin, and others. Salt growths have a significant impact on petroleum system elements, as salt is a highly impermeable rock that provides an excellent barrier against fluid migration, and the associated structure with the salt diapir serves as an excellent trap. Because salt has high heat conductivity, it elevates the thermal maturity of rocks overlying it. The sequence stratigraphic definition of the associated sediments in the mini-basins adjacent to salt diapirs will be briefly described because of its importance to hydrocarbon occurrence. These associated sedimentary sequences surrounding salt growths are commonly referred to as halokinetic sequences (HS), derived from the word halite. Similar to conventional sequence stratigraphy, an HS is a succession of sedimentary strata bounded by an angular unconformity that becomes conformable away from the salt diapir. The equilibrium between the diapir rise and the rate of sedimentation governs these deposits, which are usually linked with drape folding. Two end-member styles are defined as hook HS, in this case the upturn occurs within 200m (660ft) of the diapir edge and has strong inter-HS angular discordance (up to90°), while the wedge HS has a folding and thinning within 300 to 1000m (1,000 to 3,300ft) of the diapir and low inter HS angular discordance (generally <20°). There are different levels of hierarchies in these packages; lower-order composite halokinetic sequences (CHS) are defined as a stack of one end-member type of HS bounded by angular unconformities (Fig. 3). Hook HS stack to generate a tabular CHS with broadly parallel boundaries and all the folding occurring near diapir. The wedge HS stack to form a tapered CHS, with the youngest wedge HS having shallow dip and low-angle truncation with the upper unconformity and the oldest wedge HS having vertical to overturned dips and upto 90°angular truncation at the top of the CHS.

The geometry of the CHS, whether tabular or tapered, is determined by the ratio of salt increase and sediment-accumulation rates (Roca et al., 2021). The synkinematic strata are characterized by tabular CHS's when the salt-rise rate exceeds the sediment-accumulation rate. If sedimentation rate exceeds the rate of salt increase, sedimentary packages form wedge HS with bounding unconformities that are farther away from the diapir and have reduced angularity, thereby defining tapered CHS's. The geometry of the HS can thus provide an insight about the relative rate of sediment supply, which is key to understanding about the possibility of occurrences of good potential reservoir rock. If tapering CHS's are observed in seismic data, it means that the sedimentation rate in the adjacent mini-basin was high, with a broad zone of gradational facies changes with few debrites. The tabular CHS, on the other hand, indicates that the sedimentation rate in the neighbouring mini-basin was slow, with a narrow zone of abrupt facies alterations and debrites near the diapir border.

Stratigraphic Forward Modeling

This is a stratigraphic simulation approach that uses computer modeling to forecast stratigraphic geometries and architecture of a basin. Stratigraphic simulation investigates the key factors that control the sedimentation in a basin, such as subsidence and uplift rates, changes in eustatic sea level, and changes in sediment supply rates and directions (Shafie et al., 2008). The stratigraphic simulation is potentially used to validate seismic sequence stratigraphic interpretation and predict the main controlling factors in the identified sequences. The forward-modeling approach, in which the basin stratigraphic development is simulated using a set of predetermined parameters, such as basin topography, water depth, sea-level change, and sediment flux into the basin, is one of the most prevalent strategies for stratigraphic simulation (Fig. 4). This type of model is used in petroleum exploration to predict the distribution of source and reservoir rocks. The technique can be performed at various scales based on the data availability and the project goals (Acevedo et al., 2014). (1) Basin-scale will aid in simulating regional geological processes and depositional patterns of the lower-order sequences. (2) Sequence scale can assist us in understanding the complexities within a sequence, such as the sinuosity of the channels or the stacking configurations by simulating local patterns within sequences. (3) Reservoir scale can help to quantify the net-to-gross ratio, which is very critical in hydrocarbon exploitation.

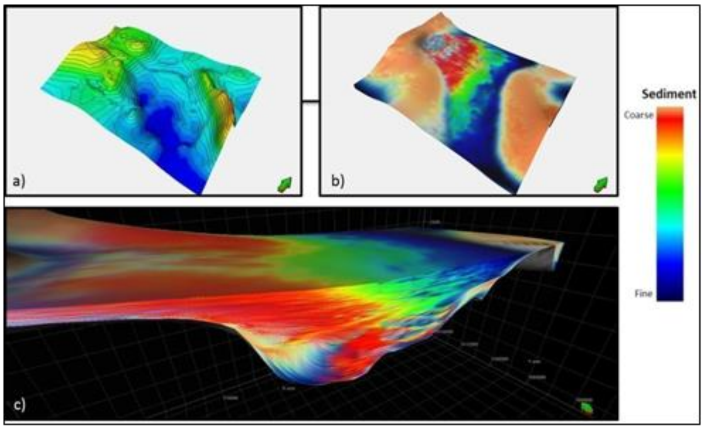

Fig. 4. Example of stratigraphic forward modelling from Campos Basin. (a)Initial basin floor topography interpreted from seismic, (b) base-case scenario of basin fill and (c) cross-section through simulation result showing sands in the deep part of the basin representing basin floor fans deposited by turbidity currents originating in the upper end of the basin (upper left of the figure) (after Acevedo et al., 2014).

As is typical with many marine impacts, the crater-filling stratigraphy at Wetumpka is related to the behavior of water-saturated materials in the target and to the return of displaced sea water after impact. The crater-filling stratigraphy unit at Wetumpka (a formal stratigraphic unit named the Wetumpka Mélange by King, 1998) has several distinctive internal stratigraphic components. In stratigraphic order, and thus in order of formation during impact, these components are: (1) impactite sands; (2) trans-crater slide unit; (3) crystalline boulder-bearing bed; and (4) resurge chalk deposits. Impactite sands are monomict clastic sediments that contain some large, stratified sedimentary target blocks; whereas the trans-crater slide unit has folded, and in some instances, inverted stratigraphy of target units (its origin is evidently related to a massive slump failure of the southern rim; King et al., 2006; King and Ormö, 2011). The crystalline boulder-bearing unit consists of a pebble and cobble-rich sandy clay matrix that contains shocked proximal ejecta, including a noteworthy component of crystalline target boulders (mainly schists and gneisses) that range up to 45 m in apparent diameter (King et al., 2006; 2015; Chinchalkar, 2019). Resurge chalks are resedimented deposits of chalk that were being deposited on an adjacent shelf area at the time of impact (i.e., the Upper Cretaceous Mooreville Chalk). These resurge chalks, in contrast to the original Mooreville Chalk, contain fine ejecta components (Petruny and King, 2018), as well as evidence of graded bedding and long-distance transport of deeper water megafauna (Markin and King, 2012). The resurge chalk has been interpreted as evidence of a turn-around of a rim-wave tsunami (King and Ormö, 2011).

Applications and Limitations

Sequence stratigraphy is widely used for interpreting stratigraphic architecture by correlating the seismic and well with the objective to predict the facies away from the data, creating accurate maps, and estimating reservoir trends in the area without sufficient data. It is very helpful in exploration by defining play boundaries and prospects; however, the application of sequence stratigraphic concepts has led to both successes and failures in petroleum exploration. This is because it only addresses the reservoir, source, and seal components of the petroleum system; trapping mechanisms still remain a significant source of risk that must be thoroughly analysed separately.

Conclusions

- This discussion reviews the concept of sequence stratigraphy in clastics, carbonates, and salt-related tectonics.
- The practical and realistic portrayal of sequence stratigraphy, its relevance in the petroleum industry is deliberated.
- The interpretation of seismic horizons, correlating logs, facies, is supportive in exploration by defining play boundaries and prospects.

Abbreviations used in this paper.

RSL- Relative Sea level
TWT- Two-way time
HS- Halo kinetic sequences
CHS- Composite halokinetic sequence
LST-Lowstand Systems Tract
TST-Transgressive Systems Tract
MFS- Maximum Flooding Surface
MTD- Mass Transport Deposit
SB- Sequence boundary

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