Workflow for high frequency Carbonate Sequence Stratigraphy: A case study from NBP (D1) field, Mumbai Offshore basin, India

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Summary

Carbonate Sequence stratigraphy is at variance to the standard sequence stratigraphic model, because the standard sequence stratigraphic model was originally developed for marine clastic depositional systems. The difference is owing to the fact that to a large extent carbonates are born within the depositional environment and forms certain geometries like rimmed platforms, reefs, atolls etc. unlike the clastics which are transported and deposited. However, the fundamental features of the model is shared by all the depositional systems irrespective of their composition, scale and physiography, therefore it is applicable to carbonates as well, with little modification in the approach and by understanding the inherent characters of the carbonate. High frequency sequence stratigraphic study carried out in the NBP (D1) area of Mumbai offshore basin to address the spatio-temporal porosity variation and hydrocarbon distribution of carbonate reservoirs which are below seismic resolution. Detailed workflow for high frequency sequence stratigraphic study has been formulated which can be readily adopted in the industry practices using seismic, well log, core, cuttings, biostratigraphic, SCAL and pressure/production data. Higher order sequence stratigraphic framework of the area was established first in a semi-regional context using the seismic data. On the basis of seismic reflection pattern 1st and 2nd Order sequences were identified which were tied to the well log data and correlated across the area. The entire sedimentary column from Deccan trap top to sea bed was divided into two 1st Order Sequences such as, (1) Paleocene to Early Eocene, Syn-rift sequence and (2)Eocene to Recent, Passive margin sequence, Passive margin sequence consists of two 2nd Order sequences viz. (i) Middle to Late Eocene and (ii) Oligo-Miocene. High frequency sequence stratigraphic study was carried out on the hydrocarbon bearing Oligo-Miocene 2nd Order sequence only, through demarcation of 3rd, 4th and 5th Order sequence. For the higher order seismic scale sequences depositional sequence approach was adopted whereas for lower order sub-seismic scale sequences genetic sequence approach was applied. Facies prediction in carbonate is non-linear; at the same time carbonate has the intrinsic character of chemically highly reactive and gets lithified within short span of time and very less susceptible to mechanical erosion on subaerial exposure which influences the sediment compartmentalization in a different way than that of siliciclastic systems across the basin during the various stages of base level cycle, such as lowstand shedding of siliciclastics vs. highstand shedding of carbonates.

Introduction

The object of this paper is to highlight the fundamental differences of clastic and carbonate sequence stratigraphy and provide a general guideline and workflow for carbonate sequence stratigraphic study suitable for industry practices. It is basically a unifying paradigm which harnesses the concepts of sedimentology and stratigraphy together to reconstruct the facies architecture, infer the depositional environment and thereby explains the spatio-temporal facies variation, diagenetic history and provides means for their correlation. The fundamentals of carbonate sequence stratigraphy were described by James and Kendall, 1992; Schlager, 1992; Hunt and Tucker, 1993; Loucks and Sarg, 1993. For detailed update readers are referred to Schlager, 2005, where a complete discussion on different aspects of carbonate sequence stratigraphy was presented.

Here our main focus is to utilize the concept to achieve finer subdivision of the strata under study using the available dataset to our advantage which can eventually address the criticalities of the individual fields such as selective porosity development, structural disparity in hydrocarbon distribution, role of diagenesis in porosity development/ destruction and productivity differences of different pays.

Differences of Carbonate and Clastic sequence stratigraphy

Sequence stratigraphic paradigm essentially revolves around the concept of base level fluctuation with time and concomitant changes in the accommodation (Posamentier and Vail, 1988, Galloway, 1989; Hunt and Tucker, 1992; Embry, 1995). The interplay of accommodation and varying rate of sedimentation produces number of genetic units with characteristic stratal stacking pattern and depositional trends. In carbonate environments, sedimentation rate depends on the carbonate productivity, which is governed by number of allogenic and autogenic factors such as climate, water depth, sun light, nutrient supply, salinity, Eh, Ph, rate of clastic influx, surface area of carbonate platform, oceanic circulation patterns, type of extant biota etc. while rate of sediment influx in a clastic environment is governed by the external agencies such as sea level fluctuation, climate, tectonics, bedrock character of the hinterland and vegetation. In case of carbonate it is more of the basinal conditions mentioned above and the biota which dominantly fixes the carbonate either as biotically controlled or biotically influenced carbonate precipitation (Schlager, 2000), with a meagre contribution from abiotic precipitation. The differences in the carbonate sequences is attributed to the inherent characters of carbonate, the way it gets deposited, the geometry of the platforms, factors which influence the carbonate productivity with time, early diagenesis and lithification, less susceptibility to mechanical erosion, more amenability to chemical erosion, karstification on subaerial exposure and tendency to form flat tops and steep slopes. For example, geometry of the carbonate shelves evolves with time, unlike the clastic shelves which always maintain the hydrodynamic equilibrium with the wave energy. Ramp types of platforms are similar to clastic shelves, which can evolve to rimmed platform over the period. In the rimmed platform, there is development of a rim offshore ward /at the shelf edge which filters out the oceanic waves providing a sheltered lagoon behind, which is not in equilibrium with the wave energy.

As the sea level falls below the platform, carbonate factory is virtually closed except narrow fringe on the slope which supports limited carbonate production during the lowstand. The limited depth window of carbonate factory (euphotic zone) especially for the tropical factory coupled with biotic linkage of carbonate production also causes the carbonate to respond very differently during the next phase of transgression, especially when overwhelmed by the rapid rate of transgression. As the transgression ensues the carbonate factory virtually needs to start up again and it follows a systematic pattern, such as proposed by (Neumann and Macintyre, 1985). Populations of organisms respond to the opening up of new living space in three steps: first, start-up phase, growth lags behind the creation of living space, second, catch-up phase, population growth exceeds the rate of change in space and third, keep-up phase when population growth is limited by the rate of growth in living space. A sigmoidal growth curve results from this three-phase growth. In case of rapid rate of transgression, facies belts jump backward rather than gradual back-stepping, which may eventually led to drowning and shutting down of the carbonate factory, if the water column deepens beyond the illumination depth.

These differences are ultimately reflected in terms of difference in the geometry of carbonate systems tracts and sediment budget across the basin during the formation of different systems tracts.

Carbonate sequences are essentially defined in the same way as the clastic and each sequence represent 'a succession of strata deposited during a full cycle of change in accommodation or sediment supply' (Catuneanu et al., 2009). Smaller sequences are nested within larger sequences in a fractal manner across a continuum of thickness and time. A sequence can be divided into number of genetic packages/systems tracts on the basis of geometry and facies stacking pattern. Figure 1, shows the geometry of different systems tracts commonly found in a tropical carbonate platform. Systems tracts shown in panel 1, 3, 6 and 7 are similar to the clastic depositional systems whereas panel 2, 4 and 5 are typical of carbonate depositional systems which are empty bucket, drowned platform prograded by clastic HST and drowned platform. All the seven sequence stratigraphic surfaces which are currently in use, such as subaerial unconformity, two correlative conformities, MFS, MRS, BSFR, and WRS can theoretically exist in carbonate systems as well. There are some additional chronostratigraphic surfaces in carbonate such as "drowning unconformity" and "slope onlap surface" which find better expression in seismic data, because of the stratal discordance they produce.

As the industry practitioner we basically need to identify different sequence stratigraphic surfaces objectively in the given data set to demarcate the sequences/systems tracts within a sedimentary succession which will enable us to predict the facies as well as diagenetic history. Any of these surfaces which are well expressed in the data set can be used to develop a fit for the purpose model. Choice of the sequence stratigraphic model may depend on which sequence stratigraphic surfaces are better expressed in the dataset.

Workflow for High frequency Carbonate Sequence Stratigraphy

Sequence stratigraphy offers an integrated platform to assimilate different dataset (exploratory, production), which otherwise may appear redundant. It has been used as an important exploration tool in frontier areas to predict the petroleum system elements i.e. source, reservoir and seal away from data control points; as well as in mature producing basins for production optimization and field development, through detailed reservoir modeling by integrating pressure production data. High-frequency sequence stratigraphy is applies to observations at a log, core, and/or outcrop scale, which are below seismic resolution. Since the lower order sequences are nested within the higher order sequence in a fractal manner hence occur in higher frequency (short duration cycles). Workflow of the high frequency sequence stratigraphy is given in Figure 4 and each of these steps are elaborated.

Study area: NBP (D1) field, Mumbai offshore basin

NBP (D1) field is a NW-SE trending elongated antiformal structure, situated very close to the Miocene shelf edge in DCS area, SW of Mumbai High, is the farthest offshore field, around 200 km off the coast at a water depth in the range of 85-90m (Figure 3).

This field was discovered on 1976 and is under production since 2006. Reserve base of the field is around 144 MMT Initial Oil in-place (IOIP).

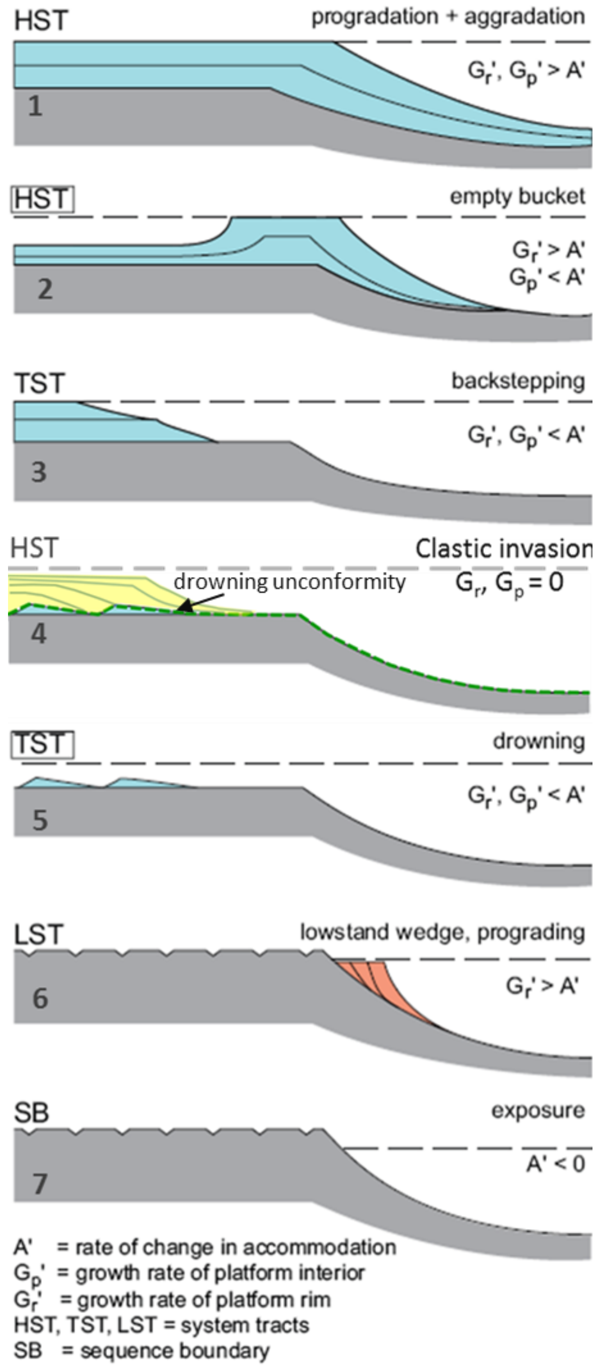

Figure 1: Basic geometries of tropical platforms and their interpretation in terms of rate of change in accommodation, A', and rate of sediment supply, G' (modified after Schlager, 2005).

Workflow for high frequency Carbonate Sequence Stratigraphy

Figure 2: Flow diagram showing the workflow for high frequency sequence stratigraphic study.

Established hydrocarbon bearing zones belong to carbonates of Early Miocene Ratnagiri Formation (Upper and Middle pays) and Late Oligocene Panvel Formation (Lower pay). Reservoirs are thin in nature alternating with tight carbonate layers.

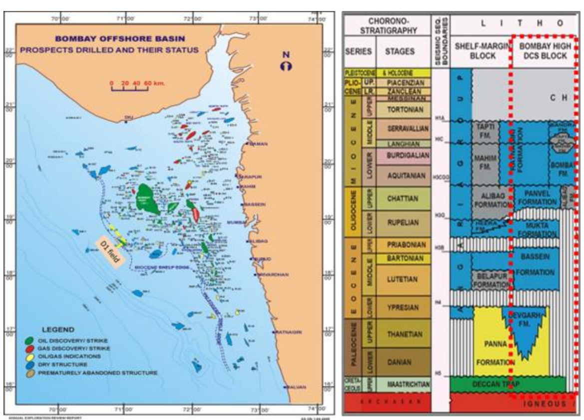

Figure 3: Location map and generalized stratigraphy of the study area, location of field is shown in red rectangle and the location of seismic profile in yellow dashed line.

Step 1: Knowledge building

Knowledge building is an important and necessary step in sequence stratigraphic study. In this step basis information regarding the basin is obtained such as tectonic setup, age, major tectonic events witnessed by the basin, exploration history, petroleum system elements (source, reservoir and seal), data sets available for analysis etc. Assessment of all the available data such as gravity-magnetic, seismic (2D and 3D), well log (including the image log), reports on source rock study, on diagenetic history, petrophysical study, geochemical /isotopic study, radiometric dating is done.

Step 2: Database building

Collection of different dataset and short listing the data sets. Some area/basin may contain sparse data while other may have rich database. Depending on the case, optimum database needs to be created and loaded in a suitable platform for its integration and analysis, having key seismic lines (dip and strike), preferably passing through the wells and key wells having good biostratigraphic control.

For example regional 2D lines provides insight into the basinal set-up, disposition of different sequence stratigraphic surface from proximal to the distal part of the basin, disposition of different depositional elements, such as platform geometry, width of the shelves, slope, canyons, slope fans, basinal fans etc. as well as the structural elements.

3D volumes afford detailed information on depositional elements, especially the seismic geomorphological study.

However in our experience, there will always be some data gaps, whether in terms of seismic coverage, well density, log quality, scarcity of biostratigraphic data, or simply the biota may just be long ranging enough to prevent you from making any conclusive inference! The point is, to make the best use of whatever data is at the hand to bring out a working model.

Step 3: Seismic sequence analysis/Seismic stratigraphy

Seismic stratigraphy is basically a geological approach to the stratigraphic interpretation of seismic data. In the seismic data, stratal (reflector) discordance is the main criteria used to define sequences and systems tracts, therefore identification of different patterns (Figure 4) such as truncations, toplaps, onlaps, offlaps, downlaps etc. are of paramount importance, which require careful examination of seismic data in regional scale. Truncations indicate erosional hiatus whereas toplaps, onlaps, offlaps, downlaps etc. indicate non-depositional hiatuses, i.e. lateral termination of strata at its original depositional limit. Sequence stratigraphic surfaces identified in the seismic data should be tied with the well log data, since well log data affords very good vertical resolution, sequences of smaller magnitude can also be identified, which may lie below the vertical resolution of seismic data. Although seismic data especially 3D seismic data affords good indication of deposition environment, even the karst surfaces can be recognized in the stratal and time slices, but 3D seismic coverage is generally restricted to smaller areas with respect to the total basinal area.

Stratal pattern and geometry affords wide range of insights into the depositional history, such as change in the accommodation during various stages of basin

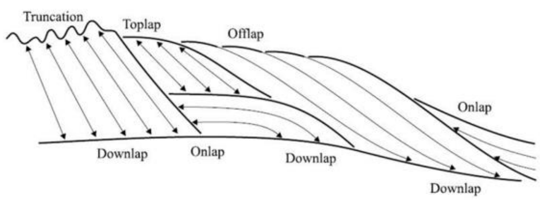

Figure 4: Stratal termination patterns (modified from Emery and Myers (1996).

fill history. However this needs to be interpreted also with reference to different depositional regime, such as clastic and carbonate. In carbonates stratal patterns are more varied than in siliciclastics particularly because there are many localized centers of high production and erosion (Figure 5).

Higher order sequences can be easily identified on the seismic data on the basis of seismic reflection pattern, as the seismic reflectors represent the rock interface, therefore generally coincide with time lines except in some unusual circumstances, when it may be time transgressive (Sheriff and Geldart, 1995). Pseudo-unconformities form in the seismic data where there is rapid facies change at each level at a similar position and the seismic tool merges these points of change into one reflection. Line diagram in (Figure 6) showing various stratal pattern and sequence stratigraphic surfaces identified in NBP (D1) area.

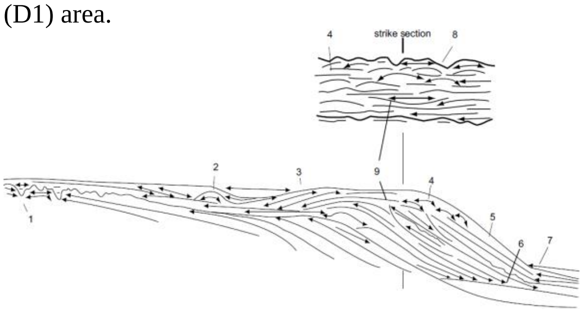

Figure 5: Stratal termination patterns of carbonates (modified from, Handford and Loucks, 1993). Numbers refer to characteristic situations: (1) karst buried by marine sediment, (2) lagoonal patch reefs or mounds, (3) prograding backreef apron, (4) bioherms at platform margin, (5) slope clinoforms, (6) slope clinoforms downlapping on basin floor, (7) onlapping basin-floor sediments, (8) incisement of shelf edge at sequence boundary, (9) shelf-margin incision within sequence.

Step 4: Well to seismic tie

Establishing the relationship between the well log and seismic is of paramount importance, since both of them are in different domain, depth vs. time. There are different ways to achieved this, such as through VSP /check shot data and synthetic seismograms. In a way this is the process to establish the linkage between the geology and the seismic data. Vertical seismic profiles (VSPs) are useful in the well tie process because they provide a link between wells and seismic at the correct scale and allows to identify horizons to pick. This high-density sampling gives good control on the time–depth relationship. Synthetic seismogram estimated from Sonic and density log is another way to establish the relationship between the well and seismic data.

Step 5: Well log sequence analysis (higher order sequences, 1st and 2nd Order)

Higher order sequences are generally defined by the seismic stratal pattern on the basis of geometrical criteria, such as unconformities are characterized by terminations below and onlap above, maximum flooding surfaces are characterized by downlap surfaces. Systems tracts are also generally definable through the stratal pattern and relative position within the sequence (Figure 6). Therefore, at this stage tying the well log data with the seismic leads to the delineation of major sequences which also have manifestation in the well log signatures. Additionally supporting data such as core analysis and petrographic study across the sequence boundaries and other stratigraphic surfaces as well as biostratigraphic data can help fix these boundaries. Care needs to be taken that the seismic and biostratigraphic time lines do not cross cut each other.

Step 6: Facies Analysis

Facies analysis is a sedimentological method of characterizing rock with unique lithological, physical, chemical and biological attributes, through integration of core, cuttings, biostratigraphic and geochemical data (Figure 7). The goal is to evaluate

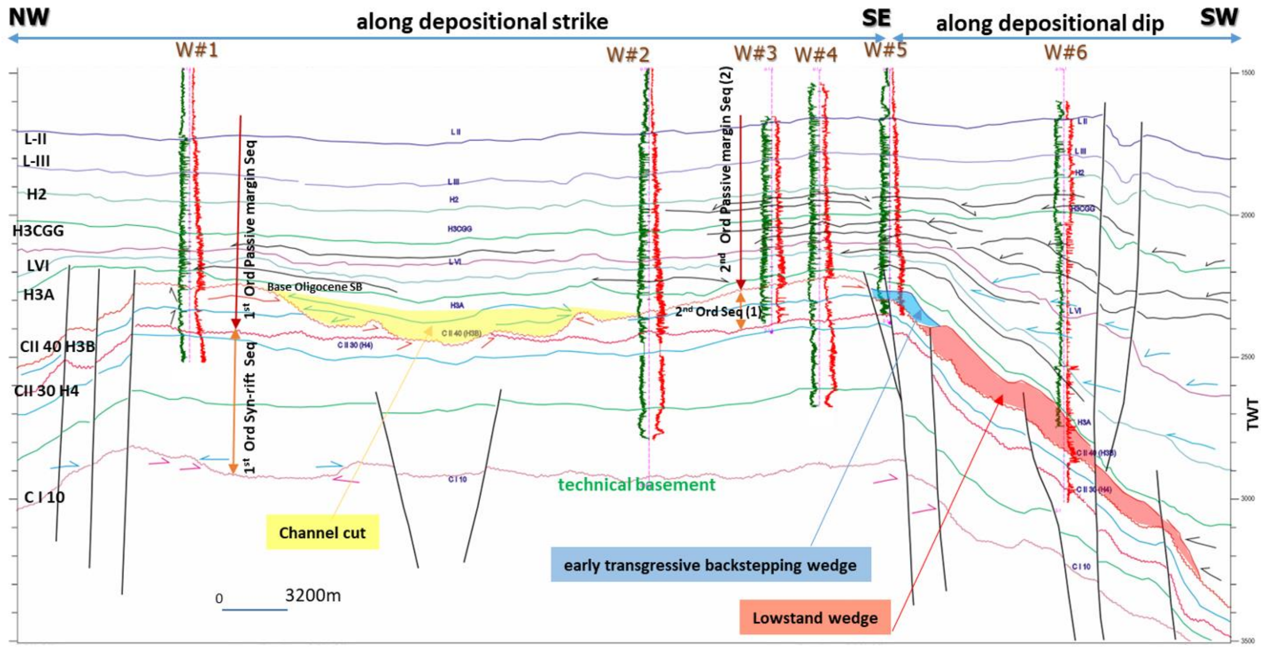

Figure 6: Higher order sequence stratigraphic framework (1st and 2nd order) and the sequence architecture is illustrated along the line covering depositional strike and dip. Stratal pattern is picked-up from the PSTM data, important local markers are also indicated. Location of the line is shown in the location map (yellow dashed line).

sedimentation processes and to interpret the depositional environments there from. It allows to classify a rock assemblage in a way that unravels the spatio-temporal shift in the palaeography as best as possible, and provides critical clues for paleo-environmental reconstructions.

For the subsurface dataset it provides the opportunity to establish the linkage between the log motif and microfacies and, between the microfacies and diagenetic facies. Understanding this relationship

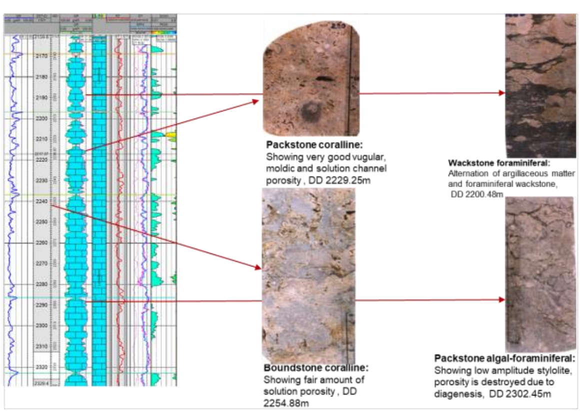

Figure 7: Integration of core, cuttings, well log and paleontological data to infer the depositional processes and diagenetic history.

allows the interpreted to predict the diagenetic history and role of diagenesis in porosity creation and destruction. Short exposure surfaces which are below the biostratigraphic resolution are also detected through detailed sedimentological study.

Step 7: Well log sequence analysis (demarcating high frequency stratigraphic cycles, 3rd, 4th and 5th Order cycles)

High frequency sequence stratigraphy is mainly done on well log data on the basis of depositional trend.

Identification of high frequency/lower order sequence boundaries and other sequence stratigraphic surfaces from the well log data considering the facies stacking pattern (aggradational, progradational, retrogradational) and depositional trend (deepening-up and shallowing-up) is performed at this stage. The difficulty encountered at this stage of sequence analysis is linked to the recognition of lower order sequence stratigraphic surfaces and their lateral correlatiblity. It is one of the big challenges in geological settings where the reservoir facies are laterally discontinuous, as there is a high risk of generating spurious correlations. For the high frequency sequence stratigraphic analysis, Genetic sequence approach is an import and useful tool and is adopted here (Figure 8), where the individual sequences are bounded at the top and bottom by the Maximum Flooding Surfaces (MFS) and their correlative surfaces are taken as sequence boundaries, this system of stratigraphic analysis is best where other sequence stratigraphic surfaces such as unconformities are not well developed or subtle and, are not readily recognizable in the seismic and well log data. These surfaces make the important reference level (markers) and allow us to generate detailed chronostratigraphic framework. This is especially well suited to the reservoir studies, since chronostratigraphic units and flow units are often closely linked. T-R Sequence approach (Embry, 1995) is also a very effective tool in such scenarios, where only two systems tracts are demarcated i.e. transgressive (bounded at the bottom by MRS and top by MFS) and regressive systems tracts (bounded at the bottom by the MFS and top by MRS). Lower order sequences (high frequency sequences) are nested within the higher order sequences (low frequency sequence), therefore as we progressively increase the scale of observation stratigraphic surfaces become subtler and typically goes below the seismic resolution.

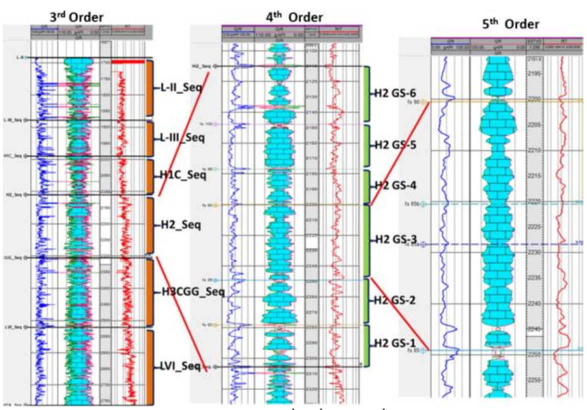

Figure 8: Genetic sequences of 3rd, 4th and 5th orders identified with progressive increase in the scale of observation.

Step 8: Petrophysical rock typing

Petrophysical rock typing is a good tool to discriminate reservoirs from non-reservoirs (Paul et al., 2017). This step is optional, however it provides a means to subdivide the complex carbonate rock bodies into discrete rock classes which are not only petrophysically significant but also geologically meaningful. A multivariate petrophysical rock typing using common logs such as GR, RHOB, NPHI and DT was developed by statistical data analysis. The linkage between the rock types and their petrophysical properties was established first through detailed facies analysis of cores, thin sections, SCAL and MICP study. The whole stratigraphic interval containing different pays is discretised into five rock classes viz. (i) High Gamma K and Th rich Shale (acts as regional cap rock), (ii) High Gamma uranium rich tight limestones (thin non-reservoirs acts as local cap rocks), (iii) Low Gamma tight limestones (thicker non-reservoirs, induces lateral reservoir heterogeneity and are the product of destructive diagenesis of cleaner limestones by sparitisation and dolomitization), (iv) Low Gamma reservoir limestones (cleaner and porous limestones, primary porosity is either preserved or selectively enhanced by diagenesis and leaching process, acts as good producers/speed zones) and (v) Marginal reservoir (acts as baffles, either the depositional facies is dirtier or the porosity of cleaner facies is occluded through diageneis, acts as baffles).

Step 9: Flow zone identification through integration of pressure-production and SCAL data

Flow zones are identified integrating the high frequency sequence (5th Order), petrophysical rock types and pressure-production data. High frequency genetic sequence boundaries (MFS) were found to act as hydraulic flow unit boundaries and enclosed individual flow zone having similar flow and geological characteristics. This is particularly useful for detailed reservoir modeling and as an input for static reservoir modeling.

Step 10: Preparation of the sequence stratigraphic framework chart (showing Sequences of different order, tectonic events etc.)

Sequence stratigraphic chart conveys the overall stratigraphic development of the area/basin with sequences of different order and hierarchy. For the sake of brevity chart is not presented here.

Discussion

For the high frequency sequence stratigraphic study it is required to establish the broader sequence stratigraphic framework first in regional/semi-regional scale (1st and 2nd Order), integrating seismic, well log, core, cuttings and biostratigraphic data. Regional seismic and well log profiles may be suitably chosen so that they represent different physiographic positions such as near shore zone, platform interior/back barrier (lagoon), reef/shoal crest, slope and basin floor. The physiographic position of individual well in the correlation profile helps to understand the depositional trends and facies stacking pattern in proper context. Within this broader framework high frequency sequence stratigraphic study (3rd, 4th and 5th Order sequences) is to be carried out only in the reservoir intervals using an appropriate approach such as genetic sequence approach or T-R Sequence approach as the data allows and the aim of the study. In the current study genetic sequence approach was adopted, where each high frequency sequences are bounded at the top and bottom by the MFS, which are chronostratigraphic units and correspond to individual hydraulic flow units. Combining the sedimentological technique of facies analysis and geometric criteria of seismic data is the key to successful sequence stratigraphic interpretation of carbonates. Wilson's facies model (Wilson, 1975) can be a general guide to facies prediction of carbonate once the physiographic position of different wells are established with respect to the basinal setup. Systems tract demarcation especially for the higher order sequences are geometrically defined, when the shoal water carbonates are located below the platform top in the slope it constitutes the Lowstand systems tract (LST), the period when the sea level has fallen below the platform edge and the platform is exposed. Transgressive (TST) and Highstand Systems tracts (HST) are deposited at the time when the platform is flooded, i.e. sea level is above the platform edge. TST carbonates are generally cleaner open marine deposits with deepening up trends whereas HST is represented by mud rich restricted conditions with progradational and shoaling-upward depositional trends.

HST is the most favorable stage for the enhanced rate of carbonate production, rate of carbonate production exceeds the rate of accommodation creation in the platform and the excess carbonate produced in the platform is shed to the adjacent slope and basin "highstand shedding" of (Droxler of Schlager, 1985), this is in contrast to the siliciclastic systems where the maximum sediment supply to the deep water is during falling stage and lowstand "lowstand shedding".

Conclusions

Carbonate sequence stratigraphy is at variance to the standard sequence stratigraphic model because of its inherent differences with the siliciclastics, however fundamentals of the concept are application to all the depositional environments irrespective of scale and lithology. It is a very effective tool; can be used as an exploration tool in frontier areas as well as in development fields for detailed reservoir characterization to address the criticalities such as to capture the lateral and vertical heterogeneity of thin reservoirs, which are below seismic resolution.

Detailed workflow for the high frequency sequence stratigraphic study of carbonates is presented, which is clinical and friendly and can be readily adopted in the industry practices using the subsurface dataset. *Step 8: Petrophysical rock typing* and *Step 9: Flow zone identification* are optional but can be of immense help in detailed reservoir characterization and as an input for static reservoir model.

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