The stratigraphic significance of paralic deposits in the Precipice–Evergreen succession, Surat Basin, Queensland

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SUMMARY

The Precipice Sandstone and Evergreen Formation in the Surat Basin, Queensland, are being examined as a reservoir-seal option for future geosequestration of CO_2. Effective reservoir modelling, and prediction of dynamic storage capacity, however, depends upon accurate depositional interpretations relating to an understanding of the stratigraphic architecture. Throughout most of the basin, the Precipice Sandstone is generally considered to have good reservoir properties and lateral continuity. Refined depositional models and a widely-applied sequence stratigraphic framework will enhance prediction of the most prospective play segments for CO_2 injection.

We utilize integrated ichnological-sedimentological facies analysis from core to interpret the Precipice Sandstone as a braided fluvial to braid-delta succession, overlain by lower delta plain to subaqueous delta and estuarine embayment deposits of the Evergreen Formation. Facies successions and core-calibrated wireline logs show brackish-water influenced deposits at several stratigraphic intervals. Brackish-water influenced deposits overlie upper delta plain or braid-plain sediments. They occur laterally adjacent to subaerial lower delta plain strata, and generally cap parasequence-sets. Seismic surveys resolve lower-order cyclicity, showing parasequence-sets within the Precipice succession that retrograde or aggrade and onlap the basal-Surat unconformity. This stratal arrangement reflects the lowstand and early transgressive systems tracts of a 2^{rd} order depositional sequence or a distinct 3^{th} order sequence. Late transgressive and early highstand systems tracts are more abundant within the lower Evergreen Formation and are interpreted to consist of restricted or estuarine central basin deposits; but these may also represent a 3^{th} order sequence. Additional chronometric data is needed to differentiate between these interpretations.

Depositional and sequence stratigraphic interpretations suggest the Precipice Sandstone has a higher degree of heterogeneity than previously appreciated. Moreover, we show that the Evergreen Formation is not a simple basin-wide sealing unit due to the presence of sandstone geobodies that complexly cross-cut each other (i.e., the ‘Boxvale Sandstone Member’) that may act as vertical fluid conduits. The sequence stratigraphic characteristics of the reservoir-seal pair should be carefully considered when selecting locations for CO_2 sequestration.

Key words: Precipice Sandstone, Evergreen Formation, Surat Basin, sequence stratigraphy, facies analysis.

INTRODUCTION

The Precipice Sandstone and Evergreen Formation have been identified as a prospective reservoir-seal target for carbon capture and storage (CCS) in the Surat Basin, due to their large theoretical storage capacity and *presumed* good, regional sealing characteristics (Bradshaw *et al*., 2011). However, the geological context in which the units are understood remains immature, largely due to the fact that they are generally not hydrocarbon bearing, particularly in the regions of the basin centre where CCS potential is highest. Detailed depositional interpretations are lacking, as are basin-wide stratigraphic correlations, hindering the predictive accuracy of reservoir performance and sealing potential.

The Jurassic-Cretaceous Surat Basin contains up to 2500 m of clastic sedimentary rocks and coal in Queensland and New South Wales, enveloping an area of 327, 000 km^2. The Surat is broadly time equivalent to the Eromanga and Clarence-Moreton basins, separated by a series of structural highs over which deposits thin locally; the Nebine and Kumbarilla ridges to the west and east, respectively (Power and Devine, 1970; Exon, 1976; Green *et al*., 1997). The basin developed as a shallow platform depression following approximately 30 Ma of uplift, exposure, and non-deposition that eroded sediments and volcanics of the underlying Bowen and Gunnedah basins (Exon, 1976; Green *et al*., 1997). Strata were laid down atop rocks of Palaeozoic or Permo-Triassic age, forming the thickest accumulation within the north-south trending Mimosa Syncline (Exon, 1976; Fielding *et al*., 1990; Hoffmann *et al*., 2009). A number of other structural features that are parallel to the Mimosa Syncline occur within the basin, and have been interpreted as reactivated incipient basement faults (Fielding *et al*., 1990; Raza *et al*., 2009).

Due to a dearth of publically available studies employing detailed facies analysis, environments of deposition are relatively poorly constrained in the Surat Basin. Most workers regard the Precipice Sandstone as representing high-energy, braided river deposits due to thick cross-bedding, and the general lack of muddy intervals with marine palynoflora. In contrast, the Evergreen Formation is considered to represent deposits laid down in meandering rivers and freshwater lakes (Sell *et al*., 1972; Exon, 1976; Exon and

Burger, 1981; Martin, 1981). The upper parts of the Evergreen Formation, including the Westgrove Ironstone Member and the Boxvale Sandstone, however, show possible marine indicators in the form of chamositic oolites, unidentified “animal tracks”, asymmetrical ripples, and low angle cross-bedding (Mollan *et al*., 1972; Exon, 1976). Nonetheless, the Early Jurassic system in the Surat Basin is interpreted to be dominated by non-marine deposits that accumulated in an intracratonic (Fielding, 1996; Yago and Fielding, 1996) or pericratonic setting (Exon, 1976; Exon and Senior, 1976; Veevers *et al*., 1982; Gallagher *et al.*, 1994; Green *et al*., 1997).

The stratigraphy of the Surat Basin has garnered substantial interest over several decades (e.g., Power and Devine, 1970; Exon, 1976; Exon and Burger, 1981; McKeller, 1998; Hoffmann *et al*., 2009; Totterdell *et al*., 2009; Ziolkowski *et al*., 2014; Wainman *et al*., 2015). Yet despite the relatively flat lying nature of the strata, a framework that is agreed upon for every interval beyond the local area has not been established. Lithostratigraphic correlation has yielded several schemes that vary in unit naming and precise timing of deposition (Figure 1; McKeller, 1998; Hoffmann *et al*., 2009; Ziolkowski *et al*., 2014). It remains unclear how depositional units relate to chronometric age dates, probably due to a lack of dateable material in the Precipice Sandstone.

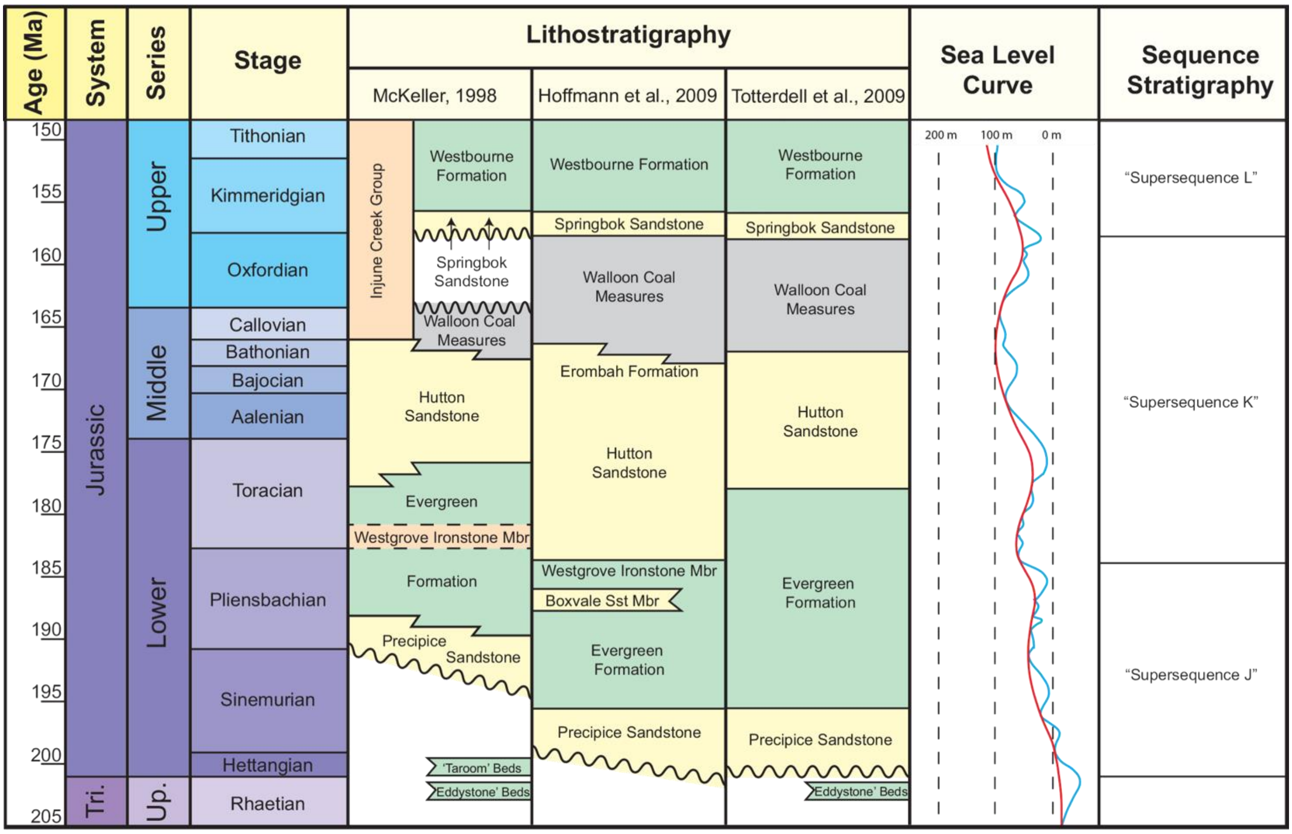

Figure 1 – Comparison of lithostratigraphic schemes usedto characterize the Surat Basin stratigraphy. The global eustaic sea level curve (Haq *et al.* 1987) and supersequences defined in Hoffmann *et al.* (2009) are shown for reference.

More recently, workers have focused on packaging rocks according to their age and genetic relationships using a sequence stratigraphic approach (e.g., Wells *et al*., 1994; Hoffmann *et al*., 2009; Totterdell *et al*., 2009; Ziolkowski *et al*., 2014). Three “supersequences” were interpreted from the Surat Basin in Queensland and New South Wales (Hoffmann et al., 2009; Totterdell *et al*., 2009). The “supersequences” broadly correlate with lithostratigraphic boundaries across the basin, and support a cyclic depositional interpretation of basin fill (Exon and Burger, 1981). On the other hand, a higher resolution sequence stratigraphic interpretation was put forth by Ziolkowski *et al.* (2014). All past sequence frameworks have used the fluvial / alluvial sequence stratigraphic concepts of Shanley and McCabe (1994) to make inference of the stratal architecture, but this may not be appropriate give alternative depositional interpretations of the strata.

The aim of this study was to integrate ichnological and sedimentological facies analysis from core to recognize the juxtaposition of facies and highlight important stratal surfaces that can be mapped with logs and seismic. In context, these will improve the current sequence stratigraphic understanding of the Precipice-Evergreen interval and be used for predicting reservoir characteristics and connectivity, in areas prospective for CCS, across the northern and central part of the Surat Basin.

DATASET AND METHODS

Eight cores that intersect the entire Precipice and Evergreen succession from the northern and eastern part of the basin were logged for their sedimentological and ichnological characteristics: Roma 8, Taroom 17, Reedy Creek MB3-H, Woleebee Creek GW4, West Wandoan 1, Condabri MB9-H, Chinchilla 4, and Kenya East GW7, from west to east, respectively. Approximately 200 additional wells that have wireline logs but no core were used to supplement the core data.

Nearly 4000 2D seismic lines, and nine 3D seismic volumes were integrated to calibrate the seismic responses to core and logs with appropriate time-depth relationships. Selected 3D seismic volumes that pass through the cored wells were the main focus but 2D seismic was used in areas lacking 3D. Seismic data was tied to well logs by creating synthetic seismograms from the density and sonic logs.

The basic process included making facies interpretations from core and then tying core to the respective wireline log motif. Process-response sedimentological criteria were the basis for the major subdivision of facies and facies associations, and ichnological details were supplemental, providing important insights into the physico-chemical conditions occurring in the environments at the time of deposition. The log signature from core was used to interpret facies associations in wells without core. Potentially important sequence stratigraphic surfaces were recognized by the juxtaposition of facies; stratal arrangements that do not obey Walther's Law. The candidate surfaces were compared with seismic data to confirm their regional significance and interpretation. The combined seismic-geological interpretation was then implemented in a series of regional cross-sections that traced the surfaces and rock packages across the basin.

RESULTS AND INTERPRETATION

Facies analysis from core revealed 20 facies, organized into 5 facies associations (Figure 2; Table 1). Facies associations were interpreted to represent deposition in 5 main environments including the alluvial plain / braid plain / upper delta plain, lower delta plain, subaqeous delta, restricted embayment / estuary central basin, and shoreface / updrift delta front:

- The alluvial plain / braid plain / upper delta plain facies association is dominated by medium to very coarse grained high-angle tabular cross-bedded sandstones, with minor thin muddy horizons. Bioturbation is low intensity and rare, occurring only in the muddy beds and bedsets, and consists of shallow-tier domiciles or deposit feeding structures of insects.
- The lower delta plain association is manifest as complexly cross-cutting facies that vary from planar tabular cross-bedded fine-sandstones, to heterolithic sandstones and mudstones, to burrow mottled siltstones and coal. Bioturbation varies greatly, depending upon facies, but shows both structures of presumed terrestrial origin (mottled siltstones), and traces suggestive of brackish-water conditions (heterolithic sandstones and mudstones).
- The subaqueous delta facies association is heterolithic and commonly displays physical sedimentary structures indicating salinity fluctuation (e.g., synaereses cracks), deposition of fluid mud (e.g., graded mud beds, muddy current ripples, grain size transitional current ripples), and mixed-energy conditions (e.g., combined flow ripples). Bioturbation is low intensity, and sporadically distributed, primarily occurring within muddy facies and consisting of marine ichnogenera.
- The restricted embayment / estuarine central basin facies association comprise mixed sandstone and mudstone or mudstone-dominated strata that show evidence of mixed-energy conditions (i.e., waves and unidirectional currents). The ichnology of the muddy beds and bedsets is higher intensity than other facies associations, and shows low, yet greater, ichnological diversity than the other associations.
- The shoreface facies association varies from mud-dominated to sand dominated, from base to top. The succession shows a laminated to scrambled appearance, with bioturbated intervals interbedded with laminated bedsets interpreted to represent storm deposition. Common sedimentary structures include HCS, wave ripples, and rare combined flow ripples. Bioturbation is rare to absent in the storm units, but is much higher intensity in the intervening beds. A mixture of ichnogenera from the *Skolithos* and *Cruziana* Ichnofacies are observed, but the suite is lower diversity than typically observed in the "open marine"; one hypothesis to explain this is that these deposits represent the updrift side of an asymmetrical delta front.

Seismic analysis indicates that there are five main reflectors within the Precipice-Evergreen succession. These broadly correspond to surfaces showing the juxtaposition of environments interpreted from core, or to unique facies such as chamositic oolites in the lower Evergreen Formation. The basal reflector (Seismic Event 5; Figure 3, orange) tracks the base-Jurassic unconformity representing a change in acoustic properties between the Surat and underlying Bowen Basin succession. However, the reflector is not consistent across the basin and does not have a unique seismic character due to truncation of the underlying strata that varies from hard impedance layers to soft impedance layers. Seismic Event 4 corresponds to the first seismic even occurring above the unconformity and is marked by a negative amplitude (Figure 3, blue) that results from low velocity and low acoustic impedance. The reflector broadly corresponds to the top of the alluvial plain / braid plain / upper delta plain facies association. Seismic Event 4 is only present on the eastern side of the basin and onlaps Seismic Event 5 towards the western part of the basin. Seismic event 3 is characterised by a high amplitude positive excursion (Figure 3, green) resulting from an increase in acoustic impedance and associated with high gamma ray values of the Evergreen Formation; it is the seismic representation of a maximum flooding surface within lower delta plain strata. Seismic Event 2 (Figure 3, red) is characterized by a high amplitude positive reflector. It is closely related to ironstone cemented sandstone bands and is interpreted to represent a transgressive surface. The interval between Seismic Events 2 and 3 ranges from approximately 40 m to 90 m in thickness, and exhibits several seismic peaks and troughs that are not laterally continuous across any appreciable distance. Finally, Seismic Event 1 (Figure 3, yellow) is a reflector with negative amplitude resulting from a decrease in acoustic impedance. This reflector relates to an interpreted regional flooding surface and generally show a back-stepping pattern towards the northwest. The sedimentary packages contained between Seismic Events 1 and 2 show variable thickness and evidence of cross-cutting.

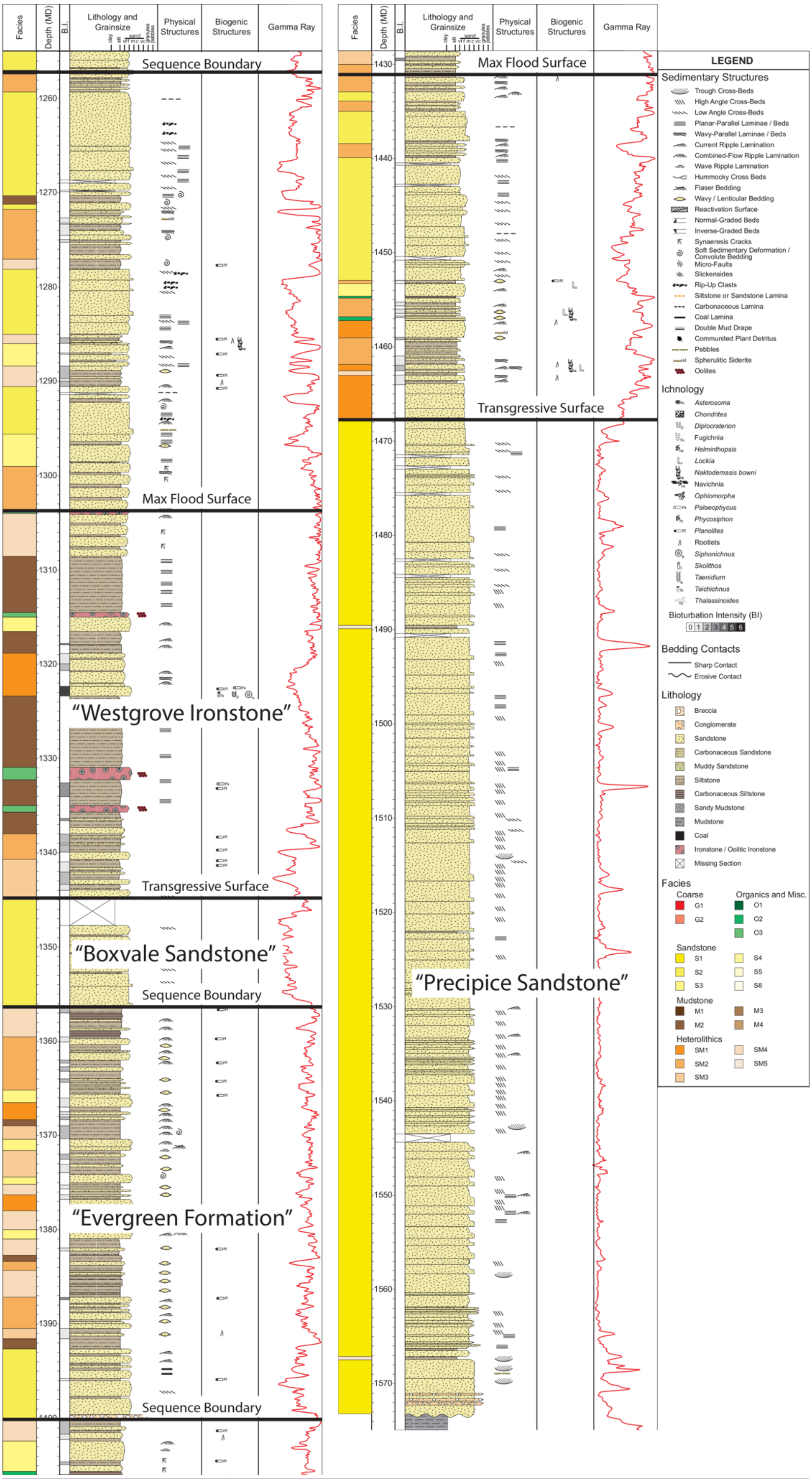

Figure 2 – Litholog for Woleebee Creek GW4 showing details of the ichnological and sedimentological characteristics of the strata, along with depositional and initial sequence stratigraphic interpretations from ~1570 m to 1260 m MD.

Facies Association	Thickness	Vertical Profile	Dominant Lithology	Sedimentary Environment
FA1	3–80 m	Amalgamated, subtly fining upward or blocky	Sandstone, minor siltstone and conglomerate	Alluvial Plain / Braid Plain / Upper Delta Plain Channel-Levee Complex
FA2	3–15 m	Fining upward	Sandstone with minor siltstone to sub-equal proportions of sandstone and siltstone	Lower Delta Plain Channel-Levee Complex
FA3	5–25 m	Coarsening upward	Sandstone dominated in proximal positions to mudstone dominated in distal positions	Subaqueous Delta (Mouthbars to Prodelta)
FA4	3–25 m	Fining upward, or none	Mudstone, minor sandstone	Restricted Embayment / Lagoon / Estuarine Central Basin
FA5	5–20 m	Coarsening upward	Sandstone to mixed sandstone and mudstone	Shoreface / Updrift Delta Front (Assymetrical Delta)

Table 1 – Facies association classification scheme developed for the Precipice Sandstone and Evergreen in the Surat Basin.

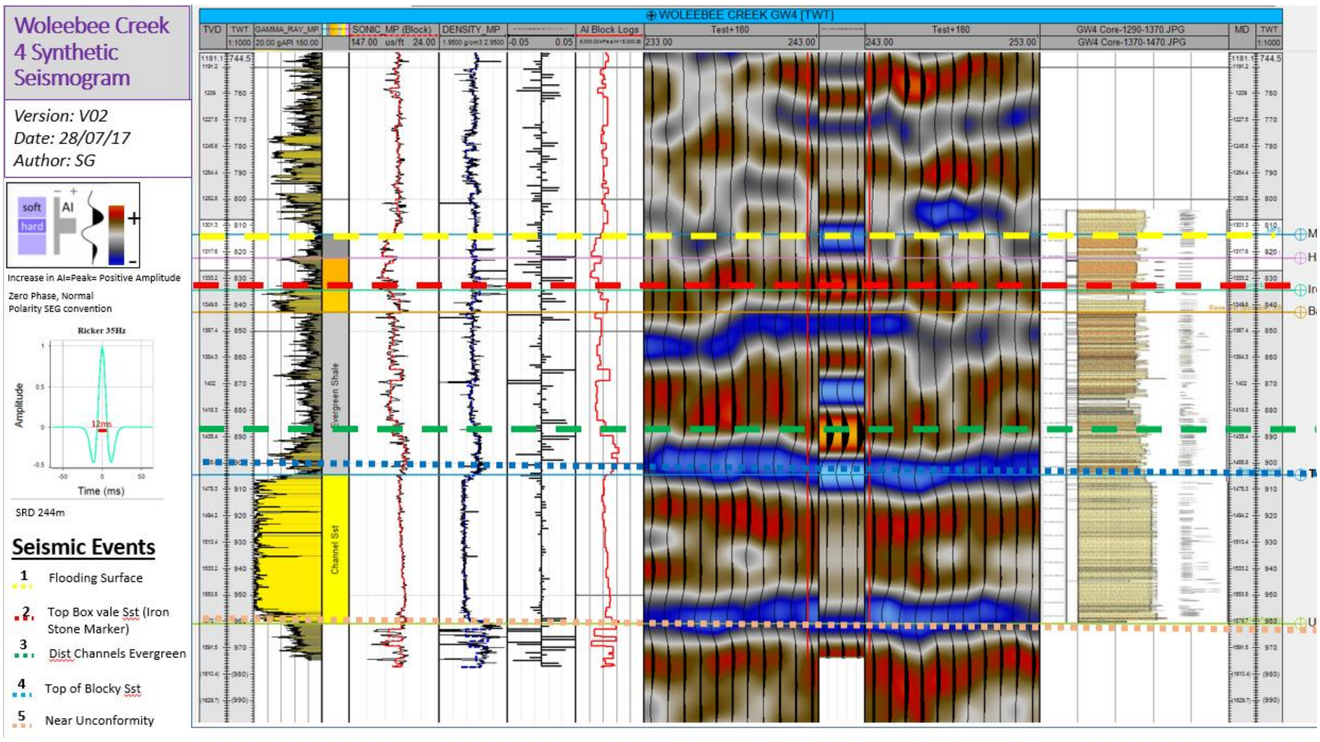

Figure 3 – Synthetic seismogram of Woleebee Creek GW4 and seismic line CO3-81-31 illustrating the main regional events observed in this study. The seismic data and synthetic seismogram is displayed in zero phase with SEGY convention polarity.

CONCLUSIONS

Our facies analysis results show that the Precipice-Evergreen succession represents a more complex set of palaeoenvironments than has previously been recognized. Integration of sedimentology and ichnology tells a story of a low-gradient fluvial through delta plain depositional environment, where brackish-water conditions increased in their distribution and magnitude throughout time. An alluvial plain or braid plain was the main environment during lower Precipice Sandstone deposition. Periods of progradation and aggradation on the lower delta plain and subaqueous delta characterize the upper Precipice Sandstone. Finally, as base level continued to rise during deposition of the lower Evergreen Formation, large parts of the northern Surat Basin were transgressed and restricted estuarine conditions prevailed.

The integration of facies analysis from core, wireline log correlations, and seismic reflection data indicate that the Precipice to lower Evergreen succession consists of three 3th-order depositional cycles, or alternatively the lowstand, transgressive, and highstand systems tracts of a 2rd order cycle. Five major seismic reflectors are observed, and they generally correspond to the juxtaposition of facies determined from core. Seismic reflectors show the backstepping of deltaic parasequneces in the upper Precipice and lower Evergreen, and highlight the basin-wide flooding associated with estuarine conditions in the Westgrove Ironstone Member.

A detailed sequence stratigraphic understanding the Precipice-Evergreen succession is important in that it allows greater predictability of reservoir characteristics and their continuity across the basin, especially for constraining geostatistical models in the absence of core or well data. Reservoir prediction is a primary concern for static reservoir modelling and for confidence in the fidelity of dynamic modelling results. Our work shows that some of the reservoir storage intervals in the Precipice Sandstone had marine influence on deposition, and geobody geometries that differ from the commonly applied sheet-sandstone model. Additionally, our work suggests that the Evergreen Formation does not have the same potential sealing capacity everywhere, due to the presence of deltaic sandstones that may act as vertical fluid transmission pathways.

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