Sequence Stratigraphy and Depositional Systems Analysis of Paleocene in Lishui Sag, East China Sea Shelf Basin*

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Abstract

The East China Sea Shelf Basin (ECSSB) located on the continental shelf is a typical back-arc rift basin, which is divided further by a series of sag and basement ridge. Lishui sag lies along the southwest margin of the ECSSB is underlain by a productive, gas-prone, marine Paleocene section. In combination with tectono-stratigraphic analysis, sequence stratigraphy and seismic geomorphology, an integrated approach was performed to map high-frequency sequence and systems tracts by using well and three-dimensional seismic data. The approach consists of (1) the indexes of the growth faults that were calculated to analyze differential activity on major faults. A relative eustatic level was reconstructed by employing accurate measurements of a series of sedimentary indicators that were obtained from seismic facies analysis. According to the combination of eustatic and tectonic forces, different sequence stratigraphic models including depositional sequences I (containing lowstand, transgressive and highstand systems tract), depositional sequences IV (containing falling stage, lowstand, transgressive and highstand systems tract) and a transgressive–regressive sequence (containing transgressive and regressive systems tract) were used to fit the field observations from a particular tectonic setting since the tectonic setting and eustatic level changed in different sequence. Five third-order sequences and thirteen system tracts were recognized in the Paleocene. (2) Due to the episodic rifting and differential activity on faults, various types of transfer zones were recognized in different sedimentary period. Transfer zones controlled the direction of sediment transportation and thus have great influence on the distribution depositional systems. (3) The depositional facies in the Lower E1m Formation and Upper E1l Formation have been imaged on a series of strata slices. Four types of depositional systems have been recognized: (a) incised valley fills; (b) shelf edge slop fan; (c) prograding tidal delta systems composed of elongate belts sand bodies perpendicular to the shoreline; and (d) onshelf barrier bar and offshelf tidal sand ridges. The distribution of sand bodies is controlled by the transfer zones indicating that the interpretation results have high reliability. Therefore,

this integrated analysis improves the accuracy of petroleum plays prediction.

Introduction

The East China Sea Shelf Basin (ECSSB) located on the continental shelf is a typical back-arc rift basin, which is divided further by a series of sag and basement ridge (Figure 1A). Lishui Sag lies along the southwest margin of the ECSSB is underlain by a productive, gas-prone, marine Paleocene section (Figure 1B). According to previous work (Chen et al., 2013), five third-order sequences were recognized in this formation by using the two-dimension seismic data, well data, and paleontological data. They are E1y, Lower E1l, Upper E1l, Lower E1m, and Upper E1m in stratigraphic order. The discovery of the Well A Gas Field on the western gentle slope is a great breakthrough in Lishui Sag exploration. Since the surrounding 1600 km^2 area of Well A Gas Field has the similar depositional setting and accumulation mechanism, there still exists a significant potential of petroleum exploration in the western gentle slope.

The objectives of this article are to (1) document the high-frequency (fourth-order) sequence-stratigraphic framework of the Paleocene succession on the Lishui Sag by using the three-dimension seismic data and well logs and (2) image the depositional systems of the major target strata (Upper E1l and Lower E1m) on a series of strata slices. The ultimate intent is to provide explorationists with additional tools and insight to help develop the voluminous untapped Paleocene resources in the Lishui Sag.

Stratigraphic Framework

Based on the third-order sequence-stratigraphic framework established by Chen et al. (2013), we further mapped the high frequency systems tracts by using the 3D seismic profiles and well log data in this research. The interpretation of the seismic data was carried out in two steps. First, seismic units were identified by description of stacking patterns of stratal units, types of stratal terminations, and the overall shape of the unit. Afterwards, each unit is interpreted in terms of sequence stratigraphy. Four seismic systems tracts (i.e. falling stage, lowstand, transgressive, and highstand systems tracts) are recognized in the Upper E1l and Lower E1m sequences respectively, which are bounded by stratigraphic surfaces: subaerial unconformity, basal surface of forced regression, regressive surface of marine erosion, correlative conformity, maximum regressive surface, and maximum flooding surface (Figure 2). The full account of these sequence stratigraphic terminologies follow the Exxon's sequence stratigraphy concepts (Van Wagoner et al., 1990; Catuneanu et al, 2006).

Upper E1l

Upper E1l strata have variable thicknesses: i.e. about 600-700 m in the offshore area and reduced in thickness to 200-300 m toward the nearshore area.

The paleoenviroment was dominated by marine environment with cold and arid conditions during the sedimentary period of Upper E1l sequence according to the paleosalinity and paleoclimate analysis (Liu, 2005).

The falling-stage systems tract is bounded at the top by a composite surface that includes the channel incision feature representing the subarerial unconformity above the fault scarp and the correlative conformity (Hunt and Tucker, 1992) that merges with the regressive surface of marine erosion basinward below the fault scarp. At the base, the falling-stage systems tract is bounded by the regressive surface of marine erosion characterized by a concave-up geometry and basal surface of forced regression (i.e. part of the T88 that located below the fault scarp). This surface is characterized by a series of subparallel seismic reflectors overlaid by prograding package with offlapping type and thus separates the forced regressive deposits with normal regressive deposits clearly.

The lowstand systems tract is bounded by the subaerial unconformity and the correlative conformity at the base, and by the maximum regressive surface at the top. A series of high amplitude and continuous reflectors expand landward by backstepping the pre-existing topography in an upstream direction and downlap the correlative conformity basinward. The geometry of bedding surfaces changes from concave-up (shape that is inherited from the regressive surface of marine erosion) to flat. The nonmarine portion of the lowstand systems tract displays channel fills.

The transgressive systems tract is bounded by maximum regressive surface at the base and by the maximum flooding surface at the top (Catuneanu et al., 2006). It is composed of backstepping wedge on the continental shelf onlapping the coast and a continuous high amplitude event in the basinward direction. The thickness variation is mainly attributes to the high sedimentation rates stimulated by the available accommodation (Catuneanu et al., 2006). The aggradation of terrigenous sediment results in a cut-off of sediment supply to the marine environment. As a result, transgressive shallow-marine deposits (i.e. the wedge deposits) accumulate primarily in areas adjacent to the shoreline, forming the transgressive wedge within the continental shelf. The convex-up shoreline trajectory implies the shoreface migrated landward.

The highstand systems tract in the Upper E1l sequence only distributes above the topographic break. It is bounded by maximum flooding surface at the base and by the subaerial unconformity at the top. The depositional trends are dominated by aggradational to progradational packages downlap on the maximum flooding surface.

Lower E1m

The lower E1m sequence ranges from 150 to approximately 500 m in thickness from northwest to southeast. It was deposited in the warm, humid lacustrine environment as is revealed from paleosalinity and paleoclimate analysis (Liu, 2005).

The stratigraphic succession of the Lower E1m starts with a FSST formed at the beginning of the base level fall, which displays an incised valley above the topographic break and a series of downlapping (offlapping) clinoforms prograding onto the basal surface of forced regression (coincide with the maximum flooding surface formed in the Upper E1l sequence) below the topographic break (both of them compose the T85 surface). The LST consists of channel fills above the topographic break and a concave-up lowstand wedge that onlaps the topographic break landward and downlaps the offlapping forced regressive deposits basinward. These deposits reflect low accommodation conditions, as expected from a stage of early base level rise, lowstand normal regression. The LST is overlain by two distinct wedges separated by an area of non-deposition around the shelf edge, which are interpreted as the TST deposits. One on the continental shelf mainly consists of backstepping foreshore deposits and the other in the deep water setting composed of relatively fine-grained sediment accumulated from suspension (i.e. healing-phase deposits). Both of these wedges onlapped the maximum regressive surface shift toward the basin margin, suggesting the general retrogradational trend. A relatively thick package of seaward dipping foresets forms a HST with internal reflections of low to medium-amplitudes, downlapping onto the maximum flooding surface. This succession accumulated as a result of shoreface deposits progradation under highstand conditions of low-rate base-level rise.

Sea-Floor Morphology of the 3D Seismic Survey

The overall shelf of the sea floor in the 3D seismic survey decreases from west to east as one moves from the inner shelf to the slope (Figure 3). In the northwest corner of the study area, down-to-the-northeast growth fault and down to the west fault occur locally on the inner shelf consisting a fault scarp that influences sediment distributions from the inner shelf into the shelf margin. The vertical throw of the topographic break (fault scarp) decreased from 250 m in the Upper E1l sequence to about 100 m in the Lower E1m sequence. The shelf-to-slope gradient ranges from 3.43^{o} to 4.7^{o} in the inner shelf area, 1.37^{o}–2.08^{o} near the shelf edge, and reaches up to commonly 5^{o} to 9.75^{o} in the slope area. The shelf wide is about 16 km and a hummocky topography is observed along the north part of shelf-edge. In addition, down-to-the-northeast counter regional faults occur locally in the southern part of shelf, influencing sediment distributions on the shelf.

Description and Interpretation of Depositional Systems

The depositional facies in the Lower E1m sequence and Upper E1l sequence have been imaged on a series of strata slices. Different types of depositional systems have been recognized: (a) incised valleys and slope fans that occupy the continental shelf; (b) prograding to aggrading tidal sand ridges that perpendicular or oblique to the shelf break; (c) the strike elongated shelf edge delta, and (d) coastal barrier bar and sand ridges that parallel the shoreface.

Upper E1l Falling Stage Systems Tract

The Upper E1l falling stage systems tract contains two channel systems and fanlike amplitude patterns on stratal slice (Figure 4A). Channel A is highly sinuous, architecturally complex, and deeply incised. The flow appears effectively confined by the levee walls on the upstream side. With the decrease of levee thickness towards the downstream direction, levee heights become ineffective at confining the high-density parts of turbidity flows, whereupon the flow splays out radially, producing a lobe pattern in front of the channel (Figure 4C, Figure 4D, and Figure 5C). The decreasing of levee heights in the downdip direction conforms previous research results (Posamentier and Kolla, 2003; Deptuck et al, 2003; Wood and Mize-Spansky, 2009). Rendering the high-coherence voxels transparent and overlaying the remaining opaque low-coherence feature (representing the channel boundaries and faults) on the root mean square (RMS) attribute enables us to obtain a composite image. The discrete high-amplitude reflectors within the channel indicate that the channel probably tend to be more mud rich (Figure 5D). Channel B is characterized by low sinuosity and low width/depth ratios (Figure 4C, Figure 4D, and Figure 5C). At the coherence attribute slice, the most proximal reaches of this channel are vaguely imaged and the lower reaches of the channel are clearly visible on the sea floor (Figure 5C). The composite image clearly shows that the channel fill is characterized by the presence of high-amplitude reflections (and therefore likely sands) (Figure 5D). This low-sinuosity, sandier channel system is coincides with the modern channel fan system put forward by Clark et al. (1992). In the baisnward direction, the offlaping character caused by the fall in relative sea level is observed on the seismic profile (Figure 4E) and a fanlike amplitude pattern is distributed below the topographic-break in the north of the continental shelf (Figure 4A). It exhibits a wedge-shaped seismic reflection packages that downlap toward the southwest in profile (Figure 4F). The morphology of the fan becomes sheetlike towards the southwest, indicating the migration (progradation) direction of the deposit (Figure 4A).

Upper E1l Lowstand Systems Tract

The continental shelf below the topographic break is dominated by high-amplitude reflectors on the RMS stratal slice, suggesting that the substrates are sand prone. Two series of diffuse, intermittent distributive, elongated linear amplitude patterns are observed in this area. Both of them are interpreted as tidal sand ridges (Figure 4B). The high amplitude patterns in the north being wider and highly dip oriented. These features range from 2-3 km wide, extend for 7-8 km on the shelf, and can be traced back to the estuary of Channel A, indicating they are fed by the incised valley. Seismic profile shows that onlap terminations of these sand ridges can be observed against the downlapping surface of the fanlike amplitude pattern (Figure 4F). Channel B fed another series of sand-rich deposits in the southern part of the shelf (Figure 4B). They are parallel to oblique to paleoembayment long axes, ranging from 20 to 30^{o} east of south. Each sand ridge is about 1 to 2 km wide and 6 to 8 km long. They were transported onto and across the shelf, en route to shorelines beyond. Triggered by the rise in base level at the shoreline, the lowstand tidal sand ridges gradually extended upstream by onlapping the correlatively conformity (Figure 4G). In addition, part of them extends northeast to southwest, which are apparently controlled by the syndepositional block faults.

Conventional core observations provide strong evidences for the presence of tidal sand ridges. Core data encountered in well A show that lithofacies association 1 (LA 1) is up to 11 m thick and predominantly consists of thick-bedded sandstone interbeded with thin (often up to 1 cm), unbioturbated and unlaminated layers and ripped-up clasts of fluid mud (Figure 6C). Sandstones exhibit massive bedding, cross bedding, and low-angle bedding in most cases. The characteristic grain-size bi-modality of these shelf ridge deposits as well as the existence of fluid mud are new key criterion for identifying tidal origin (Longhitano et al., 2012). The well logs of this succession are blocky and lack any obvious cyclic character (Figure 6A).

Upper E1l Transgressive Systems Tract

The Upper E1l trangressive systems tract is characterized by a large-scale subaqueous comb-like sand ridge field on the stratal slice (Figure 5A). Those linear sand ridges parallel to each other are orthogonal to oblique to the regional paleoshoreline and oriented parallel with paleoembayment long axes (i.e. west-northwest to east-southeast). The size of a single sand ridge is 0.8 to 1.5 km wide, 5 to 6 km long, and 10 to 20 m high. Seismic profiles show that the internal structure of sand ridges are characterized by the retrogradational architecture consisting of a series of discontinuous high-amplitude seismic events (Figure 5B). The striking similarities among the Miocene deposits of offshore northwest Java, the modern tidal deposition systems in the East China Sea, and the shelf ridges described here strongly suggest that the shelf ridges interpreted here are inferred to be associated with tidal energy and the transgression of a broad river valley (Liu et al., 1998; Posamentier, 2002). With each trangressive landward step of the embayment mouth, a new cluster of ridges formed and was transformed into tidal sand ridge in a tide-dominated setting.

Lower E1m Falling Stage Systems Tract

The strata of Lower E1m falling stage systems tract is interpreted to represent a period with at least 11 km of shelf-edge progradation. Two incised channel systems are visible above the topographic break (Figure 7A). Incised valley A appearing in the northwestern corner of the map is characterized by low sinuosity and low width/depth ratios and can be easily recognized on the dip curvature attribute slice (Figure 7C and Figure 7D). Incised valley B extends southeastward with the characteristics of low sinuosity and high width/depth ratios compared with Channel A. Both of them become linked to the canyon on the slope during relative sea-level fall.

The continental shelf below the topographic break is dominated by the offlap breaks prograding basinward, recording successive positions of the prograding shelf margin (Figure 7E). Two com-like patterns composed of multiple sand ridges are oriented oblique to the shelf break and extend for 8-9 km on the shelf. Each of them can be traced back to the estuary of the incised valley at the topographic break edge. A series of strike elongate, high amplitude reflection packages along the shelf edge are interpreted to represent mouth-bar of shelf margin deltas that can be 5–10 km wide in this direction. Amplitude map shows these mouth-bar deposits as multilobate, arcuate to lunate bodies (Porebski and Steel, 2003). Levee-channel-like erosional forms characterized by concave-up reflections have been observed at the top of the clinoform sets (Figure 7F). They link to the mouth-bar deposits landward and transport large quantities of sand to the shelf margin. These levee-channel systems are assumed to be the deltaic distributary channels that merge basinwards into thick shelf-margin deltas. At the shelf edge, a series of scours and gullies intersect the mouth bar deposits in the northeast corner of the study area (Figure 3B) and transfer sand to the slope toe, forming an onlapping wedge interpreted as thin-bedding of turbidites on the delta front.

Lower E1m Lowstand Systems Tract

The Lower E1m lowstand systems tract composed of channel fills and backsteeping clinoforms has also been interpreted as a shelf margin deltaic system. Two incised valleys above the topographic break are characterized by the presence of high-amplitude reflections representing isolated channel fills. The continental shelf below the topographic break is occupied by an aggradational reflector set that backsteps onto the correlative conformity on the middle shelf and downlap on the outer shelf (Figure 7G). This aggrading-to-backstepping pattern separates the deposits formed during the early rise in relative sea level from downstepping forced regressive deposits formed during the sea-level fall. The amplitude map indicates the presence of two lobes on the continental shelf. The arrangement of these amplitude patterns is distinct. Lobe 1 distributed in the middle shelf is dip-elongated and extends for 7.5 km on the shelf. Lobe 2 is deposited to the east and seaward of Lobe 1 and extends for more than 6 km along strike and 2 km in the dip direction. It deposits beyond the shelf margin, exhibiting a strike-elongated, locally pod-like pattern on the map. This feature is characterized by brightening seismic events stacked with each other in seismic profile (Figure 7H). The lack of shelf-edge canyons or channels means that deltaic lobes or sand sheets drape the upper slope, with minimal sediment volume reaching the deep-water lower slope and basin floor.

Core data obtained from Well A and B show that the lithofacies association 2 (LA 2) consists of upward coarsening sedimentary packages up to 34 m thick, composed of medium- to thick-bedded sandstones at the top and thin-bedded fine-grained sandstone and mudstone at the lower part (Figure 6D, Figure 6E, and Figure 6F). In numerous cases, thick-bedded sandstones at the tops of LA 2 are dominated by sets of massive bedding, cross bedding, low-angle bedding and ostracod fossils can be found occasionally. The interbedded mudstone and sandstone at the lower part of LA 2 are locally rich in fossiliferous detritus (e. g., ichthyolite and ostracod fossils) and siderite concretions. Flat lamination, convolute bedding, and deformation structure are common. The well log with a coarsening upward tendency has an upper part with a simple 'blocky' or box-shaped log pattern and a more serrated log-shape in the lower part (Figure 6B).

LA 2 is interpreted as the mouth bar deposits. Although the well-sorted thick sandstone beds dominated by massive bedding, cross bedding and low-angle bedding are probably associated with tidal processes, the lack of fluid mud and the upward coarsening succession strongly suggest a wave-dominated regime. The deformation at the lower part of LA 2 is interpreted as being the product of soft-sediment which is associated with the slope-gravity collapse.

Lower E1m Transgressive Systems Tract and Highstand Systems Tract

The Lower E1m transgressive systems tract stratal slice reveals a series of high-amplitude reflectors parallel to the shoreline. Those intermittent amplitude patterns are interpreted as barrier bar, which formed by the wave action and were transected by tidal creeks. Similar shoreface sand ridges that only distribute above the topographic-break are visible in the highstand systems tract stratal slice revealing the lack of source supply.

Conclusions

According to the sequence stratigraphy analysis, four seismic system tracts are recognized in the Upper E1l and Lower E1m sequences respectively. Different types of depositional systems including incised valleys, slope fans, tidal sand ridges, shelf edge delta, and barrier bars have been recognized.

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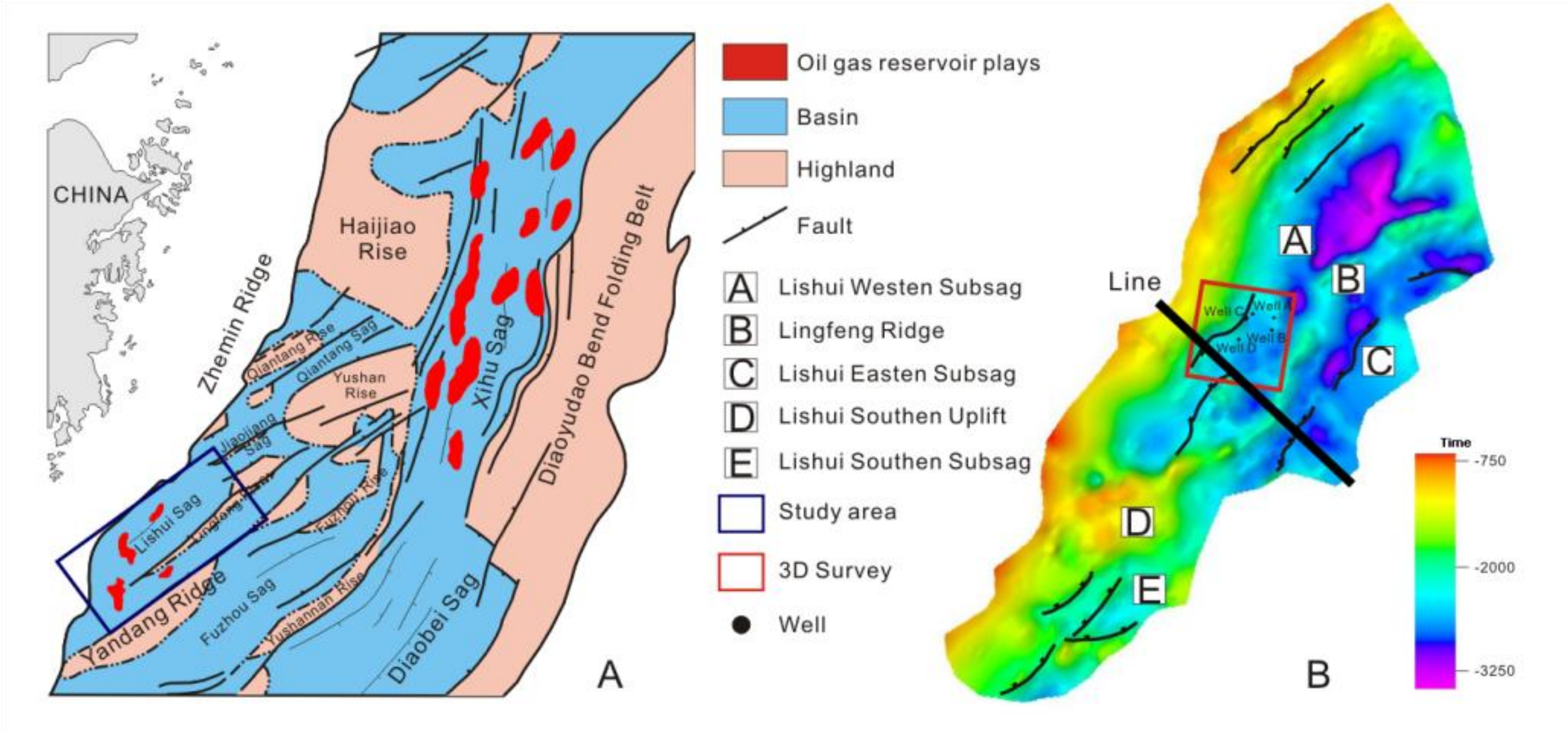

Figure 1. (A) The map highlights the location and the structural framework of ECSSB. (B) Map summarizes the main structural features of Lishui Sag.

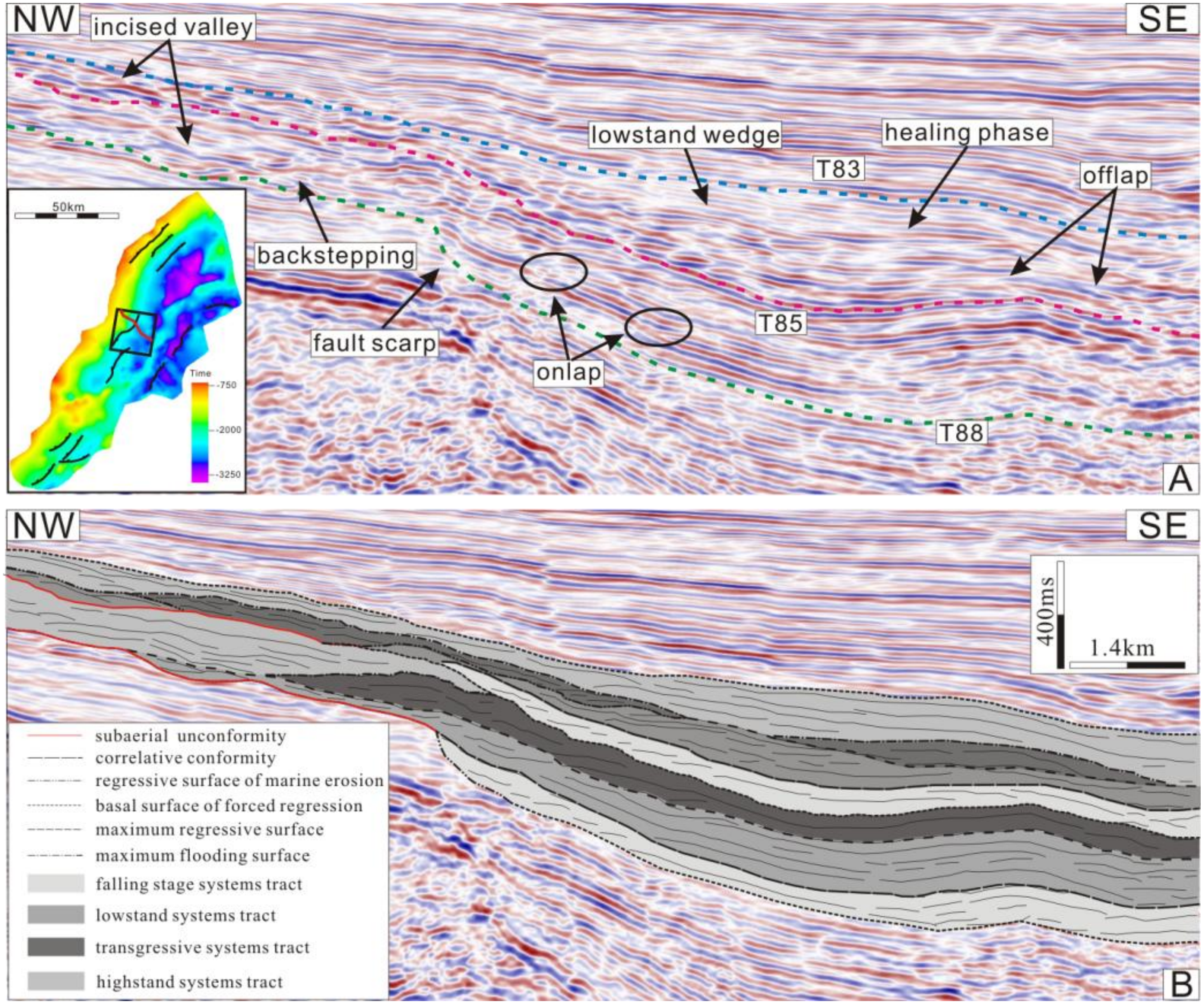

Figure 2. (A) Composite northwest-southeast–oriented 3-D seismic line along strike, showing the western shelf region in the Lishui Sag. Three main horizons were mapped across the study area to reconstruct the stratigraphic architecture of the basin. From base to top, these are T88, T85, and T83. (B) Line drawing from 3-D seismic line above, showing sequence-stratigraphic interpretation.

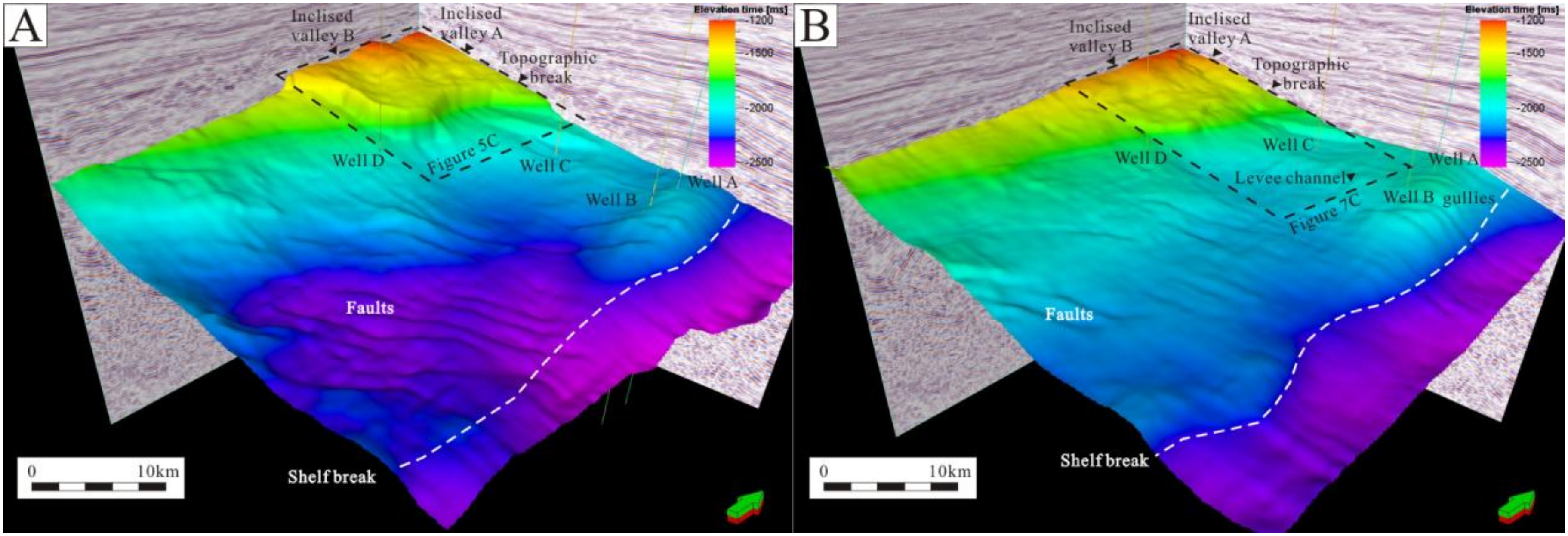

Figure 3. (A) The sea-floor morphology of the Lower E1m sequence; (B) The sea-floor morphology of the Upper E1l sequence.

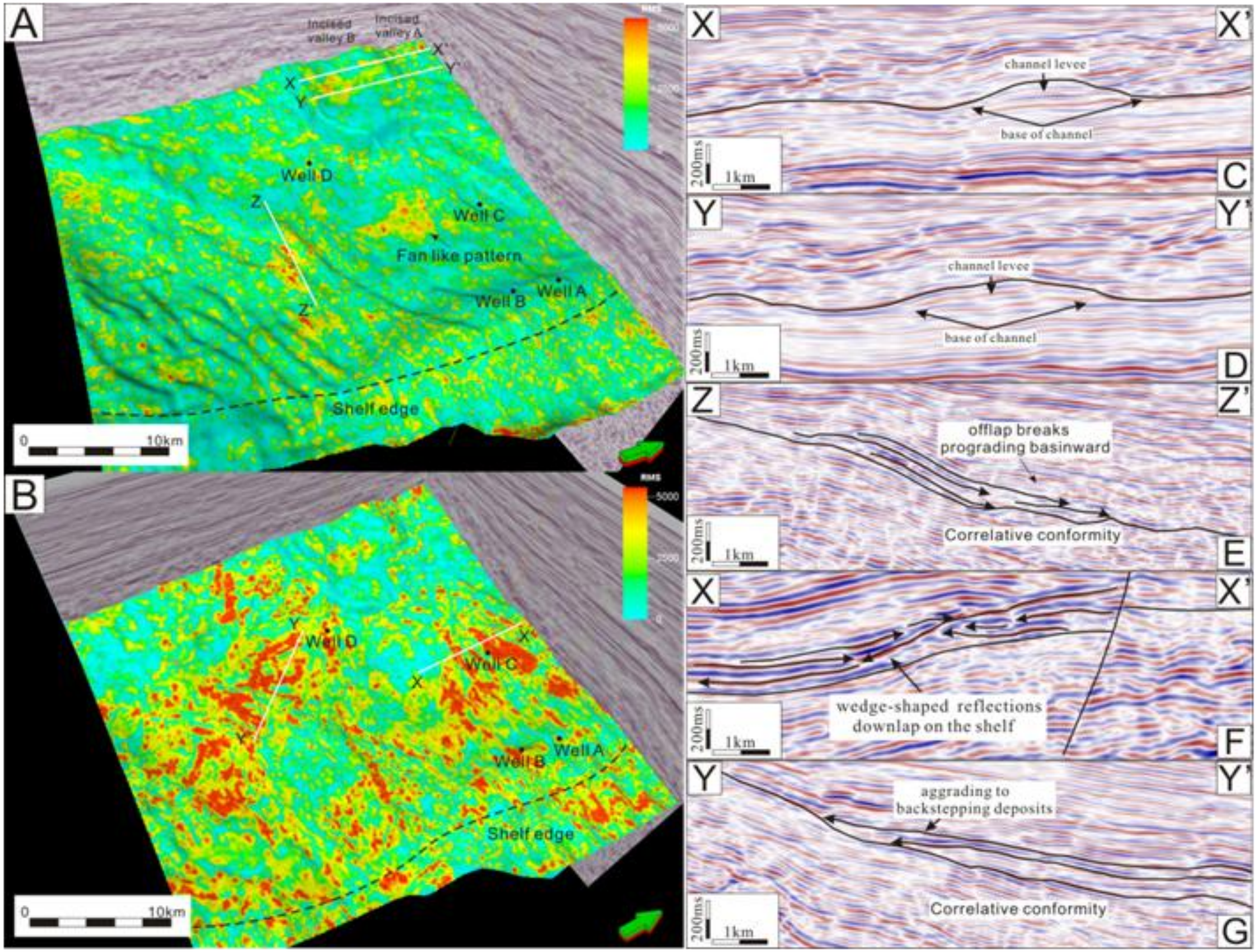

Figure 4. (A) Stratal slice of RMS at Upper E1l falling stage systems tract. Notice the clear fanlike amplitude feature below the topographic break. (B) Stratal slice of RMS at Upper E1l lowstand systems tract. The map shows two series of tidal sand ridges transported onto and across the shelf. (C) and (D) showing a cross-sectional view of the leveed-channel architecture. (E), (F), and (G) showing the stratal stacking pattern of falling stage systems tract and lowstand systems tract on the seismic profiles.

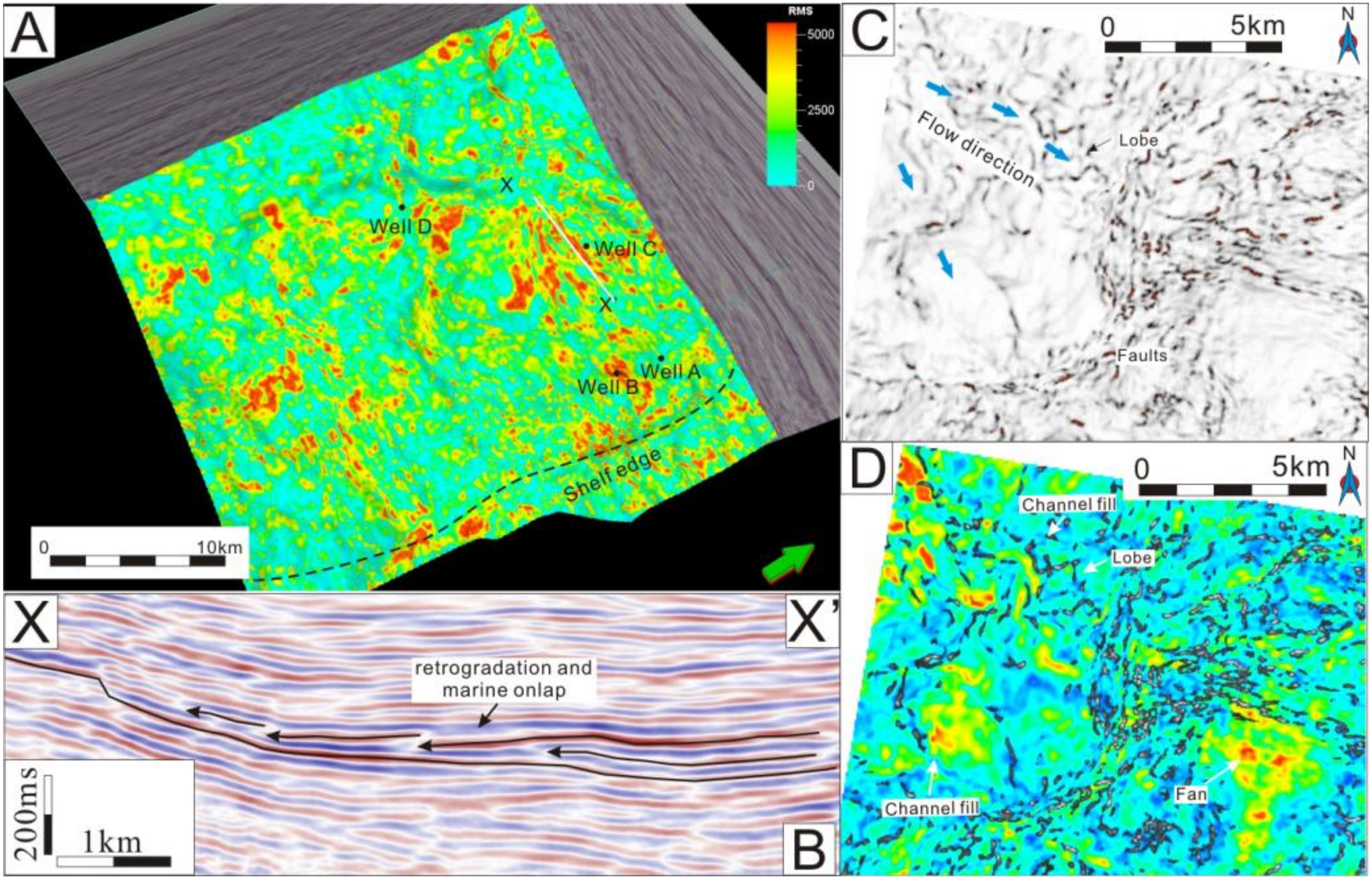

Figure 5. (A) Stratal slice of RMS at Upper E1l transgressive systems tract. Notice the linear sand ridges parallel to each other are orthogonal to oblique to the regional paleoshoreline. (B) Showing the tidal sand ridges developed during the entire stage of shoreline transgression, by gradually onlapping the continental shelf. (C) Blown-up view of the northwestern part of the coherence attribute map showing the character of the incised valleys. (D) Rendering the high-coherence voxels transparent and overlaying the remaining opaque low-coherence feature RMS attribute clearly shows the channel fill.

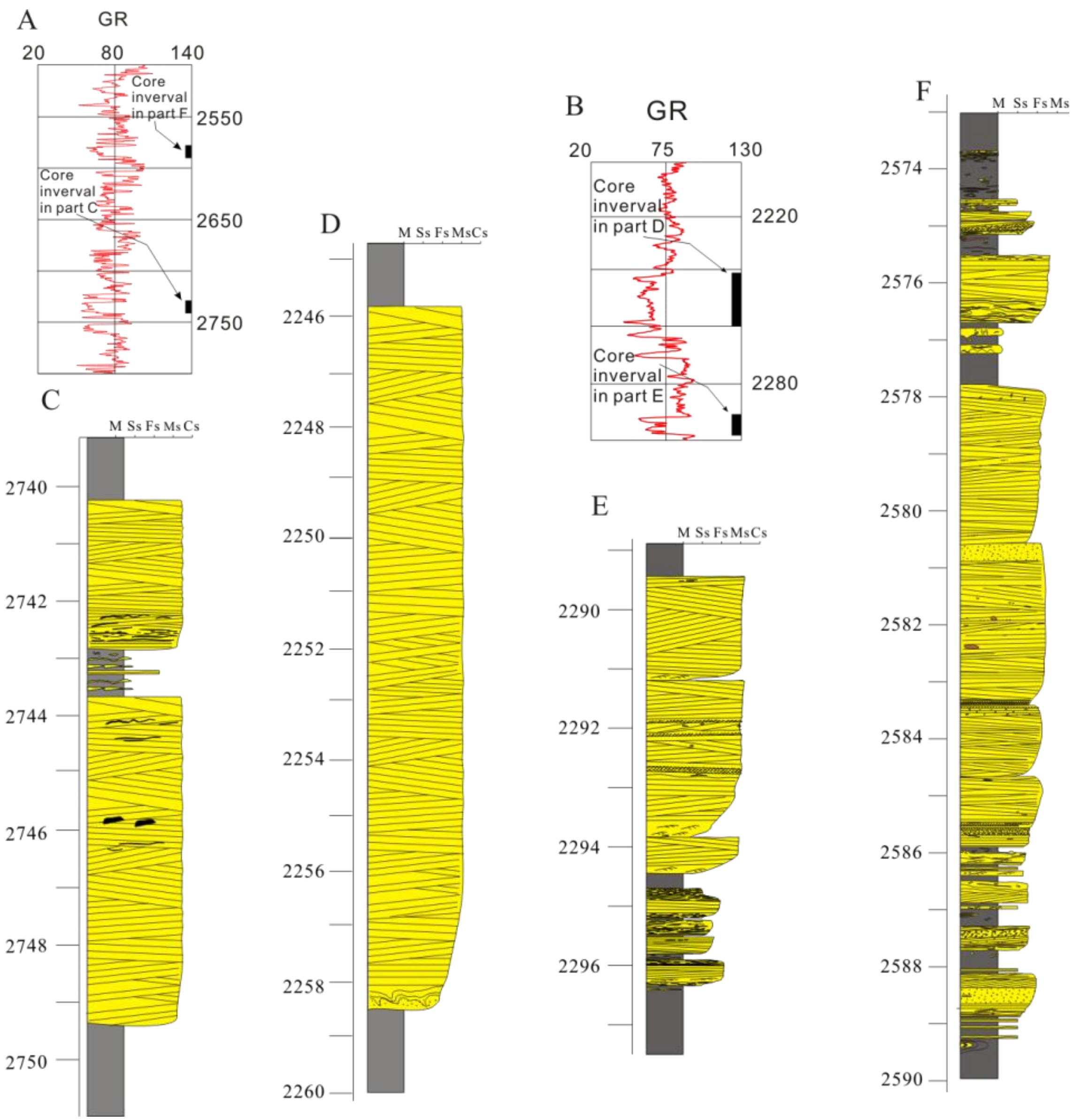

Figure 6. Lithofacies associations. (A) and (B) showing wireline-log response of lithofacies association 1 and 2. (C) Core log from borehole well A showing the thick-bedded sandstone interbedded with thin fluid mud layer. (D), (E), and (F) encountered in well A and B showing upward coarsening sedimentary packages composed of medium- to thick-bedded sandstones at the top and thin-bedded fine-grained sandstone and mudstone at the lower part.

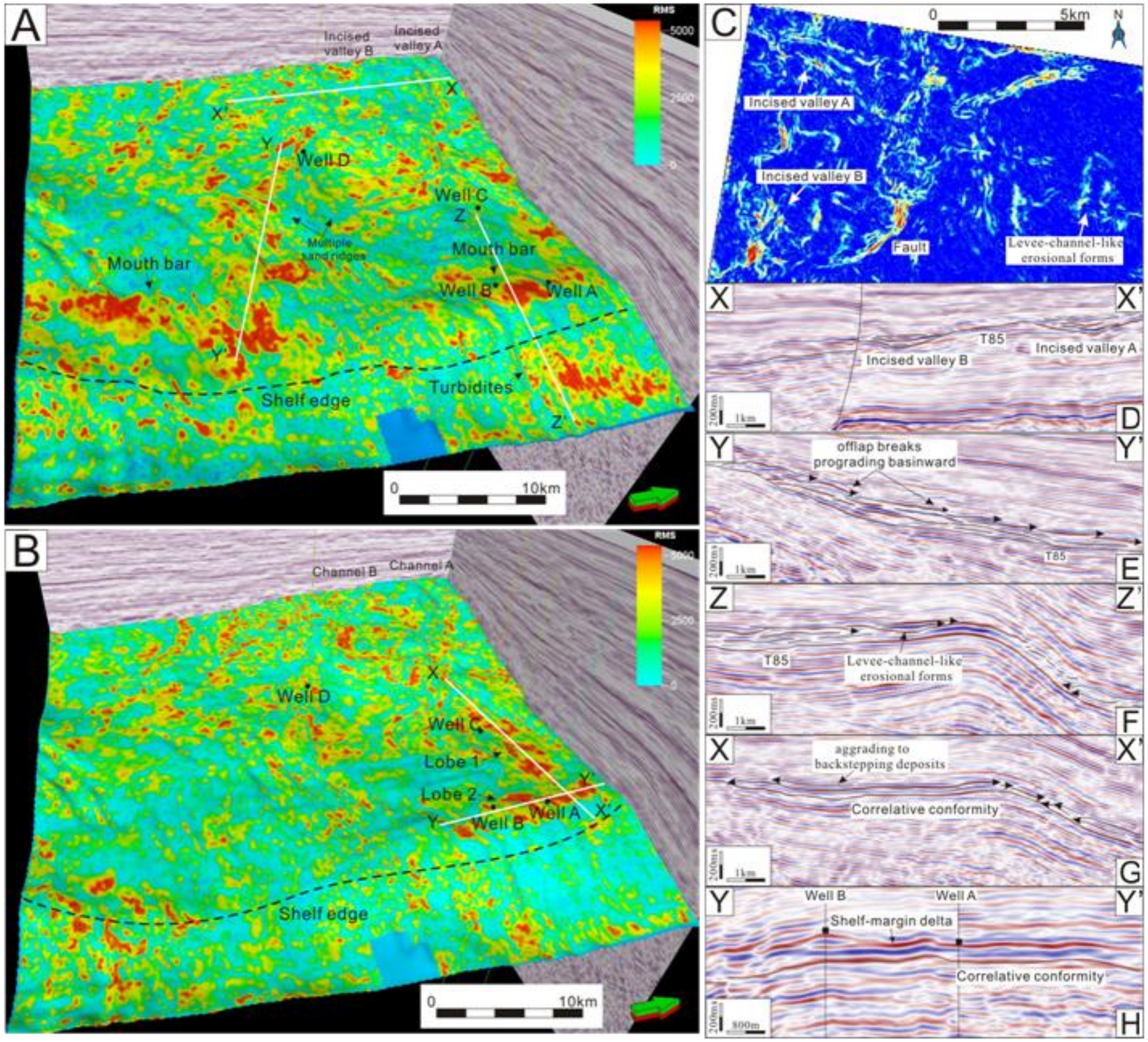

Figure 7. (A) Stratal slice of RMS at the Lower E1m falling stage systems tract. The map shows the strike elongate mouth-bar deposits near the shelf break and a series of gullies that were transporting sediments downslope. (B) Stratal slice of RMS at the Lower E1m lowstand systems tract. The map shows the shelf edge delta formed during the early rise in relative sea level. (C) Blown-up view of the northwestern part of the dip curvature attribute slice showing the character of the incised valleys and levee-channel-like erosional forms. (D) to (H) showing the stratal stacking pattern of falling stage systems tract and lowstand systems tract on the seismic profiles. Thicker lines on wells are drill-core sections.