Journal of
Sedimentary
Research

Journal of Sedimentary Research, 2023, v. 93, 469–487
Research Article
DOI: 10.2110/jsr.2021.118

STRATIGRAPHIC ARCHITECTURE AND DISTRIBUTION PATTERNS OF SUBMARINE FAN-RESERVOIR ELEMENTS: INSIGHTS DERIVED FROM THE PLIOCENE AND PLEISTOCENE BENGAL FAN

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ABSTRACT: **3-D seismic data from the Bengal Fan along with spectral decomposition and RGB color blending techniques display stratigraphic architectures and spatiotemporal distribution patterns of submarine fan-reservoir elements in stark detail. Seven reservoir elements are recognized in Pliocene and Pleistocene channel–lobe complexes (i.e., subfans) developed on the northeastern fringe of the Bengal Fan. Among them, crevasse, overbank, and avulsion splays are not well acknowledged by standard models of submarine fan-reservoir elements. Crevasse splays decrease in thicknesses towards ancestral channels, and are capped by overlying levees, whereas overbank and avulsion splays increase in thicknesses towards ancestral channels and cap underlying levees. Crevasse and avulsion splays exhibit lobate planform morphology and are linked updip to ancestral channels by feeder channels, whereas overbank splays display tongue-like planform morphology and lack feeder channels. Fills of laterally migrated channel-complex sets (CCSs) appear only in early stage of subfan evolution, whereas fills of vertically stacked CCSs can appear either in middle or late stages of subfan evolution. The inner segment of the documented subfans fostered infills of both laterally migrated and vertically stacked CCSs, whereas the outer segment of the studied subfans contains terminal lobe complexes and distributary-channel fills. Crevasse, overbank, and avulsion splays can appear either in middle or late stages of subfan evolution, and mainly occur in overbank environments of middle segments of the documented subfans, which are dominated by muddy facies as predicted by the standard model of submarine fan-reservoir elements. Pliocene and Pleistocene subfans demonstrate the importance of splay processes in submarine-fan evolution, and this has implications for understanding the evolution of the volumetrically largest sediment accumulations on Earth and the distribution of submarine fan-reservoir components. The downlap of subsequent levees onto crevasse splays and overbank splays created stratigraphic traps with the potential for large hydrocarbon accumulations.**

INTRODUCTION

Submarine-fan environments on continental margins are dominated by down-slope sediment gravity flows, along-slope bottom (contour) currents, and probably an interplay of both processes (e.g., Posamentier and Kolla 2003; Rebesco et al. 2014; Gong et al. 2018). The significance of down-slope sediment gravity flows and their resultant channels as major conduits for the delivery of terrestrial sands onto the basin floor was not fully acknowledged until about two to three decades ago, when huge volumes of submarine-fan reservoirs were seen to occur downdip of muddy slope systems, such as offshore Angola, the northern Gulf of Mexico, offshore mid-Norway, and the North American margin (e.g., Posamentier and Kolla 2003; Mayall et al. 2006; Mayall and Kneller 2021). Submarine fan-reservoir elements form prolific hydrocarbon fields worldwide, and have received considerable attention in the global hydrocarbon industry over the past two decades, largely due to significant discoveries and sustained production made in deep-water channels created by down-slope sediment gravity flows (e.g., offshore Brazil, northern Gulf of Mexico, offshore Angola, offshore mid-Norway, and most recently, the North American margin with Guyana–Suriname discoveries) (e.g., Posamentier and Kolla 2003; Mayall et al. 2006; Mayall and Kneller 2021), as well as in those constructed by an interplay of turbidity currents and bottom currents (mostly Brazilian margin and East African margin) (e.g., Fonnesu et al. 2020; Fuhrmann et al. 2020).

Turbidite channels and their associated reservoirs have been extremely well studied and documented for many years, using outcrop and well datasets as well as seismic-reflection datasets (e.g., Schwenk et al. 2005; Cross et al. 2009; Di Celma et al. 2010; Janocko et al. 2013; Koo et al. 2016; Bain and Hubbard 2016; McHargue et al. 2021). Architecture of turbidite-channel reservoirs are exceedingly complex (e.g., Deptuck et al. 2003). Many studies on turbidite channels have revealed that submarine fans are made of three main architectural elements (channel fills, levees, and lobes), all of which are genetically assembled at the simplest scale as channel–levee systems terminating as lobes (Janocko et al. 2013; Deptuck and Sylvester 2018; Zhang et al. 2020). A generic representative model of submarine fan reservoirs produced in the 1970s distinguished two discrete segments: a proximal reach dominated by a single feeder channel and a distal reach dominated by terminal or distal lobes incised by some distributary channels (e.g., Normark 1970; Posamentier and Kolla 2003).

Published Online: July 2023
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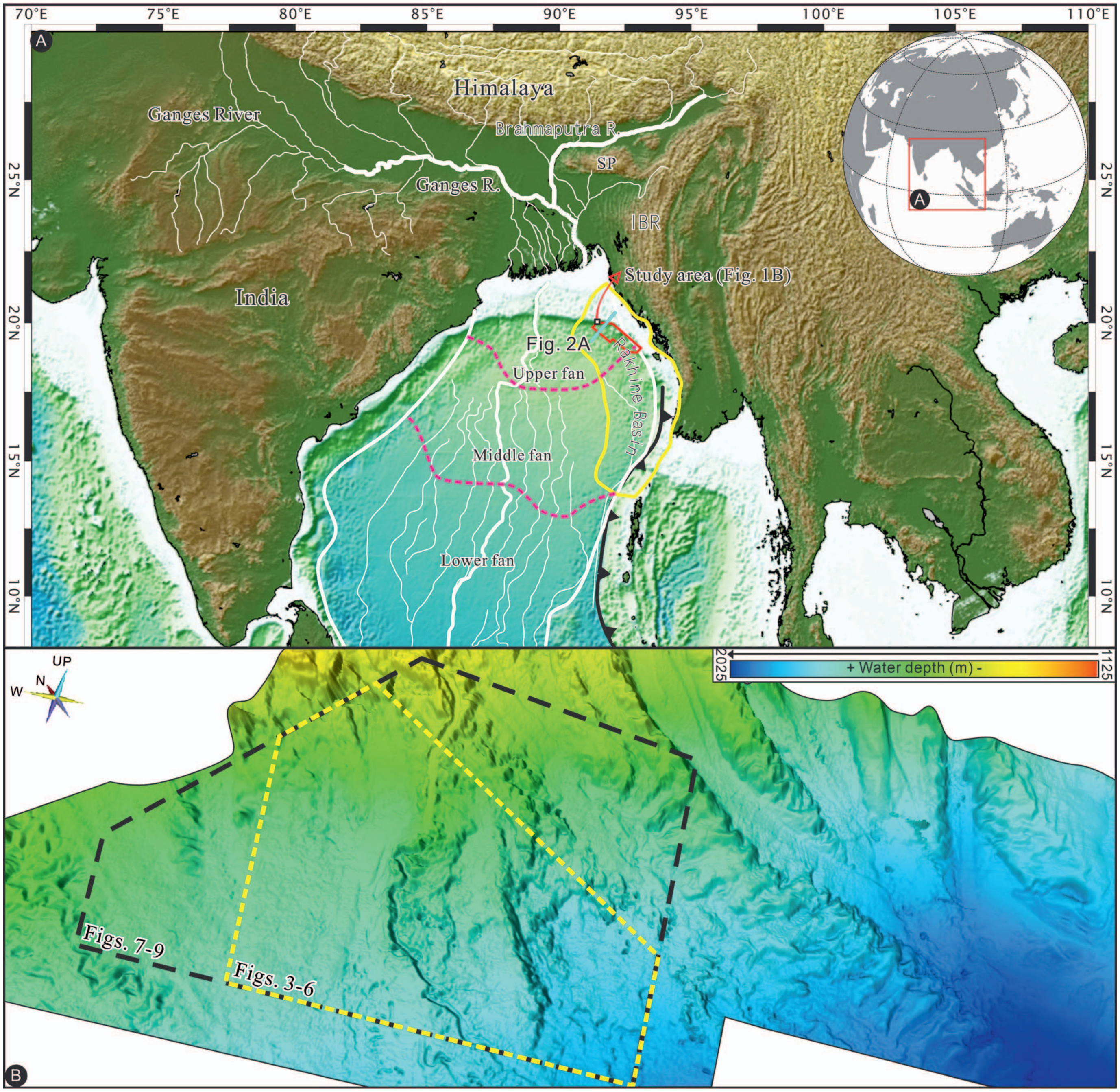

FIG. 1.—**A)** Regional map of the Ganges–Brahmaputra sediment-routing system and the geographic context of the study area in the Rakhine Basin (SP, Shilong Plateau; IBR, Indo-Burman Range). Regional map-view locations of the study area and seismic line shown in Figure 2A are also shown. **B)** 3-D perspective of the modern seafloor showing plan-view locations of RGB spectral decomposition-attribute and RMS amplitude maps shown in Figures 3–9.

Such a model of a diverging set of avulsed channel–levee complexes, each of which terminated at the distal end with a sand-rich lobe, is referred to herein as the *standard model of submarine fan-reservoir elements*. The standard model of submarine fan-reservoir elements suggests that terrestrial sediments are transported to terminal or distal lobes via a single feeder channel, that terrestrial sediments are dispersed across lobes via distributary channels, and that distal lobes grow as a consequence of avulsions or bifurcations at diverse positions along the distributary-channel pathways (Posamentier and Kolla 2003; McHargue et al. 2021). The coarser and sandier sediments in the standard model are found mainly on the floor of feeder channels and distal lobes, whereas the finer and muddier materials are seen mainly on levees asymmetrically developed along both sides of feeder channels (e.g., Normark 1970; Galloway and Hobday 1996).

The proliferation and improved imaging of industry, 3-D seismic data, particularly since the early 2000s, seafloor imagery, and seismic data from multiple IODP and joint industry and academia programs in the early 2000s (Amazon, Zaire, Bengal, and Indus fans) heralded a new era in research on turbidite-channel reservoirs (Posamentier and Kolla 2003; Mayall et al. 2006). In parallel with the widespread acquisition of 3-D

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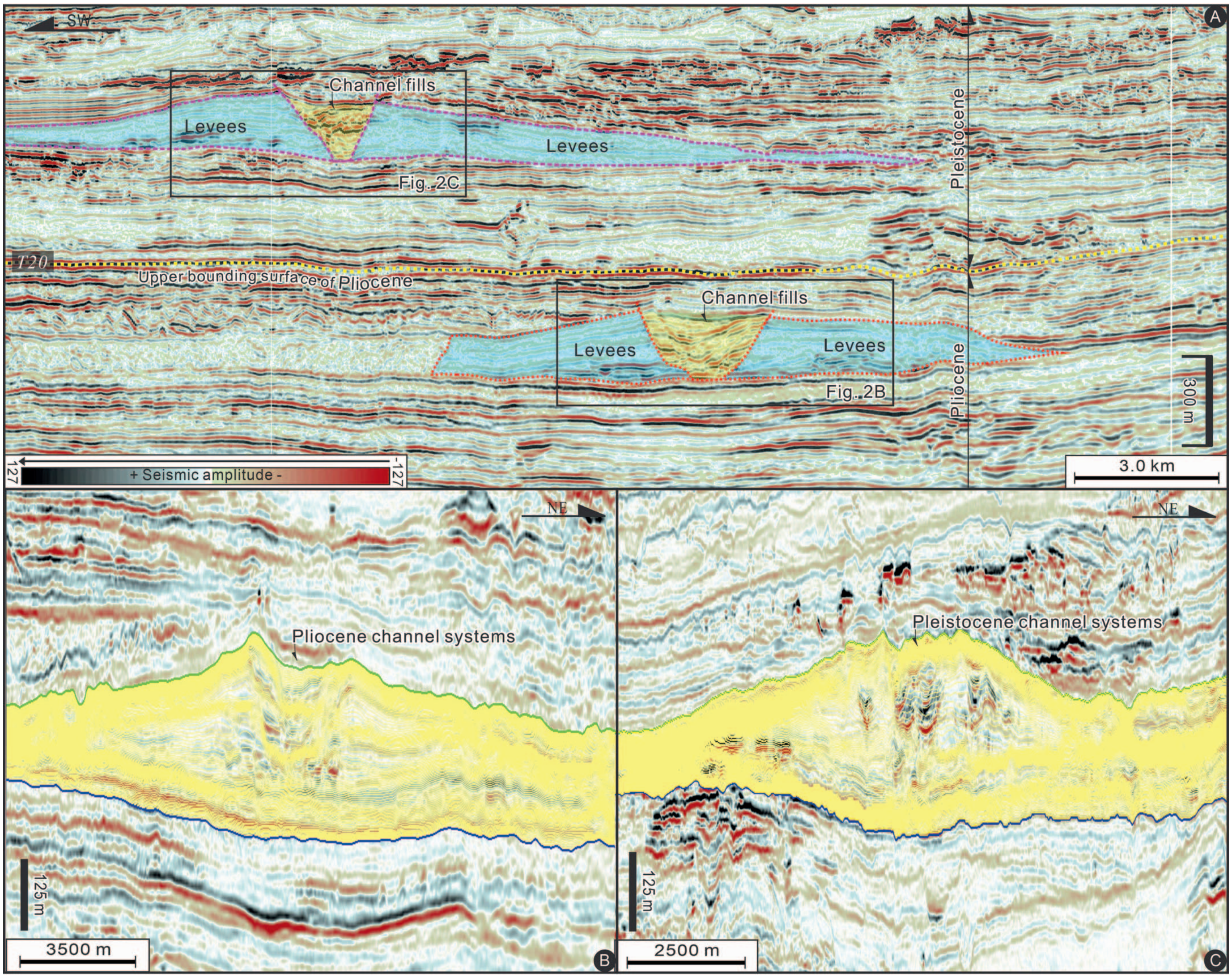

FIG. 2.—**A)** 2-D seismic transect from 3-D seismic volume illustrating a cross section through two documented channel systems (see Fig. 1 for the regional map-view location of the shown seismic profile). Strike-oriented seismic sections illustrating the horizon stack containing 100 surfaces (numbered 1–100 in chronological order) and a close-up view of Pliocene and Pleistocene subfans as documented in this study (Parts B and C, respectively). T20 refers approximately to the Pliocene–Pleistocene boundary.

seismic datasets, new techniques of seismic-data interpretations (i.e., red-green-blue (RGB) color blending of the spectral decomposition as employed in this study) have yield vivid and stunning 3-D images of submarine fan-reservoir elements (see also some examples by Oluboyo et al. 2014 and Howlett et al. 2021). The increasingly available high-quality 3-D seismic data, together with spectral decomposition and RGB color blending techniques, now illustrate well the presence of crevasse, overbank, and avulsion splays (e.g., Lowe et al. 2019; Howlett et al. 2021). The presence and distribution of crevasse splays are of particular interest, because they can form preferred pathways and reservoirs for subsurface hydrocarbons. The standard model of submarine fan-reservoir elements (Normark 1970), however, placed little to no emphasis on crevasse splays. In order to improve the characterization of deep-water fan reservoirs, it is now necessary to better understand stratigraphic architecture and a full spectrum of deep-water fan-reservoir elements (Deptuck and Sylvester 2018). Towards this end, we use conventional, industry, 3-D seismic data from the northeastern fringe of the world's largest submarine fan in the Bay of Bengal (Figs. 1, 2), along with the spectral decomposition and RGB color blending techniques, to visualize and delineate stratigraphic architectures of reservoir elements of two seismically well-imaged channel levee–lobe complexes (i.e., subfan in the sense of Curray et al. 2003, Jegou et al. 2008, and Picot et al. 2016) in unprecedented detail (Figs. 3–9) and to explore the distribution patterns of submarine fan-reservoir elements.

GEOLOGICAL SETTING OF THE STUDY AREA

The study area is located in the Rakhine Basin, a Tertiary foredeep basin located along the northern fringe of the Bengal–Nicobar Fan (Fig. 1A), which represents the terminal sink of the world's largest source-to-sink systems (i.e., Ganges–Brahmaputra–Bengal sediment-routing systems) (Blum et al. 2018; Pickering et al. 2020). The development of the Rakhine Basin is closely linked to the oblique convergence of the Indian and Burmese plates since the Paleocene, coupled with the westward migration of the Indo-Burma Ranges (Fig. 1A; Yang and Kim 2014; Ma et al. 2020). The Rakhine Basin is bounded to the east by the Indo-Burma Ranges,

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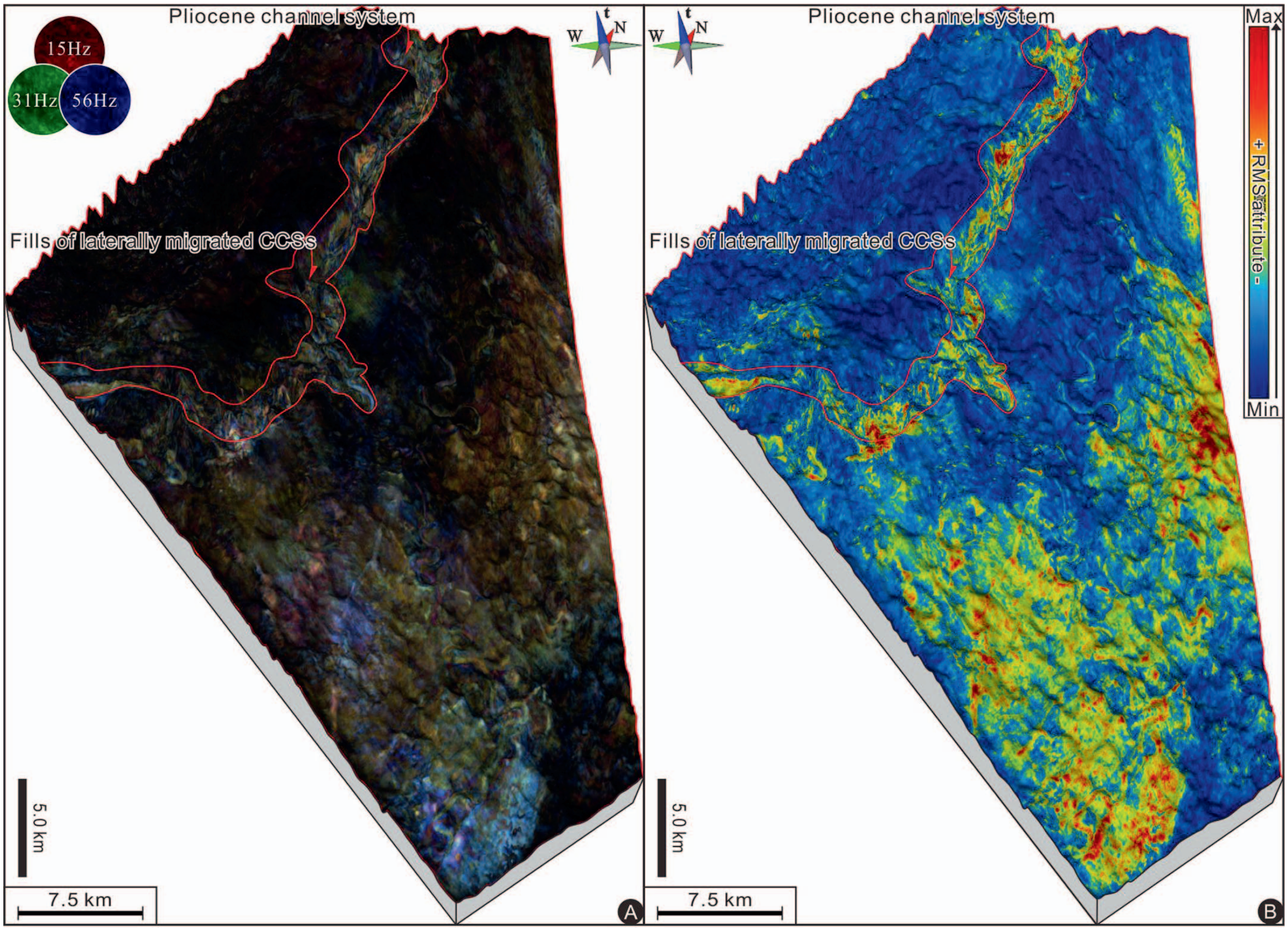

FIG. 3.—RGB spectral decomposition-attribute and RMS amplitude maps taken along the 33rd PaleoScan horizon showing plan-view geomorphological expression of fills of laterally migrated CCSs of the Pliocene Bengal channel system.

which contain flysch deposits and ophiolites. Seaward of the flysch and ophiolite belt in the Indo-Burma Ranges, three main structural belts occur, including the fold-and-thrust belt, a gently folded area, and the undeformed abyssal plain. The study area is located in the gentle fold belt, with water depth ranging from 1300 to 2100 m (Fig. 1B; Ma et al. 2020).

The subduction of the Indian plate beneath the Eurasian plate led to the closure of the Tethys Ocean, and the ensuing continental collision led to the uplift of the Himalayas and Tibetan Plateau since the Eocene (Fig. 1A; Molnar and Tapponnier 1975). The India–Asia collision, together with the uplift of the Himalayas and Tibetan Plateau, facilitated voluminous dispersal of clastic sediments from the Himalayas, shed into the Bay of Bengal through the Ganges–Brahmaputra sediment-routing system, giving rise to the world largest submarine-fan system (Yang and Kim 2014; Blum et al. 2018; Ma et al. 2020). The very thick Bengal Fan stratigraphy, related to the Himalayan tectonic uplift, has not been penetrated to its base. However, the Ocean Drilling Program (ODP) Leg 116, the Deep Sea Drilling Project (DSDP) 217/218, and IODP drilling 354 have revealed the age and origin of two basin-wide unconformities in this thick stratigraphic succession (Curray et al. 2003; Blum et al. 2018; Bergmann et al. 2020). The succession overlying the older unconformity has been dated at about 55 Ma (i.e., early Eocene), and is recognized to overlie the Paleocene–Eocene hiatus of Curray et al. (2003). It marks the initiation of the India–Asia collision, Himalayan uplift, and subsequent initial development of the Bengal Fan, and it separates pre-Bengal Fan sediments from the Bengal Fan sediments (Curray et al. 2003; Krishna et al. 2009). The younger unconformity dated at about 8 Ma (i.e., late Miocene) marks the onset of the diffuse plate-edge or intraplate deformation of the oceanic lithosphere (Krishna et al. 2009; Yang and Kim 2014; Ma et al. 2020).

These two unconformities dated to early Eocene and late Miocene divide the entire Bengal Fan succession into a lower rift supersequence and an upper post-rift supersequence (Curray et al. 2003; Yang and Kim 2014; Ma et al. 2020). The upper post-rift supersequence of late Miocene to Quaternary in age is dominated by channel–levee–lobe systems that constructed subfans (Curray et al. 2003; Schwenk and Spieß 2009; Bergmann et al. 2020; Reilly et al. 2020). It is suggested that only a single subfan was active during a given interval of time (Curray et al. 2003; Bastia et al. 2010 Bergmann et al. 2020; Reilly et al. 2020; Gong et al. 2022). Three giant gas fields (i.e., Shwe and Shwe Phyu in Block A-1, and Mya in Block A-3) were discovered in basin-floor fans in the late Miocene–Holocene succession of the Rakhine Basin (i.e., late Pliocene) in 2004 (Yang and Kim 2014).

The present-day geometry of the Bengal Fan is a complex of different channel levee–lobe complexes (i.e., subfans). On 100-kyr timescales, subfans display a considerable amount of lateral shifting, and alternately occupied the western and the eastern Bengal Fan (Curray et al. 2003;

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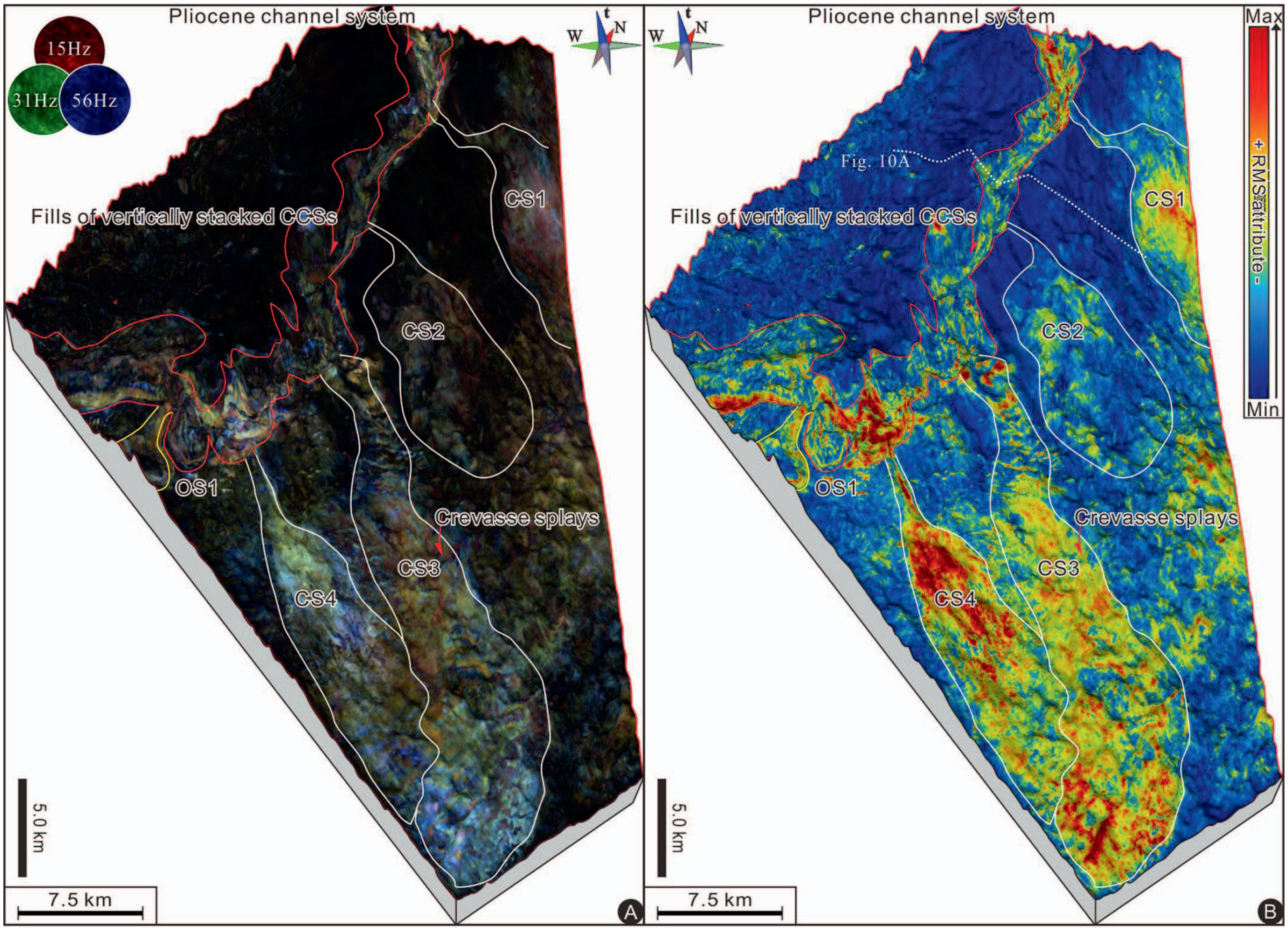

FIG. 4.—RGB spectral decomposition-attribute and RMS amplitude maps taken along the 48th PaleoScan horizon giving plan-view geomorphological manifestations of laterally migrated CCSs, crevasse splays 1 through 4 (CS1–CS4), and overbank splay (OS1) associated with the Pliocene Bengal subfan. Also shown is the map-view location of the seismic line shown in Figure 10A.

Bergmann et al. 2020). Two seismically well-imaged channel levee–lobe complexes occur in this Pliocene to Pleistocene succession, and are separated from each other by a basin-wide horizon of T20 (Fig. 2) referring to the basal bounding surfaces of the Quaternary (Fig. 2; see Ma et al. 2020 for a detailed seismic-well tie). These two well-imaged subfans (Pliocene channel levee–lobe complexes shown in Fig. 2B and Pleistocene channel levee–lobe complexes shown in Fig. 2C) are the focus of the present study.

TERMINOLOGY AND HIERARCHY OF SUBMARINE FANS

A variety of terminologies are utilized in the present study, and are detailed more in this section.

Terminology and Hierarchy of Deep-Water Channels

Gong et al. (2022) have suggested that different subfan-growth cycles in the Bay of Bengal shown to stack up over time to form the Bengal Fan, each of which is made up of a submarine channel and its genetically related lobe. A channel terminology system (*story* → *channel fill* → *channel complex* → *channel-complex set* → *submarine channel*, as graphically illustrated in Fig. 2 of Gong et al. 2021) is adopted herein to delineate different hierarchies of submarine channels. In this hierarchical framework, *story* is the smallest depositional element, and refers to a body of sediments bounded by local erosional scours filled by a fining-upward succession (Friend et al. 1979). *Channel fill* denotes the clustering of stories into a story set and records an individual downcutting and filling succession (Funk et al. 2012; Edwards et al. 2017). *Channel complex* refers to two or more genetically related channel fills of similar architectural styles, and records multiple downcutting and filling successions before abandonment (Sprague et al. 2005). *Channel-complex set* (CCS) signifies the clustering of two or more genetically related channel complexes and is bounded at its base by a major erosional surface and at its top by a surface of abandonment. A specific CCS records a single cycle of channel cutting, filling, avulsion, and abandonment (e.g., McHargue et al. 2011; Edwards et al. 2017), and likely corresponds to a depositional sequence in the sense of Van Wagoner et al. (1988). A *submarine channel system* denotes multiple CCSs that laterally migrated and vertically stacked through time, and are mainly flanked by overbank levees (Gong et al. 2021).

Terminology and Hierarchy of Terminal Lobes

Lobes refer to lobate or fan-shaped sediment accumulations at the terminal mouths of submarine channels. The hierarchical framework of

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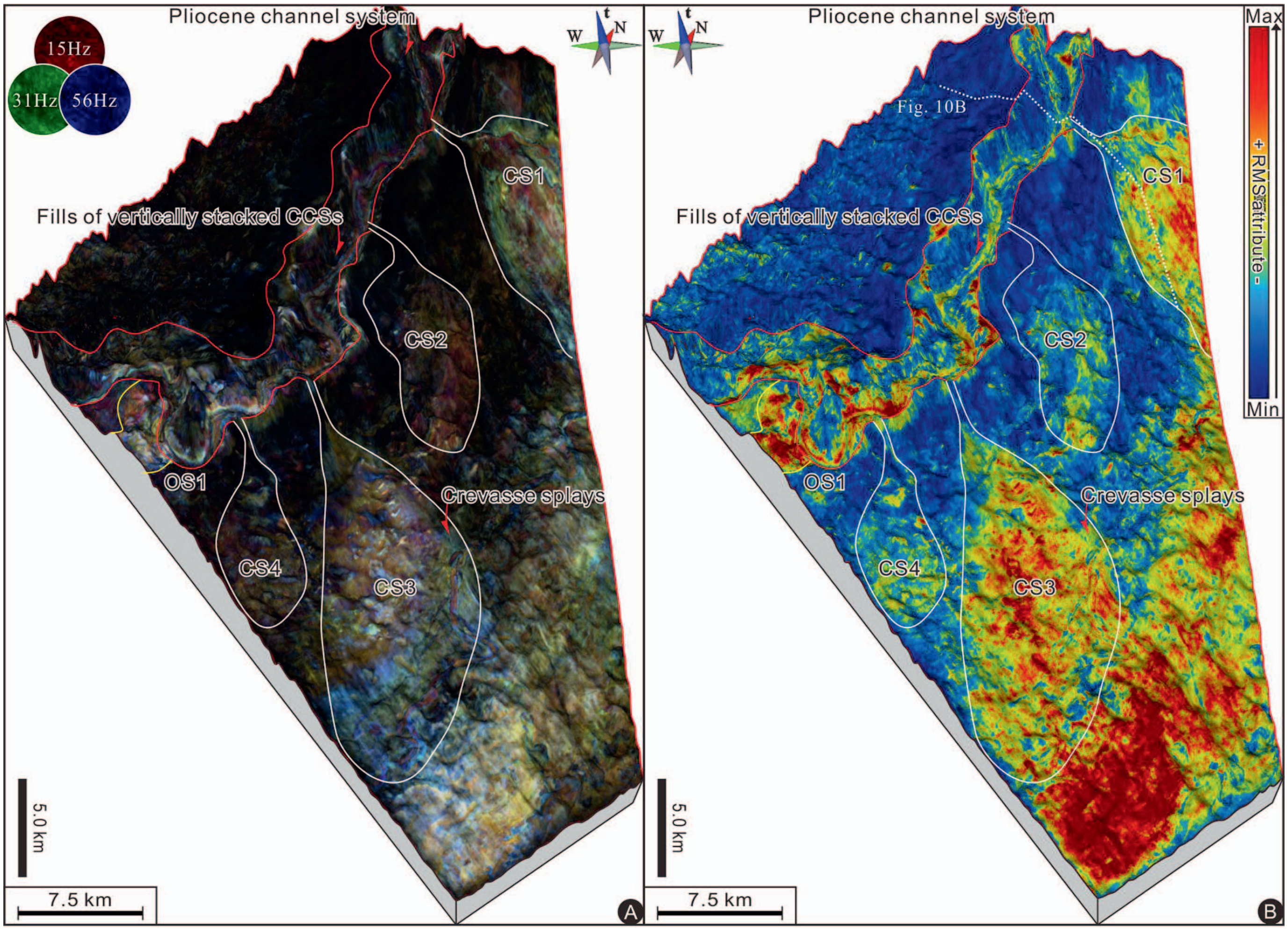

FIG. 5.—RGB spectral decomposition-attribute and RMS amplitude maps taken along the 67th PaleoScan horizon illustrating plan-view geomorphological characteristics of laterally migrated CCSs, crevasse splays 1 through 4 (CS1–CS4), and overbank splay (OS1) associated with the Pliocene Bengal channel system. Also shown is the map-view location of seismic line shown in Figure 10B.

Prélat et al. (2009, 2010) (*bed → lobe element → lobe → lobe complex*) is employed herein to delineate reservoir elements of lobes associated with Pliocene and Pleistocene Bengal subfans. In this hierarchical framework, *bed* is the smallest depositional element, and refers to a body of sediment dumped by a single depositional event. *Lobe element* denotes the clustering of individual beds into a bed set that is normally radial to elongated sandy bodies with a diameter of up to 5 km and a thickness of a few meters (Prélat et al. 2009, 2010). *Lobe* refers to the clustering of two or more genetically related lobe elements, and is commonly fed by the up-dip avulsion or migration of a single feeder channel (Prélat et al. 2009, 2010). *Lobe complex* signifies the clustering of two or more genetically related lobes, and is bounded at its base by a major erosional surface and at its top by a surface of abandonment.

Stories, channel fills, beds, and lobe elements are collectively recognizable only in outcrop, whereas channel complexes and lobes are resolvable on well logs. CCSs and lobe complexes are the smallest reservoir elements resolvable in conventional industry 3-D seismic data. The present study is based primarily on conventional 3-D seismic data, and therefore turbidite reservoir elements at the scale of CCS and lobe complexes can be inferred. A *channel levee–lobe complex* can be called a *subfan*, which is a common architectural component of large submarine fans, and has been demonstrated to be the main building component of the Amazon Fan (e.g., Lopez 2001, Jegou et al. 2008), the Congo Fan (e.g., Savoye et al. 2009; Picot et al. 2016), and the Bengal Fan (e.g., Bergmann et al. 2020; Gong et al. 2022).

In addition to the aforementioned two main reservoir elements of submarine fans, splays are employed herein to describe reservoir elements of submarine fans. *Splay* refers to a lobate or fan-shaped body of sediments accumulated in which sediment gravity flows transported from an area of confinement such as deep-water channels into an area of less confinement such as overbank environments (Lowe et al. 2019; Qi et al. 2021). According to the degree of levee erosion, splays are subdivided into three main categories, namely *crevasse splays* with extensive levee erosion, *overbank splays* characterized by little or no levee erosion and a*vulsion splays* with full levee erosion and channel diversion (Lowe et al. 2019).

DATABASE AND METHODOLOGY

3-D Seismic Datasets

The primary datasets of the present study are conventional industry 3-D seismic data acquired from the Rakhine Basin by the Chinnery Assets limited Company (polygon with red outline in Fig. 1A). They occupy an area of about 2000 km^2 and have been processed using the Kirchhoff

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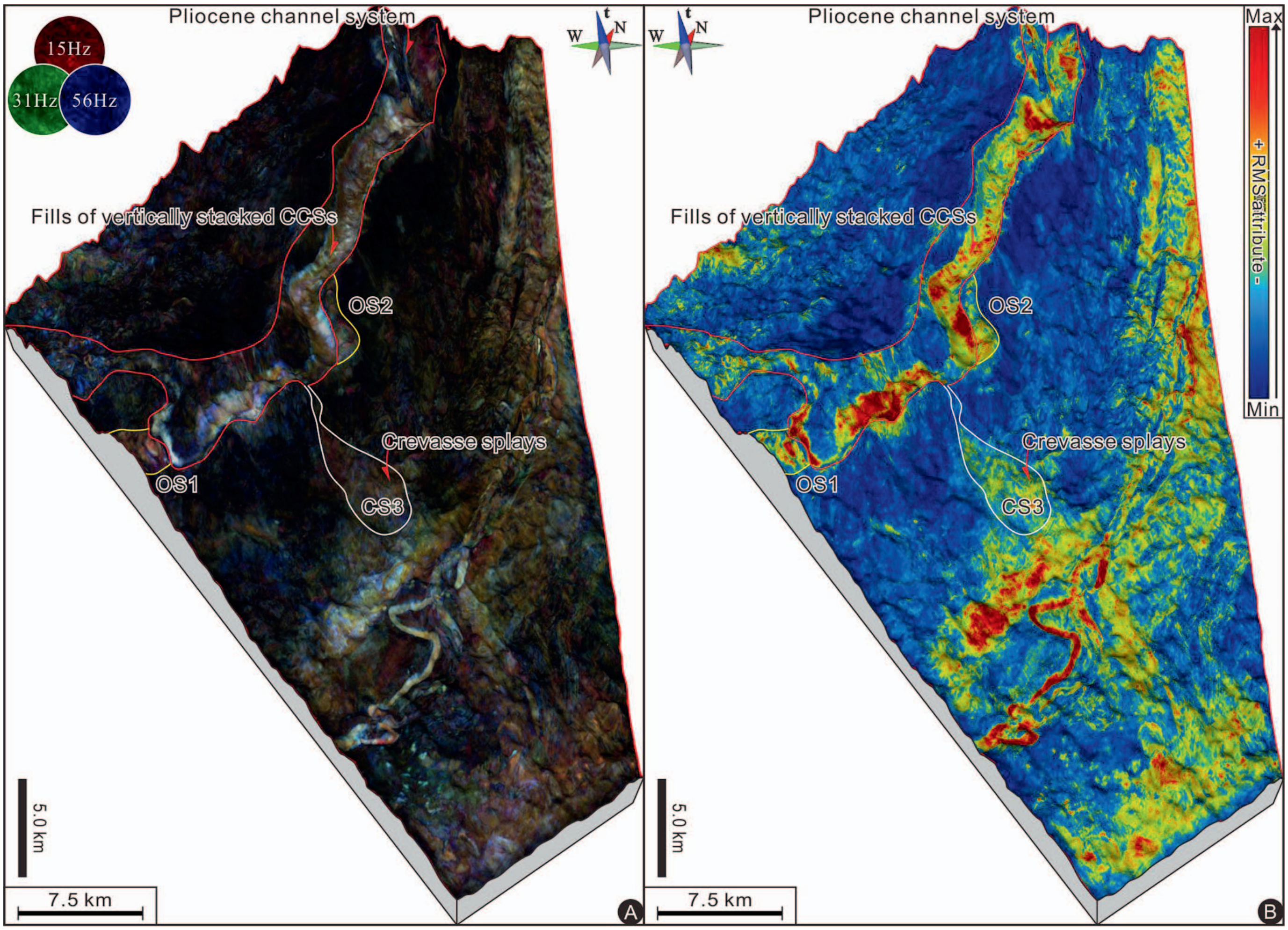

FIG. 6.—RGB spectral decomposition-attribute and RMS amplitude maps taken along the 89th PaleoScan horizon offering plan-view geomorphological characteristics of laterally migrated CCSs, crevasse splay 3 (CS3), and overbank splays 1 and 2 (OS1–OS2) associated with the Pliocene Bengal channel system.

pre-stack time migration (PSTM) algorithm. 3-D seismic data have a sampling rate of 2 milliseconds and a frequency bandwidth ranging from 10 to 55 Hz, with a dominant frequency of 30 Hz. 3-D seismic data have been processed to the zero phase and have a sampling interval of 4 ms and a bin size spacing of 25 m (in-line) by 12.5 m (cross-line). They are displayed using the SEG positive standard polarity, where a positive reflection coefficient is represented by a central peak (plotted black). Such seismic-well correlations suggest that high root-mean-square (RMS) amplitudes are sandy lithologies. The same seismic datasets from the study area of the current study were also utilized in previous studies by Ma et al. (2020) and Zhou et al. (2020), both of which suggest that amplitudes or high RMS attributes are indicative of fine-grained sandstones and siltstones. The reservoir top is, therefore, displayed as a peak of seismic sections utilized in this study (black in color) (see Ma et al. 2020, Zhou et al. 2020 for a detailed seismic-well tie).

Red-Green-Blue (RGB) Color Blending of Spectral Decomposition

The workflow for 3-D seismic interpretation of the studied subfans is: 1) defining and mapping upper and basal bounding surfaces of the documented channel levee–lobe complexes (i.e., green and blue surfaces in Fig. 2B, C), 2) creating horizon stack containing 100 surfaces (yellow surfaces in Fig. 2B, C), and 3) integrating 2-D seismic facies analysis (seismic stratigraphy) with a 3-D seismic geomorphology approach (i.e., RGB color blending of spectral decomposition and RMS attributes) to address stratigraphic architectures and distribution patterns of deep-water fan-reservoir elements.

3-D seismic attribute cubes (e.g., RGB color blending of spectral decomposition and RMS cubes) were created from the industry 3-D seismic volume (Figs. 3–9). Spectral decomposition is a technique whereby a seismic signal is broken down into band-limited components (i.e., a variety of frequency volumes) in order to delineate frequency-dependent phenomena imaged by seismic data (e.g., different bed thicknesses tuned at different frequencies) (Othman et al. 2016; Howlett et al. 2021). Specific to the Bengal subfan case, the 3-D seismic volume has been decomposed into three frequency volumes centered at 15 Hz, 31 Hz, and 56 Hz. These three frequency volumes were then mapped on 100 surfaces from the horizon stack shown in Figure 2B and C. They were then merged into a composite image, and were assigned to red, green, and blue on the RGB color blending viewer of PaleoScan™. RMS attributes calculate the square root of the sum of the time-domain energy, and therefore offer an enhanced visualization of the stratigraphic architecture of small-scale depositional elements. The horizon stack with 100 surfaces, together with their associated RMS amplitude and RGB spectral decomposition attributes, were produced by PaleoScan™. These 100 surfaces from the horizon stack shown in Figure 2 were numbered 1

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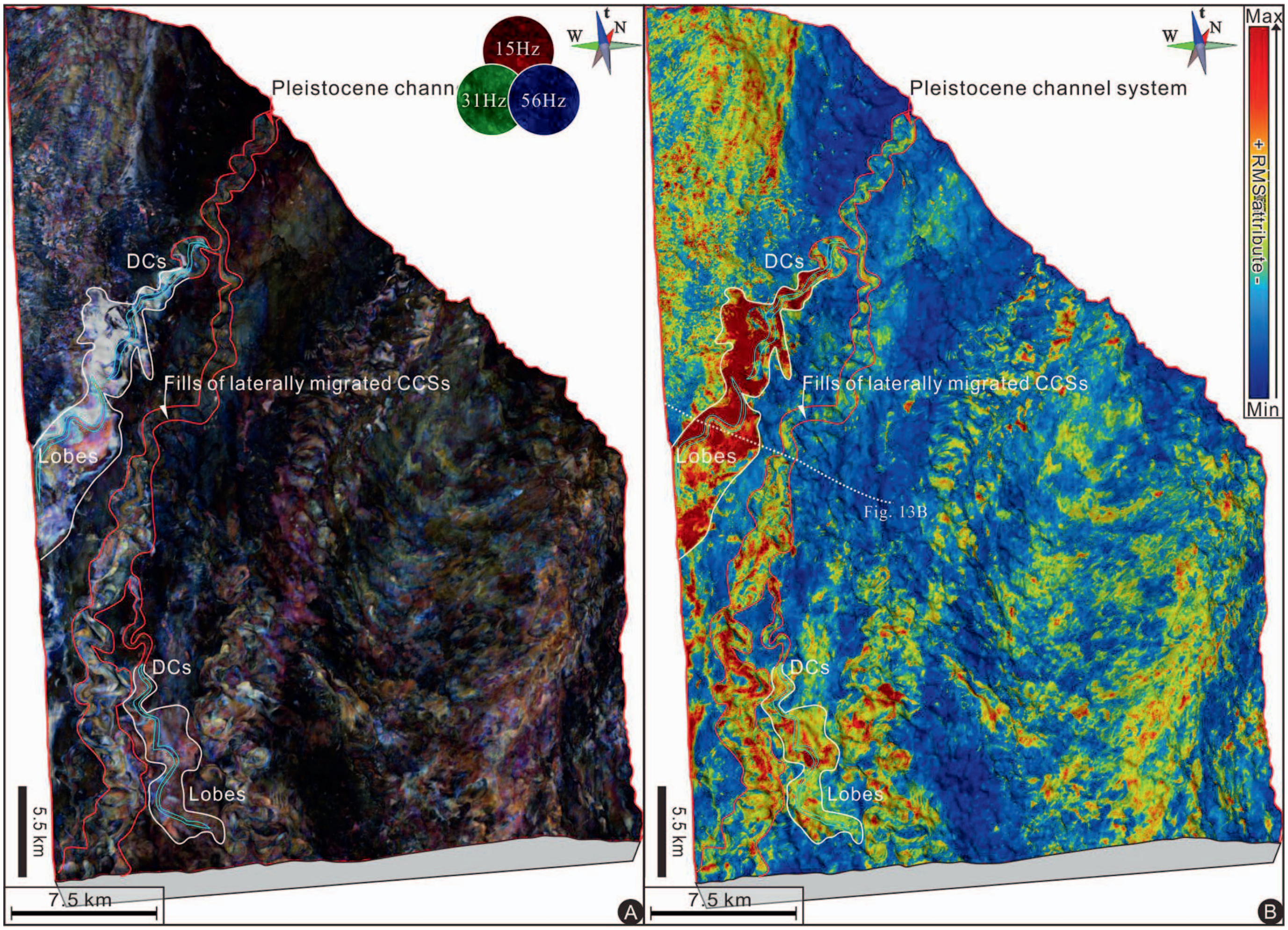

Fig. 7.—RGB spectral decomposition-attribute and RMS amplitude maps extracted from the 38th PaleoScan horizon visualizing the planform seismic geomorphology of terminal lobe complexes, distributary channels (DCs), and laterally migrated CCSs associated with the Pleistocene Bengal subfans. Also shown is the map-view location of seismic line shown in Figure 13B.

through 100 in chronological order. In this study, we selected four representative RGB spectral decomposition maps and their corresponding RMS amplitude images to be extracted from the horizon stack of Pliocene subfans (33rd, 48th, 67th, and 89th horizons, respectively, shown in Figs. 3–6) and three representative RGB spectral decomposition maps and their corresponding RMS amplitude images extracted from the horizon stack of Pleistocene subfans (38th, 58th, and 71st horizons, respectively, shown in Figs. 7–9). All of these seven RGB spectral decomposition-attribute maps and their corresponding RMS amplitude images delineate elements of, and interactions between, deep-water fan-reservoir elements in stark and vibrant detail (Figs. 3–9).

SEISMIC STRATIGRAPHY AND GEOMORPHOLOGY OF PLIOCENE AND PLEISTOCENE FAN-RESERVOIR ELEMENTS

RGB spectral decomposition attributes and RMS amplitude shown in Figures 3 to 9 suggest the occurrence of seven main depositional elements developed in the documented Pliocene and Pleistocene Bengal subfans, with a focus on sandy elements (i.e., high RMS amplitudes). Please refer to Tables 1 and 2 for a complete description and interpretation of these seven depositional elements.

Seismic Facies 1: Fills of Laterally Migrated CCSs

In seismic cross section, seismic facies 1 is composed of stacked, discontinuous, high-amplitude reflections (blue dashed scours in Figs. 10A, 11, 12, 13B; Table 1). This seismic facies exhibits channel-like, U-shaped geometry, and cuts deeply into the underlying strata, but is not flanked by concomitant levees. It ranges from 200 to 300 m in width and from 50 to 100 m in thickness, and occupies a smaller area than leveed CCSs as discussed later (Figs. 10A, 11, 12, 13B). In plan view, seismic facies 1 is imaged on attribute maps as multiple, narrow, tortuous ribbons that are continuous in highly sinuous fairways for tens of kilometers (Figs. 3, 7, 8; Table 1).

Seismic facies with the similar cross-sectional geometry and seismic geomorphologic expression are generally characteristics of deep-water submarine-channel fills (e.g., Posamentier and Kolla 2003; Mayall et al. 2006; Janocko et al. 2013; Doughty-Jones et al. 2017; Howlett et al. 2021). They are interpreted here as fills of the equivalent depositional elements (Figs. 10A, 11, 12, 13B). Because they show evidence of lateral migration through time, they are reconsidered as fills of laterally migrated CCSs (Figs. 10A, 11, 12, 13B; Table 1). These fills of laterally migrated CCSs occur in the lower stratigraphic level of both Pliocene and Pleistocene subfans, and therefore represent an early stage of channel development and

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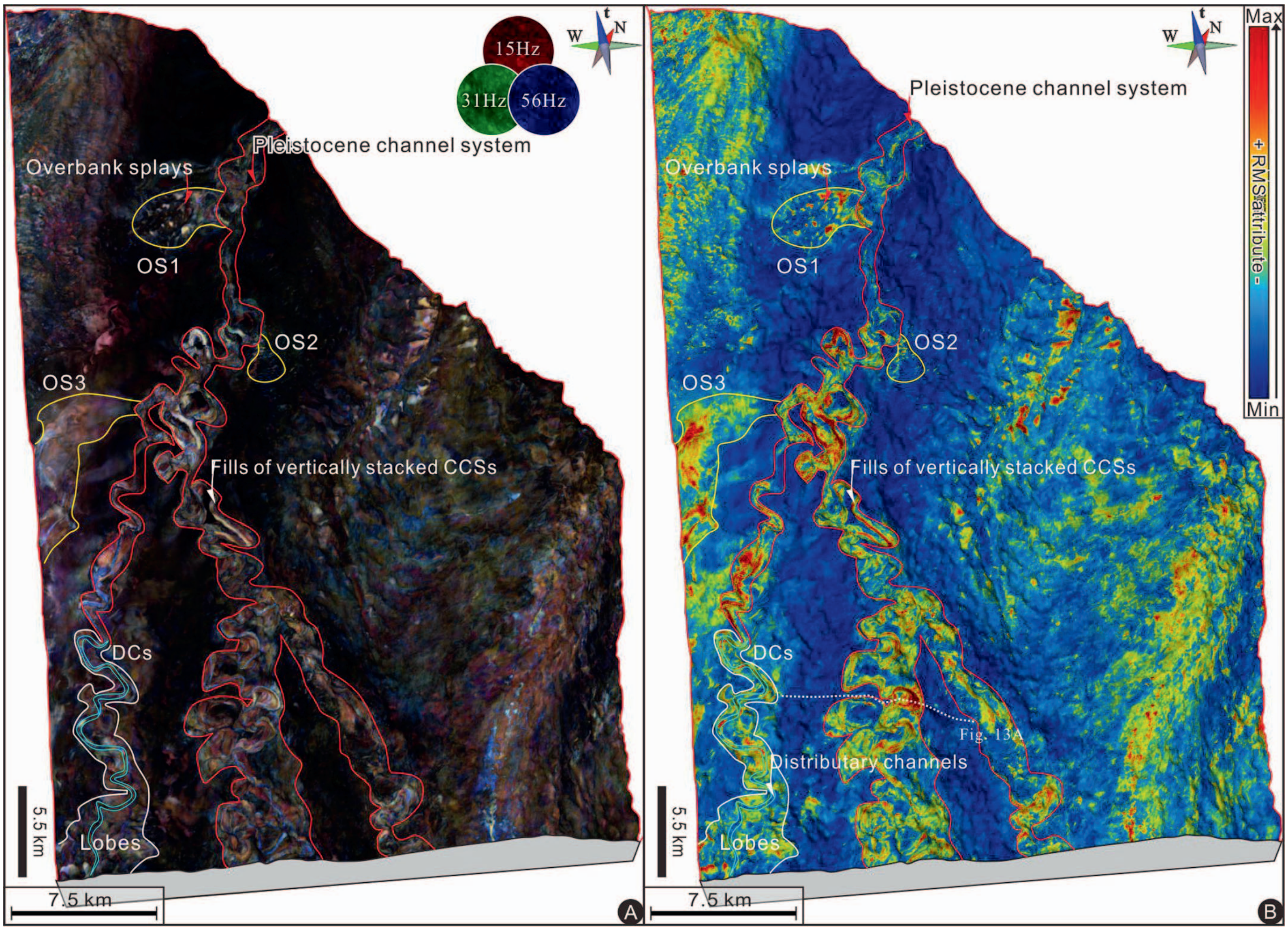

FIG. 8.—RGB spectral decomposition-attribute and RMS amplitude maps extracted from the 58th PaleoScan horizon (see Fig. 2C for their stratigraphic position) delineating the planform seismic geomorphology of overbank splays 1 to 3 (OS1–OS3), distributary channels (DCs), terminal lobe complexes, and vertically stacked CCSs associated with the Pleistocene Bengal subfan. Also shown is the map-view location of seismic transect shown in Figure 13A.

subfan evolution (Figs. 10A, 11, 12, 13B). They cut deeply into underlying strata seismically imaged as subparallel, laterally continuous, high-amplitude reflections (i.e., lobe complexes) (Figs. 10A, 11, 12, 13B).

Seismic Facies 2: Fills of Vertically Stacked CCSs

In cross section, seismic facies 2 shares some similarity with seismic facies 1 (i.e., channel-shaped, discontinuous, high-amplitude reflections) (Figs. 10–13; Table 1). However, levees are asymmetrically developed along both sides of the studied channels, and decrease in thickness away from the ancestral channel axis (Figs. 10–13; Table 1). This seismic facies ranges in width from 1000 to 3000 m and in thickness from 100 to 300 m, and is thus areally larger than the non-leveed seismic facies 1 (Figs. 10–13). In plan view, it is imaged on planform attribute maps as single, wide, highly sinuous fairways that are continuous for tens of kilometers (Figs. 4–6, 9; Table 1).

Seismic facies 2 is also interpreted as the fills of CCSs (Figs. 10–13; Table 1) but these are flanked by seismically recognizable levees, and vertically nested and stacked through time (Figs. 10–13). It is thus highly aggradational and strongly levee confined (Figs. 10–13; Table 1). Seismic facies 2 occur preferentially in the upper stratigraphic levels of both Pliocene and Pleistocene subfans (Figs. 10–13). Previous studies have suggested that sinuous deep-water channels generally developed as a consequence of repeated channel aggradation and subsequent lateral migration and not just as a consequence of lateral migration alone as in fluvial channels (Kolla et al. 2001; Jobe et al. 2016).

Seismic Facies 3: Crevasse Splays

In seismic cross-section view, seismic facies 3 is composed of parallel, high-amplitude seismic reflections that are conformable and continuous laterally for tens of kilometers, with some localized, slightly disrupted, hummocky reflections (hot color-shaded areas in Fig. 10B; Table 1). This seismic facies occurs in overbank environments that are related laterally to vertically stacked CCSs (Fig. 10B). It increases in thickness away from the ancestral channel axis, and onlaps underlying levees in a direction towards the ancestral channel axis (Fig. 10B; Table 1). Seismic facies 3 is capped by levees imaged as wedge-shaped, low-amplitude continuous reflection packages (Fig. 10B; Table 1). In plan view, it is expressed on attribute maps as relatively unconfined strata with lobate morphology (e.g., lobate accumulations of CS1 through CS4 with white boundaries in Figs. 4–6). Lobate accumulations of CS1 through CS4 are linked updip to vertically stacked CCSs of the exploring subfan by a feeder channel imaged as a single, narrow, tortuous ribbon (Figs. 4–6). CS1 through CS4, respectively,

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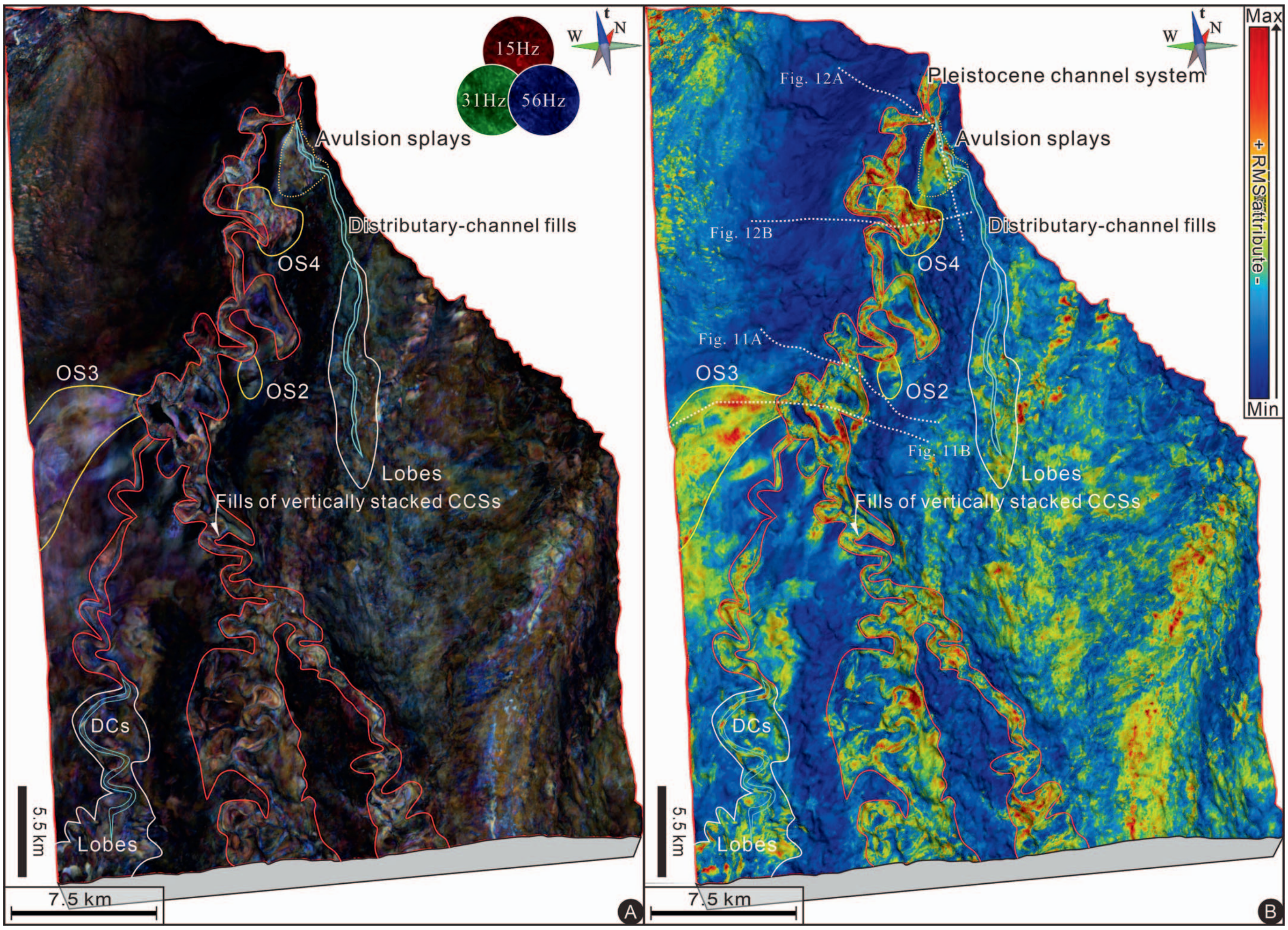

FIG. 9.—RGB spectral decomposition-attribute and RMS amplitude maps extracted from the 71st PaleoScan horizon (see Fig. 2C for their stratigraphic position) showing the plan-view geomorphological appearance of overbank splays 2 to 4 (OS2–OS4), distributary channels (DCs), terminal lobe complexes, avulsion splays, and vertically stacked CCSs associated with Pleistocene Bengal subfan. Also shown is the map-view location of seismic transect shown in Figure 13A.

occupy planform areas of 32 km^2, 41 km^2, 63 km^2, and 29 km^2 (Figs. 4–6), with average thicknesses of 182 m, 95 m, 145 m, and 77 m.

The updip linkage between lobate accumulations of seismic facies 3 and channels suggests that Pliocene Bengal CS1 through CS4 were created most likely by a spreading, fanning-out, and collapsing flow originating from a levee breach or crevasse spilling out from a sharp bend of the feeder channel (i.e., splays) (Posamentier and Kolla 2003; Maier et al. 2013; Lowe et al. 2019). We follow Lowe et al. (2019), who have suggested that splays may take three principal forms, namely crevasse splays with extensive levee erosion, overbank splays with little or no levee erosion and avulsion splays with full levee erosion and channel diversion. Feeder channels associated with splays of CS1 through CS4 are tens to hundreds of meters wide and tens of meters deep, and cut deeply into underlying levees, suggesting extensive levee erosion (Figs. 4–6, 10B; Table 1). This suggests that seismic facies 3 can be classified as crevasse splays that have accompanying extensive levee erosion (Figs. 4–6, 10B; Table 1).

Seismic Facies 4: Overbank Splays

Seismic facies 4, in cross-section view, consists of wedge-shaped, high-amplitude, moderately continuous seismic reflections (Figs. 11B, 12B; Table 2). As with the crevasse splays, seismic facies 4 also occurs in the overbank environments that are laterally related to vertically stacked CCSs (Figs. 11B, 12B). In marked contrast to crevasse splays, seismic facies 4 decreases in thickness away from the feeder channel axis, onlaps the underlying strata in a direction away from the ancestral channel axis, and caps the underlying levees (Figs. 11B, 12B; Table 2). In plan view, seismic facies 4 is expressed on planform attribute maps as relatively unconfined packages with a tongue-like morphology (i.e., OS1 and OS2 shown in Figs. 5–6 and OS1 through OS4 shown in Figs. 8, 9). These tongue-shaped overbank accumulations are also linked updip to vertically stacked CCSs, but there is a lack of seismically resolvable feeder-channel connections (Figs. 8, 9). Seismic facies 4 ranges in planform areas from 5 km^2 to 30 km^2 and in thicknesses from 5 m to 100 m, and is thus volumetrically smaller than the crevasse splays of CS1 through CS4 (Figs. 4–6 versus Figs. 8–9).

Based on their cross-sectional seismic reflection characteristics and plan-view distribution patterns (i.e., wedge-shaped, high-amplitude, moderately continuous seismic reflections with tongue-shaped map-view morphology), seismic facies 4 is interpreted as splays produced by a spreading, fanning-out, and collapsing flow probably originating from a sharp bend of an ancestral channel (Posamentier and Kolla 2003; Maier et al. 2013; Lowe et al. 2019). However, a lack of seismically resolvable feeder channels between the documented splays and their ancestral channels suggests that there was little or no levee erosion. The tongue-like accumulations of the documented OS1 and OS2 shown in Figures 4 to 6

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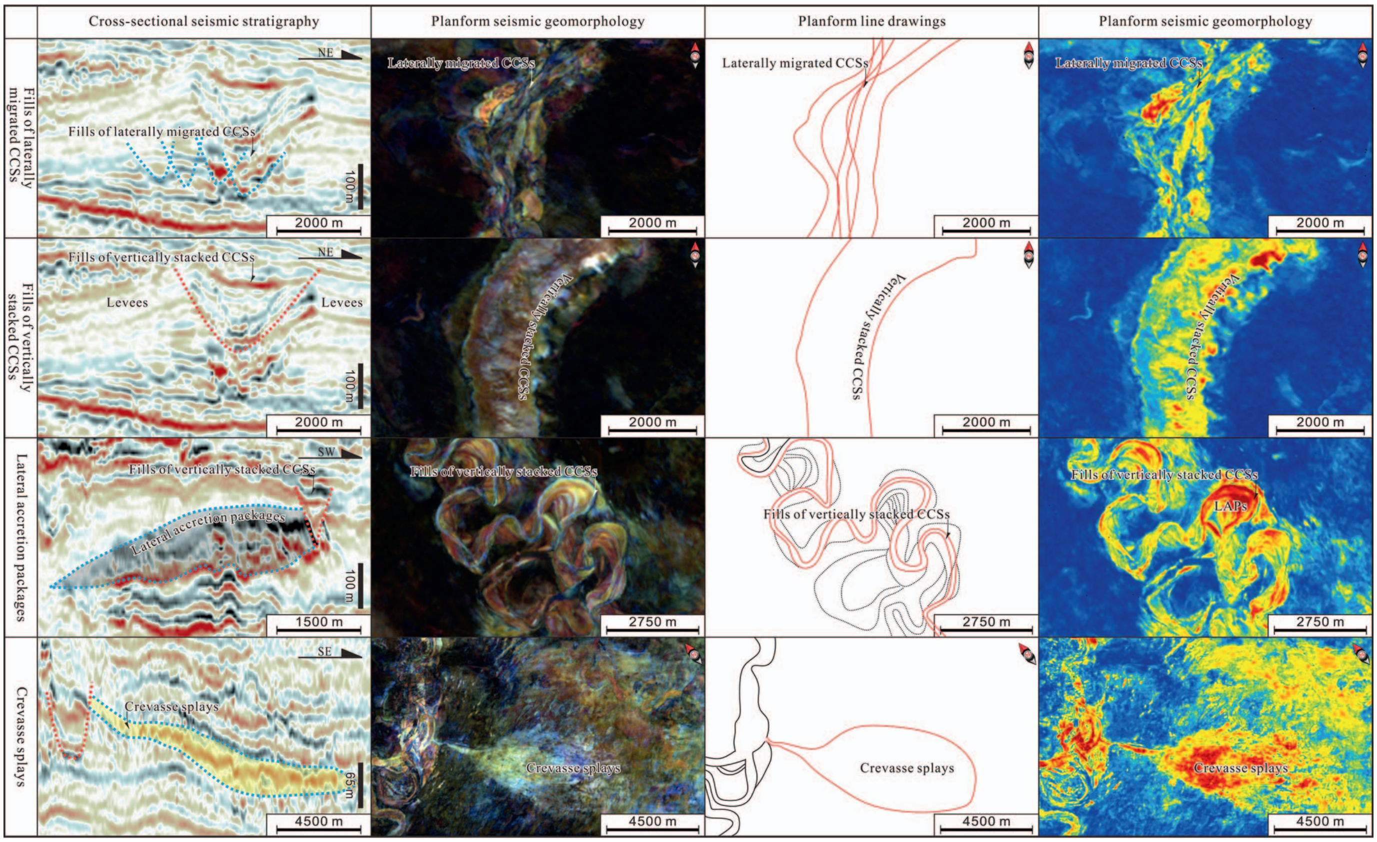
TABLE 1.—*A summary of the four main depositional elements associated with the documented Bengal channel–levee systems as observed in cross section and on RGB spectral decomposition-attribute and RMS amplitude maps (i.e., fills of laterally migrated CCSs, fills of vertically stacked CCSs, lateral accretion packages, and crevasse splays).*



and OCS1 to OCS4 shown in Figures 8 to 9 are accordingly classified as overbank splays (*sensu* Lowe et al. 2019) accompanied by little or no levee erosion (Figs. 4–6, 8–9, 12A; Table 2).

Seismic Facies 5: Avulsion Splays

Seismic facies 5 shares some similarities in cross-sectional seismic reflection characteristics and plan-view distribution patterns with the above-mentioned overbank splays. Both are composed of wedge-shaped, high-amplitude, moderately continuous seismic reflections (hot color-shaded areas with blue dashed outlines in Fig. 12A; Table 2), occur in overbank environments related to vertically stacked CCSs, and exhibit tongue-like planform morphology (Fig. 9; Table 2). However, in contrast to overbank splays, seismic facies 5 is clearly incised by younger distributary channels imaged as single, wide, tortuous ribbons (green curves in Fig. 9). Seismic facies 5 occupies a planform area of 40 km^2, with the thicknesses ranging from 0 to 120 m.

The otherwise great similarity in seismic reflection patterns and geomorphological manifestations between seismic facies 5 and 4 suggests that the former can be considered as a type of splay. The occurrence of distributary channels actively downcutting seismic facies 5 suggests a development accompanied by the processes of active avulsion. According to the splay classification of Lowe et al. (2019), tongue-like accumulations incised by distributary channels can be interpreted as avulsion splays accompanied by levee erosion and channel diversion (Figs. 12A, 9; Table 2).

Seismic Facies 6: Distributary-Channel Fills

Similar to fills of laterally migrated and vertically stacked CCSs, seismic facies 6 is distinguished in cross section by channel-shaped scours filled by stacked, discontinuous, high-amplitude reflections (Figs. 12A, 13B; Table 2) and is expressed in planform attribute maps as narrow and tortuous fairways continuous for tens of kilometers (green lines in Figs. 7–9). This seismic facies is not flanked by overbank levees (Figs. 12A, 13B; Table 2). It is tens to hundreds of meters wide and tens of meters deep, and is areally smaller than the fills of laterally migrated and vertically stacked CCSs.

Channel-shaped scours filled by high-amplitude discontinuous reflections are the normal recognition criteria used to identify deep-water channels on seismic transects (Posamentier and Kolla 2003; Mayall et al. 2006; Janocko et al. 2013; Doughty-Jones et al. 2017; Howlett et al. 2021). When they occur on deep-water lobe complexes or splays, they are normally referred to as distributary channels (Oluboyo et al. 2014; Doughty-Jones et al. 2017; Howlett et al. 2021).

Seismic Facies 7: Terminal Lobe Complexes

In cross-section view, seismic facies 7 is seismically imaged as subparallel, laterally continuous, high-amplitude reflections that are tabular to lensoidal in cross section (hot color-shaded accumulation in Fig. 13B; Table 2). The seismic facies thins and downlaps towards the system fringes and is linked updip to ancestral channels by distributary channels (Figs. 7–9; Table 2). In plan view, this seismic facies is expressed on attribute maps as relatively

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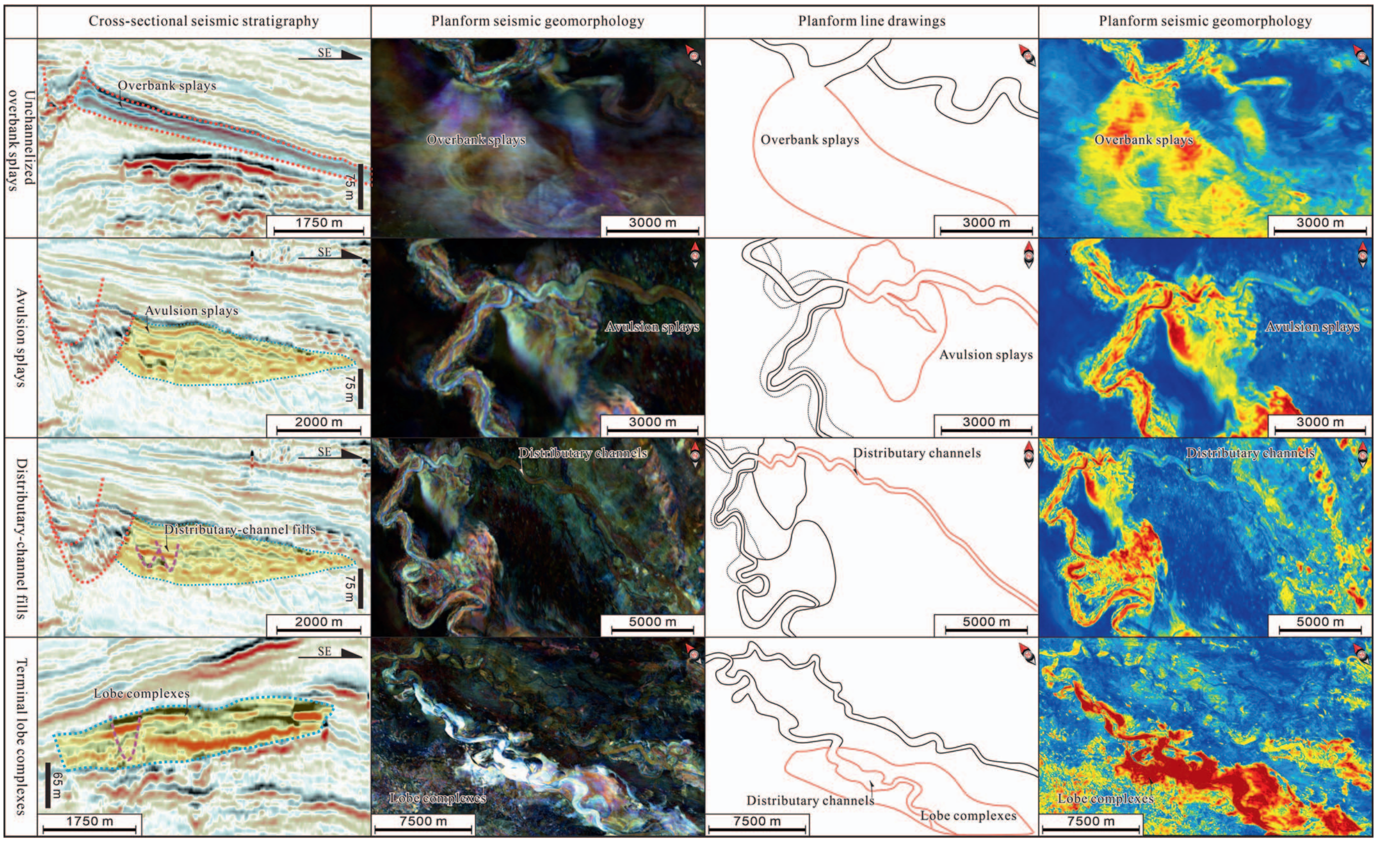
TABLE 2.—*A summary of the four main depositional elements associated with the documented Bengal channel–levee systems as observed in cross-section and on RGB spectral decomposition-attribute and RMS amplitude maps (i.e., overbank splays, avulsion splays, terminal lobe complexes, and distributary-channel fills).*



unconfined sheets with lobe-shaped morphology (Figs. 7–9; Table 2). These lobate accumulations are 30 to 60 m in thickness and in an area of 30 to 50 km^2, and are marginally more elongated than crevasse, overbank, and avulsion splays (Figs. 13B, 7–9; Table 2).

Lobate seismic facies have been widely documented in deep-water settings, in both ponded and unconfined depositional environments (Prélat et al. 2009, 2010; Oluboyo et al. 2014; Doughty-Jones et al. 2017; Howlett et al. 2021; McHargue et al. 2021); following these studies, they are interpreted as lobe complexes composed of lobes. Bengal lobe complexes as documented in this study are commonly incised by the aforementioned distributary channels (Figs. 7–9; Table 2).

Spatiotemporal Distribution Patterns of Fan-Reservoir Elements

The above seven depositional elements exhibit high RMS attribute properties, suggesting that they are sand prone and hence represent fan-reservoir elements. Space-time distribution patterns are graphically illustrated in Figure 14 and are discussed in this section.

Temporal Distribution Patterns of Submarine Fan-Reservoir Elements

Observations and results from the current study suggest that individual channel levee–lobe complexes (subfans) developed on the northeastern fringe of the Bengal Fan underwent three main evolutionary stages (i.e., early, middle, and late stages of the channel development and subfan evolution).

Firstly, RGB spectral decomposition-attribute and RMS amplitude maps shown in Figures 3 and 7 are located in the lower stratigraphic levels of both Pliocene and Pleistocene subfans, and therefore represent the early stage of channel development and subfan evolution. Fills of laterally migrated CCSs and terminal lobe complexes are seen in planform attribute maps shown in Figures 3 and 7, suggesting that these two depositional elements are dominant reservoir elements during the early stage of channel development and subfan evolution (Fig. 14A, D, G). These laterally migrated CCSs are not flanked by contemporaneous levees (Figs. 3, 7, 14A, D, G).

Secondly, RGB spectral decomposition-attribute and RMS amplitude maps shown in Figures 4, 5, and 8 are located in the middle stratigraphic levels of both Pliocene and Pleistocene subfans, and therefore represent a middle stage of channel development and subfan evolution. Fills of vertically stacked CCSs, crevasse splays, terminal lobe complexes, and overbank splays present in planform attribute maps of Figures 4, 5, and 8 suggest that these four depositional elements are the dominant reservoir elements in the middle stage of channel development and subfan evolution (Fig. 14B, E, H). These vertically stacked CCSs are flanked by concomitant levees, on which crevasse splays and overbank splays are developed (Figs. 4, 5, 8, 14B, E, H).

Thirdly, RGB spectral decomposition-attribute and RMS amplitude maps shown in Figures 6 and 9 are located at the upper stratigraphic level of the Pliocene and Pleistocene subfans, and therefore represent a late stage of channel development and subfan evolution. Fills of vertically stacked CCSs, crevasse splays, overbank splays, and avulsion splays, and terminal lobe complexes are present in planform attribute maps shown in Figures 6

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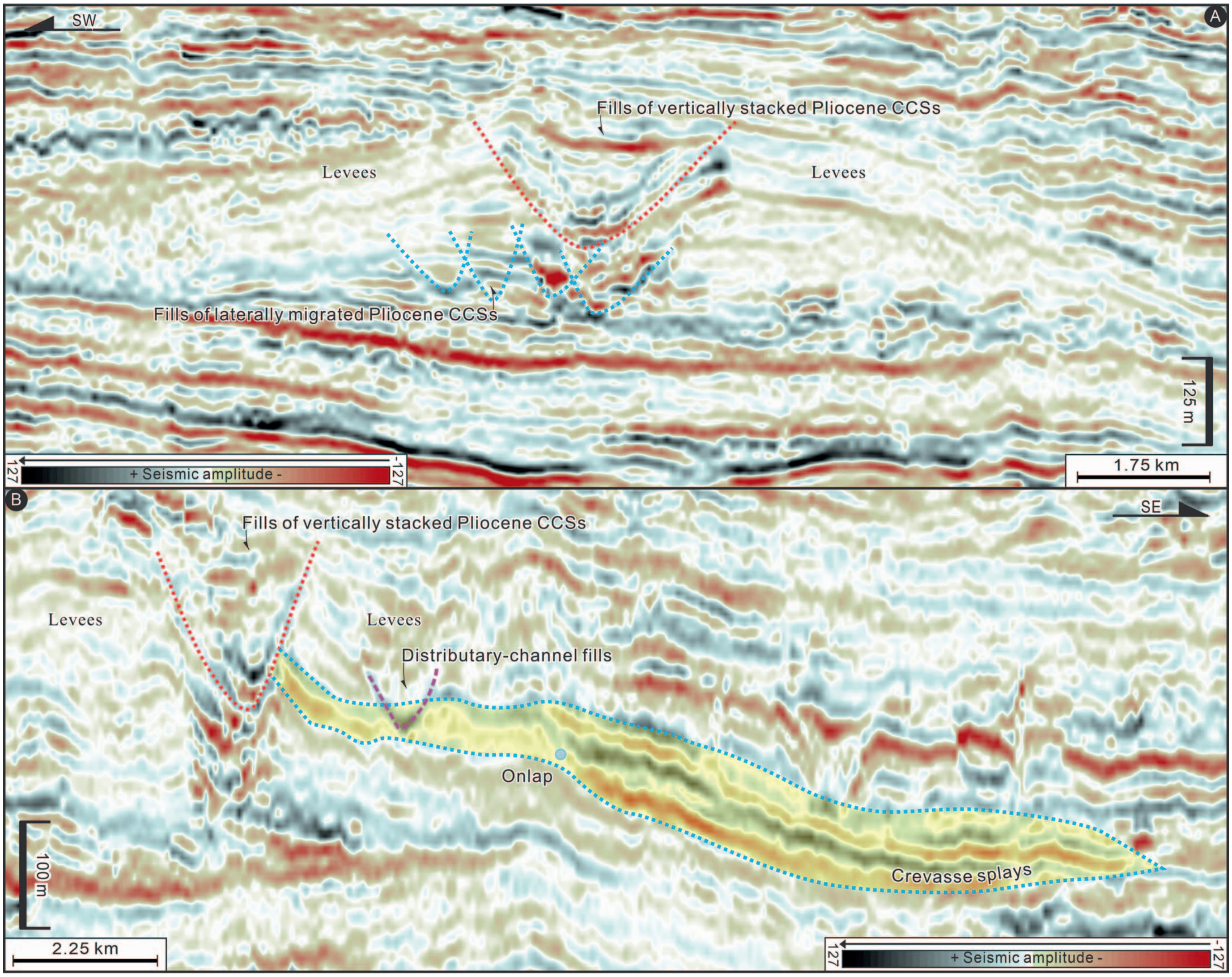

FIG. 10.—Depositional-dip-oriented seismic traverses showing cross-sectional seismic expression of fills of laterally migrated and vertically stacked CCSs, crevasse splays, and distributary channels. Please refer to Figures 4B and 5B for the plan-view locations of the seismic traverses presented in this figure.

and 9, suggesting that these six channel elements are the dominant reservoir elements during the late stage of channel development and subfan evolution (Fig. 14C, F, I). These vertically stacked CCSs are flanked by levees, on which crevasse splays, overbank splays, and avulsion splays are seen to occur (Figs. 3, 7, 14C, F, I).

The above temporal development of seven deep-water fan-reservoir elements and their associated levees are summarized in Figure 14, which can serve as the predictive model of submarine-fan architecture. We suggest that terminal lobe complexes are present throughout the early, middle, and late stratigraphic stages of channel development and subfan development and evolution (Fig. 14). Fills of laterally migrated CCSs appear only during the early stage of channel evolution (Fig. 14A, D, G), whereas avulsion splays commonly occur during the late stage (Fig. 14F). Vertically stacked CCSs, crevasse splays, overbank splays, distributary-channel fills, and their associated levees occur either in middle or late stages of channel development and subfan evolution (Fig. 14E, F). Moreover, the above-mentioned three evolutionary stages of channel development and subfan evolution, each of which exhibits a given temporal distribution pattern of submarine fan-reservoir elements, can provide an alternative interpretation of submarine-fan growth and evolution.

Spatial Distribution of Submarine Fan-Reservoir Elements

Serial RGB spectral decomposition-attribute and RMS amplitude maps shown in Figures 3 to 9 suggest that channel fills are well developed along the entire length of the documented Bengal subfans (Fig. 14). The inner segment of the studied subfans is dominated by fills of laterally migrated and vertically stacked CCSs (Fig. 14G–I). The middle segment of the documented subfans contains fills of laterally migrated and vertically stacked CCSs, crevasse splays, overbank splays, and avulsion splays (Figs. 14D–F). The outer segment of the studied subfans, in contrast, is dominated by fills of both laterally migrated and vertically stacked CCSs, lobe complexes, and distributary-channel fills (Fig. 14A–C).

The above spatial distribution of submarine fan-reservoir elements is summarized in Figure 14. From a spatial perspective, we suggest that fills of both laterally migrated and vertically stacked CCSs, and their levees, dominate throughout inner and middle segments of Bengal subfans (Fig. 14G–I, D–F), but that terminal lobe complexes and distributary-channel fills dominate the outer segment of the documented subfans (Fig. 14A–C). The middle segment of the studied subfans, in

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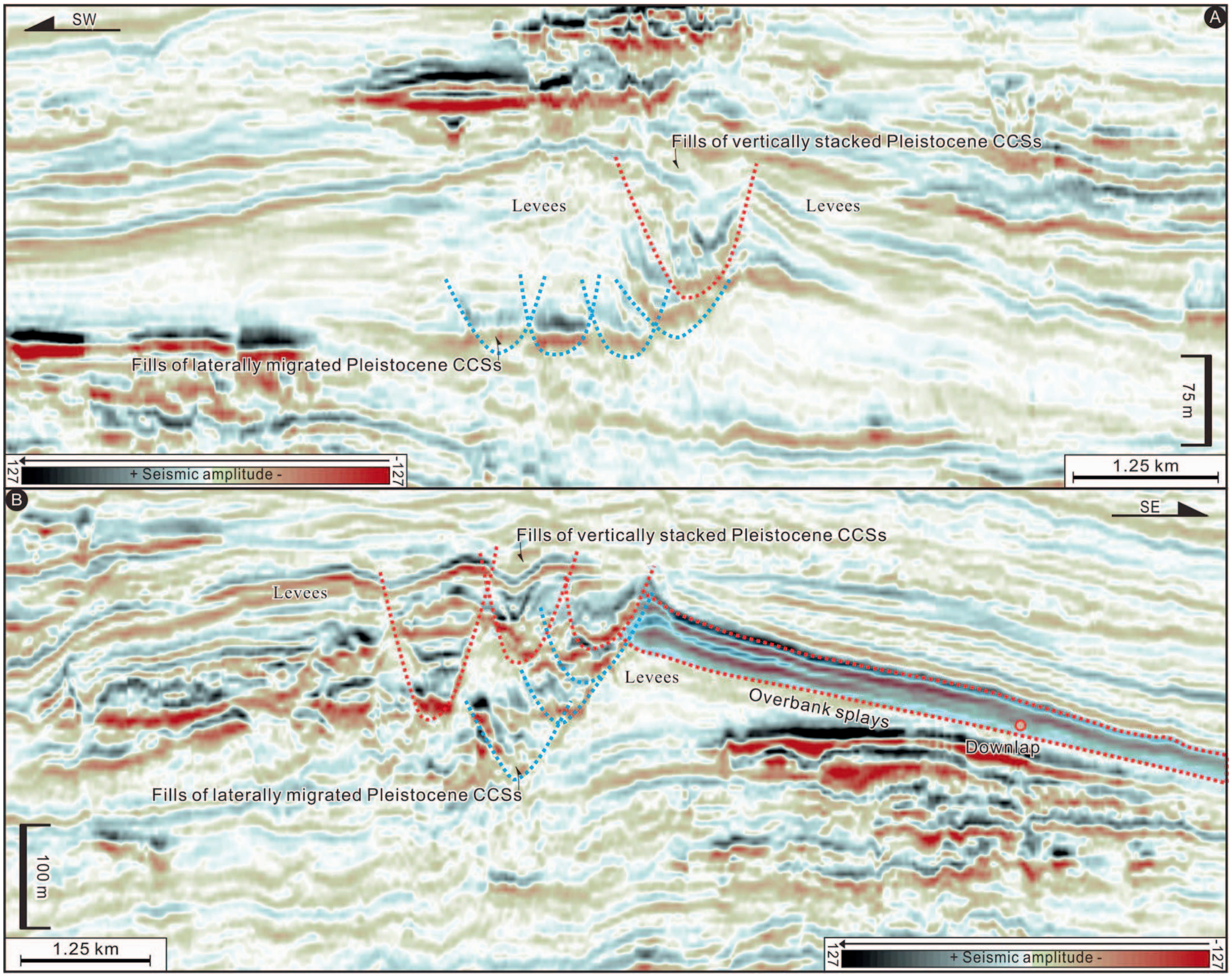

FIG. 11.—Seismic transects along depositional dip giving seismic response characteristics of fills of laterally migrated and vertically stacked CCSs and overbank splays. Please refer to Figure 9B for the plan-view locations of the seismic transects shown in this figure.

contrast, fostered mainly overbank splays, avulsion splays, and crevasse splays (Fig. 14D–F).

Conceptual Implications

Three main types of splays are recognized in the Bengal Fan study area, and are visualized by RGB spectral decomposition attributes and RMS amplitude maps shown in Figures 4 to 6 and 8 to 9. The importance of splays in the mix of the documented fan reservoirs is emphasized by their areal sizes and thicknesses as shown in Table 3. A comparison between the splays not only displays their recognition criteria (Table 3) but also highlights the important but underappreciated role of splay development in the formation and distribution of submarine fan-reservoir compartments.

The Recognition and Comparison of Crevasse, Overbank, and Avulsion Splays

The RGB spectral decomposition-attribute and RMS amplitude maps shown in Figures 4 to 6 and 8 to 9 suggest that crevasse, overbank, and avulsion splays preferentially developed during the middle and late stages of subfan evolution (Fig. 14E, F). These three main types of overbank splays differ in both seismic cross-section and planform geomorphology (see Table 3 for a comparison). In cross-sectional view, crevasse splays decrease in thicknesses towards the main channel axis, onlap the preceding levees in a direction towards the ancestral channel axis, and are capped by overlying levees (Fig. 10B). In marked contrast, overbank and avulsion splays increase in thickness towards the main channel axis, downlap the preceding levees in a direction away from the ancestral channel axis, and cap underlying levees (Figs. 11B, 12A, B). In plan view, crevasse and avulsion splays exhibit lobate planform morphology and are linked updip to the main CCSs by a single feeder channel, whereas overbank splays show a tongue-like planform morphology and lack feeder channels (Figs. 4–6, 8–9).

As highlighted by previous studies, splays are an important associate of sinuous deepwater channels and submarine fans (e.g., Posamentier and Kolla 2003; Maier et al. 2013; Lowe et al. 2019). Numerical modeling of avulsion processes (Hamilton et al. 2014) and of channel instability (Dorrell et al. 2015) has explored the mechanisms of avulsions, but with little reference to their resultant deposits. Research on the Amazon Fan by Lopez (2001) and Maslin et al. (2006) and the Bengal Fan by Bergmann et al. (2020) has collectively suggested that different and frequent avulsions

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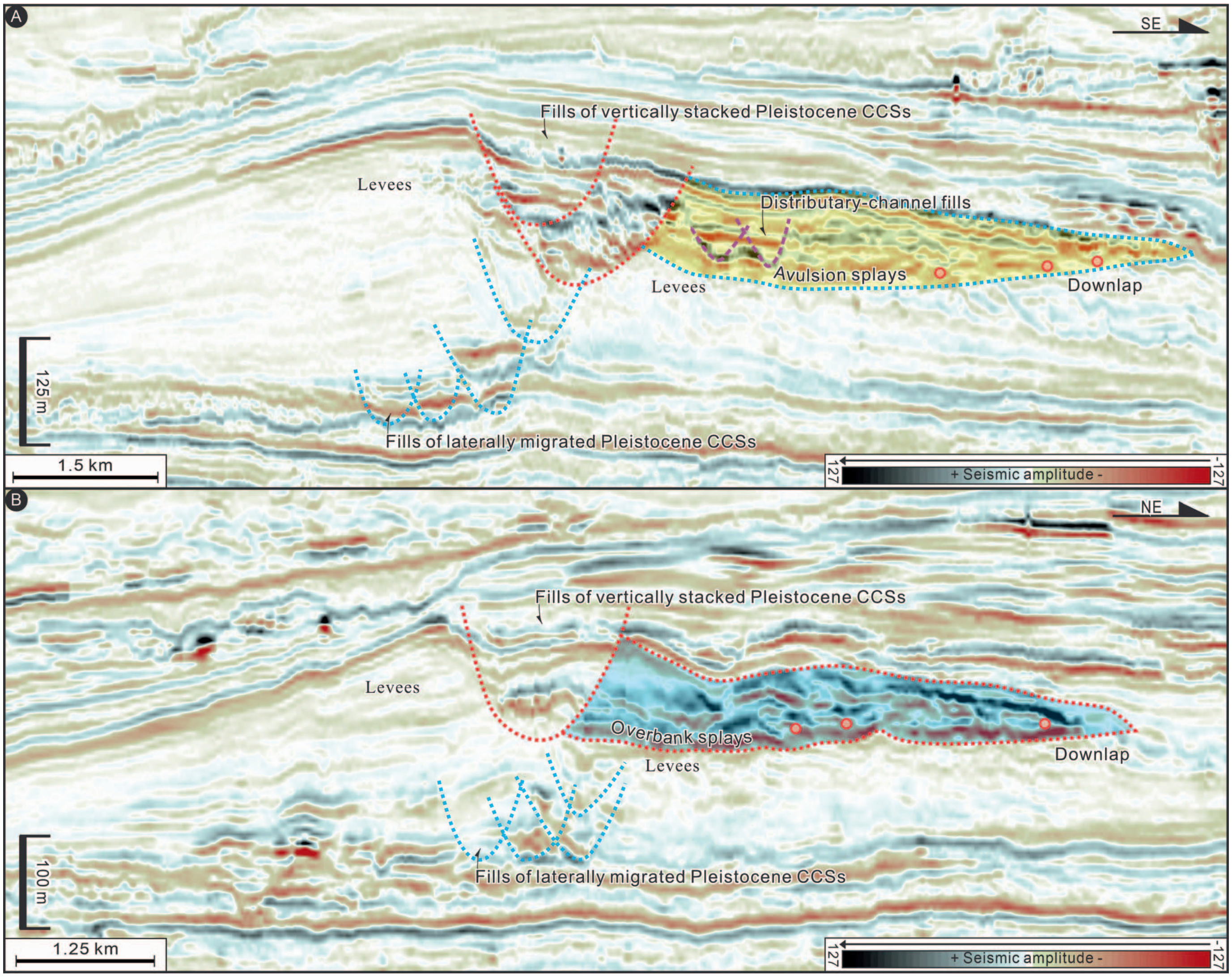

FIG. 12.—Seismic sections along depositional dip providing cross-sectional seismic manifestations of fills of laterally migrated and vertically stacked CCSs, avulsion splays, and overbank splays. Please refer to Figure 9B for the plan-view locations of the seismic transects shown in this figure.

characterize submarine fan depositional systems with depocenter migration along and across the fan, but with little information on similarities and differences between different types of avulsion processes. Previous studies have highlighted the role of splay events and avulsion nodes in submarine-channel development and evolution (e.g., Morris et al. 2016) and the controls on avulsion (e.g., Maier et al. 2011; Picot et al. 2019), but with only limited detail on how different avulsion processes leave their signals in the sedimentary record and on how avulsion processes differ from each other. Observations and results from the present study highlight similarities and differences among crevasse, overbank, and avulsion splays (see Table 3 for a comparison), and is thus a contribution to the library of splay processes and submarine fan systems.

The Influence of Splay Processes on the Distribution and Development of Reservoirs

Both crevasse and avulsion splays are linked updip to their ancestral channels by a single feeder channel (Figs. 4–6, 9). Feeder channels between crevasse splays and avulsion splays and their ancestral channels are tens to hundreds of meters wide and tens of meters deep (Figs. 4–6, 9), suggesting extensive levee erosion and, as a result of sand intake, perhaps higher-density turbidity currents to form sand-prone crevasse and avulsion splays. Sand-prone crevasse splays and avulsion splays, therefore, mostly likely have a higher and better reservoir connectivity, as compared with their overbank counterparts. In marked contrast to crevasse and avulsion splays, overbank splays lack feeder channels between ancestral channels and overbank environments (Figs. 4–6, 8, 9), suggesting little or no levee erosion and resultant delivery of more dilute or low-density turbidity currents onto the overbank levees, most likely forming mud-prone overbank splays. Mud-prone overbank splays, therefore, mostly likely have a lower and worse reservoir connectivity, as compared with their crevasse and avulsion counterparts.

From a hydrocarbon-exploration viewpoint, coarse materials in the standard model of deep-water fan-reservoir elements (e.g., Normark 1970; Posamentier and Kolla 2003) are found mainly on floors of feeder channels and distal lobes, and often fail to emphasize the importance of splay processes, especially crevasse splays and avulsion splays. Observations and results from the current study suggest that reservoir sands can also occur in overbank environments (e.g., crevasse and avulsion splays) (Fig. 14). Research on modern submarine-fan systems (e.g., the Amazon Fan

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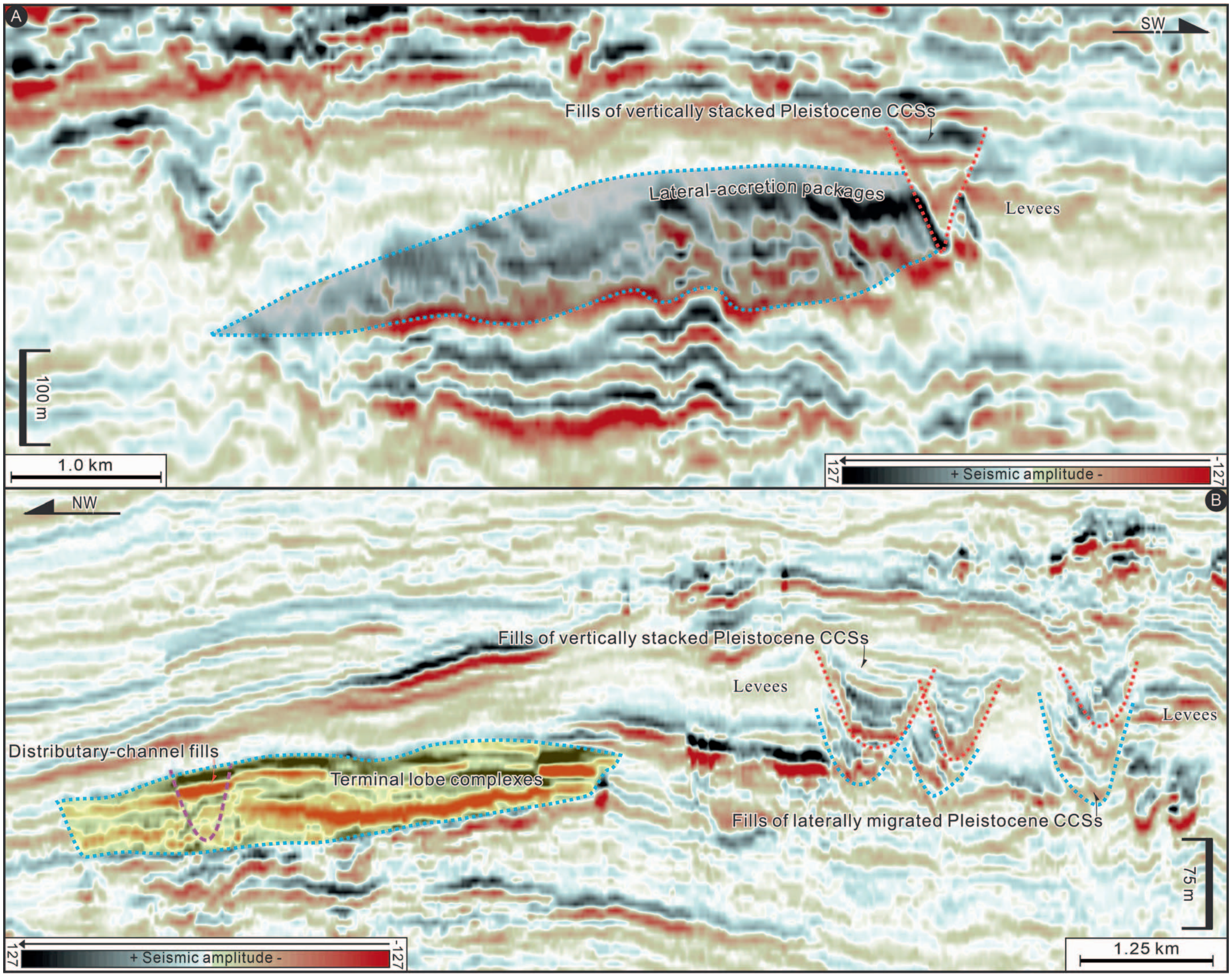

FIG. 13.—Seismic transects along depositional dip illustrating seismic reflection patterns of fills of laterally migrated and vertically stacked CCSs, distributary channels, and terminal lobe complexes. Please refer to Figures 7B and 8B for the plan-view locations of the seismic transects shown in this figure.

documented by Lopez 2001 and by Maslin et al. 2006, and the Zaire Fan documented by Picot et al. 2016 and their ancient analogues, e.g., the middle to upper Pleistocene lower Bengal Fan by Bergmann et al. 2020) also suggest that splay processes led to thick sandy layers with high reservoir potential. Spatiotemporal distribution models of submarine fan-reservoir elements shown in Figure 14, therefore, represent a more robust model for predicting the occurrence of submarine fan-reservoir elements.

The Formation of Stratigraphic Traps by the Downlap of Subsequent Levees onto Crevasse Splays and Overbank Splays

Academic and industry practitioners would like to make a step change in the volume of hydrocarbon accumulations discovered in giant stratigraphic and combination traps (e.g., Prather 2003; Gong et al. 2022). Stratigraphic and combination traps require better seismic visualization of the stratigraphic relationship of reservoirs to seals with low permeability (e.g., Prather 2003; Gong et al. 2022). The datasets and observations from their study suggest that crevasse splays and overbank splays developed during the middle stage of Bengal channel development, and subfan evolution can act as lateral trapping elements (i.e., sand pinch-outs) (Figs. 4, 5, 8, 14E). The downlap of subsequent levees formed during the late stage of channel development and subfan evolution onto these sand pinch-outs, in contrast, can serve as a competent top seal and prevent hydrocarbons from leaking out (Figs. 4, 5, 8, 14E). Crevasse splays and overbank splays are, therefore, blanketed and surrounded by accumulations of mud-rich deposits (i.e., levees), forming stratigraphic traps in overbank environments (Figs. 4, 5, 8, 14E). These stratigraphic traps have the potential for significant hydrocarbon accumulations, provided that these channel fills are charged by deeper source rocks through hydrocarbon migration pathways. They may be common, and represent potential drilling targets on many other submarine fans worldwide.

CONCLUSIONS

Spectral decomposition and RGB color-blending techniques, together with 3-D seismic data from the northeastern fringe of the Bengal Fan, are used to explore stratigraphic architecture and distribution patterns of submarine fan-reservoir elements along the northeastern fringe of the Bengal Fan.

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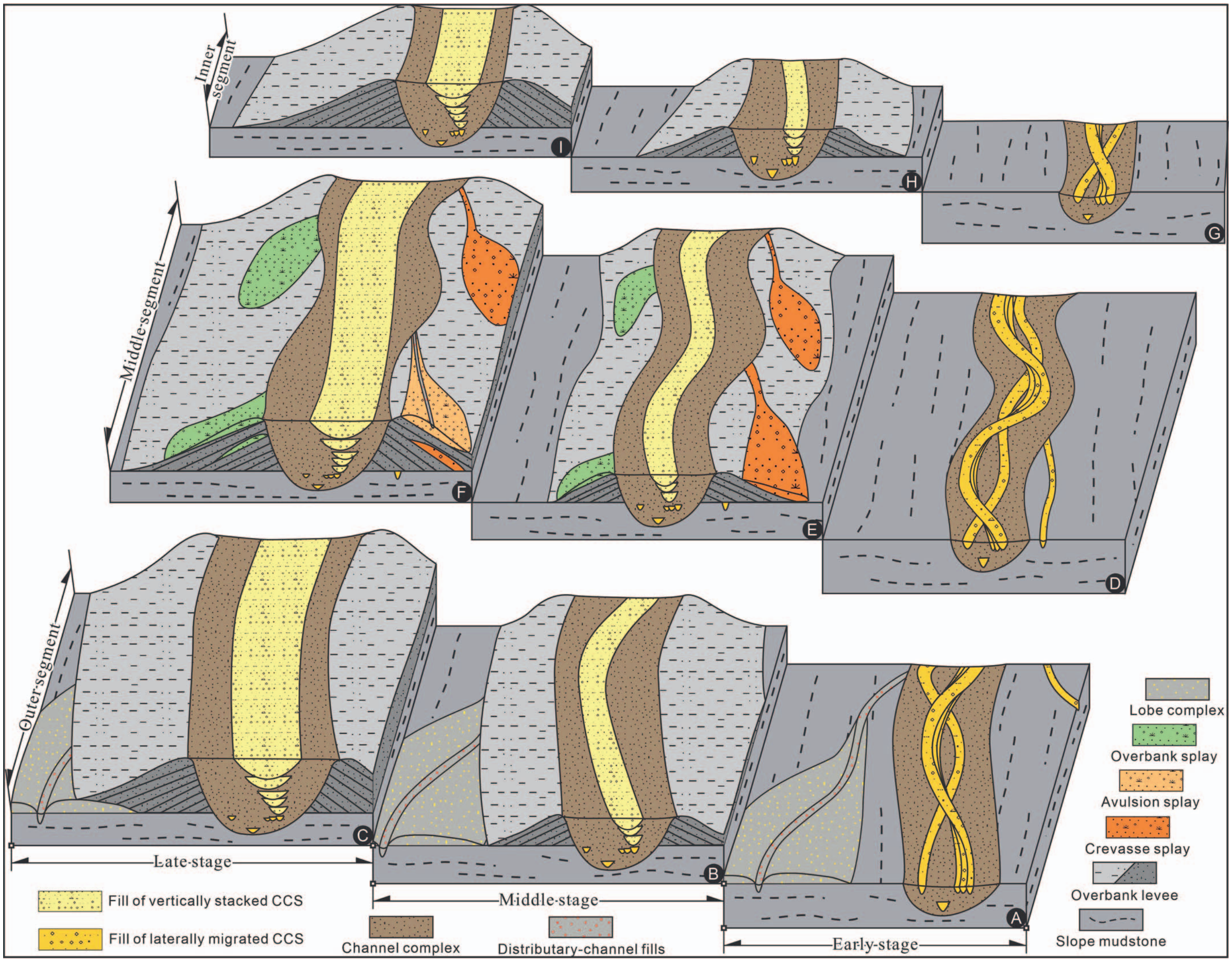

FIG. 14.—Schematic illustration of plan-view distribution patterns and vertical cuts of deep-water fan-reservoir elements of the documented Bengal Fan systems.

Overbank levees, together with seven architectural elements of Bengal Pliocene and Pleistocene subfans, are recognized, including infills of laterally migrated and vertically stacked CCSs, distributary-channel fills, terminal lobes, and crevasse, overbank, and avulsion splays. The variety of splay deposits have typically received little attention. Overbank splays and avulsion splays increase in thicknesses towards the main channel axis and cap underlying levees, whereas crevasse splays decrease in thicknesses towards the ancestral channel axis and are capped by overlying levees. Crevasse splays and avulsion splays are lobe-shaped and are linked updip to ancestral channels by feeder-channel connections, whereas overbank splays are tongue-shaped and lack feeder channels.

Fill of laterally migrated CCSs appear preferentially during early stages of fan evolution, whereas avulsion splays commonly occur during late stage of fan development. Fills of vertically stacked CCSs, crevasse splays, and overbank splays occur either in middle or late stages of Bengal subfan evolution. Terminal lobe complexes and distributary-channel fills exist throughout the entire period of Bengal subfan evolution.

The inner segment of the studied subfans fostered mainly reservoirs of vertically stacked CCSs, whereas the outer segment of the documented subfans mainly contains reservoir elements of terminal lobe complexes and distributary-channel fills. Middle segments of the studied subfans, in contrast, fostered mainly overbank splays, avulsion splays, crevasse splays, and both laterally migrated and vertically stacked CCSs. The downlap of subsequent levees onto crevasse splays and overbank splays developed during the middle stage of channel development and subfan evolution resulted in stratigraphic traps with the potential for large hydrocarbon accumulations.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ACKNOWLEDGMENTS

This research was jointly funded by the Science Foundation of China University of Petroleum, Beijing (No. 2462020YXZZ020), the Independent Project of State Key Laboratory of Petroleum Resources and Prospecting (No. PRP/indep-3-1905) and the PetroChina Hangzhou Research Institute of Geology (No. 2019D-4309). Discussions with and support of RioMar companies and University of Texas at Austin is also acknowledged. We

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TABLE 3.—*A comparison in cross-sectional seismic stratigraphy and plan-view seismic geomorphology among crevasse splays, overbank splays, and avulsion splays.*

Characteristic Features	Crevasse Splays	Overbank Splays	Avulsion Splays
Thickness pattern	Thinning toward the ancestral channel axis, with thickness of 0–200 m	Thickening toward the ancestral channel axis, with thicknesses of 0–100 m	Thickening toward the ancestral channel axis, with average thicknesses of 0–120 m
Stratal termination	Onlapping toward the ancestral channel axis	Downlapping toward the ancestral channel axis	Downlapping toward the ancestral channel axis
Relationships to ancestral channel	Linked updip to vertically stacked CCSs by single feed channels	Lack of feeder channels between splays and the main channels	Linked updip to vertically stacked CCSs by a single feeder channel
Relationship to levee	Capped by overlying levees	Capping underlying levees	Capping underlying levees
Planform morphology	Lobate morphology with planform areas of 29 to 64 km^2	Tongue-like morphology with planform areas of 5 to 30 km^2	Lobate morphology with the planform area of 40 km^2
Main process on levees	Extensive levee erosion	Little or no levee erosion	Full levee erosion and channel diversion
Formative mechanism	A spreading, fanning-out flow originating from a levee breach	Overspill and flow stripping from a sharp bend of the main channel	A spreading, fanning-out flow originating from a levee breach
Examples	Figure 10B and Table 2	Figures 11B and 12B and Table 2	Figure 12A and Table 2

acknowledge Chinnery Assets limited Company and Woodside for supporting our research and for giving permission to publish this research. The authors also thank JSR Editor Kathleen Marsaglia and Associate Editor Kyle Straub for editorial handing and comments and to two anonymous reviewers for their insightful and constructive comments, all of which significantly improved the overall quality of this research.

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Received 8 November 2021; accepted 11 May 2023.

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