

Architectural complexities and morphological variations of the sediment waves of Plio-Pleistocene channel levee backslope of the Indus Fan

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Abstract

The architecture of the turbidity current sediment waves exhibits intricate morphologies and patterns on the Indus Fan channel levee backslope. The sediment waves are present on the channel levee of Plio-Pleistocene age and are absent in the deeper sections of the study area. The architecture of channel levee backslope on the Indus Fan is poorly understood. We used seismic interpretation techniques and modelling by utilizing high-resolution seismic data to approach this problem. The morphological variations in wavelength, crest dimensions and potential wave formation patterns suggest the autogenic and allogenic processes associated with wave development. Wavelengths reach up to 1473 m with an average of 486.84 m and the height of the levee ranges between 10 m and 60 m (average 30 m). The angle of the channel levee and dimension of the sediment wave here are independent of each other. Low angle levees have accommodated high dimension sediment waves and vice versa at multiple points downslope. Characteristically, the waves have formed on the outer levee (usually left) of the channels marked by steep margins suggesting that flow overspill caused the development of the waves. Generally, the younger sediment waves followed the patterns of older sediment waves, but the varying trends are often observed in the study area. The patterns of the sediment waves towards the younger sections of the levee indicate the modified and varying architectural style of growth. Sediment waves are generated by downslope turbidity currents. However, the deformation features have also possibly triggered the development of sediment waves.

Keywords:

sediment waves; channel levee backslope; younger sections; turbidity currents deformation features

1. Introduction

The development of sediment waves has intrigued deep marine geologists for many years and yet no conclusive process of wave formation has been identified. Although the features have been described and efforts have been made to constrain the processes involved for the formation and the environment of sediment waves, no conclusive mechanism of formation has been proposed (Wynn et al., 2000; Wynn and Stow, 2002). These waves are commonly associated with Turbidity Current (TC) levee deposits and along-slope bottom current processes (Lee et al., 2002; Wynn et al., 2000). It has been postulated that sediment waves either travel upslope or downslope and develop parallel, perpendicular, or oblique to the flow. Similar features are described on the Monterey Fan that were developed on the levee backslope (Damuth, 1980; Faugères and Stow, 1993; Normark et al., 1980). Likewise, similar features are

described in the Toyama deep sea channel system on the levee backslope (Nakajima et al., 1998). Sediment waves deposited on the preexisting slope failure deposits (Howe, 1996) and generated by turbidity currents in other deep-sea environments have also been documented before. Previously, the sediment waves have been referred to as mud waves, sand waves, giant ripples, etc. Four different processes have been identified for the formation of sediment waves: (a) sediment waves generated through the downslope processes of turbidity currents; (b) sediment waves generated through along-slope bottom current; (c) sediment waves generated through slope failure and deformation processes; (d) sediment waves generated through the interaction of down-slope and along-slope processes (Gong et al., 2012; Wynn and Stow, 2002).

Turbidity current sediment waves with upward concave features are generated by overspill of confined, channelized, and unconfined flows. Unconfined flows generally occur near the channel lobe transition zones, whereas the channelized and confined sediment waves generally develop on the levee backslope (Gong et al.,

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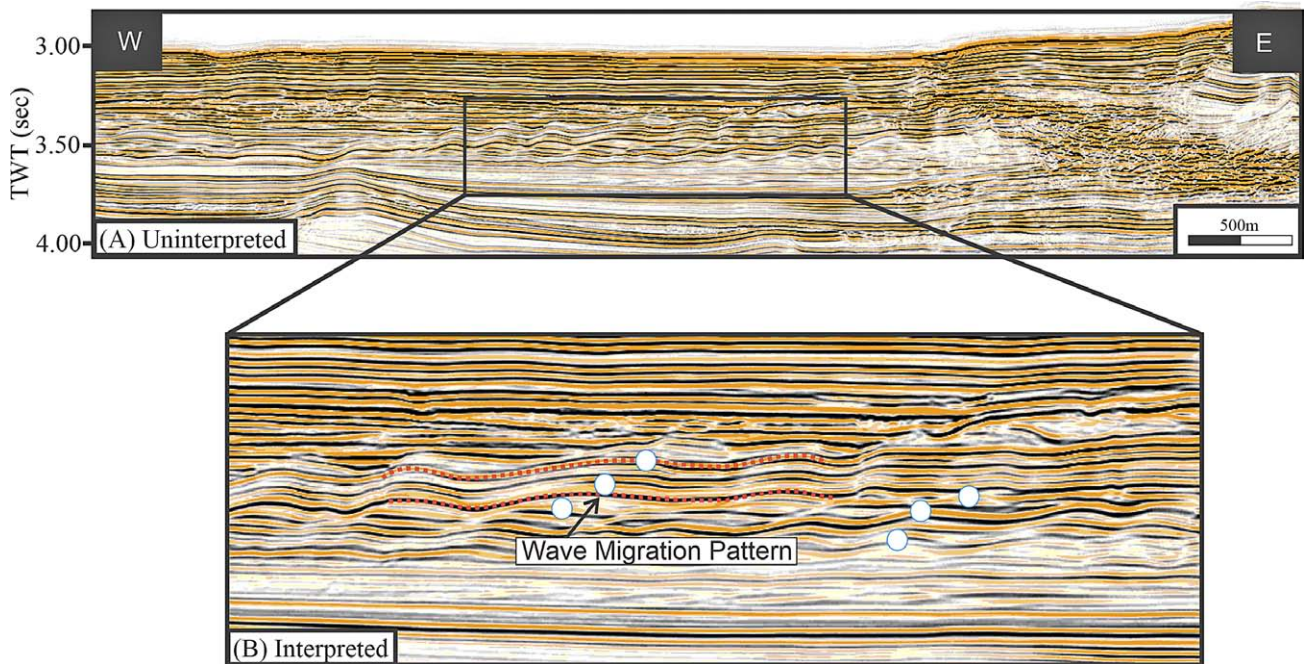


Figure 1: E-W oriented seismic line: (A) Uninterpreted section: shows the seismic cross-section from the Indus Fan. (B) Interpreted section shows the development of sediment waves on the levee backslope marked with a red dotted line. The white circles suggest the migration pattern of the sediment waves.

2012; McCave, 2017; Normark et al., 1980; Wynn and Stow, 2002). These sediment waves are generated beneath the turbidity currents possibly due to turbulent flows or the substrate wavy morphology (Nakajima and Satoh, 2001; Wynn and Stow, 2002). The fine-grained sediment waves developed on the levee backslope generally occur on one side of the channel because of the Coriolis force (Nakajima et al., 1998; Wynn and Stow, 2002). Contrary to this idea, McCave (2017) suggests that in the northern hemisphere, the sediment waves occur on both sides of the channel (looking downslope). Sediment waves are usually concentrated on the outside bend of a meandering channel as an effect of centrifugal forces on the turbidity currents (Normark et al., 2002).

This study focuses on the development of sediment waves and their process of formation on the Indus Fan. Studies have contributed to the understanding of the process of formation of sediment waves. However, the internal morphology and the effect of underlying strata have not been discussed in detail and need to be taken under careful consideration. The objectives of the study are to:

- 1) understand the morphology and internal structure of the sediment waves on the levee backslope;
- 2) understand the growth patterns and development phases of sediment waves during the development of the levee;
- 3) understand the effect of deformation features and underlying strata on the development of sediment waves.

2. Dataset and Methodology

This study utilizes industrial data consisting of 2D and 3D seismic surveys from the Offshore Indus Basin, Pakistan. Seismic data was acquired in 2001 and 2002 at a water depth of ~2700m. The standard seismic processing includes 2D and a 3D Prestack Time Migrated (PSTM) volume. 2D seismic data includes a grid with 5*5 km spacing and covers an area of 75000 km². The recorded length of seismic data is 12 sec TWT with a 160-fold data coverage sampled at 2ms. The zero phased seismic data is displayed at normal polarity at SEG a standard (Ologe et al., 2014), characterized by white, brown, and black reflection patterns signifying positive acoustic impedance (increasing downward) and negative acoustic impedance (decreasing downward), respectively. The dominant frequency of the data is 45Hz with approximately 25m vertical resolution.

The workflow started with identifying the key channel levee zones that accommodated the development of sediment waves using the available seismic data. The unavailability of core data and well cuttings inhibited the direct control for the identification of the lithologies. Seismic attributes improve the visualization of sediment waves in a two-dimensional view that augments the recognition of small-scale waves. To envisage the patterns and depositional nature of the sediment waves, time slices were generated to image the planform geometry. The Root-Mean-Square (RMS) seismic attribute was applied to estimate the square root of amplitudes to describe the internal architecture of the channel levee com-

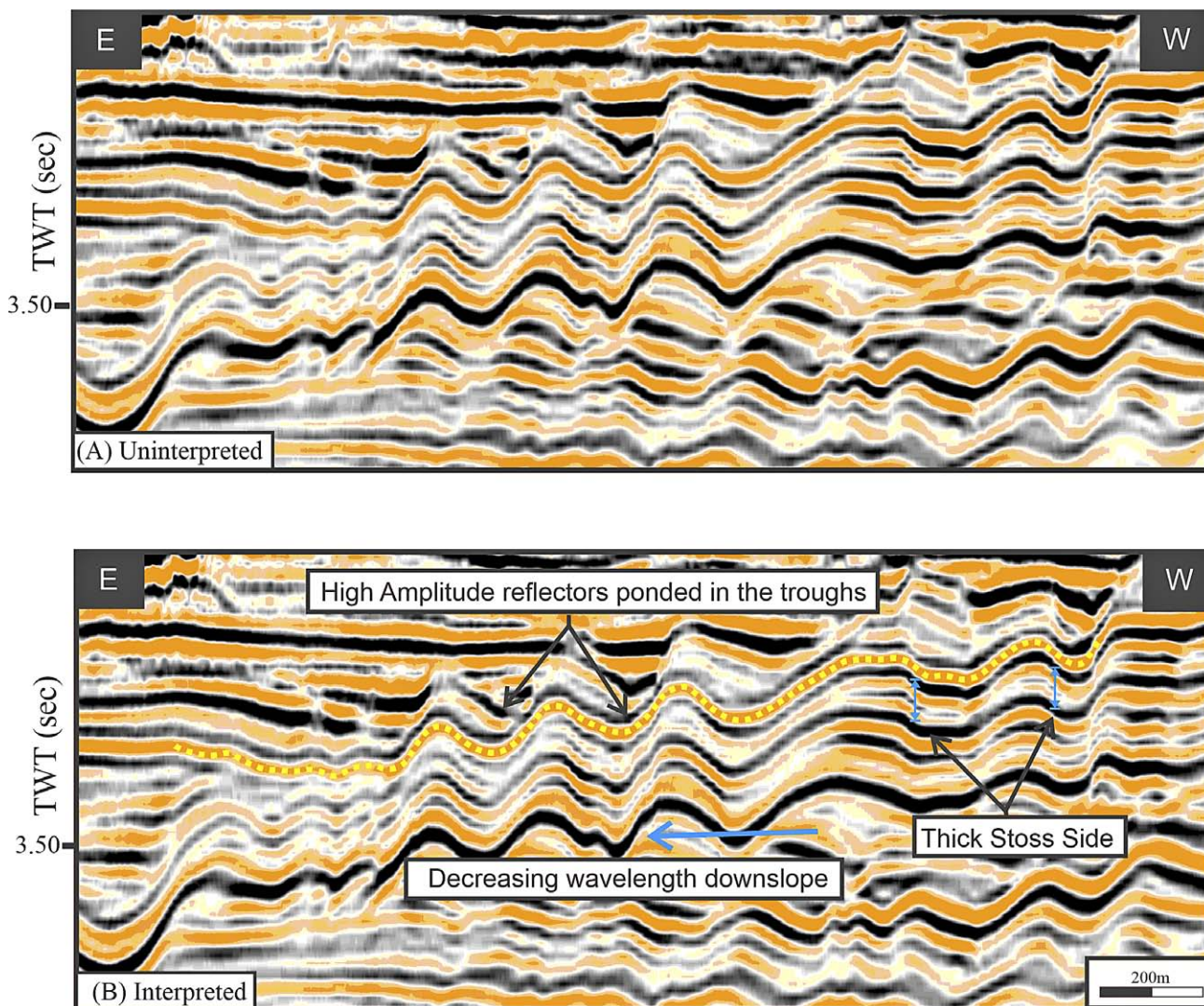


Figure 2: E-W oriented seismic: (A) Uninterpreted section: shows the seismic cross-section from the Indus Fan. (B) Interpreted section shows the downslope decrease in dimensions of sediment waves (the blue arrow). The inverted blue arrows mark the thick stoss side (upslope flank) due to higher sedimentation. The black arrows point to the ponding of hemipelagics on top of the sediment waves that smoothen the relief.

plexes that improve the understanding of three-dimensional sediment waves models. A seismic velocity of 3000 m/s (averaged) was used for seismic interpretation gridding and depth mapping. The dataset was interpreted by using the Petrel and Kingdom suits for stratigraphic and structural interpretation.

The dataset is property of the Directorate General of Petroleum Concession (DGPC), the Ministry of Petroleum and Natural Resources, Pakistan.

3. Results

3.1 Characteristics and Formation process of turbidity Current sediment waves

Sediment waves in the study area display a wavelength of up to 1473 m and a height of 30 m with a slope gradient of 1° - 3.1° (see Table 1 and 2). The dimension of

the sediment waves depends on the sediment type, slope gradient, levee height and the distance from the source as it is observed that the wavelength and height of the sediment wave progressively decrease downslope away from the channel margin (Carter et al., 1990; Normark et al., 2002). It is observed in this study that the sediment wave height and wavelength must be directly related to turbidity flow and the volume of turbidity current (see Figure 1).

With a similar levee slope, variations in the height and wavelength of sediment waves have been observed (see Figures 1, 2, 3 and 4). Wave crests are generally perpendicular as they are aligned parallel to subparallel to the slope.

Sediment waves in the study area are generally asymmetrical upslope. However, as the wave progresses downslope, the symmetry increases (see Figures 2 and 3). It has also been observed that sediment waves may

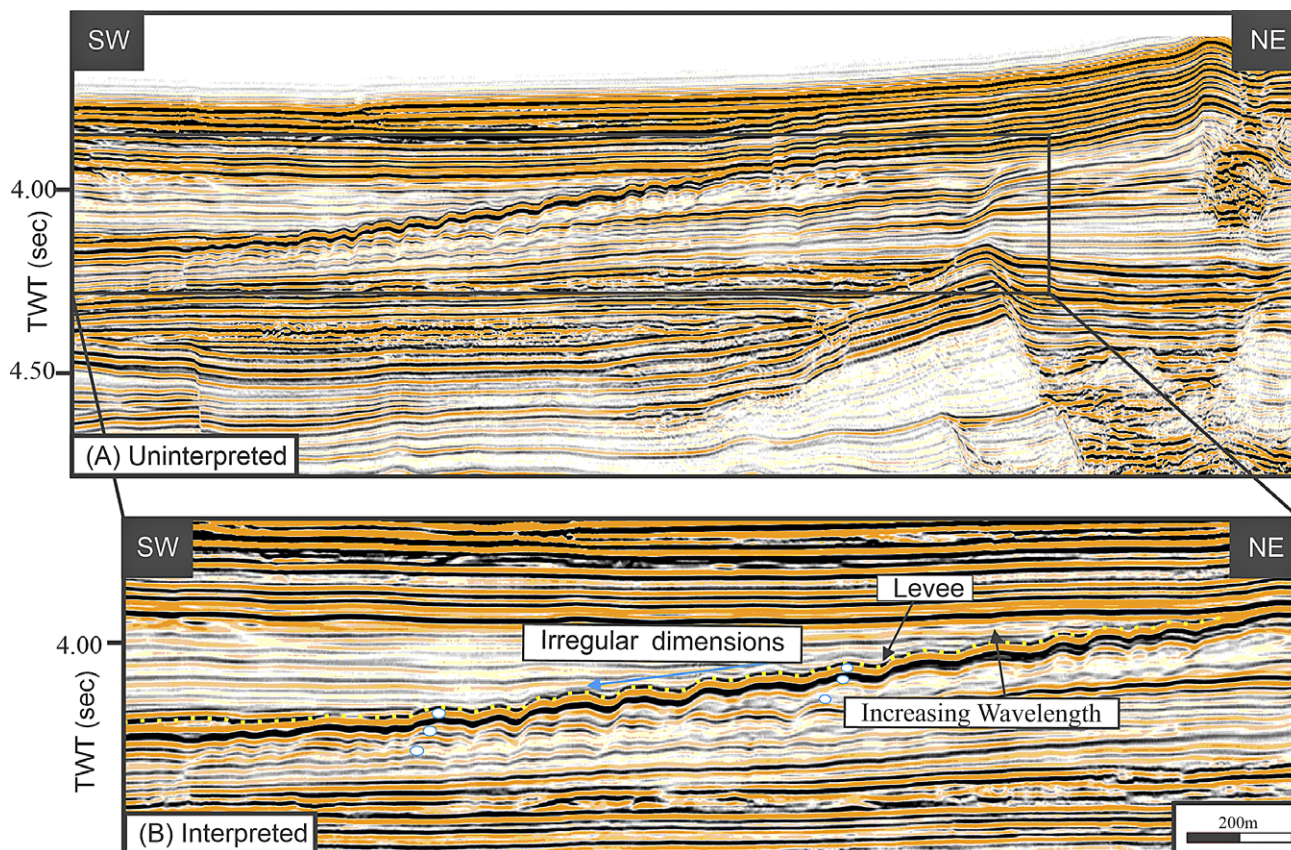


Figure 3: SW-NE oriented seismic line: (A) Uninterpreted section: shows the seismic cross-section from the Indus Fan. (B) Interpreted section shows the zoom in the section of the sediment waves with dimensions changing variably downslope and towards the top.

show unusual symmetry, as often there is no clear pattern visible. This indication shows that no clear relationship is observed between the wavelength and channel dimensions whereas he suggests that a positive correlation exists between wavelength and wave height (Normark et al., 2002). Sediment waves evolve through time as the parallel developing waves merge upslope (Wynn and Stow, 2002). Sediment waves become more aggrading upslope (see Figure 3) in time because of the ceasing of migration (Normark et al., 2002).

3.2. Distribution and Geometry of Sediment Waves

The distribution of sediment waves in the Indus Fan is limited to the levee back-slope of Plio-Pleistocene age in the study area, with the exception of a few sediment wave occurrences on the slope. The sediment waves are absent in the older succession of the Indus Fan in the study area. These sediment waves have developed on the outer bends of the channel levee complex. The wavelength of sediment waves is as small as 122 m and extends to 1463 m. The sediment waves on the levee flanks are generally high relief upslope or near the channel margin and decrease in wavelength and height downslope of the levee (see Figures 1, 2, 3, 4, 5 and 6). The NW-SE oriented sediment waves on the regional slope suggest that the flank on the stoss side is generally smaller in

contrast to flank on lee side (see Figure 2). It is observed that the sediment waves on the regional slope increase in wavelength downslope, unlike the sediment waves on the levee back-slope. The lee side appears to be much steeper than the stoss side. These waves have developed on the sediments deposited due to mass failure.

The geographical positioning of the sediment waves on the levee back-slope is also unique here on the Indus Fan. Often, the sediment waves have developed in proximity to the channel, but it is also noted that the development of sediment waves sometimes have also occurred more towards the distal side while the proximal part lacks the sediment waves (see Figures 4, 7 and 8). In another case, the wave height in the proximal part is smaller, grows higher towards the middle part of the levee and continues to reduce again distally (see Figures 2, 3 and 6).

Sediment waves show two varying patterns of wave development in the proximal portion of an older levee and the distal portion of a younger levee (younger in time) (see Figure 8). The older proximal part exhibits more pronounced sediment waves with dimensions decreasing distally. The wave pattern on the overlying levee is very mild as the reflectors are well stratified parallel to subparallel. Towards the top of the levee in the younger succession, the sediment waves grow to be

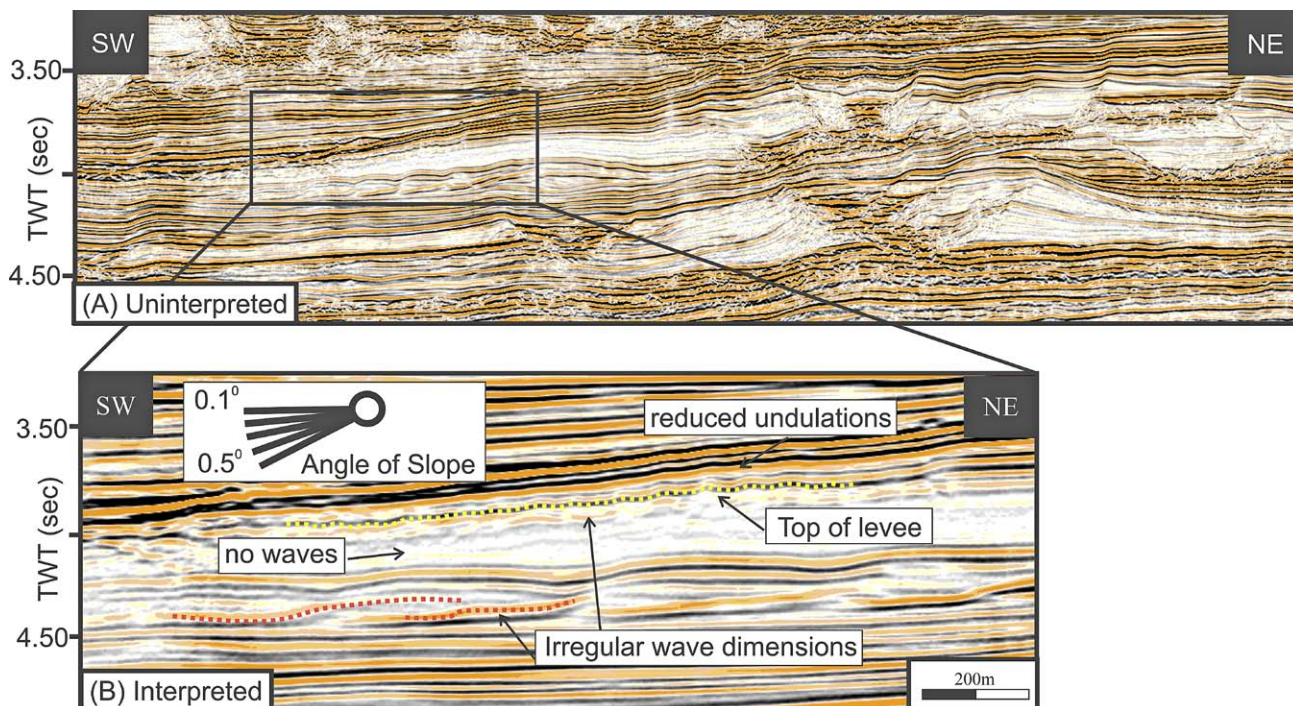


Figure 4: SW-NE oriented seismic line: (A) Uninterpreted section shows the seismic cross-section from the Indus Fan. (B) Interpreted section: the high slope angle of the levee does not concur with high dimension sediment waves. Although the high angle increases the aggradation of sediment waves from the bottom to the top of the levee.

thicker and bigger in dimension, but the wave height is highly irregular. Although, the wavelength appears to decrease gradually downslope. The rate of upslope migration is approximately similar with a higher aggradation component in both segments of sediment waves, i.e. the sediment waves developed on the bottom and the top of the levee.

The sediment waves are deficient of a clear growth pattern in the older to the younger section of the levee. Although, from the proximal to distal side, the waves appear to be symmetrical overall with decreasing dimensions. However, the vertical synchronicity is lacking. Initially, the waves do not follow the underlying undulation, but in the later phase of development, they follow the shape of the older units. A sudden significant decrease in wave dimensions is visible towards the top of the levee but maintains the upslope migration (see **Figure 2**). Similarly, the initial phase of development of sediment waves becomes irregular towards the younger successions of the levee (see **Figure 3**). Sediment waves in the proximal portion are half crest but become more pronounced distally (see **Figures 3 and 6**).

An inconsistent pattern of sediment wave development inside a single levee suggests the varying depositional process (see **Figures 8, 9 and 10**). Here, the older section of the levee accommodated the development of the sediment waves, but a sudden disappearance of waves is observed as the levee amplitude decreases from high amplitude to a significantly transparent geometry (see **Figure 4**). On top of the levee, the sediment waves

have developed again towards the distal side with a distinct upslope migration style (see **Figure 4**).

In **Figure 6**, the sediment waves are parallel to sub-parallel with normal wave dimensions and growth with a sudden amplitude increase towards the distal part of the levee. Highly chaotic, discontinuous reflections grade into more continuous, parallel sediment waves downslope (see **Figure 10**). The overlying hemiplegics strata is affected by the wavelength and height of the sediment waves. The symmetry of the wave decreases downslope as well, with stoss side getting steeper. This unique behaviour does not affect the upslope migration of the sediment waves that cease in the proximal part of the levee where the sediment waves become aggradational (see **Figures 2 and 10**).

In the study area, sediment waves have developed on both flanks of the channels (see **Figure 9**) as suggested by **McCave (2017)** but generally on the outer bend of the channel. Although the levees that host the sediment waves are different, the wave dimensions and growth patterns are similar on both levees irrespective of the direction of the flanks. The thickness and the extension of the levees have no impact on the development of the sediment waves. One important fact is that the orientation of sediment waves that have developed on both the flanks is different than those sediment waves that have developed on either side of the levees. Only the seismic profiles-oriented NE-SW have waves on both flanks in the study area (see **Figure 9**). The older sediment waves have influenced the development of younger sediment

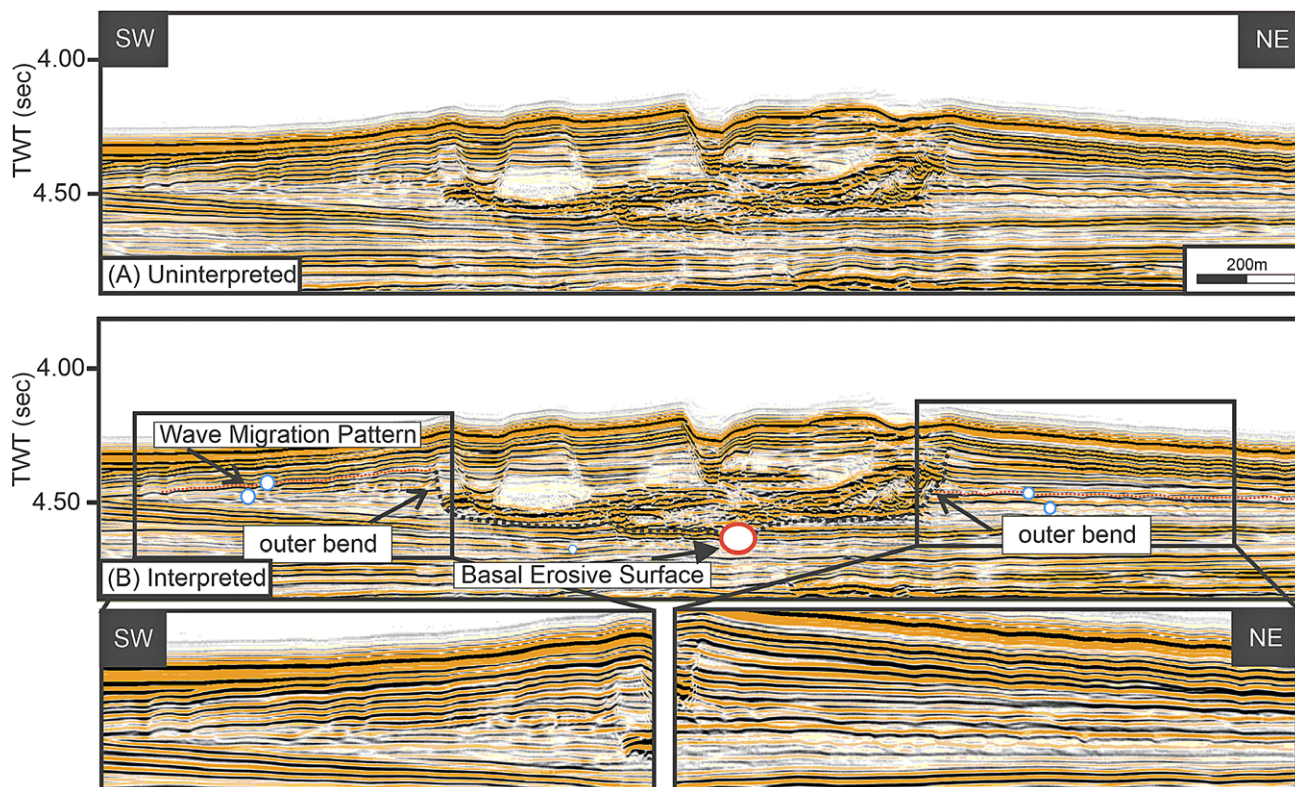


Figure 5: W-E oriented seismic line: (A) Uninterpreted section shows the seismic cross-section from the Indus Fan. (B) Interpreted section: wavelength and height of the sediment waves decrease downslope.

Table 1: The quantification of sediment wave characteristics on the Indus Fan.

S. No	Maximum (m)	Minimum (m)	Average (m)
Wavelength	1473	122	486.84
Height	60	10	30
Angle	3.51	0.49	1.58
Thickness of the levee	740	130	372.82
Length of the levee	29010	6520	21160

Table 2: Relationship between levee angle and Sediment wave dimensions in the study area.

Max Wavelength (m)	Min Wavelength (m)	Max Height (m)	Min Height (m)	Angle of Levee (degrees)
1473.91	196.88	40	20	1.00
1100.46	271.2	12	10	3.51
755.8	348.27	30	10	2.50
631.74	177.01	30	10	2.48
976.51	179.92	200	50	3.20

waves although the entire levee is devoid of sediment waves, except the portion that is overlying the sediment waves of the older levee (see **Figure 7**). Both the levees are in opposite directions and show similar behaviour as they encounter each other.

Levees that host the sediment waves are quite distinct from each other in geometry and morphology. From the

investigations, it is observed that the influence of slope angle of the levee, thickness and multiple phases of levee development have minimal impact on the sediment wave growth. High dimension sediment waves lie on low angle levees (see **Figures 1 and 9**) whereas it is also observed that sediment waves with higher dimensions have also developed on high angle slopes (see **Figures 5 and 8**). Similarly, high wavelength and low height sediment waves have also developed on high angle levee slopes (see **Figure 10**). The surface extension of the levee has accommodated the growth of sediment waves without apparently influencing their dimensions. One important element of sediment waves is that often during the entire episode of the levee build up, the formation of the sediment waves has not been terminated (see **Figures 1, 2, 3 and 8**). The dimensions may have varied but the abrupt seizure has not occurred evidently due to limited control of the levee.

3.3. Geometry of the Levees

Sediment waves have generally developed on the outer bank of the channels that suggest an overspill of the turbidity currents (see **Figures 1, 5, 6, 7, 8 and 9**). Sediment waves have developed on the levees that are steeply dipping (see **Figure 5, 8 and 9**). 2D seismic profiles (see **Figure 13a**), a line drawing (see **Figure 13b**) and 3D seismic attributes (see **Figure 13d**) endorse the fact that sediment waves have developed perpendicular to oblique to the flow direction and the slope gradient. In

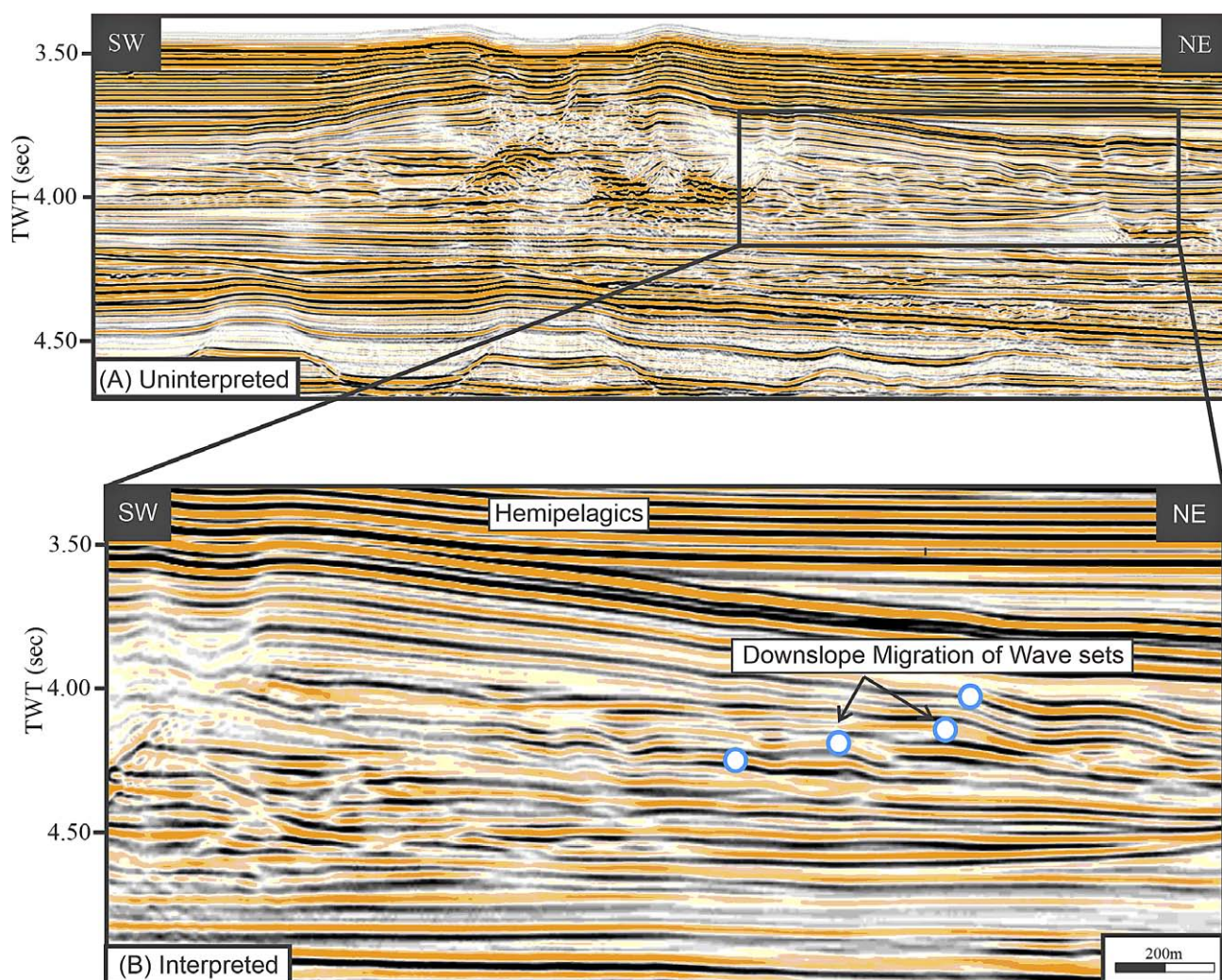


Figure 6: SW-NE oriented seismic line: (A) Uninterpreted section: shows the seismic cross-section from the Indus Fan. (B) Interpreted section shows the downslope migration of sediment waves set represented in white circles with increasing dimensions towards the top of the levee.

the presence of irregular morphology or deformation features (see **Figure 12**), the spill of turbidity flow may still lead to the generation of sediment waves even if no internal lee wave is generated. Wave initiation will take place over the deformed features which may be followed by upslope or downslope migration of the sediment waves.

4. Discussion

4.1. Wave forming process

The continuous growth and temporal persistence of sediment waves originated from the turbidity current, which indicates the existence of their continual equilibrium profile with the host turbidite system (**Lewis and Pantin, 2002**). As the slope steepens beyond 0.1° , the sediment waves begin to develop (**Lee et al., 2002**). Several studies have formulated the process of initiation

of sediment waves and concluded that waves form as antidunes with waves generated internal to the turbidity current flow (**Ercilla et al., 2002; Wynn et al., 2000**). It is also suggested that the waves may have been generated by internal lee waves (**Lewis and Pantin, 2002**). In this study, it is likely that two major processes have influenced the generation of sediment waves simultaneously:

- 1) the generation of internal waves in the turbidity currents;
- 2) the morphological irregularities underneath the turbidity currents have influenced the sediment waves formation.

Evidence for the process of formation of sediment waves through internal waves is that, despite the variations of slope angles of the levees and the turbidity current flow, the waves have generated with higher dimensions. The flow velocity may not always be an imposing factor as slow, diluted and continuous gravity flows pos-

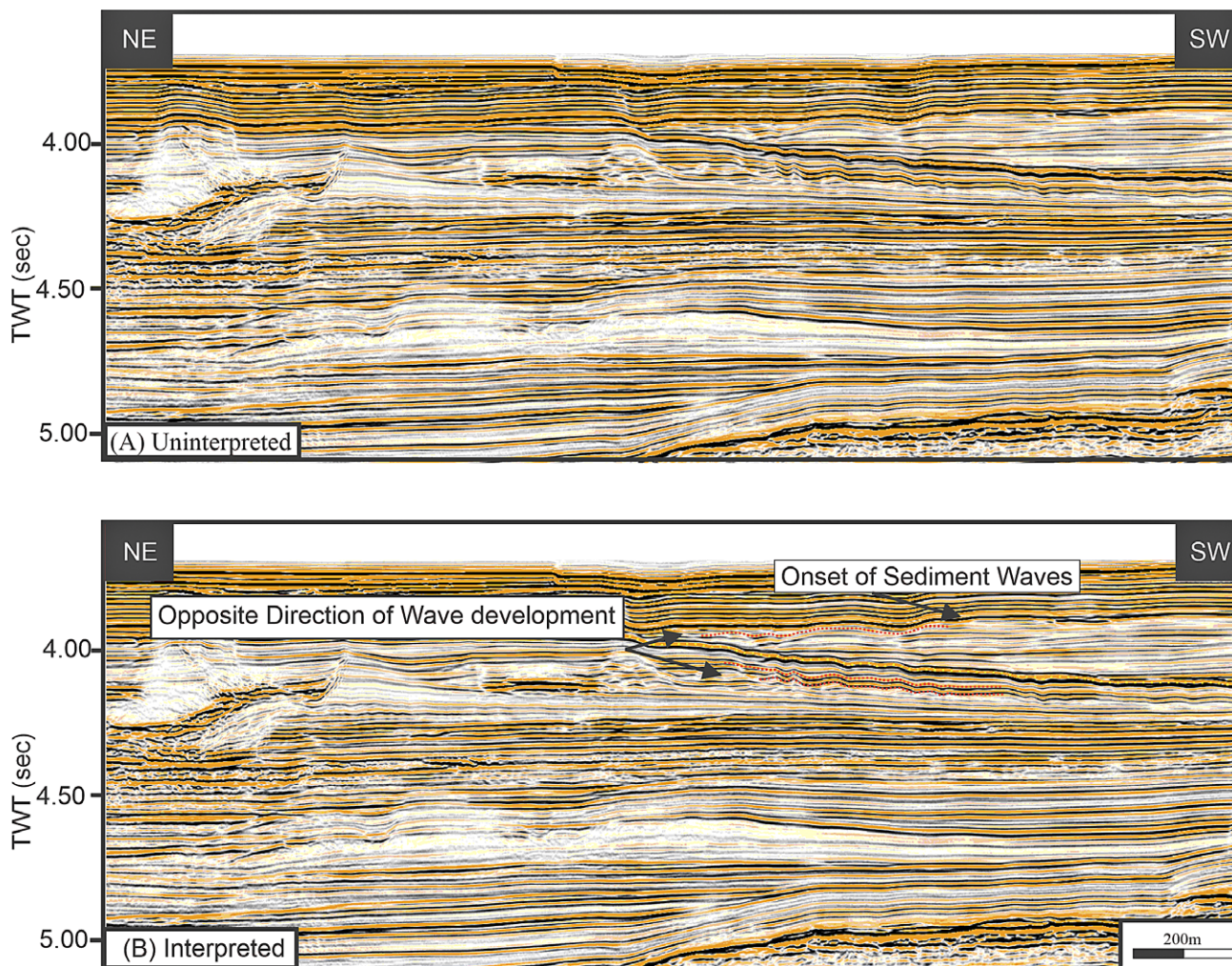


Figure 7: NE-SW oriented seismic line: (A) Uninterpreted section: shows the seismic cross-section from the Indus Fan. (B) Interpreted section shows that migration pattern of waves remains unchanged, but because of the break in formation of sediment waves, the new set has developed downslope of older sediment waves.

sibly aid in the generation of sediment waves (Wynn et al., 2000).

4.2 Wave migration

Generally, wave sediments are fine grained turbidites comprised of mud/silt with pelagic and hemipelagic interbeds (Wynn and Stow, 2002). Beds become generally thicker upslope near the channel margin. A similar feature has been observed on the Amazon Fan during Ocean Drilling Program (ODP) i.e. the drilling of sediment waves (Flood, 1994; Normark et al., 2002). Three different types of migration have been observed in the study area:

- (a) upslope wave migration;
- (b) vertical aggradation of sediment waves;
- (c) upslope or downslope wave set migration.

a) Upslope wave migration

Sediment waves display an upslope migration pattern from the distal to the proximal part of the levee

that ceases near the channel margin where the waves become thicker. On the contrary, different wave sets on a single levee that develop with different turbidity current flows display dissimilar patterns of growth (see Figure 10). The older sediment wave set displays progressive upslope migration overlain by a more aggradation display of a younger wave set at a similar distance from the channel margin. Lateral wave migrations are reported to be as high as 20m/1000 years (Lewis and Pantin, 2002).

b) Vertical aggradation of sediment waves

Over time, sediment waves witness aggradation as the upslope migration ceases (see Figures 2, 3 and 6). Here it is noted that older sediment waves are thicker in amplitude, which decreases upwards towards the younger sediment waves. The patterns of migration and aggradation are limited to individual wave sets which vary with the development of younger sediment waves. The sediment wavelength also increases towards the top of the levee (see Figure 2). An example from Amazon drilled

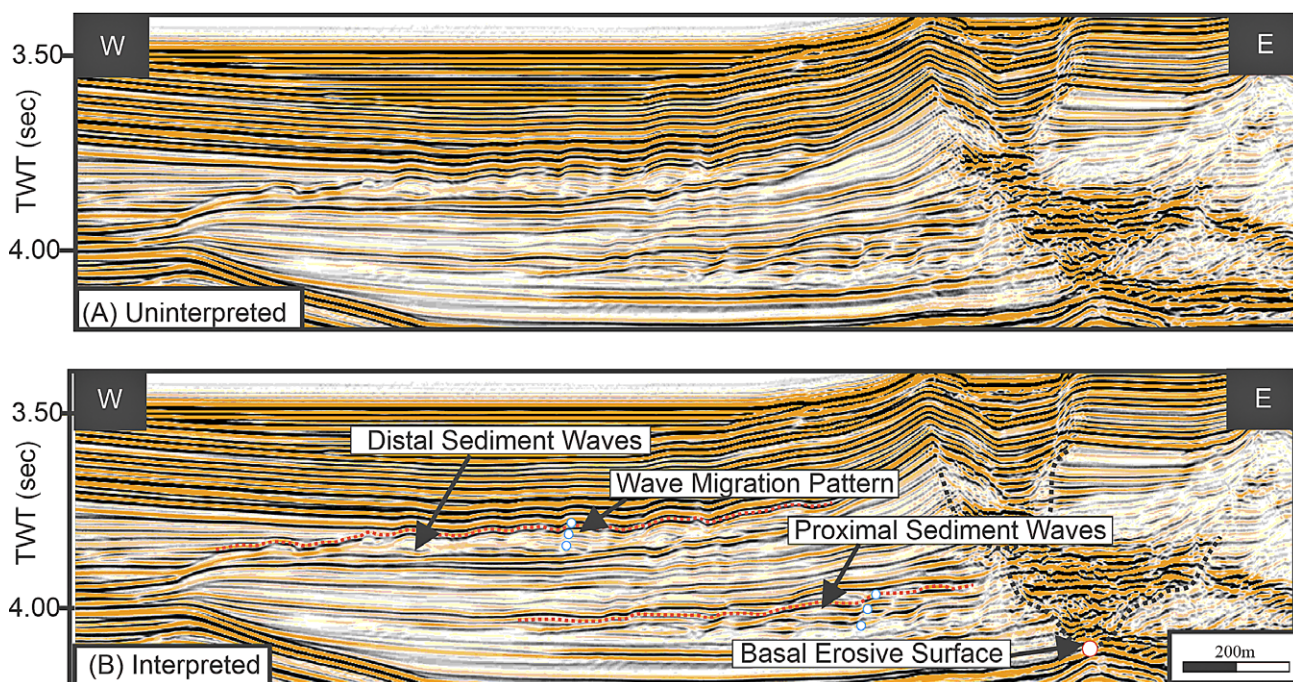


Figure 8: W-E oriented seismic line: (A) Uninterpreted section: shows the seismic cross-section from the Indus Fan. (B) Interpreted section shows change in behaviour of the sediment waves from older proximal part of the levee to younger distal portion. The white circles suggest that the sediment waves maintain their upslope migration.

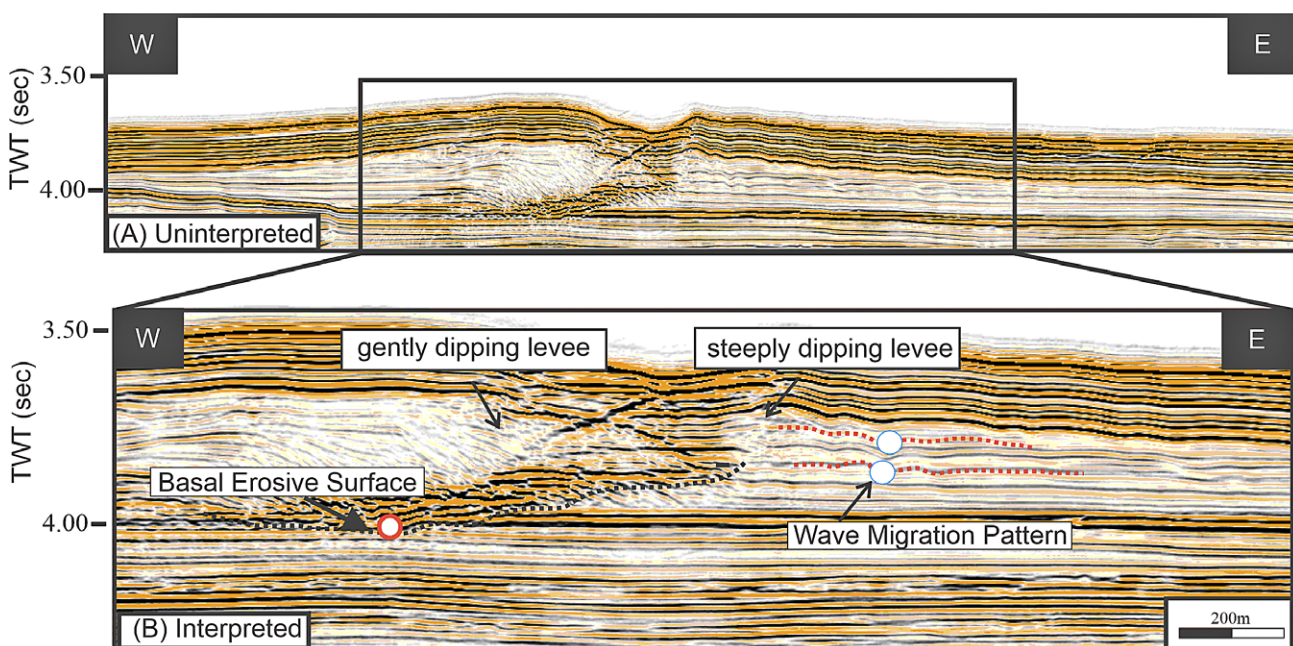


Figure 9: W-E oriented seismic line: (A) Uninterpreted section shows the seismic cross-section from the Indus Fan. (B). Interpreted section: sediment waves have developed on the outer bend of the channel belt. The inner levee is gently dipping towards the channel margin. Abbreviation: TWT: Two Way Travel Time in seconds.

portion suggest that up to 350 individual beds were amalgamated over a prolonged period of time as a result of multiple turbidity current (Lee et al., 2002).

c) Upslope or Downslope Wave Set Migration

The migration of an entire wave set is observed in the study area where the multiple set of sediment waves dis-

play distinguishing behaviours (see Figure 6). The sediment waves developed on the left side of the channel (looking downslope) (see Figure 8). Here, the wave is grouped into two sets. The older wave set is migrating upslope with a significant aggradation component. The younger set, which was deposited in the later phase of channel development, shows a predominant aggradation component with slight upslope migration as well. Pe-

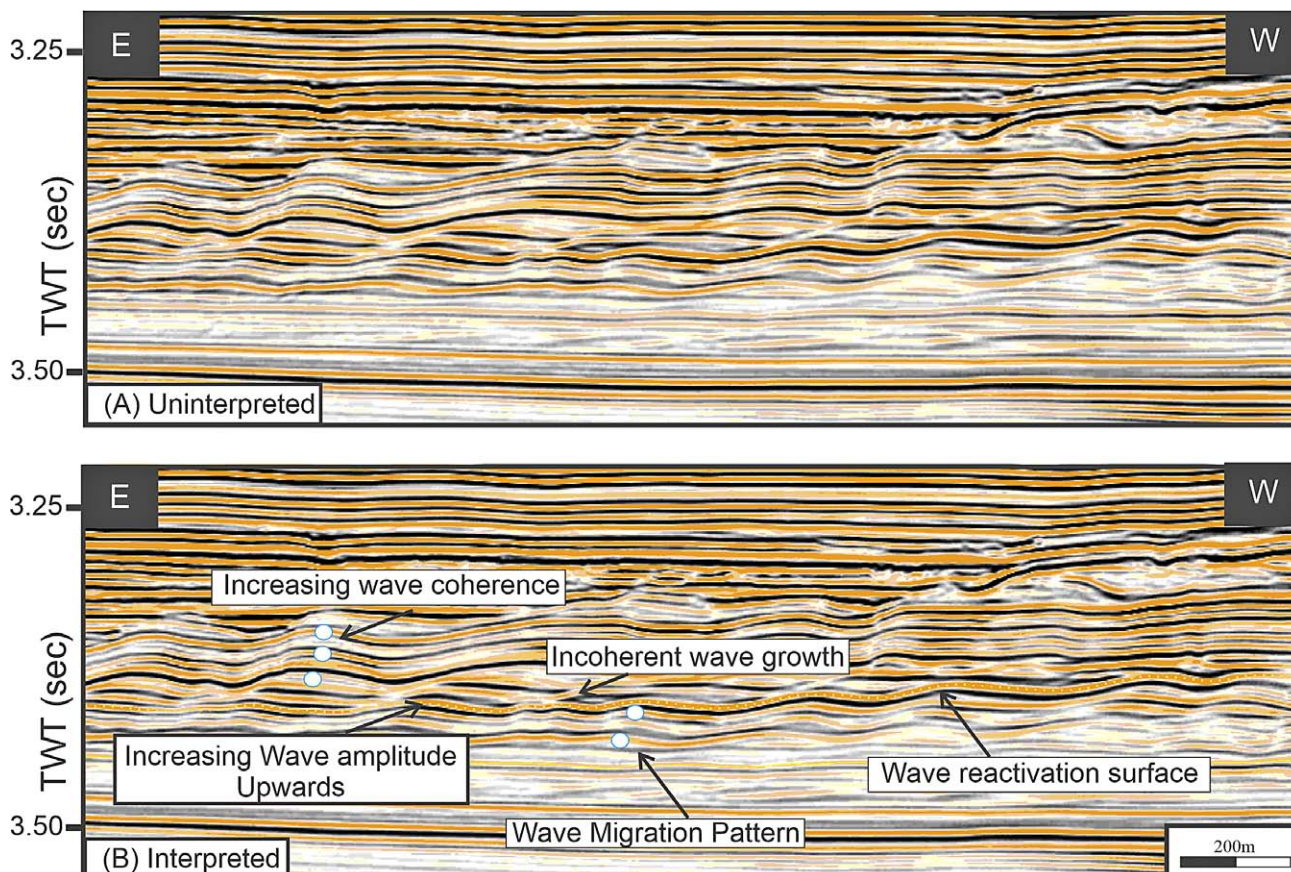


Figure 10: E-W oriented seismic line: (A) Uninterpreted section: shows the seismic cross-section from the Indus Fan. (B) Interpreted section: sediment waves over an irregular surface that acts as a wave initiation surface. Initial significant upslope movement slows towards the top where aggradation increases.

lagic / hemipelagic deposits fill the hiatus or break in levee development. The younger sediments waves are affected by the older sediment waves only in the distal section of the levee (see **Figure 7**).

4.3. Implications of Sedimentation, Turbidity Currents and Levee Slope

The variation in the wavelength and wave height are influenced by the turbidity current velocity and thickness (**Ercilla et al., 2002**). Each flow has undoubtedly travelled with different flow regimes that carried varying grain sizes and quantities (**Lee et al., 2002**). It has been observed in the study area that an upward increase in wavelength possibly occurs because of increasing flow velocity and higher sediment input (see **Figures 2, 3, 8** and **10**). The Indus Fan has witnessed an increased sediment supply between 11 m.y. and 2 m.y. after the uplift of Himalayan and Karakorum ranges that act as the source for the sediment supply to the Indus Fan (**Clift and Gaedicke, 2002; Clift et al., 2001; Gaedicke et al., 2002; Peter Clift et al., 2002; Rea, 2013**).

A break in deposition or decrease in turbidity current flow velocity changes the dimensions of the sediment waves as well (see **Figures 4** and **8**). Older sediment

waves that developed in the proximal section undergo reduced dimension towards the middle of the levee until an increase in dimensions is observed in the youngest succession of the levee towards the distal side (see **Figure 8**). This is apparently due to the episodic decrease followed by an increase in flow velocity and sediment load of the turbidity current. On the other hand, an opposite pattern is apparent in the study area that sediment waves tend to maintain their size and height toward the top of the levee (younger section) (see **Figure 8**). This indicates that each overspill of the turbidity current may deposit a significantly different kind of wave set irrespective of the underlying older sediment waves. Upslope migration is the result of increased sedimentation on the upslope flank and erosion on the downslope flank of the wave. Increased sedimentation upslope may cause the waves to be thicker upslope as well as the wave migration. It is not observed in the study area that any inner levee has hosted the sediment waves. Individual reflections are easily traceable in the sediment waves on levee backslope due to the presence of parallel to subparallel seismic reflections.

Levee slope angle in the study area is less influential to the generation of sediment waves of the channel flanks (see **Table 2**). High slope angle of the levees has

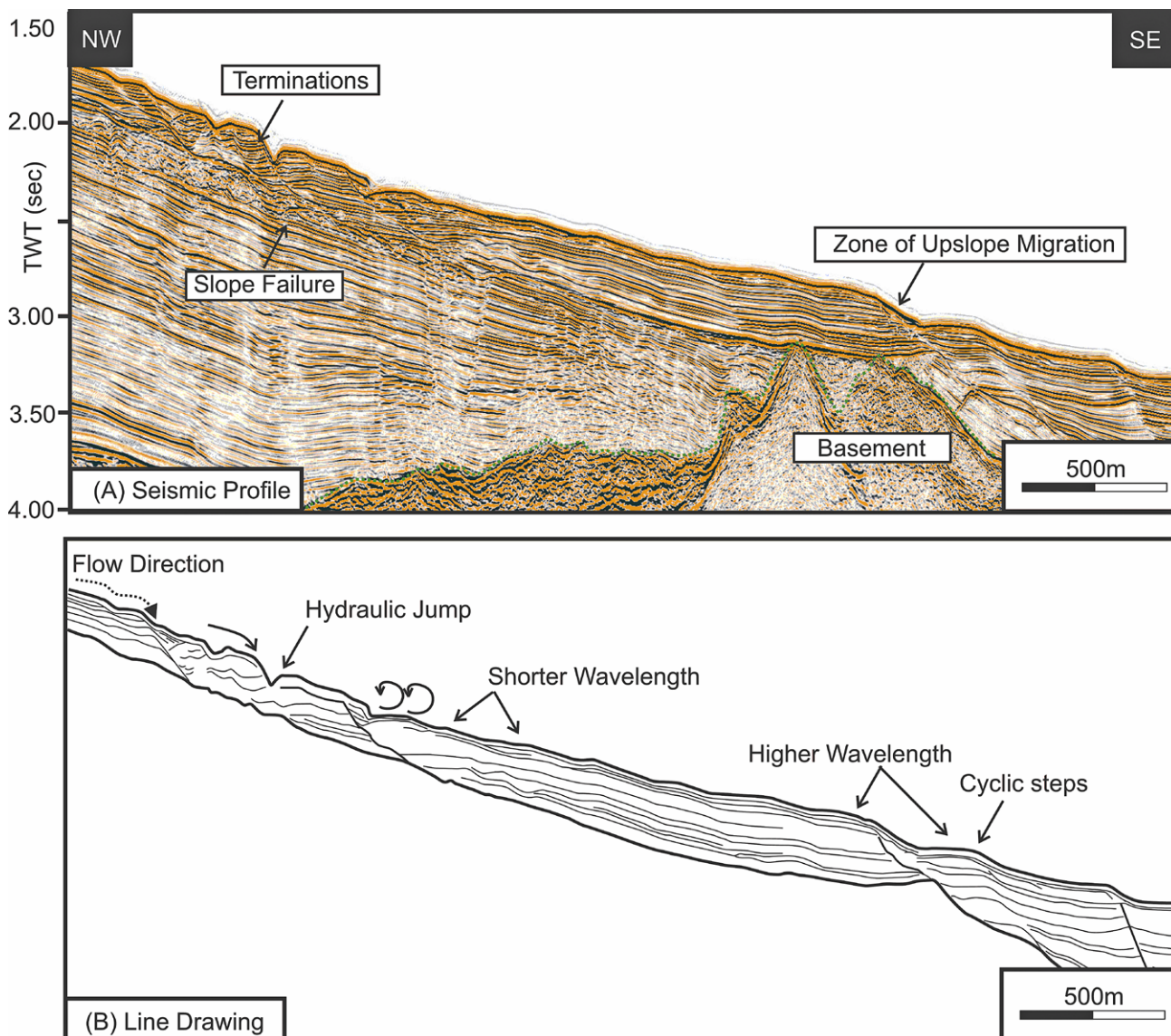


Figure 11: NW- SE: oriented seismic oriented seismic profile shows the regionally developed sediment waves on the slope. The morphology and orientation are different compared to channel levee backslope. (A) Seismic section showing the regional slope of the Indus Fan. The sediment waves (cyclic steps) have developed on the irregular surface created due to slope failure. Irregular topography also developed due to Murray ridge. (B) Line Drawing: shows the flow direction of turbidity currents. The flow velocity increased downslope that created the increasing wavelengths of sediment waves downslope

created low dimension waves. The minimum wavelength is 271 m, and the maximum reaches up to 1100 m with an average of 486 m. The minimum height of a sediment wave is 10 m and the maximum height is 30 m, with an average of 20 m in the distal portion of waves. In the proximal side, the minimum wave height is 10 m with the maximum height reaching up to 12 m which is averaged at 10 m. On the contrary levee slope with low angles have generated the higher wavelengths and heights in the study area. The minimum wavelength of the sediment wave on the low angle levee is 196.88 m whereas the maximum wavelength is 1473.91 m with an average of 832.83 m (see **Table 1**). The minimum height of the sediment waves is 10 m while it reaches to a maximum of 60 m and an average of 31.66 m. It is important

to note the wave height is 60 m at the distal end of the wave field, which is the repercussion of an undulation provided by the underlying morphological feature. This also indicates that the morphological effect on the formation of sediment waves is equally essential.

Deformation features significantly impact the sediment wave dimensions, usually in the form of an increase in wavelength and height (**Lee et al., 2002**). Sediment waves have developed on the proximal side of the levee with low dimensions but the downslope decrease in dimensions pattern followed. Near the distal end of the levee, deformation features abruptly increased the sediment wave height and wavelength that carried its effect into the overlying hemipelagic drapes (see **Figure 12**). Another morphological impact is apparent where

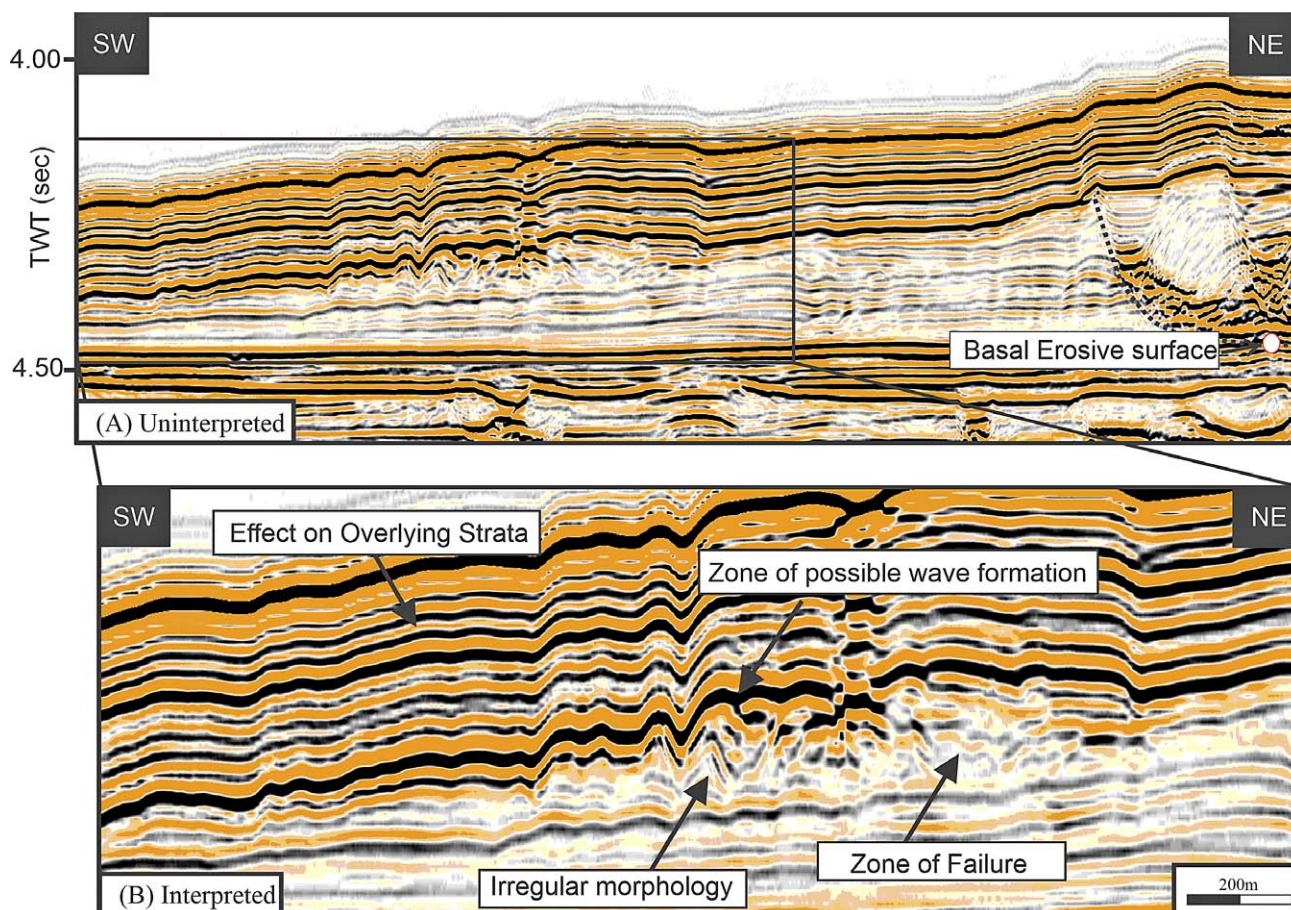


Figure 12: SW-NE oriented seismic line: (A) Uninterpreted section: shows the seismic cross-section from the Indus Fan. (B) Interpreted section shows the point where the waves may have generated due to the irregular surface caused by slumping in the levee. The black dotted line marks the boundary of the channel. The arrows point to the zone of failure on the top layers of the levees.

the sediment waves on one levee influenced the development of sediment waves on another levee of a different channel (see **Figure 7**). No sediment waves are visible in the proximal side of the levee near the channel margins but at the distal end, sediment waves have developed (see **Figure 7**). In similar scenarios, an internal wave is not essential to initiate a wave but the subsequent flows on the levee may affect the upslope migration of the sediment waves.

4.4. A comparison between Sediment Waves and Deformation features

Deformation on a submarine slope is quite prevalent, especially where slope gradients and the sedimentation rates are high (**Wynn and Stow, 2002**). The fluctuations of sea level are essentially also responsible for slope failure, either due to the retaining of sediments during high sea level or exposure of shelf and slope during falling sea level (**Posamentier and Kolla, 2003**). A few deformation features that closely resemble the sediment waves have been analyzed in the study area. These features lie on the levee backslope in the Pleistocene age that created confusion unless closely investigated. Some

discrimination features have been identified by (**Nakajima and Satoh, 2001; Wynn et al., 2000; Wynn and Stow, 2002**).

4.4.1. Migration

Fine grained sediment waves generally migrate upslope opposite to the direction of prevalent current direction. Upslope sediment waves are thicker due to higher sedimentation rate. The variation between lee and stoss side is also unique in the sense that the lee side undergoes erosion and sedimentation occurs on the stoss side. Deformation features do not display similar migration patterns, but rather in opposite direction and the thickness on both the flanks are similar (**Lee and Chough, 2001**). Here in the study area, no migration trend has been observed as the levee upslope clearly lacks any deformation feature (see **Figure 2**).

4.4.2. Reflections

Individual reflections can be traced across the sediment wave crests that are easily recognizable between the adjacent waves. On the contrary, the creep folds

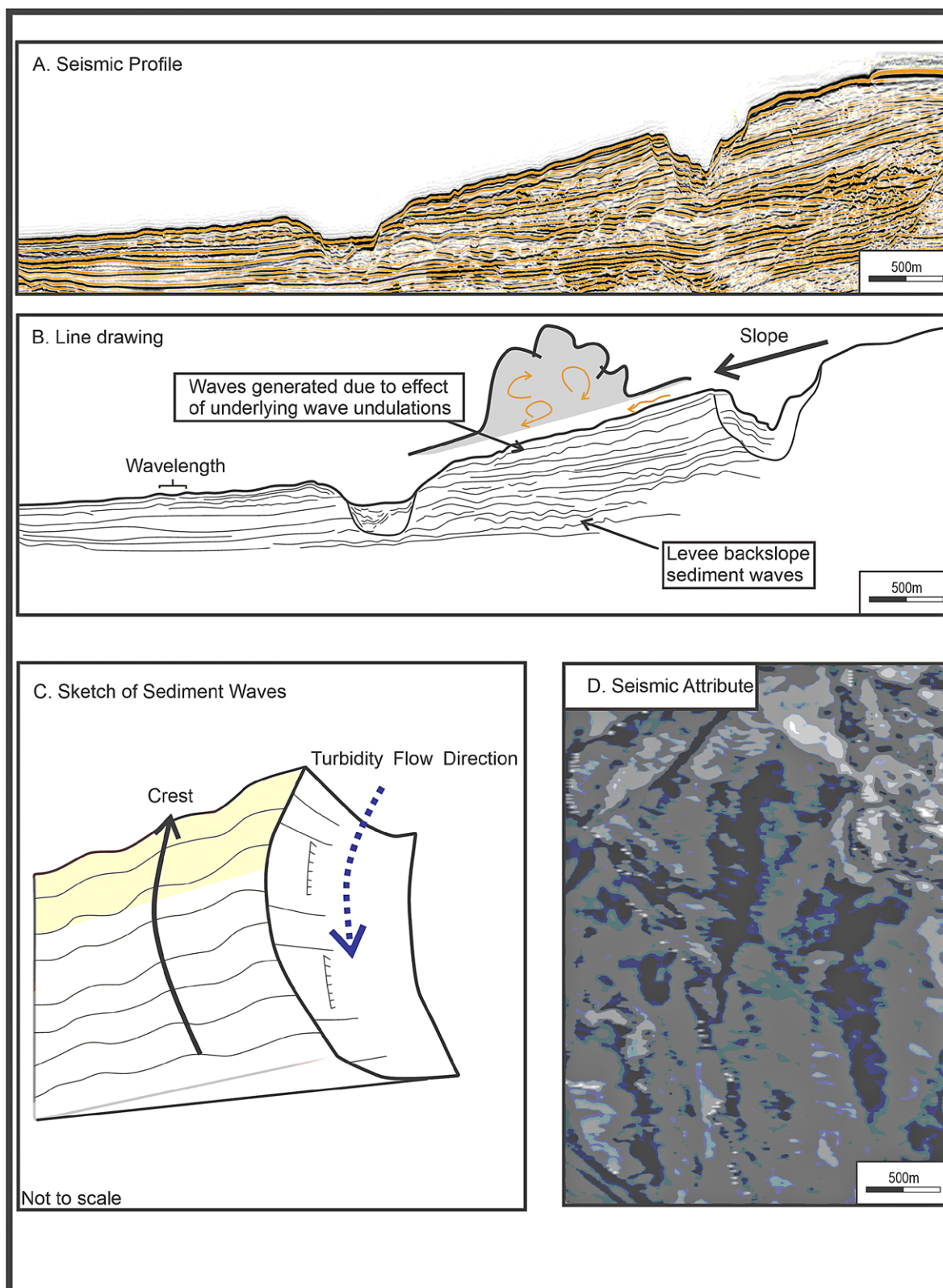


Figure 13: (A) Uninterpreted Section: shows the seismic cross-section parallel to regional slope of the Indus Fan. Two different types of sediment waves are visible. Sediment waves are associated with channel levees and sediment waves are associated with unconfined flows of turbidity current. Levee backslope sediment waves are developed at the top of the profile. Waves generated by unconfined flows are cut by the later developed channel towards the distal portion of the profile. Line drawing: (B) an interpretation of seismic profile and a sketch of turbidity current flow over the slope. (C) Sketch of the levee over which sediment waves have developed. The spilling of turbidity current here on the Indus Fan is associated with the outer bend of the channel belt. (D) Seismic attribute map from 3D seismic display the sediment waves adjacent to channel belt (not visible here) oblique to the channel levee. The orientation of the sediment waves is oblique to the channel belt.

clearly display displacement and breakage between the adjacent beds. It is often difficult to track the beds in the deformation structures (see **Figure 12**).

4.4.3. Regularity

Sediment waves are highly regular in terms of reflector spacing and crest and trough dimension (**Lee et al., 2002**). The internal structure of the waves appears to be similar from one bed to another (**Lee et al., 2002**). On the other hand, creep folds are highly irregular (**Lee and Chough, 2001**). Such regularity is observed in a study where each reflector on sediment waves can be traced to its entire length (see **Figure 1, 2, 6 and 8**).

4.4.4. Coherence

Sediment waves display a clear trend in dimensions e.g. a wave dimension decrease downslope as the turbidity current, slope angle, sedimentation decrease away from the source (**Wynn et al., 2000**). However, the varying nature of dimension patterns is also observed in the study area (see **Figures 1, 2 and 10**). Contrary to this, creep folds show a hummocky spread of dimension (see **Figure 12**).

4.4.5. Thickness

Sediment waves decrease in thickness downslope whereas deformation features may display an increased thickness away from the source of origin (**Wynn and Stow, 2002**). A similar trend in thickness of the deformation features is analyzed away from the source near the distal end of the levee (see **Figure 12**).

Creep folds modify the strata and morphological surfaces that in turn may act as the initiation surface for the sediment waves to occur. Similar features have provided the geometry for the development of sediment waves in the study area on the Indus Fan (see **Figure 12**).

4.5. Regional slope Sediment waves

An example of slope sediment waves has been observed on the Indus offshore slope which is not related to levee back slope sediment waves (see **Figure 11**). These layered, concave upwards, subparallel reflectors, sediment waves have formed because of unconfined turbidity flows as antidunes. The NW-SE seismic cross-section displays the upslope migrating sediment waves that die out in the proximity. The wave field is only visible on 2D seismic data hence any curvature and sinuosity quantification are not possible. Slope gradient in the wave area is 2.01° . Wave dimensions are an irregular form upslope to downslope. Initially, the wavelength is 50 m, and the wave height reaches up to 200 m and the minimum height is 50 m with an average of 90 m. These sediment waves are underlain by mass failure deposits which acted as a platform for wave initiation (see **Figure 11**). As the turbidity current flows across a rough floor, sediment waves develop and migrate upslope (**Lee et al., 2002**).

The NW- SE oriented seismic profile reveals that the sediment waves show a sudden increase in negative relief at the proximal side and then continue to be asymmetrical downslope. The sediment waves height decreases normally downslope, but the wavelength gradually increases till the termination of sediment wave field (see **Figure 11**). This may be the result of increasing velocity of turbidity currents downslope that restrict the deposition of sediment on the slope. Upon changes in environmental conditions, the same turbidity current may not produce the sediment waves (**Lee et al., 2002**). Lateral thinning and thickening of layers are evident because of erosion on the steeper downslope side and deposition on the gentle upslope flank.

6. Conclusion

Sediment waves are abundantly present in the Pleistocene channels that suggest the occurrence of highly turbulent and thick sediment carrying turbidity flows. No sediment waves are encountered in the older successions from Eocene-Oligocene to Miocene. The dimensions of waves are often irregular in the study area. Wave dimensions decrease downslope and away from channel margins, but random patterns of wave dimensions are also observed, which is indicative of varying downslope waves formation processes. Not only the downslope processes but also the subsurface morphology can trigger the formation of sediment waves. Wave set migration patterns are indicative of autogenic processes occurring during the wave formation. Each proceeding wave set is influenced by the architecture of earlier sediment waves.

7. Implications and prospects

Indus offshore is a frontier zone where the hydrocarbon industry has unsuccessfully made attempts for oil and gas discovery. Our study does not focus on the hydrocarbon prospects of the area, but we believe that submarine channels could provide the industry with a maybe, better prospect for future discoveries. We believe that not only channel belts, but channel levees can provide the petroleum play necessary for a successful venture.

In the study area, the sediment waves lie near the sea floor, i.e. Plio-Pleistocene age overlain by a thick succession of hemipelagic deposits that probably deposited during the high stand. Thus, the zone may prove to be a potential reservoir as long as detailed sedimentological analyses are carried out.

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SAŽETAK

Arhitektonske složenosti i morfološke varijacije sedimentnih valova plio-pleistocenskih kanala u delti Inda

Arhitektura sedimentnih valova nastalih uslijed turbiditnih struja pokazuje zamršenu morfologiju i obrasce unutar kanala i njihovih rubova u prostoru deltne lepeze Inda. Tragovi taloženja energijom valova prisutni su u plio-pleistocenskim kanalima i oko njih, no izostaju u dubljim dijelovima istraživanoga područja. Arhitektura rubova kanala u delti Inda do sada nije bila detaljno opisana. U istraživanju ovoga problema korištene su seizmičke metode i modeliranje podataka visoke razlučivosti. Morfološke varijacije u duljinama valova, dimenzijama kresta i potencijalnim obrascima stvaranja valova upućuju na autogene i alogene procese povezane s razvojem valova. Dujine valova dosežu do 1473 m s prosjekom od 486,84 m, a visina se kreće između 10 m i 60 m (prosječno 30 m). Kut rubova kanala i dimenzija vala u ovome slučaju bili su neovisni jedno o drugome. Mali kut omogućio je na nekoliko točaka u nižim dijelovima akomodiranje valova velikih dimenzija i obrnuto. Karakteristični valovi nastajali su na vanjskome dijelu nasipa kanala (obično lijevome) sa strmim rubovima, što upućuje na to da je njihovo prelijevanje utjecalo na energiju. Općenito, mlađi valni sedimenti slijedili su obrasce starijih, ali se ponekad može uočiti i promjena trenda. Obrasci valnih taložina u mlađim naslagama rubova upućuju na promjenu, pa i inverziju oblika. Općenito su valni sedimenti posljedica aktivnosti turbiditnih struja u podnožju rubova kanala, a i njihov nastanak vrlo je usko povezan s deformacijskim strukturama.

Ključne riječi:

sedimentni valovi, zaleđe kanala, mlađe sekcije, deformacijske značajke turbiditnih struja

Author's contribution:

Mr. Ehsan Ul Haq lecturer, Hazara University Mansehra, Pakistan is the principal author of this manuscript. All the ideas and analyses are original in this paper. **Dr. Ji youliang**, Professor, college of geosciences, China University of Petroleum, Beijing, China supervised the writing of this manuscript and provided guidance to understand the sediment waves and their architecture till the conclusion of the manuscript. **Dr. Khurram Shahzad** Geoscientist, Germany has previously done research on Indus Fan carbonate platforms. Identification and investigation of architectural elements were done under his guidance. **Mr. Saad Ahmed Mashwani**, lecturer, Hazara University Mansehra, Pakistan, **Dr. Muhammad Zaheer**, Assistant Professor, Hazara University Mansehra, Pakistan guided us in preparation of the interpretation scheme and methodology for the research. **Mr. Hadayat Ullah** lecturer, Hazara University Mansehra, Pakistan aided in scientific writing and proofreading.