

Acoustic structure and recent sediment transport processes on the continental slope of Yeşilırmak River fan, Eastern Black Sea

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Abstract

High-resolution acoustic data indicate that sediment erosion is a significant process in the continental slope of Yeşilırmak River Fan, occurring both related to the submarine canyons and in the open continental slope. The sediment processes observed along the slope consist of sliding and debris flows on the canyon walls together with the recent erosional surfaces at the canyon heads wherever the canyons exist, and slides and related scarp features structurally controlled by rotational faults in the central part of the open continental slope.

Formation of slides both on the open slope and in canyon walls is a multi-phase sliding process, in which successive sliding events occur at the same location producing a vertically stacked sliding, resulting in several relict slide features deeper parts in the sediments. We conclude that gravitational loading on the steep slope is the main driving force for most of the erosional features, and in place to place, overpressured pore fluids due to gas accumulation can contribute the instability.

Tributary canyon systems are observed on the slope, with slide scars in the proximal part. According to their different erosional structure, these canyons can be separated into two groups, as northern and southern sector canyon systems, where the sediment bypass and hence erosional processes are much more active on the canyon heads in the southern sector than those in the northern part. Terrigenous sediment load from Yeşilırmak River is transported along downslope by successive hyperpycnal fluxes and the activity of turbidity currents along the channel axis.

Acoustic data indicate that the continental slope of Yeşilırmak River Fan is a classical deep-sea turbidite system, where we observe slide scars in proximal part, and channel levee systems with slide and debris flow deposits inside the channels in the distal part with some small sized gullies.

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1. Introduction

Continental slopes are regions where sediments are exposed to sediment flows, slumps and slides, in which

the main triggering and driving forces can be seismic activity, bottom currents or gravitational loading. Mass movements occur in all kinds of continental shelves and slopes with relatively high bathymetric inclination and is an important process controlling the development, morphology and sedimentary structure of the slope (Casas et al., 2003). This process is one of the principal mechanisms that distributes the shelf and upper slope sediments downslope towards the abyssal depths.

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Slope stability depends on various parameters including seismic activity, existence of growth faults, possible overpressure conditions in pore spaces, gravitational loading, sea level changes, existence of gas hydrates, bottom current activities and storm waves (Hampton et al., 1996; Eschard, 2001). Investigation of mass movement processes along continental slopes is important since they are considered to be main potential natural hazard for offshore engineering installations, pipelines and submarine cables on the continental slopes (Okey, 1997; Baraza et al., 1999; Lee et al., 1999; Lee and Baraza, 1999; Lykousis et al., 2002; Casas et al., 2003), and large-scale sliding events can produce destructive tsunamis in near-shore areas (e.g. von Huene et al., 2004).

Acoustic methods, such as multichannel seismics, Chirp subbottom profiler, side-scan sonar and multi-beam echosounder systems provide significant information about existence, size and morphology of mass movements, scar faces related to slides and canyons

with channel levee systems (e.g. Damuth and Olson, 2001; Laursen and Normark, 2002; Thorne and Hanes, 2002; Casas et al., 2003; von Huene et al., 2004).

The study area is located in the southeastern margin of the Black Sea (Fig. 1) at the mouth of one of the largest rivers in Turkey, named Yeşilırmak River, which transports large amounts of terrigenous sediment into shelf and upper continental slope producing an alluvial fan consisted of coastal sediment accumulations. The continental slope of Yeşilırmak River fan is located between 300 and 1850 m bathymetric contours with a maximum slope angle of 14° and can be defined as a modern continental slope, where downslope sediment transport processes are observed. There are also extensive accumulations of shallow gas especially in the shelf and apron regions in the area (Çifçi et al., 2002; Ergün et al., 2002), and Çifçi et al. (2003) reported that the continental shelf of the fan is a broad pockmark plateau, in which large circular and elongated pockmarks are present.

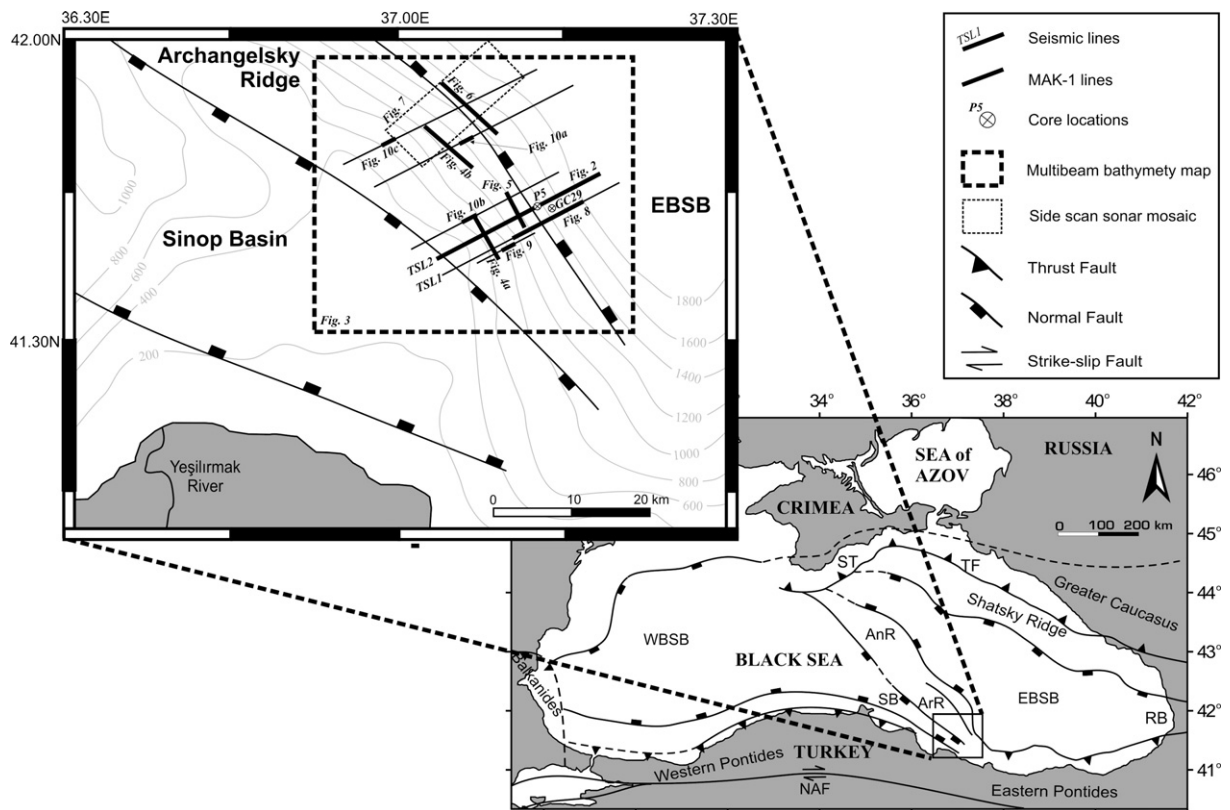


Fig. 1. Simplified tectonic map showing major tectonic elements of the Black Sea (after Spadini et al., 1996): WBSB, EBSB — Western and Eastern Black Sea sub-basins, respectively; RB — Rioni Basin, TF — Tuapse Foredeep, ST — Sorokhin Trough, AnR — Andrussov Ridge; ArR — Archangelsky Ridge; SB — Sinop Basin and NAF — North Anatolian Fault. Close-up shows the bathymetry of study area with 200 m contour interval, locations of seismic and MAK-1 (5 kHz subbottom profiler and side-scan sonar) profiles (solid lines), locations of multibeam bathymetric map (thick dashed rectangle), side-scan sonar mosaic of northern slope (thin dashed rectangle) and core locations. Thick parts of the solid lines correspond the data illustrated in figures.

The purpose of this study is to present a detailed description of the acoustic characteristics of the continental slope of Yeşilırmak River fan with acoustic evidences for erosional processes such as recent mass movements and different types of sediment transport. We integrate data from different acoustic systems with different resolutions to characterize geologic structures and mechanisms of the sediment transports, and to discuss about the mechanisms controlling different types of mass movement.

2. Regional setting

The Black Sea is originated as a back-arc basin of the northwards subducting Tethys Ocean and is located in the north of the North Anatolian Fault (NAF) that allows the tectonic escape of Anatolia towards the west due to active Arabia–Eurasia collision (e.g. Rangin et al., 2002). Although it is surrounded by compressive belts, such as Greater Caucasus, Pontides and Balkanides (Fig. 1), it has an extensional origin (Spadini et al., 1996). The Black Sea

is bathymetrically a single depocenter today, however, it comprises two major extensional basins, Western and Eastern Black Sea sub-basins separated by a continental Mid-Black Sea Ridge. Meredith and Egan (2002) suggested that major extensional faults, which produce half-graben structures, exist along both basin flanks of the ridge. The Mid-Black Sea Ridge is subdivided into two parts: the Andrussov Ridge in the north and the Archangelsky Ridge in the south (Fig. 1). While the Andrussov Ridge vanishes southwards, the Archangelsky Ridge becomes more evident in the south.

2.1. The Archangelsky Ridge

High-resolution seismic data show that the tectonic setting of the upper and middle slope is under structural control of the Archangelsky Ridge. Fig. 2 shows a high resolution multi-channel seismic line (TSL2) over the Archangelsky Ridge and its interpretation (see Section 3 for a description of data acquisition and processing

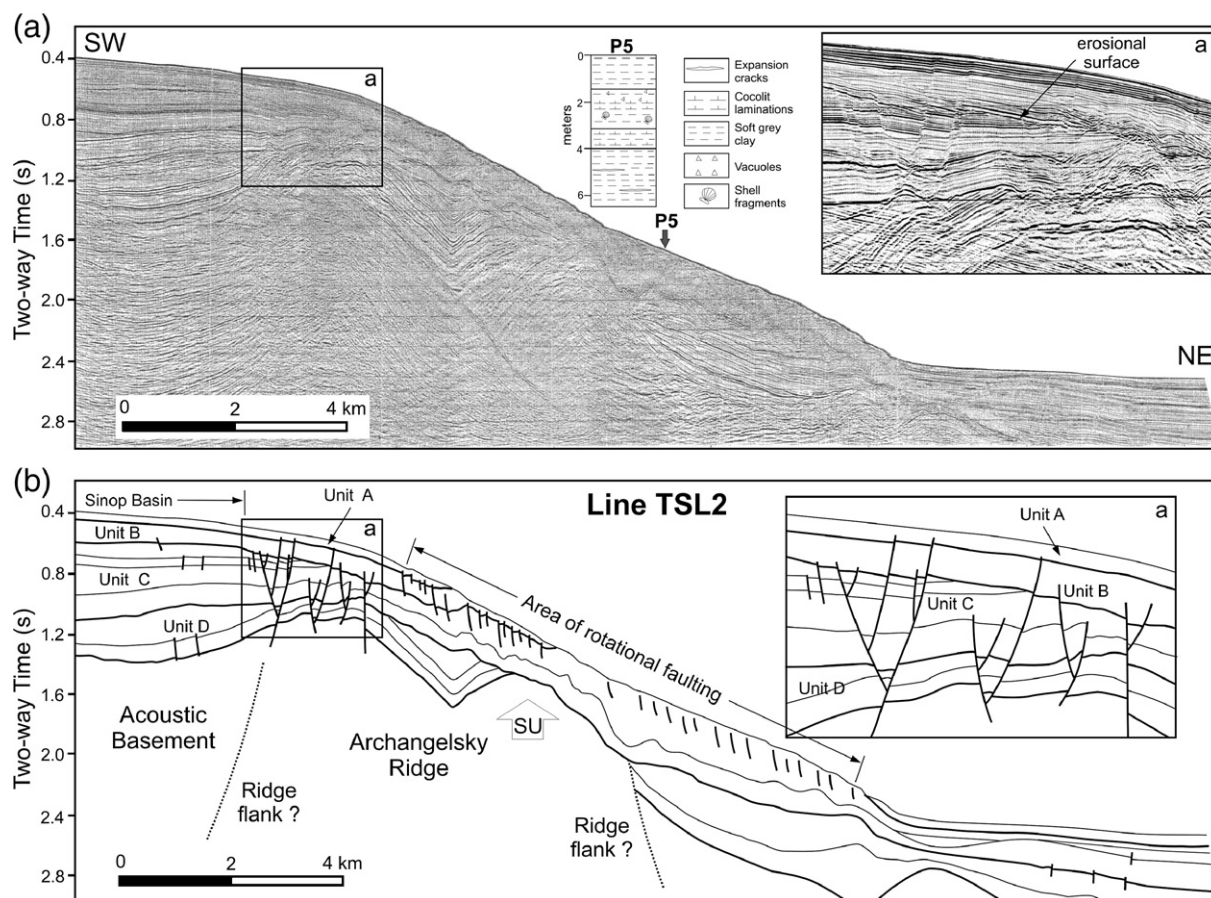


Fig. 2. (a) Part of seismic line TSL2 and (b) its interpretation (see Figs. 1 and 3 for location) showing several small offset vertical faults over the Archangelsky Ridge crest. SU represents “secondary uplift” of the ridge near the northeastern ridge flank. P5 is the piston core from open continental slope with 6.4 m sediment recovery (see Figs. 1 and 3 for core location).

parameters). Correlating with Badut-1 well data, which is located approximately 2 km south of the coast line, acoustic basement in the seismic line is attributed to Mesozoic basement of the Archangelsky Ridge. The ridge crest itself and the sedimentary units over the crest are extensively affected by normal faults which produce deformation even in the uppermost sedimentary sequence (see close up in Fig. 2a). Slip rates of these faults increase with depth and, in place to place, they constitute small-scale graben structures. In the middle slope, however, the sediments undergo rotational fault deformation and exhibit rather chaotic reflection pattern continuous along the downslope, while the sedimentary units towards the shelf and apron show rather well stratified and parallel bedding. In any other region along the slope, except the ridge crest, the acoustic basement is not affected by faulting.

The Archangelsky Ridge separates Sinop Basin to the south and Turkish continental rise or apron to the north (Fig. 2b). According to the sedimentary structures at both sides, we conclude that the apron side was possibly developed as an open slope since the ridge was relatively uplifted and the sediments in this area have started sliding downslope along rotational faults. The Sinop Basin side, on the other hand, exhibits a half-graben shape completely separated from continental slope by Archangelsky Ridge. Units A, B and C constitute Quaternary deposits, which exhibit almost no deformation in the Sinop Basin. The oldest Quaternary unit, Unit C, has a quite complex internal structure in the middle slope possibly due to the small-scale downslope sliding and mass flows. Piston core P5 sampled at the middle slope from Unit C, which recovered 6.4 m sediment sample, showed generally very soft grey clay with some shell fragments and coccolit laminations in deeper sediments. There were also some expansional cracks deeper than 5 m which were interpreted that they were possibly related to sediment movement along rotational faulting (discussed later).

In addition to the Archangelsky main rise, the ridge exhibits another smaller-scale flanking rise in the middle slope shown as “secondary uplift (SU)” in Fig. 2, which causes a localized change in the seabed bathymetry. The flanking faults of the ridge at both sides are not easily recognized on the seismic line, however, the ridge flanks are possibly located along two major normal faults just north of the secondary uplift to the north and north of the Sinop Basin to the south.

2.2. Seismicity and active tectonics

The main parts of the Black Sea and surrounding area can be summarized as a low seismicity region. In eastern Black Sea Turkish margin, the maximum seismicity is

not related to the Black Sea itself but to well known regional fracture: the dextral strike-slip North Anatolian Fault (NAF), which extends approximately 1500 km from eastern Turkey to Aegean Sea and separates the Northern Turkey province and the Black Sea regions from central Anatolian province (Barka et al., 2000). Although the compressional regime is still active in the Western sub-basin according to the recent seismic activity data (Barka and Reilinger, 1997), the southern margin including Yeşilırmak Fan area is nearly completely aseismic and seems to act as a passive margin. Indeed all the compressional stresses oriented from south to north are released by the intense seismic activity of the NAF (Fig. 1). Between 1939 and 1967, the NAF produced a series of six destructive earthquakes ($M > 7$). Three of them had the epicenters located approximately 80 km south of the study area and dextral motion reached 7.5 m in places during this large earthquake sequence (Barka et al., 2000).

3. Materials and methods

In order to identify submarine canyon systems and other large-scale geomorphological elements of the sea floor, SIMRAD EM12S multibeam echosounder system operating at 12 kHz frequency has been used. High resolution MAK-1 acoustic profiling system was used to investigate the recent mass movement processes and shallow faulting. MAK-1 is a deep-tow mapping system designed in Russia consisting of dual-frequency (30 and 100 kHz) side-scan sonar and a high-resolution (5 kHz) subbottom profiler towed 100 m above the seabed (Limonov et al., 1997). Swath range of the side-scan sonar is 1000 and 200 m for low and high frequencies, respectively. High resolution multichannel seismic data was used to investigate the relatively deeper parts of the study area. Seismic data were acquired using 600 m long streamer with 48-channel recorder, and three sleeve guns (1×20 in.³ and 2×40 in.³) were used as seismic sources. Group, shot and sampling intervals were 12.5 m, 6.25 m and 1 ms, respectively. Conventional seismic data processing steps were applied to seismic data, such as data editing, CMP sort, true amplitude recovery, velocity analysis (every 1 km), dip moveout and velocity analysis (every 0.5 km), NMO correction, outer trace mute, CMP stack to 48 fold gathers, wave equation migration and 8–300 Hz bandpass filtering.

4. Results

The mass movements in the continental slope of Yeşilırmak River fan are recognized by their erosional

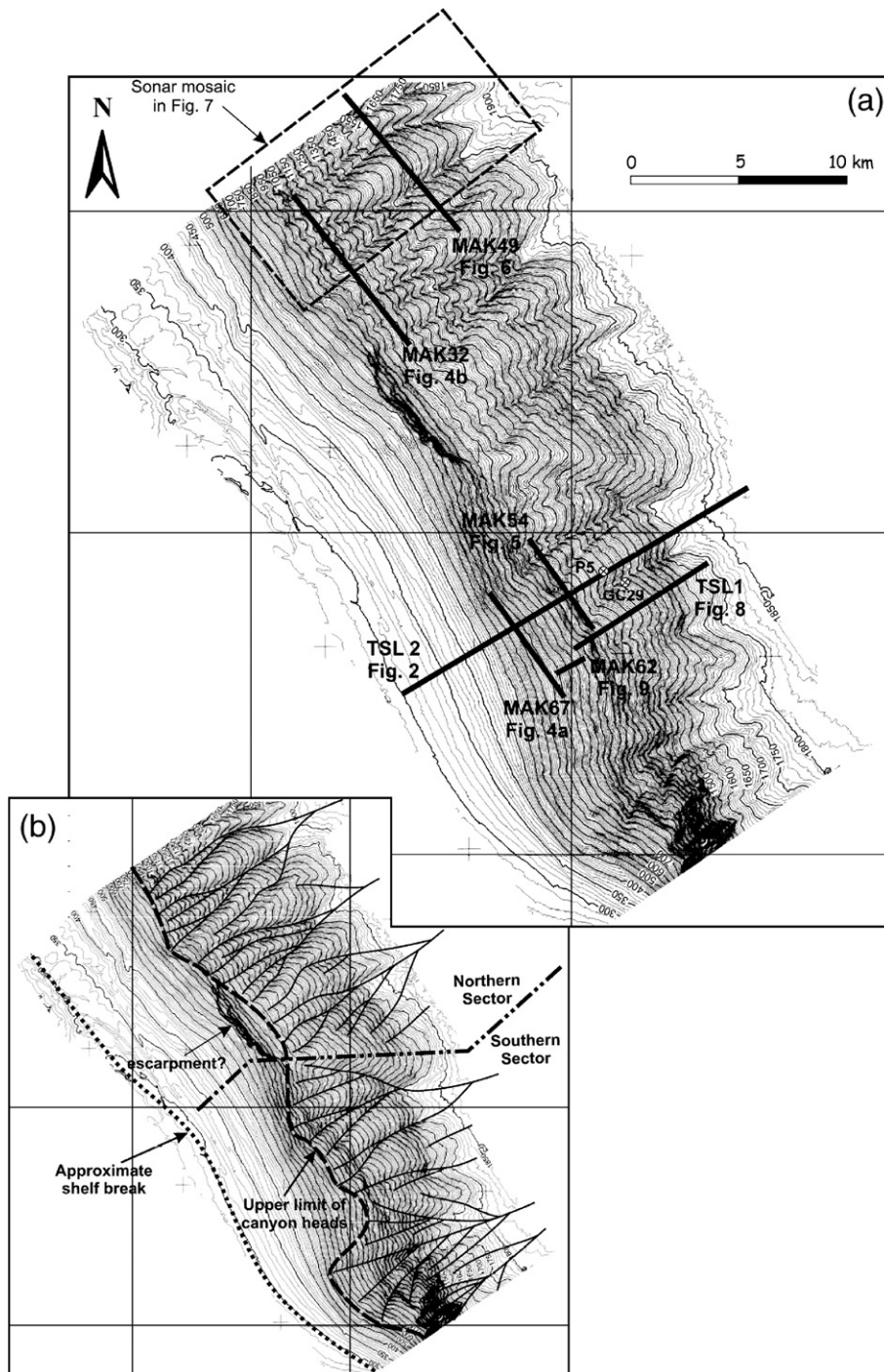


Fig. 3. (a) Uninterpreted and (b) interpreted multibeam echosounder map of the slope showing tributary canyon systems. Contour values are in meters. Canyon axes are indicated by plain lines. According to the erosional structures observed on the canyon walls, the canyons are separated into two parts, as northern and southern sector (see text for details).

surfaces with characteristic reflection patterns on the subbottom profiler data and by their significant high backscattering appearance on the side-scan sonar records. The acoustic structure of the recent sediments

and the mass movement structures are investigated by taking into consideration of (a) well-developed canyon systems which are effective almost everywhere all over the slope and erosive surfaces related to the canyon

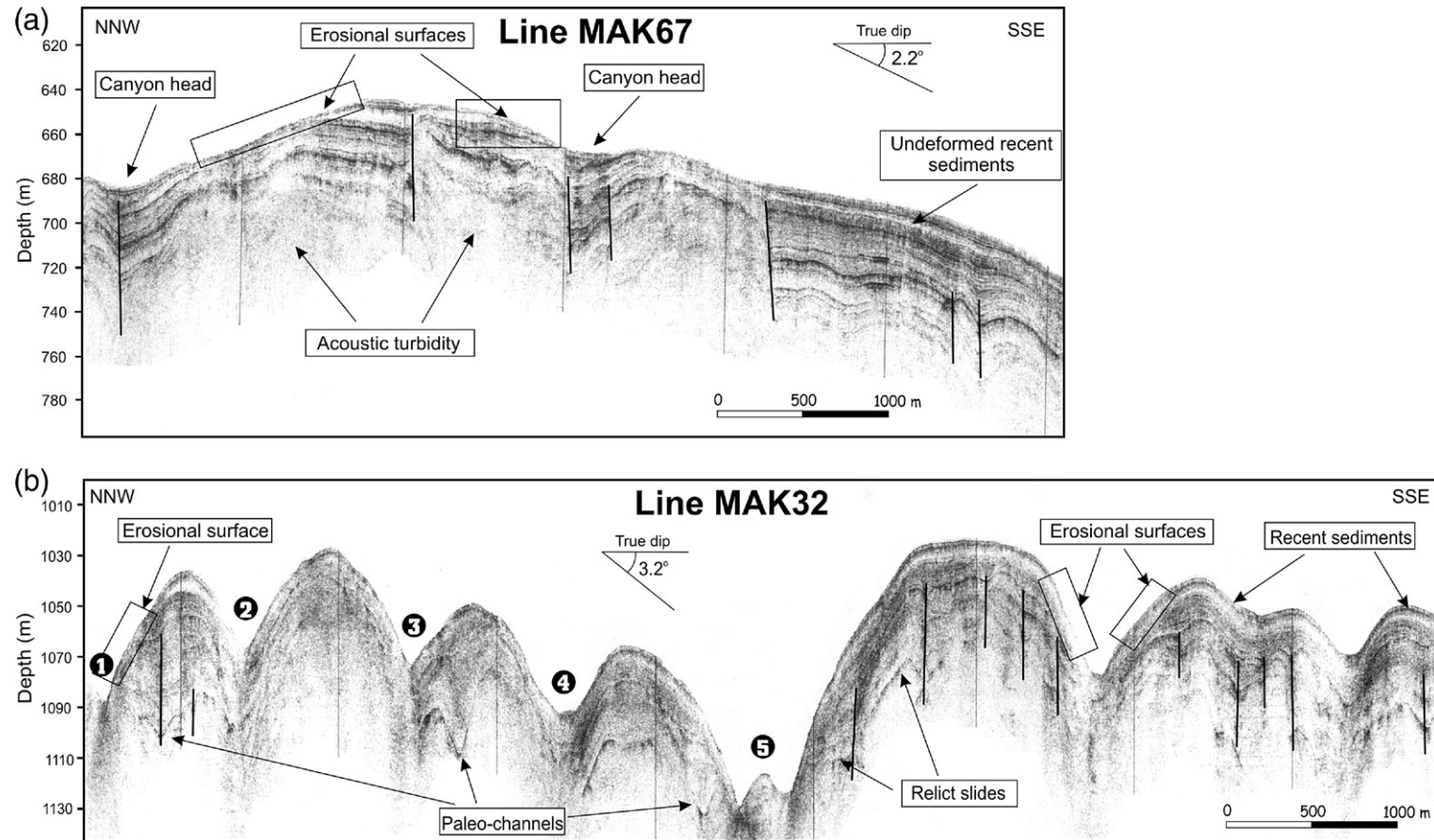


Fig. 4. Subbottom profiler sections crosscutting (a) southern sector, and (b) northern sector canyon heads, and their interpretations. Numbers in the black circles correspond to canyon axes in Fig. 7.

systems, (b) debris flows and slide structures related to the submarine canyons and steep canyon walls, (c) slides and slide scars controlled by rotational faulting on the channel banks or open continental slope, and (d) small-scale gullying located on the canyon walls in distal part of the canyons.

4.1. Canyon systems and related erosive surfaces on the slope

Multibeam echosounder map of the Yeşilirmak fan slope shows that several interconnected canyon systems exist on the slope (Fig. 3). Shelf break is located along approximately 300 m depth contour which is actually much deeper than that observed along the southern margin of the Black Sea. Depth of the shelf break in the Yeşilirmak Fan is controlled by Archangelsky Ridge main uplift which forms a plateau just south of the shelf break (see Fig. 2).

The canyon systems consist of one or two main canyons and several secondary smaller-scale canyons connecting the main canyon, which produces tributary canyon systems (Fig. 3b). The V-shaped channels broaden downslope and become U-shaped in cross-section near the apron area after they merge with the tributaries. According to the locations of the canyon heads, the multibeam bathymetric map in Fig. 3 can be subdivided into two parts as northern and southern sectors. In the northern sector of the slope, the heads of the canyons are located approximately along 750 m contour line, whereas in the southern sector, the canyon heads seem to incise towards the shelf break extending up to 500 m contour line. We interpret that this difference is directly related to the difference in the erosion intensity between northern and the southern sectors. This interpretation is also supported by subbottom profiler data in Fig. 4. When comparing the profiles crosscutting the canyon heads both at southern (Fig. 4a) and northern (Fig. 4b) sectors, the difference in the amount of erosion can be observed. In Fig. 4a, the line cuts two canyon heads, both of which are observed as small depressions with vertical faults below. Undeformed recent sediments are present at the southern part of the line, while low signal penetration is observed between two canyon heads possibly because of an acoustic turbidity zone because of the acoustic attenuation by a localized shallow gas accumulation. Channel levees show no recent deposition and appear as very sharp erosional surfaces outlined by rectangles, indicating a quite active recent erosional truncation process. A free-fall gravity core GC29 (see Figs. 1 and 3 for location) sampled mainly fine grained sediment consisting of laminated and thin-bedded (0.2 to 1 cm

thick) sandy silt layers with clay and some turbidite mud beds, which are typical for a turbidite–levee system.

In the northern sector, however, an irregular and chaotic sediment accumulation is present below the channel banks indicating relict slide structures as well as infilled paleo-channels (Fig. 4b). Although it is not easy to recognize the erosional surfaces along the canyon walls because of the steep slopes, it can be observed that an almost completely undeformed recent sedimentary drape covers almost whole line from north to south, which is especially visible over the channel banks. Only a few erosional surfaces, outlined by rectangles, over the channel levee systems can be observed, which are, however, not as sharp as those in the southern sector. Therefore, we conclude that different erosional characters of northern and southern sectors are due to the fact that the sediment incision and hence the erosional processes are much more effective in the zones of the canyon heads in the southern sector than those in the northern part. We also conclude that the effective erosional processes in the canyon heads of the southern sector erode the upper slope sediments and hence more intensive retrogressive (headward) erosion occurs at canyon heads. In the northern sector, on the other hand, where the erosive processes are relatively less effective, the canyon heads are located at deeper waters.

4.2. Debris flows and slides related to the steep channel walls

Debris flows are commonly observed on the canyon walls on both northern and southern sector canyons. Debris flows are located on the canyon walls, particularly close to the canyon axis, and can be easily recognized on the subbottom profiler sections by their lens shaped geometries and transparent to semi-transparent facies. On the sonar records they are characterized by medium-to-high backscattering curved features. Side-scan sonar records show that these deposits are generally accumulated near the canyon axes and the direction of the debris flows are from canyon wall towards the canyon axis. This kind of characteristic appearance of the debris flows can be seen in Fig. 5, in which the debris flow deposits are evident both in the subbottom profiler and side-scan sonar data. In the sonograph, compressional features correspond to the nose of the debris flow and indicate that the flow direction is towards the canyon axis (Fig. 5).

The mass movements from levees towards the channel axes were investigated using MAK-1 lines crosscutting the canyon axes (Fig. 6). The canyon axes are seen as very high backscattering lineations on the side-scan sonar records, whereas the canyon banks, covered by

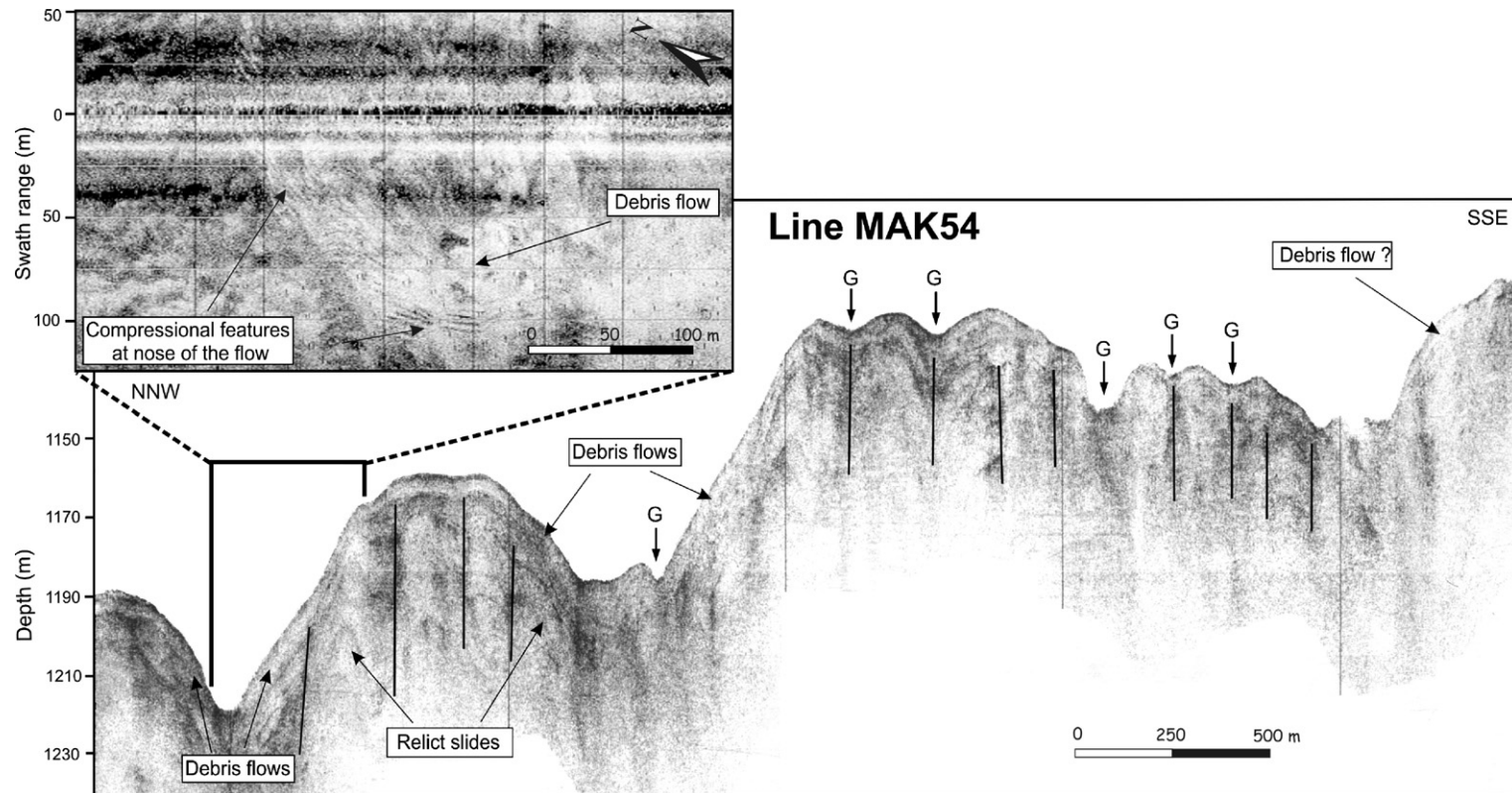


Fig. 5. Subbottom profiler record example showing gullies (G) especially on the channel banks, and transparent to semi-transparent debris flow lenses on the canyon walls. Side-scan sonar record from leftmost canyon wall indicates compressional sediment features at the nose of the debris flow.

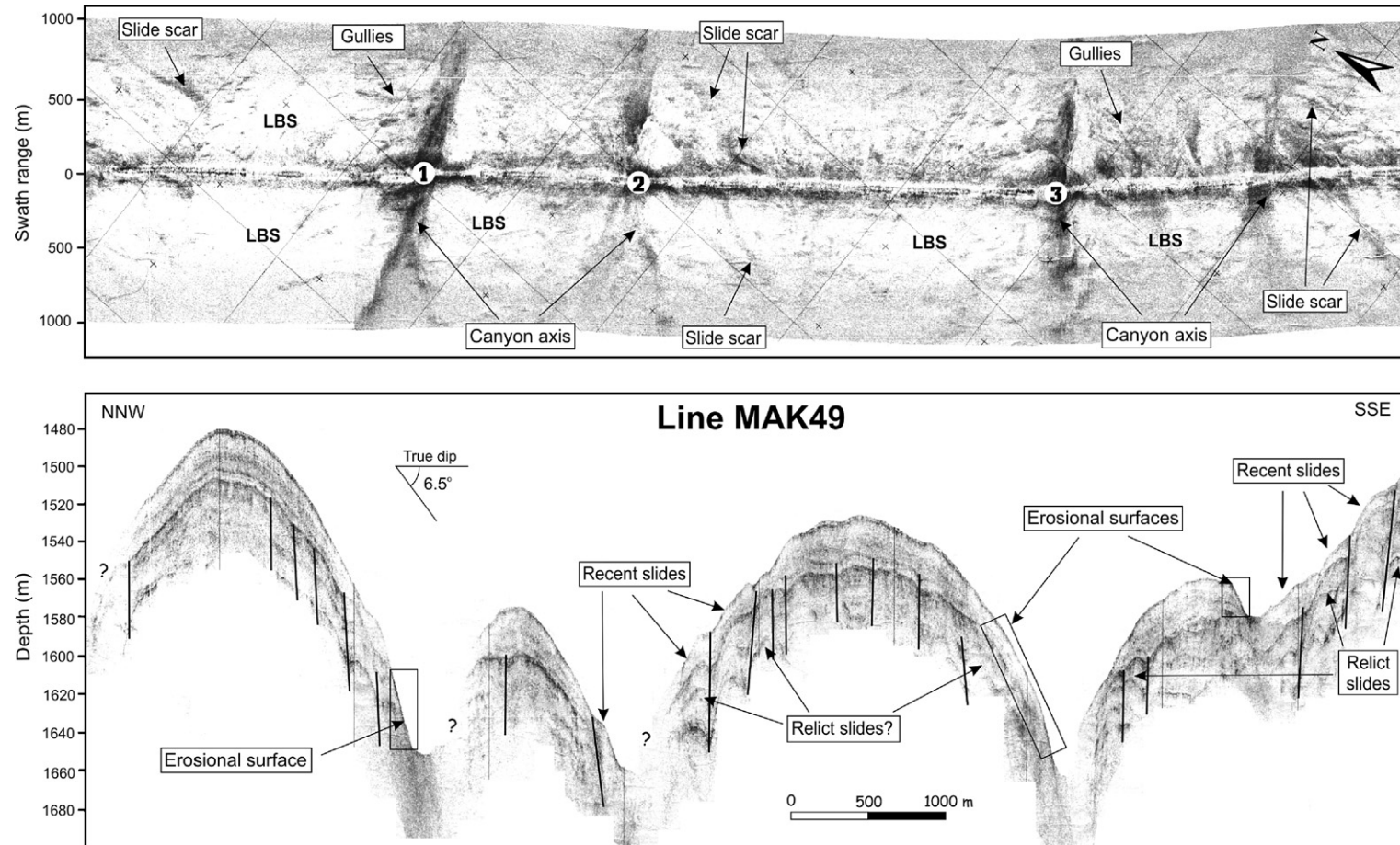


Fig. 6. Side-scan sonar (top) and subbottom profiler (bottom) record example showing gullies and both recent and ancient (relict) slide features. Numbers in the white circles on sonograph correspond to canyon axes in Fig. 7.

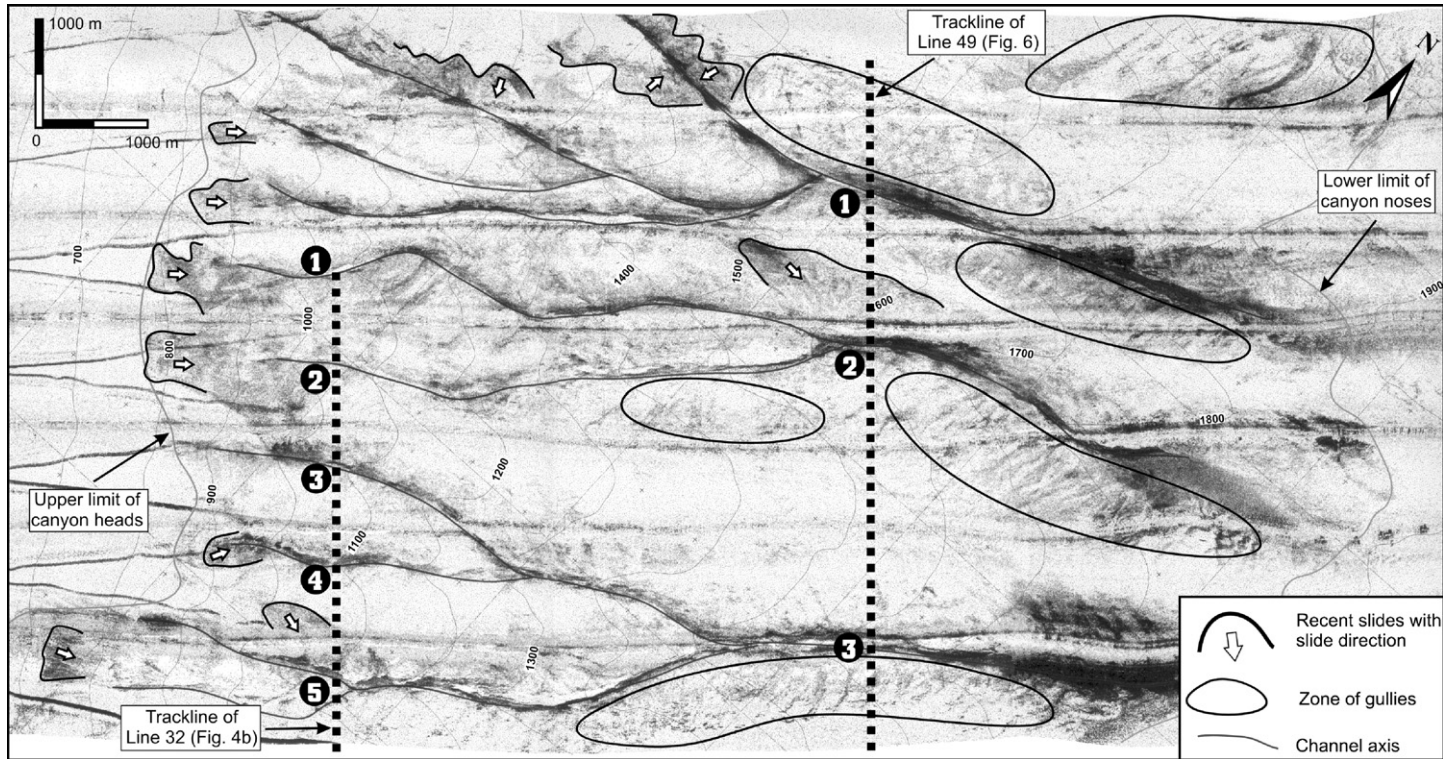


Fig. 7. Side-scan sonar mosaic from northern sector of the slope (see Fig. 1 for location). Tracklines of two subbottom profiler lines are indicated by thick dashed lines. Numbers in the circles correspond to canyon axes in Figs. 4b and 6.

undeformed recent sediments completely, exhibit low backscattering (LBS). On the walls of the central canyon, there are also several recent slide blocks with typical slide scar features seen as high backscattering linear features on the sonograph. The slope of the canyon walls is in between 6 and 8°, which is suitable for sliding on the canyon walls (Fig. 6). In addition to the indications of recent sliding, numerous folded sedimentary layers exist just below the highly inclined canyon walls between the vertical faults, and interpreted here as relict slide features.

A number of vertical faults with relatively small slip rates are also observed. Conventional seismic lines, on the other hand, do not show any clues of faulting from deeper parts to shallow sediments (see Fig. 2). We conclude that these faults are related to localized mass movements along the walls rather than being shallow extensions of a tectonically controlled deeper fault system.

4.3. Small-scale gullies

As a submarine fan having highly dissected canyon systems, gullying is observed both on the channel banks

and canyon walls of the Yeşilırmak continental slope. Small-scale channel bank gullies, indicated by G in Fig. 5, are also observed in subbottom profiler sections in the southern part in varying widths between 60 and 100 m, and depths between 3 and 13 m. These channel bank gullies exist in a limited area on the southern sector of the slope with sharp termination of reflectors against the gully walls (Fig. 5).

Fig. 7 illustrates the sonar mosaic of northernmost side of the slope. The canyon axes can be easily recognized by their high backscattering linear appearances extending approximately between 750 and 1900 m contour lines. Slide blocks on the mosaic can be recognized by their medium to high backscattering character especially around the proximal part of the canyons and channel walls at shallower water depths.

Side-scan sonar mosaic in Fig. 7 shows high backscattering strips lining up approximately perpendicular to the thalweg located on the steep canyon walls at relatively deeper waters (e.g. >1500 m). We interpret these features as small-scale gullies because of several

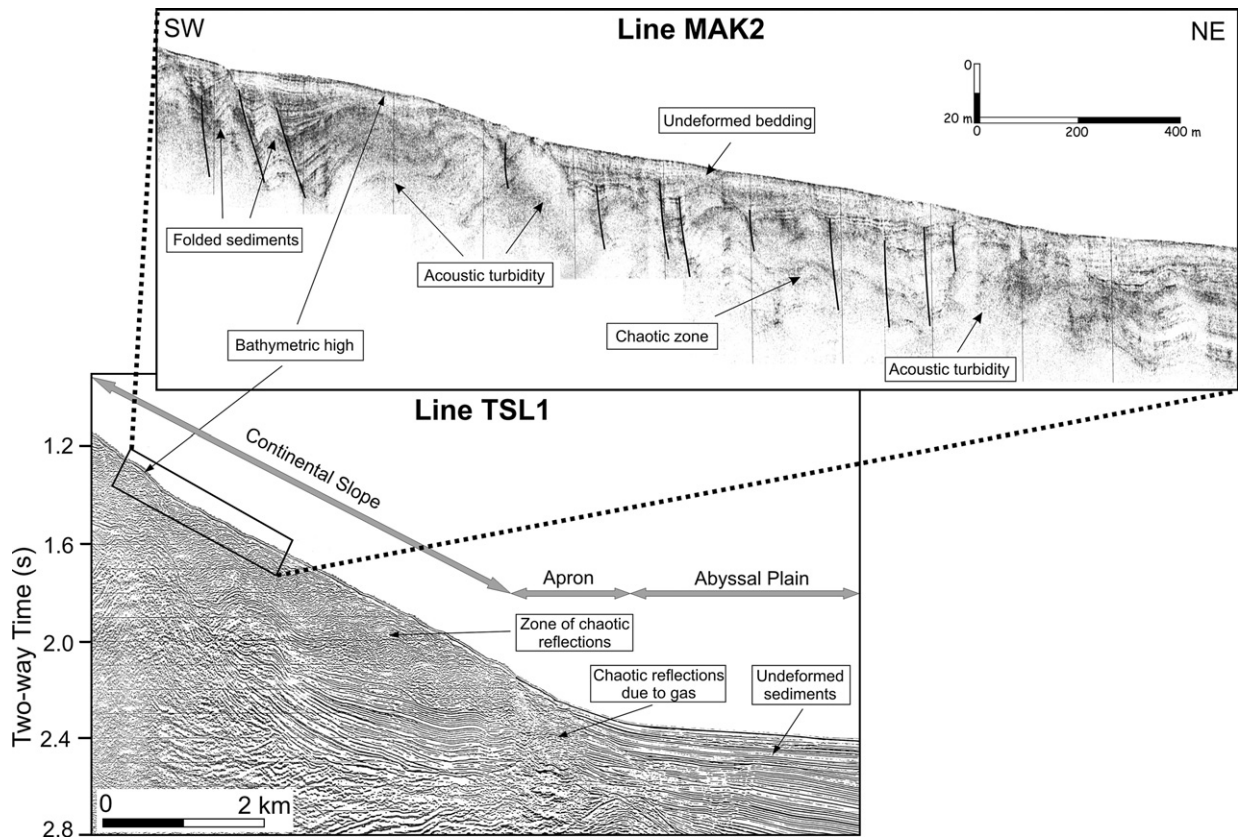


Fig. 8. Part of seismic line TSL1, showing chaotic reflection pattern observed on the central part of the slope due to multiple sliding. Close-up view shows a part of subbottom profiler data (Line MAK2) showing a detailed view of rotational faulting and gas presence.

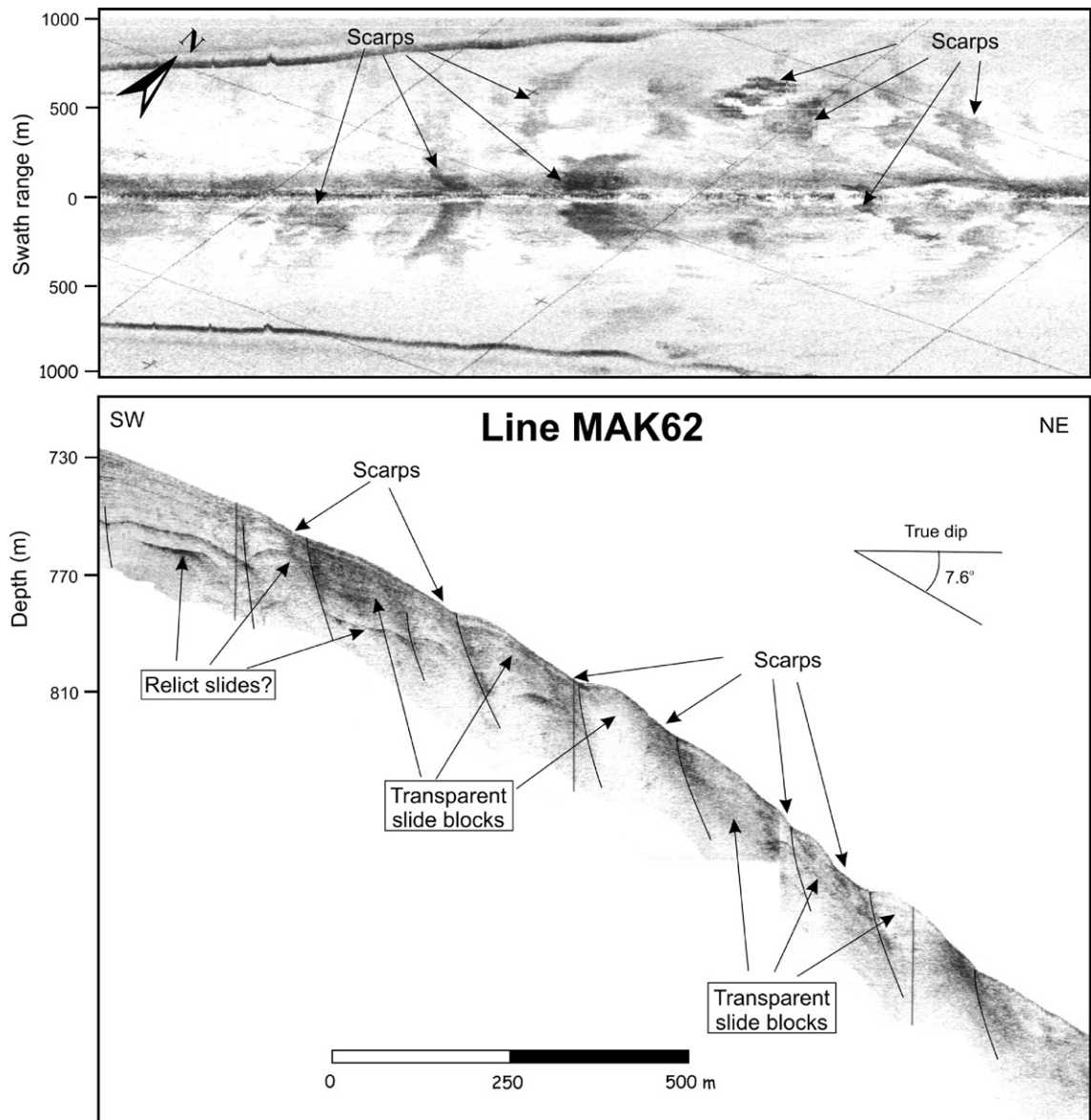


Fig. 9. Side-scan sonar (top) and subbottom profiler (bottom) record example showing transparent blocky topography of the open continental slope with rotational faults and associated high backscattering seabed scarps on the sonograph.

reasons: This kind of backscatter pattern exist only on the steep flanks of the channel walls rather than on the levees and these high backscattering bands merge down slope towards the channel as like upper slope tributaries. The features are perpendicular to both thalweg and bathymetric contours and they widen nearer the channel axis, sometimes turning downstream when they intersect the channel. Since the penetration of the profiler signal on steep channel walls is extremely low (see Fig. 6), they cannot be clearly recognized on subbottom profiler records, and therefore, it is not possible to conclude

about the axial depth or the erosional structure of the gully flanks.

4.4. Sliding along rotational faults

Large number of rotational faulting exists along the central part of the open continental slope between the water depths 450 and 1500 m, where no canyons or channels exist (Figs. 8 and 9). We propose that these faults are of primary importance in relation with multiple rotational sliding and in most places on the

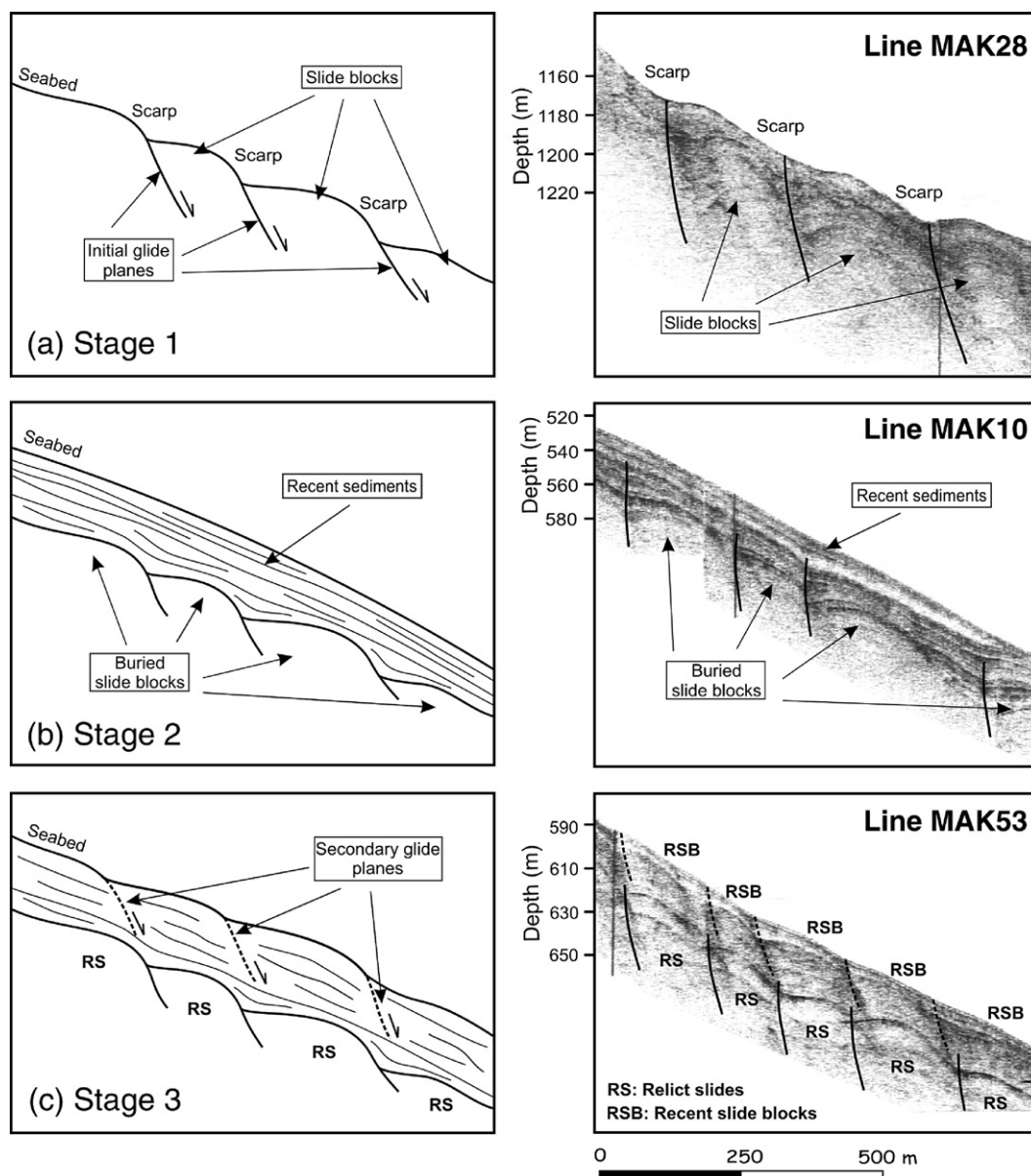


Fig. 10. Schematic illustration (left column, not to scale) and corresponding 5 kHz evidence (right column, see Fig. 1 for locations) for the evolution of multi-phase sliding observed on open continental slope and canyon heads of upper slope. (a) Recent sliding events occur along the rotational faults or initial glide planes leaving scarp structures on the upslope side, (b) recent sediments start covering slide blocks and rotational faults, and (c) new sliding occurs in the recent sedimentary unit along secondary glide planes (dashed lines) resulting in new scarps, and previously moved sediment blocks become relict slides (RS) buried below the recent slide blocks (RSB). The vertical axis in right column is in meters below the sea level.

open continental slope, we observe that the fault planes act as glide surfaces for small-scale sliding events (see Discussion section).

The seismic data from open continental slope show that the mass movements, especially sliding, along the continental slope generally occur under the structural control of the rotational faulting. These slides represent back-rotated sediment blocks with curved slide plane

surfaces (rotational faults). Average distance between rotational faults is about 150 m.

In open continental slope, some small-scale sliding features exist. The scarps located towards the upslope part of the sliding blocks suggest that the sliding is a recent process. Scarps can also be easily distinguished on the sonar records by their very high backscattering characteristics with sharp boundaries. In place to place,

buried rotational slides are also identified from 25 to 30 m below the seabed. Although it is possible to see the internal reflections in the slide blocks in shallower water depths, the slide blocks become quite transparent as traced deeper waters.

On the smooth seabed slopes, sliding can sometimes be found together with the debris flows which, at times, extend for considerable distances over the lower continental slope. In the southern sector of the open continental slope, in place to place, it is possible to observe such debris flows together with the slide blocks when the slope of the seabed is relatively low. We conclude that, in such cases, the sliding is formed primarily, and then, debris flow occurs on the slide material.

In deeper sediments, acoustic data indicates strong reflections from folded sediments, which are interpreted as relict slide features located between successive rotational faulting (see Figs. 5 and 6). These relict slides can be found especially in the upper slope of the northern sector. The rotational faults can sometimes affect the recent sedimentary units and produce small-scale collapse structures on the seabed. In the deeper water (e.g. deeper than 1600 m), the sliding blocks form positive relief on the sea floor between rotational faults. These dome-shaped structures with completely transparent internal facies are interpreted as recent slide blocks.

There are also some minor gas accumulation zones on the open continental slope, which produce transparent or semi-transparent acoustically turbid zones both on subbottom profiler and seismic lines. This kind of chaotic reflection pattern due to gas accumulation is also observed in the apron region (see Fig. 8), in which the reflections from abyssal plain sediments disappear locally. Because of the rotational faulting, shallow gas and sliding, the shallow parts of the slope show a quite chaotic reflection pattern (Figs. 2 and 8).

5. Discussion

The analysis of high-resolution acoustic data from continental slope of Yeşilırmak River fan shows that mass movements both in canyons and canyon banks (e.g. open continental slope) are recent and ongoing processes. The continental slope is a classical deep-sea turbidite system: slide scars in proximal part, channel levee systems with slide and debris flow deposits inside the channels in distal part, and small-scale gullies in deeper waters.

Terrigenous sediment movement, which is derived from coastal regions by river erosion and transported to abyssal depths, can occur in a number of ways. The sedimentary processes in the Yeşilırmak River Fan include sliding and erosional surfaces in the proximal

area of the canyons, and debris flows/lobes on the canyon walls towards the canyon axis, slides and slide scars developed under the structural control of rotational faults in the channel banks or open continental slope. These mechanisms are responsible for the movement of vast amounts of land-derived material out of coastal waters and down the continental shelf to be redistributed in the abyssal depths. Several mechanisms for this transport are closely linked one with another and operate on varying scales both spatially and in time according to the topography and inclination of the continental slope. As like our study area, sediment movement occurs more easily in the case of a narrow shelf platform with steep slopes in which direct access of the sediments to the shelf edge is easily possible (Eschard, 2001). The wider is the continental shelf the greater will be the tendency for land-derived sediments to accumulate and consolidate on the shelf itself without falling down the shelf edge into the deep water.

Sliding occurs on relatively steep slopes in the Yeşilırmak continental slope, such as on canyon walls and on steep open continental slopes. The open continental slope shows stepped topography between these rotational faults (Fig. 9) sometimes in a stacked form (discussed below). Similar structures have been observed in the Eel River slope and interpreted as a slump structure at first (e.g. Gardner et al., 1999). However, later it has been proposed that this stepped seabed topography can also reflect upflow-climbing bedforms produced by turbidity currents (Lee et al., 2002). Although those features are actually not different from the stepped structures between the rotational faulting shown in Fig. 9, there are some other observations indicating differences between two structures. For instance, internal structures are very well defined and seismic lines show sub-parallel or slightly dipping internal reflections of the features of offshore California — Eel River slope. According to Lee et al. (2002), these internal reflections can be traced across the crests and troughs of each wave and they indicate that the down- and upslope flanks of these successive waves coalesce downslope along a sharp and acoustically incoherent surface. There are no fault planes between these flanks indicating that the features are in fact slide blocks. Both indications are common characteristics of the sediment waves (e.g. Lee et al., 2002; Masson et al., 2002; Normark et al., 2002; Ercilla et al., 2002; Cattaneo et al., 2004).

On the other hand, in Yeşilırmak River slope, we observe slides as blocks with almost no internal reflections. The structures usually appear as transparent to semi-transparent blocks, generally with one strong

and deeper reflective surface, which is interpreted as relict slide (see Fig. 9). Additionally, both multichannel seismic and subbottom profiler data indicate that central parts of the continental slope are severely affected by rotational faults between these transparent blocks (see Fig. 2). Therefore, we conclude that the blocky topography of the open continental slope is a result of downward sliding which is actually controlled by rotational faulting in this area. Here, we propose a different model for downslope sliding that the formation of the sliding events on the slope are actually a multi-phase sliding process, in which several sliding events occur successively at the same location producing a multi-phase sliding over long time periods. Such an alternation of semi-transparent slide blocks resulted from a multi-phase sliding pattern is also observed in the Gulf of Cadiz slope (Baraza et al., 1999). Fig. 10 illustrates a conceptual model suggested for continental slope of Yeşilırmak Fan, explaining the phases of this multi-phase sliding together with real data examples corresponding to each sliding phases. According to this model, the multi-phase sliding process consists of three stages. In the first stage, the slope sediments start sliding downslope as separate blocks (Fig. 10a) because of individual or cooperative operations of several initiation effects, which are discussed later. Because of this initial sliding, a rotational glide plane (actually a rotational faulting) is produced between each individual slide blocks, which allow the block at the downslope side to slide down with respect to the block at the upslope side. These rotational faults also affect the seabed resulting in low-angle slide scars (or scarps) located just behind the slide blocks (Fig. 10a).

Following the initial sliding event, the slide blocks are completely covered by recent sediments in the second stage because of the continuous sedimentation and low energetic sediment transportation, such as gravity and debris flows (Fig. 10b). The slide blocks and the rotational faulting produced in the first stage become buried under a 25 to 30 m thick sedimentary cover, and therefore, no indication about sliding is observed on the sea floor.

In the last stage, sediments of the recent sedimentary unit start sliding again because of the re-activation of different initiation effects. The sliding is formed as slide blocks along the rotational faults as the case in the first stage. These glide planes are indicated by dashed lines in Fig. 10c. The recently formed rotational faults cause deformation on the seabed resulting in new scar faces. The sediment blocks moved in the first stage become relict slide (RS) structures buried just below the recent slide blocks (RSB). Relict slides appear as high-amplitude reflections (Fig. 10c) on subbottom profiler data.

Sliding processes on the continental slope continue gradually in this way to produce a multi-phase mass movement and sliding mechanism. This kind of sliding processes constitutes a sedimentary structure consisted of successively stacked slide blocks, which offers a chaotic reflection pattern on the acoustic data.

Several researchers recognize the seismic loading as the main triggering mechanism for large-scale submarine slope failures (e.g. Evans et al., 1996; Baraza et al., 1999; Lee and Baraza, 1999; Bøe et al., 2000; Cochonat et al., 2002; Casas et al., 2003; von Huene et al., 2004). The study area is located just north of the very active North Anatolian strike slip fault (NAF, see Fig. 1 for location). According to Rangin et al. (2002), NAF has a considerable effect on the tectonics in Archangelsky Ridge and in the Sinop Basin. Based on their seismic data, they suggested that the fluctuations in the stress regime along the NAF have also been evidenced offshore. Furthermore, Çifçi et al. (2003) concluded that the NAF could play an important role on the overpressure conditions present in the pockmark plateau of Yeşilırmak shelf. NAF itself can produce large earthquakes with magnitudes of $M=6.0$ or more, which can act as a trigger for slumps or slides on the slope and channel bordering levees. The seismic data, however, do not indicate such relatively large slide features along the slope, such as Columbretes in Ebro slope (Casas et al., 2003) or Karmsundet offshore of Norway (Bøe et al., 2000), where the sizes of the slides were larger than 10 and 8 km, respectively, whereas the largest slide zone observed in Yeşilırmak Fan was not larger than about 500 m in width localized at the canyon heads (see Fig. 7a). If the main triggering mechanism for the slides were seismic loading due to NAF, we would observe much larger sliding events on the seismic data. Therefore, we conclude that NAF has a minor effect on the triggering of the slides and apart from the effect of NAF, several other factors may be considered as possible triggering mechanisms for small-scale submarine slides, such as steep slope and/or gravity loading as well as excess pore fluid pressures related to shallow gas accumulation which is also observed in several places in the Yeşilırmak continental slope (Ergün et al., 2002). Although it is also possible that all of the above factors can operate together, we tentatively suggest that the gravitational loading due to continuous sedimentation on the steep slopes can be responsible for initiation of the most downslope mass movement processes, such as gravity flows or small-scale sliding. Taking into consideration of the multi-phase sliding character of the open continental slope, we also conclude that periodically repeated bottom currents, especially turbidity flows, can contribute such a multiple sliding. It should also be taken into consideration

that the area is located just north of the compressive zone of the Pontid orogenic belt, which resulted in a relatively steep continental slope along the southern Black Sea Turkish margin. It can also be suggested that such steep slope might have a secondary effect on the downslope sediment redistribution particularly for the sediment movements due to the gravitational loading.

The canyon systems on the continental slopes form the most favorable pathways for the sediment transport from coastal areas to deep waters, generally via turbidity currents flowing along the canyon axes. Well-developed tributary canyon systems exist all over the Yeşilırmak continental slope, possibly forming the most suitable pathways for sediment transport from shelf break to abyssal depths (Fig. 3). In the canyon systems of the continental slope, the sliding and slide scars generally occur near the canyon heads (Fig. 7), e.g. around the shelf/slope limit, where erosive processes are also active (Fig. 4a). The canyon heads are also considered as one of the major erosional areas where excessive amounts of sediment evacuation processes occur together with sliding (Okey, 1997 and references therein).

According to Laursen and Normark (2002), localized slope failures around the canyon heads initiate canyon evolution, and the upslope extending of a canyon is supported by headward erosion. Shanmugam (2000) suggested that the dominant process in the development of a canyon is mass movement driven by gravitational forces. Eschard (2001) proposed that canyon incision is related to three different processes, (a) fluvial incision observed in the main river mouths, (b) retrograding sliding, and (c) submarine erosion which suggests high-energy bottom currents, e.g. turbidities. Garcia et al. (2006) proposed that morphological character of the tributary valleys in Alboran Sea changes from gullies in shallower waters to leveed-channels at deeper parts, and they also suggested that the evaluation of the tributary system is controlled by various factors such as turbidity currents, hemipelagic sedimentation, sediment failure and hyperpycnal fluxes. For Yeşilırmak River Fan, we conclude that the development of the canyon systems as well as small-scale gullies is controlled by down-slope turbidity current activity. Turbidity currents are often associated with submarine canyons since they are capable of eroding channels on the seafloor. For our study area, we conclude that the erosive power of such currents is responsible for the incision into the continental slope of the canyons by headward erosion and also for much of the sediment movement into the canyons. The area is located off the Yeşilırmak River mouth where local current systems possibly exist off the river mouth, which causes repeated failures of the sediment load in the same area of

the seabed. This repetitive action carves steep sided canyons into the continental slope through which possible successive hyperpycnal fluxes and the activity of unconfined turbidity flows along the channel axis transport the sediment load from Yeşilırmak River to deep water while continually tending to cut back the canyon head towards the coast.

6. Conclusions

High-resolution acoustic data indicate that downslope sedimentary processes are predominant along the slope and mass movement is a significant process in the continental slope of Yeşilırmak River fan, which occurs both inside of the canyons and in the open continental slope. The sedimentary structures and erosional processes include sliding and debris flows on the canyon walls together with the recent erosional surfaces at the canyon heads, and slides and scarps structurally controlled by rotational faults in the central part of the open continental slope.

Formation of sliding on the open slope and canyon walls is a multi-phase sliding process, and several sliding events occur successively at the same location producing a vertically stacked multi-phase sliding, and therefore several buried relict slide features also exist in deeper parts of the sediments. The rotational faults act as initial glide planes, along which downslope sliding occurs. We tentatively conclude that gravitational loading on the steep slope acts as the main triggering mechanism for most of these mass movement processes in the area, and in some places, overpressured pore fluids due to gas accumulation and seepage can contribute the instability.

Well-developed tributary canyon systems exist all over the slope, with sliding and slide scars around the canyon heads. Large input of terrigenous sediments with the contribution of local current systems off the Yeşilırmak River mouth carves steep sided canyons into the continental slope. Sediment load from Yeşilırmak River is transported to apron and abyssal depths by successive hyperpycnal fluxes and the activity of unconfined turbidity flows along the channel axis, which also results in the incision of canyon heads towards the shelf break.

We conclude that the continental slope of Yeşilırmak River fan appears as a classical deep-sea turbidite system. In this classical system, we observe slide scars in proximal part, in distal part, however, channel levee systems with slide and debris flow deposits inside the channels and, in place to place, hemipelagic sedimentation on the channel banks.

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