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Laterally contiguous, concave-up basal shear surfaces of submarine landslide deposits (Miocene), southern Cyprus: differential movement of sub-blocks within a single submarine landslide lobe

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ABSTRACT: Detailed analysis of submarine landslide deposits from extensive outcrops of a Miocene slope succession (southern Cyprus) reveals significant information on basal shear surfaces of the slides. The deposits, 3–25 m thick, occur as lobate beds in transverse section at two stratigraphic horizons. Each slide lobe shows a series of adjacent concave-up basal shear surfaces, 30–150 m wide, which nearly intersect or overlap with their neighbors. The upward curved or stepped margins of basal shear surfaces, here called *shear wings*, exhibit variable length (ca. 5–30 m long) and inclination. The basal shear surfaces were probably initiated along a bedding-parallel weak horizon, but propagated upward at some point where downslope driving stresses decreased or resisting forces increased. Considering the dimension (ca. 5–30 m long) of the shear wings, the multiple, adjacent concave-up basal shear surfaces can be seen as a single basal shear plane in most high-resolution subbottom and seismic images because of the limit of acoustic resolution. The multiple contiguous, concave-up basal shear surfaces in each lobe suggest that a submarine landslide lobe probably moved downslope as several sub-blocks in transverse section, rather than as a single unified one. The boundary of the sub-blocks where concave-up basal shear surfaces nearly intersect or overlap with their neighbors marks a zone of differential movement between the sub-blocks, each probably showing very subtle differences in magnitude or speed of downslope movement. This subtly differential movement would create intense sediment deformation at the boundary between the sub-blocks, and may lead to longitudinal shear ridges on the upper surface.

Key words: submarine landslide, submarine mass movement, submarine landslide dynamics, submarine slope instability, Cyprus

1. INTRODUCTION

Submarine landslides are very common in both modern and ancient sedimentary environments, such as open continental slopes, submarine canyons, flanks of volcanic islands and ridges, fjord slopes, and active prodelta systems (Prior and Coleman, 1984; Piper et al., 1985; Martinsen, 1994; Hampton et al., 1996; Stow et al., 1996; Bøe et al., 2000; Masson et al., 2002). They have an important impact on human life by destabilizing offshore installations and generating tsunamis, and are also responsible for the transfer of a large amount of sedimentary material to the deep ocean (Lee et al., 1993; Stow et al., 1996; Tappin et al., 2001; Ward, 2001; Canals et al., 2004). Submarine landslides have a basal failure zone overlain by displaced masses of sediments or rocks showing a variety of internal deformation. They range in size and volume from a few cubic meters to several thousand cubic kilometers (Garfunkel, 1984; Booth et al., 1993; Hampton et al., 1996; Mulder and Cochonat, 1996; Vorren et al., 1998; Gee et al., 2001; Locat and Lee, 2002; Canals et al., 2004; Lastras et al., 2004).

Recent developments in high-resolution offshore remote-sensing technology (e.g. multi-beam echo sounding, high-resolution subbottom or seismic reflection, side-scan sonar and deep-towed systems) have revealed some important features of submarine landslide deposits (Piper et al., 1992; Gardner et al., 1999; Gee et al., 2001; Lee et al., 2002; Masson et al., 2002; Canals et al., 2004; Haflidason et al., 2004; Lastras et al., 2004, 2006; Lindberg et al., 2004). These include the documentation of multiple events within a single mega-landslide unit, the presence of longitudinal and transverse ridges on the surface, and the close correspondence of debris-flow lobes with submarine landslide deposits. Such data sets have provided invaluable information about the causes of initiation and post-failure evolution or dynamics of submarine landslides.

In submarine landslide deposits, medium-scale (several meters to a few tens of meters in dimension) basal and internal sedimentary features are important for understanding dynamics of submarine landslide (Hampton et al., 1996; Lucente and Pini, 2003; Gee et al., 2006). However, these sedimentary features can not be easily revealed in most high-resolution subbottom or seismic profiles because of the limit of acoustic resolution. Although outcrop studies have provided detailed information on micro- to small-scale (less than a few meters in dimension) internal and basal sedimentary features of submarine landslide deposits, most outcrops are not still large enough to document their medium-scale sedimentary features. In the southern Cyprus, many large (30–120 m high, 0.5–2 km wide) outcrops along a recently constructed highway provide unprecedented access to a full cross-sec-

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*Corresponding author: sanglee@kordi.re.kr tion of the Miocene submarine landslide deposits. This paper provides detailed medium-scale features of basal shear surfaces in the submarine landslide deposits, which leads us to a new understanding of dynamics of submarine landslide.

2. GEOLOGICAL SETTING

The Neogene (Miocene–Pliocene) sedimentary basins in the southern Cyprus were formed by the northward subduction of the African plate beneath Cyprus. The sedimentation was strongly influenced by the uplift of Troodos ophiolitic terrain, which culminated in the late Miocene (Robertson et al., 1991; Eaton and Robertson, 1993). The study area is located in the Miocene Pakhna Formation, Khalassa Basin (Fig. 1). The Pakhna Formation is dominated by marine chalks, marls and calcarenites with subordinate carbonate submarine landslide deposits and conglomerates, which are interpreted to be deposited in basin-margin to basin-plain environments (Robertson et al., 1991). The submarine landslide deposits are generally associated with massive to graded and thin- to medium-bedded calcarenites, interbedded with marls and chalks, which were deposited in basin-margin or basin-slope environment (Eaton and Robertson, 1993). The distribution of facies associations and paleocurrent directions indicate that the basin margin was dipping to the south from the Troodos ophiolitic terrain with an outer high locally present further southward (Robertson et al., 1991; Eaton and Robertson, 1993).

The measured outcrops are oriented NE–SW or NW–SE (Fig. 1), which is oblique to the inferred paleoslope direction. The submarine landslide deposits occur as lobate beds at two stratigraphic horizons just below a prominent white chalk bed (known as the *Discospirina* band, ca. 6 Ma), which is present in the entire Khalassa Basin (Fig. 2; Eaton and Robertson, 1993). The two stratigraphic slide horizons can be traced over ca. 10 km laterally throughout the study area.

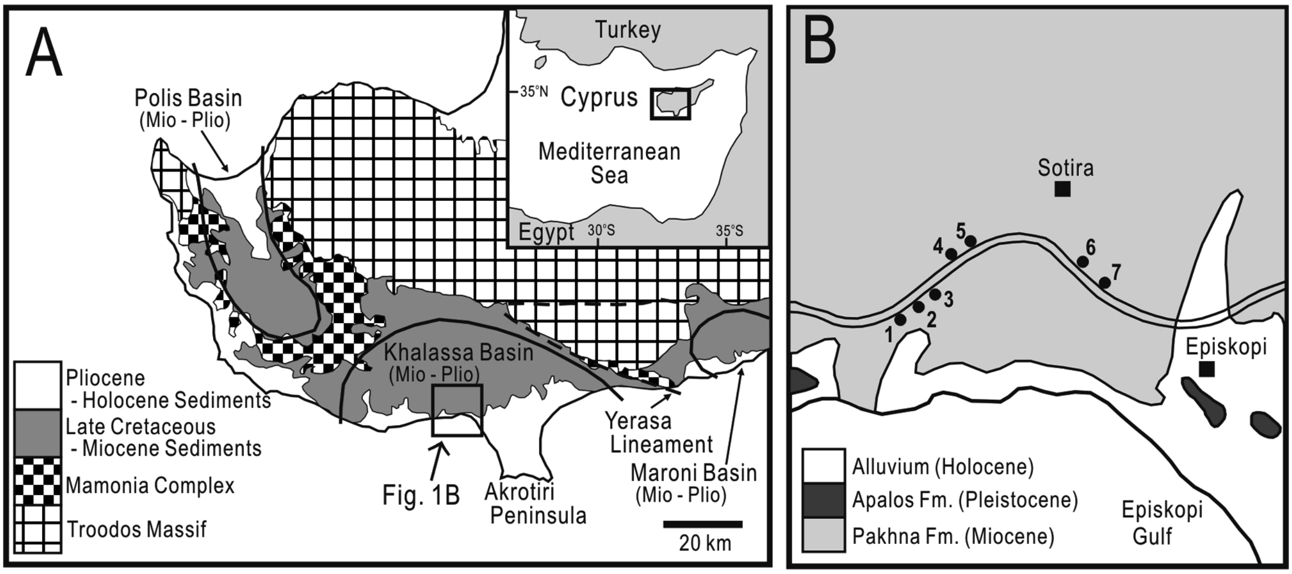

Fig. 1. (A) Major geological units and structural elements of the southern Cyprus, together with the main Neogene sedimentary basins. Modified from Eaton and Robertson (1993). (B) Geologic map of the study area (Cyprus Geological Survey, 1995). Circles with number indicate the location of measured sections.

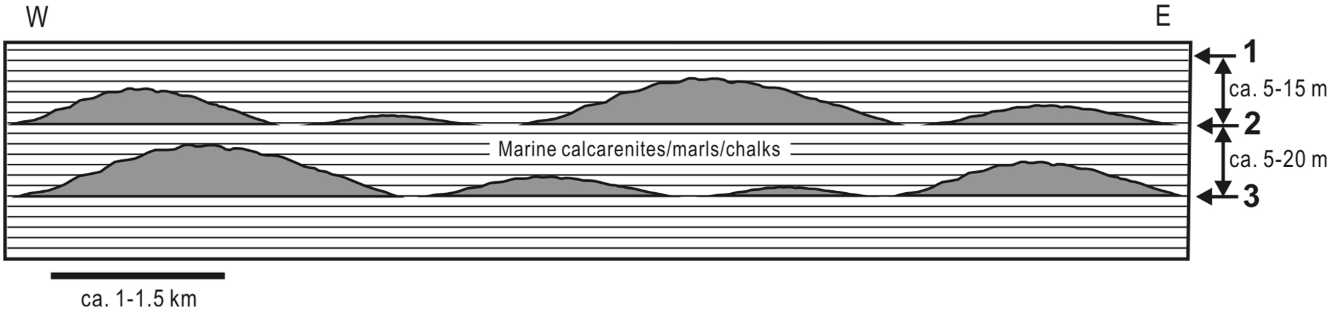

Fig. 2. Schematic diagram showing occurrence of submarine landslide deposits (gray color) in the study area. Note occurrence of the lobate slide deposits at two stratigraphic horizons (2 and 3) below the *Discospirina* band (1). Vertical scale is exaggerated.

3. SEDIMENTARY FEATURES OF SUBMARINE LANDSLIDE DEPOSITS

The submarine landslide deposits ranges from 3 to 25 m in thickness. The deposits generally show a large-scale, convex-upward upper boundary and nearly flat, distinct lower boundary (Figs. 3, 4 and 5). The upper boundary commonly exhibits a slightly rugged topography less than 3–4 m in relief (Figs. 4 and 5). The submarine landslide deposits pinch out on both sides (Fig. 3), indicating several distinct

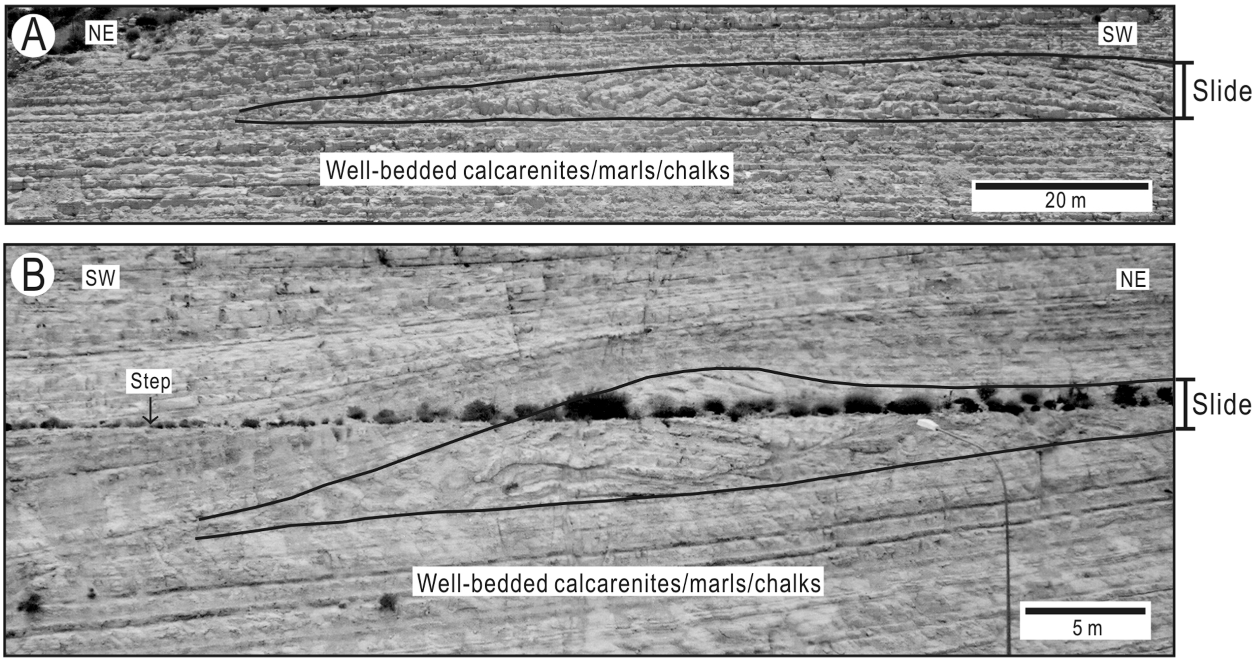

Fig. 3. Photographs showing large-scale, convex-upward upper and nearly flat, distinct lower boundaries of submarine landslide deposits at sections 2 (A) and 5 (B). Note a laterally wedged geometry of the slide deposits between well-bedded marine calcarenites/marls/chalks. For locations of the sections, see Fig. 1B.

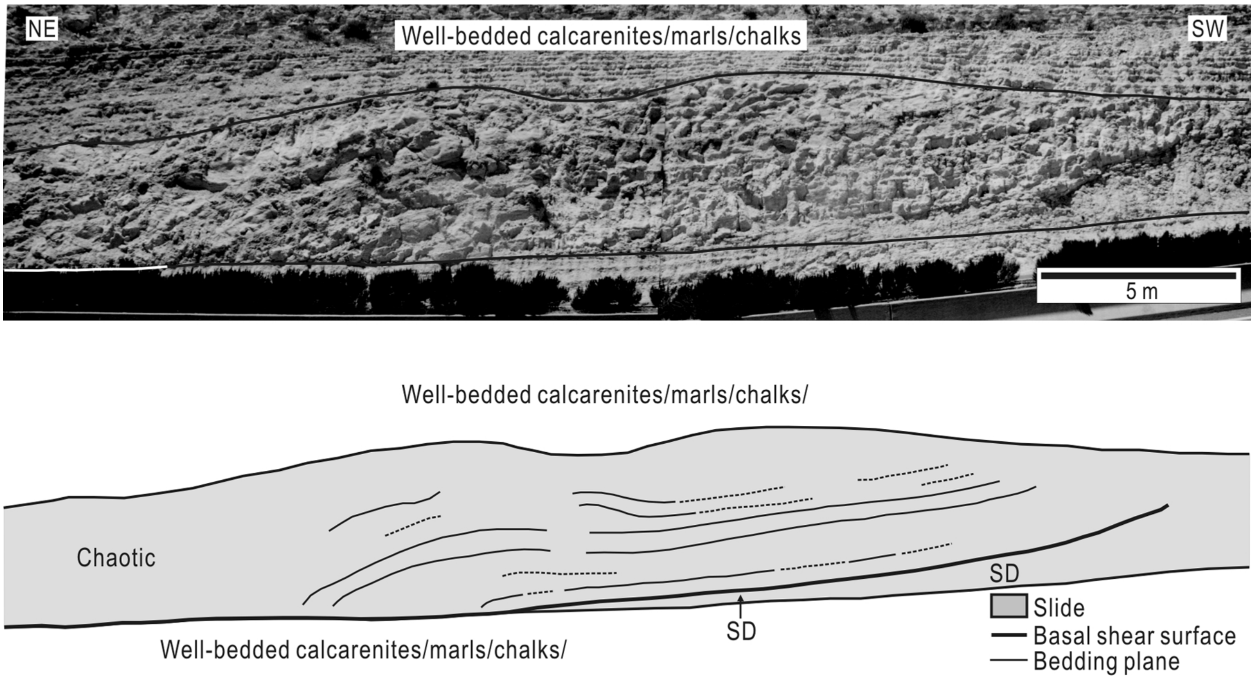

Fig. 4. Photograph (top) and line drawing (bottom) displaying sedimentary features of submarine landslide deposits (Section 3). Note a slightly rugged morphology of the upper surface and a tangentially curved geometry of the basal shear surface at end of the flat portion. SD in the bottom indicates a severe or intense deformation. For location of the section, see Fig. 1B.

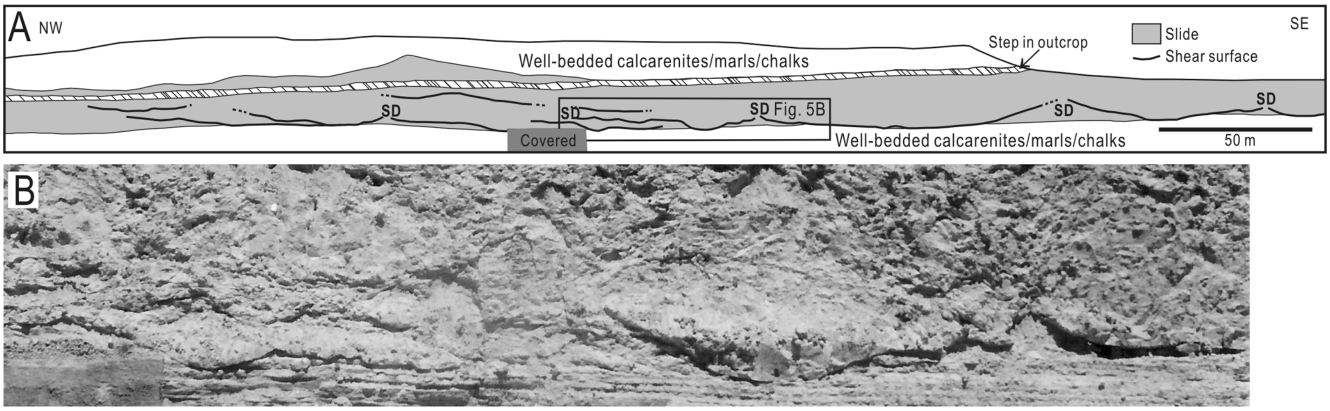

Fig. 5. Line drawing (A) and photograph (B) showing laterally contiguous, multiple concave-up shear surfaces in the basal shear zone of a slide lobe (Section 7). Note a severe or intense deformation (SD) between the upward curved margins (shear wings) of basal shear surfaces. For location of the section, see Fig. 1B.

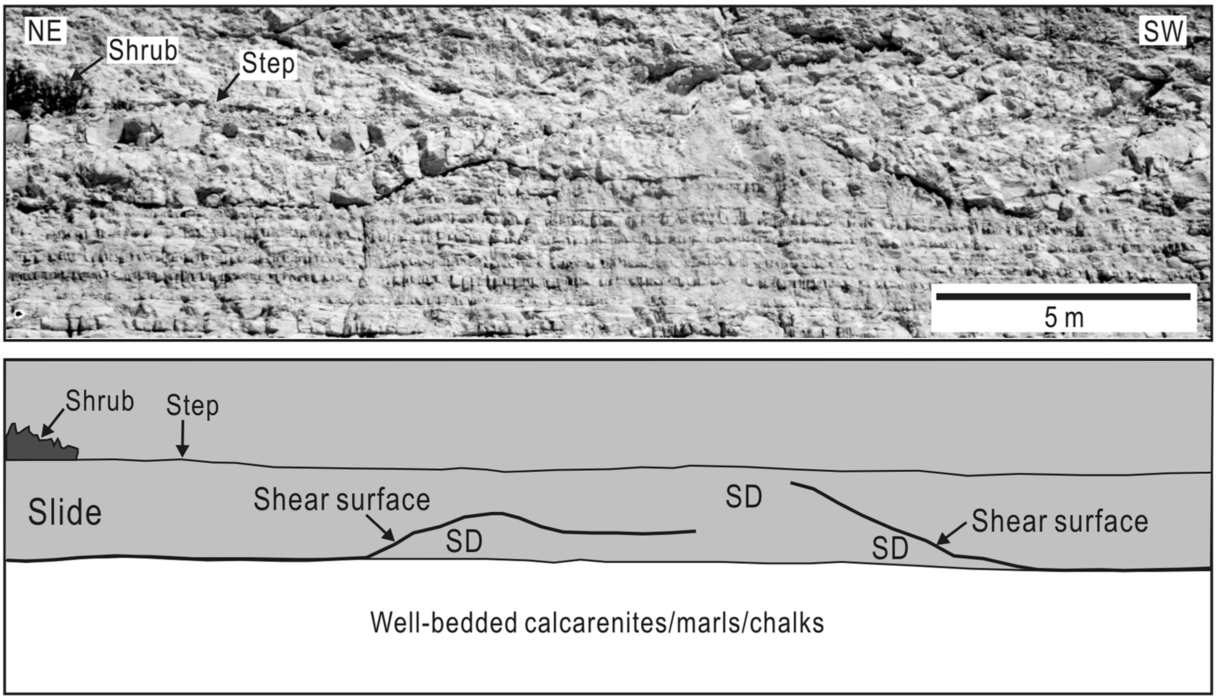

Fig. 6. The upward curved margins of basal shear surfaces at each end of the flat portion (Section 1). SD indicates a severe or intense deformation. For location of the section, Fig. 1B.

submarine landslide lobes at each stratigraphic horizon (Fig. 2). The interior of submarine landslide lobes shows a variety of sedimentary features, ranging from largely intact sub-horizontal bedding, through slightly to severely folded to blocky or chaotically deformed (Figs. 3 and 4).

Each submarine landslide lobe is characterized by a prominent basal shear zone in which shear surfaces may at first appear planar and relatively continuous. In detail, however, the basal shear surfaces are curved upward with tangential or stepped geometry at the end of the relatively flat portion (Figs. 4, 5 and 6), forming laterally contiguous, multiple concave-up basal shear surfaces in each slide lobe (Fig. 5). The basal shear surfaces range from 30 to 150 m in length. Besides the basal shear surfaces, internal shear surfaces occur in the middle part of submarine landslide deposits and show either slightly concave-upward or inclined geometry (Fig. 5).

The upward curved or stepped parts of basal shear surfaces, called here *shear wings*, vary in length (about 5–30 m long) and angle of inclination, and often extend into the middle part of submarine landslide deposits (Figs. 4, 5 and 6). Sediments below the shear wings are generally characterized by intense or severe deformation (Figs. 4, 5 and 6). Where the shear wings either nearly intersect or overlap with neighboring ones, the sediments show severe deformation and chaotic appearance (Figs. 5 and 6).

4. DISCUSSION

Several sedimentary features of the submarine landslide deposits in the study area are very compatible with recent observations of submarine landslides on the modern slope setting using high-resolution side-scan sonar and subbottom/seismic images. In sections oblique to the paleoslope direction, the segmented lobate geometry of submarine landslide deposits suggests that several tongue-shaped slide masses were present. This corresponds well with the multiple slide lobes noted in a number of modern seafloor, even though their dimensions are highly variable (Bøe et al., 2000; Haflidason et al., 2004, 2005; Lastras et al., 2004; Lindberg et al., 2004). On the modern slope of the Eivissa Channel (western Mediterranean Sea), four small distinct submarine landslide lobes occur concurrently, with positive relief about 1–3.5 km wide and 20–40 m thick (Lastras et al., 2004, 2006). Their dimensions are almost similar to those of the submarine landslide lobes in the study area. The slightly rugged upper topography of each slide lobe in the study area is well matched with wrinkled surface forms or surface ridges of modern submarine landslides frequently observed on high-resolution acoustic images (Piper et al., 1992; Lee et al., 2002; Lindberg et al., 2004; Lastras et al., 2006).

The prominent basal shear zone of each slide lobe suggests that the sliding was probably initiated along an interval of bedding-parallel weak layer. The concave-up basal shear surfaces were initially developed in the basal shear zone, but were curved upward with tangential or stepped geometry at some points where downslope driving stresses decreased or resisting forces, such as sediment shear strengths, increased (Martinsen, 1994). Assuming that the basal shear wings of similar dimensions (ca. 5–30 m long) exist in modern submarine landslides, the basal shear wings can not be clearly resolved even in high-resolution subbottom or seismic profiles because of the limit of acoustic resolution. It is, therefore, most likely that the multiple, contiguous, concave-up basal shear surfaces would be seen as a single basal shear plane in most subbottom and seismic profiles of modern submarine landslides.

The multiple, contiguous, concave-up basal shear surfaces in each slide lobe suggest that the sliding mass probably moved downslope as several sub-blocks in transverse section, rather than a single unified one (Fig. 7). The sub-blocks are bounded by region where the concave-up basal shear surfaces nearly intersect or overlap with neighboring ones. Between the sub-blocks, very subtle difference in magnitude or speed of downslope movement probably existed (Fig. 7). This subtly differential movement between the sub-blocks can not be easily recognized in episodically downslope-moving submarine landslides. The boundary of the sub-blocks marks a zone accommodating the differential movement between the sub-blocks, leading to more

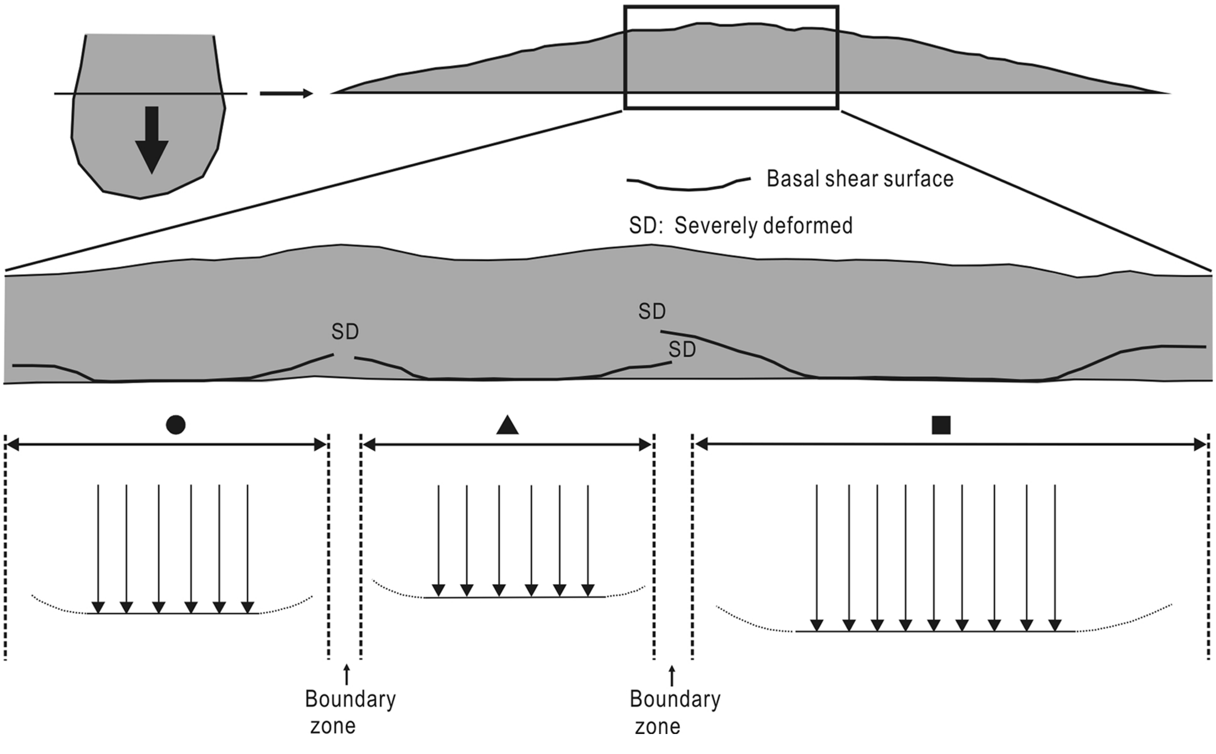

Fig. 7. A schematic model for submarine landslide dynamics showing downslope movement of several sub-blocks (denoted as •, ▲ and ■) in transverse section. Note a very subtle difference in magnitude or speed of downslope movement between each sub-block (bottom).

severe sediment deformation. Furthermore, the differential movement between the sub-blocks may help explain the formation of longitudinal shear ridges, which are commonly observed on the surface of modern submarine slides using high-resolution side-scan sonar images (Prior and Coleman, 1984; Hampton et al., 1996).

5. CONCLUSIONS

In the southern Cyprus, there are two distinct stratigraphic horizons of landslide deposits in the Miocene submarine slope sediments. Each horizon contains several submarine landslide lobes. These slide lobes are characterized by laterally adjacent, medium-scale (ca. 30–150 m long) concave-up shear surfaces in the basal shear zone. The upward curved or stepped margins of these basal shear surfaces, *shear wings*, vary in length (ca. 5–30 m) and inclination. The basal shear surfaces were probably initiated along a bedding-parallel weak layer, but propagated upward where downslope driving stresses decreased or resisting forces increased. The multiple contiguous, concave-up basal shear surfaces within each slide lobe suggest that the slide mass probably moved downslope as several sub-blocks in transverse section, rather than as a single unified one. At the boundary of the sub-blocks where the basal shear surfaces overlap or nearly intersect with neighboring ones, the intervening sediments were severely deformed, probably as a result of very subtle difference in magnitude or speed of downslope movement between the sub-blocks. This subtly differential movement may produce the longitudinal shear ridges, commonly observed on the surface of modern submarine landslides.

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REFERENCES

Booth, J.S., O'Leary, D.W., Popenoe, P. and Danforth, W.W., 1993, U.S. Atlantic continental slope landslides: their distribution, general attributes, and implication. U.S. Geological Survey Bulletin, 2002, 14–22.

Bøe, R., Hovland, M., Instanes, A., Rise, L. and Vasshus, S., 2000, Submarine slide scars and mass movements in Karmsundet and Skudenesfjorden, southwestern Norway: morphology and evolution. Marine Geology, 167, 147–165.

Canals, M., Lastras, G., Urgeles, R., Casamor, J.L., Mienert, J., Cattaneo, A., De Batist, M., Haflidason, H., Imbo, Y., Laberg, J.S., Locat, J., Long, D., Longva, O., Masson, D.G., Sultan, N., Trincardi, F. and Bryn, P., 2004, Slope failure dynamics and impacts from seafloor and shallow sub-seafloor geophysical data: case studies from the COSTA project. Marine Geology, 213, 9–72.

Cyprus Geological Survey, 1995, Geological Map of Cyprus (1: 250000).

Eaton, S. and Robertson, A., 1993, The Miocene Pakhna Formation, southern Cyprus and its relationship to the Neogene tectonic evolution of the eastern Mediterranean. Sedimentary Geology, 86, 273–296.

Gardner, J.V., Prior, D.B. and Field, M.E., 1999, Humboldt Slide - a large shear-dominated retrogressive slope failure. Marine Geology, 154, 323–338.

Garfunkel, Z., 1984, Large-scale submarine rotation slumps and growth faults in the eastern Mediterranean. Marine Geology, 55, 305–324.

Gee, M.J.R., Gaawthorpe, R.L. and Friedmann, S.J., 2006, Triggering and evolution of a giant submarine landslide, offshore Angola, revealed by 3D seismic stratigraphy and geomorphology. Journal of Sedimentary Research, 76, 9–19.

Gee, M.J.R., Watts, A.B., Masson, D.G. and Mitchell, N.C., 2001, Landslides and the evolution of El Hierro in the Canary Islands. Marine Geology, 177, 271–293.

Haflidason, H. Lien, R., Sejrup, H.P., Forsberg, C.F. and Bryn, P., 2005, The dating and morphometry of the Storegga Slide. Marine and Petroleum Geology, 22, 123–136.

Haflidason, H., Sejrup, H.P., Nygård, A. Mienert, J., Bryn, P., Lien, R., Forsberg, C.F., Berg, K. and Masson, D.G., 2004, The Storegga Slide: architecture, geometry and slide development. Marine Geology, 213, 201–234.

Hampton, M.A., Lee, H.J. and Locat, J., 1996, Submarine landslides. Reviews of Geophysics, 34, 33–59.

Lastras, G., Canals, M., Amblas, D., Ivanov, M., Dennielou, B., Droz, L., Akhmetzhanov, A. and TTR-14 Leg Shipboard Scientific Party, 2006, Eivissa slides, western Mediterranean Sea: morphology and processes. Geo-Marine Letters, 26, 225–233.

Lastras, G., Canals, M., Urgeles, R., Hughes-Clarke, J.E. and Acosta, J., 2004, Shallow slides and pockmark swarms in the Eivissa Channel, western Mediterranean Sea. Sedimentology, 51, 837–850.

Lee, H.J., Schwab, W.C. and Booth, J.S., 1993, Submarine landslides: an introduction. U.S. Geological Survey Bulletin, 2002, 1–13.

Lee, S.H., Chough, S.K., Back, G.G. and Kim, Y.B., 2002, Chirp (2–7 kHz) echo characters of the South Korea Plateau, East Sea: styles of mass movements and sediment gravity flows. Marine Geology, 184, 227–247.

Lindberg, B., Laberg, J.S. and Vorren, T.O., 2004, The Nyk Slide - morphology, progression, and age of a partly buried submarine slide offshore northern Norway. Marine Geology, 213, 277–289.

Locat, J. and Lee, H.J., 2002, Submarine landslides: advances and challenges. Canadian Geotechnical Journal, 39, 193–212.

Lucente, C.C. and Pini, G.A., 2003, Anatomy and emplacement mechanism of a large submarine slide within a Miocene foredeep in the northern Apennines, Italy: a field perspective. American Journal of Sciecne, 303, 565–602.

Martinsen, O., 1994, Mass movements. In: Maltman, A. (ed.), The Geological Deformation of Sediments. Chapman & Hall, London, p. 127–165.

Masson, D.G., Watts, A.B., Gee, M.J.R., Urgeles, R., Mitchell, N.C., Le Bas, T.P. and Canals, M., 2002, Slope failures on the flanks of the western Canary Islands. Earth-Science Reviews, 57, 1–35.

Mulder, T. and Cochonat, P., 1996, Classification of offshore mass movements. Journal Sedimentary Research, 66, 43–57.

Piper, D.J.W., Cochonat, P., Ollier, G., Le Dreezen, E., Morrison, M. and Baltzer, A., 1992, Evolution progressive d'un glissenment rotationnel en un courant de turbidité: cas du séisme de 1929 des Crands Bancs (Terre Neuve). Académie Science Comptes Rendus, 314, 1057–1064.

Piper, D.J.W., Farre, J.A. and Shor, A., 1985, Late Quaternary slumps and debris flows on the Scotian slope. Geological Society of America Bulletin, 96, 1508–1517.

Prior, D.B. and Coleman, J.M., 1984, Submarine slope instability. In: Brunsden, D. and Prior, D.B. (eds.), Slope Instability. John Wiley and Sons, New York, p. 419–455.

Robertson, A.H.F., Eaton, S., Follows, E.J. and McCallum, J.E., 1991, The role of local tectonics versus global sea-level change in the Neogene (Miocene-Pliocene) evolution of the Cyprus active margin. In: MacDonald, D.I.M. (ed.), Sedimentation, Tectonics and Eustacy. International Associations of Sedimentologists, Special Publication, 12, 331–372.

Stow, D.A.V., Reading, H.G. and Collison, J.D., 1996, Deep seas. In: Reading, H.G. (ed.), Sedimentary Environments: Processes and Facies and Stratigraphy (3rd edition). Blackwell Science, Oxford, p. 395–453.

Tappin, D.R., Watts, P., McMurtry, G.M., Lafoy, Y. and Matsumoto, T., 2001, The Sissano, Papua New Guinea tsunami of July 1998 - offshore evidence on the source mechanism. Marine Geology, 175, 1–23.

Vorren, T.O., Laberg, J.S., Blaume, F., Dowdeswell, J.A., Kenyon, N.H., Mienert, J., Rumohr, J. and Verner, F., 1998, The Norwegian-Greenland Sea continental margins: Morphology and late Quaternary sedimentary processes and environment. Quaternary Science Reviews, 17, 273–302.

Ward, S.N., 2001, Landslide tsunami. Journal Geophysical Research, 106, 11201–11215.

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