CHAPTER FOURTEEN

Mapping Submarine Slope Failures

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14.1 ABSTRACT

Geographic information systems (GISs) are ideally suited for mapping submarine landslides. Deep-water landslides, though seldom affecting humans, are responsible for moving vast quantities of sediment from continental slopes to the deep ocean. Earthquakes are believed to be responsible for many mid- to lower-slope slides, which in turn can be used as indicators of past earthquakes. The increasing amount of oil exploration and production in deepwater environments raises concerns over slope instability. Multibeam bathymetric data are used, with or without seafloor reflectivity data from side-scan sonar, to locate and quantitatively characterise very large submarine mass movements. The data acquired on size, water depth, thickness, slope gradient on which the slide occurred, gradient of the runout zone, gradient of the headscarp, and slope within the slide scar help in assessing slope stability. Once the conditions that triggered existing slides are defined, they can be applied to present-day conditions (sedimentary, seismic), and landslide hazard may be assessed.

14.2 INTRODUCTION

Submarine landslides are not only an important process in shaping the seafloor on continental margins and transporting sediment from the continental shelf break to the deep-water environments, but can have significant influence on humans as well. A submarine landslide triggered by an earthquake on the Grand Banks in 1929 created a turbidity current that severed trans-Atlantic communication cables almost 600 km away (Heezen and Ewing, 1952; Hampton *et al.*, 1996). In 1964, the great earthquake in Prince William Sound, Alaska triggered submarine slides that eventually retrogressed past the coastal zone, swallowing the towns of Seward and Valdez, and creating tsunamis that repeatedly washed over low-lying coastal areas (Coulter and Migliaccio, 1966; Lemke, 1967; Hampton *et al.*, 1996). Twenty-meter high waves associated with Hurricane Camille caused slope failures which damaged petroleum platforms on the Texas and Louisiana Gulf of Mexico shelf in August of 1969 (Bea *et al.*, 1983). Although many submarine slides occur in the deepwater, far offshore, their influences on humans can be substantial, and mapping them can prove beneficial to many concerns.

The primary challenge in studying submarine landslides is the relative inaccessibility and invisibility of the submarine environment. Slides undoubtedly occur without our knowledge. The only way to know where and when a submarine slide has occurred is to have data before and after a slide. Presently, governments and industry are in the process of acquiring high-resolution side-scan sonar and bathymetric data for ongoing studies of the seafloor for academic, economic, and military purposes. Data from side-scan sonar systems are similar to aerial photographs that show acoustic reflectivity (analogous to visual reflectivity in aerial photographs). Multibeam bathymetry data yield spatially referenced depths to the seafloor that can be morphometrically analysed in three dimensions. In digital format, these data are ideally suited for compilation and spatial analysis in a GIS framework.

McAdoo *et al.* (in prep.) created a GIS database of almost 100 geomorphically expressed submarine landslides on the continental slopes offshore Oregon, California, the Texas/Louisiana Gulf Coast, and New Jersey/Maryland ranging in size from 1 km^2 to over 5,500 km^2. The database has morphometric measurements including area, scar slope gradient, runout length and slope, headscarp height and slope, and slope gradient of the adjacent unfailed slope, which is used as a proxy for the pre-failure slope angle. Collected data can be used to assess and mitigate potential landslide hazards in offshore regions of similar geology and geomorphology, and perhaps start investigating the triggers for deepwater mass movements.

14.3 DATA

A ship collects “multibeam” or “swath” bathymetric data by broadcasting an acoustic signal in a fan pattern beneath the ship while surveying at speeds generally around 10 knots (Figure 14.1). Sixteen or more beams collect depth data, corrected for beam angle, geographically referenced to the ship’s global positioning system. The bathymetric data used to identify the submarine landslides in the McAdoo *et al.* (in prep.) study were collected using the Sea Beam swath-mapping system (deMoustier, 1988). The data have a vertical resolution of $\leq$ 1% of water depth and a position accuracy $\leq$ 50 m (Grim, 1992). Pratson and Coakley (1996) created gridded data sets (100 m) from the Northeast Consortium for Oceanographic Research and the National Oceanic and Atmospheric Administration (NOAA) surveys of the Oregon, California, Texas/Louisiana, and New Jersey/Maryland margins. Existing data sets can be acquired from a number of sources, often with only minimal charge. The National Geophysical Data Center (NGDC) is a clearinghouse for numerous types of geophysical data. Their web site, http://www.ngdc.gov/mgg/bathymetry/multibeam.html is the gateway to these data.

The formats of the data are as varied as the software packages that create and analyse them. For mapping even the largest submarine slides, it is best to use data sets with grid size < 0.04 km^2 (< 200 m or 0.002^o on a side for a square grid cell), but these particular data sets are often difficult to acquire. Much of the gridded

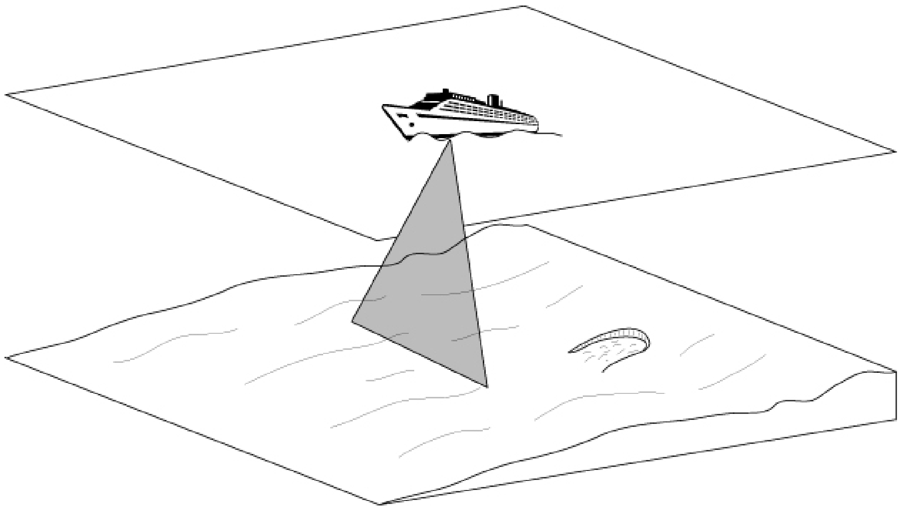

Figure 14.1 Cartoon of multibeam bathymetric data collection from ship. Surveying at 10 knots, a ship can cover between 100 and 4000 km^2 per day in water depths between 200 and 6000 m.

multibeam bathymetric data come in either a binary Generic Mapping Tools (GMT) format or Arc interchange (.e00) format for those with access to the Environmental Systems Research Institute's (ESRI) Arc/INFO or ArcView software. GMT is collection of Unix tools designed for spatial data (x, y, and z), and can display data in many different map projections (Wessel and Smith, 1991). Graphical output is in the form of Encapsulated PostScript (EPS) files. It can be downloaded, free of charge, from http://imina.soest.hawaii.edu/gmt. Once a gridded data set is acquired, it is possible to convert GMT binary grid (.grd) files to Arc/INFO™ ASCII format. A public domain converter can be downloaded from http://dusk.geo.orst.edu/arcgmt (Wright *et al*., 1998).

To make morphometric measurements using ArcView's Spatial and 3-D analyst tools, it is helpful to have the same x, y, and z units. In Arc/INFO, re-project geographic projections with x (longitude) and y (latitude) decimal degrees, and z (usually) in meters, to a Universal Transverse Mercator (UTM) projection where all units are in meters. This way, the analysis programs that calculate slope gradients and aspects, and artificial hillshading will operate properly.

14.4 DATA ANALYSIS

When mapping any geomorphic feature, be it incised steam beds, drumlins, or landslides, it is useful to view the data in a format that accentuates rapid changes in surface elevation. The artificial hillshading and slope gradient algorithms available in many software packages will cast “shadows” on or illuminate regions of steep local slope. This is very helpful in identifying landslide scars.

The first step in identifying slides is to make slope and artificial hillshade maps. Regions with rapid changes in slope gradient help point out the landslides (McAdoo *et al.*, in prep). Figure 14.2 shows how clearly the diagnostic arcuate headscarps are illuminated by the slope gradient maps. The slope gradients of the landslides’ headscarps and sidewalls can be measured at any point in the grid. By casting various artificial sun angles and altitudes, headscarps, sidewalls, and occasionally material at the slide base can be alternately lit up or darkened (Figure 14.3). Aspect maps are helpful in identifying regions of anomalous direction, and highlight regions such as canyons and slides’ sidewalls where the erosive walls are directed ~90^{o} to the headscarp and local downslope trend (Figure 14.4). Again, to get a statistically significant value of slope, it is helpful to average as many points within the area of interest as possible.

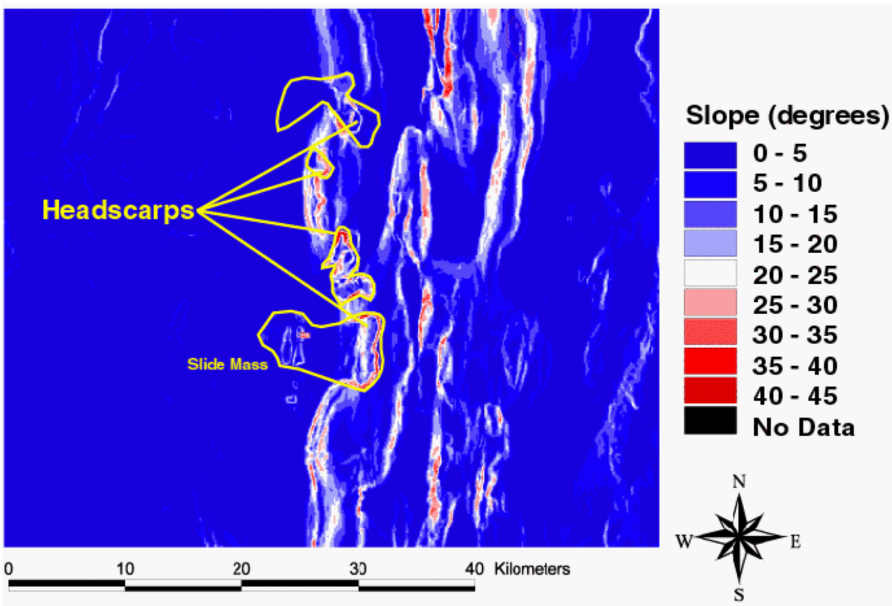

Figure 14.2 Slope gradient map of the base of the Oregon continental slope. In this figure, lighter shading indicates higher gradients and darker, lower. Arcuate headscarps have anomalously high slope gradients. Smooth, continuous regions of high slope gradient are the flanks of anticlinal ridges caused by the subduction of the Juan de Fuca plate beneath the North American plate.

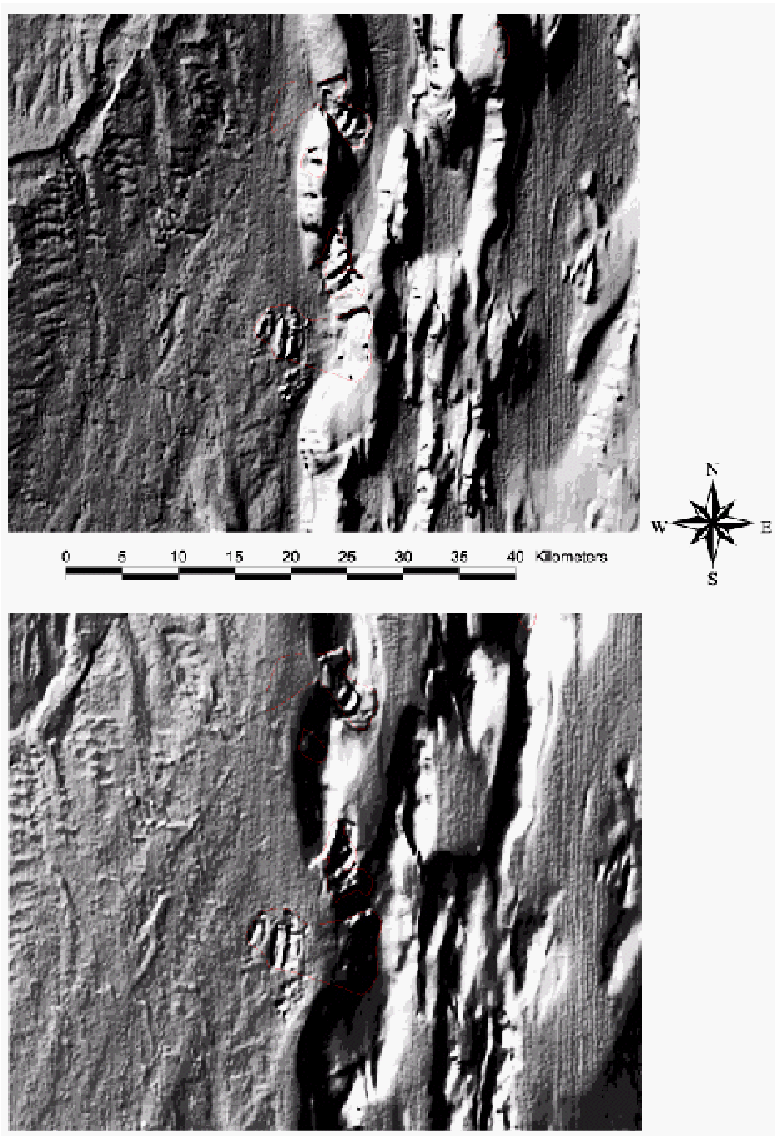

Figure 14.3 Artificial hillshade maps of the base of the Oregon continental slope. Same view as Figure 14.2. Top figure has a sun illumination angle from the northwest (315°), and the bottom figure is with the sun angle at the same altitude, but from the southeast (225 °).

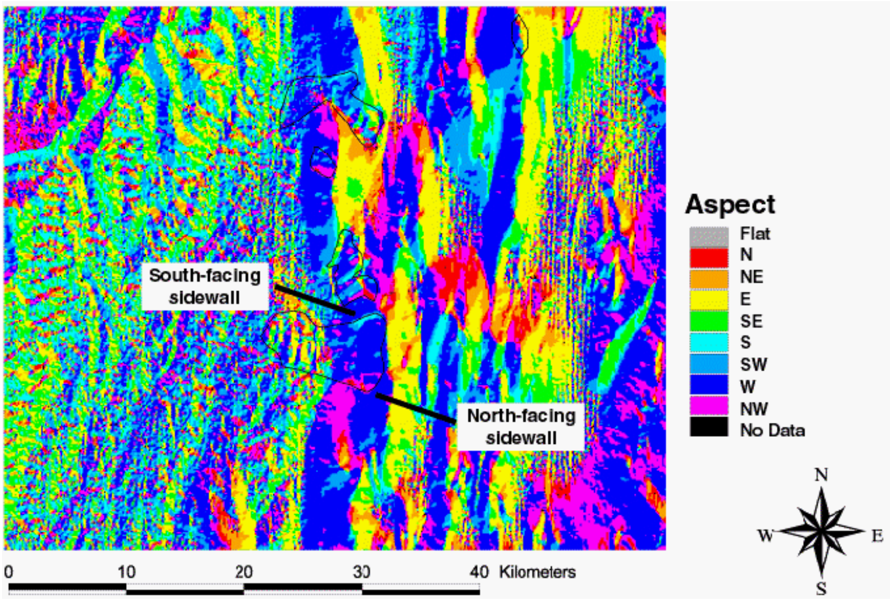

Figure 14.4 Aspect map of the base of the Oregon continental slope. N, NE, E, etc. represent compass directions north, northeast, east, etc. The anticlinal ridges at the base of the slope are directed dominantly to the east and west. The sidewalls of the landslides show with as north and south aspects.

Cross-sections or profiles through a slide help verify of potential landslide surfaces. From downslope profiles, headscarps are easily identified, and their height can be measured in various sections (Figure 14.5). Profiles taken across slides, can be helpful in identifying the lateral extent of erosion or deposition, and help constrain the geometry of the slide deposit (Figure 14.5). In addition, they can assist in identifying the characteristics within the slide scar. For instance, slump blocks, which have detached from a headscarp, and do not exceed the downslope extent of the sidewalls (Figure 14.6). Profiles through the slope maps identify headscarps as the region of steepest slopes, and yield the point of the maximum slope within a given profile.

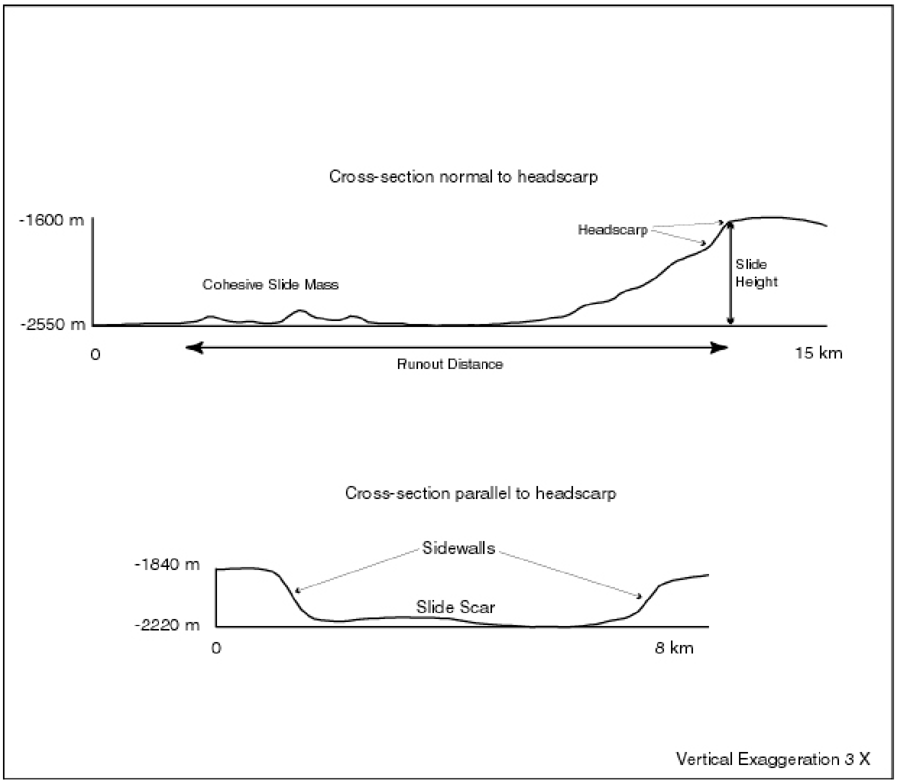

Figure 14.5 Profile normal and parallel to a slide's headscarp. Vertical exaggeration is 3 times. The cross-sections are from the southernmost slide illustrated in Figures 14.2 and 14.3. Note the slide mass at the base of the slide, with a 10 km runout distance from the headscarp. The height of the slide is measured from the top of the headscarp to the level at which the slide mass came to rest, or the base of the slide scar if slide mass is not apparent. The headscarp is the steepest portion at the head (top) of the slide.

14.5 DATA INTERPRETATION

The data acquired by morphometric mapping in a GIS framework can be interpreted to provide critical information on the location, distribution, and hazards associated with submarine slides. Bathymetry data provides information on the water depths where failures occur, slide thickness, heights from top of the headscarp to base of the scar, runout maximum, and height of the headscarp and slide thickness. Slide area assessment can tell us how important landslides are as sediment transport and landscape shaping processes in particular regions. Furthermore, defining the slide area helps with hazard mitigation by showing us how large slides tend to be in a given region.

Slope gradient measurements are critical in slope stability analyses and subsequent hazard recognition. There are numerous methods of calculating slope stability, most of which include some combination of material properties (strength, degree of consolidation or previous burial, ability to build up pore-pressures with cyclic earthquake loading, etc.) and slide morphology, including slope and thickness of slide. Assuming a slope with similar physical properties (which is not unlikely over relatively small areas in the marine environment), the only variables in calculating a factor of safety for a particular region are slope angle and slide thickness. By looking at the morphology of existing slides, we can assess slope stability based on the slide thickness and slopes where previous slides have occurred.

Charts and tables of the measurements can be compiled directly into the spatial framework of the GIS. Outlining the extent of the slide with a polygon, then tying in each of the variables on the attribute table for that polygon is an effective means of cataloguing the data on each of the slides in a particular area. Location, type of failure (i.e., cohesive or disintegrative), depth to headscarp, area, runout distance, headscarp height, and slope gradients of the headscarp, local unfailed slope, scar, and runout zone are added to the attribute table of the theme. Individual slides can be interrogated for their statistical measurements, and the statistical data can be viewed as a whole in the theme’s attribute table.

14.5.1 Bathymetry

One of the more fundamental measurements made on submarine slides is water depth of the headscarp. Some continental margins, especially active convergent margins such as offshore Oregon, tend to have continental slopes that get steeper with depth (Pratson and Haxby, 1996). Working on the assumption that slides tend to occur where slopes are the steepest, we might expect to see more slides on the lower slope of active margins. A simple histogram of a number of slides in given water depths can be used to assess this hypothesis. If there are more slides in shallow water, on or near the shelf break, perhaps slides are related to rapid sediment deposition and fluid overpressuring during times when shelf break deposition is occurring. On the other hand, perhaps erosion and deposition cycles erased past landslide activity, therefore more slides are preserved in quieter, deeper water. Interpretations may vary based on how much is known about depositional history of a region, and its present-day geotechnical properties.

Headscarp height is a good proxy of material strength (McAdoo *et al.*, in prep.). Regions with overconsolidated, high strength material tend to produce failures with higher headscarps, resulting in deeper-seated slides (McAdoo *et al*., in prep.). These deep-seated slides expose material that is even more overconsolidated than the original unfailed, but eroded, surface. These slides often maintain a degree of post-failure cohesion, leaving blocky masses at the base of the slide scar (Figure 14.2). Shallow seated slides, like those at the base of Mississippi canyon in the Gulf of Mexico (Figure 14.7), suggest weaker (perhaps high fluid pressure) sediment. These slides are quite often very large, despite occurring on gentle slopes (McAdoo *et al.*, in prep.).

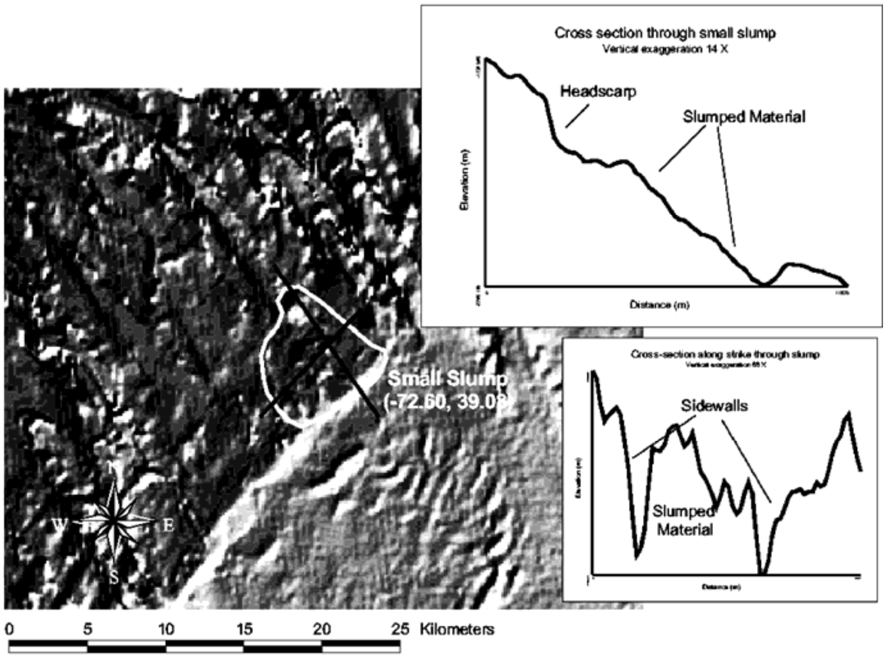

Figure 14.6 Cross-sections through a slump offshore New Jersey. The top section is approximately normal to the headscarp and the lower section is taken across the slide. Note the steep headscarp at the top of the slide followed by a downslope decrease in gradient at the top of the slump block. The cross-section from across the slumped mass shows separation of the mass from the sidewalls.

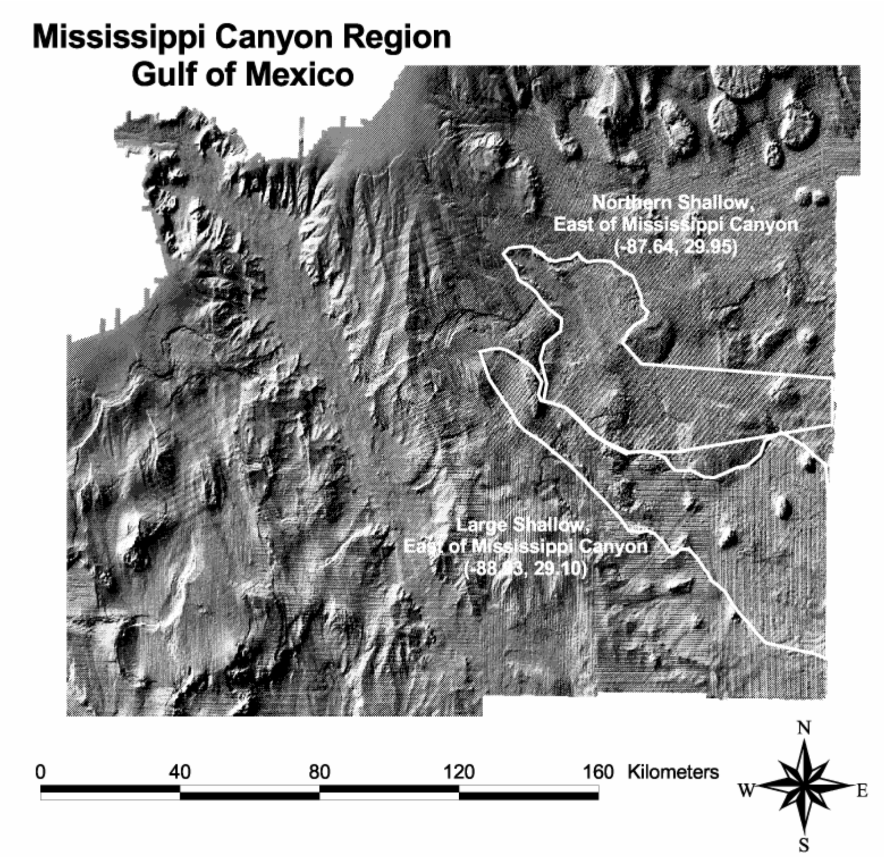

Figure 14.7 Very large slides in the Gulf of Mexico, east of Mississippi canyon, offshore Louisiana. These slides combined encompass over 5,000 km^2 of seafloor. Slides of this magnitude could pose substantial hazard to offshore drilling and/or production infrastructure.

The height of the failure's headscarp is also important when considering landslides as a sediment transport mechanism, and when assessing hazard based on runout distance potential (Figure 14.7). Runout length is one way that submarine landslides differ substantially from their subaerial counterparts. Runout for a given submarine slide tends to be on the order of 10^2 to 10^3 times higher than a subaerial slide with the same slide height (Keefer, 1984; McAdoo *et al.*, in prep). Runout distances (and slide area) in submarine environments are higher due in part to hydroplaning of submarine slides (Mohrig *et al.*, 1998).

14.5.2 Area

The larger the area of a submarine landslide, the more sediment is moved, the greater the area of seafloor affected, and hazards potential. Slide area can be divided into two regions: the scar (erosive) and slide mass (depositional). It is often difficult to find evidence of the slide mass, either in the bathymetry data, because the slide mass is too thin to be resolved, or in a side-scan system such as GLORIA, because the failed material does not sufficiently contrast with the surrounding seafloor.

The minimum slide area that can be reasonably measured in a 100-m gridded data set is ~1 km^2. McAdoo *et al.* (in prep.) report a slide at the base of Mississippi canyon that exceeds 5,500 km^2 (Figure 14.7). Slides such as this are responsible for transporting large quantities of sediment. A rough estimate of slide volume (V) can be calculated by using the slide area (A), headscarp height (h), and a shape coefficient (k) related to the slide geometry.

$$V = k\,A\,h \tag{14.1}$$

Figure 14.8 shows the two end member models of the volume calculation. If the sidewalls of the slide are of similar height as the headscarp, then $k = 1$. If the sidewalls taper to nothing at the slide base, the geometry is approximately wedge-shaped, and $k = 1/2$.

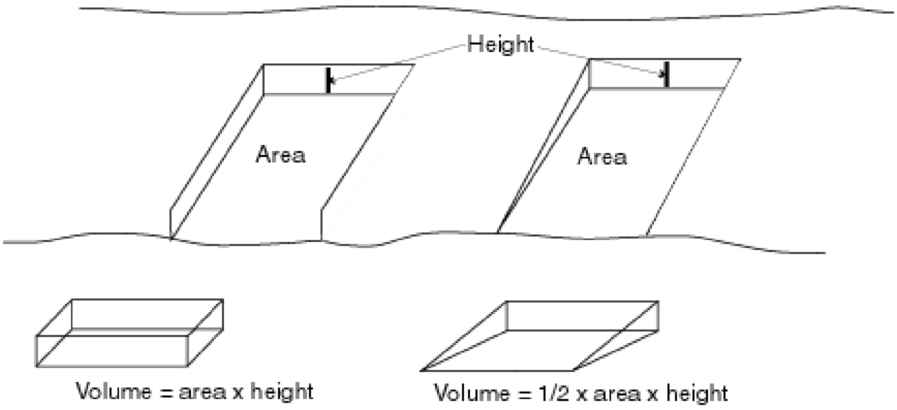

Figure 14.8 3-D cartoon of two submarine slides. The slide on the left has sidewalls that do not diminish in height downslope. The right slide has sidewalls that taper to nothing at the base of the slide. End-member volume calculations are approximated by a shape with a given surface area and uniform heights around that surface area (volume is the area of the base multiplied by the thickness of the slide), and one where heights taper off at the base of the slide, where volume is approximately half of the volume calculated using uniform thickness.

Erosive processes below ~200 m are limited primarily to deepwater ocean currents, sediment laden hyperpycnal flows, and mass movements of rock/sediment. Over time, multiple landslides in the same location will have a significant effect on the morphology of the continental slope. Similarly, regions that lack evidence of repeated mass movements will have a different appearance (Figure 14.9). By comparing the landscape of margins in different geologic and tectonic environments, we can gain some insight into sediment transport and landslide triggering mechanisms.

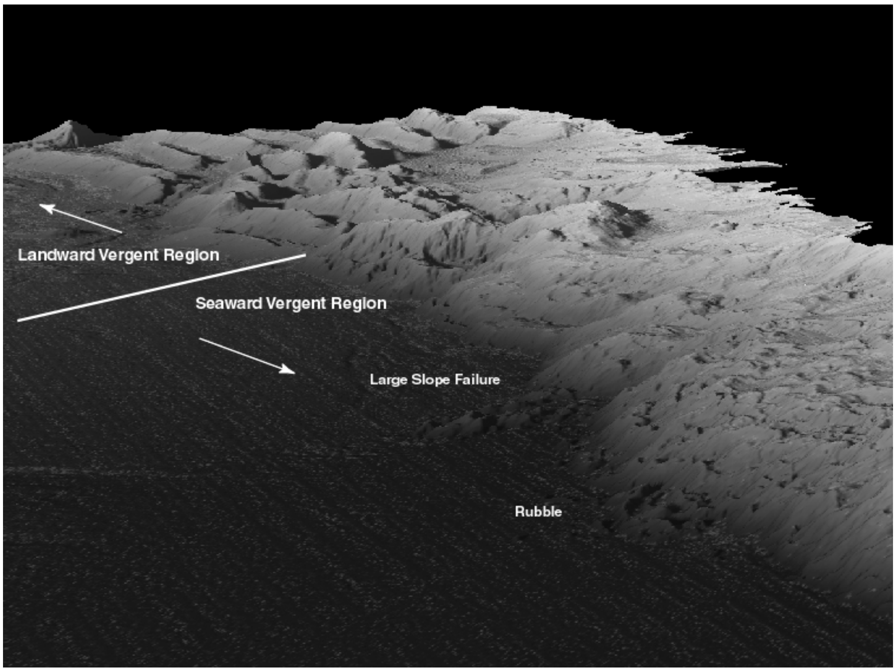

Figure 14.9 Three-dimensional perspective of the lower Oregon continental slope comparing eroded and non-eroded regions. View is looking northeast, vertical exaggeration ~3 times. In the southern (lower) portion of the image, the slope has a rough, blocky appearance. North, in the regions where the anticlinal ridges formed by accretion verge landward, the slopes are equally steep, but smooth and non-eroded.

Measurements of the area and volume of submarine landslides can also directly influence hazard determination. Submarine deltas are often regions of offshore oil production (i.e. Mississippi and Niger deltas). The search for oil is moving exploration into deep-water slope environments, where slope stability is an issue. Large runout slides that often occur in overpressured sediment are capable of wiping out entire production platforms (Bea, 1971; Prior and Coleman, 1982; McAdoo *et al.*, in prep.). By analysing runout pathways in a GIS, it is possible to illustrate where landslides have occurred in the past, what path they followed, and where they are likely to occur in the future, and what path they are likely to follow.

Landslides triggered by earthquakes may add to tsunami hazard if a large volume slide displaces the seafloor creating a wave in phase with the wave created by the uplift or subsidence caused by fault displacement. For example, the M_s = 7.2, 1992 Nicaragua earthquake displaced a water mass of ~30 km^3, creating a 9.7 m wave run-up and was responsible for ~170 deaths (Sataki, 1994). A 300-km^2 landslide with a 100-m high headscarp (which is large, but reasonable, McAdoo *et al.*, in prep.) could produce a similar size tsunami. Mapping submarine landslides will disclose margins with potential for landslide-generated or landslide-enhanced tsunamis.

14.5.3 Slope

Measurements of slope gradient are critical for assessing slope stability and aid in examining submarine landslides as a landscape altering process. By knowing the slope gradient, the stability of a region can be assessed assuming reasonable ranges of physical properties. Many GIS software packages have algorithms that automatically calculate slope by averaging the gradient between the eight neighbouring cells. Resulting maps (Figure 14.2) can be interrogated for the average slope at individual cells. To find the slope of a particular feature such as a headscarp or runout region, it is important to average the values of numerous cells within the given area. Small-scale topographic roughness can produce both flat and very steep regions that may not be representative of the feature in question.

The majority of submarine slopes on continental margins are very low (< 6^o; Pratson and Haxby, 1996) when compared to their subaerial counterparts. With this in mind, unconsolidated marine sediment will not fail on a slope less than the angle of repose (ϕ, which ranges between 25^o for silt to 36^o for some sands and gravel (Lambe and Whitman, 1969) unless disturbed or affected by an increase in fluid pressure.

A simple factor of safety (F) is calculated by dividing the sediment strength by the stress imposed on the slope.

$$F = [C_0 + \mu(\gamma' \; h \cos^2\theta - P_f)] \;/\; (\gamma' \; h \sin\theta \cos\theta) \qquad (14.2)$$

where C_0 is the material cohesive strength, $\mu = \tan\phi$, γ' is the buoyant unit weight of the sediment ($\gamma' = \gamma_{sed} - \gamma_{water}$), h is the depth to a potential failure plane, θ is the slope angle, and P_f is the existing pore-fluid pressure. An $F \leq 1$ suggests that the slope is statically metastable. A slope with $F > 1$ is most likely stable under the present conditions, and increasing F values indicate increasing stability.

The above equation suggests that an increase in fluid pressure or stress could trigger a slope failure for a gradient below the angle of repose. Rapid sedimentation and loading by large storm waves can lead to increased fluid pressures, and possibly slope failure (Seed and Rahman, 1978; Prior and Colemen, 1982), but are unlikely in deepwater continental slope environments. Earthquakes, however, act independent of water depth and can both increase the stress on the sediment and increase fluid pressure (Lee and Edwards, 1986). Lee *et al.* (in prep.) have proposed a model for slope stability that requires only slope angle, sediment unit weight (γ), and an empirical relationship between water content and sediment type, and strength degradation associated with cyclic loading (CSR_{10}). The critical acceleration (k_c as a fraction of gravity) that would cause a failure on slope of θ with γ unit weight and γ' buoyant unit weight is

$$k_c = (\gamma / \gamma') \, (CSR_{10} - \sin\theta) \qquad (14.3)$$

Lee *et al.* (in prep.) implement this model using measurements of sediment total density from numerous cores in the Eel River basin (northern California). Using the core location and slope data in a GIS database, they create hazard maps that show where a range of critical accelerations would cause failure.

14.5.4 Statistical Analysis

Relationships between measured features yield insight into submarine landslide behaviour. McAdoo *et al.* (in prep.) present measurements of the slide area, headscarp height, water depth, runout distance, along with slopes gradients of the headscarp, scar, runout zone and the local unfailed slope (LUS) which is used as a proxy for the pre-failure condition.

Histograms often elucidate interesting relationships. For example, where are slides occurring? More slides in shallow water near sediment depocenters (upper slope) might suggest sedimentation-related failures. What is the most common mode of failure size? Is there a difference in the areas of slides that maintain post failure cohesion and those that disintegrate? A distribution of headscarp heights skewed towards the smaller end might indicate weaker sediment.

Cross-correlations show trends (or lack thereof) between variables. For example, McAdoo *et al.* (in prep.) found that runout distance tends to decrease with the LUS and runout slope (perhaps because steeper runout slopes may distribute the material so that there is no remaining bathymetric or reflectivity signal). Curiously, McAdoo *et al.* (in prep.) found that the shallowest slopes in the Gulf of Mexico produce the largest slides. In addition, steep slopes tend to produce steep scars and steep headscarps, reinforcing the idea that steep slopes are stronger than less steep slopes. The relationships between various variables may vary based on the local prevailing conditions, giving us insight into process in different geologic/tectonic settings.

14.6 IMPLICATIONS AND CONCLUSIONS

Submarine landslides are important erosional and depositional processes. GIS gives us the power to examine the spatial relationships of landslides in submarine, subaerial, and even extraterrestrial environments. The analysis provides insight into many critical processes, including hazards, paleoseismology, sediment transport and landscape evolution. The field is in its infancy, and data acquisition technology along with the volume of existing databases are increasing at a rate that will make the deepsea environment the exploration and research frontier for the 21st century.

There has been increasing concern about hazard mitigation, especially with steadily increasing costs associated with replacing damaged property (van der Vink *et al.*, 1998). Oil companies are increasingly looking towards the deepwater as shelf exploration is becoming less economic. Extraordinary costs are associated with continental slope exploration and production, and the chance of a catastrophic landslide destroying production/exploration platforms increases on steeper slopes. Advances in directional drilling in the oil industry make moving a platform (for the sake of possibly saving it) an economically wise decision. Increasing coastal development not only means far more loss due to hurricanes (van der Vink *et al.*, 1998), but also increases the potential for significant tsunami hazard, especially on the Pacific rim. Maps of existing submarine slides and predictions of possible landslide locations can help mitigate property loss by clearly identifying the most hazardous regions.

From an academic point of view, mapping submarine landslides is critical in understanding erosion, deposition, and landscape forming processes on the continental slope. Are landslides on the continental shelf break responsible in part for slope deposition? What triggers submarine slides? There are numerous examples of seismically active regions where landslides are scarce including the Eel River basin and the Cascadia margin (McAdoo *et al.*, in prep.; Lee *et al.*, in prep.). Repeated landslides over time may armour the continental slope by exposing overconsolidated material. The resulting slope will able to withstand steeper gradients because it is stronger than slopes with normally consolidated or overpressured sediment. On accretionary and convergent margins, landslides may play a role in maintaining the critical taper of the slope (Davis *et al.*, 1983).

All of these issues can be addressed by a well-organised and thorough GIS. With the increasing technology and data library, GIS will be able to integrate multibeam bathymetry, side-scan sonar, slope stability and core data with bottom photographs and samples, along with sub-bottom profiles and structure location of man-made structures. These databases will lead us to a better understanding of the marine environment.

14.7 FUTURE WORK

GISs are ideally suited for mapping submarine landslides. Future efforts need to be concentrated on acquiring more offshore data (bathymetry and reflectivity) to investigate how important submarine landslides are as sediment transport mechanisms, and paleoseismic indicators. In addition, landslides can be an import geodynamic process, maintaining critical taper in both submarine accretionary prisms and subaerial mountain ranges. Furthermore, large mass wasting events can aid in unroofing of both compressional and extensional orogenic belts.

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