Advances in Natural and Technological Hazards Research

Geoffroy Lamarche · Joshu Mountjoy
Suzanne Bull · Tom Hubble · Sebastian Krastel
Emily Lane · Aaron Micallef · Lorena Moscardelli
Christof Mueller · Ingo Pecher
Susanne Woelz *Editors*

Submarine Mass Movements and their Consequences

7th International Symposium

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Preface

This sixth volume of *Submarine Mass Movements and Their Consequences* presents an impressive collection of papers presented at the 7th International Symposium held in Wellington, New Zealand, in November 2015. The meeting is the cornerstone for the submarine landslide research community. Both this community and society at large owe much to the support of the International Union of Geological Science (IUGS) and the United Nations Educational, Scientific and Cultural Organization (UNESCO) who have now sponsored three International Geoscience Programmes in this research area: IGCP-511 (SMMTC, Submarine Mass Movements and Their Consequences); IGCP-585 (E-Marshal, Earth's Continental MARgins: aSsessing the geoHazard from submarine Landslides); and, as of 2015, IGCP-640 (S^4SLIDE, Significance of Modern and Ancient Submarine Slope LandSLIDEs). It is through this support that the research community continues to flourish in terms of collaborative research, student support, and integration of developing nations. It is our pleasure to bring you this volume of fine research papers that capture the exciting state of research in our field. We believe this volume provides both a snapshot of the state of research in submarine mass movements and confirmation of the strong directions in which the field is moving and growing.

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Chapter 1
Submarine Mass Movements and Their Consequences: Progress and Challenges

Geoffroy Lamarche, Joshu Mountjoy, Suzanne Bull, Tom Hubble, Sebastian Krastel, Emily Lane, Aaron Micallef, Lorena Moscardelli, Christof Mueller, Ingo Pecher, and Susanne Woelz

Abstract This sixth edition of the *Submarine Mass Movements and Their Consequences* volume, coincident with the seventh eponymous conference includes 61 papers that span a variety of topics and are organized into nine parts as follows: (1) Submarine mass movement in margin construction and economic significance; (2) Failure dynamics from landslide geomorphology; (3) Geotechnical aspects of mass movement; (4) Multidisciplinary case studies; (5) Tectonics and mass movement processes; (6) Fluid flow and gas hydrates, (7) Mass transport deposits in modern and outcrop sedimentology; (8) Numerical and statistical analysis; and, (9) Tsunami generation from slope failure. The breath and quality of this body of work underpins a positive outlook and our enthusiasm for the future direction of research in this area of science as it moves towards ever more detailed analysis and monitoring. We also emphasize in this volume the need to look at mountain-scale

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outcrops to better understand our seismic imaging, to carry out statistical studies that draw on global data sets to better constrain broad behavioural characteristics, and to undertake numerical modelling to understand the sensitivity of a range of natural slopes.

1.1 Introduction

Research on submarine mass movements remains highly topical and vibrant, whether it focuses on the consequences that such events may have on human and natural environments or on process-oriented science. The consequences of submarine landslides on infrastructure and coastal communities is reasonably well-known, thanks to a few notorious events that made global headlines, such as: the 1929 Grand Banks submarine landslide, Newfoundland (Piper and Aksu 1987) that ruptured a series of submarine cables and triggered a tsunami; the collapse of reclaimed land at Nice airport in 1979 (Kopf et al. 2011), which also generated a local tsunami; the dramatic landslide-generated Papua New Guinea tsunami in 1998, which claimed more than 2,000 lives (Tappin et al. 2001); or the hyperpycnal flow that ruptured communication cables south of Taiwan following the 2009 typhoon (Carter et al. 2012).

In order to improve our understanding of the potential impacts of submarine landslides, the research has focused on a variety of processes, approaches and methodologies. Field surveys undertaken immediately after catastrophic events have provided valuable information of magnitude-frequency relationship that underpin the development of hazard studies (Tappin et al. 2001). But arguably, investigations of mass-transport deposits (MTD) and source areas has represented the richest research effort pertinent to submarine landslides. MTD vary tremendously in geometry and size, ranging over at least five orders of magnitude in volume. There is a wide diversity of physical and mechanical processes that govern initiation and emplacement of submarine landslides, which has called for a plethora of research techniques. These include geophysical surveying, (e.g., seismic reflection, multibeam bathymetry), geological sampling (e.g., coring) and geotechnical investigations, analogue and numerical modelling. More recently, state-of-the-art technologies such as the use of remotely-operated vehicle (ROV) and autonomous underwater vehicles (AUV) have unveiled unprecedented details about the morphology of MTD (Huvenne et al. 2016).

The present volume is the sixth of its kind, and is associated to the seventh conference on Submarine Mass Movements and their Consequences. It contains 61 papers, spanning a variety of topics that are organized in nine parts.

The geographic focus of the research papers produced in this volume is predominantly the European and North American continental margins (Fig. 1.1), with 27 and 10 studies herein, respectively. Oceania, with the margins of New Zealand, eastern Australia and Indonesia, features strongly, possibly in part

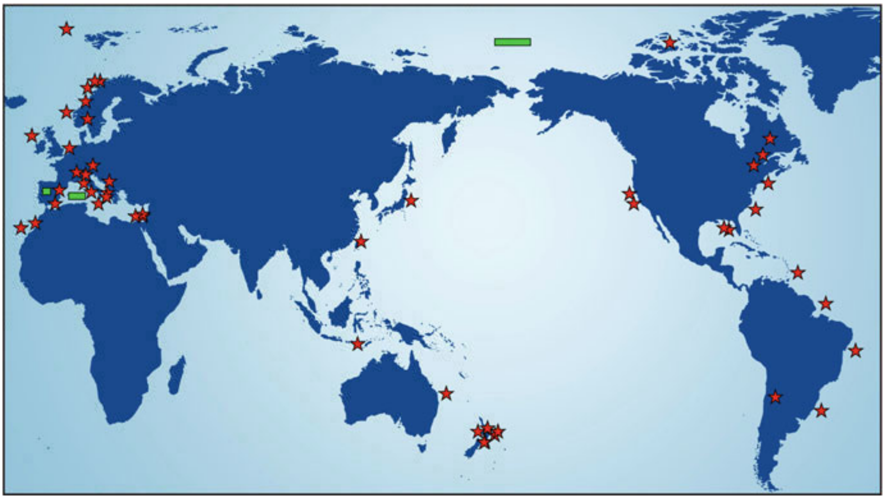

Fig. 1.1 Geographic distribution of paper focus for the submarine mass movement and their consequences 2015 volume. Local (*red stars*) and regional (*green rectangles*) studies are indicated

because the conference will be held for the first time in the southern Hemisphere, but more likely and most importantly because the southeastern Pacific region is highly tectonically active, which likely facilitate the occurrence of submarine landslides, at least those seismically triggered. Paradoxically, western North America is represented by only two papers, and western South America, southwest Africa and the Indian Ocean have no papers in this volume. The paucity of baseline data from some of these areas is an issue that the submarine landslide-research community should attempt to address. Another conspicuous absence is mid-ocean ridges, which is somewhat disappointing as recent studies have demonstrated that these regions present some interesting examples of submarine landslides (Ferrini et al. 2013; Gao 2006; Tucholke 2016).

Contributions from high latitude regions solely concern the northern hemisphere, specifically on the northern Atlantic, including two papers on the Canadian Arctic (Normandeau et al. 2016; Priest and Grozic 2016).

There is an increase from previous years in the number of papers on landslides affecting lakes. These studies provide valuable observations and conclusions on the tsunami hazard associated with such events as well as paleoseismicity indicators (Locat et al. 2016). Perhaps “submarine” is too exclusive, and should be replaced by “subaqueous” if only to encourage such lacustrine studies to develop. Likewise studies of submarine MTD outcrops provide a means to gather new evidence on emplacement processes.

Submarine landslides occur on a wide range of scales. However, this year we note a lesser focus on large-scale “giant” features in comparison to previous issues. This may correlate with the increase in social, economic and hazard relevance of the research, which tend to concentrate less on rare giant submarine events.

If comparing the 2003 and 2015 volume is any measure of a trend, we surmise that the research is healthy and vibrant. We note since 2003, an increase focus on lakes, as mentioned above, but also an intensification in the use of emerging technology such as AUV and ROV, numerical modelling, and progress on event observation. Although the collection of in situ observations, let alone measurements, of mass movements remains a very challenging task, it is now a conceivable objective that is attracting strong interest from of some research groups, as e.g., to assess the role of pore pressure in slope stability. These ambitions are being invigorated by new technology deployed from the ocean surface and mechanisms to make observatories on the ocean floor directly. Better multibeam bathymetry, including micro bathymetry from underwater vehicles and viable 3D-seismic data sets, has led to major improvement in our understanding of landslide dynamics, internal geometries and the failure process, and it is now well-accepted that major landslides are multiple events. Concentrated seafloor mapping efforts, at margin scales, has also allowed the development of frequency-size relationships. Of major importance was the scientific drilling of landslide deposits (e.g. IODP 308 in the Gulf of Mexico, and IODP 340) which allowed a quantitative assessment of specific pre-conditioning factors for individual landslides and an understanding of recurrence rates at targeted sites.

1.2 The 2015 Volume

1.2.1 Part I: Submarine Mass Movement in Margin Construction and Economic Significance

The Society for Underwater Technology estimates that the cost of damage to pipelines caused by submarine mass movements is about $400 million annually (Mosher et al. 2010). This direct economic risk to exploration and production platforms is most relevant to small events with short reoccurrence intervals, and warrants ongoing research investment to enhance our understanding of processes and risk prediction. The study of submarine landslides also has an important geopolitical connotation as, their geomorphology has been used to define the distal toe of the continental slope and Extended Continental Shelf (ECS) by the UN Convention for the Law of the Sea (UNCLOS) (Mosher et al. 2016).

While it is generally accepted that submarine mass movements have a role in the development of petroleum systems (in particular in generating traps and seals), the understanding of the processes involved remains limited. It is estimated that ~90 % of submarine landslides are mud-prone but recent exploration has found some sand-rich MTD that could be considered petroleum reservoirs (Beaubouef and Abreu 2010; Meckel III 2011). Submarine landslides have proven to play a role defining hydrocarbon reservoir location and geometry, facies distributions, development of stratigraphic traps and integrity of seal intervals. In this volume, a specific case study in the Gulf of Mexico is analysed by studying fabric development and pore-throat reductions of a local MTD that is clearly linked to a reservoir interval (Cardona et al. 2016). Such approaches, where seismic scale observations are combined with rock properties, provides a glimpse into the future study of MTD in the context of hydrocarbon systems.

It is noticeable that with the global increase in deep-water hydrocarbon exploration and production, the need to study and understand, let alone forecast, the occurrence of submarine landslides will continue to be the focus of the community (Omeru et al. 2016). Issues such as security of offshore infrastructure, and economic relevance of hazard and risk are the focus of contributions in following parts of this volume.

1.2.2 Part II: Failure Dynamics from Landslide Geomorphology

The complexity and variety of physical mechanisms involved in submarine failures is still up for debate. Whilst the consequence on human life is of paramount importance, the potential impact that any submarine landslides may have on seafloor or coastal infrastructures is increasingly concerning, especially with the increasing development of high seas infrastructures associated with deep-sea petroleum exploitation, communication cable and deep sea mining. There is also a rising awareness about the potential impact that submarine landslides can have on the natural environment. For the first time to our knowledge, these consequences could be ecologically positive, as suggested in the case of the Ionian Sea where hard strata and irregular small-scale topography resulting from landslides are likely to have facilitated cold water coral (re-)colonization (Savini et al. 2016). This shows linkages developing between submarine landslides research and economic, social and environmental issues.

1.2.3 Part III: Geotechnical Aspects of Mass Movement

Advances in geotechnical technology has been driven by the need for quality data required to quantify slope sensitivity response to deformation. Such progress in the recent past is being driven by engineering concerns around seafloor stability with respect to infrastructure hazard (Forsberg et al. 2016). Unprecedented insights into mass movement are now being offered by recent technological advances, in the laboratory (Torbahn et al. 2016), through the comparison between laboratory to in-situ observations (Kluger et al. 2016), and by correlating geophysical and in-situ geotechnical experiments (Stegmann et al. 2016). The confines offered by fjords and estuaries make perfect natural laboratories to study detailed geotechnical aspects of mass movements that can then provide insight into less accessible submarine processes (Forsberg et al. 2016; Kluger et al. 2016; Mastbergen et al. 2016; Turmel et al. 2016).

1.2.4 Part IV: Multidisciplinary Case Studies

High resolution bathymetric imaging combined with advanced geotechnical methods are truly providing significant advances in the field. Shipboard and AUV multibeam bathymetry remains unarguably the most used tool in submarine landslide investigations. Great advances in this technique mean that very high resolution studies are increasingly becoming routine. However, the significance of these data is further amplified when combined with multidisciplinary field investigations. We are very pleased to see outstanding contributions from investigations in the very challenging environment of the northern Arctic, revealing insights of previously unsurveyed areas (Forwick et al. 2016; Laberg et al. 2016; Normandeau et al. 2016). As well as a case study examining micro scale controls on mass movement complexes (Kuhlmann et al. 2016), another study reveals the long-term failure history of a confined subaqueous environment (Lindhorst and Krastel 2016).

1.2.5 Part V: Tectonics and Mass Movement Processes

The hazard and risk associated with submarine mass movement remains a fundamentally important focus of the scientific community. Intense efforts have been made to improve our understanding of the relation between tectonics and mass movement occurrence (Katz et al. 2016; Locat et al. 2016; Moore and Strasser 2016). The effect of tectonic activity on seismic strengthening is a hypothesis that is being supported by a comparison of shear strength in cores from active and passive margin settings (DeVore and Sawyer 2016). The use of submarine landslides to develop paleoseismic records at local or regional scales is building momentum and is providing some beneficial outcomes for constraining earthquake recurrence intervals and improving seismic hazard assessment (Chapron et al. 2016; Gracia et al. 2013). Other studies use a generic modelling approach to tackle the overarching question on the role of earthquakes in slope destabilization (Trandafir and Popescu 2016).

1.2.6 Part VI: Fluid Flow and Gas Hydrates

Understanding the role that fluids plays in pre-conditioning slope instability remains a significant challenge. New contributions made herein on the role of gas in slope failures (Gwiazda et al. 2016; Micallef et al. 2016) shed light on the possibility that fluids have a controlling influence on landslide basal failure planes. These observations are largely the result of recent technological developments. Similarly, the role of gas hydrates in submarine landslides remains a controversial one. Crutchley et al. (2016) present a series of different slope failure scenarios on the New Zealand continental margin that highlight a range of processes related to gas hydrates that could weaken sediments.

Priest and Grozic (2016) picks up on the widespread observations that climate change is destabilizing gas hydrate deposits in the Arctic regions. Using a modelling approach, they provide a thought provoking thesis on the role that climate change could play in inducing large slope failures.

1.2.7 Part VII: Mass Transport Deposits in Modern and Outcrop Sedimentology

Marine geophysical (seismic, multibeam echosounder) and geological (sediment cores, seafloor operations) still lack the fine-scale information and cross-sectional insights on mass failure processes that can be preserved and yielded from the study of fossilized landslides in outcrops onland. Outcrop investigations provide detailed insight into the kinematics (Ogata et al. 2016) and internal mixing and structure (Sobiesiak et al. 2016) of MTD. Sympathetic to these approaches are fine-scale sedimentological studies that provide a modern context of present day seafloor processes (Postma et al. 2016; Sawyer and Hodelka 2016). The link between onland outcrop studies of MTD and detailed marine studies is one that deserves to be strengthened given the benefits of cross pollination between these disciplines.

1.2.8 Part VIII: Numerical and Statistical Analysis

Statistical models allow us to develop rules and quantify relationships that encompass our analysis. Better understanding of magnitude-frequency relationships for submarine landslides is imperative if we are to develop robust hazard models (Clare et al. 2016; Mueller et al. 2016). GIS models developed to predict where slope failures can occur often become the underpinning driver for hazard assessments (Borrell et al. 2016; Dabson et al. 2016; Haneberg 2016), while advanced numerical modelling can be the key to understanding the sensitivity of individual slopes to external perturbations (Huhn et al. 2016). Numerical modelling and statistical analysis theme continues to run strongly in this volume, and reflect the state-of-the-art in terms of our general understanding of spatial causes of submarine landslides.

1.2.9 Part IX: Tsunami Generation from Slope Failure

Tsunamis are one the biggest hazards to coastal environments caused by submarine landslides. In this volume we have papers covering a broad range of landslide-related tsunami generation, including volcanic generation (De Lange and Moon 2016), landslides into an ice-covered lake (Leblanc et al. 2016), and advanced models that couple landslide deformation processes to wave generation (Wang et al. 2016). With increasing coastal populations and on-going climate change, the need to continually refine and test robust tsunami hazard assessments is more pressing than ever. These papers capture some of the diverse range of processes that need to be considered in these assessments.

1.3 Looking to the Future

Of excellent augur to the future is the announcement in 2015 of the IGCP-640 S^{4}SLIDE (Significance of modern and ancient submarine slope landslides – https://sites.google.com/a/utexas.edu/s4slide/). This project builds on the success of IGCP-511 and IGCP-585, and is the third IGCP project that focuses on submarine landslide-related science. This will no doubt continue to promote the research and foster relationships across the globe.

The S^{4}SLIDE project intends to create an international and multidisciplinary platform to allow geoscientists from academia and industry to sustain a dialogue conducive to the integration of findings from different fields into a more cohesive understanding of submarine landslides. The initial project submission, listed the following series of key scientific questions as those needing to be addressed in the near future:

1. What is the nature of the interaction between local structural controls, seafloor morphology, sediment supply, relative sea-level fluctuations, current-controlled sedimentation and submarine landslides in lacustrine and marine environments?
2. What role do transient, turbulent-laminar flows play in the formation of submarine landslides?
3. What is the impact of climatic variations on the occurrence of submarine landslides?
4. What is the role of submarine landslides in the realm of hydrocarbon exploration and production?
5. Do we understand the hazard that submarine landslides poses in mid-oceanic ridges with regard to the developing deep-sea mining activities?
6. What are the indicators of incipient submarine slope instability in different geological-tectonic settings?
7. How do submarine landslides evolve after initiation and how do their dynamics affect their impact on coastal areas, including the generation of tsunamis?
8. Is it possible to develop a submarine landslide early-warning system?

The initial strategy was included in the S^{4}SLIDE proposal to address the above key questions:

1. Continue of increase investment in sub-seafloor characterization and sampling to reduce data uncertainty in the third dimension.
2. Generate statistically significant submarine landslide data sets to allow robust probabilistic stability and hazard assessment.
3. Repeat multibeam surveys to address dynamic slope behaviour during failure and transient phenomena in slope failure preconditioning and triggering.

4. Advance the capability to model submarine landslide triggered tsunamis, particularly by better constraining the disintegration of material during failure.
5. Promote multiscale quantitative geomorphological investigations by integrating field measurements, remote sensing, and numerical models.

We are very enthusiastic about the future direction of research in Submarine Mass Movements and Their Consequences. As we move toward ever more detailed analysis with surgical seafloor operations, we also need to step back and take in the broad context offered by mountain scale outcrops of our seismic imaging, carry out unifying statistical studies that draw on global data sets, and explore numerical modelling to understand the sensitivity of natural slopes.

New IODP drilling proposals may also offer unprecedented opportunities. A couple of completed IODP projects on landslides have already contributed to great gains in our understanding of failure processes. However with at least two proposals in the system to date, and the linkages developing through S^4SLIDE, we expect to see some major paradigm shifts in our understanding of landslide architecture and controlling influences. Installing monitoring equipment in IODP holes may offer that opportunity to monitor landslide controls and we encourage the whole community to consider how an IODP proposal could advance this science over the next decade.

The rich scientific literature on the topic of submarine mass movement is testimony to the strength and agility of the research community, exemplified by the biannual Submarine Mass Movements and Their Consequences symposium and the high standard of material included in this book. We greatly look forward to contributing to the sixth volume and seeing just how much our understanding of these fascinating and societally important processes have advanced.

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Part I
Submarine Mass Movement in Margin Construction and Economic Significance

Chapter 2
The Role of Submarine Landslides in the Law of the Sea

David C. Mosher, Jan Sverre Laberg, and Alain Murphy

Abstract Article 76 of the United Nations Convention on the Law of the Sea prescribes two approaches that a nation may employ to determine the extent of its' legal continental shelf: (1) 60 nautical miles (M) seaward of the foot of the continental slope (FoS), or, (2) to a point seaward of the FoS where the sediment thickness is 1 % of the distance from the FoS. In both of these formulae, the "foot of the continental slope" is a critical metric. Article 76 defines the "foot of the continental slope" as: "*In the absence of evidence to the contrary, the foot of the continental slope shall be determined as the point of maximum change in the gradient at its base*". Geomorphologic complexity or low gradients (<1°) of continental slopes rarely permit a ready determination of the maximum change in gradient; particularly at a position that a geologist might qualitatively recognize as the base-of-slope zone. Recognizing that submarine mass movement is a slope process that also influences the shape of the continental margin, several nations have successfully argued that the downslope termination of mass transport deposits assist in distinguishing the continental slope from the rise and abyssal plain. The Commission on the Limits of the Continental Shelf have now made recommendations for a number of coastal States with rift margins, transform margins and subduction margins where the extents of surficial mass transport deposits were used to help delineate the base of slope zone within which the foot of the continental slope is chosen.

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2.1 Introduction

The Commission on the Limits of the Continental Shelf (CLCS); the body that reviews extended continental shelf submissions under the UN Convention on the Law of the Sea, in its guidelines and decisions to date, has encouraged coastal States to use scientific arguments in defining the elements of a continental margin and thereby delimit its outer edges. One of the critical metrics in this process is establishment of the “foot of the continental slope” (FoS) and submarine landslides can assist in identifying this metric.

The outer edge of the legal continental shelf is defined in article 76 of the United Nations Convention on the Law of the Sea as the submerged prolongation of the land mass of the coastal State, consisting of the seabed and subsoil of the shelf, the slope and the rise. It does not include the deep ocean floor. The outer edge of the legal continental shelf is determined by either 60 nautical miles (M) from the foot of the continental slope (known as the Hedberg formula (Hedberg 1981)), or not more than the distance in which the thickness of sedimentary rocks is 1 % of the shortest distance from the foot of the continental slope (the Gardner formula) (Fig. 2.1). One can appreciate from these formulae that the foot of the continental slope is an essential metric in definition of the continental margin and therefore entitlement to an extended continental shelf, yet the language is simple and ambiguous. The foot of the continental slope is defined within article 76 as ‘the point of maximum change in the gradient at its base’.

Geologic complexities of continental margins rarely allow for the identification of a single point of maximum change in gradient, and if so, these points would rarely coincide with the area that a geologist would identify as the base of slope. As a result of this and other ambiguities, the CLCS adopted a set of scientific and technical guidelines to assist State’s in the preparation of their submission (CLCS 1999). These guidelines provide that identification of the foot of the continental slope first requires identification of the region defined as the base of the continental slope; and then the determination of the location of the point of maximum change in gradient within the base of the continental slope (see Fig. 2.1). In order to identify the base of the continental slope, one must first distinguish the various elements of the margin.

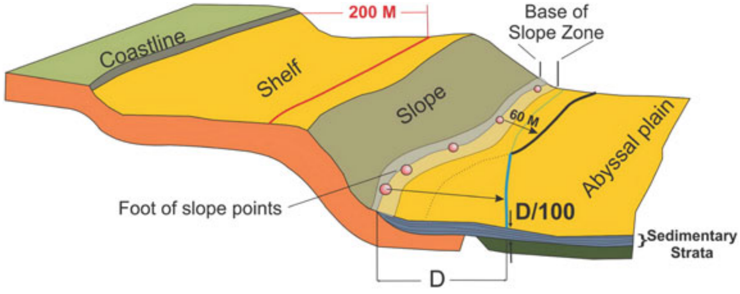

Fig. 2.1 Elements prescribed in article 76 for defining the outer edge of the legal continental shelf: (1) the foot of the continental slope plus 60 nautical miles (M) (Hedberg formula), or (2) the distance (D) from the foot of the continental slope where it is equal to 1 % of the thickness of sedimentary rocks (D/100) (the Gardner formula)

The simple concept of a margin comprising shelf, slope, rise and deep ocean floor distinguished by slope angle or bathymetry alone, as described by Heezen et al. (1959) is rarely observed in nature. As a result, the CLCS has allowed the use of arguments based on geological and geophysical observations of natural processes to distinguish these components of a margin. Submarine landslides, for example, are a slope phenomenon and thereby characterize the continental slope and distinguish it from the shelf, rise and abyssal plain. To date, the CLCS has accepted arguments from a number of State submissions regarding establishment of the foot of the continental slope with submarine landslide processes, including examples from passive rift (Norway, Ireland), transform (French Guiana), and active (Sumatra) margins. This paper will demonstrate how submarine landslides are used in application of article 76 to establish the outer edge of the continental margin by way of presenting these case studies.

2.2 Case Studies

2.2.1 Rift Margins

2.2.1.1 Ireland, Porcupine Bank

Porcupine Bank offshore of Ireland extends the Irish Shelf more than 300 km westwards from the coast. West of Porcupine Bank is the Porcupine Abyssal Plain lying in water depths greater than 4000 m (Fig. 2.2). The western edge of Porcupine Bank is a rounded shoulder, providing a gradual and indistinct shelf break from 150 to >500 m water depth. This shoulder evolves into an upper slope segment that is more than 10° down to a depth of about 3000–3500 m. At this depth, there is a distinct gradient change of the slope to between 2 and 4°. This segment is referred to as the lower slope. The angles of this lower slope then decrease as water depths increase to the deep ocean floor. The maximum change in gradient of the slope occurs at the initial gradient change in 3000–3500 m water depth, but the seafloor clearly continues to dip toward the deep ocean. There is no subsequent distinctive change in gradient to separate the 'slope' from a 'rise' from the 'deep ocean floor' (Porcupine abyssal plain).

In its interaction with the CLCS, Ireland argued for a two-segment continental slope and that the base of slope region did not include the local maximum between the upper and lower slope segments, but rather laid seaward (Ireland 2005). In particular, Ireland presented multichannel seismic and vintage scanned seismic data showing mass slumps and slides along the Porcupine Bank margin (van Weering et al. 2003), which combined with the multibeam data demonstrated the nature of the two segment slope. The base of the continental slope was shown to lie at the outer edge of the complex lower slope formed by mass-transport depositional processes associated with slope failure and erosion of the Porcupine Bank margin and not at the more landward maximum change in regional gradient (i.e. the base of the upper slope). Foot of the continental slope (FoS) points were chosen at the maximum change in gradient within this seaward zone, therefore (Fig. 2.2).