Fractal statistics of the Storegga Slide.

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Abstract

The statistics of submarine mass movement inventories are poorly characterised in comparison to those of subaerial mass movements. In this study we investigate the aggregate behaviour of the Storegga Slide by carrying out a statistical analysis of its constituent mass movements. By using area as a proxy for mass movement magnitude, we demonstrate that the non-cumulative frequency-magnitude distribution of mass movements within the Storegga Slide is a power law with an exponent of 1.52. The Storegga Slide has the characteristics of a dissipative system in a critical state, where the input of sediment is continuous in the form of hemipelagic sedimentation and glacial deposition, and the output is represented by mass movements that are spatially scale invariant. We conclude that the Storegga Slide may be modelled as a large-scale geomorphic system that exhibits self-organised critical (SOC) behaviour. In comparison to subaerial mass movements, the aggregate behaviour of submarine mass movements is more comparable to that of the theoretical 'sandpile' model. The origin of SOC may be linked to the retrogressive nature of the Storegga Slide. Since SOC is an emergent feature, the large-scale behaviour of the Storegga Slide should be autonomous of the smaller-scale elements. A power law distribution also implies that incomplete submarine mass movement inventories may be extrapolated within the limits of power law behaviour, which is important in terms of hazard management.

1. Introduction

Concepts of non-linear dynamic systems, such as scale invariance and the fractal model, provide a powerful approach to the representation of a wide range of geoscientific data (e.g. fluvial systems (e.g. Pelletier 1999), coastal profiles (Southgate and Möller 2000). Scale invariant properties of data inventories are identified by demonstrating a single power law exponent in a frequency-magnitude distribution (Mandelbrot 1983). A power law distribution implies that when we compare the number of events of size A or greater, with the number of events of size ηA or greater (η is an arbitrary factor), the number always differs by the same factor $\eta^{-\beta}$, regardless of the absolute size of the events (Hergarten 2003). A power law distribution can be replaced with other measures of the size of the event (e.g. area, volume and thickness of mass movements are strongly correlated with each other, and a distribution can be converted between variables (Hovius *et al.* 1997)); thus a power law distribution is free of a characteristic scale and can be described as fractal (Mandelbrot 1983).

The Storegga Slide, located 120 km offshore Norway, is a mega-scale geomorphic system (Figure 1). Like most other submarine slides, the Storegga Slide has been investigated using an engineering approach. In subaerial geomorphology, the statistical characteristics of landslide inventories have become a recent focus of study (e.g. Guzzetti *et al.* 2002). In comparison, the statistics of submarine mass movement data are still poorly characterised. The extensive coverage and the excellent quality of the acoustic imagery from the Storegga Slide allow us to investigate the aggregate behaviour of the Storegga Slide and carry out a statistical analysis of its constituent mass movements. The objectives of this study are to assess whether the size statistics of the Storegga Slide mass movements exhibit scale invariance, and to explain the origin and implications of such behaviour.

Fig. 1

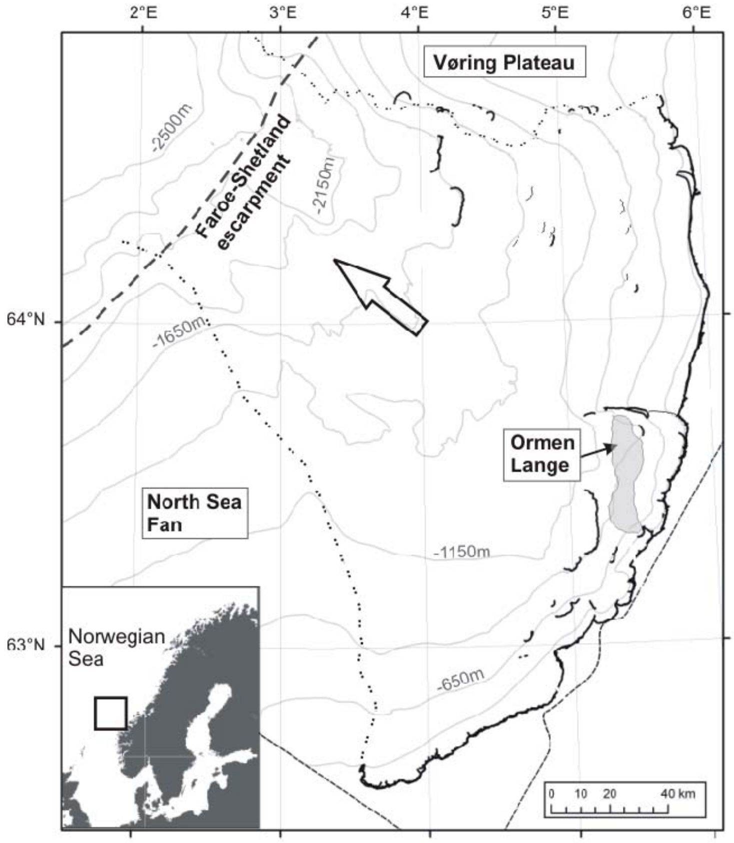

Figure 1: Bathymetric contour map of the Storegga Slide (contour interval of 250 m). The headwalls that were extracted from the bathymetric data set are represented by solid black lines. The arrow indicates the direction of sediment mobilisation. The location of the Storegga Slide is shown in the inset.

2. Method

The study is based on a high resolution multibeam bathymetry data set covering the slide scar from the main headwall down to a water depth of ca. 2700 m (Figure 1). Most of the data have a horizontal resolution of 25 m or better. A mass movement is defined as a single episode of slope failure where sediment moves downslope under the influence of gravity. The area of the mass movement is delineated by a steep scarp at the upslope limit (headwall) and the distal point of the depositional section at the downslope limit. We use mass movement area as a proxy for magnitude. The estimation of the slide area is hindered by the difficulty in defining the boundaries of quasi-simultaneous slides in a retrogressive slope failure. Thus we try to estimate mass movement area using the length of the associated headwalls, which constitute easily identifiable and prominent features located at the upslope limit of the mass movement. Previous studies of the Storegga Slide have estimated the dimensions of sixty-three mass movements (Haflidason *et al.* 2004). We plot the headwall lengths against the mass movement areas from these published data (Figure 2a). $R^2 = 0.91$ implies a strong statistical dependency between area and length in the form:

$$A = 0.87\, l^{\,1.98} \qquad (1)$$

where
A is the area of mass movement (in m^2)
l is the length of headwall (in m)

Fig. 2

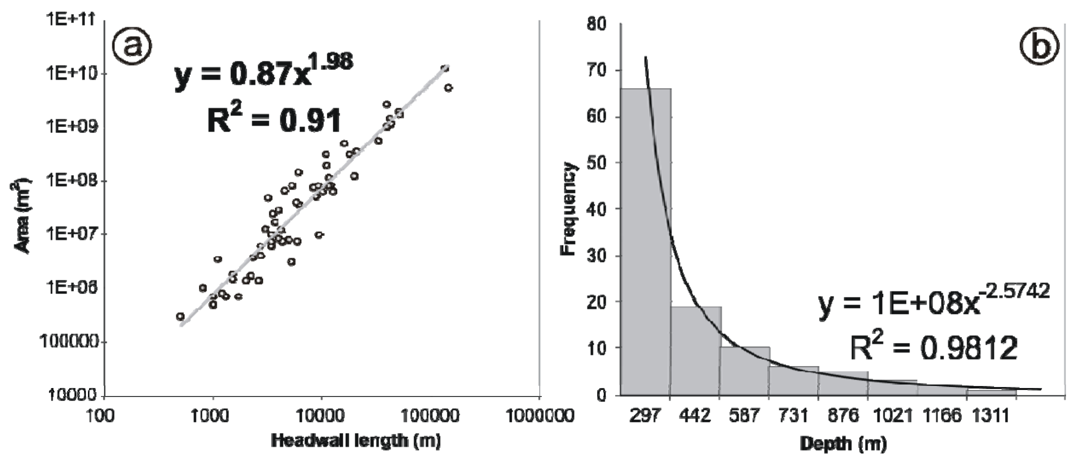

Figure 2: (a) Plot of mass movement area vs. headwall length for the mass movements identified in Haflidason *et al.* (2004). (b) Variation of the number of mass movements extracted from the bathymetric data set (frequency) with depth.

We used a suite of geomorphometric techniques to extract the headwalls automatically from the bathymetric data set. A geomorphmetric map, which is a parametric representation of a landscape decomposed into its elementary morphological units, was generated for the study area. The technique for producing a geomorphometric map is explained in more detail in Micallef *et al.* (2007). Headwalls are extracted as one-cell thick lineaments. Since the geomorphometric techniques delineate headwalls at the resolution of the bathymetric data, rather than at the scale at which the study area is being observed by an investigator, the techniques are more accurate than manual digitisation. Using geomorphometric mapping we were able to extract one hundred and five individual headwalls. The extent of a headwall is defined by the section of the headwall where sediment evacuation has occurred perpendicularly to the lineament. The length of each headwall was calculated using a Geographic Information System, and the area of the mass movement associated with each headwall was estimated using equation (1). A cumulative frequency-area graph was plotted for the mass movements. A non-cumulative distribution, defined in terms of the negative of the derivative of the cumulative distribution with respect to A, was then derived to enable comparison with previous studies (e.g. Guzzetti *et al.* 2002).

3. *Results*

The estimated areas of the mass movements range between 0.27 km^2 and 1174 km^2. The data in the non-cumulative distribution can be best correlated with an inverse power function (Figure 3a):

$$dN/dA = 3900\, A^{-1.52} \qquad (2)$$

where
N is the cumulative number of mass movements with an area > A

The exponent of this power function is 1.52. The range over which this function is valid is 0.3 – 100 km^2.

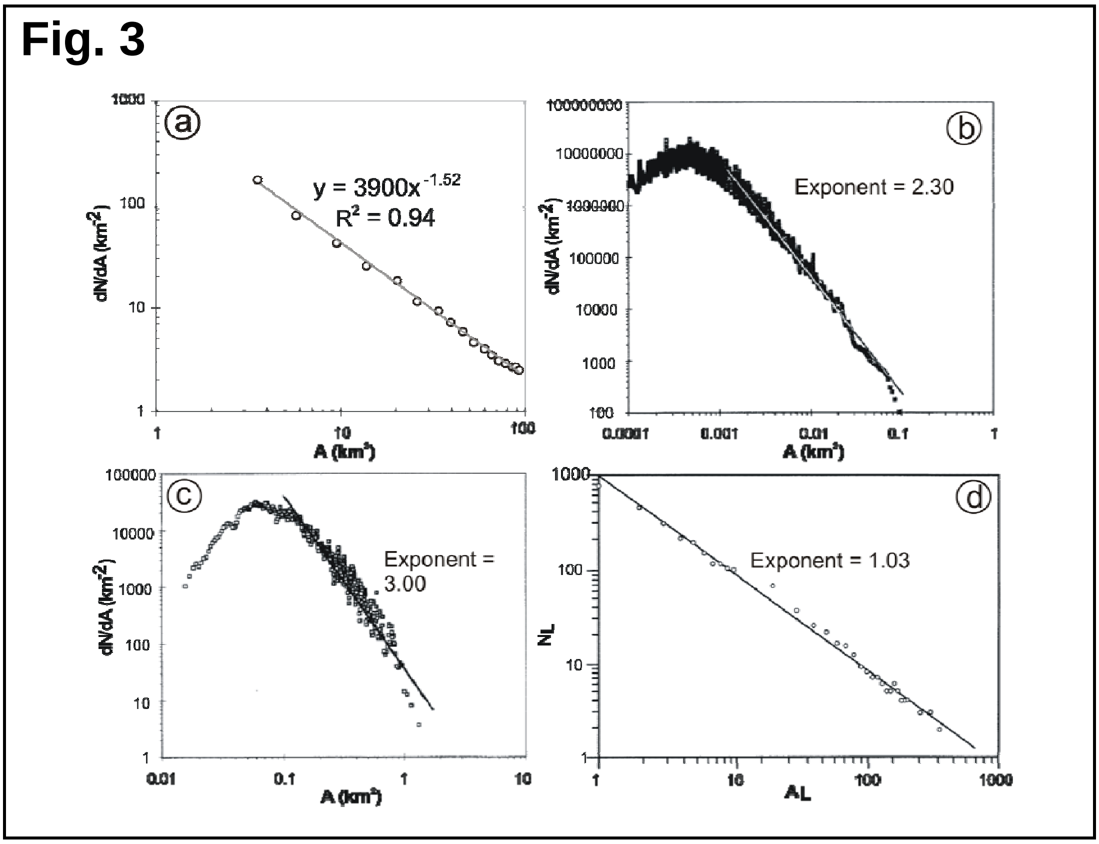

Figure 3: (a) Non-cumulative frequency-area distribution for mass movements within the Storegga Slide. Subaerial mass movements from (b) California (Harp and Jibson 1995) and (c) Akaishi ranges, central Japan (Ohmori and Sugai 1995) exhibit similar power law distributions, although the exponents are higher. (d) Non-cumulative frequency-area distribution for a 'sandpile' model based on a 50 × 50 grid (Kadanoff *et al.* 1989). The distribution is also power law with an exponent ~1. (Figures 3b-d are adapted from Turcotte (1999)).

4. Discussion

The inverse power law distribution of mass movement areas, observed over ~2.5 orders of magnitude of the area, is evidence of fractal spatial statistics within the Storegga Slide system. Similar power law distributions have been identified in numerous subaerial mass movements of different types and sizes, occurring in a range of environmental settings and triggered by a variety of mechanisms (Figure 3). A power law has also been detected in other natural phenomena, such as earthquakes (Turcotte *et al.* 2006).

Explaining the origin of this fractal distribution in geological terms is difficult. The most prevalent explanation to this behaviour in subaerial environments has been self-organized criticality (SOC) (Bak *et al.* 1987). SOC is a property of complex systems whereby, in spite of heterogeneity at the small-scale of individual elements (e.g. sediment grains), the large-scale, aggregate behaviour of the system exhibits order in the form of a fractal distribution. This order is an emergent property of the system, which occurs through autogenic dynamics and feedback mechanisms (Phillips 1995). In a self-organised critical system, the "input" is nearly constant and the "output" is characterised by a series of events. Self-organised critical systems are characterised by three conditions (Bak *et al.* 1987): (i) the distribution of the 'outputs' is scale invariant; (ii) the system is in a quasi-stationary (critical) state and (iii) the temporal behaviour of the system is a 1/f (red) noise.

The Storegga Slide is a dissipative system, where sediment is mobilised or removed from the slide area in the form of mass movements. The driving force of this system has been the continuous deposition of glacially-derived material (during glacial maxima) and hemipelagic sedimentation (during interglacials), for at the least the last 3 million years (Rise *et al.* 2005). This deposition resulted in a progressive increase in sediment pore pressure, gravitationally-induced stress and surface slope gradient. Seismicity, associated to glacially-induced tectonic movements, may constitute another driving force as it enables the system to exceed thresholds. These are all characteristics of a system in a quasi-stationary state. The distribution of mass movements within the Storegga Slide is spatially scale invariant (Figure 3a). On the other hand, we are not able to demonstrate temporal scale invariance of the mass movements due to a low temporal resolution of the data. In consideration of the above, we conclude that the Storegga Slide may possibly exhibit SOC.

SOC can be theoretically modelled using the 'sandpile' model, which is a simple cellular automata model (Bak *et al.* 1988) (Figure 4). In this model, particles are dropped randomly and continuously into a square grid of boxes. When a box accumulates four particles, these are redistributed to the four adjacent boxes. This redistribution may result in further instability, creating an avalanche. The non-cumulative frequency-magnitude distribution of these avalanches was shown to satisfy a power law, with an exponent of ~1 (Kadanoff *et al.* 1989) (Figure 3d).

Fig. 4

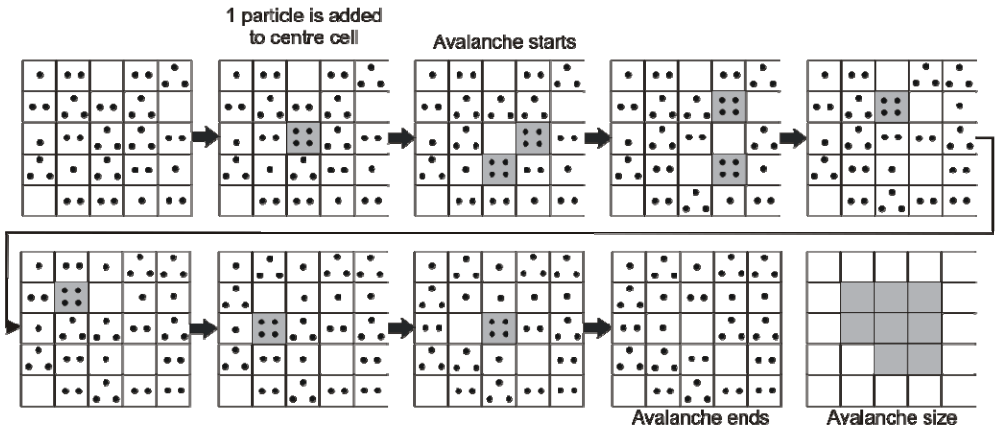

Figure 4: The theoretical 'sandpile' model based on a 5 × 5 grid. The dots indicate the number of particles within each cell of the grid. When a particle is added to the centre cell in this example, an avalanche of a size of 8 cells is triggered. In the 'sandpile' model, the frequency-magnitude distribution of these avalanches is power law.

The elements of the 'sandpile' model can be related to the components of the Storegga Slide system. The dropping particles represent sediment deposition, the avalanches are the individual mass movements, and the thresholds are associated with changes in slope gradient, pore pressure and gravitationally-induced stress. The exponent associated with the power law distribution of subaerial mass movements is generally >2.2 (e.g. Dai and Lee 2002; Guzzetti *et al.* 2002; Malamud *et al.* 2004), whereas for the Storegga Slide, the exponent is 1.52. The value of the exponents for mass movements is higher than that of the theoretical 'sandpile' model. The difference may be explained by the large number and variety of forces and controls associated with 3D 'real' mass movements, in comparison to the simpler 2D 'sandpile' model. The consideration of factors such as geological heterogeneity or soil moisture content tends to increase the exponent of frequency-size distributions in landslide models (e.g. Pelletier *et al.* 1997; Sugai *et al.* 1994). The fact that the exponent for mass movements within the Storegga Slide is considerably lower than that for subaerial slides could imply that, in comparison to subaerial mass movements, submarine mass movements are less complex and that the dynamics are more comparable to those of the 'sandpile' model. Submarine settings are characterised by gentler slopes, consistent geology and morphology over extensive areas (Shepard 1963), and therefore homogeneous boundary conditions. Subaerial settings, in contrast, consist of rougher landscapes where numerous driving forces, such as tectonic uplift and fluvial incision, interact with weathering and variable degrees of saturation, to generate a higher exponent for the power law distribution. An important role may also be played by cohesion. The sediments failing within the Storegga Slide are mainly clays. Mass movements in cohesive sediments were shown to exhibit lower exponents than those occurring in less cohesive material (Dussauge *et al.* 2003).

Some uncertainties do arise with the applicability of the 'sandpile' model to submarine mass movements, however. For example, the 'sandpile' model disregards aspects of inertia and cohesion, which are quite important in sliding within the Storegga Slide. SOC is not a sole property of cellular automata models. For example, Hergarten and Neugebauer (1998) developed a model of landsliding that exhibits SOC using partial differential equations. For our study area, another explanation of the fractal distribution of the mass movements and the potential SOC behaviour may be the fact that the Storegga Slide was a retrogressive slope failure (Haflidason *et al.* 2004). The slide was initiated close to the Faroe-Shetland Escarpment (Bryn *et al.* 2005). Large mass movements within this region destabilised neighbouring and upslope areas**.** The development of the Storegga Slide may be likened to a retrogressive cascade, because as the instability propagated upslope via the repeated collapse of the headwall, the mass movements became more numerous (Figure 2b) and smaller (Haflidason *et al.* 2004). The Storegga Slide extends over most of the continental slope, where topography is smooth, and boundary conditions are homogeneous (Shepard 1963). The extent of the Storegga Slide is in fact limited by changes in boundary conditions at its perimeter, in particular the decrease in slope gradient and the increase in the consolidation of sediments at the continental shelf (Gauer *et al.* 2005), as well as the presence of the North Sea Fan in the south and the Vøring Plateau in the north. The retrogressive cascade is also qualitatively similar to the activation of avalanches in the 'sandpile' model and may explain the fractal distribution of submarine mass movements. Other cascade models, such as the inverse cascade model, have been used to reproduce the self-organized critical behaviour of forest-fires (Turcotte *et al.* 1999).

The origin of the fractal distribution may also be attributed to factors that are unrelated to SOC. A power law distribution may be the signature of pre-defined geological structures (e.g. Hergarten 2003; Pelletier *et al.* 1997) or external mechanisms. Since we do not have detailed information about the spatial variation of geological structures within the Storegga Slide, we are unable to confirm the role of geological structures in relation to the observed fractal distribution.

5. Conclusions

Our results have direct implications relating to the modelling of submarine mass movements. SOC is put forward as the most likely origin of the observed power law distribution of submarine mass movements. The Storegga Slide may thus be modelled as a large scale geomorphic system in a critical state, incorporating dynamics of the 'sandpile' model. SOC is an emergent property of a system, and thus it is not built into the fundamental physical equations. This means that the aggregate behaviour of the Storegga Slide cannot be modelled using a reductionist approach based on the small-scale elements of the system. This also means, however, that limitations in data acquisition techniques can be circumvented when considering these emergent features. The retrogressive cascade, which is based on an open system where loss of support constitutes the threshold exceeding mechanism, fits the SOC behaviour well and emphasizes the importance of considering the interconnectivity of individual slides. The evolution of a retrogressive cascade on the continental slope, where boundary conditions are generally uniform, would explain the large size of the Storegga Slide. In fluvial systems, SOC has been associated with minimum energy dissipation (Rigon *et al.* 1994). We are not able to measure energy in a complex system such as the Storegga Slide, so we may only theorise that the Storegga Slide is a geomorphological system operating at the level of minimum energy dissipation, with SOC as an emergent feature. Another application of our results is in hazard management. Frequency-magnitude distribution of mass movements can be used to extrapolate incomplete inventories within the limits of power law behaviour (in our case, for mass movements ranging between 0.3 – 100 km^2 in area) and thus estimate event magnitude and total number of mass movements.

6. Acknowledgements

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7. References

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