Landslides at volcanic insular margins

Roger Urgeles *Institut de Ciències del Mar (CSIC), Barcelona, Catalonia, Spain*
✓ Ocean volcanoes – an introduction

✓ Slope failure types in ocean volcanoes

✓ Trigger mechanisms of slope instability processes in ocean volcanoes

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✓ Final remarks
**Ocean volcanoes**

*Island volcanoes may form in:*

- *Ocean-Ocean subducting boundaries*
- *Mid-ocean ridges*
- *Hot-spots*

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**Diagram:**

- **ISLAND ARC PLATE SUBDUCTION**
  - Mafic to intermediate intrusives (plutonism)
  - Mafic to intermediate extrusives (volcanism)
  - Island arc volcano
  - Subduction zone

- **PLATE DIVERGENCE**
  - Basaltic extrusives
  - Basaltic intrusives
  - Mid-ocean ridge

- **HOT-SPOT VOLCANISM**
  - Basaltic extrusives
  - Basaltic intrusives
  - Hot-spot volcano

- **CONTINENTAL PLATE SUBDUCTION**
  - Mafic to felsic intrusives
  - Mafic to felsic extrusives
  - Subduction zone
  - Continental margin volcano

- **Partial melting of upper mantle**
  - Rising magma

- **Oceanic crust**
  - Mantle plume (hot spot)
  - Mantle
Ocean volcanoes

GLOBAL TECTONIC AND VOLCANIC ACTIVITY OF THE LAST ONE MILLION YEARS

PAUL D. LOWMAN JR.
NASA/Goddard Space Flight Center
Greenbelt, Maryland 20771
March 1997

Van der Grinten Projection

Mainly oceanic crust

LEGEND
Active ridges and continental extensions; minor transform faults generalized
Total spreading rate, cm/year; (Minster and Jordan, J. Geophys. Res. 83, 5331, 1978); directions approximate
Major active fault or fault zone; dashed where nature or activity uncertain
Normal fault or rift: hachures on downthrown side
Reverse fault (subduction or overthrust zone), hachures on upthrown side
Volcanoes active within the last million years; generalized (some isolated basaltic centers omitted)

From http://denali.gsfc.nasa.gov/research/lowman/lowman.html
Ocean volcanoes

- Hot spot → magmatic plume at a fixed location in the astenosphere
- Lithosphere drift above it → trail of volcanoes
- The most youngest is usually located above the hot spot
Ocean volcanoes

1. Bowie Seamount
2. Cobb Seamount
3. Yellowstone
4. Baja California
5. Hawaiian Islands
6. Galapagos Islands
7. San Felix I.
8. Juan Fernandez Islands
9. Easter I.
10. Patcain Island
11. MacDonald Seamount
12. Society Islands
13. Marquesas Islands
14. Discovery Seamount
15. Tristan da Cuhna Group
16. Bouvet Island
17. Trindade
18. Fernando de Noronha
19. Ascension
20. St. Helena
21. Cape Verdi Islands
22. Canary Islands
23. Madeira Islands
24. Azores
25. Iceland
26. Ahaggar
27. Tibetsi
28. Cameroon
29. Jabal Marrah
30. Afar Triangle
31. Zambria
32. Comoro Islands
33. Reunion
34. Crozet Islands
35. Kerguelen Islands
36. Melbourne
37. Louisville Ridge
38. Samoa Islands
39. Ebon Atoll
Ocean volcanoes

✓ History of ocean islands

- **Growth**
  - Stage 1: The Initial Stage
  - 2a Shield-building submarine substage
  - 2b Shield-building stage
  - 3 Giant landside stage
  - 4 Capping stage

- **Erosion**
  - 5 Erosional stage
  - 6 Renewed volcanism stage
  - 7 Atoll stage

- **Subsidence**
  - Wave eroded surface
  - Coral reef and sediments
  - Lava flow
  - Cinder cone
  - Tuff cone

- **History of ocean islands**

- **Growth**
  - Volcano
  - Ocean floor
  - Shield
  - Steam explosions

- **Erosion**
  - Tephra cone
  - Cinder cone
  - Reef

- **Subsidence**
  - Sand island
  - Lagoon
  - Eroded surface
Ocean volcanoes

**Thickness and flexure of the oceanic crust**

- **Flexure Model**
  - Bulge
  - Infill
  - Load
  - Infill
  - Bulge
  - Flexed Crust
  - Mantle

- **Gravity Anomaly**
  - Observed
  - Calculated

- **Velocity/Density Model**
  - 0 km
  - 5 km
  - 10 km
  - 15 km
  - 20 km
  - 25 km
  - 30 km
  - 35 km
  - 40 km

- **Flexure**
  - Infill
  - Load
  - Flexed Oceanic Crust

- **T_{0} (Oceans) vs Plate Age**
  - Long-Term Elastic Thickness
  - Short-Term Elastic Thickness

- **CDP**
  - TWTT (Sec)
Ocean volcanoes

✓ Morphology of the Hawaiian chain, moat and arch

(from Rees et al., 1993)

(from Leslie et al., 2002)
Ocean volcanoes

The Hawaiian Islands moat and arch

From http://geopubs.wr.usgs.gov/i-map/i2809/
Ocean volcanos

ISLAS CANARIAS

ISLAS HAWAII
Ocean volcanoes

✓ Calderas vs. landslides

Las Cañadas

Tenerife, Las Cañadas caldera?

La Orotava

Valle de Güímar

From NASA/JPL Imaging Radar Program
✓ Mt. St. Helens – prior to the 1980 eruption
Ocean volcanoes

- Mt. St. Helens (after the 1980 eruption)
Ocean volcanoes

✓ ~80s mapping of the Hawaiian EEZ

http://walrus.wr.usgs.gov/posters/underlandslides.html
Moore et al., 1984
Ocean volcanoes

Submarine Landslides along the Hawaiian Ridge
✓ At least 70 landslides >20 km long
✓ Some to 200 km and 5000 km³
✓ Cover >50% of volcano flanks

(Moore, Normark, Holcomb, 1994)
Ocean volcanoes

Watts and Masson, 2005
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### Slope failure types

**Mass Movement types**

<table>
<thead>
<tr>
<th>Mass slide</th>
<th>Creeping</th>
<th>Block gliding, rock avalanche</th>
<th>Translational Slide (Glide)</th>
<th>Rotational Slide (Slump)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No discrete shear surface. Low level deformation</td>
<td></td>
<td></td>
<td>Well-defined shear surface. Structure &gt; 100 m</td>
<td>0.15 &lt; z/l &lt; 0.33</td>
</tr>
<tr>
<td>Isolated elements of decimetric to hectometric scale not included in the matrix</td>
<td></td>
<td></td>
<td>z/l &lt; 0.15</td>
<td></td>
</tr>
</tbody>
</table>

**Mass flow**

- **Gravity flow**
  - Laminar flow: c ≥ 0.09
  - Mass flow
    - Matrix supported movement
    - Motion supported by fluid
      - Interstitial fluid important during triggering. Mixed fluid and sediment
      - Interstitial fluid important during transport. Sediment floating in fluid
- **Turbidity current**
  - Turbulent flow: c < 0.09
  - High density
    - Catastrophic trigger
    - Progressive trigger
  - Low density, fine grained and thin-bedded deposits

**Debris flow**

- **Liquified flow**
  - Grain size: silt and clay
- **Fluidized flow**
  - Grain size > silt

**Mud flow**

- **Silt flow**
- **Sand flow**
- **Grain flow**

**Turbidity Cloud**

- Auto-supported

**Low Density Turbidity Current**

Global classification of submarine mass movements (modified from Mulder & Cochinat (1996)).
Slope failure types

- **Debris avalanches**
  - Shallow landsliding
  - Surficial avalanching
  - No basal sliding
  - Unpredictable, catastrophic, and tsunamigenic!!

- **Slumps**
  - Seaward displacements
  - Basal sliding & earthquakes
  - Shallow landsliding
  - More predictable, slow, and “stable” (but also tsunamigenic) → possible monitoring

(Morgan and McGovern, 2005a)
✓ El Hierro and La Palma: Major debris avalanches as identified from multibeam bathymetry

(Slope failure types)

(After Urgeles et al., 2001)
Slope failure types
**Slope failure types**

- **Landslide is well disaggregated by the time it is deposited**
- **However, blocks up to 1 km across still remain intact**
- **Evidence of progressive slope failure?**

---

**TOBI sidescan mosaic of El Golfo**

- Limit of landslide deposit
- Shadows cast by blocks of volcanic debris in landslide
- Sediment failure due to landslide
- Blocky landslide debris

Masson et al., 1996
La palma: EM12 derived backscatter

(After Urgeles et al., 1999)
La Palma: debris avalanche blocks

(After Urgeles et al., 1999)
Slope failure types

- Wai'anae
- Nu’uanu
- Wailau
- Hana
- South Kaua’i
- Clark 1 & 2
- Hilina
✓ Seaward spreading of Kilauea’s south flank to 12 cm/yr
Slope failure types

✓ Line 2 crosses the broadest part of the midslope bench, as well as an elongate landslide block in front of the slope.
Slope failure types

- Upper flank → submarine erupted basalts covered by a 1 km thick blanket of hyaloclastite slope sediments.
- Midslope bench → imbricate stack of thrust sheets derived from stratified sediments and debris accumulated in front of flank.

- Strong reflection beneath the flank → top of the Cretaceous oceanic crust and pelagic sediment cover.
- Strong reflections above this deep horizon → thrust faults and base of volcanic edifice.
- Volcanic edifice slides seaward along pelagic sediment on the pre-existing volcanic plate;
- Shortening → 10 to 20 km

Morgan, et al., 2000
Slope failure types

San Andrés aborted collapse on El Hierro
✓ **Gravitational Spreading Simulations**

✓ **Particles in the sandpile have constant internal friction, \( \mu_{\text{int}} \) of 0.6 (i.e., Byerlee’s law), no cohesion.**

✓ **Basal friction, \( \mu_{\text{bas}} \) and cohesion, \( C_0 \) are variable parameters, and may vary along substrate length.**

  ✓ **Strong base (e.g. Canary Is): Shallow landslideing.**
  ✓ **Weak base (e.g. Hawaii): Gravitational spreading, oldest strata at edges.**

(Morgan and McGovern, 2005a & b)
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✓ Final remarks
Summary of Mechanisms Promoting Collapse

**Inherent Causes**
- Composition
- Physiochemical setting
- Structure, strength, and discontinuities
- Ambient (seasonal) groundwater conditions*

**Increase in Shear Stress**
- Removal of lateral support
- Static loading*
- Dyke intrusion*
- Dynamic loading*
- Slope steepening (volcano growth)

**Decrease in Shear Resistance**
- Physiochemical factors*
- Pore fluid pressures*
  - Sea-level
  - Meteoric
  - Hydrothermal
- Changes in structure

Fluids are implicated in the most energetic collapses
- Static groundwater pressures and hydrothermal alteration
- Magmastatic pressures
- Magmatic overpressures
  - Strength
  - Rheology

\[ F_s = \frac{\text{Shear strength} \downarrow}{\text{Shear stress} \uparrow} \]

*Influenced by Fluids

[Voight and Elsworth, 1997]
Trigger mechanisms

Carracedo, 1999

Gee et al., 2003
Trigger mechanisms

Giant landslide
Ridge
Active rift (ridge)
Dikes
MB-like fracture
Least stress

\[ \alpha_1 = \alpha_2 = \alpha_3 = 120^\circ \]

Carracedo, 1999
Trigger mechanisms

✓ 1m of rain 9 days before the slip event (pore pressure) → causal relationship

- Observed (black) and predicted (orange) displacements from November 2000 deformation event.
- Stations in white are continuous GPS; green stations are tilt meters; red stations are strain meters. Hexagons depict seismicity from 1 to 14 November 2000.

Cervelli et al., 2002
Trigger mechanisms

La Palma: pore pressure

Urgeles et al., 1999
Structure

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Tsunami potential

✓ Tsunami wave heights (m), 5 hours after Nu’uanu landslide

Satake, Smith, & Shinozaki (2004)
Tsunami potential

Slide Area: 3456 km²
Slide Volume: 500 km³
Slide Velocity: 45-100 m/s
Slide Duration: 600 sec
Excavation Area: 360 km²

Time = 2 minutes

Time = 5 minutes

Time = 10 minutes

Time = 15 minutes

T = 30 Minutes

T = 1 Hour

T = 3 Hours

Ward and Day, 2001
✓ **Ages of volcaniclastic turbidites emplaced on the Madeira Abyssal Plain within the last 1.3 Ma left compared with the ages of landslides derived by dating onshore volcanic sequences.**

✓ **Solid lines are well constrained age ranges; dotted lines show greater uncertainty.**

(After Masson et al., 2001).
Tsunami potential

✓ Turbidite correlation and sedimentology
  ✓ TURBIDITE B = EL GOLFO (~15 ka)
  ✓ TURBIDITE G = ICOD (~170 ka)

✓ Correlation:
  ✓ Various methods (sand composition, mud geochemical signature, isopachs) all indicate El Hierro/La Palma source

✓ Sedimentology:
  ✓ Turbidite bounded by pelagics

✓ Within turbidite are three-nine distinctive stacked fining-upwards sequences

✓ Unlikely to be due to flow reflection

✓ This may indicate multiple stages of landslide failure....?
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✓ Final remarks
- Turbidite deposition south of Gran Canaria
- Volcaniclastic flows entering the basin as early as 15 Ma.
- Large number of flows occur in the lower part of the section

(After Goldstrand, 1998)
✓ **Seismic stratigraphy of the Madeira Abyssal Plain**

(After Alibés et al., 1999)
✓ Relative abundance of turbidite types in the MAP
✓ volcaniclastic events → marked increase at about 6 Ma (Tenerife).
✓ The number of volcaniclastic events is lower
✓ Fewer flows during the Miocene.
✓ Volcanic cycles vs. volcanic turbidite events in the MAP

✓ Volcanic rich turbidites related to the initial volcanic cycles of Fuerteventura, Lanzarote and Gran Canaria were unable to reach the MAP

✓ opening of the moat flanking the islands due to the new imposed loads?

(After Alibés et al., 1999)
Structure

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- Final remarks
Stratigraphy of volcaniclastic aprons

**Theoretical across-moat stratigraphy**

- Onlap of the flexural arch in the lower section
- Offlap in the upper section

(from Watts and ten Brink, 1989)
Stratigraphy of volcaniclastic aprons

*Theoretical across-moat stratigraphy*

- **Onlap of the flexural arch at the position of new volcano development**
- **Offlap towards the upper part of the section**

(from Watts and ten Brink, 1989)
Seismic profile and stratigraphy of the Hawaiian Islands moat

(from Rees et al., 1993)
**Stratigraphy of volcaniclastic aprons**

**Typical moat stratigraphy**

- **Bottomed by the oceanic basement**

1. **Transparent unit, with constant thickness and draping the basement → pre-volcanic pelagic sediments**

2. **Unit with more prominent reflectors and chaotic regions → product of mass-wasting in the island flanks**
   - Onlapping both the island flank and the flexural arch in its lower section
   - Offlap on the upper one → distal position

3. **Topped by a ponded unit with flat reflectors → subsidence has effectively ceased.**

(After Rees et al., 1993)
Stratigraphy of volcaniclastic aprons

- Long profile across FHM.
- Little topographic moat exist, but landward dipping nature of the top of the oceanic basement.
- Landward diverging reflectors → continued landward subsidence of the basement.
Predicted stratigraphy of the Hawaiian Moat and Arch in the FHM

A. Turbidites and pelagic sediments on the Hawaiian Arch.

B. Gradually thicker volcaniclastic deposits approaching the FHM.

C. Debris avalanche and turbidity current deposits dominate along the axis of the FHM.

D. Thickest accumulation of sediments overlain by slump deposits predicted at the toe of the volcanic edifice.
Stratigraphy of volcaniclastic aprons

✓ Thickness of Hawaiian moat units

(from Rees et al., 1993)
Volcanic island stratigraphic evolution

1. Swell and uplift due to mantle plume
2. Volcanic materials extrude
3. Load by volcanic materials → flexure of the lithosphere and moat is infilled by volcanic derived sediments
4. As the plate moves uplift and a new volcanos take place
5. As volcano grows instability of the flanks develop with derived sediments onlapping the flexural arch and island flanks
6. Repeated in stages 6 to 9 → in areas where subsidence has ceased a ponded unit forms.

In general the overall geometry created is that of onlap at the leading edge of the volcanic hot spot chain and offlap at its trail.

(Stratigraphy of volcaniclastic aprons - Urgeles et al., 1998)
Structure

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**Significance of landslides on Volcanic Islands**

- Major process during the evolution of volcanic islands (construction vs. destructive events).
- Large scale mass wasting shaping the islands and the submarine slopes.
- Major Geohazard.

**What do we know?**

- Debris avalanches and slumps are large sudden but multiple events. The tsunami potential is high but overestimated.
- Good ideas about triggers (intrusions, heating of aquifers) but there is no proof for these hypothesis.
- Major volcanic phases on the islands are accompanied by landslides.
- Recurrence rate for giant events is long (e.g. 50 – 100 ka for Hawaiian and Canary Is) but recurrence rate around some smaller volcanic edifices in the Mediterranean is very short (years to 10s of years).
- Mass-wasting events on volcanic islands are a major source of sediment to the volcanic aprons, moats and adjacent basins
- Input of volcanic sediments to distal areas depends on volcanic activity but also on moat evolution.
What could be learnt by drilling?

✓ Are giant volcanic island slides single or multiple events? How dangerous are these slides?
✓ What are the strength properties, chemical alteration, pore pressure at shear planes bounding slumps?
✓ Roles of liquids and gasses in short term?
✓ Roles of weathering in the longer term?
✓ Roles of environmental factors, e.g. sea-level change and rainfall?
✓ What is the frequency of giant and small volcanic slides?
✓ When will happen the next slide (long term monitoring)?
✓ What is the dynamics of volcanic debris avalanches and slides?