Flank collapses and new relative instability analysis (RIA) techniques applied to active strato-volcanoes
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Colima Volcano - 2011

Mt. St. Helens - 1979
Volcanoes flank collapses
The 1980 sector collapse and debris avalanche at Mount St. Helens triggered the recognition of many similar debris avalanche deposits worldwide (Siebert, 1984; Ui and Glicken, 1986; Siebert et al., 1987; Francis and Wells, 1988; Vallance et al., 1995). Since then, several studies have revealed that many volcanoes are susceptible to failure caused by exogenous or endogenous processes (McGuire, 1996),
Instability of a volcanic edifice may be caused by many factors:

- direct magmatic intrusion into the edifice (Bezymianny-type activity, Gorshkov, 1962; Day, 1996; Elsworth and Voight, 1996),
- deposition of voluminous pyroclastic deposits on steep slopes (McGuire, 1996),
- hydromagmatic processes (Dzurisin, 1998),
- phreatomagmatic activity (Bandai-type activity, Moriya, 1980).
- faulting and tectonic settings (McGuire, 1996; Siebert, 1984)
- Earthquake (Keefer, 1994)

Gravitational failures may occur in response to progressive weakening of an edifice. Other triggering mechanisms include phreatic explosions and Hurricane-induced rainfall trigger (flank collapse at the Casita volcano in Nicaragua in 1998, Sheridan et al., 1999; Scott et al., 2005).
A recently developed technique of analysis applied to strato-volcanoes by Borselli et al. (2011)*, offers new insights for assessment of degree of instability for flank collapse of volcanic edifices.


The new technique combines three methodologies:

1) slope stability by limit advanced equilibrium analysis (ALEM) of multiple sectors on the volcano using SSAP 4.0 (*Slope Stability Analysis Software*, Borselli 2011) which include fluid internal overpressure or progressive dissipation (Borselli et al. 2011), and rock mass strength criteria (Hoek et al. 2002, 2006) for local, stress state dependent, shear strength;

2) the analysis of relative mass/volume deficit in the volcano structure, made using the new *VOLCANOFIT 2.0* software (Borselli et al. 2011);

3) Statistical analysis of major flank debris avalanche ages in the last 10,000 BP, using *stochastic arithmetic methods* (Vignes, 1993), and calculating the mean time of recurrence of them.
Relative slope stability by advanced limit equilibrium method (ALEM)

Limit equilibrium method (LEM) Slope stability analysis (Duncan 1996): Calculation of Factor of Stability (FS) which is associated to each section of volcanic edifice

Multiple sections of volcanic structure each 30° clockwise

Factor of stability determination:
\[ Fs \leq 1.0 \] unstable
\[ Fs > 1.0 \] stable

According to standard rigorous LEM

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SSAP 4.7.8 is a full freeware software

http://WWW.SSAP.EU (Borselli 1991, 2016)

- Generic shape random search of minimum FS sliding surface by Monte Carlo method
- Fluid pressure function (overpressure and dissipation fields Inside volcanic edifice) (Borselli et al. 2011)

\[
\sigma_f = \gamma_w z F_D + U_{0MIN} \\
F_D = 1 - A e^{-kD}
\]
Volcan de Fuego, Colima (November 2011)
W view

From, Saucedo et al. 2010

ALEM analysis application to Volcan de Fuego, Colima, MX (Approx 3880 m a.s.l. In the 2011)

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Volcan de fuego
Colima, MX

Selected area for analysis

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Simulated Over pressure fluid field
The advanced Limit equilibrium method (ALEM) and Relative instability analysis (RIA).

Scenarios and Geomechanical parameters (rock mass using GSI Hoek et al. 2002)

Shear strength parameterization of main bodies of the stratovolcano following the Hoek and Brown strength criterion (Hoek et al., 2002).

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Description</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Geomechanical parameters as in Table 2</td>
<td>No seismic effect</td>
</tr>
<tr>
<td>2</td>
<td>Geomechanical parameters as in Table 2 with GSI increase of 50%</td>
<td>No seismic effect</td>
</tr>
<tr>
<td>3</td>
<td>The same as scenario 2, but seismic coefficients Kh = 0.2; Kv = 0.1</td>
<td>Seismic effect by LEM pseudostatic analysis</td>
</tr>
<tr>
<td>4</td>
<td>The same as scenario 2, but seismic coefficient Kh = 0.25; Kv = 0.125</td>
<td>Seismic effect by LEM pseudostatic analysis</td>
</tr>
</tbody>
</table>
Final results colima with ALEM

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The sector with minimum relative stability is W-SW flank (between 270° and 210°) 

The Relative stability index

\[ R_{fs} = \frac{F_{s_i}}{F_{s_{\text{max}}}} \]

(Borselli et al. 2011)
Volcanofit 2.0
WWW.VOLCANOFIT.ORG

\[ Z = a e^{-\sqrt{(x-x_0)^2 + (y-y_0)^2}} + c \quad \text{if } Z \leq Z_1 \]

**VOLCANOID SURFACE OF REVOLUTION**

**ALTERNATIVE VOLCANOID’S GENERATRIX**

\[ Z = a \cosh \left( \frac{\Gamma - c}{b} \right) \]

for \( \forall r < c \) and \( a, b, c > 0 \).

\[ Z = \frac{z_1 - a}{1 + e^{\frac{r-c}{b}}} \]

with \( z_1 > a \) and \( z_1, a, b, c > 0 \).

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Colima Volcanofit 2.0
Result:
Using Negative exponential Volcanoid’s generatrix

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Volume (mass) Deficit in SW flank

\[ \Delta z_{x_i, y_i} = z_{x_i, y_i} - z_{\text{fit} x_i, y_i} \]

Software
volcanofit 2.1
(Borselli et al. 2011)

www.lorezno-borselli.eu/volcanofit

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The most potentially unstable Flank: Azimuth 270°-210°

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Mt. St. Helens Before 18 May 1980

Mt. St. Helens Now

USGS DEM 1979

USGS DEM after 18 May 1980

DTM by University of Washington, Earth and Space science, 2010.
http://rocky.ess.washington.edu/data/raster/thirtymeter/mtsthelens/OldMtStHelens.zip

Borselli–“Flank collapses and new relative instability analysis techniques (RIA).”, Boise State University –19/09/2016, Boise (ID)
Mt st. helens 1979 DTM
Analysed by VOLCANOFIT 2.0 (Borselli et al. 2011)

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From Hausback and Swanson (1990)

Figure 7: Northeastern asymmetric distribution of extrusive domes younger than Pine Creek age at Mount St. Helens. Small “x” is pre-1980 summit. These domes include east dome (ED), Sugar Bowl dome (SB), summit dome (SD), and Goat Rocks dome (GR, removed by 1980 landslide and blast). The 1340-m (4400-ft) contour encircles volcano. Dome outlines from unpublished mapping by C.A. Hopson.

DTM by University of Washington, Earth and Space science, 2010.
http://rocky.ess.washington.edu/data/raster/thirtymeter/mtsthelens/OldMtStHelens.zip

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View of the "bulge" on the north face of Mount St. Helens, from a measurement site about 2 miles to the northeast 27 April 1980.

[Links to related resources]

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Volcan de Colima

time of recurrence of last 5 debris avalanche events (DAE) (Borselli et al. 2011)

<table>
<thead>
<tr>
<th>Event ID</th>
<th>VEI*</th>
<th>Te1 (years BP)</th>
<th>Te1 Uncertainty on DAE (years)</th>
<th>Delta Te1 Interval from previous DAE (years)</th>
<th>Delta Te1 Uncertainty on interval from previous DAE (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,2,3</td>
<td>4</td>
<td>2580</td>
<td>140</td>
<td>1020</td>
<td>184</td>
</tr>
<tr>
<td>2,3</td>
<td>3</td>
<td>3600</td>
<td>120</td>
<td>3440</td>
<td>200</td>
</tr>
<tr>
<td>2,3</td>
<td>2</td>
<td>7040</td>
<td>160</td>
<td>2631</td>
<td>183</td>
</tr>
<tr>
<td>2,3</td>
<td>1</td>
<td>9671</td>
<td>88</td>
<td>3699</td>
<td>149</td>
</tr>
<tr>
<td>1,2</td>
<td>0</td>
<td>13370</td>
<td>120</td>
<td>n.a</td>
<td>n.a</td>
</tr>
</tbody>
</table>

Mean interval of last four DAE (expressed as stochastic number)

**ΔTe Mean interval of last four DAE (years): 2698 years**

**εΔTe Standard deviation associated to mean DAE interval (years): 180 years**

1 Komorowski et al. (1997); 2 Cortes et al. (2005); 3 Cortes et al., 2010; *from Mendoza-Rosas and De La Cruz-Reyna (2008).

Mean interval of last 4 DAE interval is **2698 years** with a mean standard deviation of **+/- 180 years**

Using **stochastic arithmetic** (Vignes, 1993; Markov and Alt, 2004)

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USE of Stochastic arithmetic for Debris avalanche recurrence time

The number of DAEs is much lower than the number of total explosive events. De la Cruz-Reyna (1993) established a Poissonian model for the recurrence intervals and occurrence frequency of explosive eruptions, and Mendoza-Rosas and De la Cruz-Reyna (2008, JVGR 176, 277–290) analysed the distribution of events with VEI>4, which may be related to large DAEs, finding an 85% probability of a VEI>4 event within the next 500 yrs, and an average recurrence time for VEI>=5 over 2500 yr. (this analysis include all events 2<VEI<6)

Instead we used stochastic arithmetic techniques (Vignes, 1993; Markov and Alt, 2004) adapted to the mean age of DAE and its band of uncertainty. This technique accounts for the error propagation and uncertainty associated with the computation of successive intervals between collapses. The proposed methodology resembles that proposed by Akçiz et al. (2010, Geology 38 (9), 787–790) for the assessment of large earthquake recurrence times at the San Andreas Fault (California, st. Andreas Fault system). In this chase the recurrence time for the Big Ones is much more shorter than previous assessments.
Fig. 6. DAE events vs. time interval from previous debris avalanche event. The projection of a possible scenario for the next DA event is included in the horizontal axis.
Present time $t=0$

**Stochastic arithmetic applied to DAEs recurrence and next DAE forecasting** *(see Borselli et al. 2011 for technical details)*

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Colima: Combined results of ALEM (by SSAP 4.1.3) (www.ssap.eu) and VOLCANOFIT2.0 (www.volcanofit.org) (as available in April 2012).

The most potentially unstable Flank: Azimuth 270°-210°

By VOLCANOFIT 2.0

By SSAP2010 (rel. 4.1.3)

Borselli—“Flank collapses and new relative instability analysis techniques (RIA),” Boise State University –19/09/2016, Boise (ID)
Highlights (until June 2012)

- **ALEM techniques** applied to Volcán de Colima point to the **W-SW quadrant as potentially the most unstable sector of the edifice** under a wide range of scenarios.

- The VOLCANOFIT application to Colima shows a n important deficit of volume in the same W-SW quadrant (approx. 0.4 km$^3$). The VOLCANOFIT Application to Mt. St. Helens pre-eruption1980 DEM shows the distribution of local mass deficit/surplus association that may be easily correlated with the 1980 incipient flank collapse process. **So there is the possibility that Sector Volume Deficit/Excess anomalies may be correlated to a possible mayor relative instability**.

- The recurrence interval of major collapse events in Colima volcano, during the last 10,000 years, calculated here using a stochastic arithmetic approach, yielding a mean recurrence interval of 2698 yrs, with an uncertainty range of 180 yrs.

- Our analysis point out an increased **possibility of flank collapse in the interval between -110 yrs and +345 yrs from the present**. This generates a series of scenarios ranging from **optimistic, considering a collapse within the next 345 years**, to **pessimistic, derived from the 110-year delay**.

- The proposed **new approach may be applied to any stratovolcano with a potential of flank collapse** and for his future hazard assessments.

*Borselli– “Flank collapses and new relative instability analysis techniques (RIA).”*, Boise State University –19/09/2016, Boise (ID)*
Next forecast of debris avalanche event (DAE) by stochastic arithmetic technique (SAT) : application to Colima and Shiveluch Volcanoes

Colima Volcano - 2011

From Belousov et. al. 1999

Borselli– “Flank collapses and new relative instability analysis techniques (RIA).” , Boise State University –19/09/2016, Boise (ID)
• few or very few existing data associated to recurrent DAEs in a stratovolcano edifice, because it is usually an extremely rare event. In SAT the error band associated to each DAE dating is fundamental..

In any case may be useful try to improve this technique in DAE field... trying to extend it with an other well know technique as the Survival Analysis...
Table 5. Age of major debris avalanches and flow deposits in the Holocene. The uncertainties of intervals and their standard deviation were calculated with the method of Borselli et al. (2011). References in Table: 1 Robin et. al. (1987); 2 Luhr and Prestegaard (1988); 3 Siebe et al. (1992); 4 Komorowski et al. (1997); 5 Capra and Macías (2002); 6 Cortes et al. (2005); 7 Capra (2007); 8 Cortes et al. (2010a); 9 Borselli et al. (2011). A pre-Holocene event is added in the last row to estimate the first Holocene time interval.

<table>
<thead>
<tr>
<th>Calibrated age of DAE-generating collapse event (years BP-2012)</th>
<th>Uncertainty in age of DAE (yr)</th>
<th>Time interval between DAE’s (yr)</th>
<th>Dating uncertainty of interval from previous DAE (yr)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>2629</td>
<td>214</td>
<td>1293</td>
<td>403</td>
<td>5</td>
</tr>
<tr>
<td>3922</td>
<td>341</td>
<td>1102</td>
<td>513</td>
<td>3,4,6,8,9</td>
</tr>
<tr>
<td>5024</td>
<td>383</td>
<td>2923</td>
<td>488</td>
<td>5,6,7,8,9</td>
</tr>
<tr>
<td>7947</td>
<td>302</td>
<td>3013</td>
<td>924</td>
<td>2,6</td>
</tr>
<tr>
<td>10960</td>
<td>873</td>
<td>4988</td>
<td>996</td>
<td>4,6,8,9</td>
</tr>
<tr>
<td>15948</td>
<td>479</td>
<td>-</td>
<td>-</td>
<td>1,6,9</td>
</tr>
</tbody>
</table>

Mean interval and standard deviation between DAE’s: 2664 ± 1574 yr

Uncertainty associated to the mean DAE interval ± 708 yr

From De la Cruz-Reyna S., Mendoza-Rosas A.T, Borselli L., Sarocchi D. VOLCANIC HAZARD ESTIMATIONS FOR VOLCÁN DE COLIMA. (in press). An additional DAE event available (from Roverato et al. 2011) and Recalibrated dating.
In calendar years, next DAE is centered in 2047 AD, and between 1307 and 2786 AD, it contains the date (2012).

We have to note that right part of uncertainty range indicate the most pessimistic assessment (next DAE is delayed...!)


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(*some additional dating and calibrated dating with respect Borselli et al. 2011)

<table>
<thead>
<tr>
<th></th>
<th>Borselli et al. (2011)</th>
<th>Revision De la Cruz Reyna et al (in press)</th>
<th>Last Update <em>(this presentation)</em></th>
</tr>
</thead>
<tbody>
<tr>
<td>Average DAE recurrence time</td>
<td>2698 (yrs)</td>
<td>2664 (yrs)</td>
<td>2649 (yrs)</td>
</tr>
<tr>
<td>average standard deviation of DAE intervals</td>
<td>+/- 180 (yrs)</td>
<td>+/- 704 (yrs)</td>
<td>+/- 673 (yrs)</td>
</tr>
<tr>
<td>next DAE</td>
<td>2130 AD (+/-180 yr)</td>
<td>2047 AD (+/-704 yr)</td>
<td>1326 AD ← 2032 AD → 2737 AD</td>
</tr>
</tbody>
</table>

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Stochastic arithmetic applied to SHIVELUCH volcano DAEs.

We consider the only data from DAEs in the south flank of volcano.

Total 12 DAEs, including the last one 1964 AD (Ponomareva et al 1998,2006)

Images from: Ponomareva et al. (1998; 2006) (with some modifications)

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Excellent source of informations on Shiveluch DAEs:


<table>
<thead>
<tr>
<th>Debris avalanche</th>
<th>Rounded ¹⁴C ages (yr BP)</th>
<th>Approximate calendar years</th>
</tr>
</thead>
<tbody>
<tr>
<td>XIV</td>
<td>1450</td>
<td>AD630</td>
</tr>
<tr>
<td>XIII</td>
<td>1100</td>
<td>AD970</td>
</tr>
<tr>
<td>XII</td>
<td>500</td>
<td>AD1430</td>
</tr>
<tr>
<td>XI</td>
<td>1600</td>
<td>AD430</td>
</tr>
<tr>
<td>X</td>
<td>1700</td>
<td>AD380</td>
</tr>
<tr>
<td>IX</td>
<td>1850</td>
<td>AD150–190</td>
</tr>
<tr>
<td>VIII</td>
<td>1900</td>
<td>AD120</td>
</tr>
<tr>
<td>VII</td>
<td>2550</td>
<td>BC780</td>
</tr>
<tr>
<td>VI</td>
<td>3100</td>
<td>BC1330</td>
</tr>
<tr>
<td>V</td>
<td>3700</td>
<td>BC2080</td>
</tr>
<tr>
<td>IV</td>
<td>4000</td>
<td>BC2490</td>
</tr>
<tr>
<td>III</td>
<td>5500</td>
<td>BC4350</td>
</tr>
<tr>
<td>II</td>
<td>5700</td>
<td>BC4530</td>
</tr>
</tbody>
</table>

Excluded

Calibrated ages.. used in order to apply SAT to SHIVELUCH

Shiveluch v.s. others DAEs Frequency in Kamchatka volcanoes (from PONOMAREVA et al. 2006)

(from PONOMAREVA et al. 2006)
### Survival analysis Technique (SAT) applied to young SHIVELUCH

Using DAE’s ages and its error range from Ponomareva et al. (1998,2006)

<table>
<thead>
<tr>
<th></th>
<th>At present time (2012 AD)</th>
<th>At 1964 AD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Using 12 DAEs</td>
<td>Using 11 DAEs</td>
</tr>
<tr>
<td></td>
<td>(last DAE 1964 AD +/- 0 YRS)</td>
<td>(last DAE 1430 AD +/- 57 yrs)</td>
</tr>
<tr>
<td>Average DAE recurrence time</td>
<td>590 (yrs)</td>
<td>596 (yrs)</td>
</tr>
<tr>
<td>average standard deviation of DAE’s intervals</td>
<td>+/- 98 (yrs)</td>
<td>+/- 101 (yrs)</td>
</tr>
<tr>
<td>next DAE FORECAST (by SAT)</td>
<td>2457AD ← 2554 AD → 2652 AD</td>
<td>1910 AD ← 2026 AD → 2142 AD</td>
</tr>
</tbody>
</table>

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Survival analysis can be applied considering the lifetime of a temporary volcanic edifice, that had grown between two DAEs, as a fully random variable*.

Steps:

I – Calculating the sample of intervals (in yrs.) between DAEs

II - Generating empirical CDF of DAEs intervals (in yrs.)

III – Fitting e CDF with Weibull CDF and obtain best F(t) (the lifetime distribution)

IV – calculating The survival function $S(t) = 1 - F(t)$

V - Calculating the residual probability of present edifice to survive, after last DAE, at present time (mean residual lifetime)

VI – calculating probability of present edifice to die or collapse (by a DAE) in the next 1, 10, 20, 50, 100, 200, years.

* Speculation !!
Some basic equations we used

Weibull lifetime CDF

\[ F(t \mid \alpha, \beta) = 1 - \exp\left(-\left(\frac{t}{\beta}\right)^\alpha\right) \]

Survival function CCDF

\[ S(t \mid \alpha, \beta) = 1 - F(t \mid \alpha, \beta) \]

expected future lifetime. In reliability problems the expected future lifetime is called the mean residual lifetime after given time \( t_0 \).

\[ t_{mr} = \frac{1}{S(t_0)} \int_{t_0}^{\infty} S(t) \, dt \]
Non linear fitting of empirical CDF (lifetime distribution) of Shiveluch and Colima temporary edifices after they start to regrow after a DAE.

Weibull CDF fitting of life time distribution of edifices

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Weibull lifetime distribution for temporary edifices

- SHIVELUCH 1964 AD, t=534 years from last DAE
- COLIMA 2012 AD, t=2629 years from last DAE
Weibull survival distribution $S(t)$ for temporary edifices

- **SHIVELUCH**
  - SHIVELUCH 1964 AD
  - $t=534$ years from last DAE
  - CCDF = 0.316

- **COLIMA**
  - COLIMA 2012 AD
  - $t=2629$ years from last DAE
  - CCDF = 0.375
Survival analysis indicates that SHIVELUCH (in 1964 AD) and COLIMA (in 2012 AD) were in a similar situation in term of survival probability after the last recognized DAE.

Calculated Expected future lifetime (or mean residual lifetime $t_{mr}$) and mean expected life at $t_0=0$ (born) are:

<table>
<thead>
<tr>
<th></th>
<th>Mean residual lifetime $t_{mr}$ (yrs)</th>
<th>Mean expected life at born $t_{mr}$ for $t_0=0$ (yrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SHIVELUCH</td>
<td>261</td>
<td>437</td>
</tr>
<tr>
<td>(1964 AD)</td>
<td>(t_0=534)</td>
<td></td>
</tr>
<tr>
<td>COLIMA</td>
<td>1195</td>
<td>2350</td>
</tr>
<tr>
<td>(2012 AD)</td>
<td>(t_0=2629)</td>
<td></td>
</tr>
</tbody>
</table>

But...

*Borselli– “Flank collapses and new relative instability analysis techniques (RIA).”*, Boise State University –19/09/2016, Boise (ID)
The calculated probabilities of next DAE using $S(t_0) - S(t_0+t_N)$ are:

**SHIVE LUCH 1964 AD**

<table>
<thead>
<tr>
<th>N Years</th>
<th>1</th>
<th>10</th>
<th>20</th>
<th>50</th>
<th>100</th>
<th>200</th>
<th>500</th>
</tr>
</thead>
<tbody>
<tr>
<td>prob(%)</td>
<td>0.114112</td>
<td>1.128967</td>
<td>2.230857</td>
<td>5.373499</td>
<td>10.07123</td>
<td>17.5444</td>
<td>28.48088</td>
</tr>
</tbody>
</table>

**CO LIMA 2012 AD**

<table>
<thead>
<tr>
<th>N Years</th>
<th>1</th>
<th>10</th>
<th>20</th>
<th>50</th>
<th>100</th>
<th>200</th>
<th>500</th>
</tr>
</thead>
<tbody>
<tr>
<td>prob(%)</td>
<td>0.026995</td>
<td>0.269506</td>
<td>0.538014</td>
<td>1.337485</td>
<td>2.649382</td>
<td>5.193554</td>
<td>12.15161</td>
</tr>
</tbody>
</table>

Number of years we need to obtain in Colima the same % of probability as Shiveluch in 1964 AD

*Borselli– “Flank collapses and new relative instability analysis techniques (RIA).” , Boise State University –19/09/2016, Boise (ID)*
10-11 July 2015 eruption

Short communication

Preliminary report on the July 10–11, 2015 eruption at Volcán de Colima: Pyroclastic density currents with exceptional runouts and volume

L. Capra a,*, J.L. Macías b, A. Cortés c, N. Dávila d, R. Saucedo e, S. Osorio-Ocampo f, J.L. Arce g, J.C. Gavilanes-Ruiz h, P. Corona-Chávez g, L. García-Sánchez f, G. Sosa-Ceballos b, R. Vázquez i

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Borselli–“Flank collapses and new relative instability analysis techniques (RIA).” Boise State University – 19/09/2016, Boise (ID)
Dome and side crater partial collapse 10 July 2015, 10 km large runout and pyroclastic flow, as block and ash flow SW view (images by Google Earth)
Colima volcán de Fuego
Full SW view (images by Google Earth)
Distal portion

Colima volcán de Fuego
Full SW view
(images by Google Earth)
Colima volcán de Fuego
Median portion
Monte Grande
And San Antonio Ravine
(images by Google Earth)
Colima volcán de Fuego
Fan at Distal portion of Montegrande Ravine
(images by Google Earth)

Distal Fan image
(capra et al. 2016)

Borselli—“Flank collapses and new relative instability analysis techniques (RIA).” Boise State University –19/09/2016, Boise (ID)
After the 10 July event we reconsider the previous RIA approach. In this case we use new tools available in SSAP software developed after 2013 and until now.

- **New local FS color map, obtained by Quasi FEM algorithm (Borselli 2013, 2016)** (knowledge of main stress directions and magnitude as obtained from solutions ALEM)
- **Color Map of pressure (overpressure) fluids**
- **Various Improvements on Monte Carlo surface generation engines and on ALEM rigorous computational models used by SSAP.**
Fluid overpressure model
SSAP 4.7.8 (2016)

Graph rendering Credits to: GNUMPLOT 5.1 www.gnuplot.info


Borselli–“Flank collapses and new relative instability analysis techniques (RIA).”, Boise State University –19/09/2016, Boise (ID)
Fluids overpressure Map of slope section azimuth 210°
SSAP 4.7.8 (2016)

Borselli–“Flank collapses and new relative instability analysis techniques (RIA).”, Boise State University –19/09/2016, Boise (ID)
A More detailed analysis required here.

Local safety factor (FS) map of slope section azimut 210° SSAP 4.7.8 (2016)
Local safety factor (FS) map of slope section azimuth 210°
SSAP 4.7.8 (2016) – detailed analysis of Upper edifice

Credits to: GNUPLOT 5.1 www.gnuplot.info
SSAP 2010 rel. 4.7.8 (1991, 2016) by L. Borselli, lborselli@gmail.com
http://www.ssap.eu

Borselli–“Flank collapses and new relative instability analysis techniques (RIA),” Boise State University – 19/09/2016, Boise (ID)
Mappa ottenuta con algoritmo Gauss Integration by QuasiFEM algorithm (Borselli 2013,16)

Fattore di sicurezza Globale (superficie con Fs minimo): 0.5540

Metodo di calcolo: MORGESTERN-PRICE (1965)

Local safety factor (FS) map of slope section azimut 210°
SSAP 4.7.8 (2016) – detailed analysis of Upper edifice

Borselli– “Flank collapses and new relative instability analysis techniques (RIA).” , Boise State University –19/09/2016, Boise (ID)
Application of SSAP
To a volcanic edifice where
Knowledge on internal structure
Are available
From Rosas-Carabjal et al. 2016 (fig. 2)

Borselli– “Flank collapses and new relative instability analysis techniques (RIA).” , Boise State University –19/09/2016, Boise (ID)
From Rosas-Carabjal et al. South Flank section2016 (fig. 3)

Borselli—“Flank collapses and new relative instability analysis techniques (RIA).” Boise State University –19/09/2016, Boise (ID)
### SLOPE Model of La Soufriere South flank Loaded in SSAP 4.7.8 (2016)

#### Parametri Geotecnici degli strati

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<th>Cu (kPa)</th>
<th>Gamm (kN/m³)</th>
<th>GammSat (kN/m³)</th>
<th>sgci (MPa)</th>
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Data: 19/9/2016
Località:
Descrizione: [n] = N. strato o lente
Max overpressure factor $S=2.5$
$U_{0\text{max}}=6.0\text{ Mpa}$
$F_s\text{ (global)}=0.86$
Max overpressure factor $S=2.5$
$U_{0\text{max}} = 6.0$ Mpa
$F_s$ (global) 0.86

**Borselli—“Flank collapses and new relative instability analysis techniques (RIA).”**, Boise State University – 19/09/2016, Boise (ID)
Max overpressure factor $S = 2.5$
$U_{0max} = 6.0$ Mpa
$F_s$ (global) 0.86

Borselli–“Flank collapses and new relative instability analysis techniques (RIA).”, Boise State University –19/09/2016, Boise (ID)
Max overpressure factor $S=3.5$
$U_{0\text{max}}=9$ MPa
$F_s(\text{global})=0.3$
Max overpressure factor $S = 3.5$
$U_{0\text{max}} = 9 \text{ MPa}$
$F_s(\text{global}) = 0.3$
La Soufriere - Effect of OverPressure Factor on Global South Flank Stability - by SSAP 4.7.8 (2016)

Global Safety Factor (FS)

OverPressure factor (S)

- $U_0 \text{ Max (MPa)}$
- Full Collapse conditions

Borselli–“Flank collapses and new relative instability analysis techniques (RIA).”, Boise State University –19/09/2016, Boise (ID)
Highlights and ... Speculations -1

• Special acknowledgments to All field volcanologists for their past and future studies and dating of Debris avalanche deposits (DAE)...

• Big importance of correct (calibrated) DAEs dating

• Stochastic arithmetic and Survival Analysis can be applied considering the lifetime of a temporary volcanic edifice as a fully random variable.

• SHIVELUCH (in 1964 AD) and COLIMA (in 2012 AD) *Was* in a similar situation...!? May be... Event July 2015 suggests and confirms the global fragile situation of Colima edifice. A reappraisal of global stability with SSAP new tools enforces these hypotheses.
SSAP used in a context of Relative Instability analysis may have a good potential to be used with the objective of better evaluation of the threshold conditions/scenarios for edifice collapse...

The proposed new approach may be applied to any strato-volcano with potential of flank collapse and for his future DAE’s hazard assessments.
Many thanks for Your attention !!!