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

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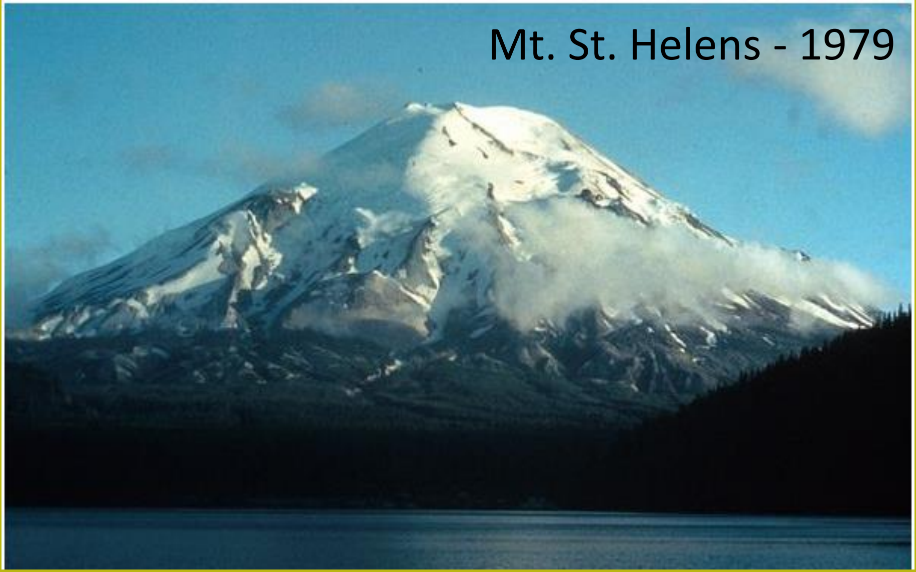


Volcanoes flank collapses

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),

NASA Earth Observatory Image 2009

Volcanoes flank collapse : causes and triggers

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,1984)

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**.

BORSELLI L., CAPRA L., SAROCCHI D., De La CRUZ-REYNA S. (2011). Flank collapse scenarios at Volcán de Colima, Mexico: a relative instability analysis. Journal of Volcanology and Geothermal Research. 208:51–65.

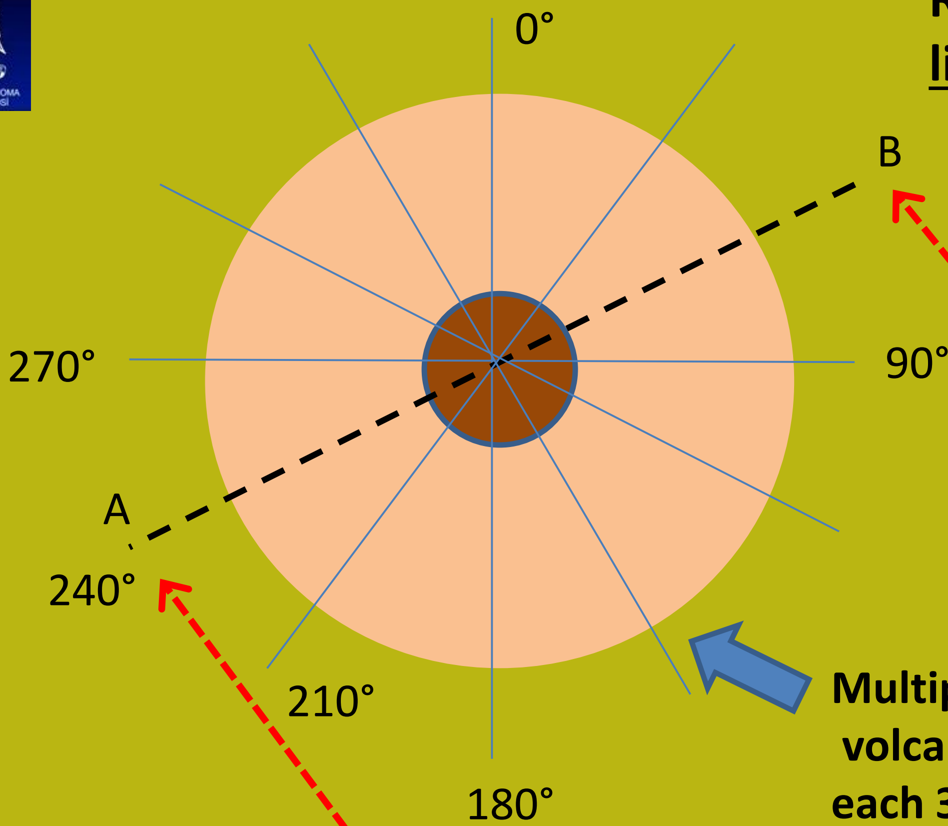
The new technique combines three methodologies:

- 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.

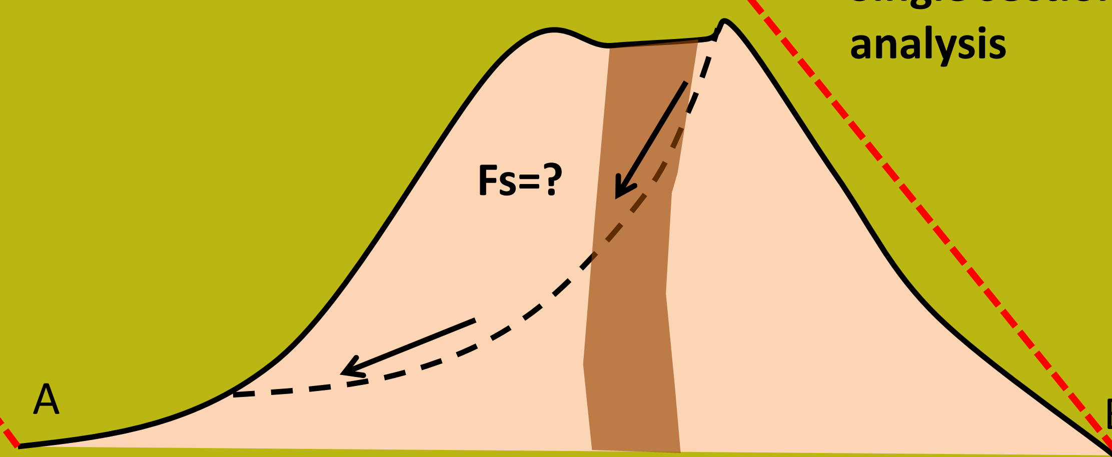
Relative slope stability by <u>advanced limit equilibrium method</u> (ALEM)



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

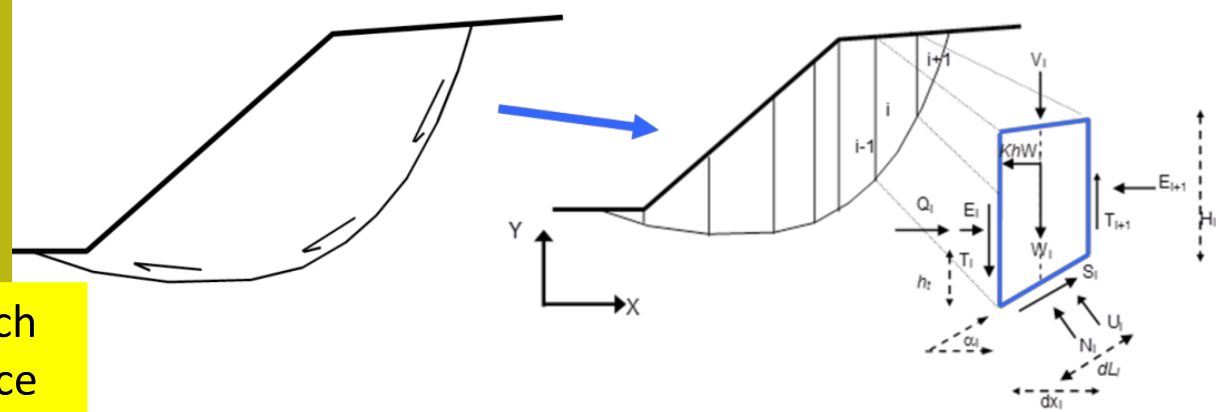
Single section analysis



Factor of stability determination:
Fs <=1.0 unstable
Fs > 1.0 stable
According to standad rigorous LEM

SSAP 4.7.8 is a full freeware software

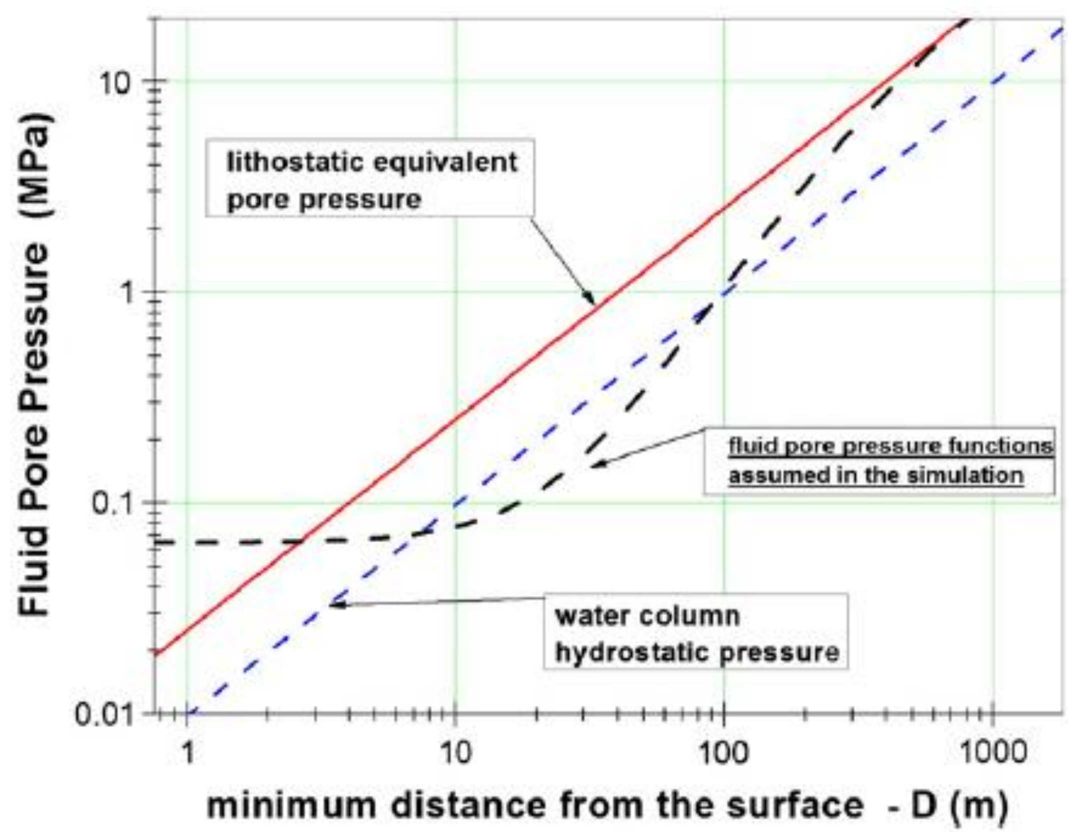
http://WWW.SSAP.EU (Borselli 1991, 2016)

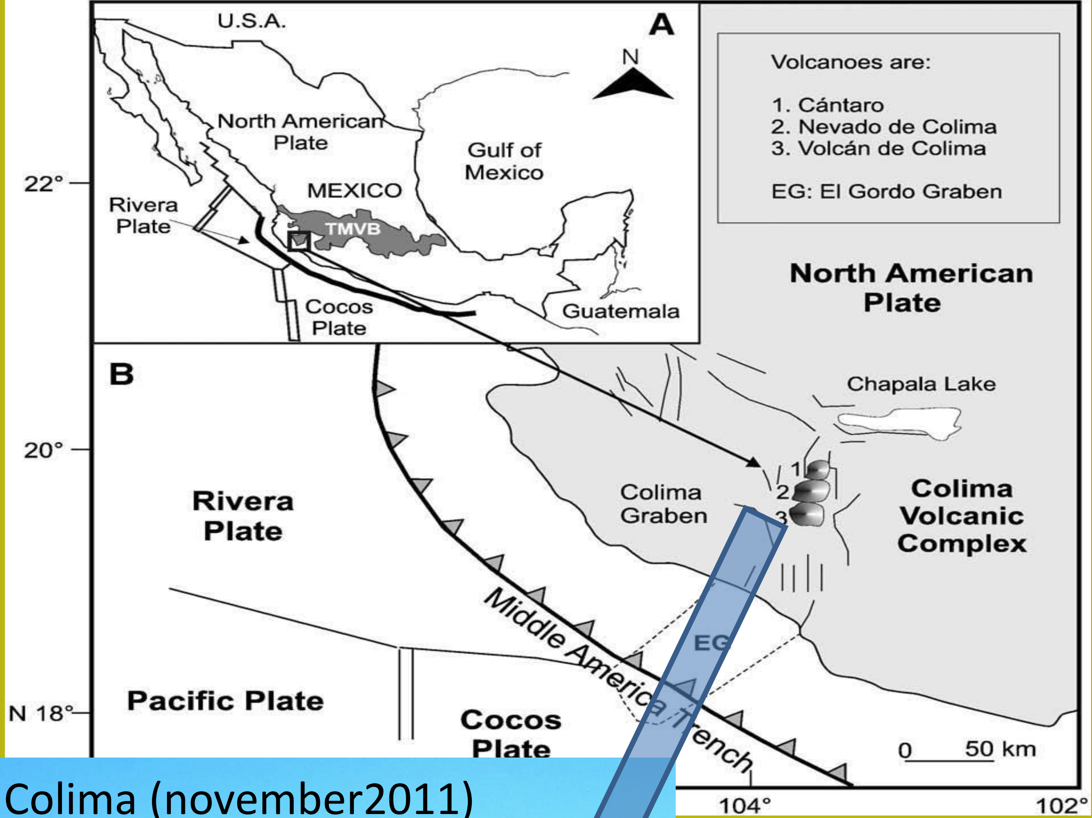


- Generic shape random search of minimum FS sliding surface by Monte Carlo method
- Rock mass strength criterion (Hoek et al. 2002,2006).
- Fluid pressure function (overpressure and dissipation fields Inside volcanic edifice) (Borselli et al. 2011)

$$\sigma_f = \gamma_w z F_D + U_{0_{MIN}}$$

$$F_D = 1 - Ae^{-kD}$$



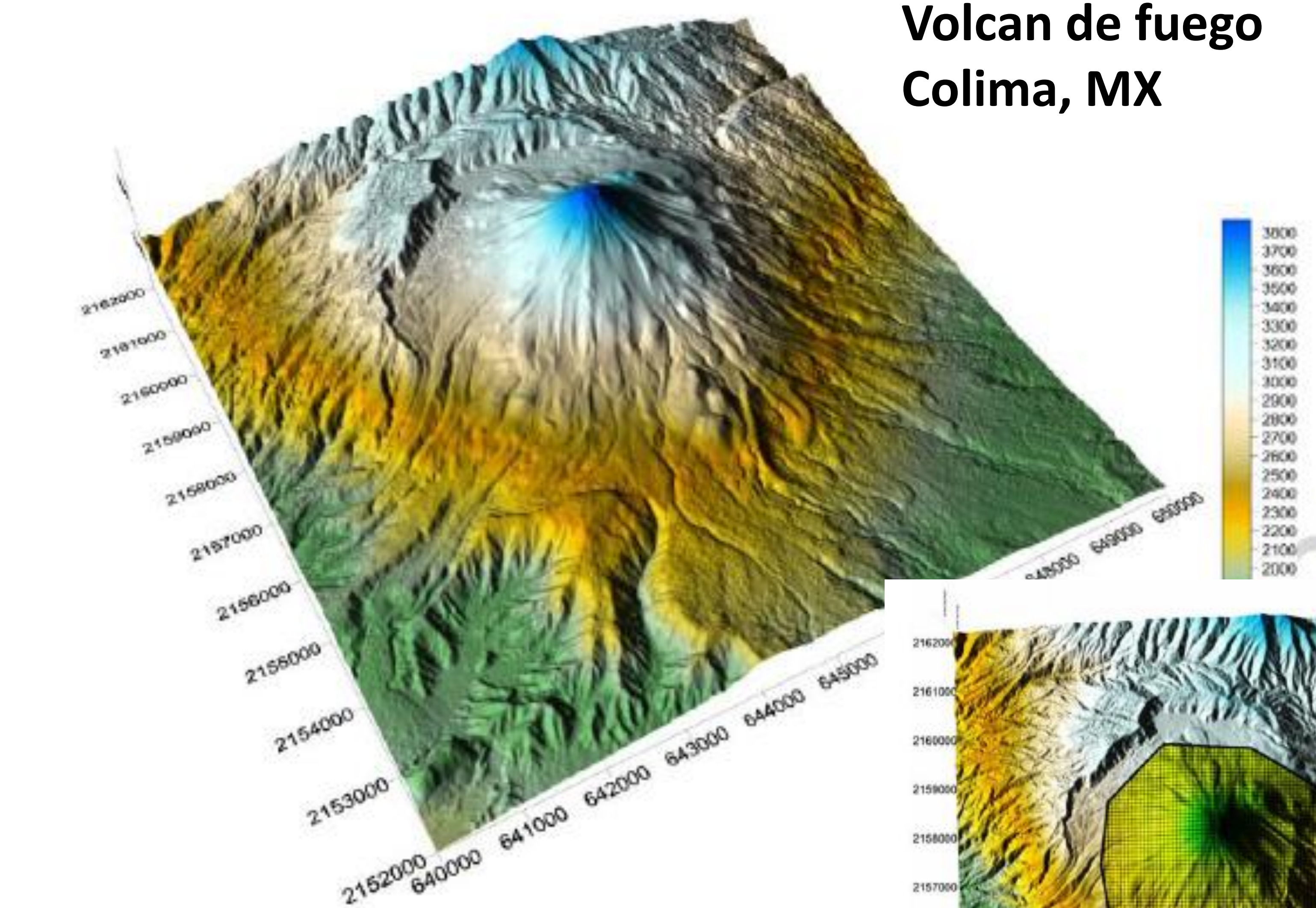


From, Saucedo et al. 2010

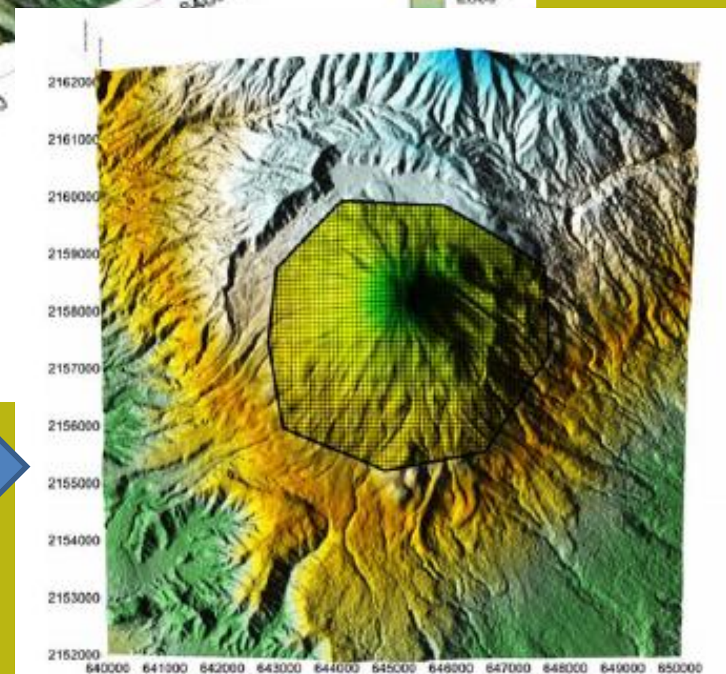
Volcan de Fuego, Colima (november2011)
W view

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

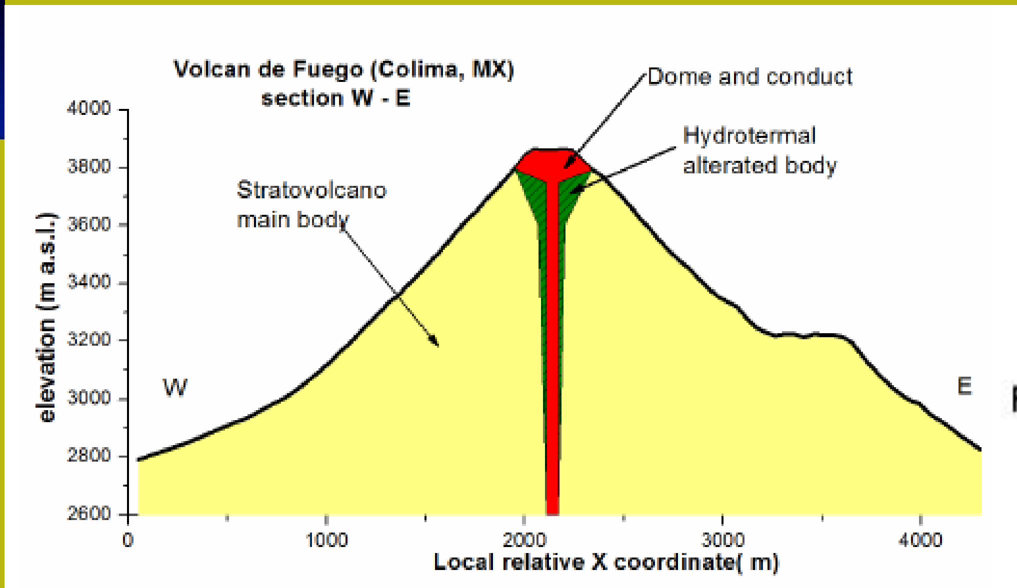
Volcan de fuego Colima, MX

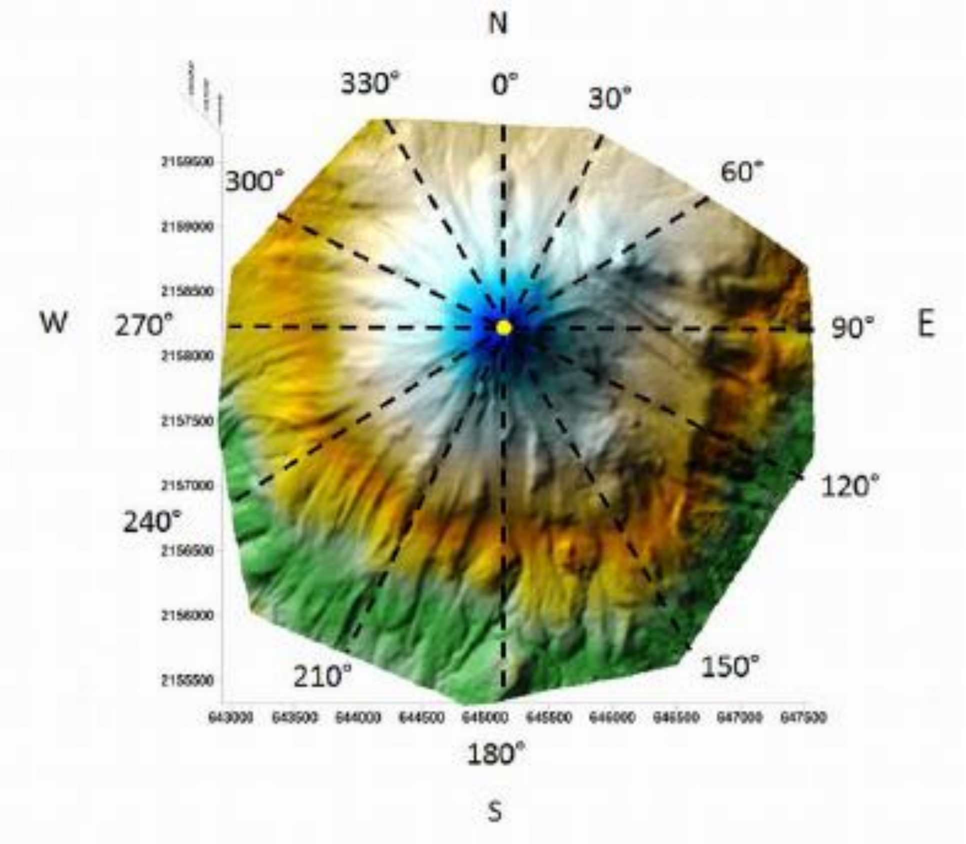


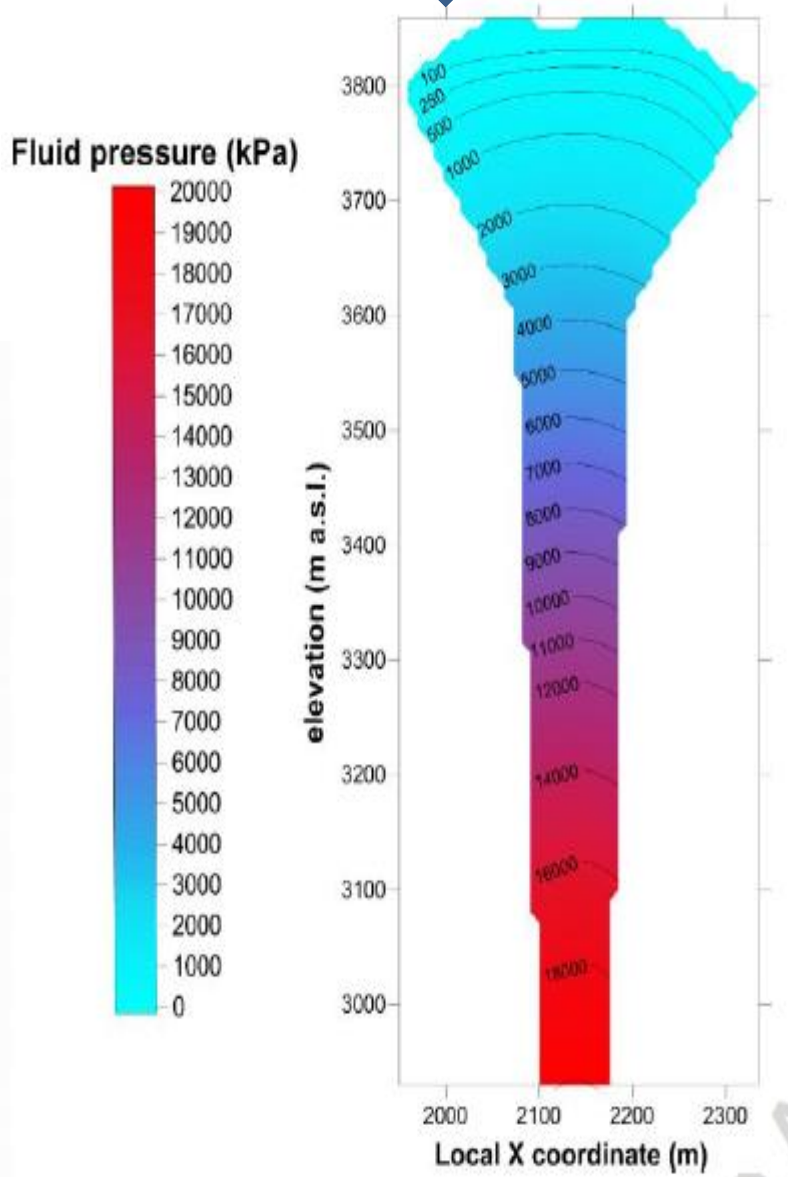
Selected area for analysis



Simulated Over pressure
fluid field







The advanced Limit equilibrium method (ALEM) and Relative instability analysis 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).

	γ unsaturated unit weight (kN/m^3)	γs saturated unit weight (kN/m^3)	σI uniaxial compressive strength of intact rock element (MPa)	GSI geological strength index (adimensional)	m_i lithological index (adimensional)	D disturbance factor (adimensional)
Strato volcano main body	24.5	25.0	50	40, (60)*	22	1.0
Hydrothermal altered body	24.0	24.5	40	30, (45)*	22	1.0
Dome and conduct	24.0	24.5	25	20, (30)*	22	1.0

*In parentheses the GSI value for scenario analysis Nos. 2, 3 and 4 (50% increase assumed with respect to GSI of scenario no. 1).

Simulation Scenarios adopted

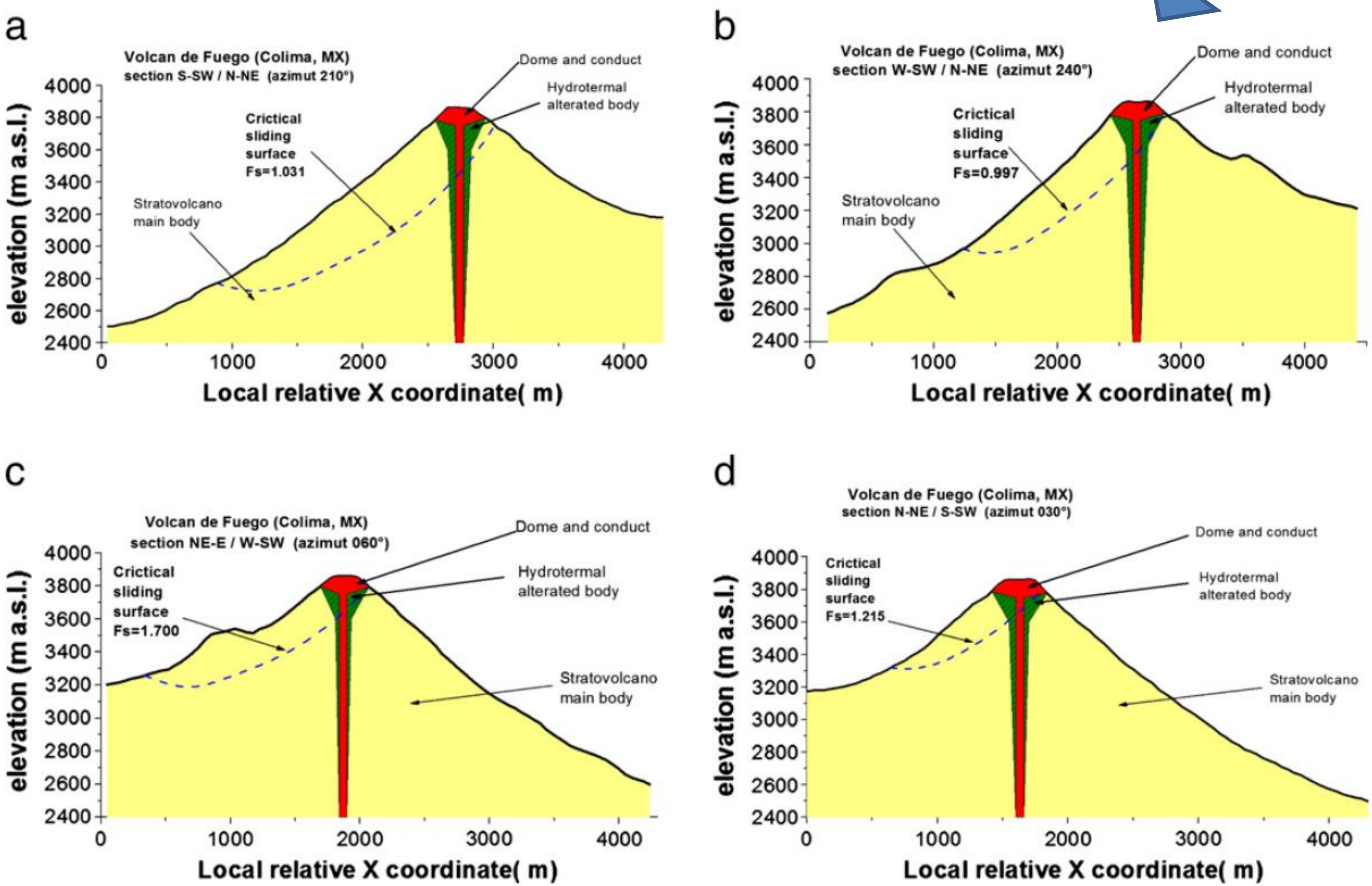
Characteristics of scenario analysis adopted for limit equilibrium analysis.

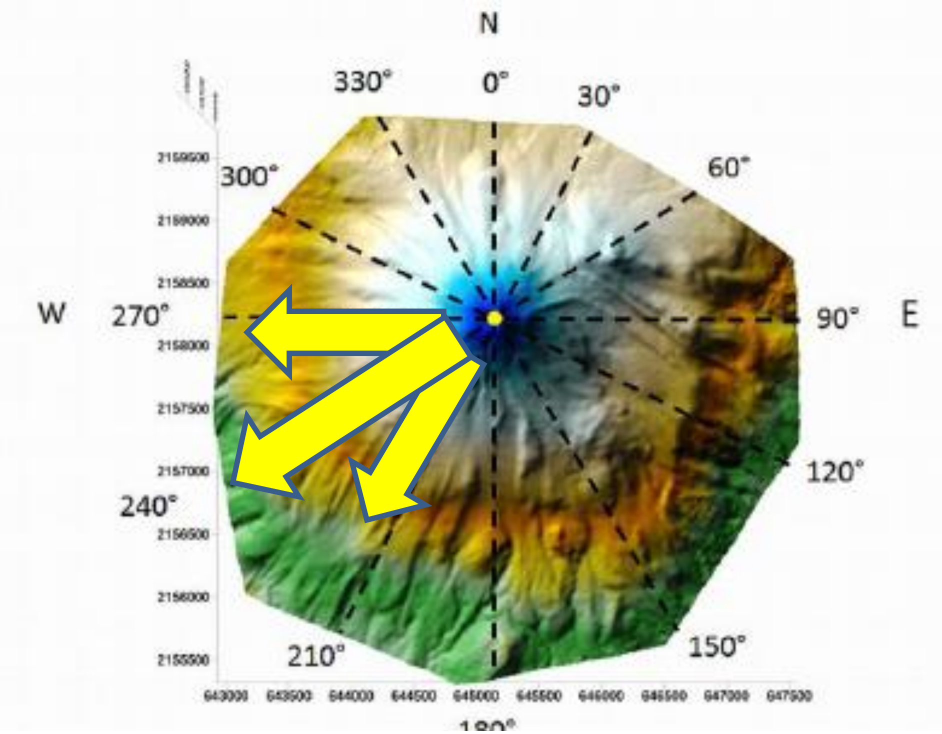
Scenario no. 1	Description	Notes
1	Geomechanical parameters as in Table 2	No seismic effect
2	Geomechanical parameters as in Table 2 with GSI increase of 50%	No seismic effect
3	The same as scenario 2, but seismic coefficients Kh = 0.2; Kv = 0.1	Seismic effect by LEM pseudostatic analysis
4	The same as scenario 2, but seismic coefficient Kh = 0.25; Kv = 0.125	Seismic effect by LEM pseudostatic analysis

Final results colima with ALEM

More pessimistic result

L. Borselli et al. / Journal of Volcanology and Geothermal Research 208 (2011) 51–65



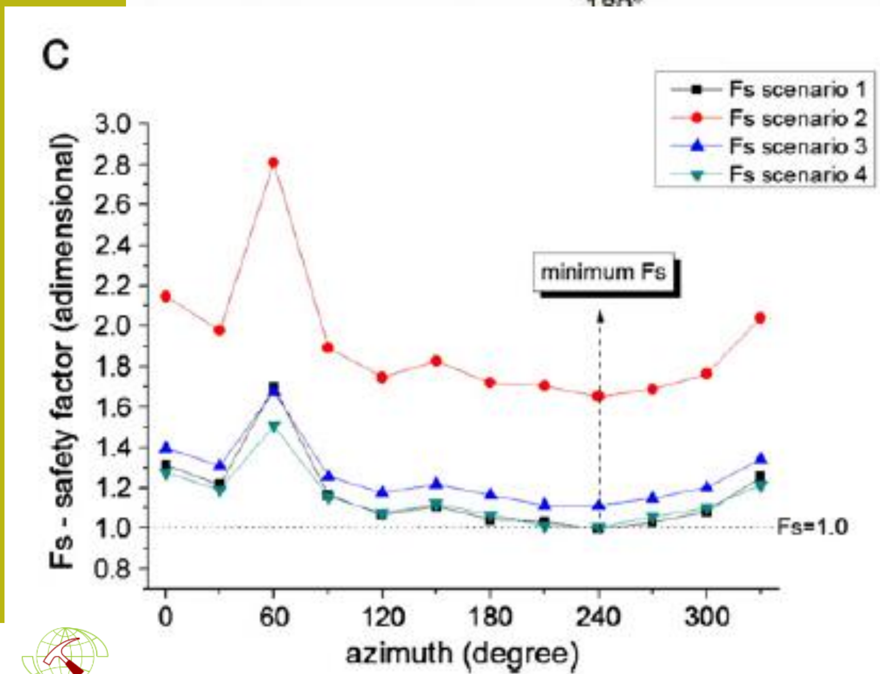


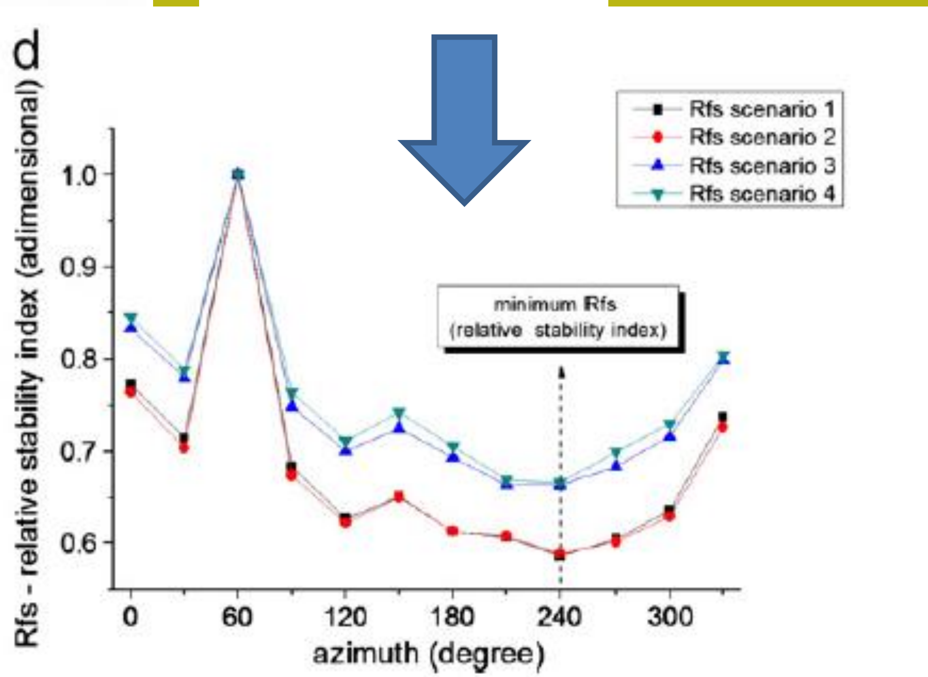
The sector with minimun relative stability is W-SW flank (between 270° and 210°)

The Relative stability index

$$R_{fs_i} = \frac{Fs_i}{Fs_{max}}$$

(Borselli et al. 2011)





Volcanofit 2.0

WWW. VOLCANOFIT.ORG

$$Z = a\, e^{-\frac{\sqrt{(X-X_0)^2+(Y-Y_0)^2}}{b}} + c \quad \text{if } Z \le Z_1$$

VOLCANOID SURFACE OF REVOLUTION

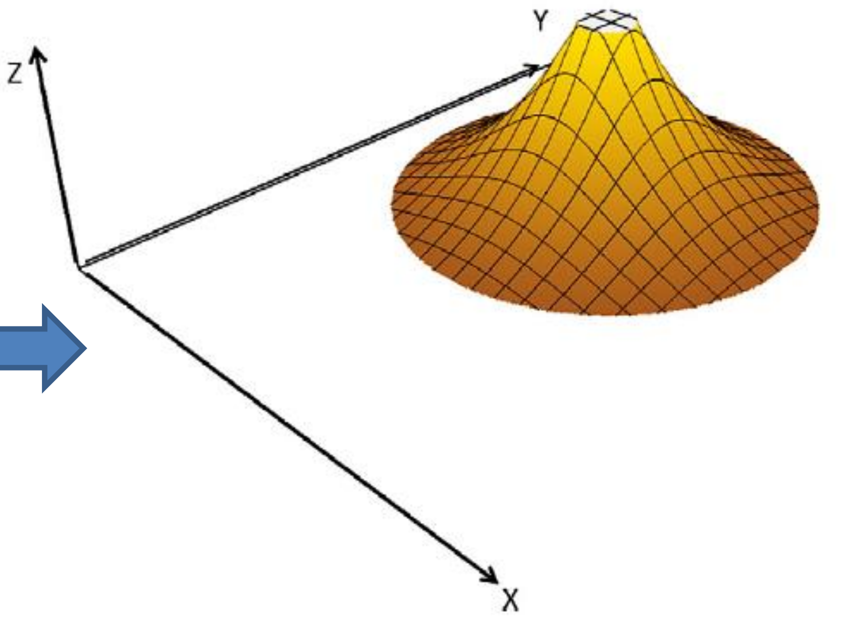


Fig. A.2. Example of volcanoid with constant negative curvature (Eq. (A.5)).

ALTERNATIVE VOLCANOID'S GENERATRIX

$$Z = a \cosh\left(\frac{r-c}{b}\right)$$

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 $z_1, a, b, c > 0$.

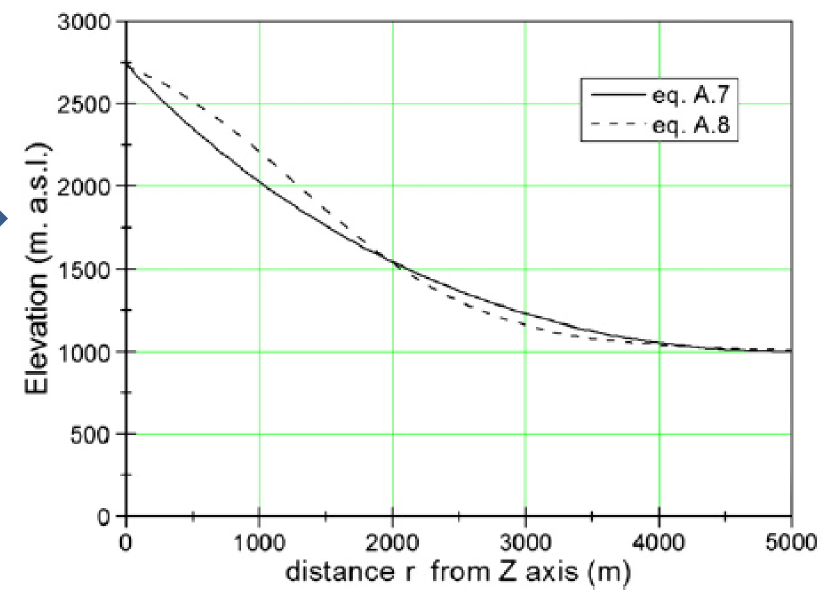


Fig. A.5. Alternative generatrix function of 3D volcanoid.

Colima Volcanofit 2.0 Result:
Using Negative exponential *Volcanoid*'s generatrix

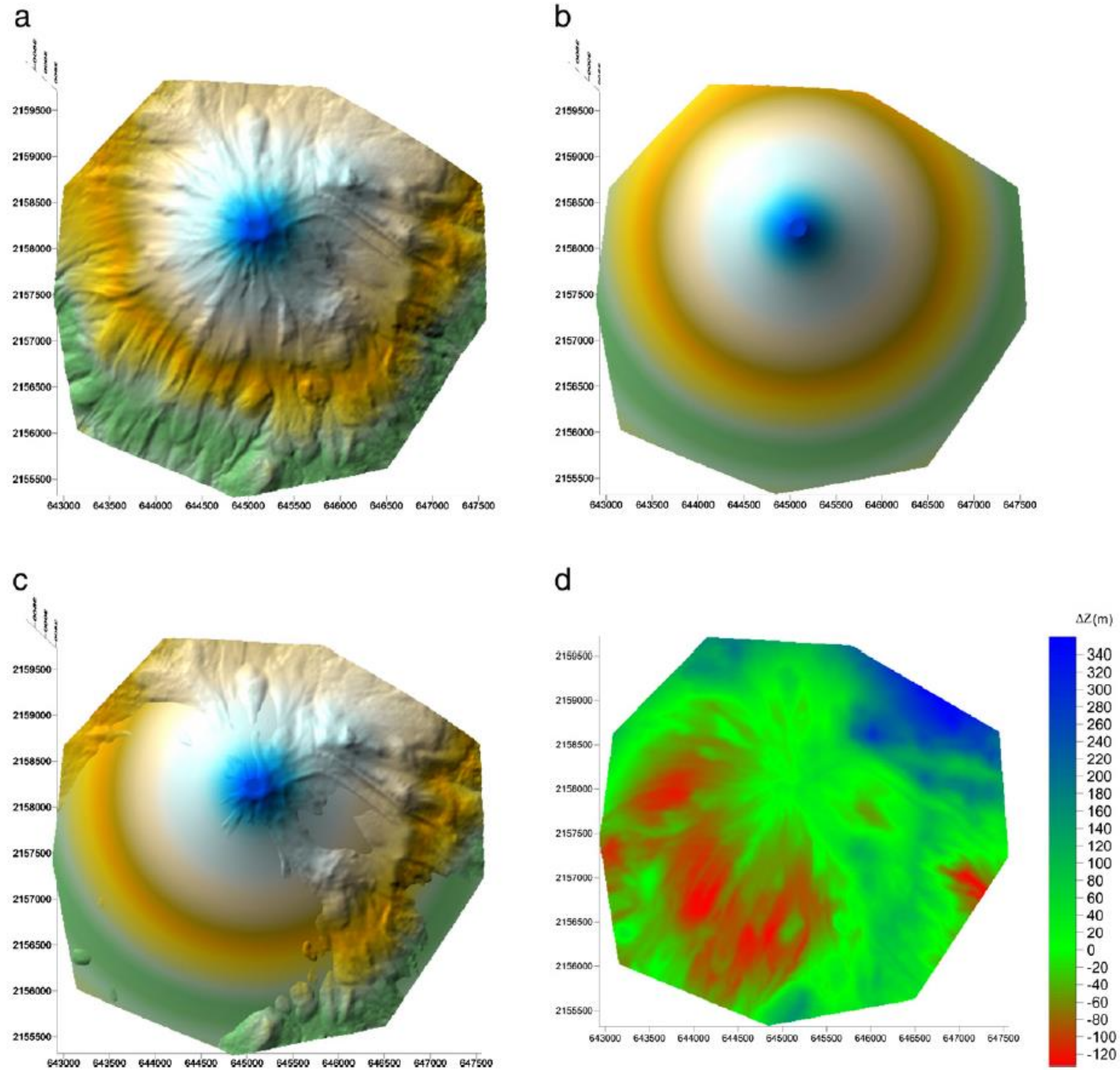
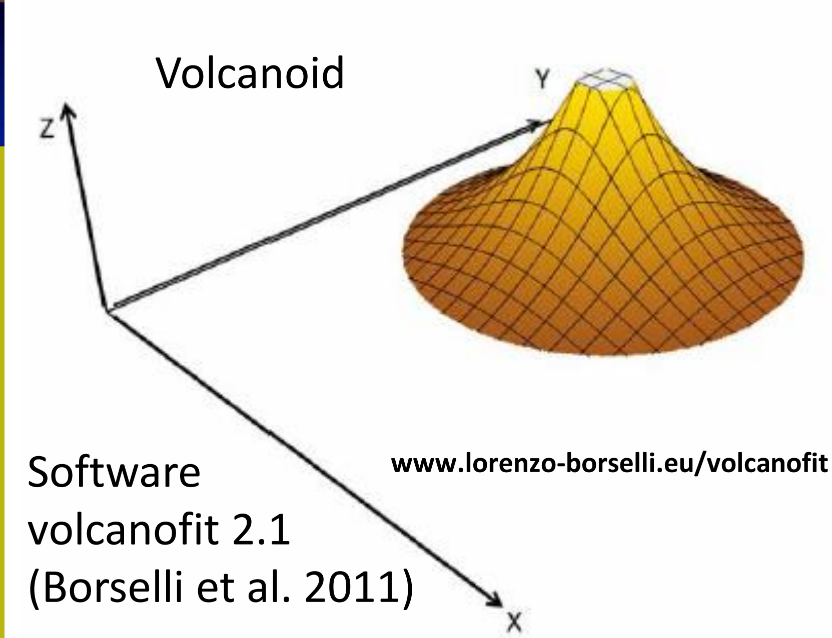
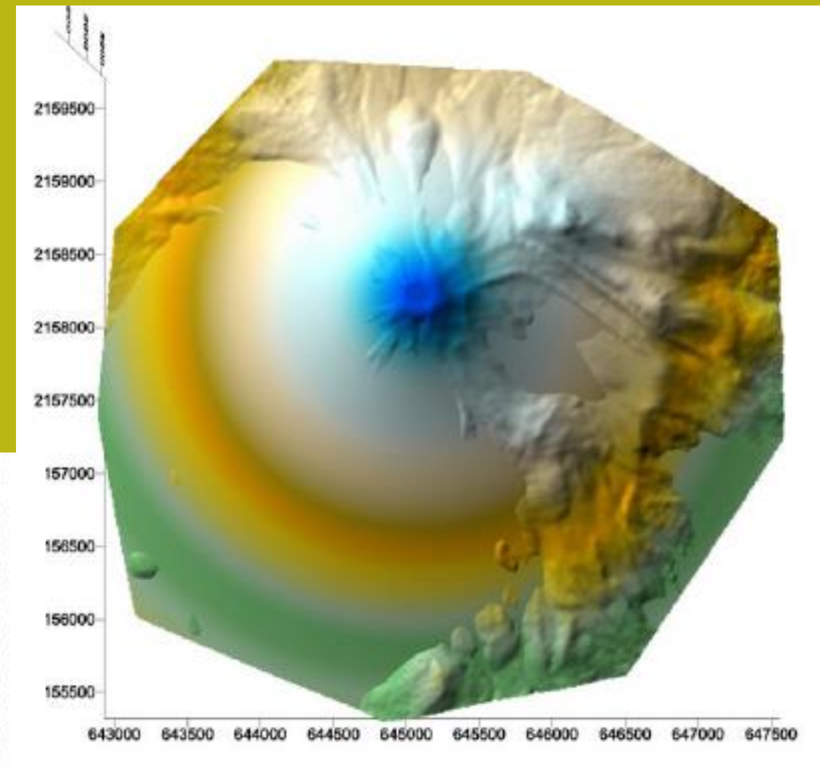
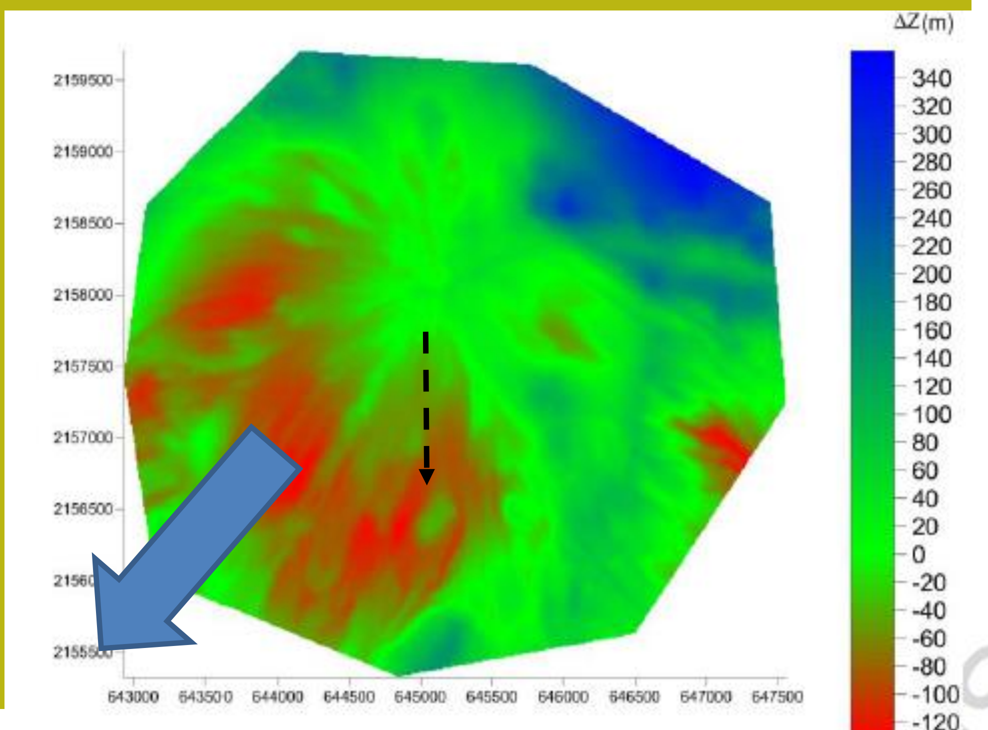


Fig. 7. a) Upper edifice of Colima volcano DEM (2005) b) fitted volcanoid 3D surface Eq. (A.5); c) Upper edifice Colima Volcan de Fuego DEM with overlaid volcanoid Eq. (A.5); d) plot of local deficit (negative values) or surplus (positive values) calculated with Eq. (A.6).

Details overlay DEM and Fitted Volcanoid by volcanofit



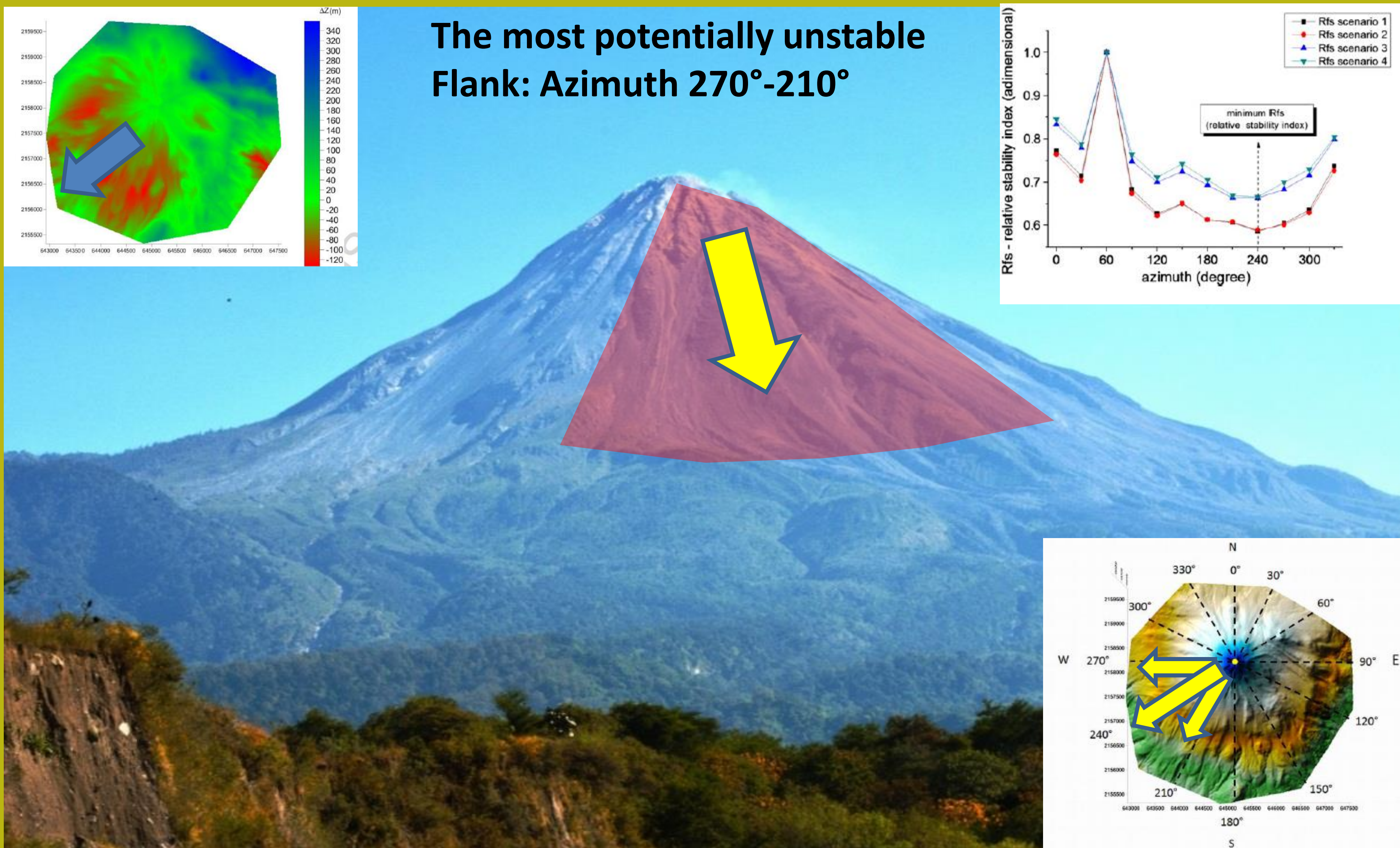


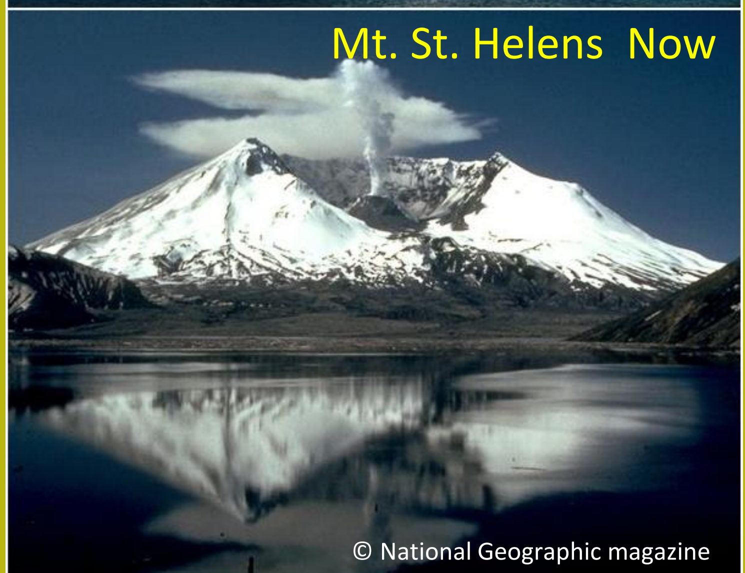


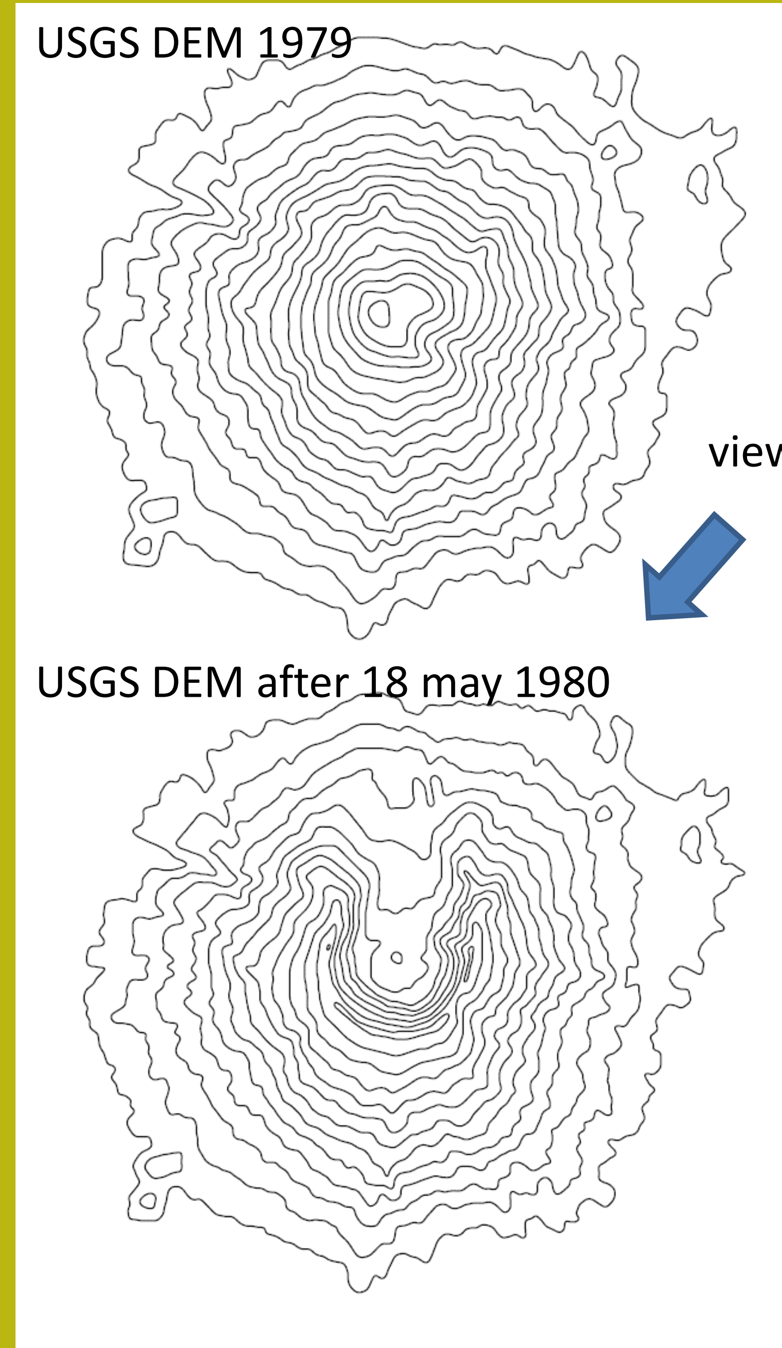
Volume (mass) Deficit
in SW flank

$$\Delta z_{x_i,y_i} = z_{x_i,y_i} - z_{fit\,x_i,y_i}$$

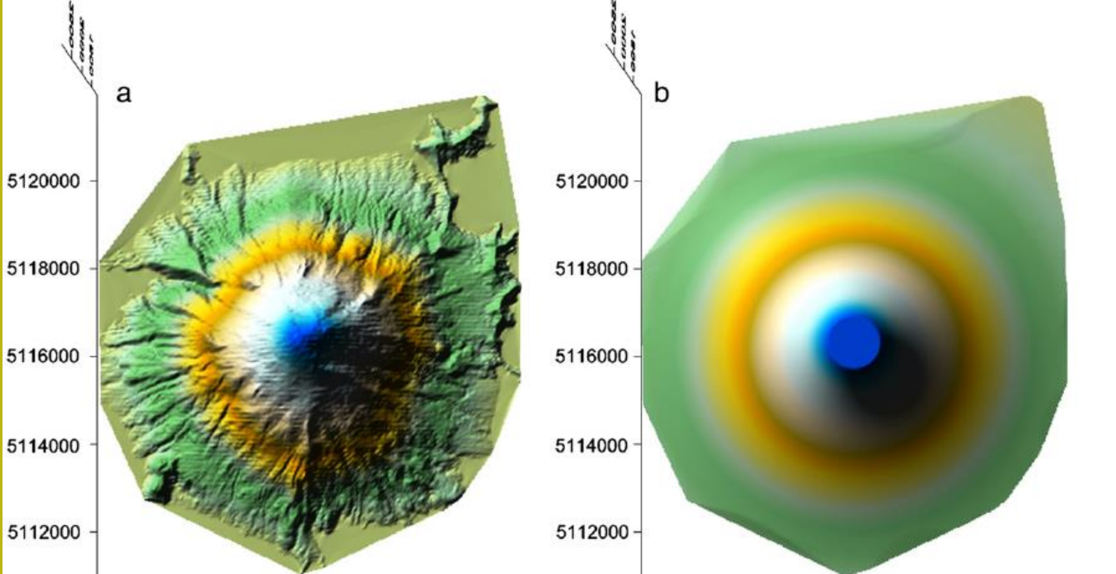
Combined resulys of ALEM (by SSAP 4.0) and VOLCANOFIT2.0







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



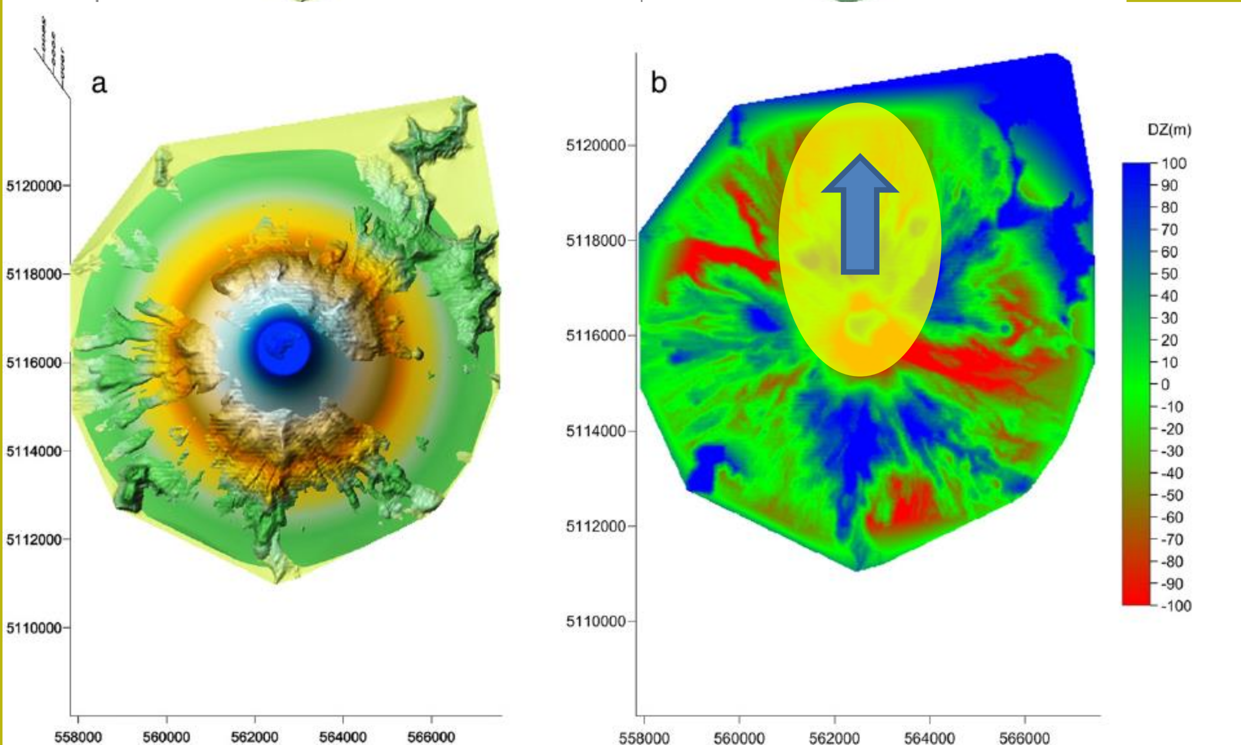
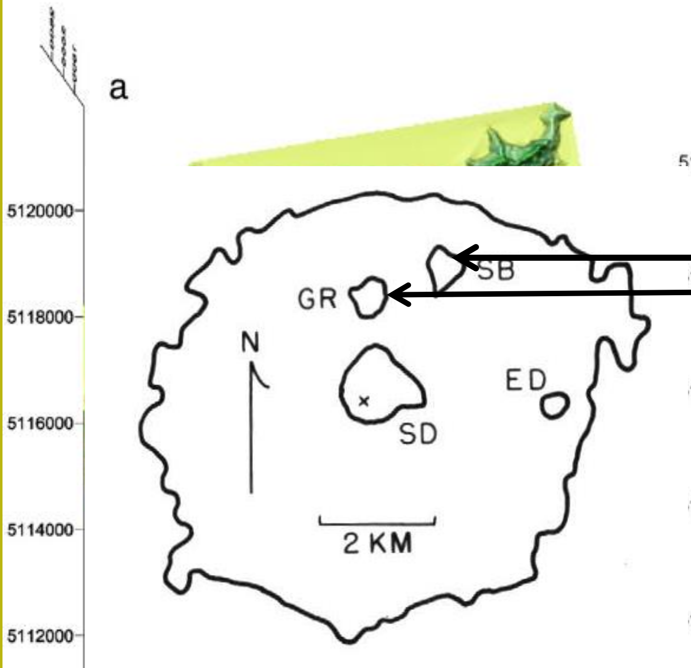


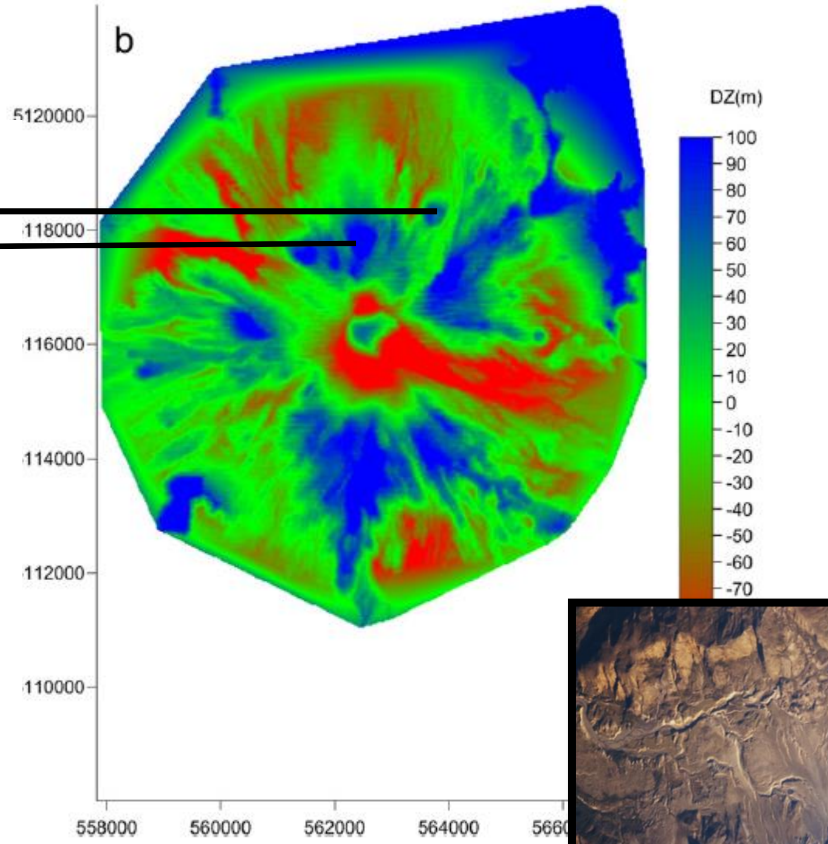
Fig. A.4. a) Pre-eruption 1980 DEM with overlaid volcanoid Eq. (A.5). b) Plot of local deficit (negative values) or surplus (positive values) calculated with Eq. (A.6).

Mt st. helens 1979 DTM
Analysed by **VOLCANOFIT 2.0**
(Borselli et al. 2011)



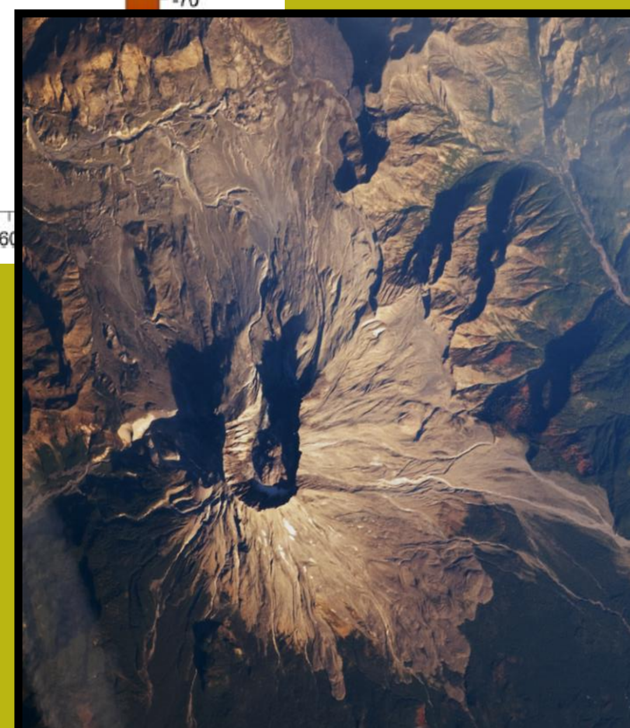
From Hausback and Swanson (1990)

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.*



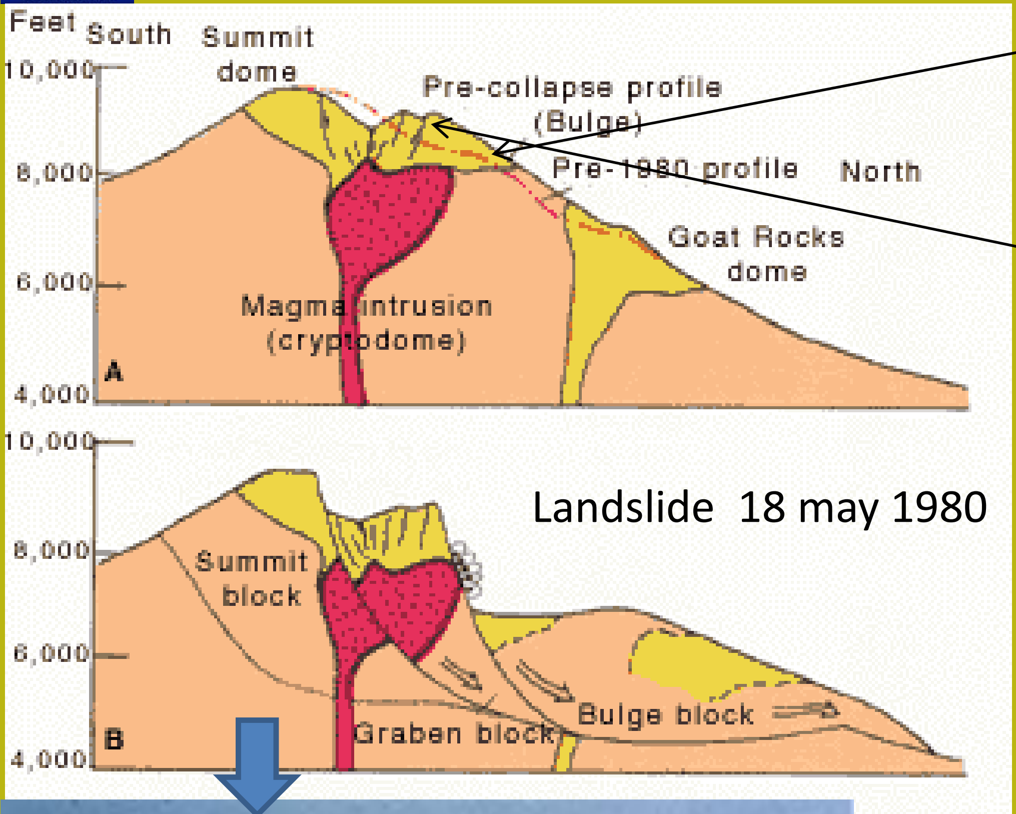
DTM by University of Washington, Earth and Space science, 2010.

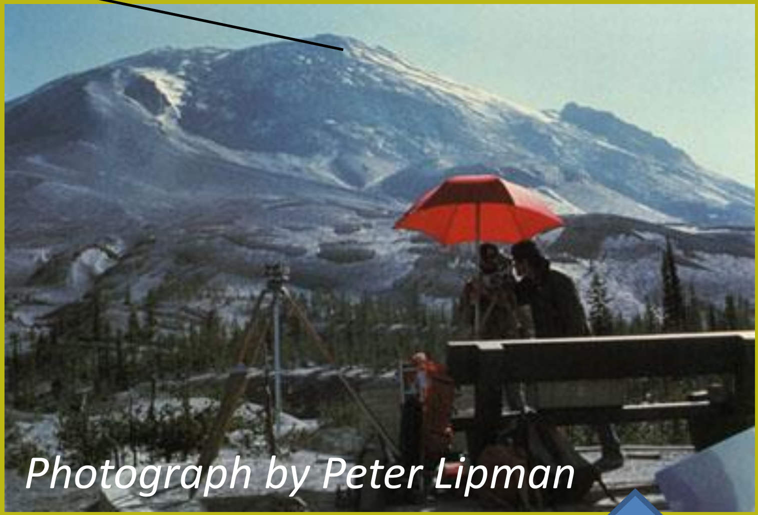
http://rocky.ess.washington.edu/data/raster/thirtymeter/mtsthelens/OldMtStHelens.zip



NASA Earth Observatory Image 2009

By (USGS Professional Paper 1250)





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

http://mountsthelens.com/history-1.html
http://vulcan.wr.usgs.gov/Volcanoes/MSH/Publications/MSHPPF/MSH_past_present_future.html

Volcan de Colima

time of recurence of last 5 debris avalance events (DAE) (Borselli et al. 2011)

Available ages of debris avalanche in the last 10,000 years BP, VEI and calculated intervals between the successive collapses and their corresponding band of uncertainty.

Data source	Event ID Number (–)	VEI* (–)	Te_i Debris avalanche events (DAE) (years BP)	εTe_i Uncertainty on DAE (years)	ΔTe_i Interval from previous DAE (years)	$\varepsilon \Delta Te_i$ Uncertainty on interval from previous DAE (years)
1,2,3	4	5	2580	140	1020	184
2,3	3	5	3600	120	3440	200
2,3	2	6	7040	160	2631	183
2,3	1	5–6	9671	88	3699	149
1,2	0	5–6	13370	120	n.a	n.a
Mean interval of last four DAE (expressed as stochastic number)					ΔTe Mean interval of last four DAE (years)	$\varepsilon \Delta Te$ Standard deviation associated to mean DAE interval (years)
					2698	180

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 standad deviation of +/- 180 years

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

USE of Stochastic arithmetic for Debris avalance 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. (<u>this analysis include all events 2<VEI <6</u>)**

<u>**Instead we usesed a stochastic arithmetic techniques**</u> (***Vignes, 1993; Markov and Alt, 2004***) **adapted to the mean age of DAE and its band of uncertainty**. This technique <u>**accounts for the error propagation and uncertainty**</u> 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.

By Borselli et al. (2011)

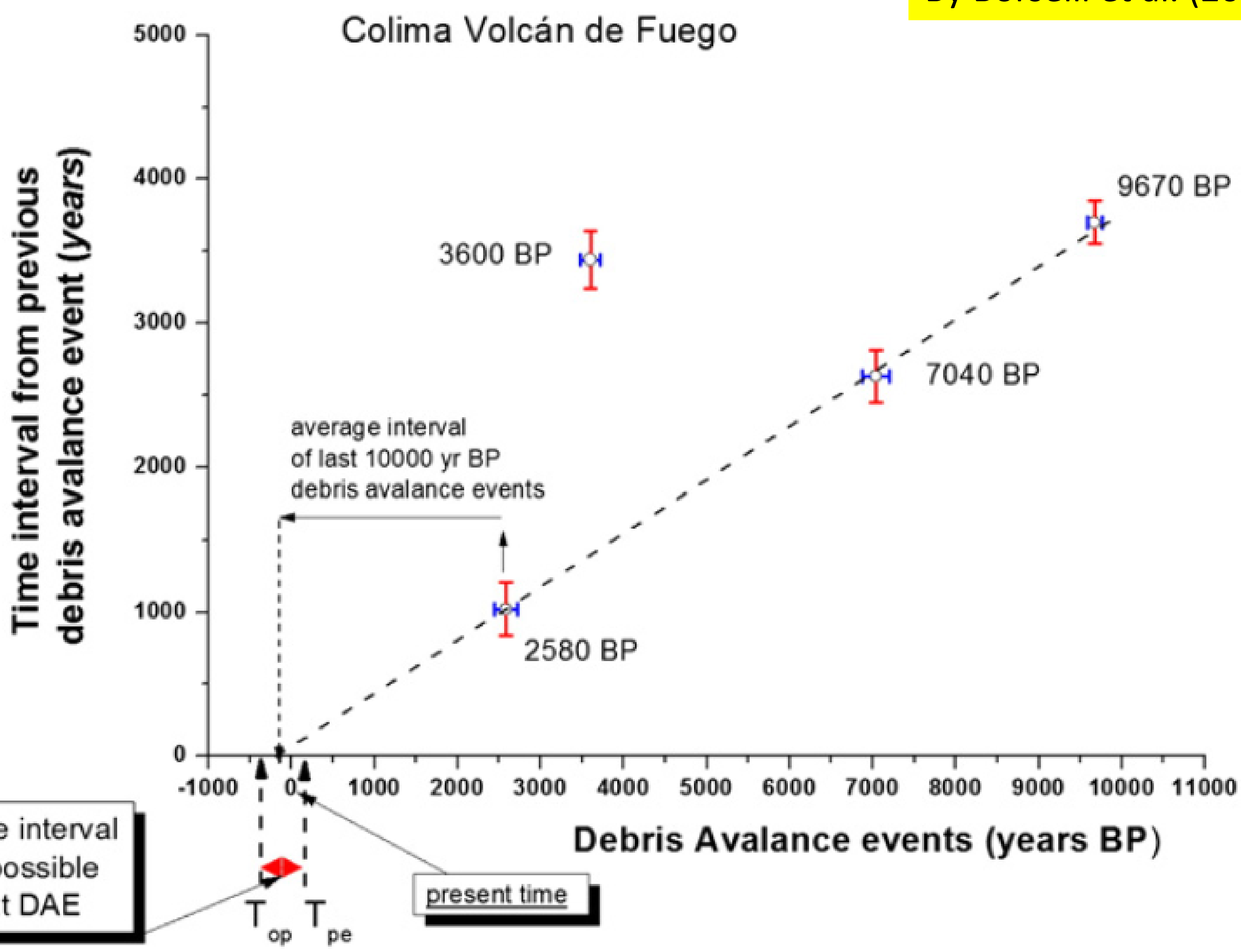
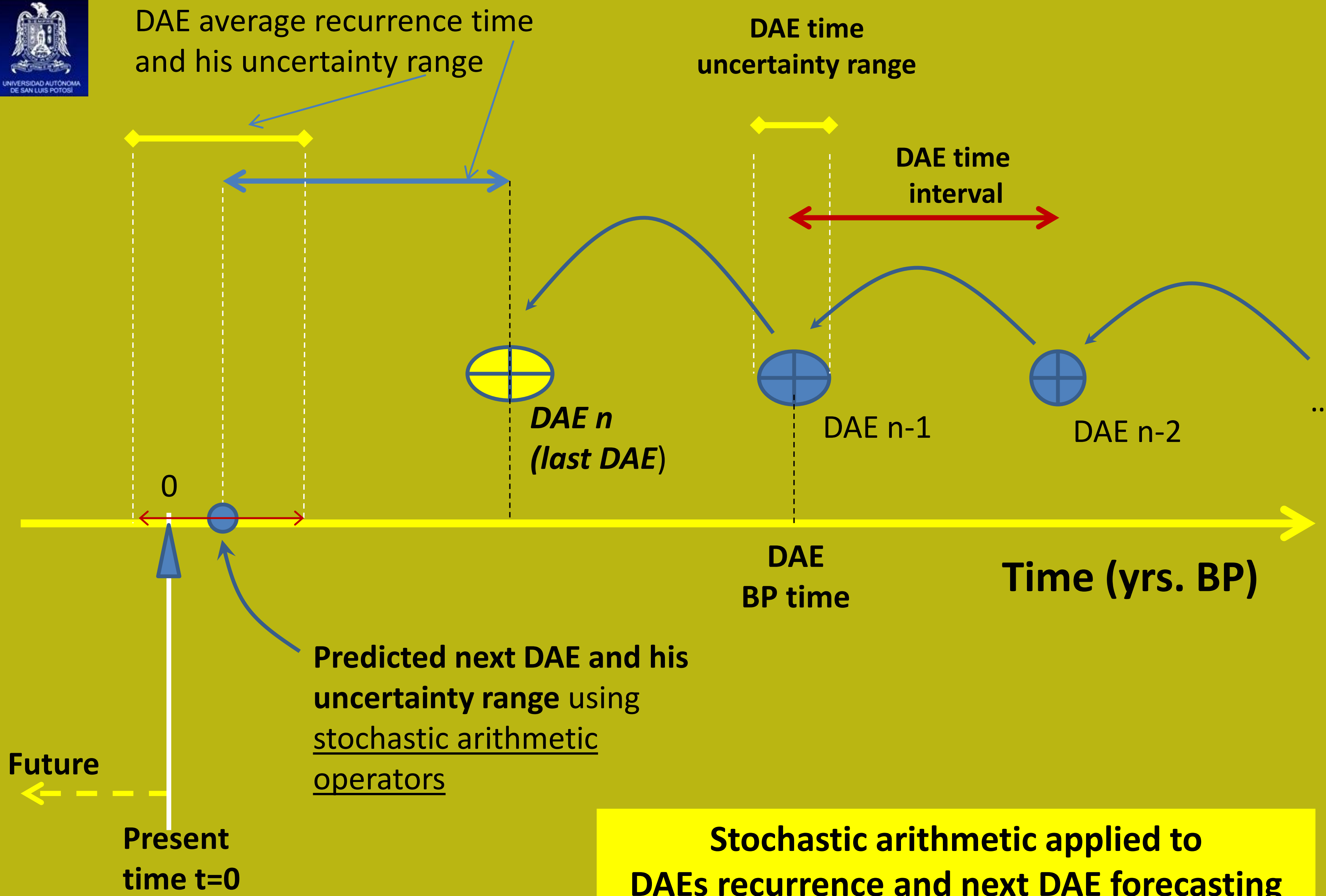


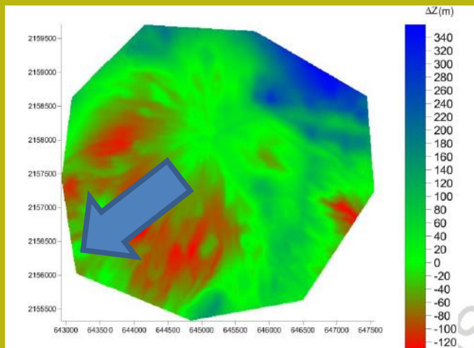
Fig. 6. DAE events vs. time interval from previous debris avalanche event. The projection of a possible scenario for the next DA event is included in the horizontal axis.



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

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

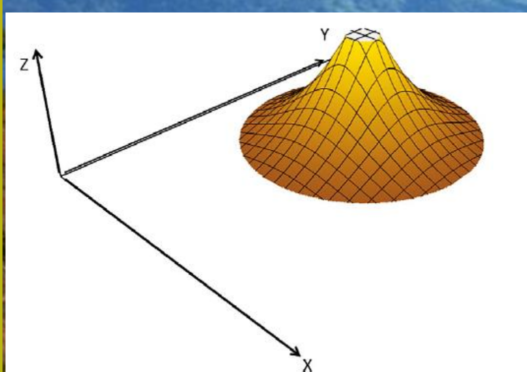
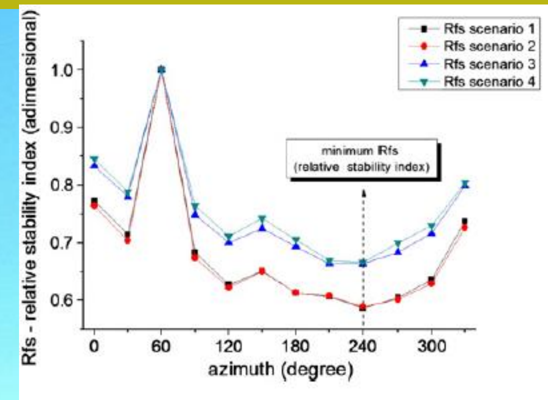
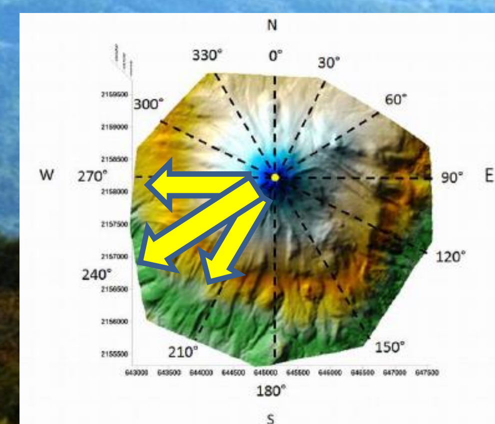


Fig. A.2. Example of volcanoid with constant negative curvature (Eq. (A.5)).



by SSAP2010 (rel. 4.1.3)



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.

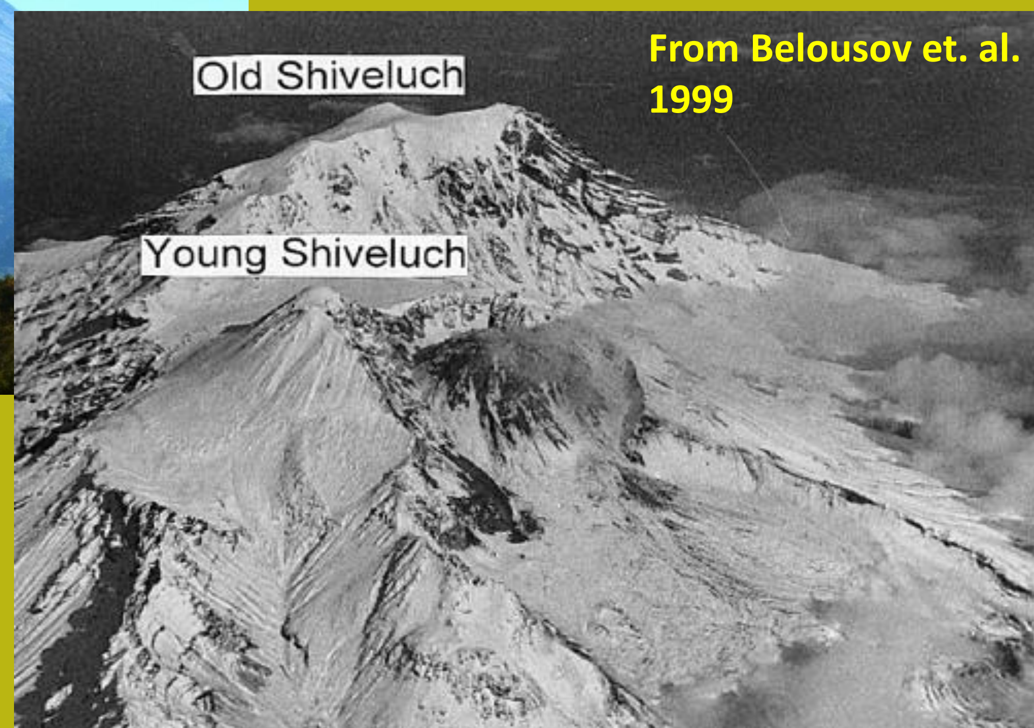
- The VOLCANOFIT application to **Colima shows a n important deficit of volume in the same W-SW quadrant (approx. 0.4 km^3)**.. The **VOLCANOFIT Application to Mt. St. Helens pre-eruption1980** DEM shows the distribution of local mass deficit/surplus association that may be easily correlated with the 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.**

Next forecast of debris avalanche event (DAE) by stochastic arithmetic technique (SAT) : application to Colima and Shiveluch Volcanoes



USE of Stochastic arithmetic technique (SAT) for Debris avalance events (DAE) recurrence time: PROBLEMS !!!

- **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…

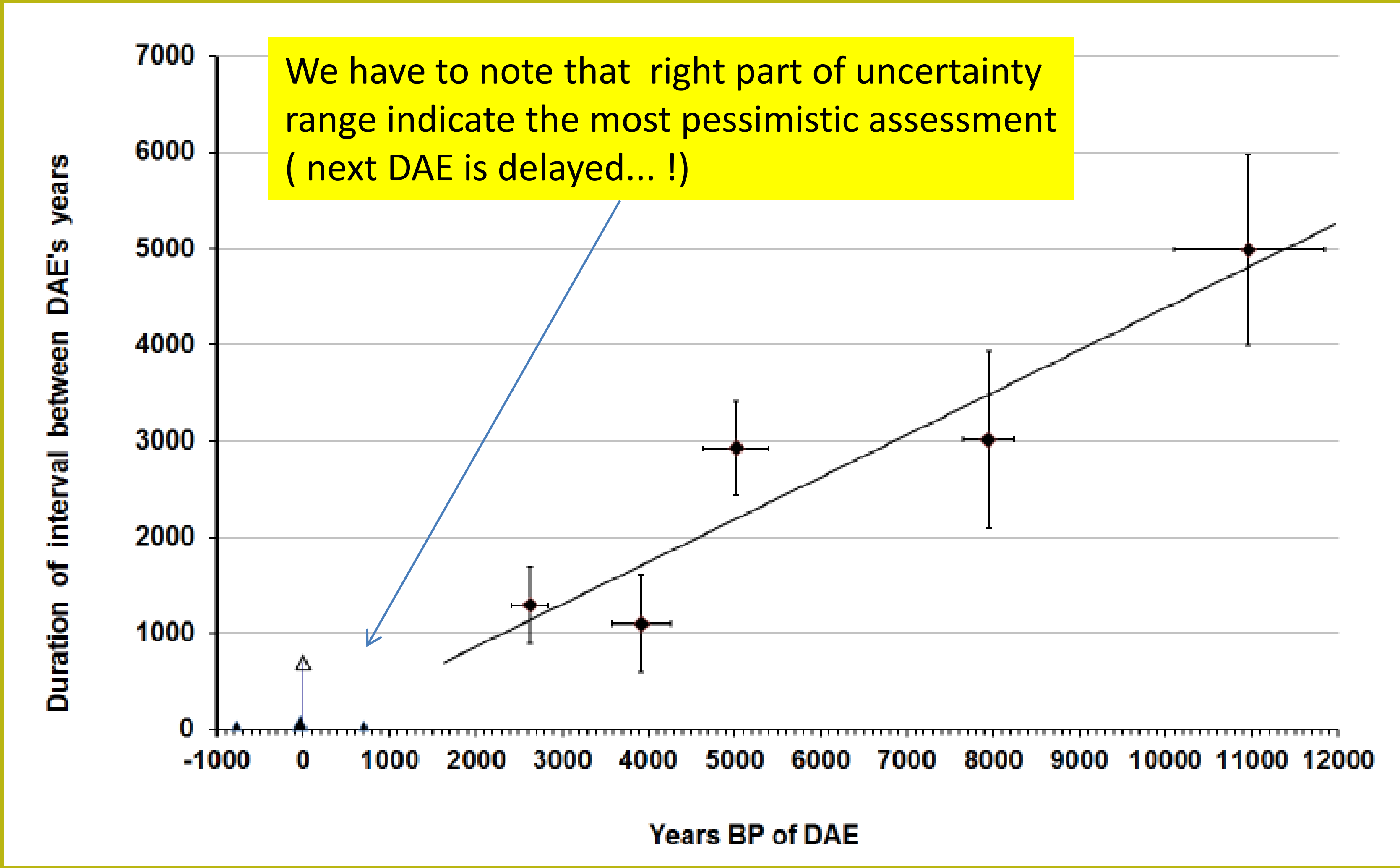
Colima Available data revised

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.

Calibrated age of DAE-generating collapse event (years BP-2012)	Uncertainty in age of DAE (yr)	Time interval between DAE's (yr)	Dating uncertainty of interval from previous DAE (yr)	Reference
2629	214	1293	403	5
3922	341	1102	513	3,4,6,8,9
5024	383	2923	488	5,6,7,8,9
7947	302	3013	924	2,6
10960	873	4988	996	4,6,8 9
15948	479	-	-	1,6,9
				4
		Mean interval and standard deviation between DAE's: 2664 ± 1574 yr	**Uncertainty associated to the mean DAE interval ± 708 yr**	9

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)



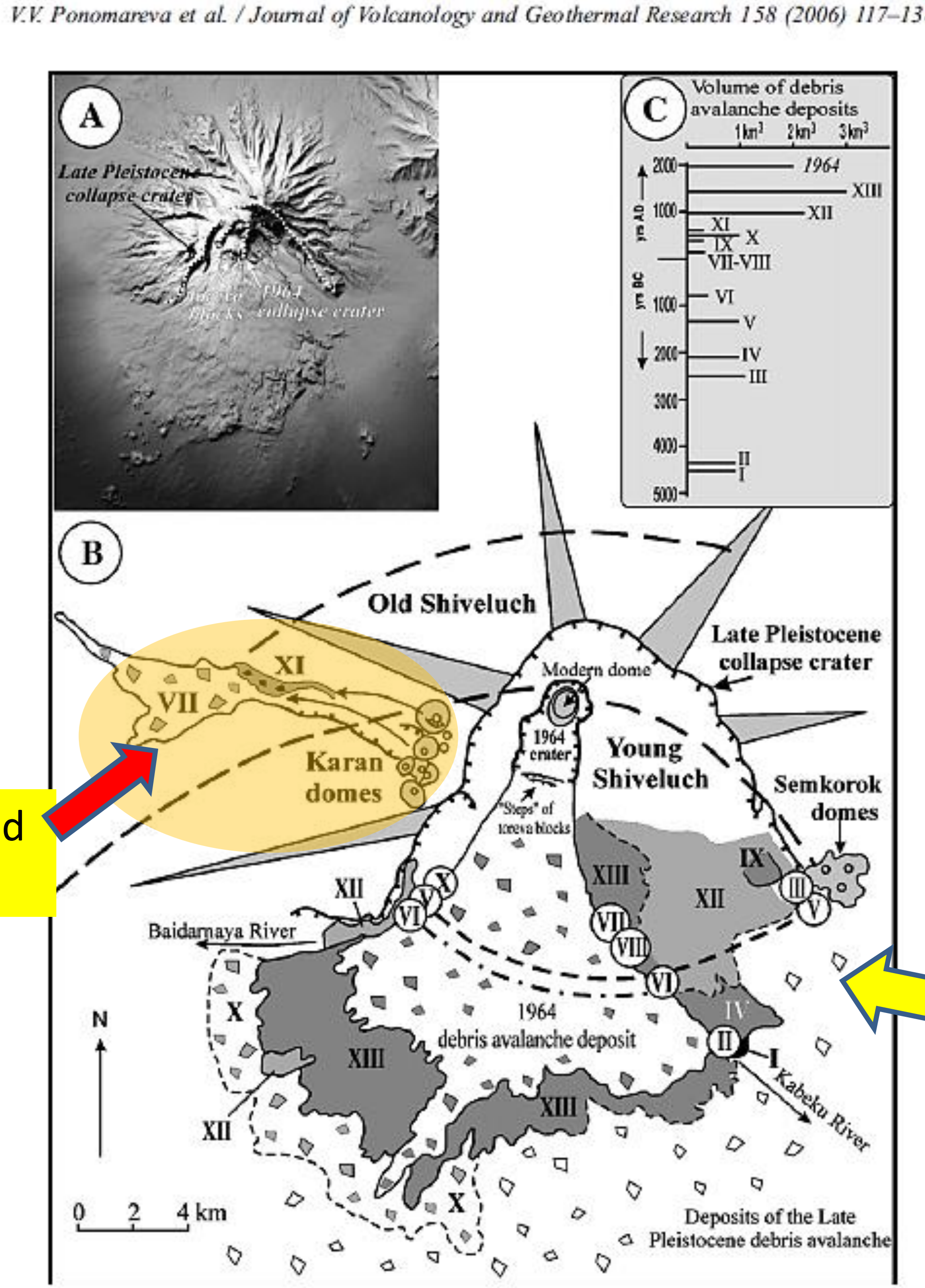
De la Cruz-Reyna S., Mendoza-Rosas A.T, Borselli L. , Sarocchi D. (2012). VOLCANIC HAZARD ESTIMATIONS FOR VOLCÁN DE COLIMA. (in press)

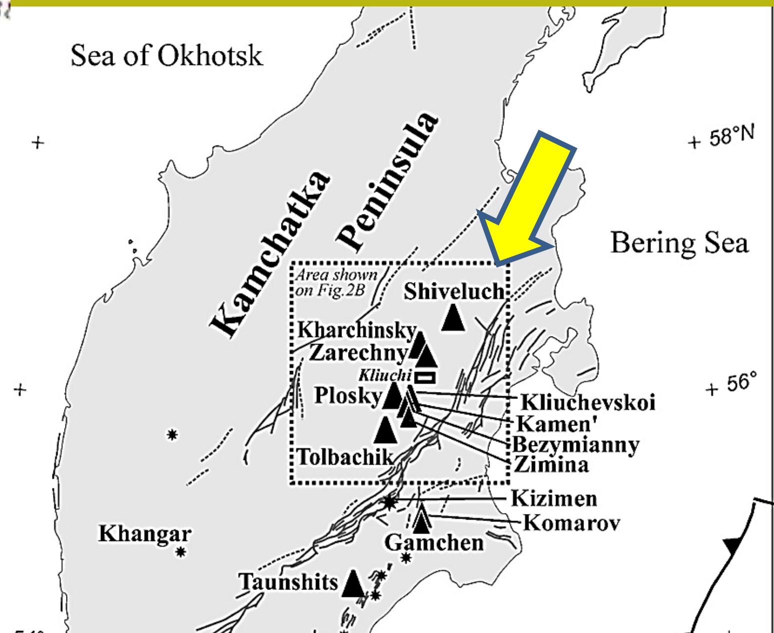
Data revision and re-computations after:
De la Cruz-Reyna S., Mendoza-Rosas A.T, Borselli L. , Sarocchi D. (2012). VOLCANIC HAZARD ESTIMATIONS FOR VOLCÁN DE COLIMA. (in press)*. + one additional DAE* (from Roverato et al. 2011).

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

	Borselli et al. (2011)	Revision De laCruz Reyna et al (in press)	Last Update * (*this presentation*)
Average DAE recurrence time	2698 (yrs)	2664 (yrs)	2649 (yrs)
average standard deviation of DAE intervals	+/- 180 (yrs)	+/- 704 (yrs)	+/- 673 (yrs)
next DAE	2130 AD (+/-180 yr)	2047 AD (+/-704 yr)	1326 AD ← **2032 AD** → 2737 AD

Next DAE centered here





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

Excluded DAEs

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)

Excellent source of informations on Shiveluch DAEs:

PONOMAREVA et al. 1998. Large debris avalanches and associated eruptions in the Holocene eruptive history of Shiveluch volcano, Kamchatka, Russia. Bull. Volcanol. 59 (7), 490–505.

BELOUSOV et al. 1999. Multiple edifice failures, debris avalanches and associated eruptions in the Holocene history of Shiveluch volcano, Kamchatka, Russia. Bull. Volcanol. 61, 324–342.

PONOMAREVA et al. 2006. Sector collapses and large landslides on Late Pleistocene–Holocene volcanoes in Kamchatka, Russia. Journal of Volcanology and Geothermal Research 158:117–138

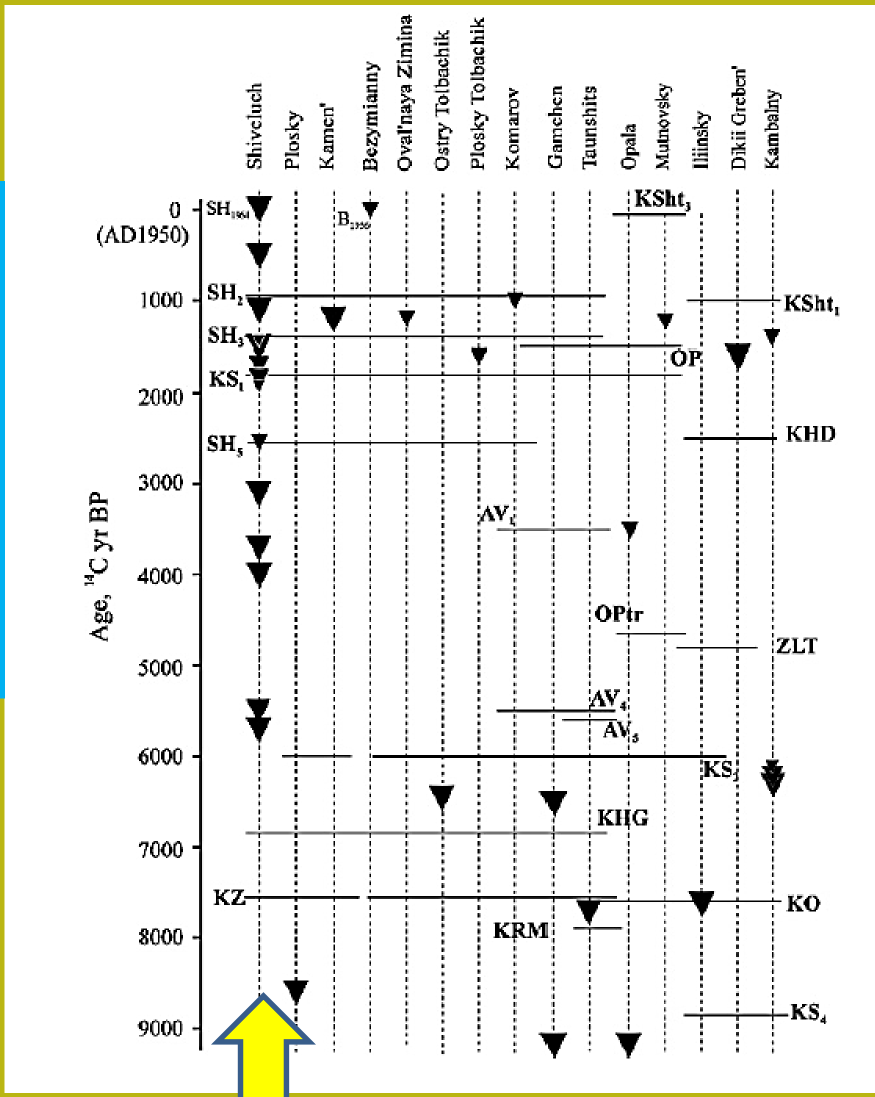
Debris avalanche	Rounded ^{14}C ages (yr BP)	Approximate calendar years
XIV		AD1964
XIII	500	AD1430
XII	1100	AD970
XI	~~1450~~	~~AD630~~
X	1600	AD430
IX	1700	AD380
VIII	1850	AD150–190
VII	~~1900~~	~~AD120~~
VI	2550	BC780
V	3100	BC1330
IV	3700	BC2080
III	4000	BC2490
II	5500	BC4350
I	5700	BC4530
–	Pre-Holocene	–

(from *PONOMAREVA et al. 2006*)

Excluded

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*)

Survival analyis Technique (SAT) applied to young SHIVELUCH

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

VIRTUAL ... PREDICTION OF A VOLCANOLOGIST IN THE 1964 AD !!

	At present time (2012 AD) Using 12 DAEs (last DAE 1964 AD +/- 0 YRS)	At 1964 AD Using 11 DAEs (last DAE 1430 AD +/- 57 yRS)
Average DAE recurrence time	590 (yrs)	596 (yrs)
average standard deviation of DAE's intervals	+/- 98 (yrs)	+/- 101 (yrs)
next DAE FORECAST (by SAT)	2457AD ← **2554 AD** → 2652 AD	1910 AD ← **2026 AD** → 2142 AD

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) iI the next 1,10,20,50,100,200 , years .

*** Speculation !!**

Some basic equations we used

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

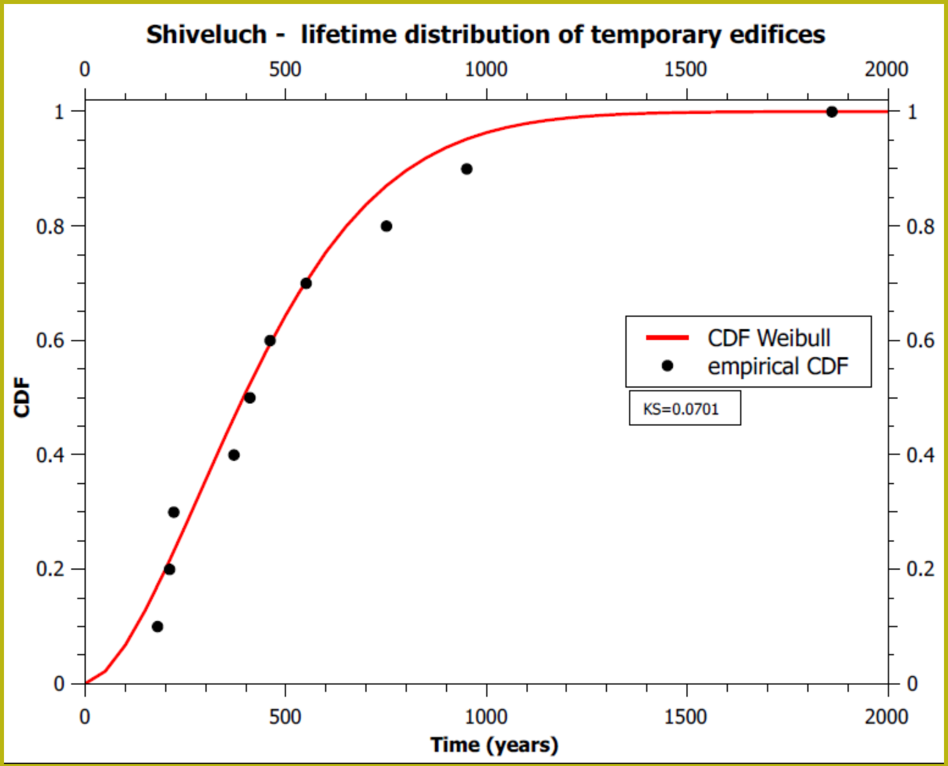
Weibull lifetime CDF

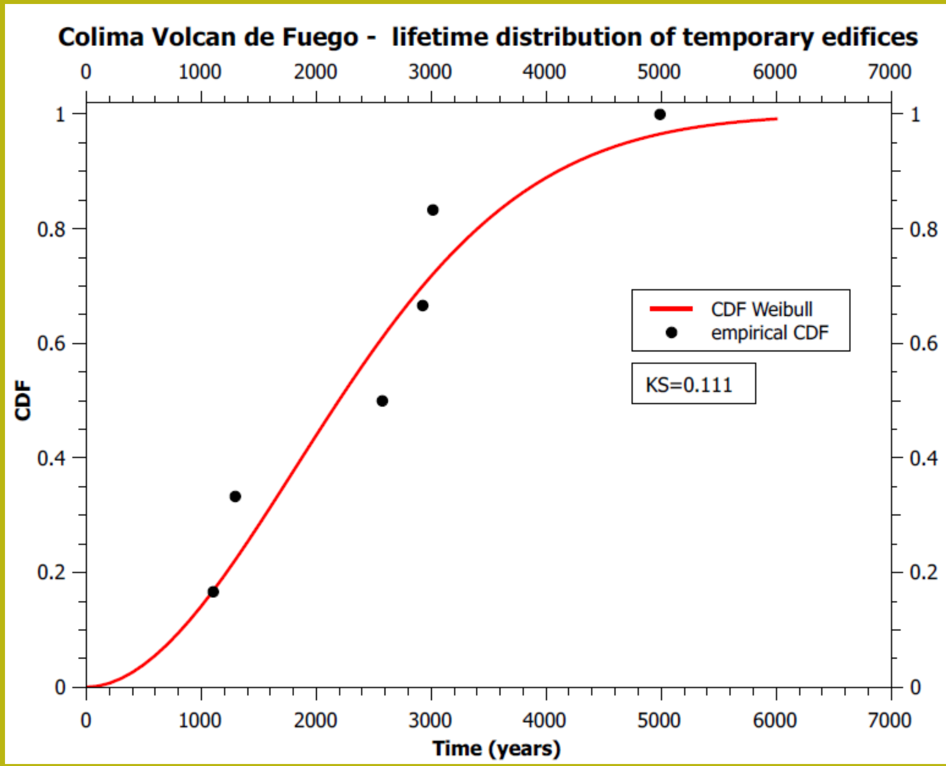
$$S(t \mid \alpha, \beta) = 1 - F(t \mid \alpha, \beta)$$

Survival function CCDF

$$t_{mr} = \frac{1}{S(t_0)} \int_{t_0}^{\infty} S(t)\,dt$$

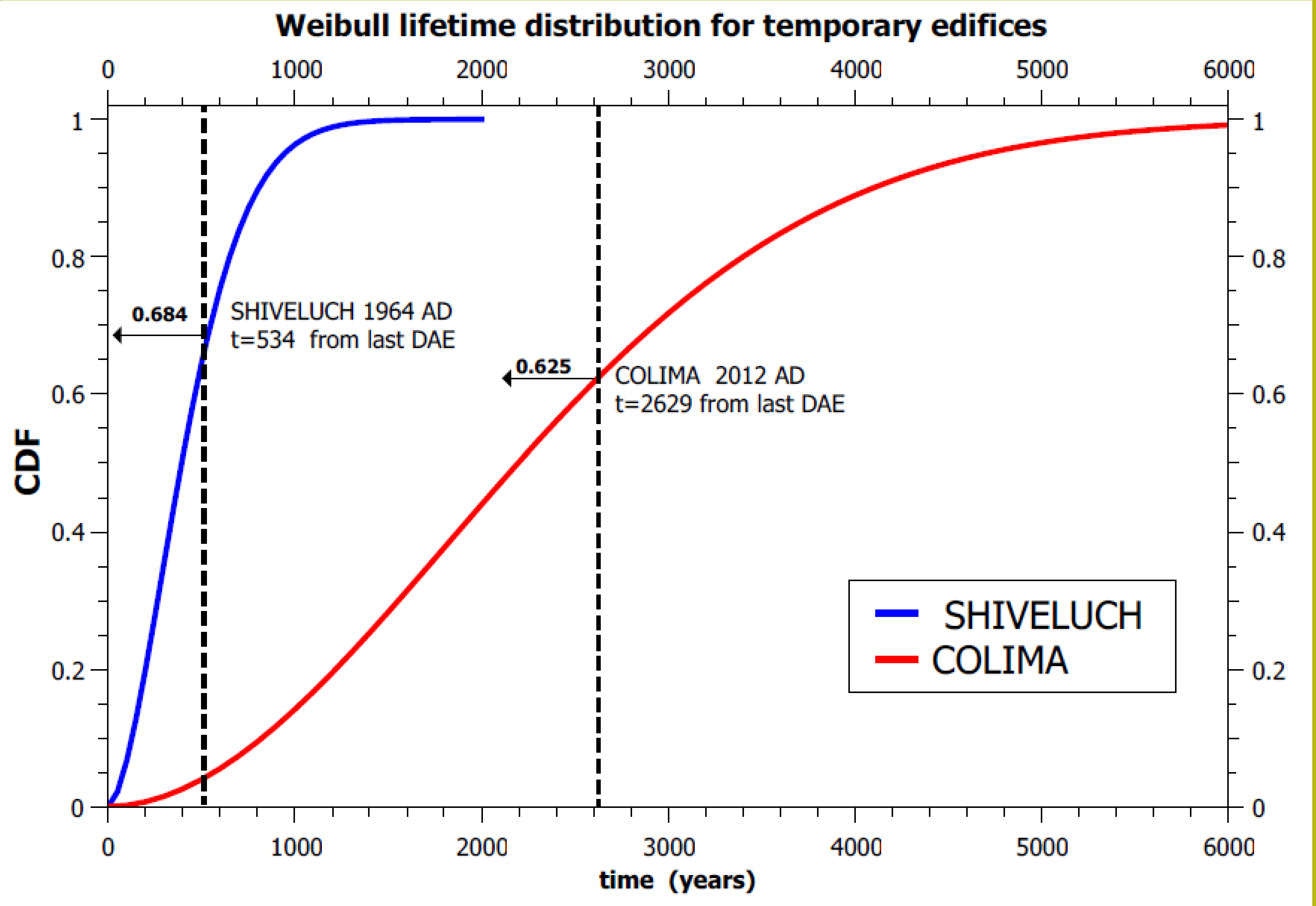
expected future lifetime.
In reliability problems the expected future lifetime is called the mean residual lifetime after given time t_0.



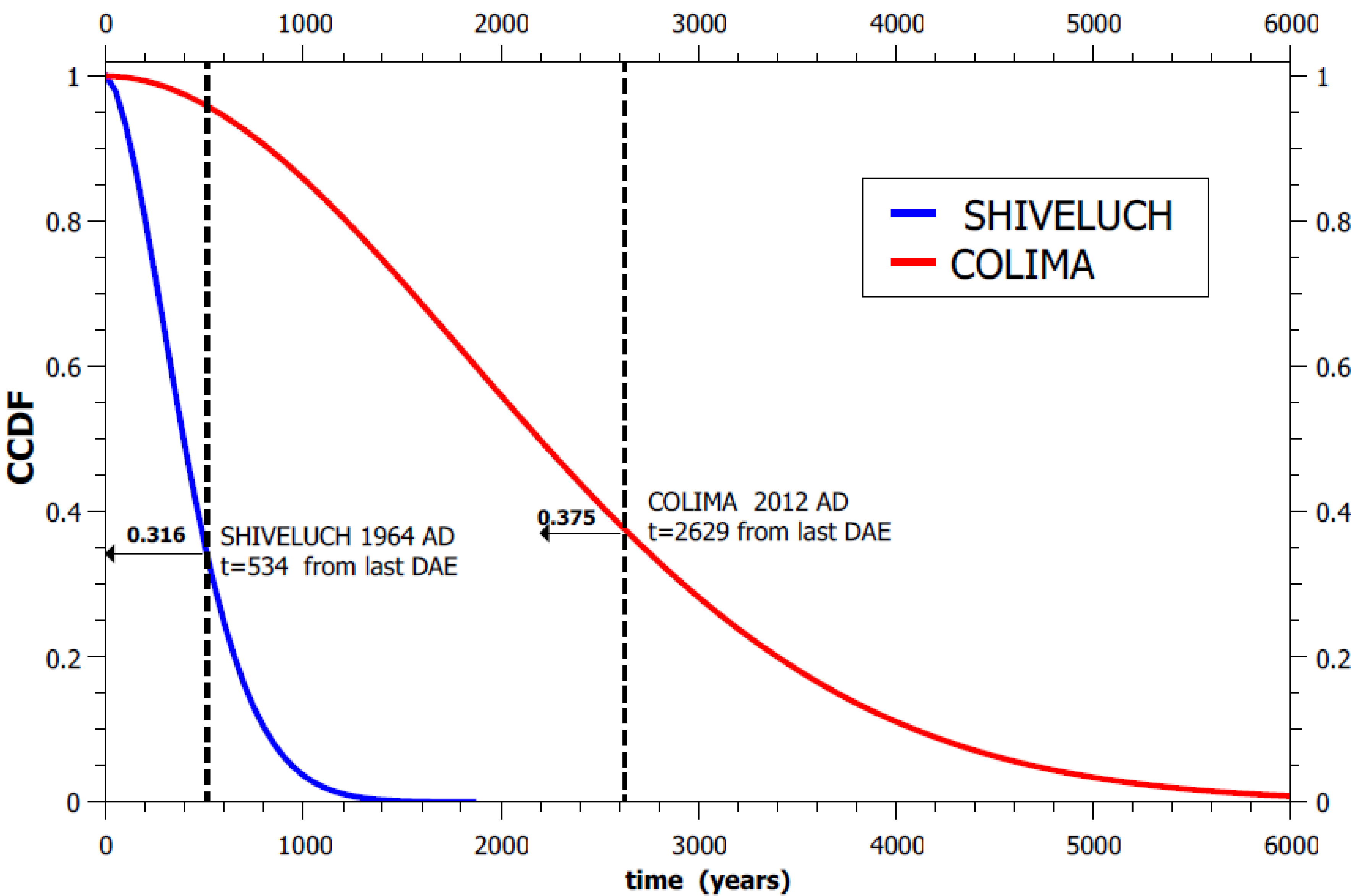


Non linear fitting of empirical CDF (lifetime distribution) of Shiveluch and Colima temporary edifices <u>after they start to regrow after a DAE.</u>

Weibull CDF fitting of life time distribution of edifices


Weibull lifetime distribution for temporary edifices
CDF
time (years)
0.684
SHIVELUCH 1964 AD
t=534 from last DAE
0.625
COLIMA 2012 AD
t=2629 from last DAE
SHIVELUCH
COLIMA
0
1000
2000
3000
4000
5000
6000
0
0.2
0.4
0.6
0.8
1

Weibull survival distribution S(t) for temporary edifices



Survival analysis indicates that **SHIVELUCH (in 1964 AD)** and **COLIMA (in 2012 AD)** **Was / Are** in a **similar situation in term of survival probability after last recognized DAE.**

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

	Mean residual lifetime t_{mr} (yrs)	Mean expected life at born t_{mr} for $t_0=0$ (yrs)
SHIVELUCH **(1964 AD)**	**261** **(t_0=534)**	**437**
COLIMA **(2012 AD)**	**1195** **(t_0=2629)**	**2350**

But…

The **calculated probabilities of next DAE** using **$S(t_0)$ – $S(t_0+t_N)$ are:**

SHIVELUCH 1964 AD

shiveluch(1964): probability of failure in the following N years

N Years	1	10	20	50	100	200	500
prob(%)	0.114112	1.128967	2.230857	5.373499	10.07123	17.5444	28.48088

COLIMA 2012 AD

colima(2012): probability of failure in the following N years

N Years	1	10	20	50	100	200	500
prob(%)	0.026995	0.269506	0.538014	1.337485	2.649382	5.193554	12.15161

4.25
0.114662

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

10-11 july 2015 eruption

Journal of Volcanology and Geothermal Research 310 (2016) 39–49

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Short communication

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

CrossMark

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]

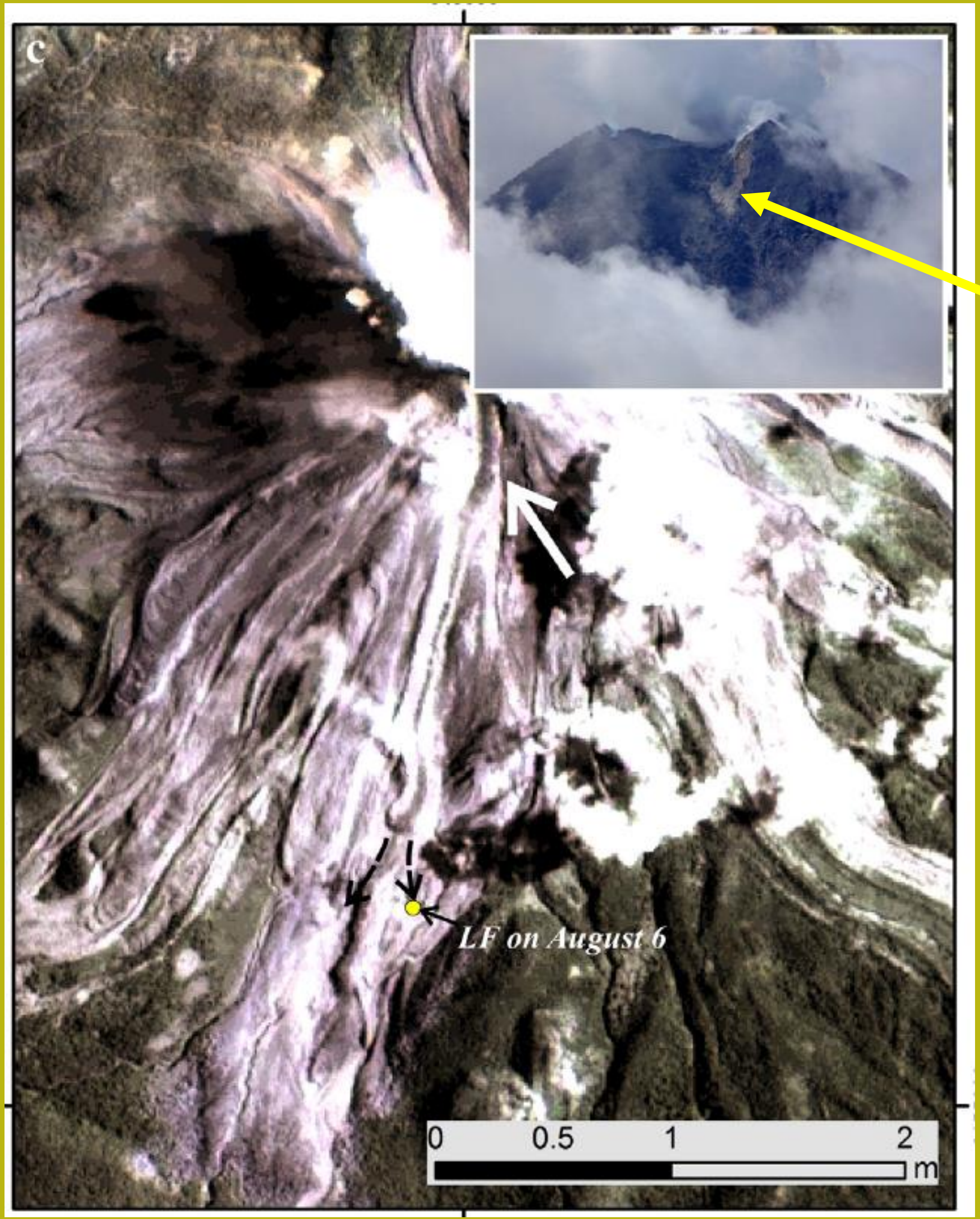


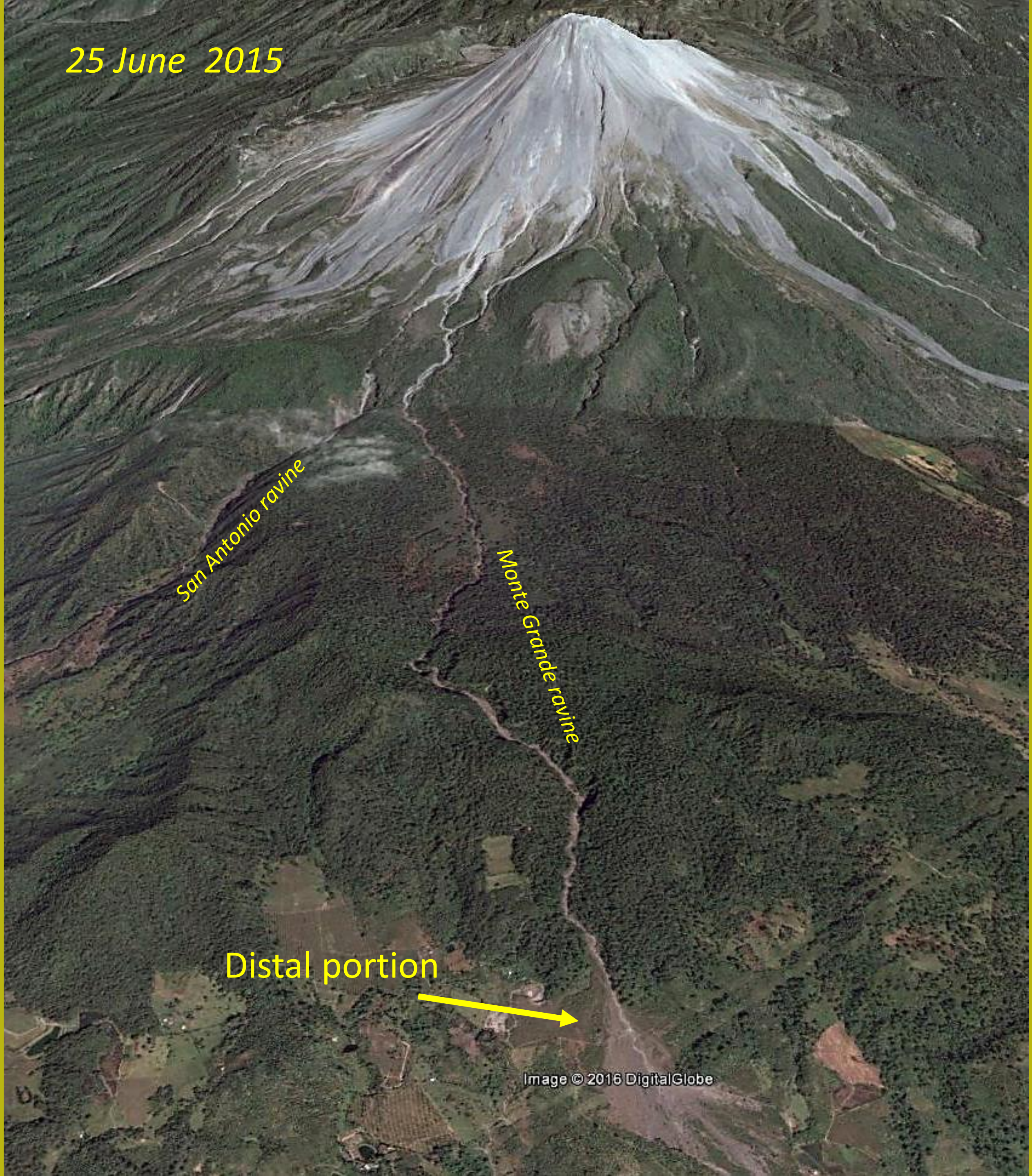
Image of July 2015
By Capra L.
of upper portion of
collapsed edifice of
Colima Volcano

(by capra et al. 2016)

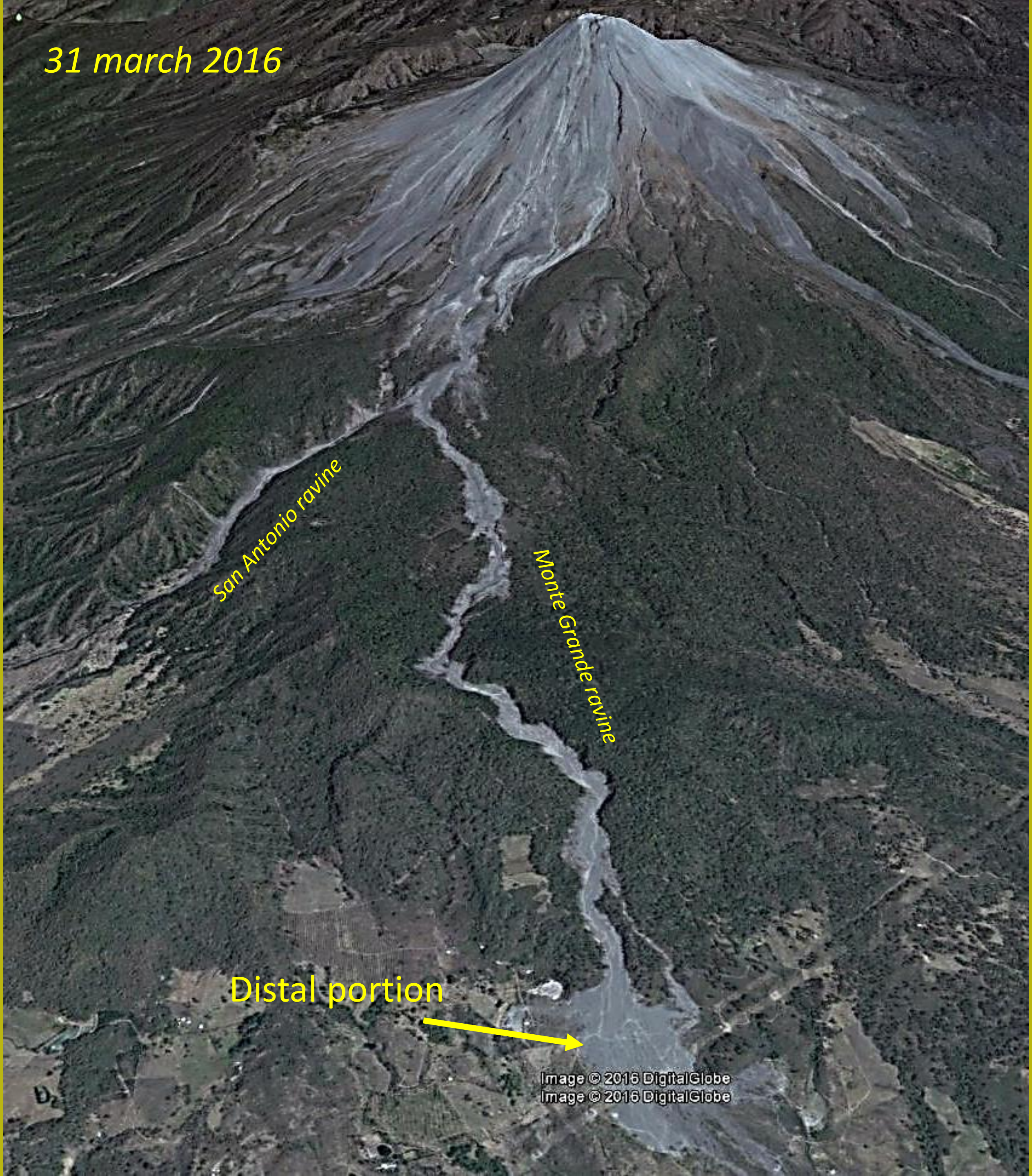
Colima volcán de Fuego upper edifice

Dome and side cráter partial collapse 10 july 2015, 10 km large runout and piroclastic flow, as block and ash flow SW wiew (images by Google Earth)

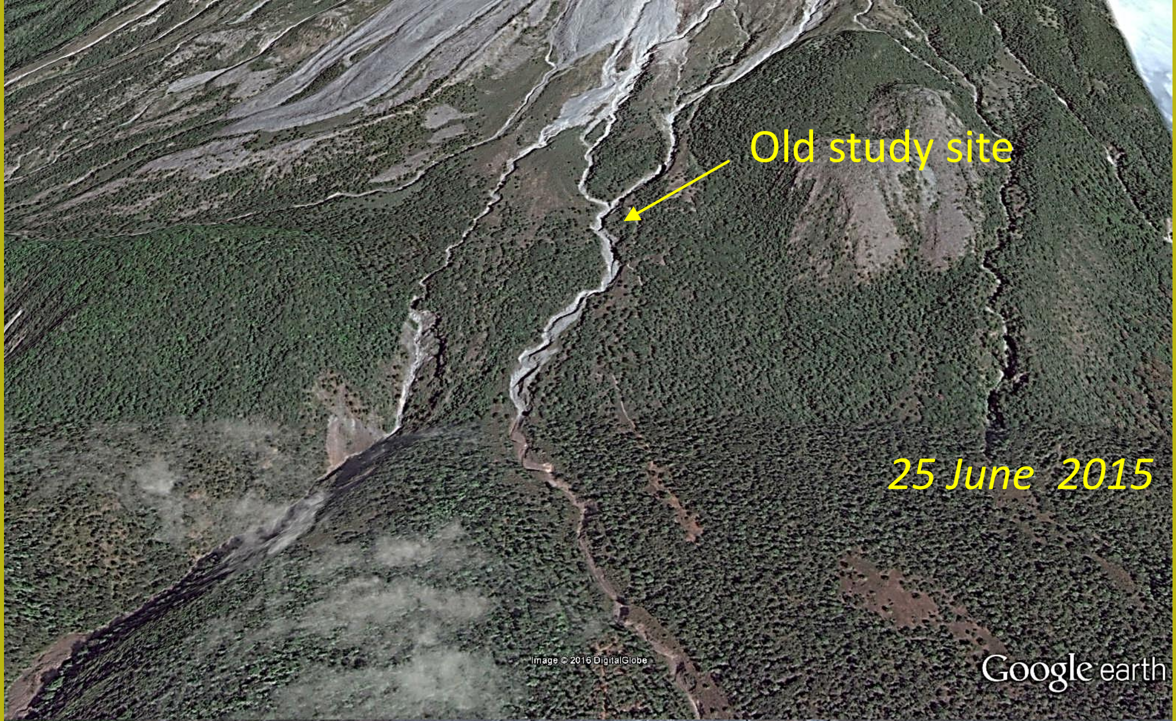
Colima volcán de Fuego Full SW wiew (images by Google Earth)

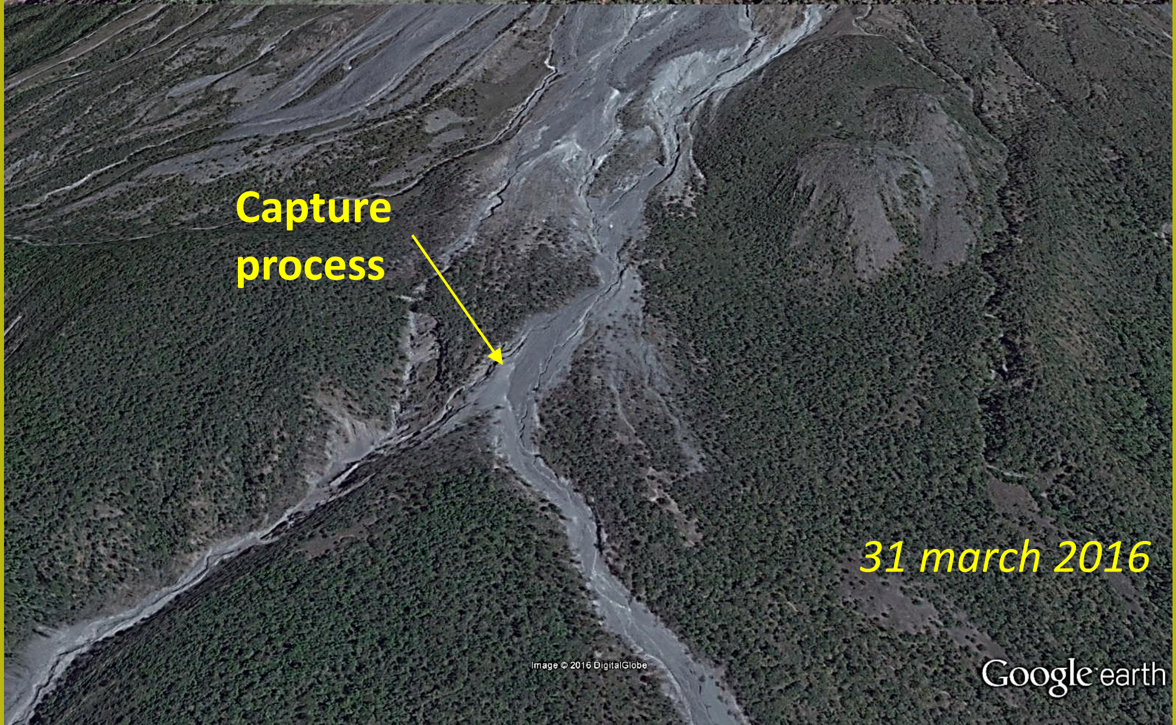


Colima volcán de Fuego Full SW wiew (images by Google Earth)



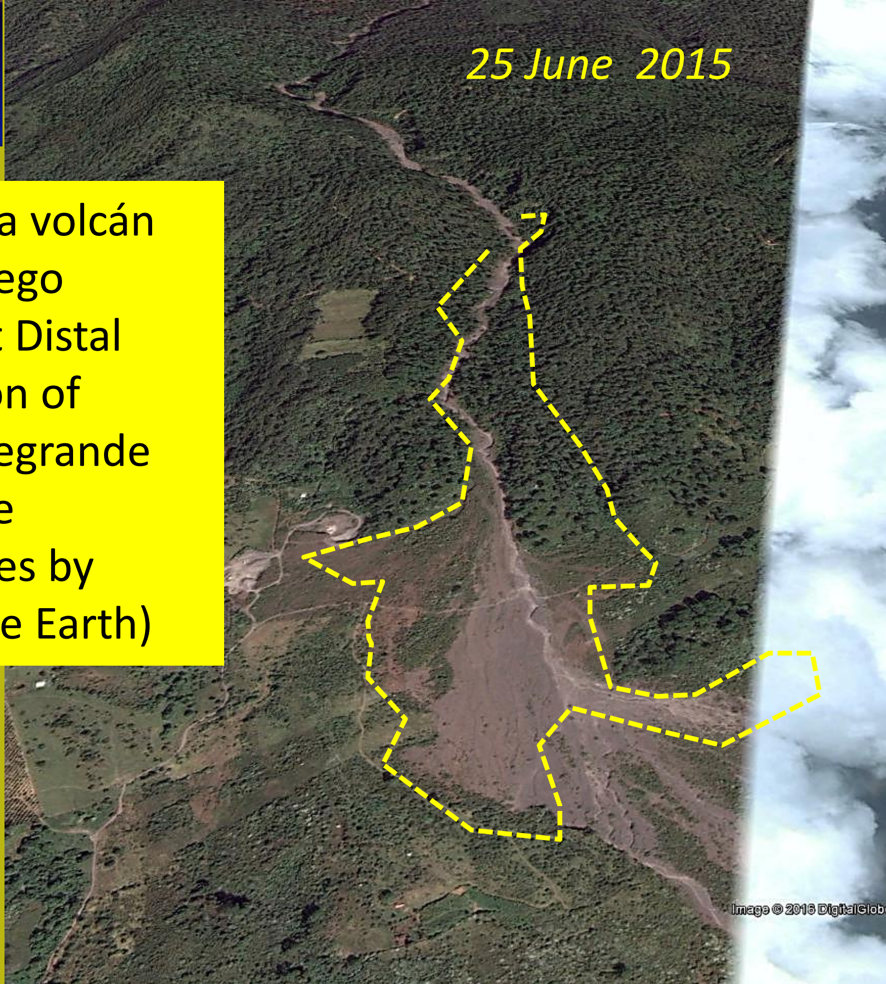
Colima volcán de Fuego Median portion Montegrande And san Antonio Ravine (images by Google Earth)

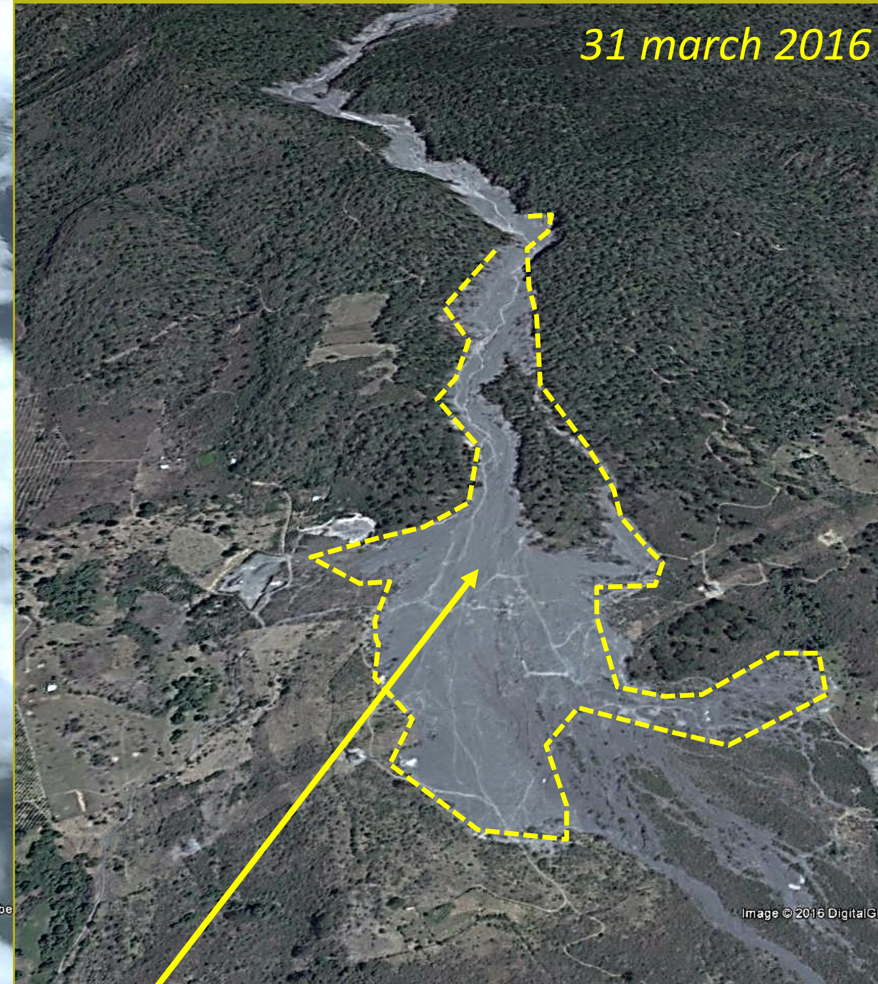




UNIVERSIDAD AUTÓNOMA DE SAN LUIS POTOSÍ

Colima volcán de Fuego Fan at Distal portion of Montegrande Ravine (images by Google Earth)

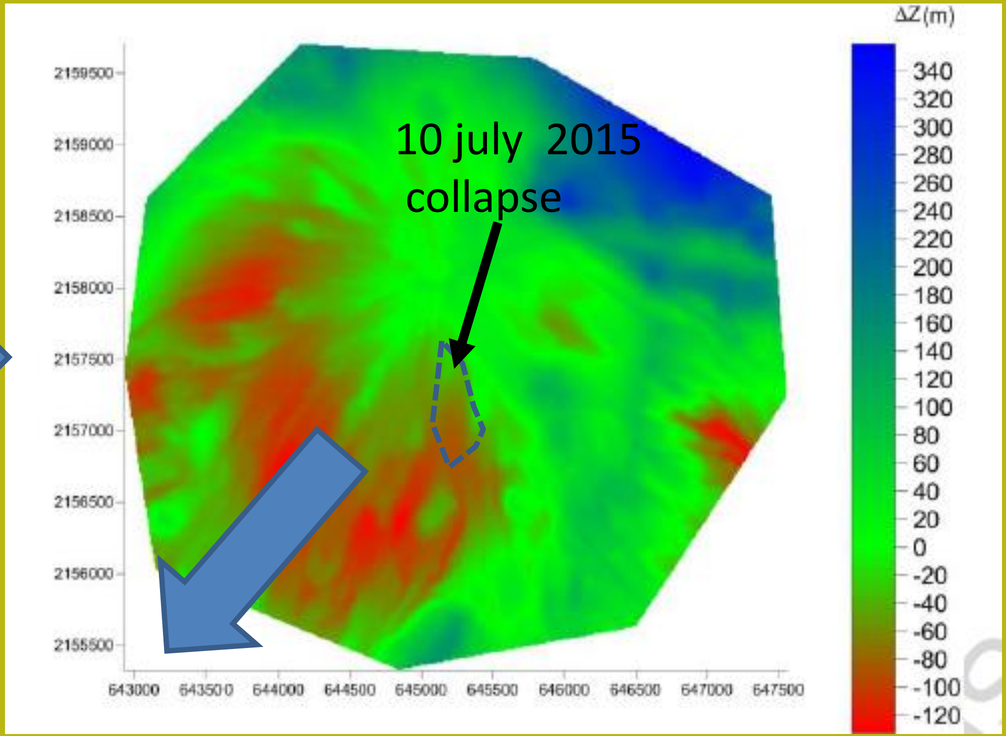


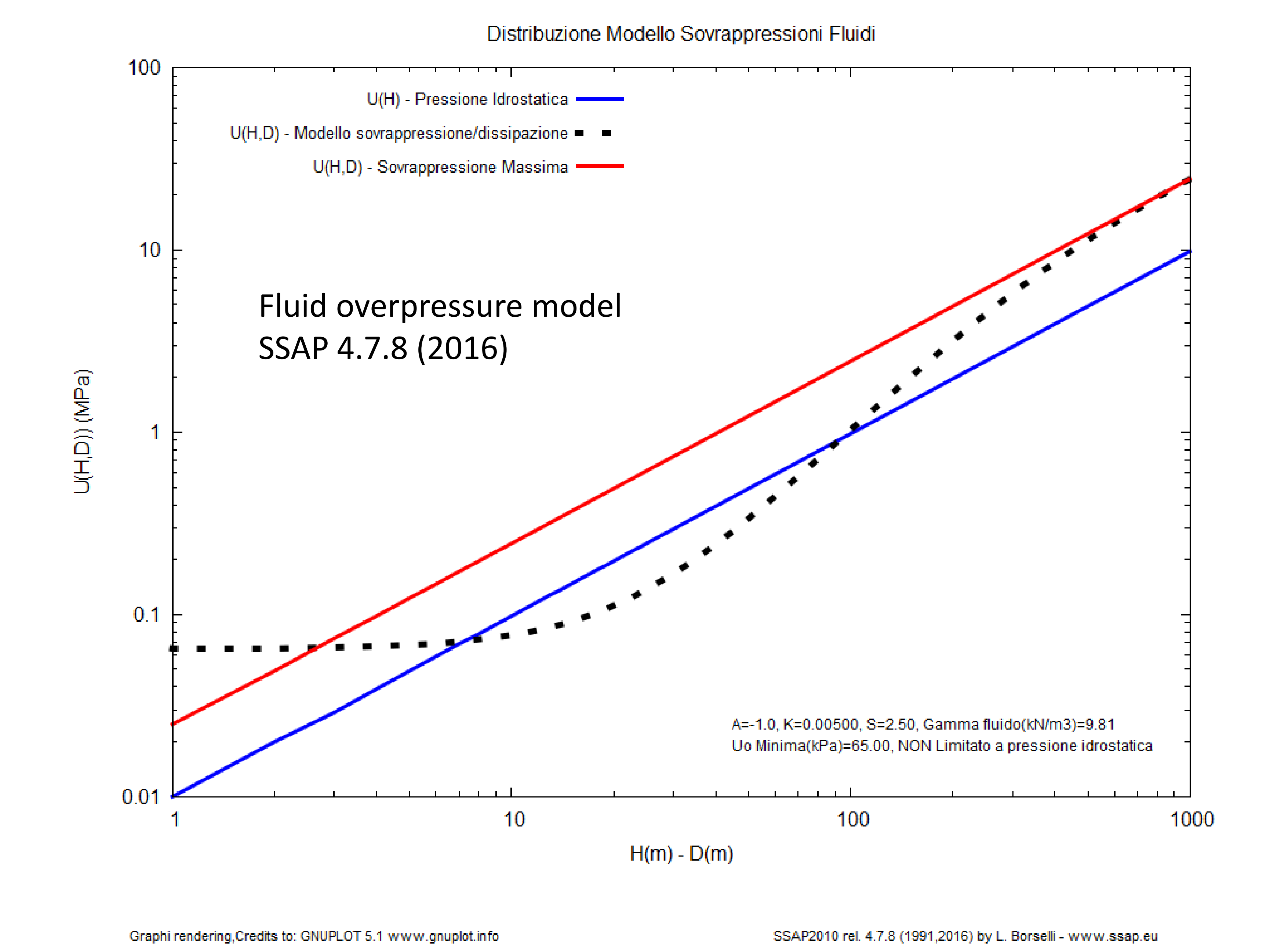


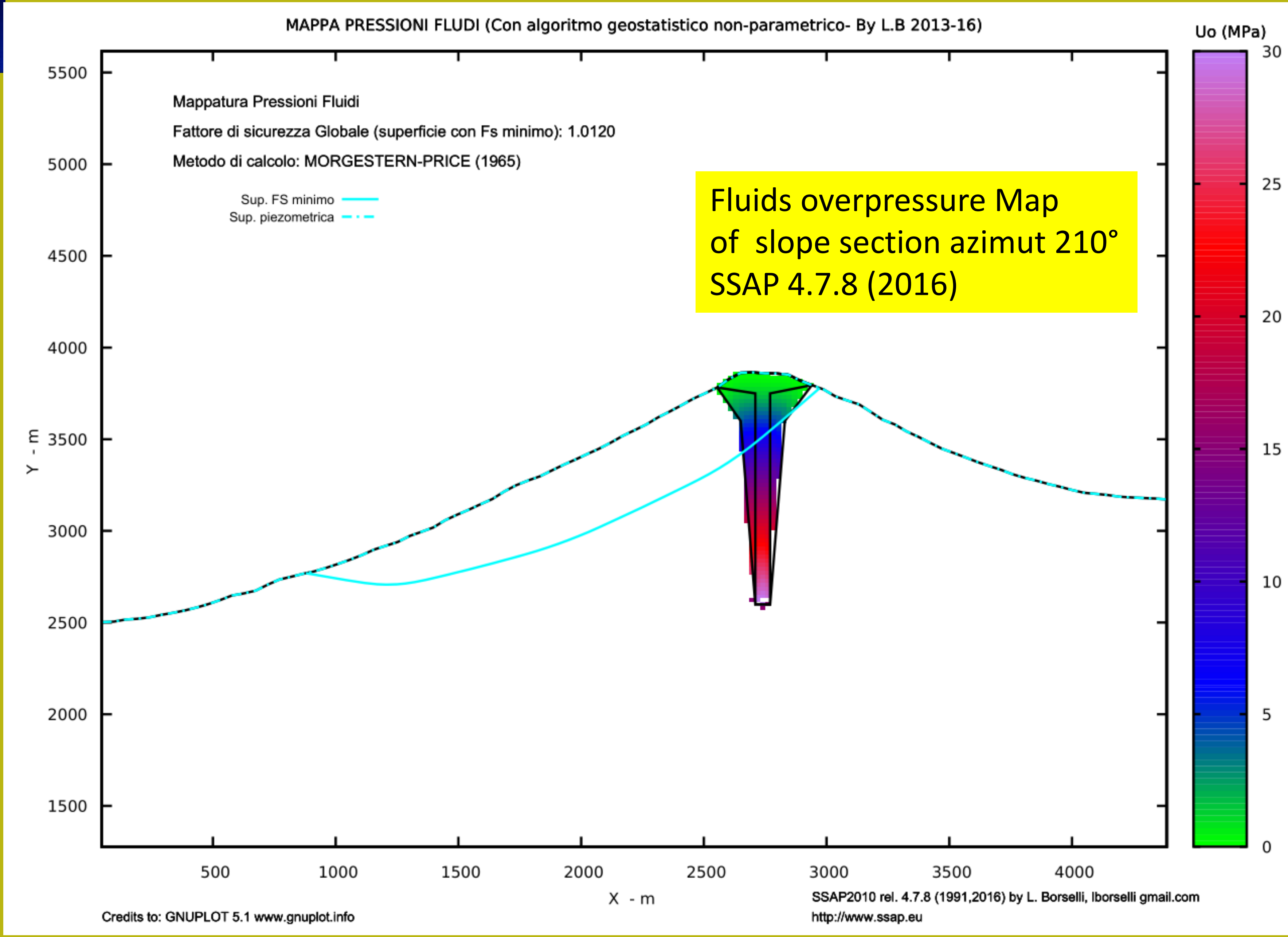
After the 10 July event we reconsider the previous RIA approach In this case we use new tools available in SSAP software developed after 2013 and until Now.

- ***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.***

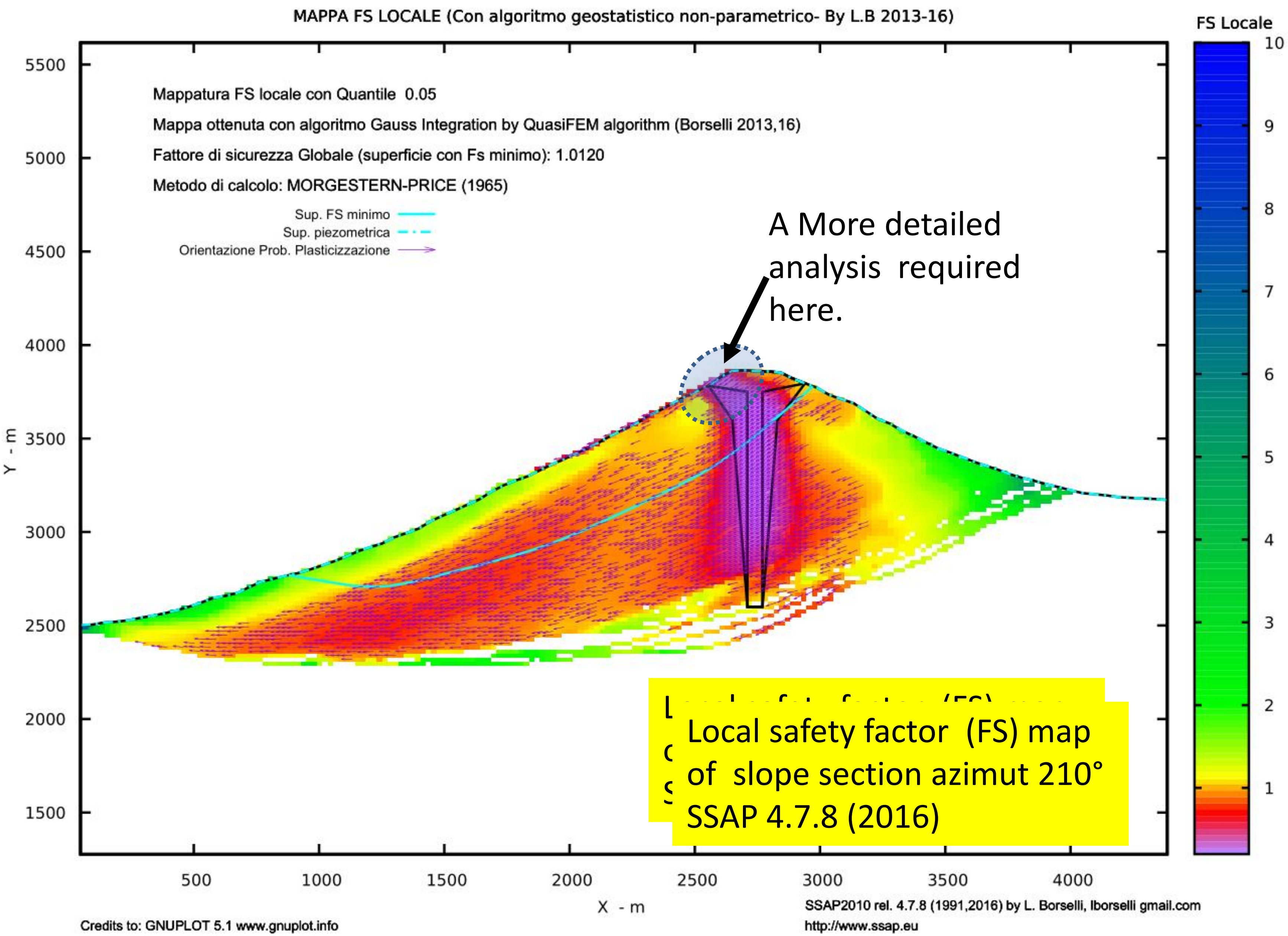
Volume deficit map Obtained by Volcanofit 2.1

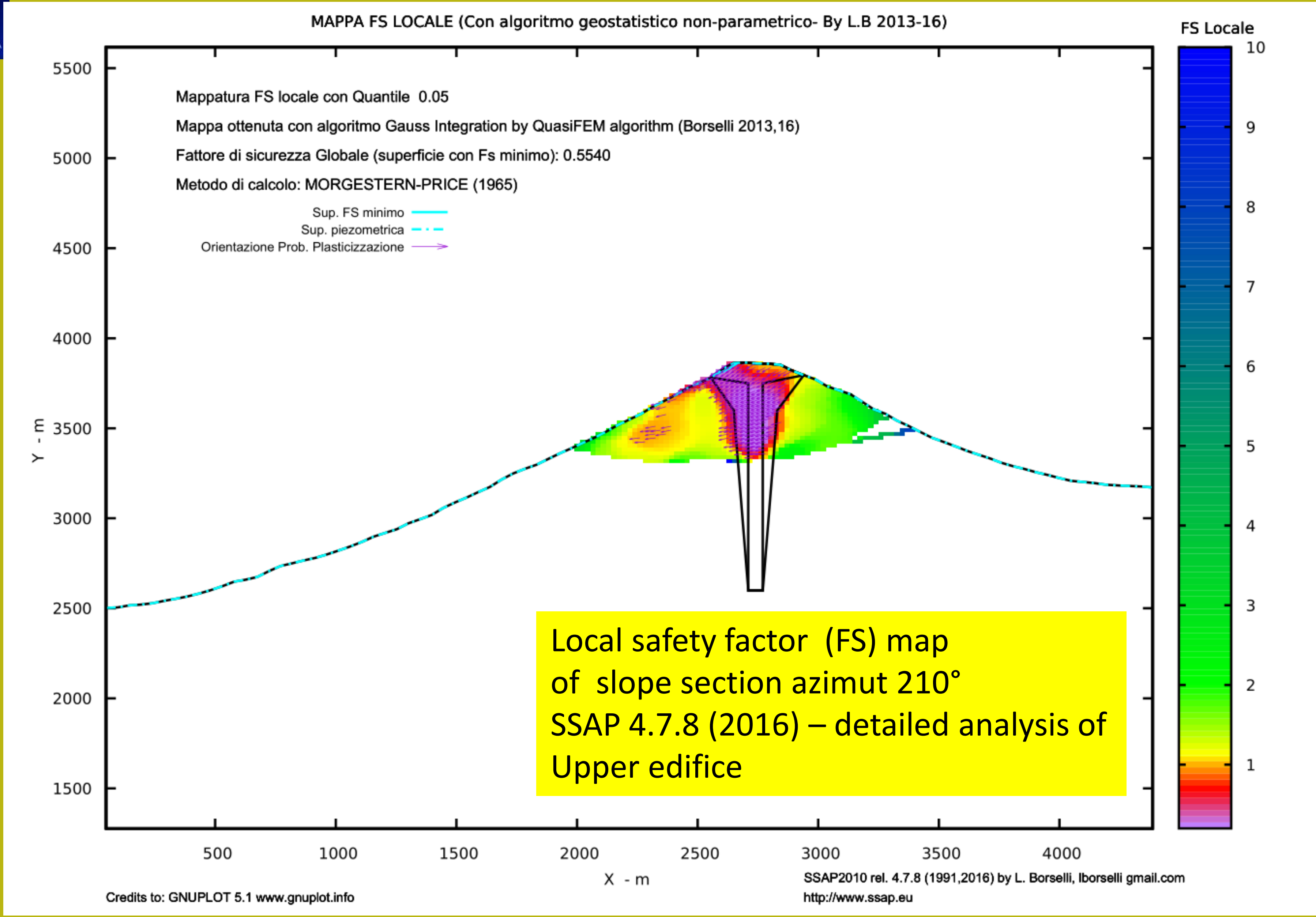


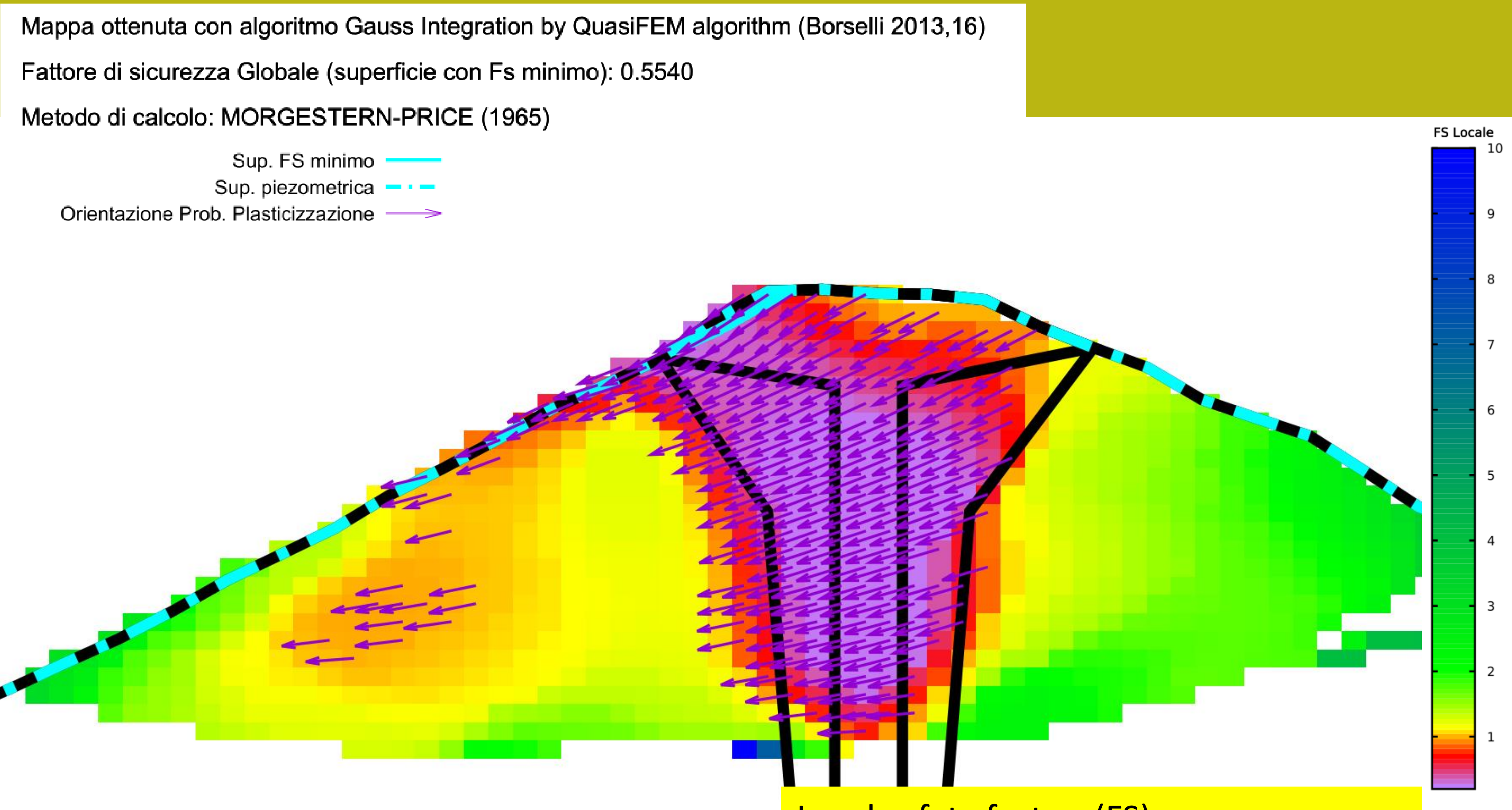

Distribuzione Modello Sovrappressioni Fluidi
U(H) - Pressione Idrostatica
U(H,D) - Modello sovrappressione/dissipazione
U(H,D) - Sovrappressione Massima
Fluid overpressure model
SSAP 4.7.8 (2016)
U(H,D)) (MPa)
H(m) - D(m)
A=-1.0, K=0.00500, S=2.50, Gamma fluido(kN/m3)=9.81
Uo Minima(kPa)=65.00, NON Limitato a pressione idrostatica
Graphi rendering,Credits to: GNUPLOT 5.1 www.gnuplot.info
SSAP2010 rel. 4.7.8 (1991,2016) by L. Borselli - www.ssap.eu



MAPPA PRESSIONI FLUDI (Con algoritmo geostatistico non-parametrico- By L.B 2013-16)
Mappatura Pressioni Fluidi
Fattore di sicurezza Globale (superficie con Fs minimo): 1.0120
Metodo di calcolo: MORGESTERN-PRICE (1965)
Sup. FS minimo
Sup. piezometrica
Fluids overpressure Map
of slope section azimut 210°
SSAP 4.7.8 (2016)
Uo (MPa)
30
25
20
15
10
5
0
Y - m
5500
5000
4500
4000
3500
3000
2500
2000
1500
500
1000
1500
2000
2500
3000
3500
4000
X - m
Credits to: GNUPLOT 5.1 www.gnuplot.info
SSAP2010 rel. 4.7.8 (1991,2016) by L. Borselli, lborselli gmail.com
http://www.ssap.eu


MAPPA FS LOCALE (Con algoritmo geostatistico non-parametrico- By L.B 2013-16)
Mappatura FS locale con Quantile 0.05
Mappa ottenuta con algoritmo Gauss Integration by QuasiFEM algorithm (Borselli 2013,16)
Fattore di sicurezza Globale (superficie con Fs minimo): 1.0120
Metodo di calcolo: MORGESTERN-PRICE (1965)
Sup. FS minimo
Sup. piezometrica
Orientazione Prob. Plasticizzazione
A More detailed analysis required here.
Local safety factor (FS) map of slope section azimut 210° SSAP 4.7.8 (2016)
FS Locale
Y - m
X - m
SSAP2010 rel. 4.7.8 (1991,2016) by L. Borselli, lborselli gmail.com
http://www.ssap.eu
Credits to: GNUPLOT 5.1 www.gnuplot.info


MAPPA FS LOCALE (Con algoritmo geostatistico non-parametrico- By L.B 2013-16)
Mappatura FS locale con Quantile 0.05
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)
Sup. FS minimo
Sup. piezometrica
Orientazione Prob. Plasticizzazione
FS Locale
Y - m
X - m
Local safety factor (FS) map
of slope section azimut 210°
SSAP 4.7.8 (2016) – detailed analysis of
Upper edifice
Credits to: GNUPLOT 5.1 www.gnuplot.info
SSAP2010 rel. 4.7.8 (1991,2016) by L. Borselli, lborselli gmail.com
http://www.ssap.eu



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

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Volcano electrical tomography unveils edifice collapse hazard linked to hydrothermal system structure and dynamics

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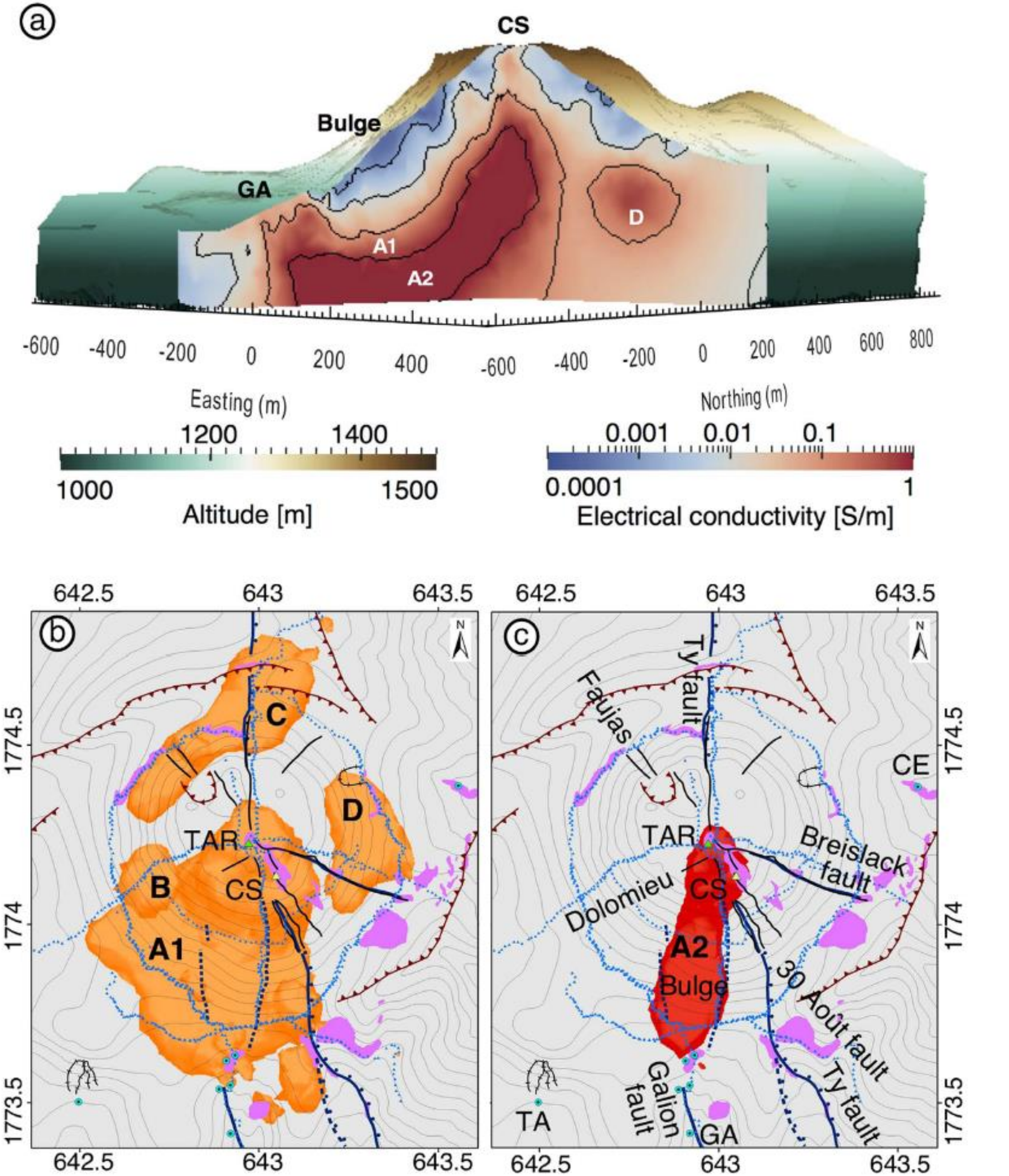
Published: 26 July 2016

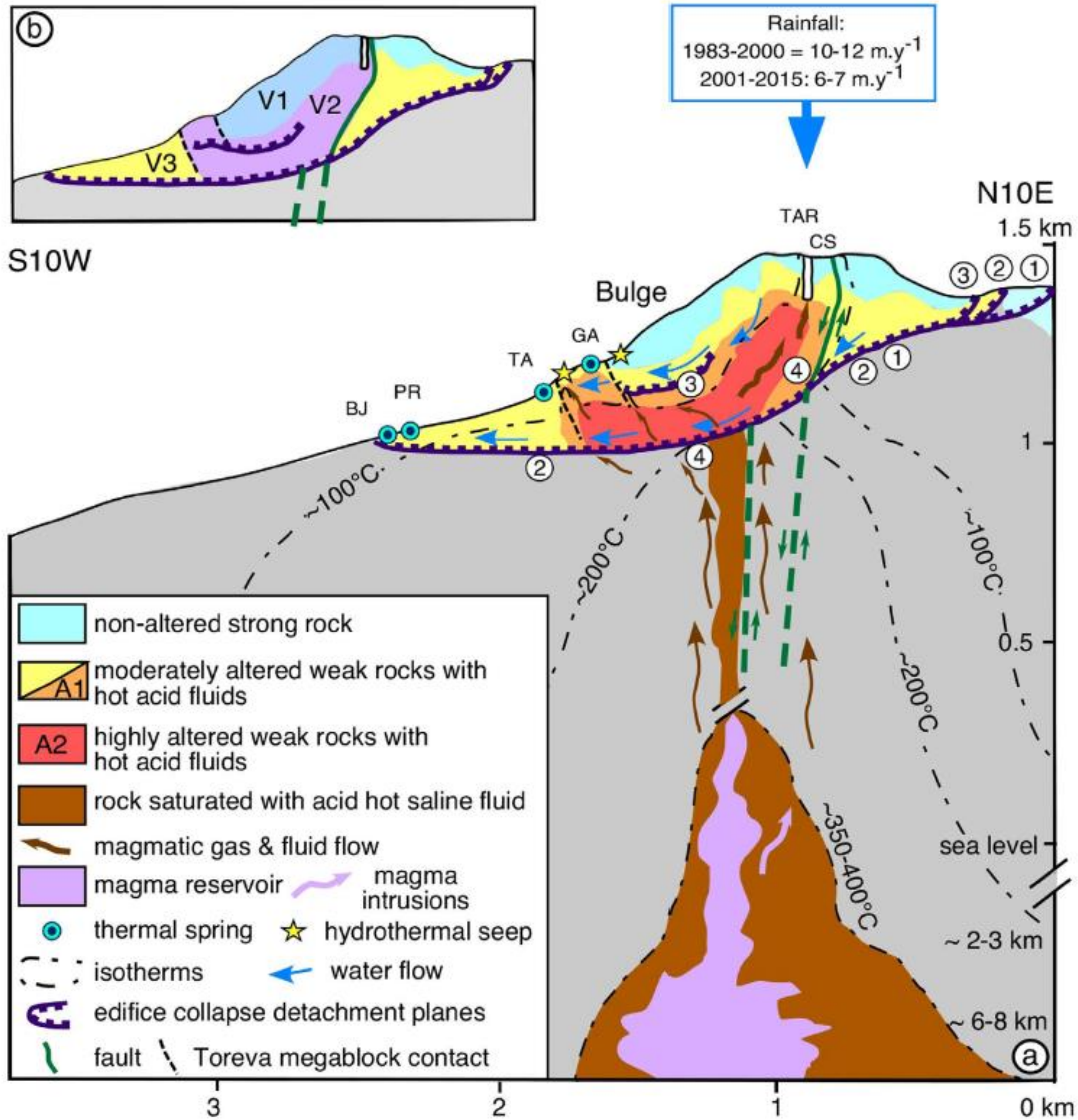
Marina Rosas-Carbajal[1], Jean-Christophe Komorowski[1], Florence Nicollin[2] & Dominique Gibert[1,2]

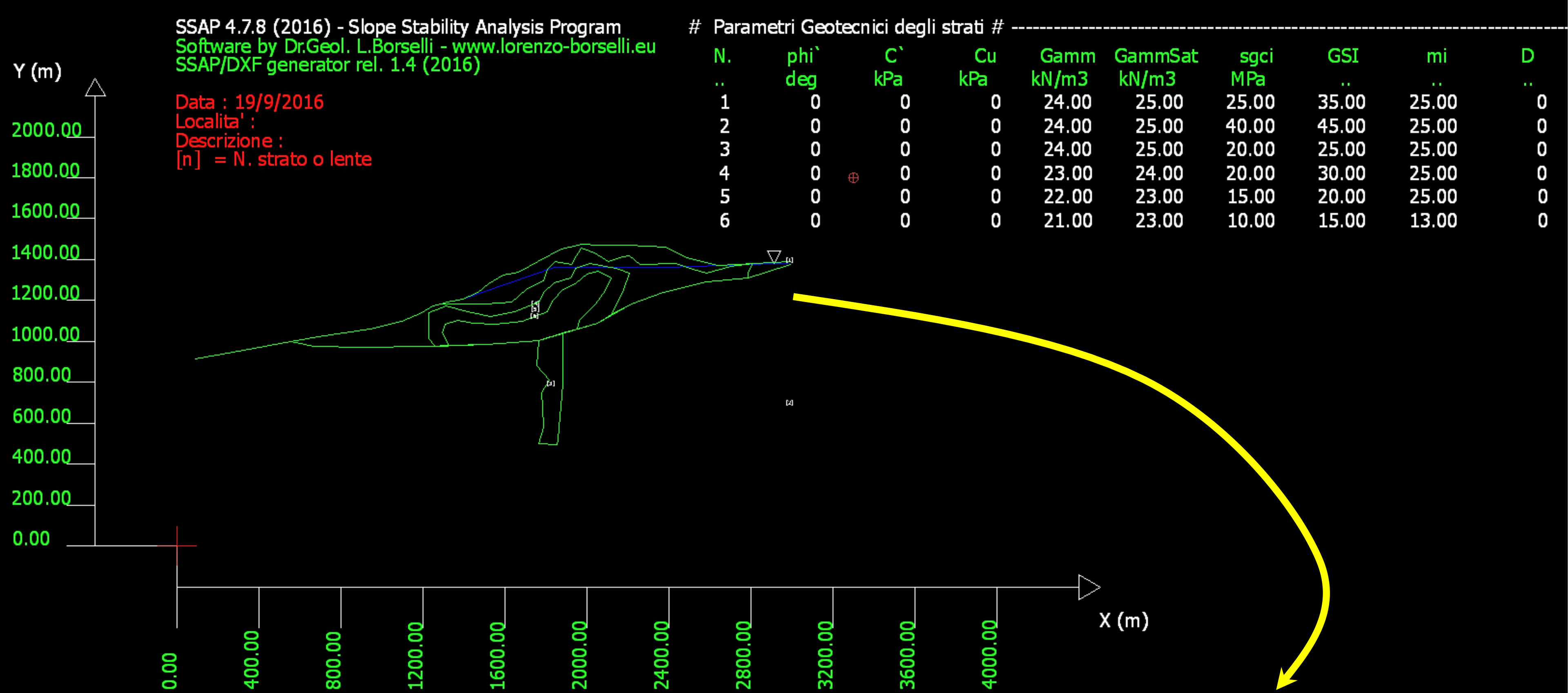
Application of SSAP
To a volcanic edifice where
Knowledge on internal stucture
Are available

From
Rosas-Carabjal et al. 2016
(fig. 2)

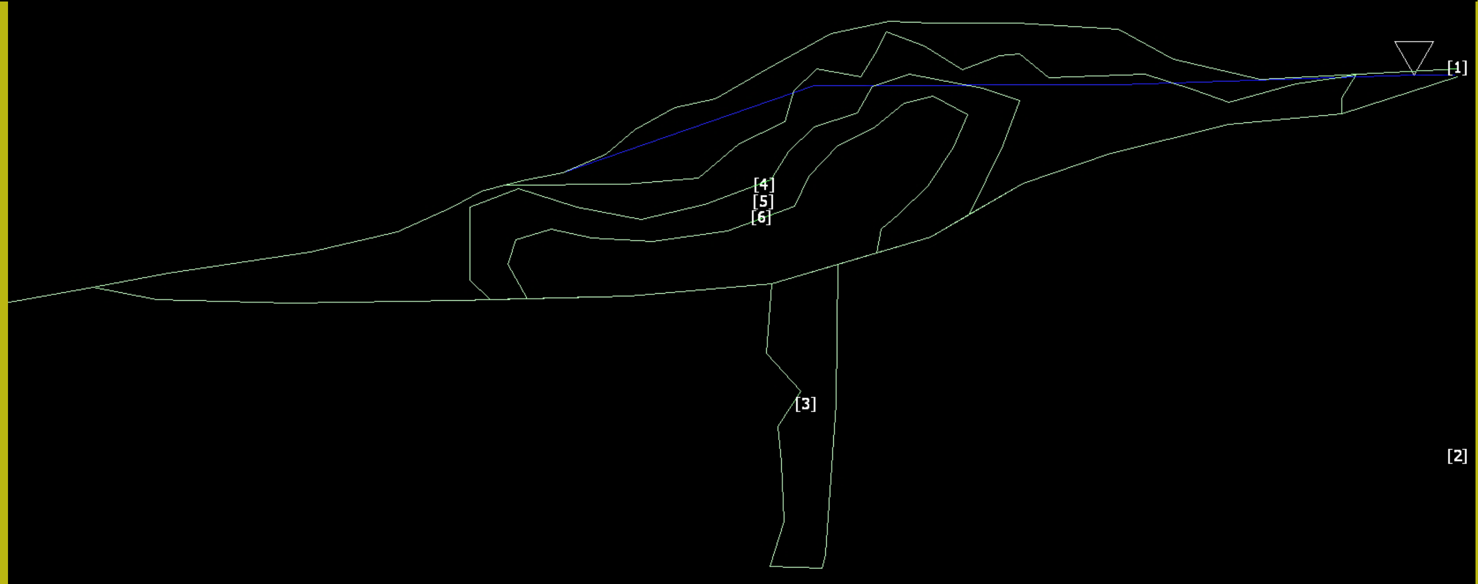


From Rosas-Carabjal et al. South Flank section2016 (fig. 3)

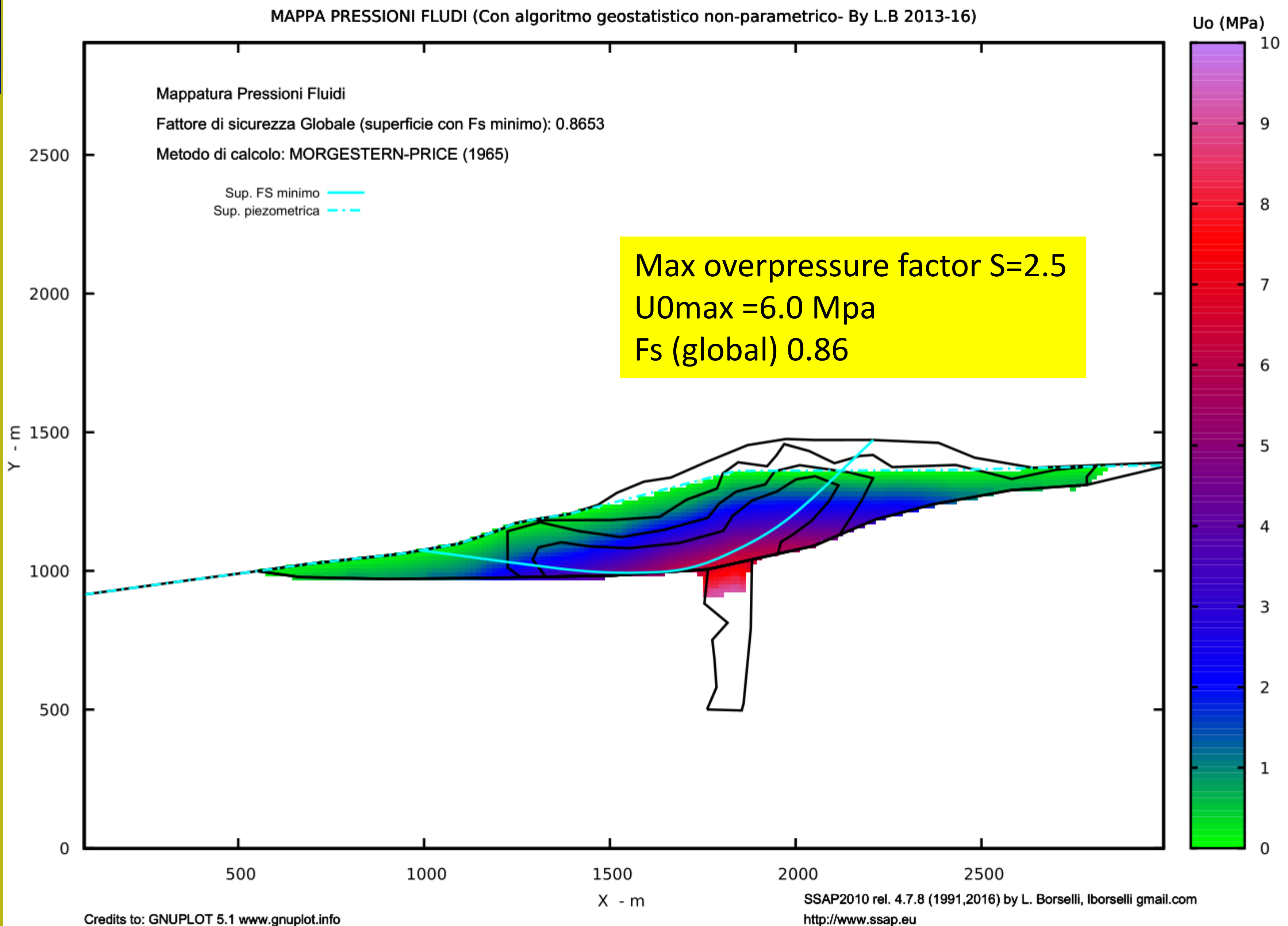




N.	phi`	C`	Cu	Gamm	GammSat	sgci	GSI	mi	D
..	deg	kPa	kPa	kN/m3	kN/m3	MPa	..	..	..
1	0	0	0	24.00	25.00	25.00	35.00	25.00	0
2	0	0	0	24.00	25.00	40.00	45.00	25.00	0
3	0	0	0	24.00	25.00	20.00	25.00	25.00	0
4	0	0	0	23.00	24.00	20.00	30.00	25.00	0
5	0	0	0	22.00	23.00	15.00	20.00	25.00	0
6	0	0	0	21.00	23.00	10.00	15.00	13.00	0



SLOPE Model of La Soufriere South flank Loaded in SSAP 4.7.8 (2016)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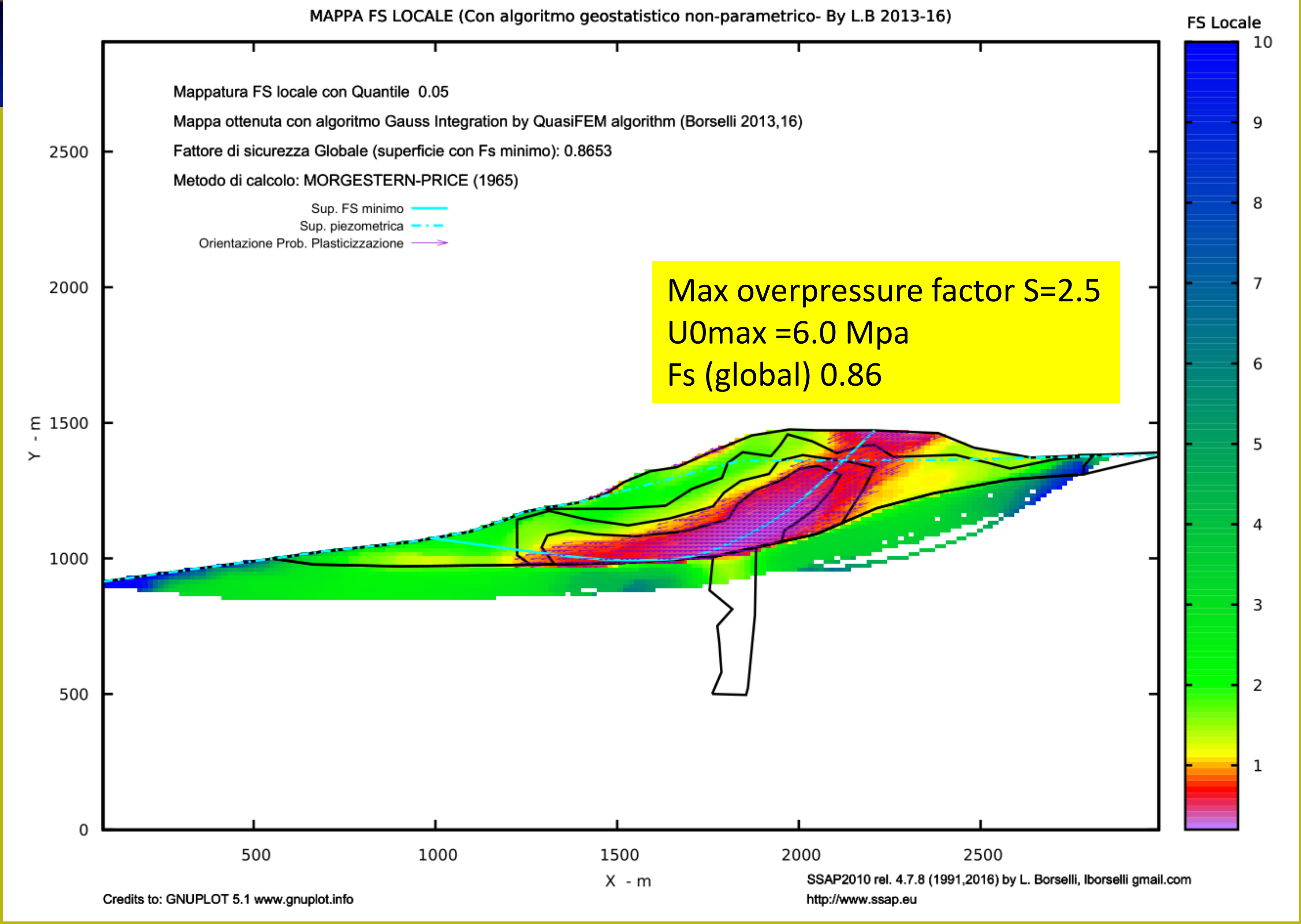
Mappatura Pressioni Fluidi
Fattore di sicurezza Globale (superficie con Fs minimo): 0.8653
Metodo di calcolo: MORGESTERN-PRICE (1965)
Sup. FS minimo
Sup. piezometrica
Max overpressure factor S=2.5
U0max =6.0 Mpa
Fs (global) 0.86
Uo (MPa)
Y - m
X - m
Credits to: GNUPLOT 5.1 www.gnuplot.info
SSAP2010 rel. 4.7.8 (1991,2016) by L. Borselli, lborselli gmail.com
http://www.ssap.eu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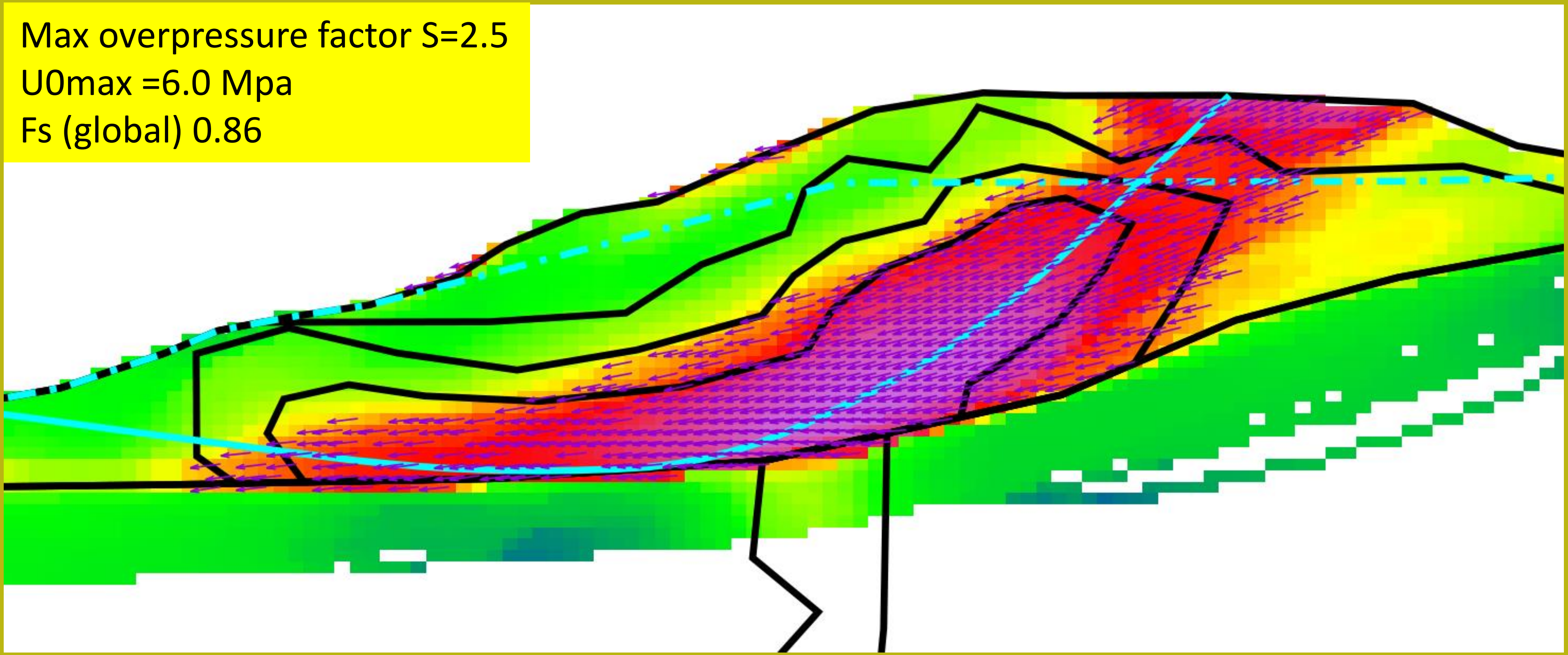
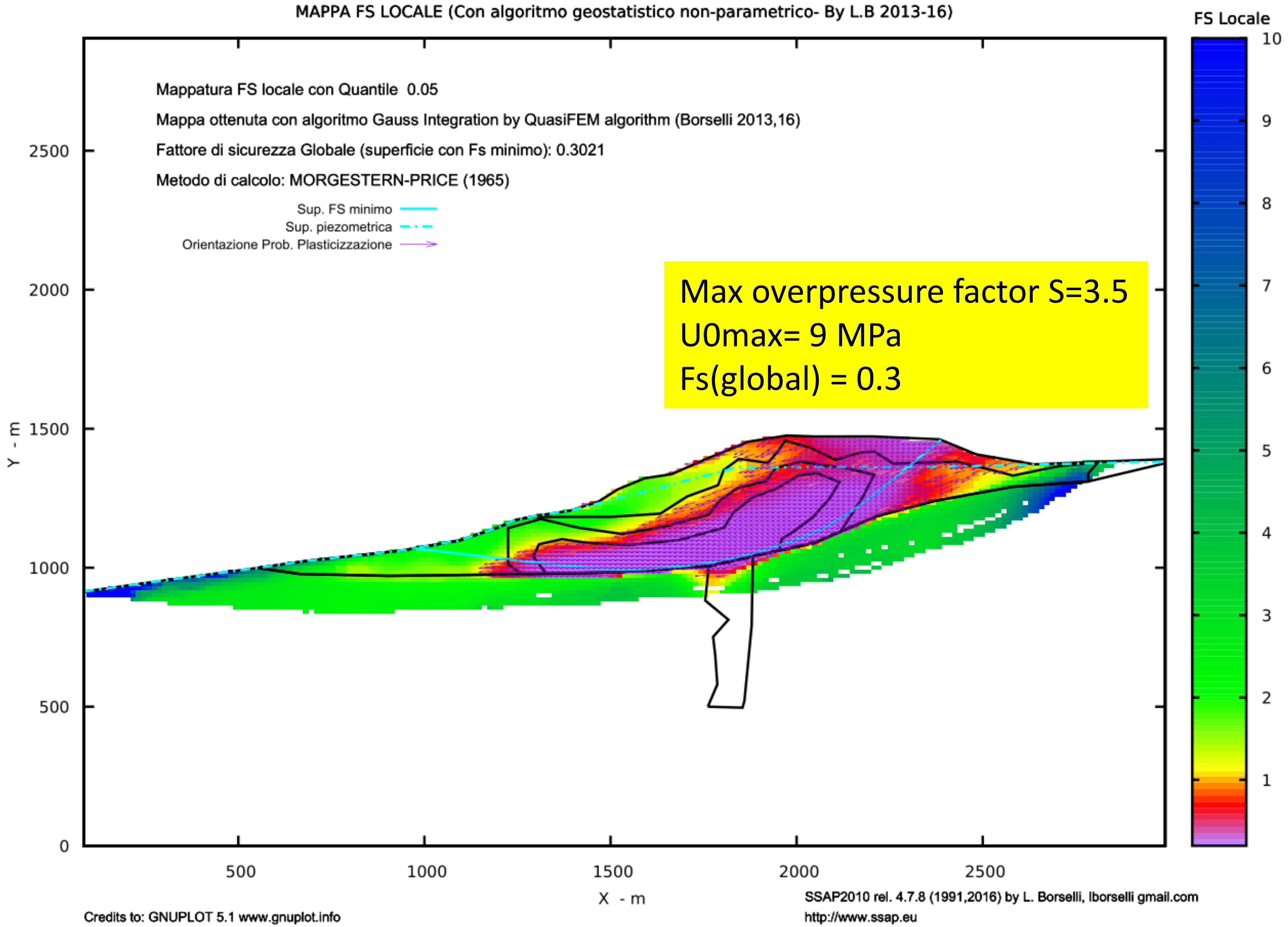
Mappatura FS locale con Quantile 0.05
Mappa ottenuta con algoritmo Gauss Integration by QuasiFEM algorithm (Borselli 2013,16)
Fattore di sicurezza Globale (superficie con Fs minimo): 0.8653
Metodo di calcolo: MORGESTERN-PRICE (1965)
Sup. FS minimo
Sup. piezometrica
Orientazione Prob. Plasticizzazione
Max overpressure factor S=2.5
U0max =6.0 Mpa
Fs (global) 0.86
FS Locale
Y - m
X - m
Credits to: GNUPLOT 5.1 www.gnuplot.info
SSAP2010 rel. 4.7.8 (1991,2016) by L. Borselli, lborselli gmail.com
http://www.ssap.eu

Max overpressure factor S=2.5
U0max =6.0 Mpa
Fs (global) 0.86

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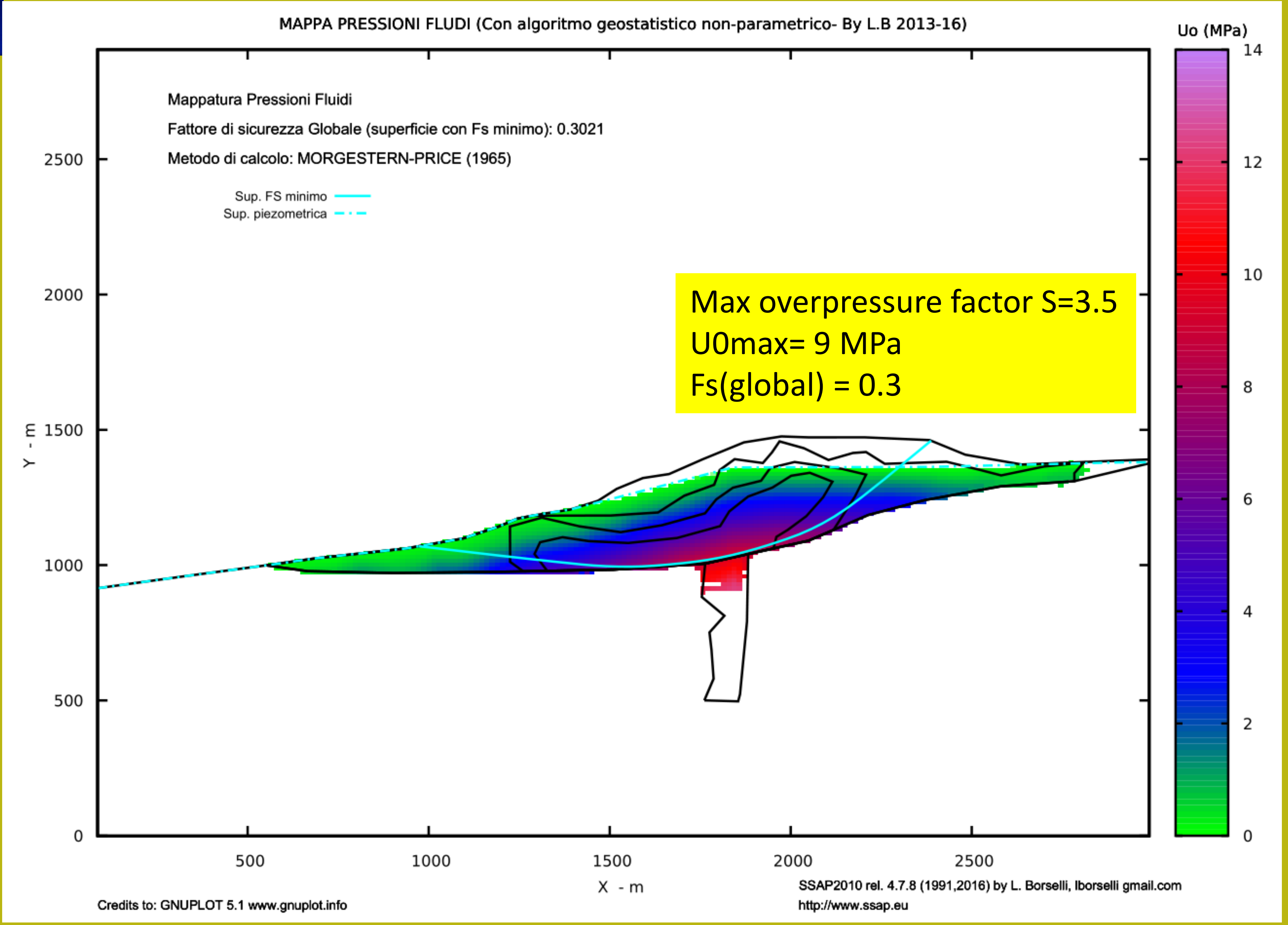
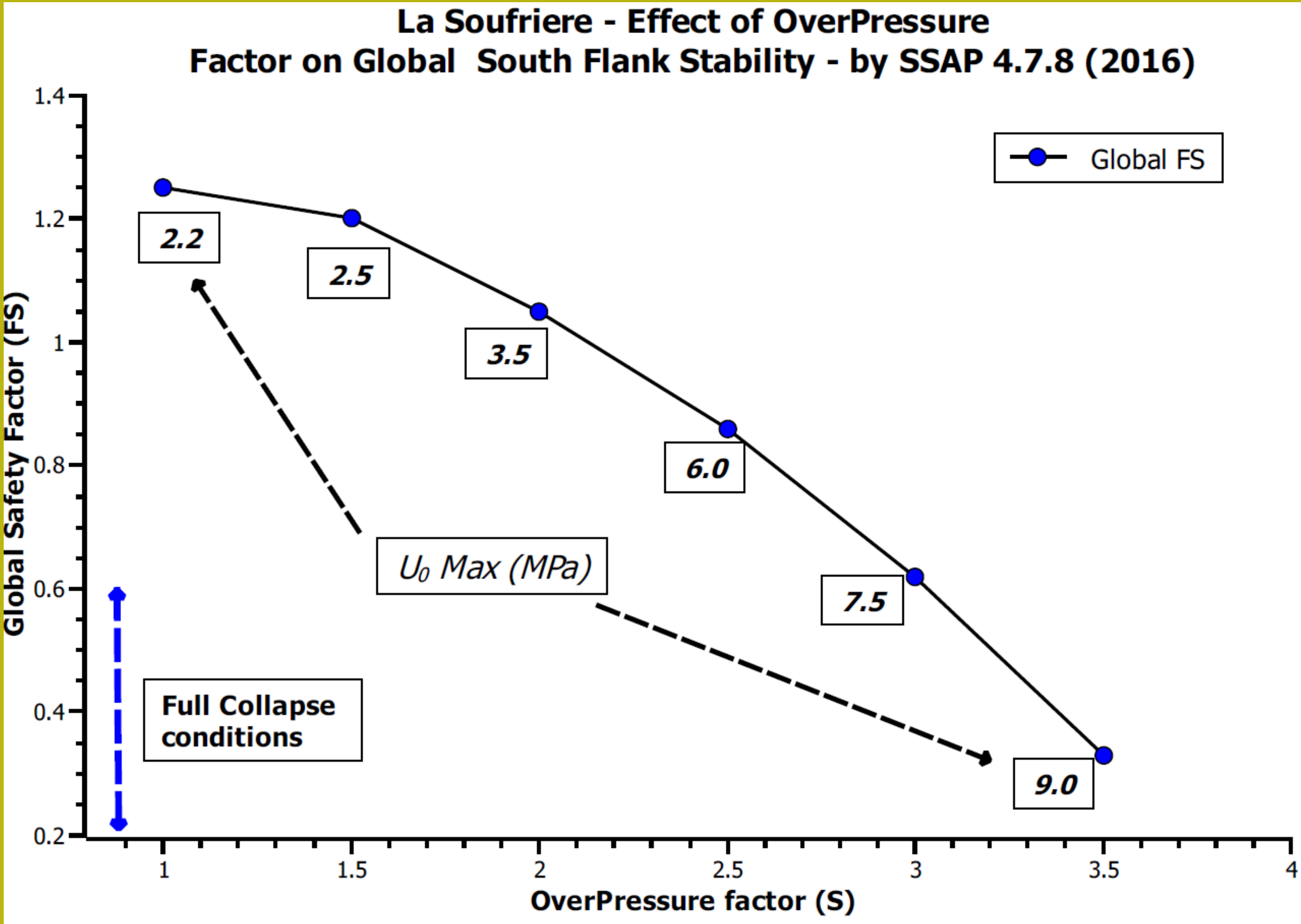
Mappatura FS locale con Quantile 0.05
Mappa ottenuta con algoritmo Gauss Integration by QuasiFEM algorithm (Borselli 2013,16)
Fattore di sicurezza Globale (superficie con Fs minimo): 0.3021
Metodo di calcolo: MORGESTERN-PRICE (1965)
Sup. FS minimo
Sup. piezometrica
Orientazione Prob. Plasticizzazione
Max overpressure factor S=3.5
U0max= 9 MPa
Fs(global) = 0.3
FS Locale
Y - m
X - m
SSAP2010 rel. 4.7.8 (1991,2016) by L. Borselli, lborselli gmail.com
http://www.ssap.eu
Credits to: GNUPLOT 5.1 www.gnuplot.info


MAPPA PRESSIONI FLUDI (Con algoritmo geostatistico non-parametrico- By L.B 2013-16)
Mappatura Pressioni Fluidi
Fattore di sicurezza Globale (superficie con Fs minimo): 0.3021
Metodo di calcolo: MORGESTERN-PRICE (1965)
Sup. FS minimo
Sup. piezometrica
Max overpressure factor S=3.5
U0max= 9 MPa
Fs(global) = 0.3
Uo (MPa)
Y - m
X - m
Credits to: GNUPLOT 5.1 www.gnuplot.info
SSAP2010 rel. 4.7.8 (1991,2016) by L. Borselli, lborselli gmail.com
http://www.ssap.eu


La Soufriere - Effect of OverPressure
Factor on Global South Flank Stability - by SSAP 4.7.8 (2016)
Global FS
2.2
2.5
3.5
6.0
7.5
9.0
U₀ Max (MPa)
Full Collapse conditions
Global Safety Factor (FS)
OverPressure factor (S)
1.4
1.2
1
0.8
0.6
0.4
0.2
1
1.5
2
2.5
3
3.5
4

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.**

Highlights and … Speculations

- **SSAP used in a context of Relative Instability analysis may has 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 <u>be applied to any strato-volcano with potential of flank collapse</u> and for his future DAE's hazard assessments.**


North Appenine
Italy - spring 2003
Photo by L.B.
Gracias por su atención !!!
Many thanks for Your attention !!!