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DEEP-SEATED SPREADING MODEL **TESTED ON ETNA MOUNT WITH FEM**

Pulvirenti F.*^{1,2}, Aloisi M.¹, Mattia M.¹ and Monaco C.²

¹ Istituto Nazionale di Geofisica e Vulcanologia, Catania, Italy

² Dip. di Scienze Geologiche, Università di Catania, Catania, Italy

* Corresponding author: INGV, Piazza Roma 2, 95123, Catania - Italy, fabiopulvirenti@yahoo.it

The sliding of volcano's flank is a phenomenon that occurs for different volcanoes in the world. Spectacular examples are:

Socompa (Chile)

Bandai-san and Ontake
(Japan)

Mount. St. Helens
(Washington)



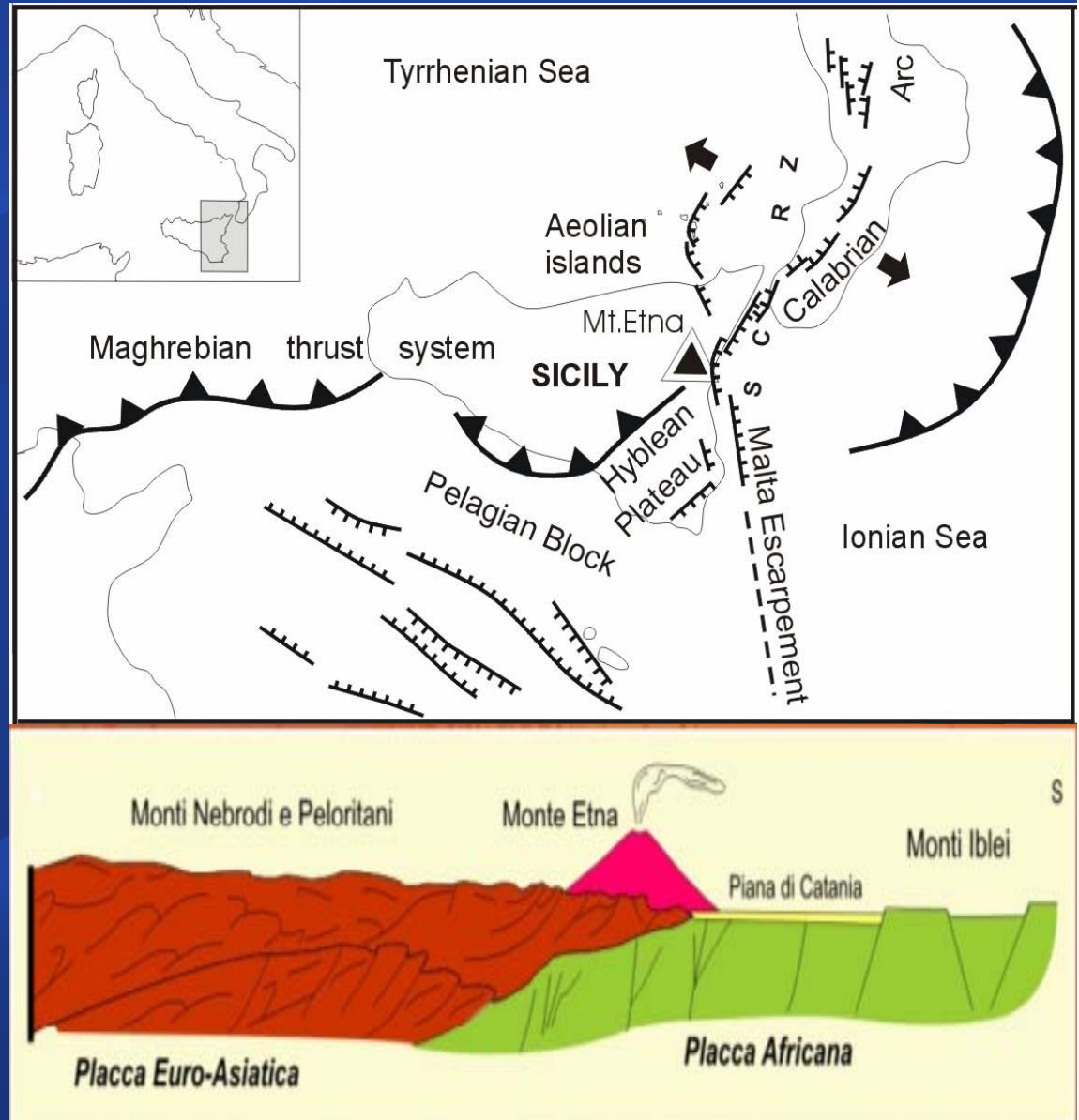
450 m of the summit was removed by slope failure

The common factor of these volcanoes is to lie on very active tectonic systems, regardless of the presence of a magmatic complex inside. Among instable volcanoes, particular attention should be paid for Etna....

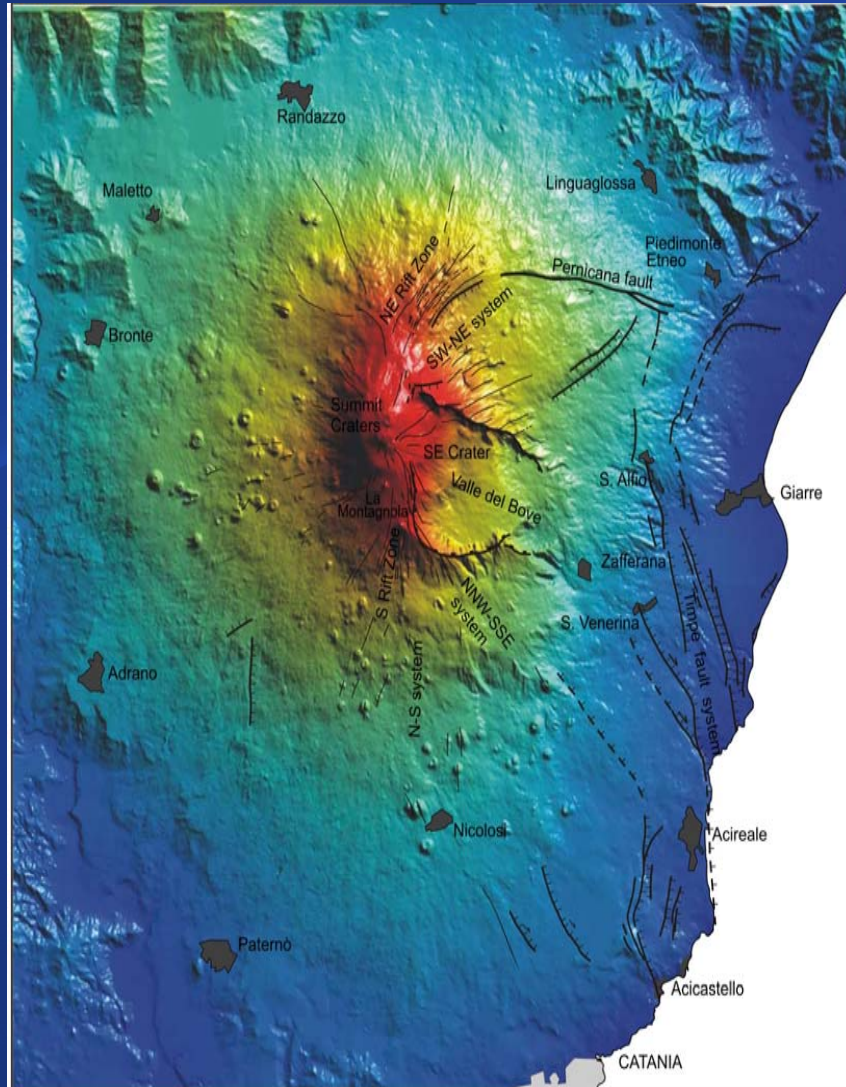
The Etna volcano: structural scenario

Mount Etna is located in a particular tectonic position on the west side of the Ionian coast, where the Messina-Fiumefreddo system and the Malta escarpment intersect each other, and on the collision zone between the African plate and the Euro-Asiatic one.

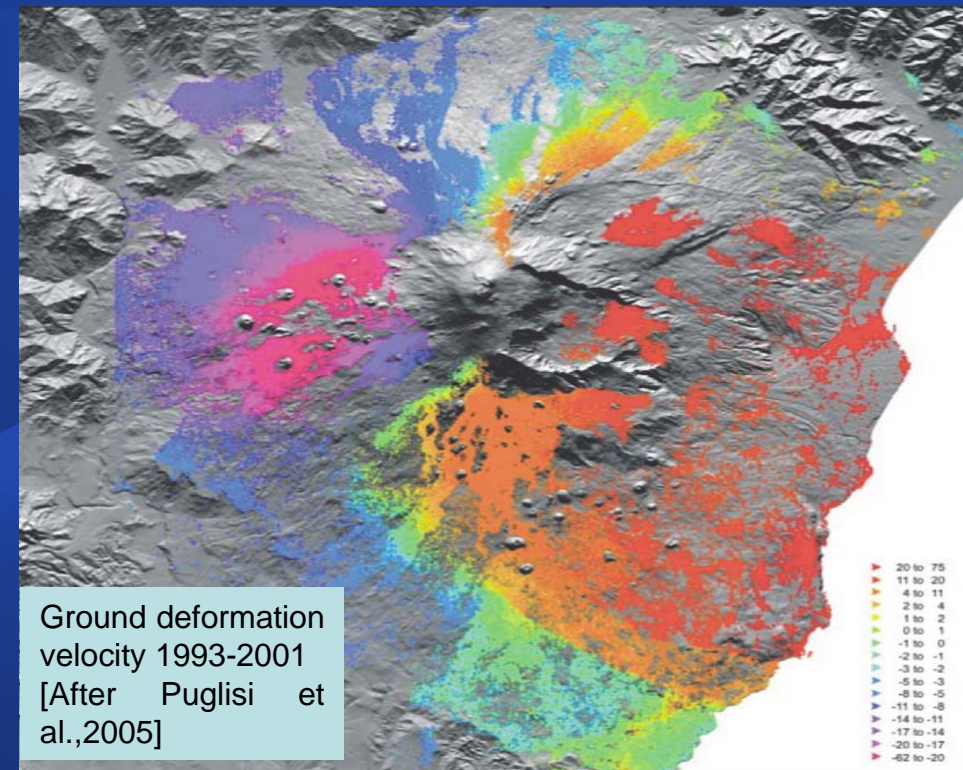
Its activity is moreover affected by the opening of the Siculo-Calabrian Rift in WNW-ESE direction.



The east flank of Etna is characterized by several active faults associated with middle-low seismic activity of low ipocentral depth and by the presence of a great volcano tectonic depression known as “Valle del Bove”.



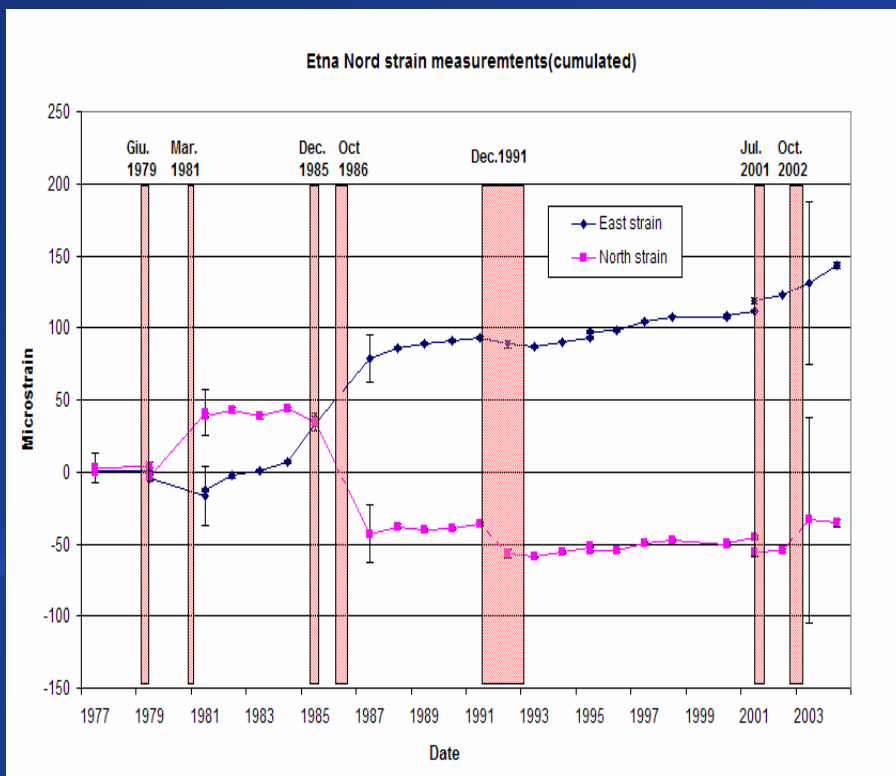
In the last 20 years several geodetic networks have been installed on Etna mount. The data acquired show that the eastern flank of Etna is unstable and is moving towards the sea. This behaviour is also confirmed by other techniques as SAR interferometry.



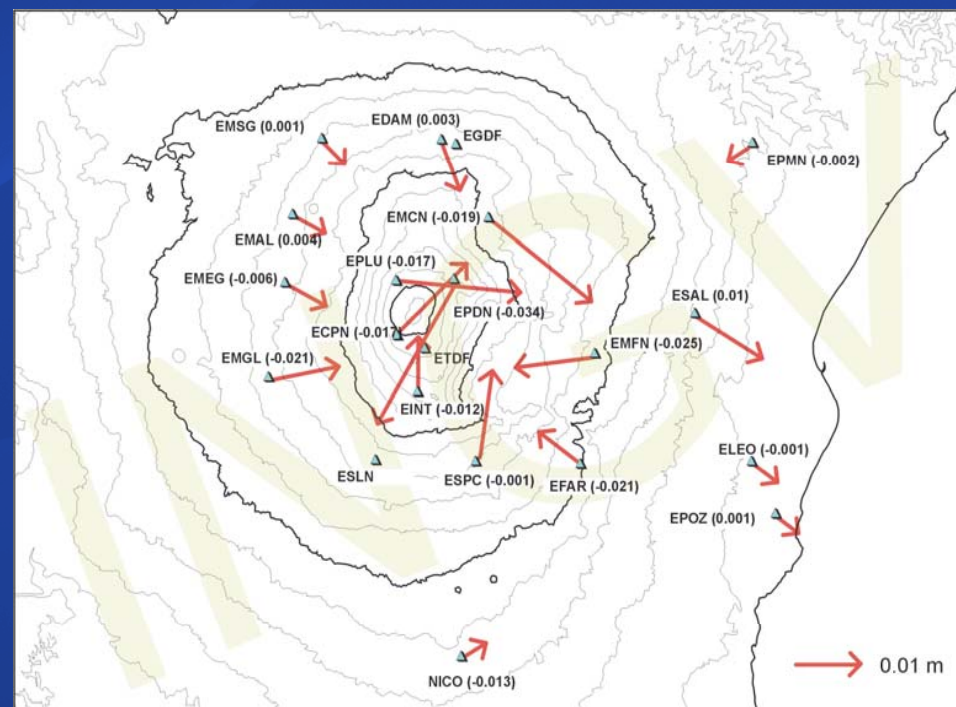
Ground deformation velocity 1993-2001
[After Puglisi et al., 2005]

Cinematics of the eastern Etna flank

EDM data



GPS permanent network data



Displacements estimation from 14 May 2008 to 10 July 2008

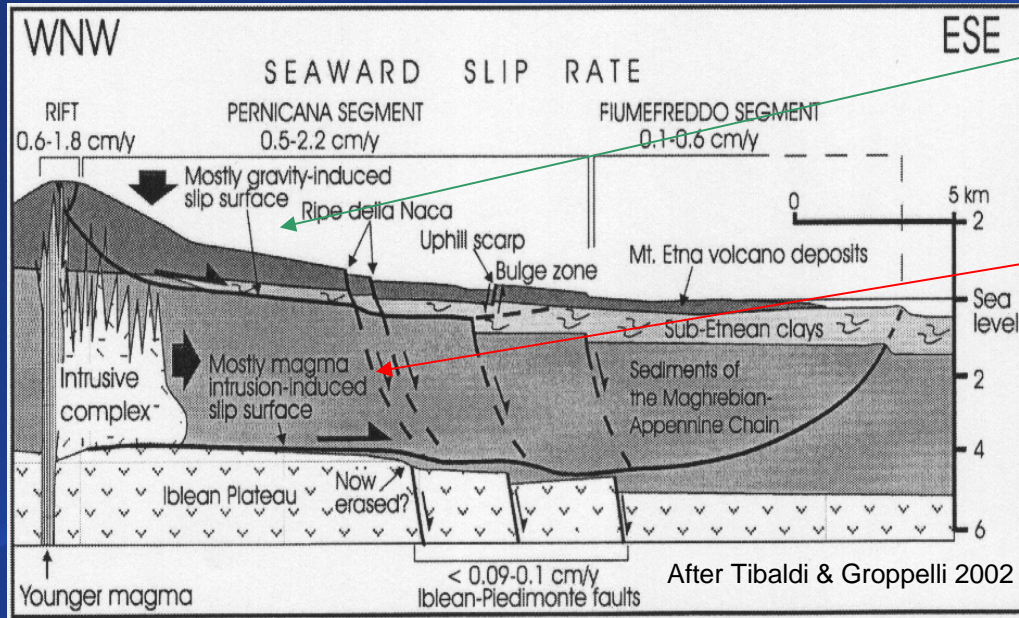
>Horizontal slip rates of some cm/year (especially along the coast);

>The displacement vectors along the coast are always directed towards east or southeast independently from inflation/deflation of the volcanic edifice;

>Displacements cannot be attributed to tectonic processes only because these would imply slip rates of some mm/year.

Possible causes

Several models have been proposed using geological and geophysical data

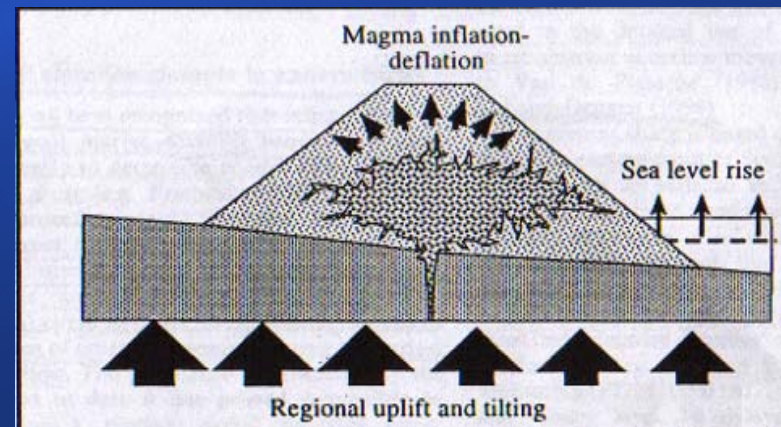
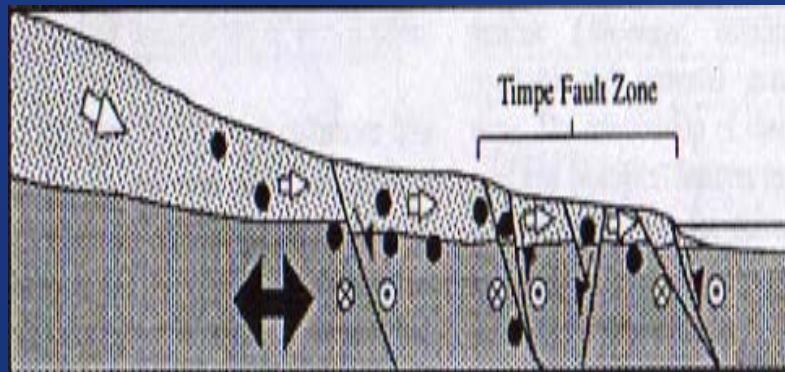


Shallow sliding model [Labaume et al., 1990; Lo Giudice & Rasà, 1992; Rasà et al., 1996; Puglisi & Bonforte, 2004].

Deep-seated spreading model [Borgia et al., 1992; Rust and Neri, 1996; Tibaldi and Groppelli, 2002; Neri et al., 2005; Rust et al., 2005].

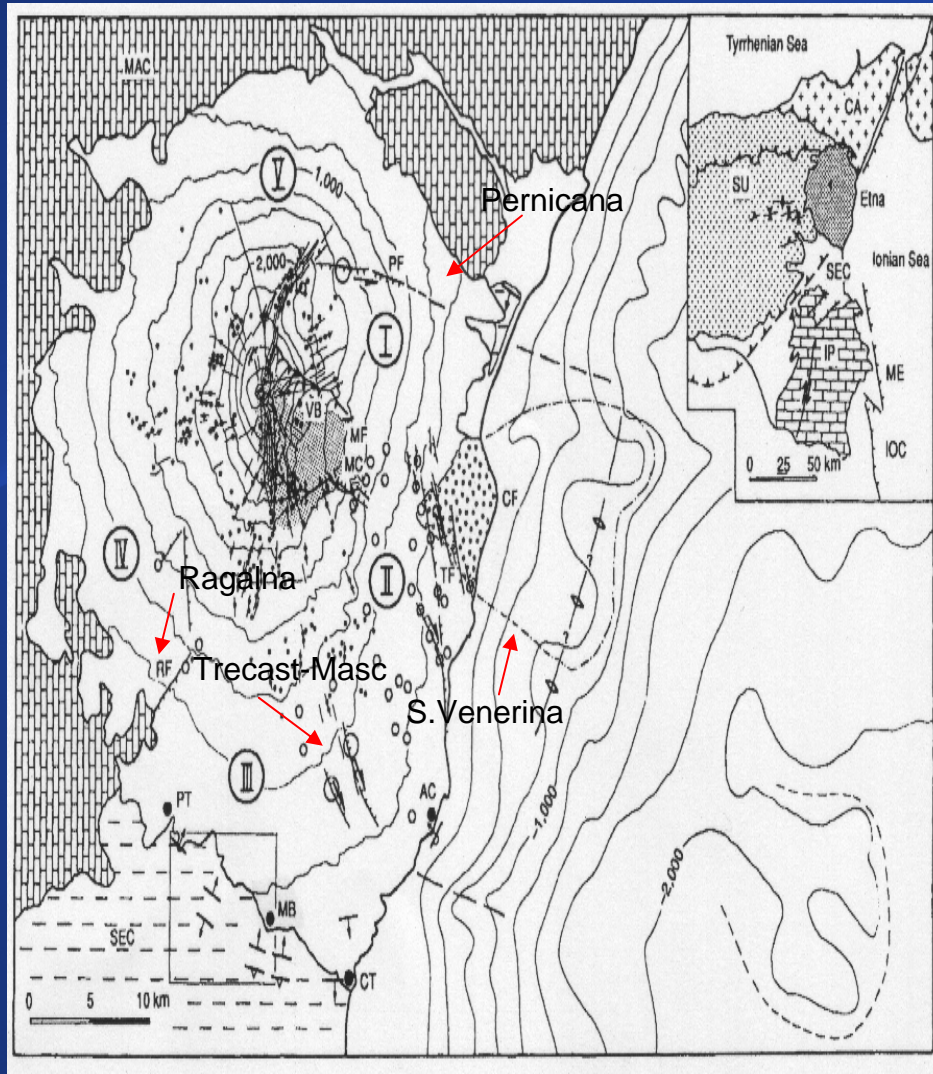
Other models: inflation/deflation processes, regional uplift with tilting or sea level rising with erosion of the coast. [Labaume et al., 1990; Montalto et al, 1996; Firth et al., 1996].

Tectonics block movements model
[Monaco et al., 1995; 1997; 2005]



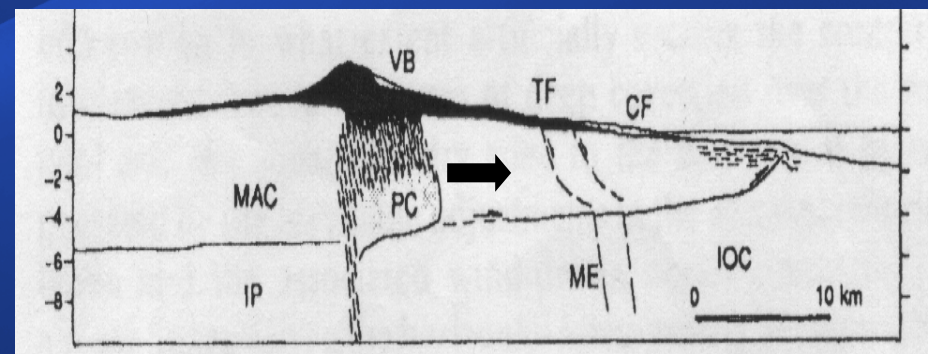
The deep-seated spreading model

The model, formulated originally by Borgia et al. 1992, is based on the study of the Hawaiian volcanoes (Poàs and Kilauea). According to the model Etna Mount is divided in five blocks on the base of the different slip rates observed.



Different phases can be summarized:

- Magma uprising from the upper mantle to the crust on the west border of a PC;
- Push of a dike complex (located 2-5 Km b.s.l.) over a thrust fault;
- Increasing of the Coulomb stress at the faults;
- Sequential movement of the blocks;
- Extensional movements in the summit area and compressive one at the base of the east and south flanks are generated with formation of anticlinal folds near Misterbianco-Paternò and off-shore.



The deep seated spreading model tested with FEM

Step 1 : Creation of the geometry

COMSOL Multiphysics - Geom1/Structural Mechanics Module - Solid, Stress-Strain (smsld) : pulvi_layers.mph

File Edit Options Draw Physics Mesh Solve Postprocessing Multiphysics Help

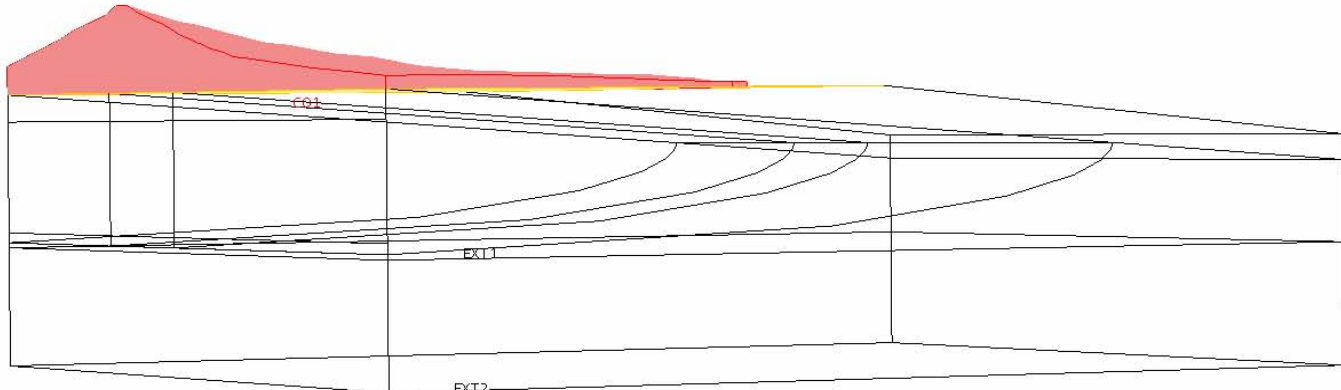
Model Tree

- Geom1
 - Solid, S

Using a specific script the Etna DEM is converted in ASCII STL format. The STL file is then imported.

DEM resolution is 200 m

Total domain dimension: 40x40 Km



[untitled]

(8398.352, 2.149e5, -1.285e5) | AXIS | GRID | EQUAL | CSYS

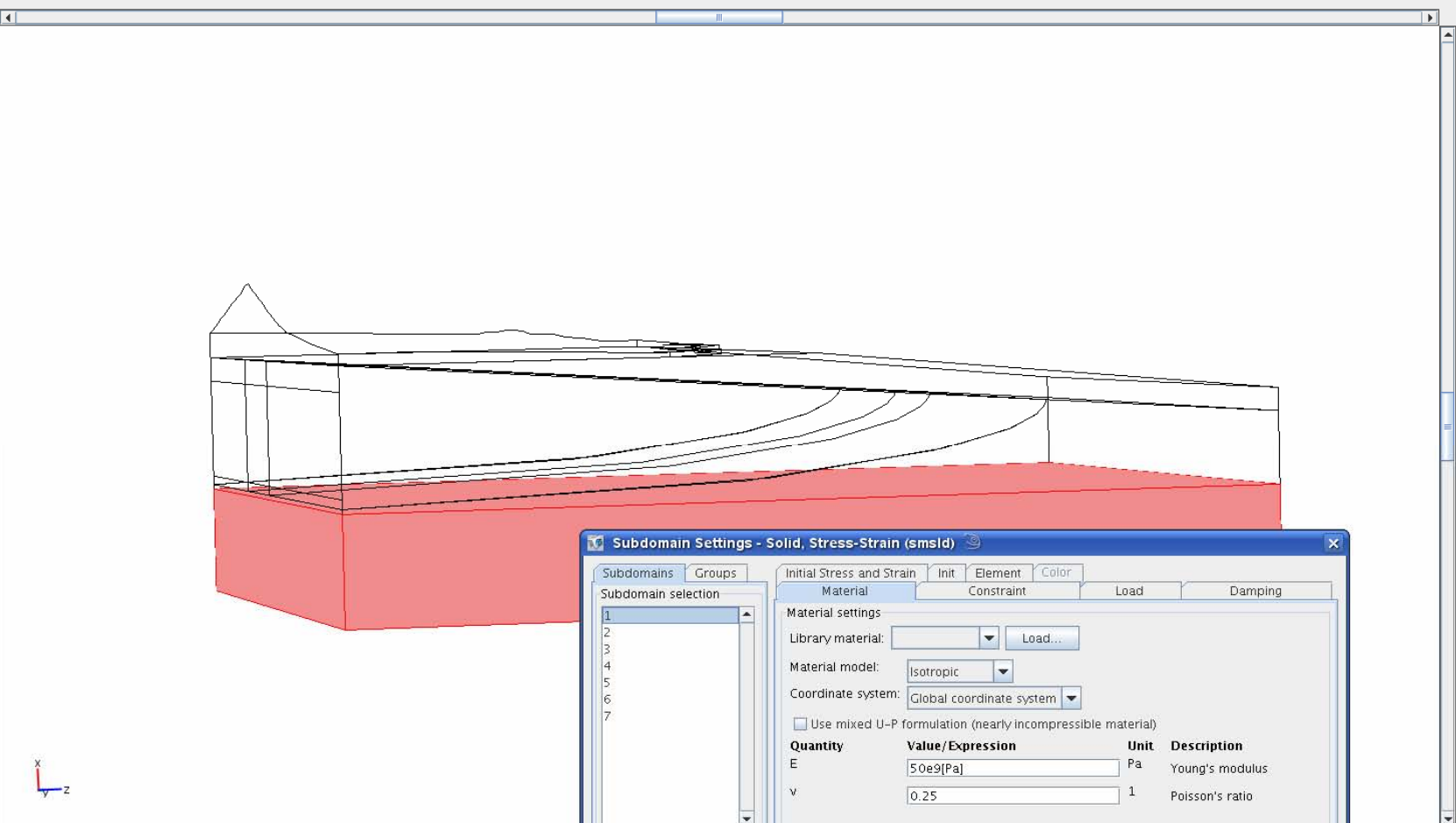
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19:18

Step 2: The Subdomain Setting

COMSOL Multiphysics - Geom1/Structural Mechanics Module - Solid, Stress-Strain (smsld) : pulvi_layers.mph

File Edit Options Draw Physics Mesh Solve Postprocessing Multiphysics Help



The screenshot displays the COMSOL Multiphysics interface. The main window shows a 3D model of a pulvi_layers.mph. A red subdomain is highlighted at the bottom of the model. The Subdomain Settings dialog box is open, showing the material settings for the selected subdomain. The dialog box has tabs for Subdomains, Groups, Initial Stress and Strain, Material, Init, Element, Color, Constraint, Load, and Damping. The Material tab is active, showing the following settings:

- Library material: [Dropdown]
- Material model: isotropic
- Coordinate system: Global coordinate system
- Use mixed U-P formulation (nearly incompressible material)
- Quantity Value/Expression Unit Description
- E 5.0e9[Pa] Pa Young's modulus
- ν 0.25 1 Poisson's ratio
- α 7e-6[1/K] 1/K Thermal expansion coeff.
- ρ 2600[kg/m^3] kg/m^3 Density

Subdomain selection

Subdomain
1
2
3
4
5
6
7

Group: [Dropdown]

Select by group

Active in this domain

(-4961.203, 2.478e5, -5.381e4) | AXIS | GRID | EQUAL | CSYS

Modelo con moduli di you | Shell - COMSOL34 <2> | COMSOL Multiphysics - Ge |

Shell - COMSOL34 | COMSOL Multiphysics - C | system/media/sdg1 - Kon | 19:25

Step 3: Boundary conditions and contact setting

The screenshot displays the COMSOL Multiphysics interface for a structural mechanics model. The main window shows a 3D model of a rectangular block with a red vertical bar on its top surface. A red arrow points from the text 'For para > 1 a push of 100 cm is applied.' to the 'ampli' boundary expression in the 'Boundary Expressions' dialog box.

Boundary Expressions Dialog:

Boundary selection	Name	Expression	Unit
24	ampli	(para > 1)*(-1+para)	
25			
26			
27			
28			
29			
30			

Solver Parameters Dialog:

- Analysis: Static
- Auto select solver:
- Solver: Parametric
- Linear system solver: Direct (PARDISO)
- Preconditioner: (empty)
- Matrix symmetry: Automatic

Boundary Settings - Solid, Stress-Strain (smsid) Dialog:

Constraint condition: Prescribed displacement
 Coordinate system: Global coordinate system

Constraint	Value/Expression	Unit	Description
<input type="checkbox"/> R_x	0	m	Constraint x-dir.
<input type="checkbox"/> R_y	0	m	Constraint y-dir.
<input checked="" type="checkbox"/> R_z	spos*ampli	m	Constraint z-dir.
General notation, $H_u=R$			
H	Edit...	1	H Matrix
R	Edit...	m	R Vector

The bottom status bar shows the coordinate system as 'AXIS GRID EQUAL CSYS' and the current time as 18:17.

Step 4: Load parametrization

Through the `ampli2` function the load grows linearly when `para` is ≤ 1 and is maintained at 100% when `para` is greater than 1

Subdomain Expressions

Subdomain selection	Name	Expression	Unit
1	ampli2	$(para \leq 1) * para + (para > 1)$	
2			
3			
4			
5			
6			
7			

Subdomain Settings - Solid, Stress-Strain (smsld)

Subdomains: 1, 2, 3, 4, 5, 6, 7

Group: []

Select by group

Active in this domain

Initial Stress and Strain | Material | Constraint | **Load** | Damping

Load settings

Coordinate system: Global coordinate system

Quantity	Value/Expression	Unit	Description
F_x	$-26000 * ampli2$	N/m^3	Body load (force/volume) x-dir.
F_y	0	N/m^3	Body load (force/volume) y-dir.
F_z	0	N/m^3	Body load (force/volume) z-dir.

Include thermal expansion

Temp	0	K	Strain temperature
Tempref	0	K	Strain ref. temperature

Step 5: Mesh generation

COMSOL Multiphysics - Geom1/Structural Mechanics Module - Solid, Stress-Strain (smsld) : pulvi_layers.mph

File Edit Options Draw Physics Mesh Solve Postprocessing Multiphysics Help

Model Tree

Geom1
└ Solid, S

Total degrees of freedom :80232

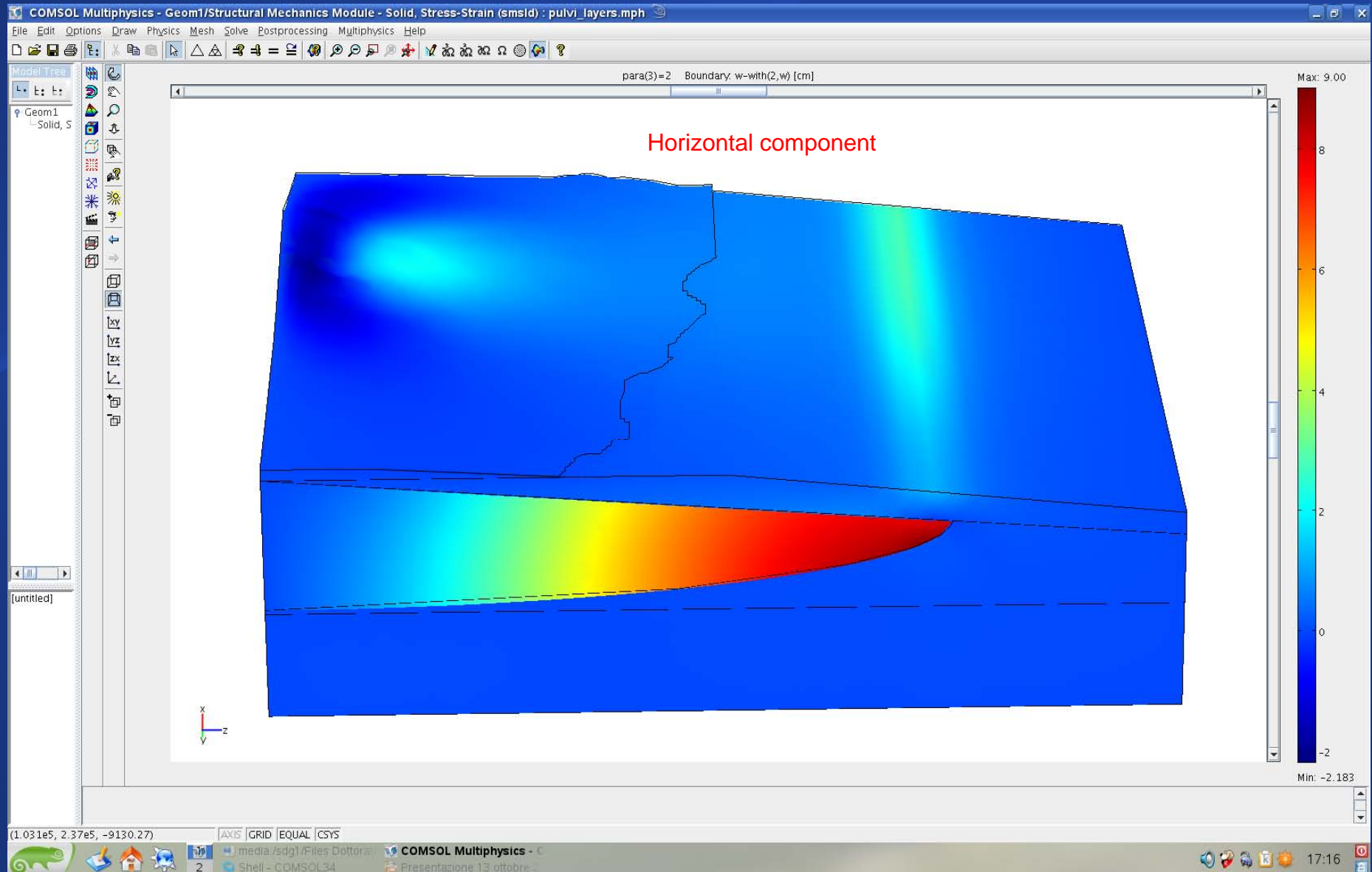
Swept tool used

(1.595e4, 2.126e5, -1.3e5) | AXIS | GRID | EQUAL | CSYS

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Shell - COMSOL34 COMSOL Multiphysics - system/media/sdg1 - Konig

19:17

Step 6: Results and post processing



Discussion

FEM Model results:

- The greatest displacements are observed in the “Valle del Bove” and in the final part of the ramp (anticlinal folds forming?);
- The uplift is one order greater than the horizontal components;
- Along the coast, an uplift of about 5 cm and an eastward movement of about 1 cm is observed;

Observed GPS data:

- “Valle del Bove” is not covered by GPS network. Usually, during inflation periods, variations of some cm are recorded around it. The presence of anticlinal folds off-shore is still debated in literature;
- The horizontal component is one order greater than the vertical one;
- A downlift of about 2 cm and an eastward movement of about 3 cm is observed along the coast;

Conclusion

- Important differences are observed between FEM model results and recorded deformation pattern;
- The FEM model needs to be upgraded with structural and stratigraphical elements;
- Viscoelastic and elasto-plastic regimes could be tested;

Work in progress

- Complete Etna DEM;
- Addition of the High Velocity Body (Plutonic Complex);
- Addition of the principal faults: **Pernicana, S.Venerina, Trecastagni Mascalucia, Ragalna;**

THE END

Acknowledgments. We are very grateful to Gianluigi Zanotelli and Valerio Marra (COMSOL Italy) for the productive discussions and for all the hours dedicated to the model developing.

DEFORMATION THEORY AND STRAIN PARAMETERS

By the Jacobian of the transformation from the coordinate space (x,y) to the displacement space (u,v) we get (avoiding the rotational part) the strain tensor [Livieratos, 1980]:

$$e_{ij} = e_{ji} = \begin{bmatrix} e_{xx} & \frac{1}{2}Y_2 \\ \frac{1}{2}Y_2 & e_{yy} \end{bmatrix}$$

$e_{xx} = \Delta L/L$ (East strain) (>0 for extension)

$e_{yy} = \Delta L/L$ (North strain) (>0 for extension)

$$\gamma_2 = e_{xy} + e_{yx}$$

shear through each line parallel to the east axis (>0 for right lateral shear)

$$\gamma_1 = e_{xx} - e_{yy}$$

shear through each line parallel to NW-SE direction (>0 for right lateral shear)

$e_{xy} = e_{yx}$ shear through each line parallel to the east direction (>0 for right lateral shear)

$$\Delta = e_{xx} + e_{yy}$$

Areal dilatation: area on area unit variation (>0 for area increasing).

Considering a network with n baselines, the strain tensor parameters are calculated from the minimum squares solution of the system defined by n equations of the type: [Livieratos, 1980]

$$e_n = e_{xx} \sin^2(\alpha_n) + \frac{1}{2}Y_2 \sin(2\alpha_n) + e_{yy} \cos^2(\alpha_n)$$

e_n is the strain of the n baseline with an azimuth (α_n) respect to the north and obtained comparing the misures on two subsequent campaigns.