Analogue and numerical modeling of fault patterns produced by a blind, seismogenic, low angle normal fault

L. Bonini (1), D. Finocchio (2, 4), S. Barba (2), D. Di Bucci (3), G. Toscani (1), S. Seno (1), G. Valensise (2)

(1) *Dipartimento di Scienze della Terra, Università di Pavia, via Ferrata 1, 27110 Pavia (ITALY)*
(2) *Istituto Nazionale di Geofisica e Vulcanologia, via Vigna Murata 605, 00143 Rome (ITALY)*
(3) *Dipartimento della Protezione Civile, Via Vitorchiano 4, 00189 Rome (ITALY)*
(4) *Dipartimento di Scienze della Terra, Università di Urbino, Via Saffi 1, 61029 , Urbino (ITALY)*

Summary

We present series of 2Danalogue and numerical models reproducing the tectonic evolution of a low angle (30°), blind, normal fault. The experiments investigate both newly formed structures and strain distribution in the hangingwall of the modelled fault, to identify and discuss a general mechanism underlying this setup. Our case study is represented by a seismogenic fault associated with the disastrous 28 December 1908, Messina Straits, Southern Italy earthquake (Mw 7.1). It consists of a 40 km-long, 30°-dipping normal fault extending between 3 and 12 km depth.

Analogue models show the activation of the entire surface of the master fault. Many high angle synthetic and antithetic normal faults developed in its hanging wall, particularly at the upper tip point. These structures are often organized in one or, less frequently, two graben systems.

Numerical models have been carried out to investigate the strain distribution of the analogue model setup, and to test the hypothesis of a progressive strain migration from the upper tip of the master fault plane downwards.

A comparison between the results of the analogue and numerical models shows agreement in the overall evolution of the system in the localization and development of the deformation.

Introduction

The surface expression of a seismogenic blind normal fault is a hot topic in earthquake geology because the correct localization of this kind of seismogenic source can be much more difficult to be defined than in the case of surface-breaking seismogenic faults. A well known example is represented by the blind, low-angle, normal fault located in the Messina Straits (Southern Italy), which was blamed for the highly destructive 28 December 1908, M_W 7.1 earthquake (Boschi et al., 1989; Valensise and Pantosti, 1992).

A first approach to this topic based on analogue modelling techniques was attempted through a set of 3D analogue models designed with the same setup presented here (Bonini et al., 2008). It was carried out to analyze the consistency between the shallow faults mapped on- and off-shore in the Messina Straits and the presence at depth of a large, blind, seismogenic fault (Bonini et al., under review).

In the present study, using the same setup, we investigate in 2D both the normal fault pattern and the strain distribution produced by the slip along a blind, low angle normal fault, and then we compare the results of the analogue modeling to the equivalent numerical experiments.

Numerical and analogue modeling methods are independent techniques which allow investigating the evolution of secondary structures due to the slipping on the deep master fault. We expect results comparable from these techniques when applied to the same setup.

Experiment set-up

Analogue modeling

We simulated a simplified stratigraphic sequence, which represents the natural conditions of upper crustal rocks (e.g., Hubbert, 1937), by using dry sand to model the uppermost brittle crust. The models were scaled 1:100,000 (1 cm = 1 km).

The apparatus was specifically designed to reproduce in 2D the motion of the seismogenic fault lying beneath the Messina Straits (hereinafter master fault: MF). It is formed by a 60 cm-wide sandbox (Figure 1A) and a 30°-dipping plane, which simulates the MF; above it, homogeneous dry sand represents the hanging wall rocks. A ~1 cm-thick microbeads layer spread on the MF plane reduces the basal friction and allows the hanging wall materials to slide. The box is filled with a 3 cm-thick layer of dry sand, which corresponds to the uppermost crust above the master fault (Figure 1A).

Shaft-driven, progressive motion of the sliding backstop (Figure 1A) enables slip on the right side of the apparatus over a width of 20 cm, corresponding to the scaled length of the seismogenic fault. This allows the evolution of the fault system to be observed in 2D, where the inception and development of newly formed fault segments is expected. We carried out the experiments under normal gravity with a final displacement value of 3.50 cm and two intermediate steps of 0.50 and 3.50 cm, respectively, to test the development of newly formed structures at different steps.

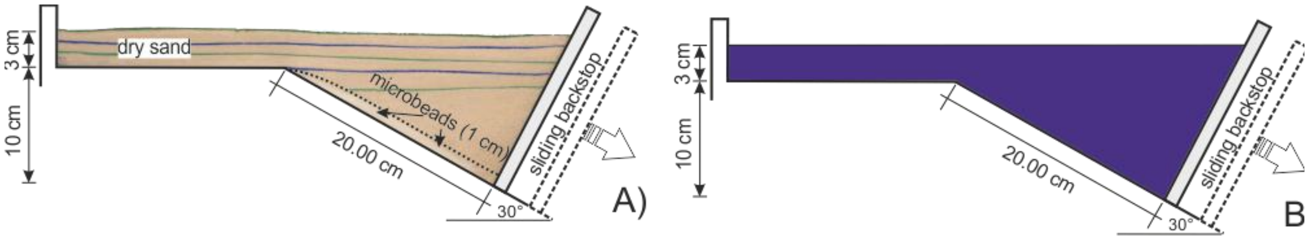

Figure 1. Setup for the analogue (A) and numerical (B) modelling.

Numerical modeling

The numerical modeling was implemented by means of finite element analysis, and solved through the software MSC Marc 2010 (MSC Software Corporation, 2010). The numerical sandbox has the same geometry of the analogue model (Fig. 1). The finite element grid for the sand includes 9697 nodes and 9405 quadrilateral elements of variable dimension. The element size is 0.15 cm in the region with more detail. A friction value μ=0.1 is applied between the sliding backstop and the sand. As in the analogue model, the backstop moves in three displacement steps of 0.50 cm (MS 1), 2.00 cm (MS 2) and 3.50 cm (MS 3; Fig. 2). We modelled the "sand" as an elastoplastic medium represented by a Lagrangian formulation; the material properties are shown in table 1.

Table 1. Analogue and numerical model parameters

Parameter	*Analogue model*	*Numerical model*
Cohesion	~ 10 Pa	-
Internal friction	sand: 33° microbeads: 24°	-
Scaling length ratio	1:100,000	1:100,000
Young's modulus	-	11 MPa
Poisson ration	-	0.35
Mass density	-	2 g/cm^3

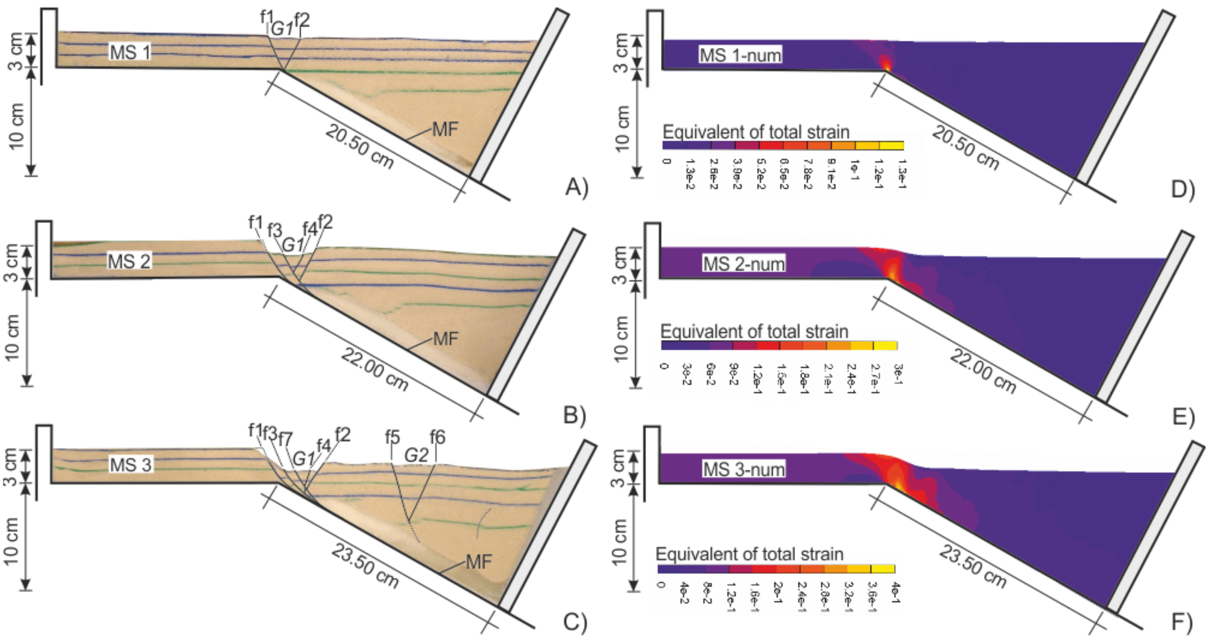

Figure 2. Left side - Results of the analogue experiments (A, B, C). Right side - Results of numerical simulation with magnitude of the maximum principal strain 0.50 cm (D), 2.00 cm (E) and 3.50 cm of extension.

Model results

Analogue modeling results are here synthesized.

(1) All synthetic and antithetic high angle normal faults are directly linked to the low angle master fault and are all nucleated during the very early stages of deformation. These structures are exclusively located at the upper tip point of the master fault (from 0.00 to 2.00 cm of extension).

(2) By increasing the extension (e.g. > 2.00 cm), part of it is transferred towards the deeper part of the master fault plane. Moreover, new faults are developed to the central part of the MF hangingwall (f5 and f6 in Figure 2C).

Previous results are consistent with the numerical modeling results. Indeed, as a consequence of the sliding of the virtual backstop, the strain has risen up from the tip point of the MF to a wider area located above the fault plane.

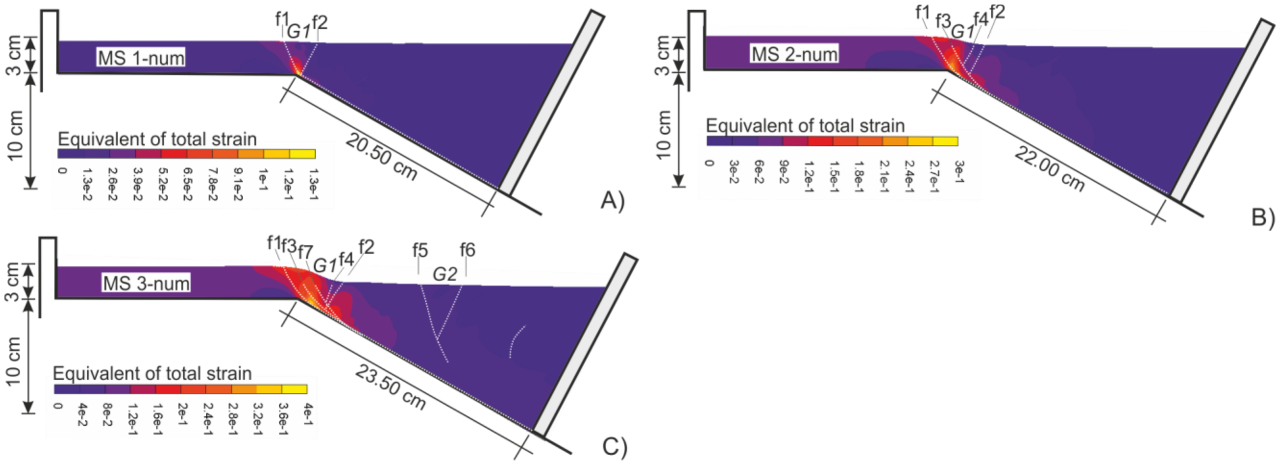

Figure 3. Results of the numerical model. White dashed lines represent the faults obtaioned by the analogue experiments.

Conclusions

Based on the comparison of analogue and numerical experimental results with our natural laboratory of the Messina Straits, we infer that in nature the long-term activity of a blind normal fault produces: 1) maximum deformation close to the buried upper tip of the master faults during the early stages of development; 2) progressive migration downward the fault plane of both stress and strain (as the extension increases), and consequent widening of the zone hosting active secondary structures.

REFERENCES

Bonini, L., Di Bucci, D., Seno, S., Toscan,i G., Valensise, G., 2008. Integrazione tra assetto strutturale di superficie e faglie sismogenetiche nello Stretto di Messina sulla base di modelli analogici. Riassunto e comunicazione orale presentati al convegno “1908-2008: scienza e società a cento anni dal grande terremoto”, Reggio Calabria, 10/12 Dicembre 2008. Volume dei riassunti estesi. *Miscellanea INGV*, **3**, 17-18.

Bonini, L., Di Bucci, D., Toscani, G., Seno, S., Valensise, G. (under review). Reconciling deep seismogenic and shallow active faults through analogue modeling: the case of the Messina Straits (Southern Italy). *Journal of the Geological Society*, London.

Boschi, E., Pantosti, D. & Valensise, G. 1989. Modello di sorgente per il terremoto di Messina del 1908 ed evoluzione recente dell’area dello Stretto. *Atti VIII Convegno G.N.G.T.S.*, Roma, 245–258.

Hubbert, M. K. 1937. Theory of scale models as applied to the study of geologic structures. *Geological Society of America Bulletin*, **48**, 1459−1520.

Valensise, G. & Pantosti, D. 1992. A 125 Kyr-long geological record of seismic source repeatability: the Messina Straits (southern Italy) and the 1908 earthquake (Ms 71/2). *Terra Nova*, **4**, 472−483.