Active strain-rate Across the Messina Straits and Kinematics of Sicily and Calabria From GPS Data

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Abstract

The Messina Straits (Soutehrn Italy) is the locus of one of the strongest seismic event that ever hit Italy during historical times, the 1908 Mw 7. earthquake, and the same region also suffered major damage from other strong earthquakes in the last few centuries [http://emidius.mi.ingv.it/CPTI]. However, despite the large amount of studies carried out, our knowledge of the present-day deformation of the area is still debated, particularly regarding the rate and shape of interseismic loading across the Straits, and its kinematic and geodynamic framework. In this work we analyze all the observations collected over the Messina non-permanent GPS network for the 1994-2008 time span, and data from about 700 Continuous GPS (CGPS) stations in the Euro-Mediterranean region. The output of our analysis is a new and denser velocity field (Fig. 1), which confirms the change in the velocity trends between Sicily and Calabria [D'Agostino & Selvaggi, JGR, 2004; Serpelloni et al., GJI, 2007], moving from NNW-ward to NE-ward, and details a fan-like pattern across the Straits (Fig. 1 inset), demonstrating that this area is acting as a primary tectonic boundary between two different kinematic domains. The maximum strain-rates observed across the Straits are ~90 nanostrain/yr (Fig.2), with extension oriented about normal to the coasts of Sicily, according to the presence of normal faults driving crustal deformation. GPS velocities are used to model the creeping dislocation at depth, adopting a half space dislocation model (Fig.3), and obtaining optimal values of 3.4 and 1.8 mm/yr for the dip-slip and strike-slip rates, respectively, along a 30° dipping normal fault, locked at 7.8 Km depth. However, the measured velocity gradient across the Straits is likely to be significantly affected by the elastic strain contribute of other nearby active (and locked) faults. For this reason we develop a regional elastic block model to investigate these effects, and particularly seeking for signals of the possibly locked subduction interface beneath the Straits onto the observed velocity gradients in NE-Sicily and SW-Calabria.

Velocities and Strain-rate

We process the data collected on the Messina GPS Network [Anzidei et al., J. Geodyn., 1998] during the 1994, 2002, 2004 and 2008 campaigns, together with data from about 700 CGPS stations in the Euro-Mediterranean and African region, by mans of the GAMIT/GLOBK [wwwgpsg.mit.edu/~simon/gtgk] and QOCA [http://gipsy.jpl.nasa.gov/qoca] software. Loosely constrained daily solutions of all GPS networks are combined by means of the ST_FILTER program of QOCA together with global solutions from SOPAC, aligning position time-series to the IGSO5 realization of the ITRF reference frame. Velocities of Epoch GPS (EGPS) stations are computed by fitting a constant rate and uncertainties are evaluated adopting a white+random walk error model. Velocities for CGPS stations are obtained by modeling jumps and seasonal signals, while realistic uncertainties are computed adopting a white+flicker noise error model [Williams et al., JGR, 2004].

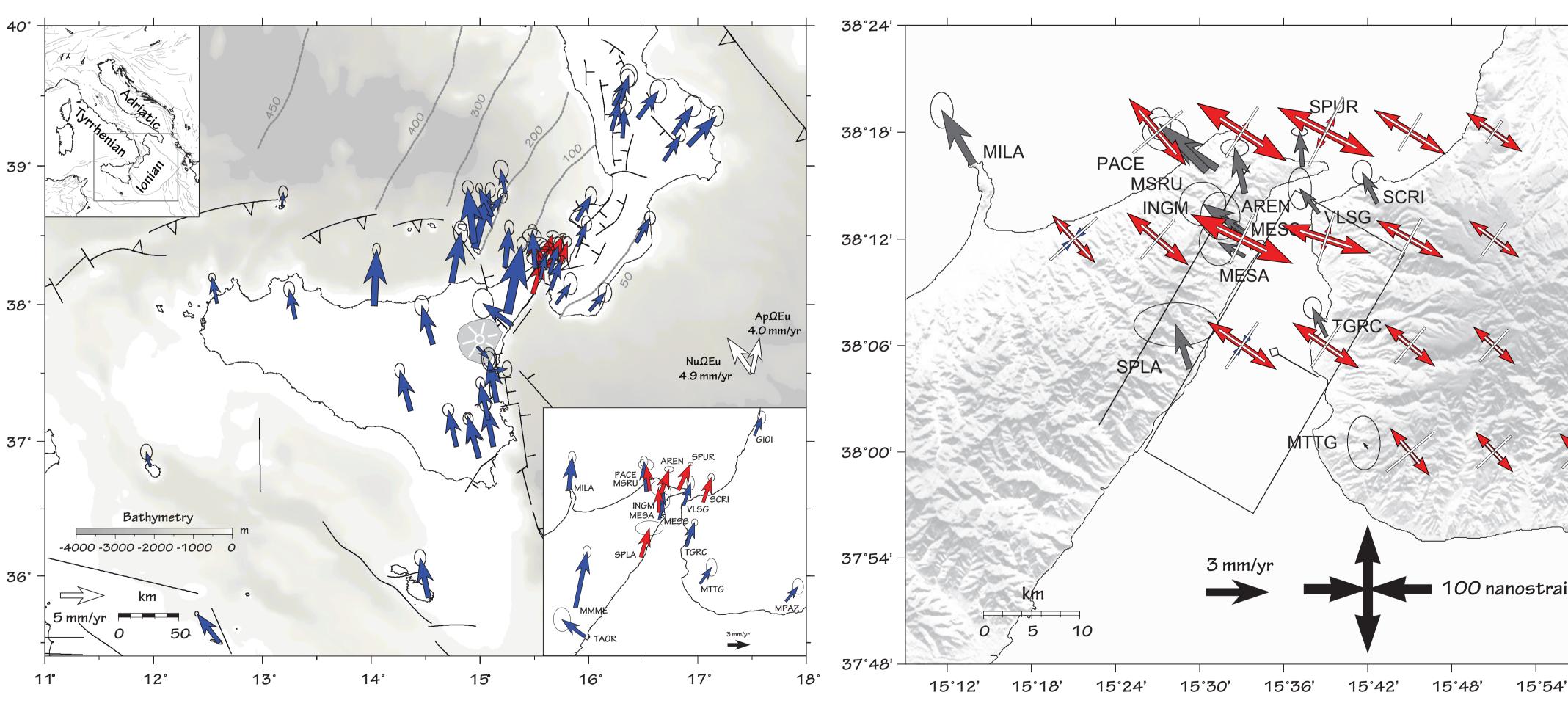


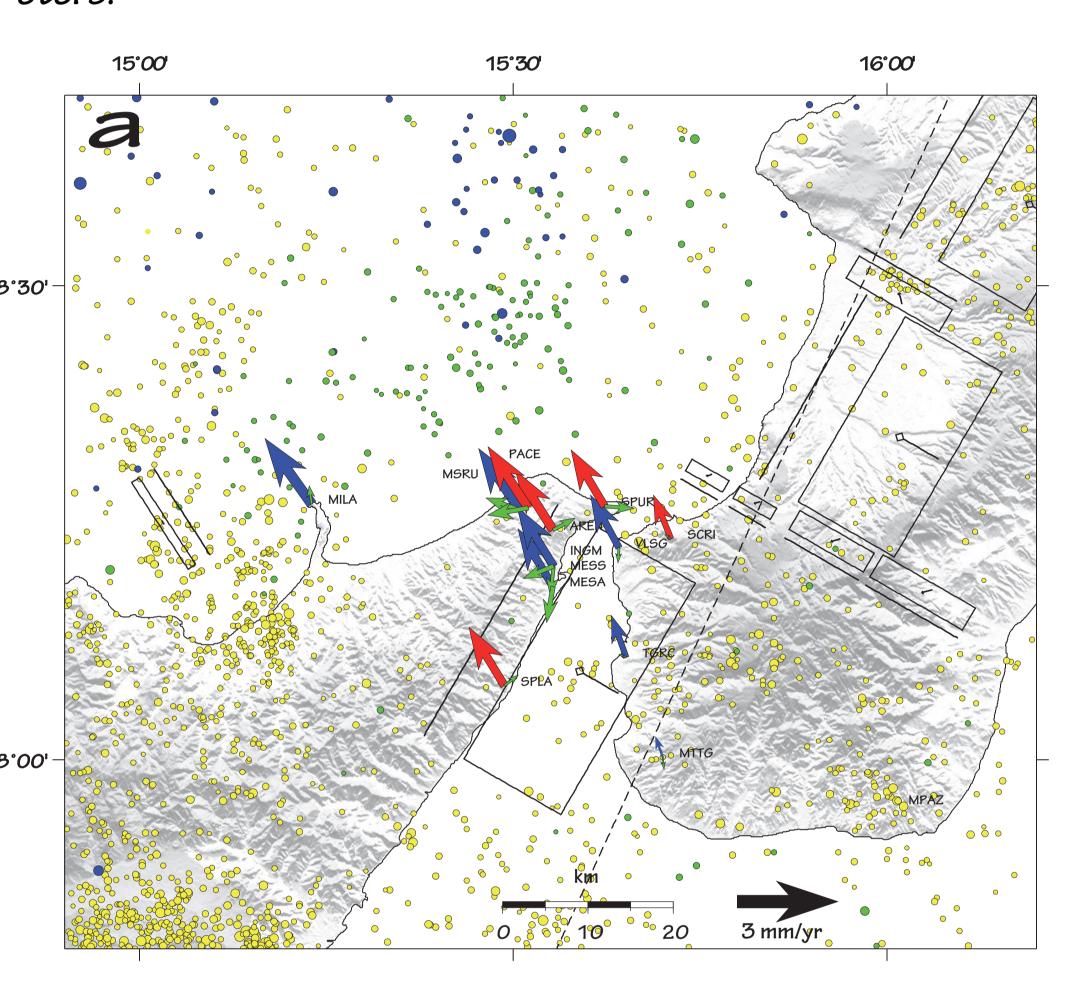
Figure 1. Horizontal GPS velocities (with 95% confidence ellipses) w.r.t Eurasia. Red arrows and blue arrows show EGPS and CGPS station velocities, respectively. White arrows in the Ionian Sea display kinematic boundary conditions given by two alternative plate models [D'Agostino et al., JGR, 2008].

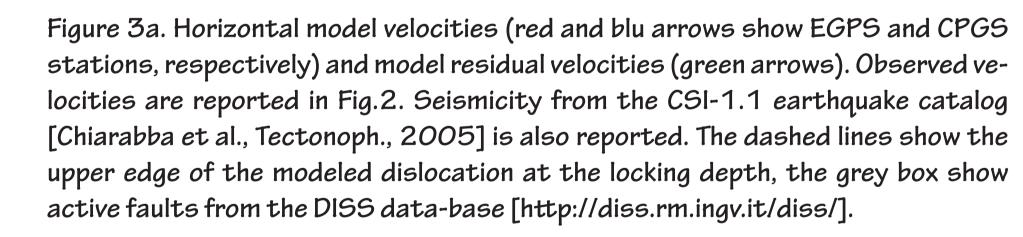
Figure 2. Horizontal velocities given with respect to station MPAZ (grey arrows) and strain rate eigenvectors. Red arrows and white bars show maximum extensional rates and uncertainties,

Horizontal velocities (Fig. 1 inset) are used to compute the strain rate field (Fig. 2) across the Messina Straits. However, given the discrepancies observed at stations in the SW region of the study area (i.e., TAOR and MMME in Fig. 1), we excluded those sites from our computation. Interpolation of the station velocities is done, over a regular grid, through least squaress, each time estimating strain and rotation rates at one spot using velocity data in the neighborhood [Shen et al., JGR, 1996], reweighted by a Gaussian function $\exp(-\Delta^2/d^2)$; where Δ is the distance between a GPS station and the spot being evaluated, and d is a smoothing distance that, optimally through balancing a trade-off between the formal uncertainty estimate of the strain rate and the total weight assigned to the data. We obtain d ranging between 20 and 46 km, with a typical value of ~21 km.

Fault Model

Horizontal GPS velocities and uncertainties allow us to develop first-order models of the deformation using elastic dislocation theory and model optimization methods, assuming that the observed velocity gradient is the effect of slip on a planar dislocation locked above a given depth and that all strain that accumulates interseismically is elastic. In the inversion we employ rectangular [Okada, 1985], uniform-slip dislocations embedded in an elastic, homogeneous and isotropic half-space. We use a constrained, non-linear optimization algorithm [Bürgmann et al., JGR, 1997], which solves for the best fit rectangular dislocation geometry (parameterized by length, depth, width, dip, strike, and fault edge location) and fault slip rate. We use 15 GPS stations (Fig. 3) across the Straits and assume a quasi-2D model geometry (i.e., a very long fault along strike and along dip). On the basis of the computed strain rate field (Fig.2) we constrain the fault strike to be close to N30°E (i.e., perpendicular to the maximum extensional strain). The optimal model fault plane (WRSS/N = 3.8) and slip-rates are reported in Table 1, together with 95% confidence intervals estimated using the bootstrap percentile method [Arnadottir and Segall, JGR, 1994]. Figure 4 displays histograms of model parameters from 5000 random bootstrap resamples and the corresponding mean values and uncertainties for all the inverted param-





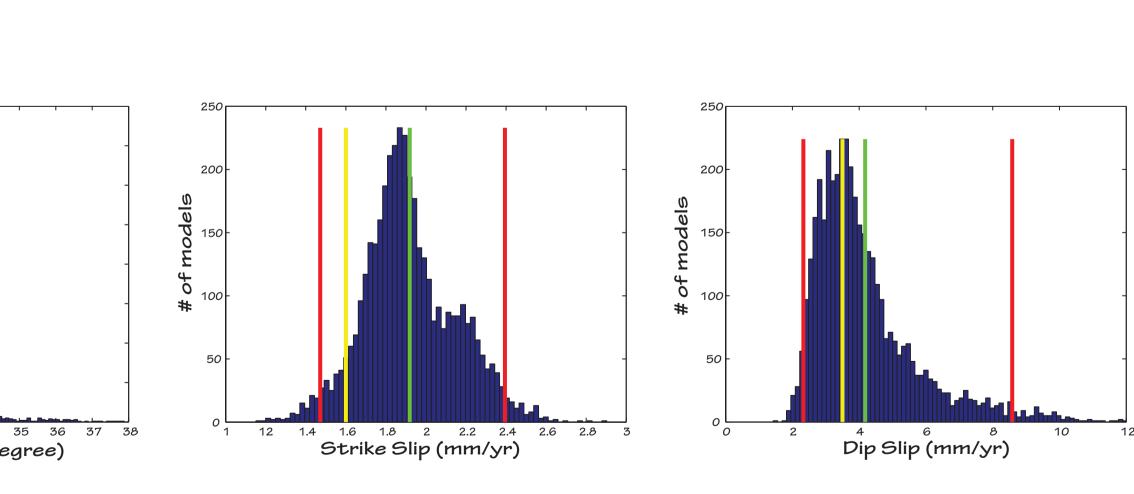


Figure 3b. N120°E cross section showing the modeled velocity gradient from optimal fault parame-

ters (green line) and observed velocity values (red and blu circles, with uncertanties, show EGPS

and CGPS stations, respectively). The two stations on the Peloritani Mts. (PACE and MSRU) show

larger model residuals, even if their velocities are well constrained by the available data.

Figure 4. Histograms of modeled fault parameters from 5000 bootstrap resamples of the original data. Red lines mark lower and upper bounds values of 95% confidence level, evaluated adopting the bootstrap percentile method. Green and yellow lines mark mean and optimal values of each parameter, respectively.

30.1	1.6	3.5
30.8	- 0.4 1.9 + 0.5	-1.8 4.1 +4.4
	5.1 -1.5 30.8	5.1 -1.5 - 0.4 30.8 1.9

Table 1. The upper row shows the values of optimally inverted model parameters estimated with the non linear inversion algoritm. The bottom row shows the mean values, obtained by running inversion with 5000 bootstrap resamples of the original data, with 95% confidence level interval estimated using the bootstrap percentile method.

Block Model

The measured velocity gradient across the Straits is modeled assuming that it is the effect, at the surface, of a single normal fault accumulating strain. However, around the Messina Straits other active faults are likely to be interseismically accumulating elastic deformation. In particular the Tindari-Giardini fault system (TGF in Fig. 5c), the Calabrian extensional system (CAL1, CAL2 and CAL3 in Fig.5c), and, possibly, the subduction interface offshore Calabria (SI1, SI2 and SI3 in Fig. 5c). In order to investigate the effects of other faults onto the measured velocity gradient of Fig.3b, we develop an elastic block model [Meade & Hager, JGR, 2005] that accounts for crustal block rotations and block-bounding faults strain accumulation. In this work we investigate, in particular, the effects of the possibly locked subduction interface, which is modeled as three NW-ward 20° dipping planes (Fig.5c), as indicated by geological and geophysical data [eg., Cernobori et al., Tectonoph., 1996]. Given the uncertainties about the shallow subduction fault geometry and coupling degree, keeping fixed all other faults, we vary the locking depth of the subduction interface segments (S1, S2, and S3 in Fig. 5C) between 0 and 40 Km, evaluating the reduced chi squared statistics (Fig.7) for the both kinematic boundary conditions (Fig.5a and b). We find a minima for a value of 22 Km, which corresponds to a subduction interface width of about 64 Km. Figure 6 shows the model residual velocities obtained using Nubia fixed velocities. We find a significant trade-off between subduction interface locking depths and interseismic slip rates of normal faults along Messina and Calabria (Fig.8), suggesting that the degree of coupling of the subduction interface can significantly affect the measured velocity gradients in NE-Sicily and Calabria. If we look in details the residual velocities of GPS stations across the Straits (Fig. 9a), we find that two stations in particular, MSRU and PACE on the Peloritani Mts., significantly reduce their velocity residuals when accounting for some degree of locking of the subduction interface (see Fig.9b). It is worth noting that those two sites are the stations that display largest residuals in the Messina fault inversion (Fig. 3).

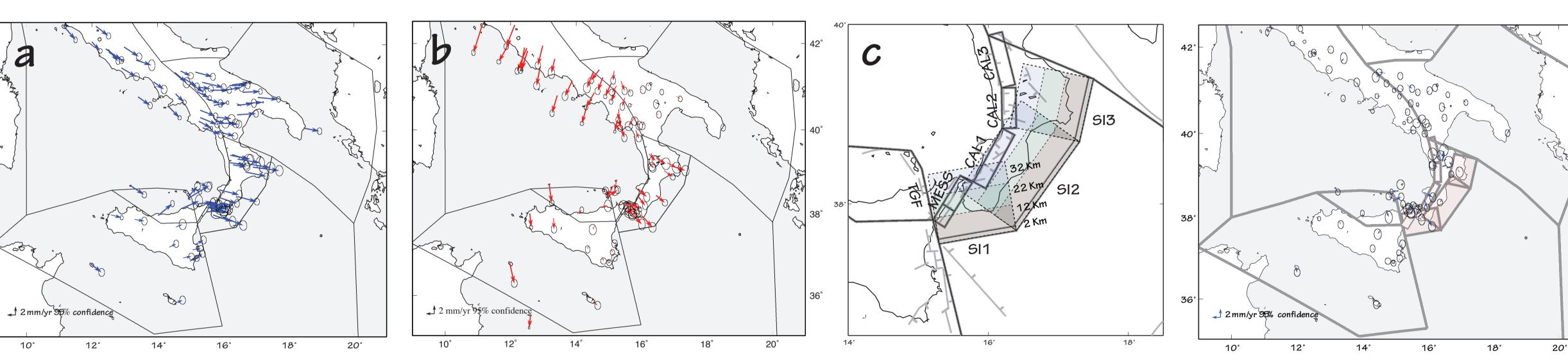


Figure 5. GPS velocities given w.r.t. Nubia (a) and Apula (b) plates [D'Agostino et al., JGR, 2008] and blocks geometry. We use vertical dislocations, locked at 10 Km for all faults, except for the subduction interface in the Ionian Sea (SI1, SI2 and SI3) which are 20° NW-ward dipping and normal faults in NE-Sicily and Calabria (MESS, CAL1, CAL2 and CAL3), which are 30° SE-ward dipping. We vary the locking depth of the subduction interface segments from 0 to 40 Km depth, (Fig.5 c), while keeping all other faults geometry fixed, and evaluate the chi squared statistics (Fig.7).

Figure 6. Model residual velocities for the value of subduction interface locking depth giving the minima in Fig.7 (i.e., 22 Km). The figure refers to starting velocities given w.r.t. Nubia.

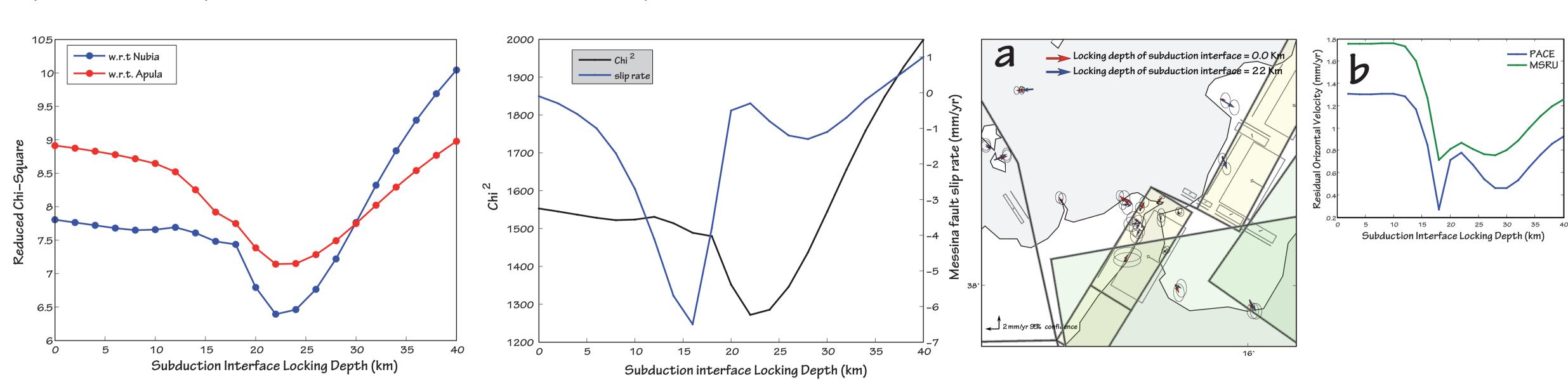


Figure 7. Reduced chi squared with respect to subduction interface Figure 8. Chi squared values with respect to subduction locking depth for both kinematic boundary conditions,

interface locking depth and slip rates of Messina fault at varying the subduction interface locking depths.

Figure 9. Residual velocities across the Messina Straits for the O Km and 22 Km locking depths of the subduction interface (a) and residual velocities of PACE and MSRU plotted with respect to the subduction interface locking depth (b).

Conclusions

We use GPS velocities to measure and model crustal deformation across the Messina Straits. We compute the strain-rate field in NE-Sicily and SW-Calabria, and find that the largest extensional rates across the Straits (~90 nanostrain/yr) are oriented perpendicularly to the coasts of Sicily. We use horizontal velocities and model optimization methods to invert for geometry and slip-rates of the Messina Straits fault, finding that the observed velocity gradient is in agreement with the presence of a 30° SE-ward dipping normal fault, locked at 7.6 Km depth, with 3.4 and 1.8 mm/yr of dip-slip and strike-slip rates, respectively. We use a bootstrap approach to evaluate the parameter uncertainties, and find sistematic larger residual for two, but well constrained, stations in NE-Sicily (PACE and MSRU). A simple elastic block model reveals that velocity gradients measured in NE-Sicily and Calabria, and consequently inverted fault sliprates, can be significantly affected by the superimposed signal of a possibly locked subduction interface.