KINEMATIC MODEL OF ACTIVE EXTENSION ACROSS THE UMBRIA-MARCHE APENNINES FROM GPS MEASUREMENTS: FAULT SLIP-RATES AND INTERSEISMIC COUPLING OF THE ALTO TIBERINA LOW-ANGLE NORMAL FAULT

L. Anderlini[1,2], E. Serpelloni[3], M.E. Belardinelli[1]

[1]Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Bologna, Italy
[2]Dipartimento di Fisica, Settore di Geofisica, Università di Bologna, Italy
[3]Istituto Nazionale di Geofisica e Vulcanologia, Centro Nazionale Terremoti, Roma, Italy

Introduction. The growing number of continuously recording GPS stations over Italy, particularly during last 5 years, gives the possibility to detect, with higher accuracies and precisions than in the past, gradients of ground deformation rates across major fault structures. Using a kinematic block-modeling approach it is possible to model the observed gradients in order to estimate fault parameters and long-term slip-rates, inferring new information useful to evaluate the seismic potential of a region.

The Umbria-Marche Apennines are characterized mainly by SW-NE oriented extensional deformation (see Fig. 1), as documented by geodetic (D'Agostino *et al.*, 2009), geologic (Tondi, 2000; Boncio and Lavecchia, 2000a) and seismological (Pondrelli *et al.*, 2006) data. Most of major historical and instrumental earthquakes occurred mainly on the western side of chain,

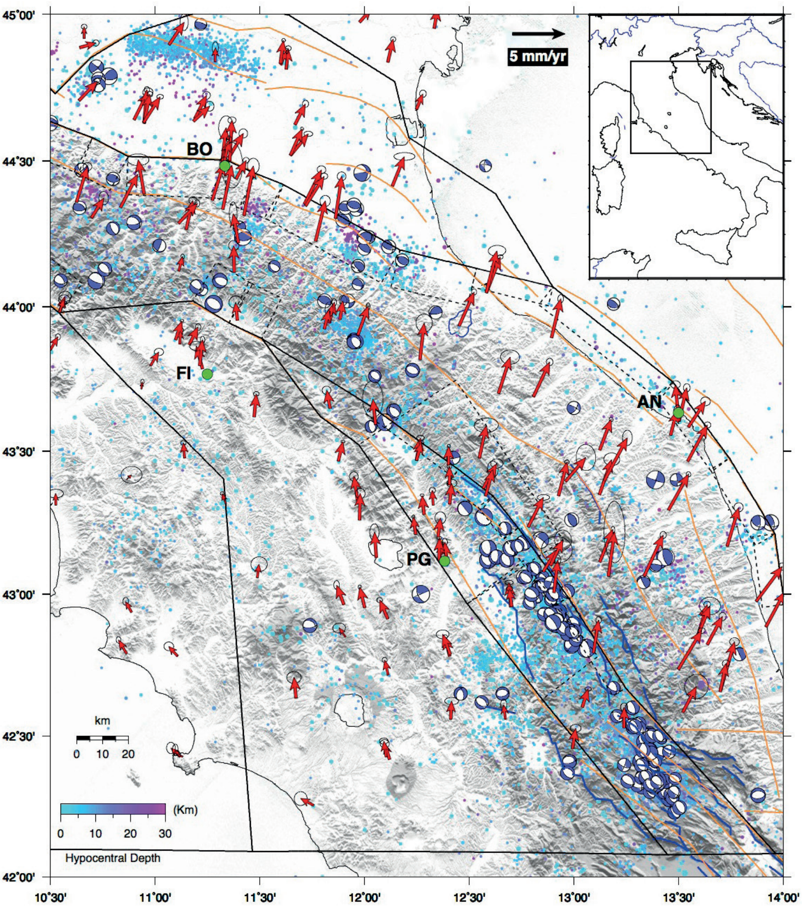

Fig. 1 – Seismotectonic framework of central Italy, red arrows show observed GPS velocities, black lines indicate bounds of the elastic blocks, blue dots represent instrumental seismicity, and also available focal mechanisms are shown; orange lines are DISS fault sources and blue lines are fault boxes from Lavecchia *et al.* (2002).

bounded by west-dipping buried high-angle normal faults (Boncio and Lavecchia, 2000b; DISS working group, 2010; Rovida *et al.*, 2011). Nevertheless which of the known fault systems play a major role in accommodating the extension, and which are the modes (seismic VS aseismic deformation) this extension is taken up, is still a debated topic. In particular recent studies about the northernmost part of Umbria-Marche region show seismic and tectonic activity (Chiaraluce *et al.*, 2007, Hreinsdóttir and Bennet, 2012, Mirabella *et al.*, 2011) on correspondence of Alto Tiberina (AT) low-angle normal fault (LANF), which is widely documented by geological data (Brozzetti, 1995; Boncio *et al.*, 2000; Collettini, 2000) and deep seismic reflection profiles (CROP03, Barchi *et al.*, 1998). The supposed detachment of AT fault is an interesting case in which crustal extension could be driven by a LANF, considered by "Andersonian" theory as averse to faulting.

During last years on Umbria-Marche Apennines close to Gubbio fault (GuF) a dense network of continuous GPS stations, belonging to the RING-INGV network, has been installed, improving significantly the spatial resolution of the detectable geodetic gradients. Using kinematic block models to reproduce GPS velocity field, we define the optimal fault boundaries accommodating the tectonic extension.

GPS data processing. To estimate the present-day deformation on Northern Apennines, we analyzed data from a dense network of continuous and survey-mode GPS stations. Survey-mode stations are those installed in the framework of the RETREAT project (Bennett *et al.*, 2012). The processing follows a three-step approach, as described on Serpelloni *et al.* (2006), which includes: 1) raw phase data reduction, 2) combination of loosely-constrained solutions and reference frame definition, and 3) time series analysis.

In the first step, we use the GAMIT (V10.4) software (Herring *et al.*, 2010) on daily GPS phase observations to estimate geodetic parameters applying loose constraints. We apply the ocean-loading and pole-tide correction model FES2004, and use the parameterized version of the VMF1 mapping function, the GMF for both hydrostatic and non-hydrostatic components of the tropospheric delay model. We use the IGS absolute antenna phase center model for both satellite and ground-based antennas. Continuous GPS data are divided into several subnets and processed independently; each subnet share a set of high quality IGS stations, which are subsequently used as tie-stations in step 2. Survey-mode GPS networks are processed separately, adding a larger number of high quality cGPS stations, in order to reduce the average baseline lengths.

In the second step we use the ST_FILTER program of the QOCA software (Dong *et al.*, 2002) to combine all the daily loosely constrained solutions, for both cGPS and sGPS subnets, with the global and regional solutions made available by SOPAC (http://sopac.ucsd.edu), and simultaneously realize a global reference frame by applying generalized constraints (Dong *et al.*, 1998). Specifically, we define the reference frame by minimizing the horizontal velocities of the IGS core stations (http://igscb.jpl.nasa.gov), while estimating a seven-parameter transformation with respect to the IGS08 realization of the ITRF2008 frame (Altamimi *et al.*, 2011).

In the third step we analyze the position time series in order to estimate velocities and uncertainties. For the cGPS and sGPS stations we estimate a constant velocity term together with annual and semi-annual seasonal components and, if present, offsets at specific epochs, and adopt a white + flicker noise model, following Williams *et al.* (2004). We incorporate data from cGPS and sGPS stations with an observation period longer than 2.5 years, as shorter intervals may result in biased estimates of linear velocities (Blewitt and Lavallée, 2002).

We use velocities and uncertainties of cGPS stations located on tectonically stable domains of the Eurasian and Nubian plates in order to estimate their Euler rotation poles. The final GPS velocity field is calculated w.r.t. Eurasia fixed frame and in this study we use overall 594 velocities (from continuous and survey-mode stations), located on Italian peninsula and European region.

Block modeling setting and analysis. The final geodetic interseismic velocity field provides information on both crustal blocks and microplate rotations and elastic responses of the major fault systems. The so called elastic block modeling method is a kinematic approach with which geodetic velocities are modeled considering the crust subdivided on discrete rigid and elastic blocks, bounded by faults embedded in an homogeneous and isotropic half-space (Okada, 1985). This kind of approach follows the *back-slip* concept (Savage, 1983), where the surface velocity field is decomposed into a rotational component of blocks and an elastic component, representing a coseismic slip-deficit on the block-bounding faults boundaries. In our analysis we use the block model formulation implemented in the Matlab code of Meade and Loveless (2009), which performs a linear inversion of geodetic data to determine rotational poles for each block and the corresponding fault slip-rates.

Since this approach requires defining the blocks geometry *a-priori* apriori, we set the block-boundary positions and fault parameters (dip angle and locking depth, i.e. seismogenic thickness of fault) using geological (DISS working group, 2010; Lavecchia *et al.*, 2002) information, taking into account also information from the available instrumental seismic catalogs. The whole model consists on 16 blocks related to Alps, Dinarides and Central Apennines, in order to consider a self-consistent kinematic scenario of the northern Apennines and Adriatic region. In particular we define the AT fault segment as a ~70 km long, 15° east-dipping fault, with a locking depth of 12 km, as shown by relocated microseismicity of Chiaraluce *et al.* (2007) and the isobaths obtained by Mirabella *et al.* (2011). Moreover we define the antithetic GuF as west-dipping plane of 40° with 6 km of locking depth, as a mean of the values proposed in the literature (Lavecchia *et al.*, 2002; Collettini *et al.*, 2003; Pucci *et al.*, 2003).

Focusing our analysis on the northern sector of the Umbria-Marche Apennines, we perform different tests to verify which of the fault boundaries proposed accommodates the tectonic

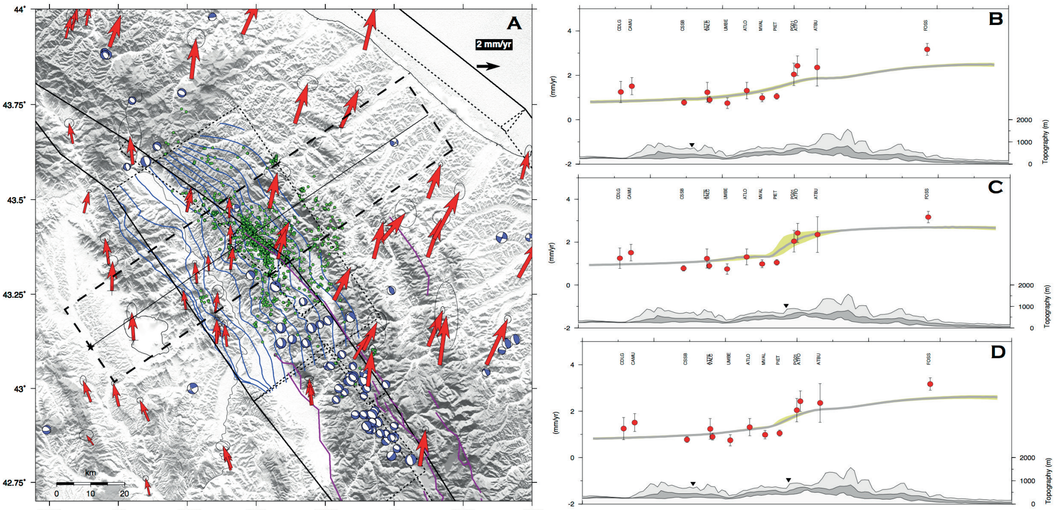

Fig. 2 – A) Near-field observed GPS velocities (red arrows) with block boundaries (black lines) and dipping planes (small dashed lines); blue lines are the ATF isobaths from Mirabella *et al.* (2011), violet ones represent fault boxes from Lavecchia *et al.* (2002) and green dots are the relocated microseismicity from Chiaraluce *et al.* (2007); large dashed box indicates the area interested by profiles shown on B-C-D; profile elements – red dots indicate observed velocities projected on the 55°N direction, with one standard deviation error bars and gray line represents the projected mean value of modeled velocities computed on a dense grid, yellow envelope indicates the variability of the modeled velocities within the swath profile and black triangle shows emerging faults tracves; B) modeling profile considering as fault boundary only the ATF fault; C) only antithetic faults as fault boundary; D)both fault systems.

extension-rate measured by geodetic data, which is of the order of ~2-3mm/yr oriented NE-SW (see Fig. 1). In particular we test three different scenarios in which we consider as fault boundary: 1) the Alto Tiberina LANF, 2) the antithetic high-angle normal faults and 3) both faults. To estimate the best model solution we compute for each inversion the reduced chi squared of data and we use the Fisher test (Stein and Gordon, 1984) to evaluate the acceptance between *n* and *n+1* plate models, i.e. to asses if more complex models are justified by the data.

Tab. 1 reports the results of our tests, together with the corresponding slip-rates obtained in each inversion. As we can see from Tab. 1, the reduced chi-squared values are lower assuming geometry 3, for which also the F-test is positive. The corresponding fault slip-rates obtained from each inversion are representative of the attempt of inversions to reproduce the horizontal tectonic extension by mean elevated slip-rates on faults, which are higher than those proposed on literature (Collettini *et al*., 2003; Pucci *et al*., 2003), but on geometry 1 we obtain the same slip-rate as on Hreinsdóttir and Bennett (2010). Using two fault systems as plate boundary we obtain lower down-dip slip-rates more in agreement with geological information, giving a total horizontal extension comparable with geodetic signal. Considering thus the result here obtained with the numerous information proving a very likely activity of both faults, we could infer that the tectonic extension on this sector of Apennines should be accommodated by at least these two major fault systems.

Tab. 1 – Reduced chi-squared values computed for the whole GPS dataset (tot) and for a selected set of stations (sel) located close to the northern sector of Umbria-Marche Apennines, for each inversion, performed with different setting geometries: 1 – only AT fault as block boundary; 2 – only antithetic faults as block boundary; 3 – considering both fault systems; the sixth and seventh columns report inferred down-dip fault slip-rates from elastic block modeling and in the last one is computed the corresponding horizontal slip-rate on extensional direction.

Geometry	Chi2rid (tot)	Chi2rid (sel)	ATF S.R. (mm/yr)	GuF S.R. (mm/yr)	Hor. S.R. (mm/yr)
1 - ATF	9.49	8.46	-2.4	-	-2.3
2 - GuF	9.51	7.89	-	-2.8	-2.1
3 - ATF + GuF	9.36	7.29	-1.5	-1.3	-2.4

Discussion and interseismic coupling on the ATF plane. Our block-modeling analysis suggests that on northern sector of the Umbria-Marche Apennines both the Alto Tiberina LANF and the antithetic, west-dipping, high-angle normal fault, here defined by the Gubbio fault, accommodate the tectonic extension measured by GPS stations. Nevertheless looking a velocity cross section about normal to the strike of major faults (see Fig. 2), we observe that a group of GPS sites, located between the two fault systems, show a systematic "flattening" of the velocity gradient, which is not well modeled by the three inversions discussed above. We tried to understand if the gradient can be better explained using different fault parameters for ATF and for this purpose we performed a series of inversions varying systematically locking depth and dip of the fault (Mastrolembo Ventura, 2012). Evaluating for each inversion the corresponding reduced chi-squared, we found a minimum for the ATF parameters that are close to the initial values (10 km of locking depth instead of 12 km). This result suggests that the ATF could have a significant elastic contribution on the observed geodetic gradient.

The approach used so far considers faults as rectangular planes. To evaluate a model including variable, non-uniform slip-deficit on the ATF, we generate a curved surface, meshed with triangular patches, using the GMSH software (Geuzaine and Remacle, 2009), and following the depth contour lines provided by faults isobaths from Mirabella *et al.* (2011). Moreover we modified the original code to invert for the slip-deficit distribution using a linear least-square

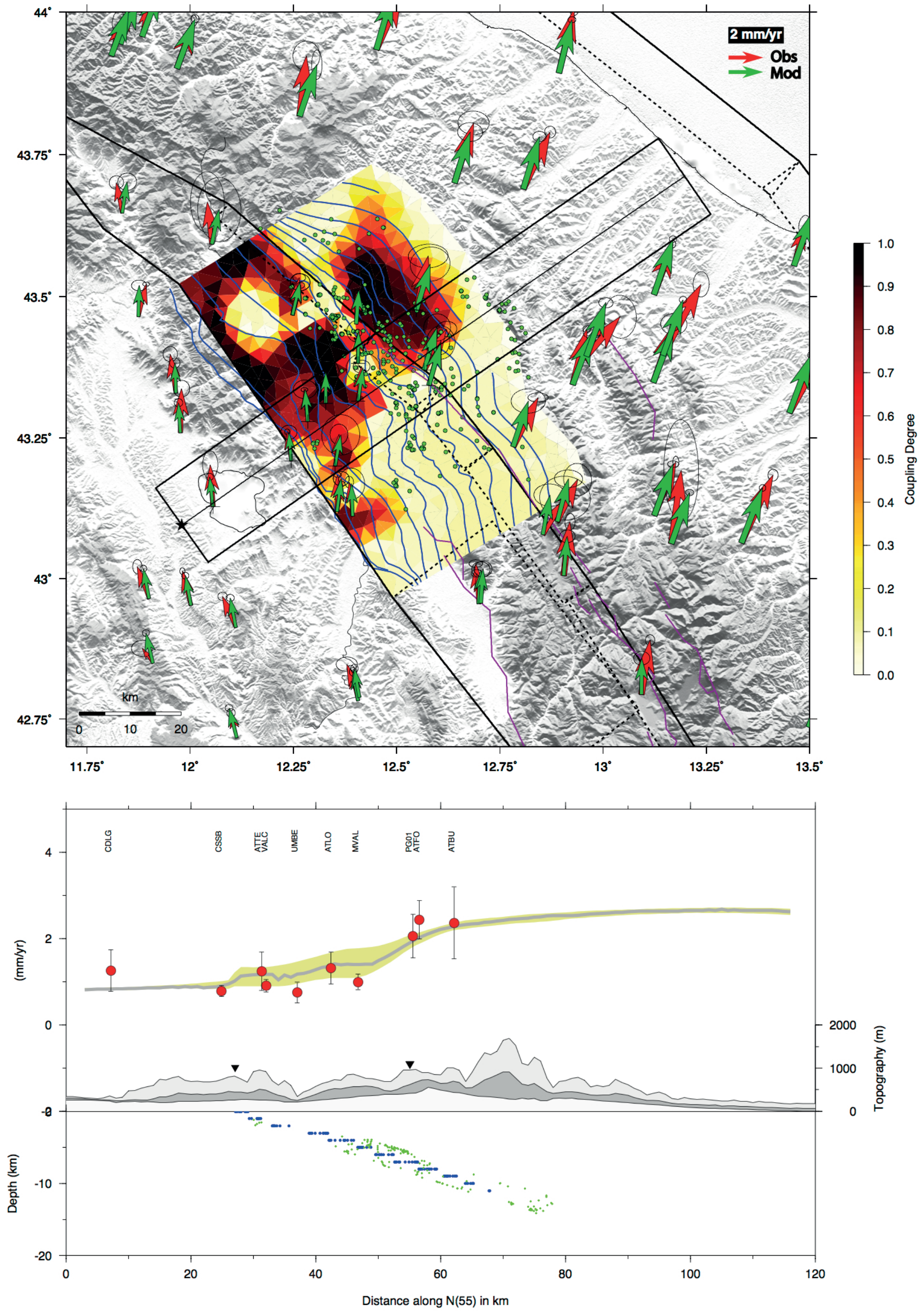

Fig. 3 – Modeling of GPS data inverting for ATF interseismic coupling: blue, violet and black lines are the same as on Fig. 2, green arrows are modeled velocities; on section below we present the same kind of profile as on Fig. 2, showing on depth the microseismicity and isobaths falling inside the box profile.

algorithm, while constraining the slip-rate of each fault patch to be equal or less than the long-term slip-rate estimated from the uniform-slip block model (see Tab. 1). This approach allows us to highlight portions of the fault surface that are characterized by low coupling (i.e., creeping patches) or elastic coupling (i.e. elastic slip-deficit). However, in this way the number of model parameters is greater than the number of data, and we perform a regularization of the inversion adding a smoothing constraint to the solution. The regularization is weighted by a factor β which controls the relative importance of minimizing the reduced chi-squared versus minimizing the roughness of the slip. We choose the optimal value of β equal to 0.7, following a trade-off curve approach (Harris and Segall, 1987). We applied a further constraint to the slip-deficit, forcing it to tape to zero at the bottom edge, at depth of ~13 km, a depth roughly corresponding to the brittle-ductile transition, expected for depth below of 11 km (Boncio *et al.*, 2004).

The final slip-deficit distribution gives a total (the whole model) reduced chi-squared value that is close to that obtained in the uniform slip inversion, but the reduced chi-squared statistics, computed on local stations, drops to 5.27. We represent the slip-deficit distribution as Interseismic Coupling (IC), defined as the ratio between slip-deficit on each patch and the long-term velocity slip-rate (considered in this study -1.5 mm/yr from Tab. 1). The IC ranges between 0 and 1, where 0 means fully uncoupled fault patches (i.e. aseismic creeping) and 1 means fully coupled fault patches (i.e. elastic asperities). Fig. 3 shows the final IC distribution, which shows two main asperities on northern part of the curved surface, and the relocated microseismicity recorded between October 2000 and May 2001 from Chiaraluce *et al.* (2007), selected within +-1.5 km from the ATF surface. The IC distribution shows a correlation between the selected microseismicity and a narrow uncoupled area, located between the two asperities, which position corresponds exactly of bottom edge of Gubbio fault. We perform a resolution test, adopting a checkerboard approach, in order to evaluate the reliability of our IC distribution. These tests show that the transition zone between two asperities is resolved by our data.

Conclusions. Using a self-consistent kinematic block modeling we study the northern sector of the Umbria-Marche Apennines, where several GPS stations show SW-NE oriented extensional deformation. We tested different block model geometries in order to understand which fault system is accommodating the tectonic extension. We found that the best model is the one considering two fault systems, i.e. the Alto Tiberina LANF and the antithetic high-angle Gubbio normal fault, since we obtain lower residuals on data and kinematic agreement with geological slip-rates (Collettini *et al.*, 2003; Pucci *et al.*, 2003). Nevertheless obtaining systematic residuals at a group of GPS sites located between the two fault systems, we parameterized the ATF fault as a, more realistic, curved surface to infer the distribution of interseismic coupling, which is validated by numerous resolution tests. The obtained IC distribution shows a correlation between relocated microseismicity and uncoupled patches attributed to aseismic creeping behavior (Vergne *et al.*, 2001; Schmidt *et al.*, 2005; Rolandone *et al.*, 2008), which could be explained by the presence of fluid overpressure, as was hypothesized by Collettini (2002). Otherwise this correlation has been verified with a very small quantity of events (almost 400) and it might be of interest to evaluate this correlation with future available data.

References

Altamimi, Z., X. Collilieux, and L. Métivier (2011), ITRF2008: an improved solution of the international terrestrial reference frame, *J Geodesy*, 85(8), 457-473, doi:10.1007/s00190-011-0444-4.

Boncio, P., & Lavecchia, G. (2000). A structural model for active extension in Central Italy. Journal of Geodynamics, 29, 233-244.

Bennett, R. A. *et al.* (2012), Syn-convergent extension observed using the RETREAT GPS network, northern Apennines, Italy, *J Geophys Res*, *117*(B4), doi:10.1029/2011JB008744.

Blewitt, G., and D. Lavallée (2002), Effect of annual signals on geodetic velocity, *J. Geophys. Res.*, 107(B7), 2145, doi:10.1029/2001JB000570.

Boncio, P., Lavecchia, G., (2000a), A structural model for active extension in Central Italy. *Journal of Geodynamics* 29, 233-244.

Boncio, P., Lavecchia, G., (2000b), A geological model for the Colfiorito earthquakes (September–October 1997, central Italy). *Journal of Seismology* 4, 345-356

Boncio, P., Brozzetti, F., and Lavecchia, G., 2000, Architecture and seismotectonics of a regional low-angle normal fault zone in central Italy: *Tectonics*, v. 19, p. 1038-1055.

Boncio, P., G. Lavecchia, and B. Pace (2004), Defining a model of 3D seismogenic sources for Seismic Hazard Assessment applications: The case of central Apennines (Italy), *J. Seismol.,* 8, 407-425, doi:10.1023/ B:JOSE.0000038449.78801.05.

Brozzetti, F. (1995): Stile deformativo della tettonica distensiva nell'Umbria Occidentale: l'esempio dei Massicci Massicci Mesozoici Perugini, *Studi Geologici Camerti*, 1, 105-119.

Chiaraluce L., Chiarabba C., Collettini C., Piccinini D., Cocco O M.; 2007: Architecture and mechanics o fan active low-angle normal faults: Alto Tiberina Faults, Northern Apennines, Italy. J. Geophys. Res., 112, B10310, doi:10.1029/2007JB005015.

Collettini, C., Barchi, M., Pauselli, C., Federico, C. and Pialli, G., 2000, Seismic expression of active extensional faults in northern Umbria (central Italy), J. Geodyn. 29, 309-321.

Collettini, C., L. Chiaraluce, F. Mirabella, S. Pucci and M.R. Barchi (2003): The Gubbio seismogenic normal fault: can different methods picture the same object?, J. Geodyn.

D'Agostino, N., S. Mantenuto, and E. D'Anastasio (2009), Contemporary crustal extension in the Umbria-Marche Apennines from regional CGPS networks and comparison between geodetic and seismic deformation, Tectonophysics, 476,3-12, doi:10.1016/j.tecto.2008.09.033.

DISS Working Group (2010). Database of Individual Seismogenic Sources (DISS), Version 3.1.1: A compilation of potential sources for earthquakes larger than M 5.5 in Italy and surrounding areas. http://diss.rm.ingv.it/diss/, © INGV 2010 - Istituto Nazionale di Geofisica e Vulcanologia - All rights reserved; DOI:10.6092/INGV.IT-DISS3.1.1

Dong, D., T. A. Herring, and R. W. King (1998), Estimating regional deformation from a combination of space and terrestrial geodetic data, *J. Geod*., 72, 200-211, doi:10.1007/s001900050161.

Dong, D., P. Fang, Y. Bock, M. Cheng, and S. Miyazaki (2002), Anatomy of apparent seasonal variations from GPS-derived site position time series, *J Geophys Res-Sol Ea*, 107, –, doi:10.1029/2001JB000573.

Geuzaine, C. and J.-F. Remacle, (2009), Gmsh: a three-dimensional finite element mesh generator with built-in pre- and post-processing facilities. *International Journal for Numerical Methods in Engineering* 79 (11), pp. 1309-1331

Harris, R.A. & Segall, P., 1987. Detection of a locked zone at depth on the Parkfield, California, segment of the San Andreas Fault, *J. geophys. Res*., 92, 7945-7962.

Herring, T., King, R.W. & McClusky, S., (2010), GAMIT Reference Manual, Release 10.4, Massachussetts Institute of Technology, Cambridge, MA.

Hreinsdóttir, S., and R. Bennett (2009), Active aseismic creep on the Alto Tiberina low-angle normal fault, Italy, Geology, 37, 683-686, doi:10.1130/G30194A.1.

Lavecchia, G., Boncio, P., Brozzetti, F., Stucchi, M., Leschiutta, I., 2002. New criteria for seismotectonic zoning in Central Italy; insights from the Umbria – Marche Apennines. Boll. Soc. Geol. It., Vol. Spec. 1, 881-891.

Mastrolembo Ventura, B., (2012), Kinematics of the Sicily and Calabria subduction system from elastic block modeling of GPS data, Ph.D. Thesis, University of Bologna, Italy

Meade, B. J., and J. P. Loveless (2009), Block modeling with connected fault-network geometries and a linear elastic coupling estimator in spherical coordinates, Bull. Seismol. Soc. Am., 99, 3124-3139, doi:10.1785/0120090088.

Mirabella, F., F. Brozzetti, A. Lupattelli, and M. R. Barchi (2011), Tectonic evolution of a low-0angle extensional fault system from restored cross-sections in the Northern Apennines (Italy), Tectonics, 30, TC6002, doi:10.1029/2011TC002890.

Okada, Y. (1985), Surface deformation to shear and tensile faults in a halfspace, Bull. Seismol. Soc. Am., 75, 1135-1154.

Pondrelli, S., S. Salimbeni, G. Ekstrom, A. Morelli, P. Gasperini and G. Vannucci (2006), The Italian CMT dataset from 1977 to the present, *Phys. Earth Planet. Inter*., 159, 286-303, doi:10.1016/j. pepi.2006.07.008, 159/3-4

Pucci, S., P. M. De Martini, D. Pantosti, G. Valensise (2003): Geomorphology of the Gubbio Basin (Central Italy): understanding the active tectonics and earthquake potential, Ann. Geophysics, 46 (5), 837-864

Rovida, A., Camassi, R., Gasperini, P. & Stucchi, M. (eds), (2011), CPTI 11, the 2011 Version of the Parametric Catalogue of Italian Earthquakes, Milano, Bologna, Available at http://emidius.mi.ingv.it/CPTI

Savage, J.C., 1983, A dislocation model of strain accumulation and release at a subduction zone: Journal of Geophysical Research, v. 88, p. 4984-4996, doi: 10.1029/JB088iB06p04984

Stein, S., Gordon, R. (1984): Statistical test of additional plate boundaries from plate motion inversion. *Earth Planet. Sci. Lett*, 69, 401-412.

Tondi, E. (2000), Geological analysis and seismic hazard in the central Apennines (Italy), J. Geodyn., 29, 517-533, doi:10.1016/S0264- 3707(99)00048-4.

Williams, S.D.P., Bock, Y., Fang, P., Jamason, P., Nikolaidis, R.M., Prawirodirdjo, L., Miller, M., Johnson, D.J., (2004), Error analysis of continuous GPS position time series. *J. Geophys. Res*.