Rend. online Soc. Geol. It., Vol. 22 (2012), pp. 120-122, 0 figg.

The Ferrara Basal Thrust (northern Italy): geological and seismological evidence for a multi-layered crust-scale seismogenic source

GIUSY LAVECCHIA (*), RITA DE NARDIS (*-**), PAOLO BONCIO (*), FRANCESCO BROZZETTI (*) & DANIELE CIRILLO (*)

RIASSUNTO

Il sovrascorrimento basale dell'arco ferrarese (Italia settentrionale): evidenze geologiche e sismologiche per una sorgente sismogenetica multistrato

L'identificazione delle faglie individuali responsabili dei terremoti del 20 e 29 maggio 2012 (M_w 6.1 e 6.0) contribuisce a porre un vincolo alla ricostruzione della geometria 3D del sistema di sovrascorrimenti attivi al fronte dell'arco ferrarese-romagnolo ed a definirne uno stile deformativo di tipo *thick-skinned*. L'integrazione di dati geologico-strutturali, sismologici e reologici mostra come il sovrascorrimento basale del sistema penetri attraverso l'intera crosta e sia sismogenetico a livelli strutturali ben definiti, coincidenti con la crosta superiore (fino ad una profondità di circa 10-12 km) e con la parte superiore della crosta inferiore (all'incirca tra 20 e 25 km).

KEY WORDS: *Earthquake, northern Italy, Seismogenic source, thrust.*

INTRODUCTION

The recent Ferrara 2002 seismic sequence has definitively proven the ongoing compressional activity of the north-verging Ferrara-Romagna arc. Such system belongs to the Outer Thrust System (OTS) of Italy active since late Pliocene times (LAVECCHIA *et alii*, 2003 and 2007). The associated fold-and-thrust structures are buried beneath the late Quaternary deposits, making difficult the identification of the active fault segments (BURRATO *et alii*, 2012). Nevertheless, the OTS can be considered active due to its association with a number of relevant historical earthquakes (e.g. 1570 Ferrara M_w 5.5; 1624 Argenta M_w 5.5; 1688 Romagna M_w 5.8; 1831 and 1832 M_w 5.5) and with a few compressional and strike slip earthquakes with P-axes mainly radial to the thrust front direction (BONCIO & BRACONE, 2009; MONTONE *et alii.* 2012). Recent geodetic data also support the ongoing NNE motion of the Apennine compressional units above the Adriatic foreland (DEVOTI *et alii*, 2011).

The present paper aims to identify the most like fault pattern responsible for the 2012 Ferrara seismic sequence, as well as to analyze at a regional scale the possible earthquake-fault associations along the down-dip project of the outer thrust of Ferrara-Romagna arc, hereafter referred to as the Ferrara Basal Thrust (e.g. FBT). A multi-layered seismogenic source is identified which fit available data on the rheological stratification of the crust (VIGANÒ *et alii*, 2012).

FAULT SOURCES OF THE FERRARA 2012 SEISMIC SEQUENCE

The seismic sequence associated to the 20 May earthquake (M_L 5.9, M_w 6.1) covered an epicentral area extending in direction N105°E for a length of ~30 km, from Mirabello to Mirandola. The sequence associated to the 29 May earthquake (M_L 5.8, M_w 6.0) covered an area elongated ~20 km in direction N120°E, from Medolla to Novi di Modena, and was arranged in a left-stepping en echelon pattern with respect to the 20 May epicentral area (LAVECCHIA *et alii,* 2012). The focal mechanism of both events show an almost pure thrust kinematics, with a ~N10°E trending P-axis, and southward dipping preferential seismic plane.

Three major thrust structures may be identified within the Ferrara 2012 epicentral area: the Ferrara basal thrust, its Quarantoli hanging-wall splay and the innermost Mirandola thrust. The analysis of the geometric fault correlation with the preliminary seismic locations, as reported by the ISIDe database (at *http://iside.rm.ingv.it/ iside/standard/index.jsp*), allowed us to define the most likely earthquake-fault associations. The 20 May event, after rupturing the Ferrara basal thrust at depths between 3 and 7 km, with nearly pure dip-slip kinematics, propagated WNW-ward toward its SW-NE striking lateral ramp. On 29 May, the rupture jumped on an inner splay (Quarantoli thrust) and started to propagate WNW-ward with nearly pure dip-slip kinematics. The basal thrust of the Mirandola anticline, located

(*) Laboratorio di Geodinamica e Sismogenesi, DiSPUTer, Università «G. d'Annunzio», Campus Universitario, 66013 Chieti Scalo, Italy

some kilometers SSW-ward, appears to be not, or only subordinately, involved in the sequence.

SEISMOGENIC ZONING OF THE FERRARA BASAL THRUST

The Ferrara 2012 compressional sequence, as well as its 19 May 2012 foreshock (Mw 4.3) plus another nearly E-W thrust earthquake occurred one year before (2011 Mw 4.8), activated the FBT at depths corresponding to the sedimentary crust (< 10 km). Some other recent instrumental events, with reverse or reverse oblique solutions, sited some dozens of kilometers in the rear of the FBT front, nucleated at mid-lower crust depths. Among these events we especially recall the Canossa 2008 seismic sequences (M_w 5.5, BRAGATO *et alii*, 2012), whose hypocentral areas lie at depths of 20-25 km, along the down-dip projection of the FBT, suggesting that the FBT cuts also the basement with seismogenic behaviour. Some other compressional events located beneath the upper crust, such as the Reggio Emilia 1996 earthquake, located at depths of 15 km (SELVAGGI *et alii*, 2001), and the Monghidoro events (Mw 5.3) at depths of 20-25 km (PICCININI *et alii*, 2006) are not directly associated to the FBT, but depict NW- or NNW-dipping seismogenic planes which can be interpreted as antithetic to the main FBT.

We have plotted in section view the major instrumental earthquakes occurring along an interpretative geologic sections built through the Ferrara ridge, along the trace of the line ENI, App. East-1. The section shows as the FBT is likely active both at upper and mid-to-lower crustal depths. The spatial correspondence observed between the down-dip fault geometry and the seismicity is in agreement with the thermo-mechanical properties of the crust. A rheological profile reconstructed by VIGANÒ *et alii* (2012) close to the trace of the section points out the brittle *versus* plastic behaviour of the crust at different depths. In particular, the strength envelope elaborated using the minimum possible geotherm is characterized by two brittle layers separated by a low-strength plastic horizons. The shallowest brittle layer (0-10 km) mainly corresponds to the sedimentary cover; the lower brittle layer (20 to 23 km) corresponds to the upper part of the lower crust. An evident consistency between the depth interval of the brittle layers and location of earthquake hypocentres is observed, while plastic layers should remain relatively aseismic.

CONCLUSIONS

The Ferrara 2012 earthquakes are the most evident proof of the activity of the FBT. This evidence may be further supported by the occurrence of other mid-to-lower crustal compressional earthquakes along the projection at large depths of the FBT. The involvement of the overall crust in the seismogenic shearing associated to the FBT may be simply explained in a frame of thick-skinned style of compressional deformation across the Apennine belt.

The deep geometry and earthquake-fault association pointed out for the FBT is equivalent to that pointed out for the W-dipping Adriatic Basal Thrust, e.g. the southern prolongation of the Ferrara thrust (LAVECCHIA *et alii*, 2003 and 2007), as well as for the N-dipping Sicilian Basal Thrust (SROI *et alii*, 2012). The ABT, which penetrates across the crust of the Marche area with an average deep of nearly 30°, is characterized by two distinct seismogenic layers at depths 0-10 and 15-25 km, with an intermediate aseismic layer, consistent with the rheological stratification of the crust.

REFERENCES

BONCIO P. & V. BRACONE V. (2009) - *Active stress from earthquake focal mechanisms along the Padan–Adriatic side of the Northern Apennines (Italy), with considerations on stress magnitudes and pore-fluid pressures*. Tectonophysics, **476**, 180–194.

BRAGATO P.L., SUGAN M., AUGLIERA P., MASSA M., VUAN A. & SARAÒ A. (2012). *Moho reflection effects in the Po Plain (Northern Italy) observed from instrumental and intensity data*. Bull. Seism. Soc. Am. **101**, 2142–2152.

BURRATO P., VANNOLI P., FRACASSI U., BASILI R. & VALENSISE G. (2012) - *Is blind faulting truly invisible? Tectonic-controlled drainage evolution in the epicentral area of the May 2012, Emilia-Romagna earthquake sequence (northern Italy).* Annals of Geophysics, in press.

DEVOTI R. , ESPOSITO A., PIETRANTONIO G., PISANI A.R. & RIGUZZI F. (2011) - *Evidence of large scale deformation patterns from GPS data in the Italian subduction boundary. Earth Planet. Sci. Lett.* **311,** 230-241.

LAVECCHIA G., BONCIO P. & CREATI N. (2003) - *A lithospheric-scale seismogenic thrust in Central Italy*. Journ. Geodynamics, **36**, 79-94.

LAVECCHIA G., DE NARDIS R., VISINI F., FERRARINI F. &. BARBANO M.S. (2007) - *Seismogenic evidence of ongoing compression in eastern-central Italy and mainland Sicily.* Ital. J. Geosci., **126**, 209-222.

LAVECCHIA G., DE NARDIS R., CIRILLO D., BROZZETTI F. & BONCIO P. (2012) - *The May-June 2012 Ferrara earthquakes* *(northern Italy): Structural control on the spatial evolution of the seismic sequence and on the surface pattern of coseismic fractures.* Annals of Geophysics, spec. vol. The Emilia (Italy) seismic sequence of May-June, 2012: preliminary data and results, **55**, in press.

MONTONE P., MARIUCCI M. T. & PIERDOMINICI S. (2012) - *The Italian present-day stress map*. Geophysical Journal International, **189**, 705-716

PICCININI D., CHIARABBA C., AUGLIERA P. & THE MONGHIDORO EARTHQUAKE GROUP (M.E.G.) (2006) - *Compression along the northern Apennines? Evidence from the Mw 5.3 Monghidoro earthquake*. Terra Nova, **18**, 89–94.

SELVAGGI G., FERULANO F., DI BONA M., FREPOLI A., AZZARA R., BASILI A., CHIARABBA C., CIACCIO. M.G., DI LUCCIO F., LUCENTE F.P., MARGHERITI L. & NOSTRO C. (2001) - *The M_w 5.4 Reggio Emilia 1996 earthquake: active compressional tectonics in the Po Plain, Italy.* Geophys. J. Int. **144**, 1-13.

SGROI T., DE NARDIS R. & LAVECCHIA, G. (2012). *Crustal structure and seismotectonics of central Sicily (southern Italy): New constraints from instrumental seismicity.* Geophys. J. Int. **189**, 1237-1252.

VIGANÒ A., DELLA VEDOVA B., RANALLI G., MARTIN S. & SCAFIDI D. (2012) - *Geothermal and rheological regime in the Po plain sector of Adria (Northern Italy)*. Ital. J. Geosci. **131**, 228-240.