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Quaternary evolution of “blind” fault-related folds in the Central Po Plain (Northern Italy).

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RIASSUNTO

Evoluzione quaternaria di strutture plicative sepolte lungo il settore centrale dell'alta Pianura Padana.

Attraverso la ricostruzione tridimensionale di due superfici appartenenti al record stratigrafico quaternario del bacino padano (Superficie Azzurra, 1.6 Ma e Superficie Rossa 0.89 Ma) si è giunti a delineare parte dell’evoluzione quaternaria di sovrascorrimenti sepolti. Il pattern deformativo è stato ricostruito a partire dall’analisi delle pieghe associate a queste strutture ed in funzione della loro evoluzione nel tempo. L’analisi di dettaglio di un profilo passante attraverso il sistema di faglie di Capriano del Colle (BS) e l’analisi del record stratigrafico sindeformativo ha permesso di definire lo stile strutturale tipico di questo settore ed i ratei di sollevamento associabili alle strutture di Capriano.

Key words*: fault-related folds; Southern Alps; Quaternary tectonics*

INTRODUCTION

The study of quaternary folds as indicators of active crustal shortening and coseismic slip on related thrusts, especially in areas characterized by blind thrusting, is attracting increasing interest among specialists due to the recent dramatic evolution of the methodology for their structural analysis, which now allow to attain excellent resolution in the deep interpretation of earthquake sources (BURBANK *et alii*, 1996; SHAW & SUPPE, 1996, MUELLER & SUPPE, 1997; SHAW *et alii*, 2002; ISHIYAMA *et alii*, 2004; LIN & STEIN, 2006, DOLAN *et alii*, 2003, LAI *et alii*, 2006, CHEN *et alii*, 2007, LEON *et alii*, 2007, STREIG *et alii*, 2007; OKAMURA *et alii*, 2007).

We selected an area between Lake Como and Lake Garda where several evidence of Quaternary tectonics has been reported. Some isolated small hills (Capriano del Colle, Castenedolo, Ciliverghe and Pievedizio hill), rising from the surrounding plain, have been already mentioned by DESIO (1965) as evidence of Quaternary tectonics. Secondary faulting and folding at Capriano del Colle sites have been also recently documented (LIVIO *et alii*, 2008; MICHETTI *et alii,* 2008). BURRATO *et alii* (2003) describe river anomalies in the Valle dell’Oglio sector, probably induced by active growing folds. In order to depict the recent evolution of the structures recognized in the Po Plain basin we analyzed ca. 18000 km of seismic lines, provided by ENI E&P, constrained by hundreds of deep exploratory wells, over an area of about 6800 Km^2 (Fig.1).

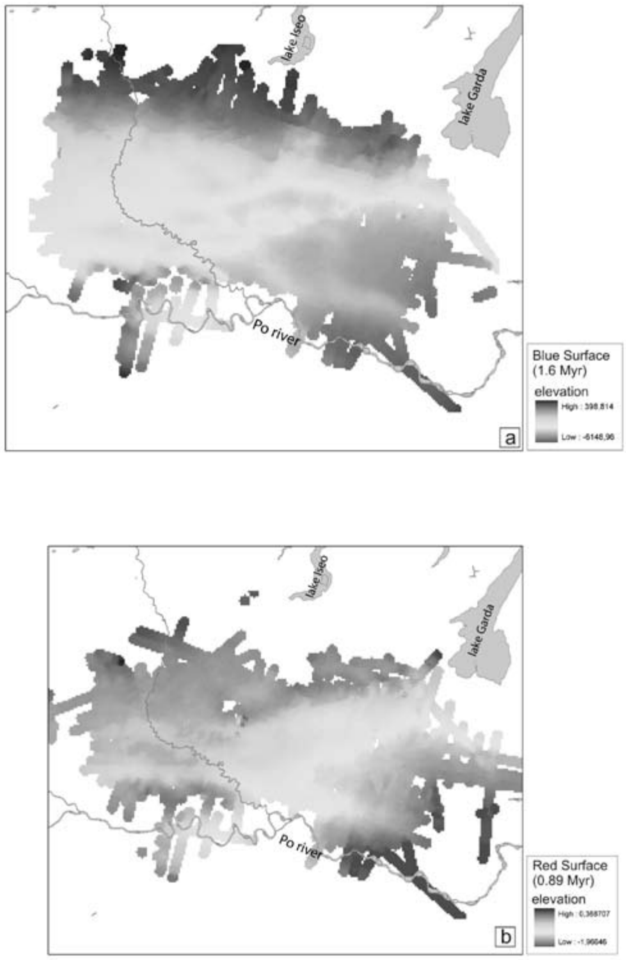

Fig. 1 – Areal extent of the analyzed surfaces: (a) Blue Surface – 1.6 Myrs; (b) Red Surface - 0.89 Myrs.

Faults were defined both by obvious truncation of strata on seismic profiles (e.g. footwall and hangingwall stratigraphic cutoffs) and by construction of contour maps of folded horizons of various age in the Quaternary sequence that infills the Po Plain basin. Folds associated to underlying thrusts were in fact

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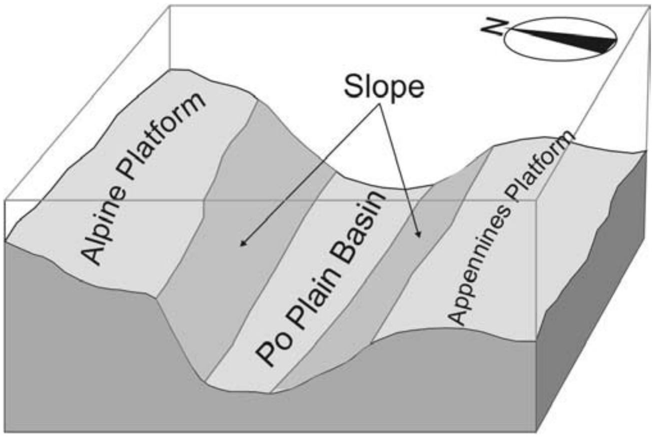

Fig. 2 –Block-diagram of the Plio-Pleistocene Po Plain Basin: the main domains, described in the present work, have been indicated.

recognized based on deformation recorded by two regional sequence boundary horizons (Blue Surface – 1.6 Myr; and Red Surface - 0.89 Myr; e.g. CARCANO & PICCIN, 2002, MUTTONI *et alii,* 2003), characterized by good stratigraphic and age bracketing, and marking significant changes in the sedimentary architecture of the basin.

Age controls are based on stratigraphic, paleontological and magnetostratigraphic analysis by ENI E&P and Regione Lombardia (CARCANO & PICCIN, 2002, SCARDIA *et alii*, 2006) and on an extensive database of shallow well logs acquired in boreholes drilled for groundwater. The analysis of strain induced on these horizons allowed to recognize a belt of active fold & thrust structures, each 10 to 20 km long, that extents with an *en echelon* arrangement across the Po basin.

PATTERN OF DEFORMATION IN THE CENTRAL PO PLAIN

Blue Surface (1.6 Myr)

The Blue Surface covers about 7800 Km^2. From north to south the following major domains can be recognized: an alpine platform domain, an Apennine platform domain and two slopes linking this platforms with the basin (Fig. 2 and 3).

The basin is ca. 40 km wide (Fig. 3) and progressively deepens eastward. The northern flank of the basin is less steep than the southern one and shows some erosive features in its northern sector. We characterized segmentation of blind thrusts using several methods that including mapping of single segment faults that terminate at a transverse structure (e.g. a transfer fault) or where folding decreases to zero at the end of structures as defined by the regional dip of mapped strata.

On the northern edge of the basin two structures has been identified (Fig. 3 structures number 1 and 2). We interpret these structures as north-verging fault-propagation folds characterized by ramps that detach the Gonfolite Lombarda Group (Oligo – Miocene; BERNOULLI *et alii*, 1989) from the underlying upper Cretaceous sediments. Surface deformation caused with these structures is associated with the Castenedolo and Capriano del Colle hills. On the basin floor we recognized nine structures interpreted as folds overlying growing blind faults. The northern structures belong to the Alpine domain and we interpreted them as south-vergent fault propagation folds (structures number 3, 4 and 6 of Fig. 3). These structures have an average length of 11 - 16 km and are ca. N 110° trending.

Structure number 7 is the most external Apennine front (Soresina High; e.g. BIGI *et alii*, 1990) while structures number 9, 10 and 11 represents segments of Central - Eastern sector of the Emilia folded Arc. The westernmost segment (11) is the San Colombano High. Structure 10 is the Piadena High, the most external structure of this sector of the Emilia Arc (e.g. BIGI *et alii*, 1990).

At this stage of deformation (ca. 1.6 Myr) the morpho-bathymetry of the basin floor clearly shows two opposite verging structural fronts, facing each other in the central sector of the Po Plain, characterized by an array of fault-related folds, segmenting each one of these belts.

Red Surface (0.89 Myrs)

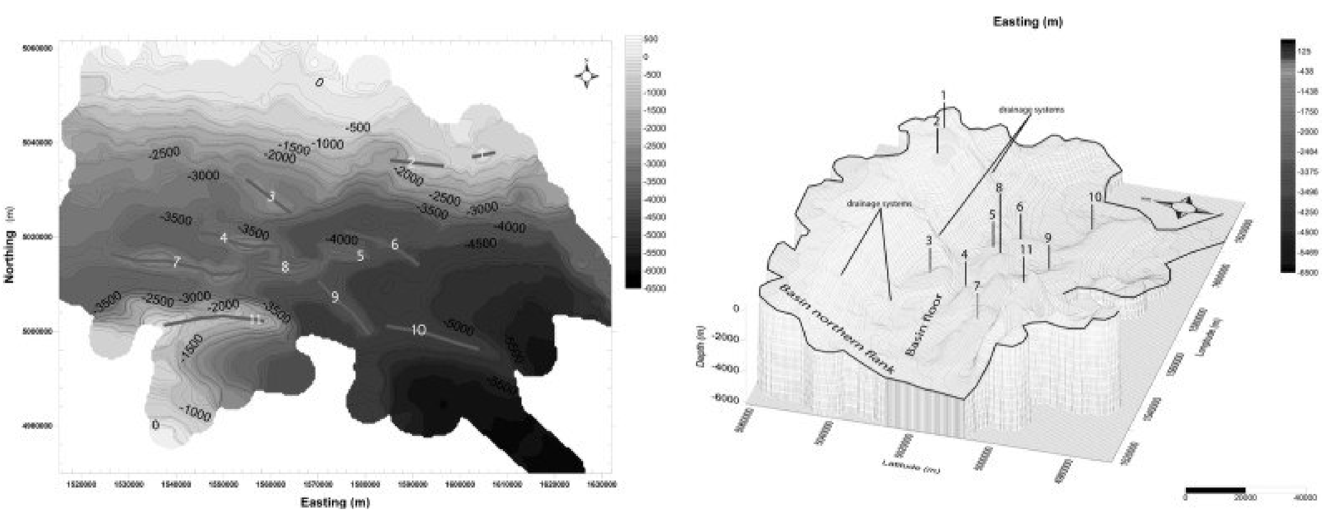

Fig. 3 – Blue Surface in map view and in 3D wireframe. Main recognized structures are indicated. See text for details.

The evolution of the basin between the formation of the Blue Surface and the formation of the Red Surface (averaging ca. 710.000 yrs.) is summarized as follows. The Alpine platform domain spreads out southward; a less steep scarp links it with a wider but less deep Apennines - Alps basin domain and the Apennines platform domain has been deformed by the most external Apennines structures.

At this stage the basin is still strongly asymmetric, and at the eastern edge is ca. 30 km wide, narrowing toward west to ca. 20 Km.

Folds recognizable on this surface are less than those mapped on the Blue surface; moreover they are generally longer.

This trend is consistent with a spatially – varying shortening rate model (e.g. SALVINI & STORTI, 2002) according to which folds grow with a constant fault geometry but with displacement varying along strike. Faults migrate laterally as displacement accumulates and, in the case of two or more adjacent structures, the growth along strike could produce the linkage among the adjacent structures with the formation of double plunging folds (MUELLER & TALLING, 1997, KELLER *et alii*, 1999; CHAMPEL *et alii,* 2002).

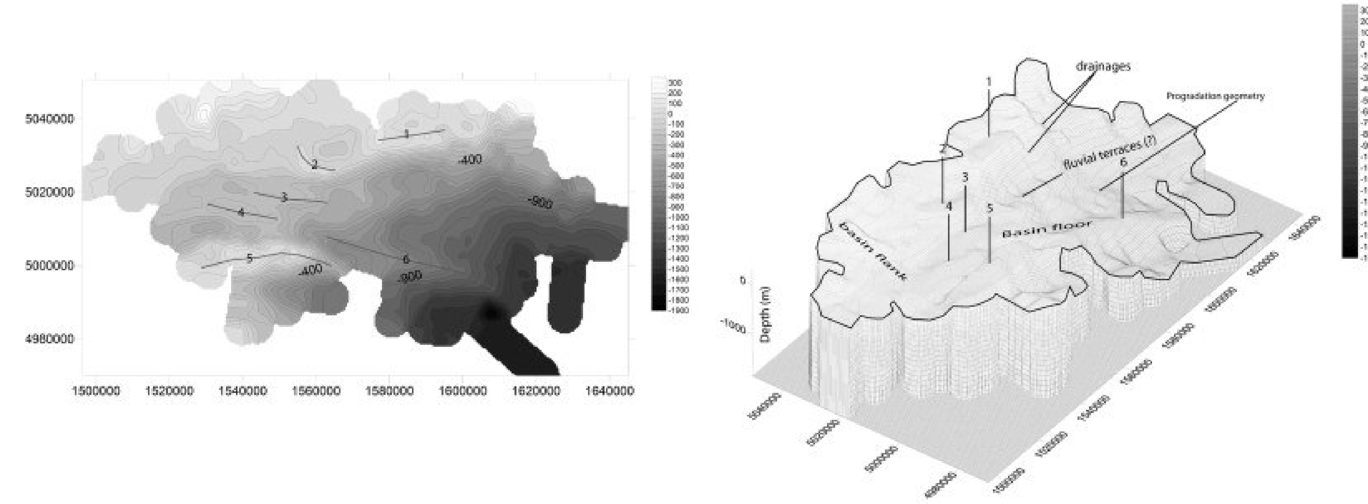

Fig. 4 – Red Surface in map view and in 3D wireframe. Main recognized structures are indicated. See text for details.

CAPRIANO DEL COLLE FAULT SYSTEM

A seismic reflection profile, cutting through some representative structures in the northern sector of the Po Plain, has been selected and analyzed (Fig. 5).

The Capriano del Colle Fault System (CapFS) is composed by a south-vergent thrust (CCT) and an associated high angle backthrust (CCB). The structural style here depicted is therefore characterized by a triangle zone, or structural wedge, defined by a primary south-vergent fore-thrust and a connected north-vergent backthrust (Fig. 5 and 6). Secondary flexural slip faults (CCB_{FSF} e CCT_{FSF}) are associated with both these structures (Fig. 6). Flexural slip faults play an important role in the accommodation of strain above blind thrusts (e.g., YEATS, 1986; ROERING *et alii*, 1997; NINO *et alii*, 1998; ISHIYAMA *et alii*, 2004; OKAMURA *et alii,* 2007). Several models and natural examples, indicate in fact that bedding-parallel strain tends to consume slip and therefore hinder the upward propagation of faults and fault-related folds.

Tectono-sedimentary history of the Capriano del Colle Fault System

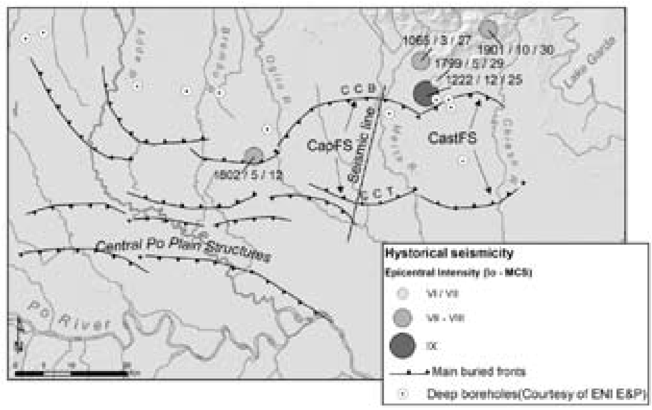

Fig. 5 – Shaded relief map based on a 20 m DTM showing the locations of buried active thrusts in the northern sector of the Po Plain; barbs indicate the hanging-wall of the thrusts. ENI E&P deep boreholes and seismic line location are also represented. Main historical earthquakes are indicated. (CPTI, 2004, modified).

Syntectonic growth theory (SUPPE *et alii*, 1992) suggests that cumulative displacement will decrease upward within the stratigraphic interval deposited during deformation. In contractional environments syntectonic strata typically thin across folds limbs towards structural highs. Methodology adopted for uplift rates calculation is summarized in Figure 7a (e.g., MASAFERRO *et alii,* 2002;). *In situ* accumulation rates (S) were also calculated and compared to relative uplift rates (U/S ratio; Fig. 7b). A very high accumulation rate, with respect to

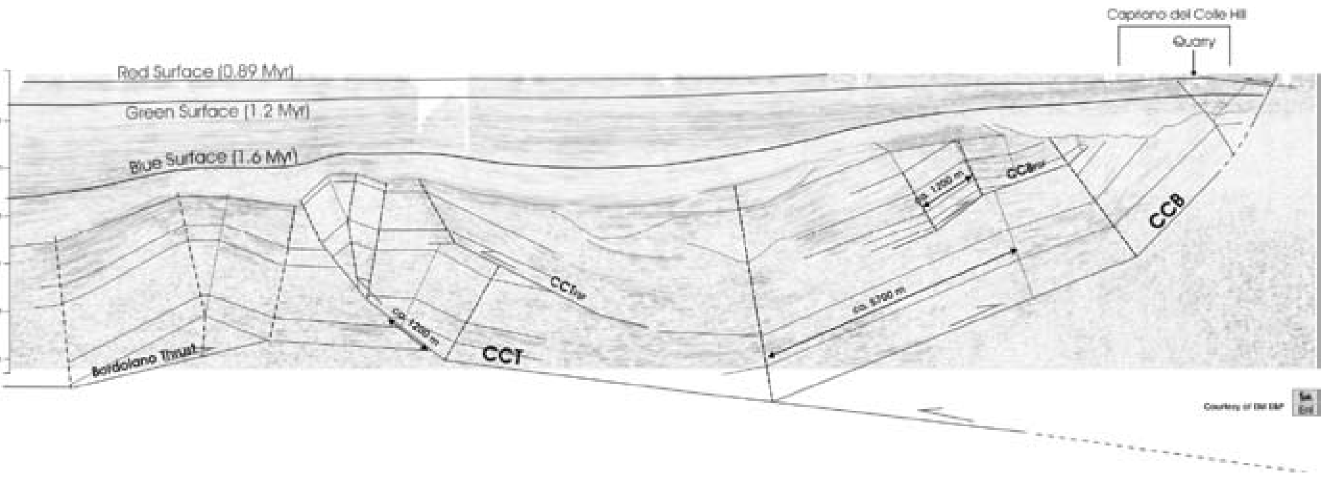

Fig. 6 – Depth-converted interpreted seismic profile, across the Capriano del Colle Fault System, constrained by constant thickness fault-related fold theory. Location is shown on Figure 2a. There is no vertical exaggeration. Abbreviations are: CCT, Capriano del Colle thrust; CCB, Capriano del Colle backthrust; CCTFSF & CCBFSF are associated flexural slip faults. Values above arrows indicate limb widths, measured on the section. Thick dashed lines, active axial surface; dash and dotted thin lines, inactive axial surface, blue dashed lines, erosional features.

uplift rate (very low ratio U/S), can in fact obscure the tectonic signal and appear as an interval apparently not influenced by contemporary uplift. Uncertainties in uplift and sedimentation were evaluated in terms of the resolution and variability in seismic reflector character (ca. 25 m), and errors in age bracketing (ca. ± 0.1 – 0.05 Myr, according to the considered surface).

For calculations we used the above-mentioned Blue and Red Surface and an intermediate horizon, called Green Surface, dated ca. 1.2 Myr. Results, relative to each structure, are summarized as follows (Fig. 7b).

- For the CCT: during the first chronostratigraphic interval (Pliocene – 1.6 Myr) very low values of uplift and sedimentation rates have been recorded. Growth beds onlapping the fold limb and thinning as they approach the fold crest predominated during the first part of this period. Such a low value of average rock uplift rate may be related to averaging a relatively short episode of tectonic deformation over a very long time period (duration is ca. 3.6 Myr). The second time window (1.6-1.2 Myr) records seemingly higher values both in uplift and sedimentation rates. The following period is characterized by a deactivation of this thrust, as testified by syntectonic growth strata that maintain the same thickness throughout the CCT crest. Since S value is constant for this period, compared to the previous interval, it is apparent that the tectonic signal has not been concealed by a significant increase in sedimentation rates. The 0.89 Myr to present chronostratigraphic interval records a decrease both in uplift and sedimentation rates.

- For the CCB: during a Pliocene to 1.6 Myr time window, our analysis suggests that this structure initially experienced similar low values of sedimentation and uplift rates.

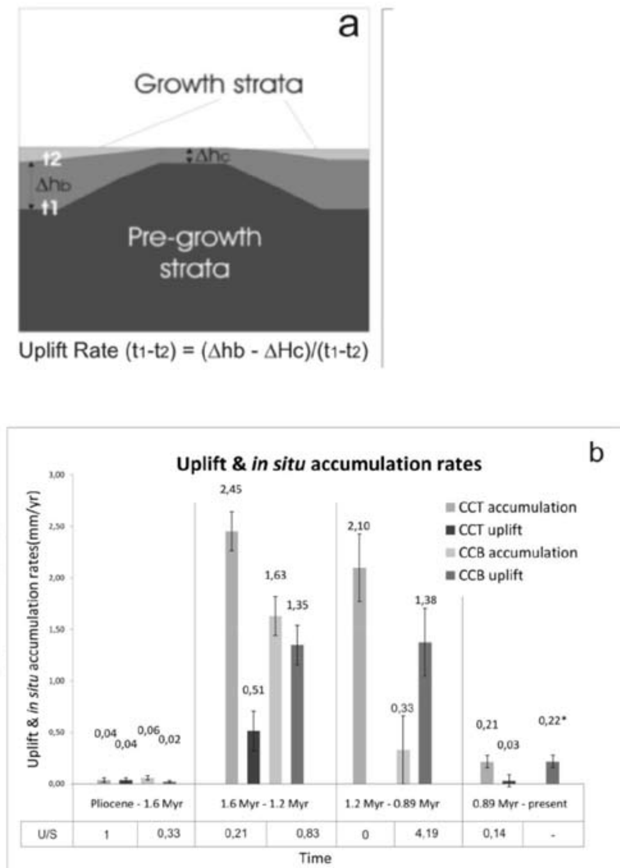

Fig. 7 – Assessment of uplift and in situ sedimentation rates relative to chronologic intervals: a) Sketch of the methodological approach (e.g. Masaferro et al., 2002) applied to calculate uplift rates; b) graphic summary of the results according to the considered time windows. Error bars and U/S ratio value are also indicated. (*) indicates minimum uplift rate value, according to a fill-to-the-top growth model.

We consider the same considerations discussed above for calculations on rock uplift CCT structures to be valid. During the 1.2 – 0.89 Myr period the high value of U/S ratio marks a significant decrease in sedimentation rates. This drastic lowering in sedimentation rate is consequence of the progressive infilling of the Po Plain basin that, for this sector, was starting to shift to a continental-type environment. The latest period is characterized by the onset of regional non-deposition and/or erosional conditions over the entire Po Basin whole area. The Red Surface is thus not visible throughout the entire CCB structural high. Thus, assuming a fill-to-the-top growth model, the calculated rate has to be considered as a minimum value.

CONCLUSIONS

Deformation pattern of the Po Plain basin has been analyzed over two time windows (1.6 and 0.89 Myr and 0.89 Myr – Present). It is noteworthy the reactivation of north-verging backthrusts and associated folds, instead of the main forethrusts, maybe related to a differential sedimentary load between proximal and distal portions of the basin. Uplift rates obtained for the CapFS characterize these thrusts as moderate to low strain rate structures.

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