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STRATIGRAPHIC RECORD OF CRUSTAL-SCALE TECTONICS IN THE QUATERNARY OF THE NORTHERN APENNINES (ITALY)

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ABSTRACT - *Riscontro stratigrafico di tettonica a scala crostale nel Quaternario dell'Appennino settentrionale (Italia)* - Il Quaternario *Italian Journal of Quaternary Sciences*, **10**(2), 1997,595-602 - Detailed analyses of seismic stratigraphic packages in Northern Apennines--related sedimentary basins (Po Plain foredeep and western Tuscany grabens) allowed to work out a chronological scheme of deformational events. On a regional scale two main regimes can be identified: a) dominant horizontal motion until the early Pliocene, and b) prevailing vertical motion in the late Pleistocene. This evolution could be accounted for by a vertical detachment, and perhaps slab break off, of the subducted Adriatic continental lithosphere underneath Tuscany.

Key words: Plio-Quaternary, seismic stratigraphy, stratal architecture, regional tectonics, geodynamics, Apennines, Italy
Parole chiave: Plio-Quaternario, stratigrafia sismica, architettura stratigrafica, tettonica regionale, geodinamica, Appennini, Italia

1. INTRODUCTION

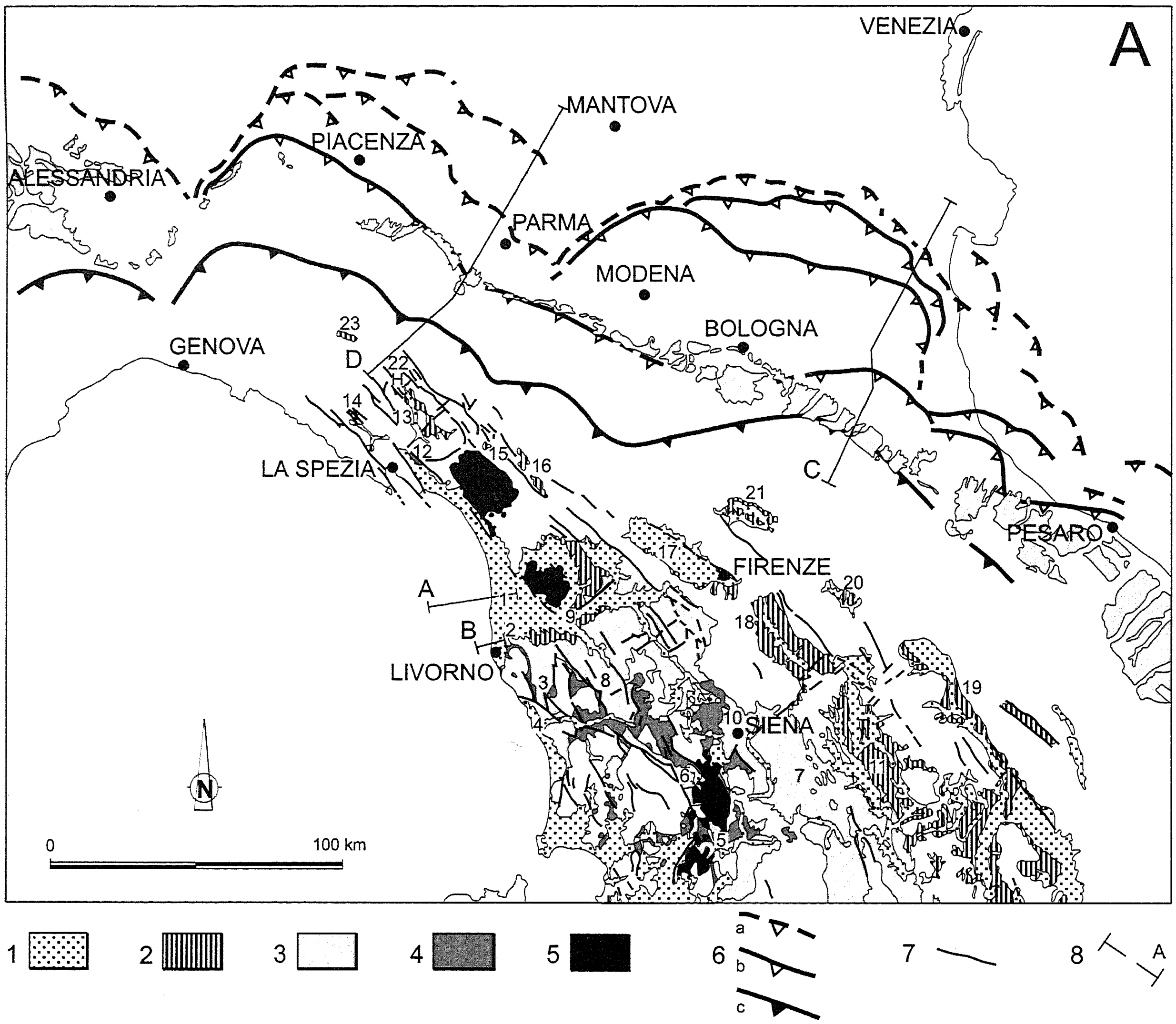
Tectonic and sedimentary processes interact in depositional settings to build up the stratigraphic architecture. Thus, the detailed study of the geometry and stratigraphy of sedimentary units allows to extract information on the tectonic and depositional history of the basin. This approach has been proven to work particularly well on seismic datasets, which offer a roughly three dimensional continuous picture of the sedimentary bodies, and can be applied at various scales from the single structure to an entire basin. In this contribution, the analysis of stratal architecture was applied to the Plio-Quaternary sediments of basins in the Northern Apennines, in order to define the chronology of events on a regional scale and to develop a working hypothesis on the geodynamic processes responsible for the last stages of evolution of the Northern Apennines.

The bulk of dataset was obtained from a dense grid of industrial seismic profiles covering the Po Plain and the extensional basins of western Tuscany, and was calibrated with stratigraphic logs from a large number of exploration wells. In addition, field data, both from the literature and original, were used to obtain a picture on a regional scale.

2. GEOLOGICAL SETTING

The Northern Apennines are a fold and thrust belt that originated during the late Cretaceous developing up to the present convergence between the European and African plates. The initial stage of oceanic subduction brought to the formation of the Ligurian accretionary wedge, which is now the uppermost nappe system of the Apennine stack (Elter, 1960; Abbate & Sagri, 1970). Subsequently, the local convergence between the continental domains of the Corsica-Sardinia block ahead of the opening Balearic backarc basin, and Adria led to a progressive deformation of the units of the Adriatic continental margin and to the eastward migration of foredeep basins (Ricci Lucchi, 1986). The last foredeep basin is at present located in the Po Plain and Adriatic sea. For the large part of this second evolutionary stage, delamination of the lower continental lithosphere of Adria likey occurred as the oceanic lithosphere had already been consumed. This process of continental delamination led also to the opening of the Northern Tyrrhenian basin on the wake of the collisional belt with an associated large amount of volcanic products (Serri *et al.*, 1993).

The thin crust detected by seismic refraction (Fig. 1) and the high values of heat flow support the presence of a thinned lithosphere underneath Tuscany and the Northern Tyrrhenian sea (Scarascia *et al.*, 1994; Mongelli *et al.*, 1991). Seismicity is mainly concentrated in the belt of highest elevation of the Apennines range and hypocentral depths reach 100 km, roughly outlining the shape of the subducted Adriatic plate (Amato & Selvaggi, 1991). Good quality focal mechanisms are very limited and mostly show extensional faulting solutions (Frepoli & Amato, 1996). Seismic tomography indicates the presence of an almost vertical high velocity body at the depth of 200-250 km (Amato *et al.*, 1991). If this body, that likely represents a portion of subducted Adriatic lithosphere, is or not attached to the Adriatic plate is, however, still a matter to debate as teleseisms point to an attached slab (Amato *et al.*, 1991) whereas shear wave attenuation data seem to support the presence of an interposed low velocity zone (Mele *et al.*, in press). The presence of hot asthenosphere underneath Tuscany is further supported by the elevated heat flow there observed.



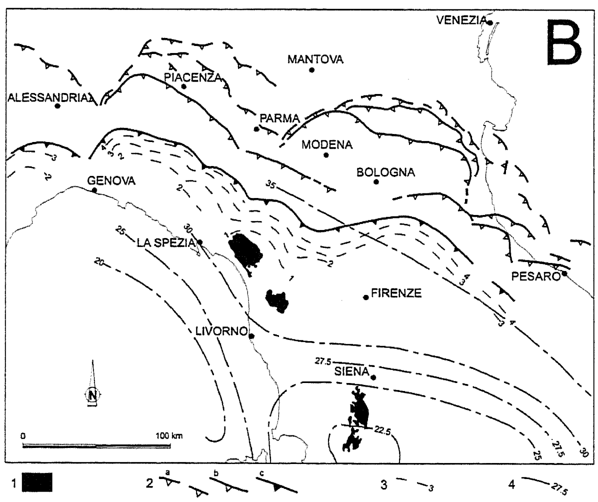


Fig. 1 - Maps of the Northern Apennines with the outcrops of Plio-Quaternary sediments and deeper tectonic elements. A): 1 - Undifferentiated Quaternary deposits; 2 - Fluvio-lacustrine deposits (Villafranchian); 3 - Terrigeneous marine deposits (Lower Pleistocene-Pliocene); 4 - Clastic and evaporitic deposits (Messinian); 5 - Metamorphic complex; 6 - Main blind thrust fronts: a) external front; b) Mesozoic carbonates front; c) "basement" front; 7 - Main extensional faults; 8 - Cross-sections (A, B Fig. 2; C, D Fig. 4). B): 1 - Metamorphic complex; 2 - Main blind thrust fronts [as in A)]; 3 - Contour lines of the top of "basement", isochrons in seconds (TWT); 4 - Moho isobaths (km).

Carte dell'Appennino settentrionale con indicazione degli affioramenti dei sedimenti plio-quaternari e degli elementi strutturali più profondi. A): 1 - Depositi quaternari indifferenziati; 2 - Depositi fluvio-lacustri (Villafranchiano); 3 - Depositi marini terrigeni (Pleistocene inferiore-Pliocene); 4 - Depositi clastici ed evaporiti (Messiniano); 5 - Complesso metamorfico; 6 - Principali fronti sepolti: a) fronte esterno; b) fronte dei carbonati mesozoici; c) fronte del "basamento"; 7 - Principali faglie estensionali. B): 1 - Complesso metamorfico; 2 - Principali fronti sepolti (come sopra); 3 - Isolinee della superficie del "basamento" in secondi (TWT); 4 - Isobate della Moho (km).

3. STRATIGRAPHY AND STRATAL ARCHITECTURE

3.1 Plio-Quaternary of Tyrrhenian margin of Tuscany

Seismic and well data from the Tyrrhenian side of Tuscany show that this area was affected by a regional extensional regime in late Messinian-early Pliocene times. The geometries in seismic profiles indicate that extensional activity decreased after the early Pliocene. Furthermore, over the greatest part of Tuscany a regional uplifting event occurred at about 2.5 Ma, creating a large stratigraphic gap with total absence of upper Pliocene

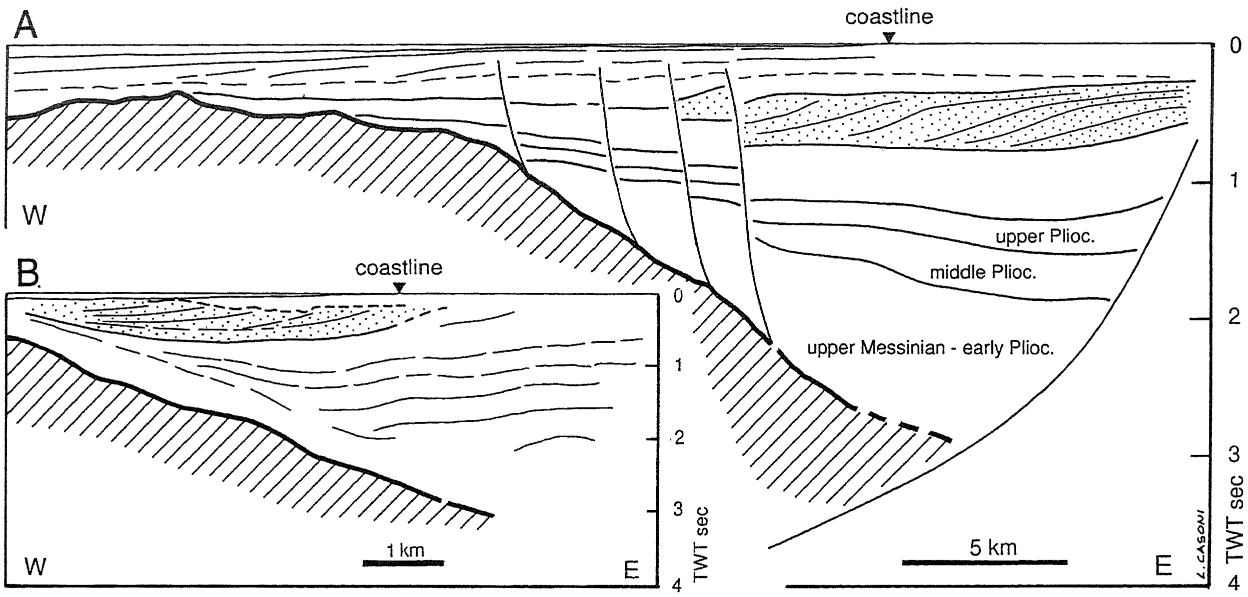


Fig. 2 - Line drawings of two profiles along the western coast of Tuscany. A) Pisa basin and B) Livorno hills. See location in Figure 1a.
Disegno di due profili lungo la costa occidentale della Toscana. A) Bacino di Pisa e B) Colline di Livorno. Per la posizione dei profili, vedi Fig. 1

sediments. While this uplift was occurring, extension continued in the Pisa basin up to the Present (Fig. 2). A further major uplift occurred in Tuscany during the Pleistocene. The timing of this uplift is difficult to constrain on the basis of outcrop data only; however, during this process a portion of a sedimentary basin offshore the Livorno promontory was inverted and a prograding unit followed the uplift (Fig. 2). Seismic stratigraphic correlations with exploration wells and outcrops (Zanchetta, 1995) in and around the Pisa basin, show that this unit is sealed by mid-Pleistocene sediments (0.8 Ma). An aggradation package dipping towards the Tyrrhenian basin and overlying the prograding unit can be observed on seismic profiles (Fig. 2). A similar progradation/aggradation couplet of a compar-able age is also found in the Quaternary of the Po Plain.

3.2 Plio-Quaternary of the Northern Apennines

Intermontane extensional basins occur all along the Northern Apennines range with sedimentary fills as old as late Miocene (Bartolini *et al.*, 1982). Some recent papers, however, call for an initial thrust-related origin, only later overprinted by extension (Bernini *et al.*, 1994; Boccaletti *et al.*, 1995) as the early tectonic history is difficult to constrain. The sedimentary fill of these basins can typically be subdivided into packages separated by either non-depositional, erosional or angular unconformities (Fig. 3). At the regional scale, marine sediments dominate in western Tuscany whereas the easternmost basins of the Apennines range, are filled with continental deposits. In the intermediate position sedimentary fill presents early marine deposition, later followed by continental sediments (Fig. 3). Despite the difficulties in dating and correlating continental sediments, a large set of stratigraphic data from various sources (forams, molluscs, mammals, pollens, magneto-stratigraphy, etc.) allowed for a correlation of depositional packages in the different basins (Fig. 3; Bernini *et al.*, 1990; Boccaletti *et al.*, 1995). In particular, the Plio-Pleistocene sediments can be distinguished from one another on the basis of two widespread physical discontinuities: the first one is located in the late Pliocene and is defined by the *Globorotalia crassaformis* and *G. inflata pars* biozones for marine sediments, and by the Mammal zone MN17 for continental deposits; the second one dates to the upper part of the early Pleistocene (Sicilian stage for marine sediments and Cassia "erosional phase" for continental deposits). It is worth noting that this second unconformity separates middle Pleistocene continental deposits characterized by coarse- to very coarse-grained fluvial sediments from previously deposited relatively fine-grained lacustrine to alluvial sediments. Close to the Apennines range, the middle Pleistocene alluvial deposits are mainly composed of Macigno-derived boulders and this coarse-grained sedimentation episode can be related to a remarkable uplift of the fold and thrust belt that brought to the erosion of the Ligurian Units. Other geomorphological lines of evidence concerning a mid-Pleistocene uplift of the chain, with ensuing erosion, come from: a) the eastward motion of the Apennines watershed (Ghelardoni, 1958; Giannini & Pedreschi, 1949; Puccinelli, 1991; Sestini, 1950); b) the distribution of remnant surfaces on either side of the mountain range (Bartolini, 1980; Bartolini *et al.*, 1984, Bernini *et al.*, 1977; Clerici, 1988; Marchetti *et al.*, 1979; Schiroli, 1983); c) the widening of the PedeApennines area and the tilting of mid-Pleistocene PedeApennines fluvial terraces, which are also located on the divides between valleys. Furthermore, Quaternary sedimentation rates calculated for the Po Plain appear much higher than the Pliocene sedimentation rates, indicating a possible increase in the erosion rate (Bartolini *et al.*, 1996).

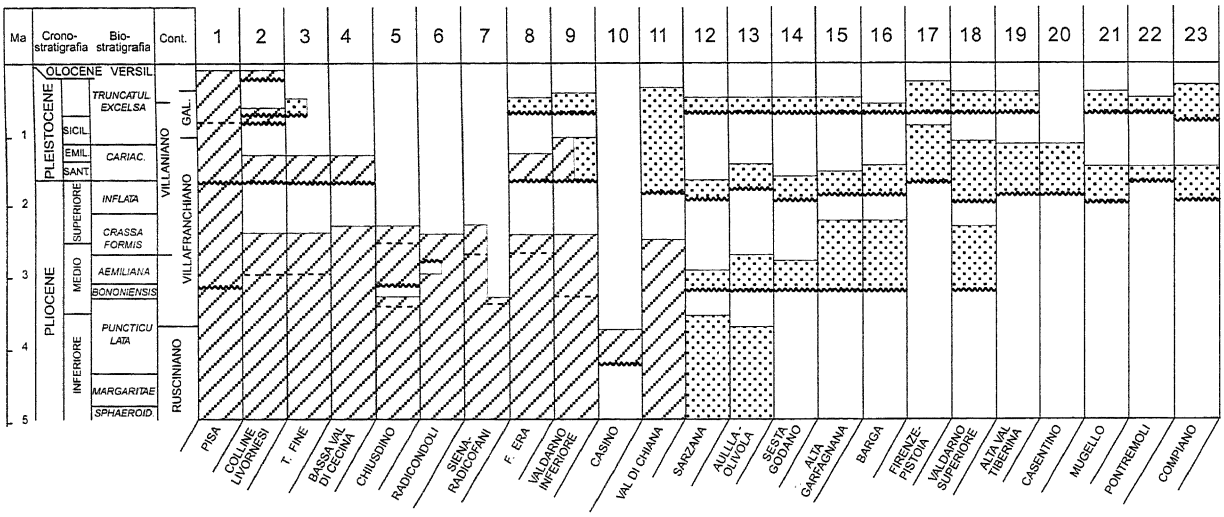


Fig. 3 - Chronostratigraphy of the Northern Apennines basins as obtained from various sources. Dotted areas = continental deposits; dashed areas = marine sediments.

Cronostratigrafia dei bacini del Nord Appennino sulla base di varie fonti. Le aree puntinate indicano i depositi continentali; le aree a tratto indicano i depositi marini.

3.3 The Plio-Quaternary of the Po Plain

The coverage and quality of seismic and well data are excellent all over the Po Plain and allow for the detailed reconstruction of both stratal geometry and timing of events.

Two regional geoseismic cross sections from the outer slope of the Apennines to the Po Plain, can be used to illustrate the structural setting and geometry of the foredeep basin fill (Fig. 4). The southern section (Fig. 4a) crosses a portion of the Apennines where the *Marnoso-Arenacea* Formation crops out extensively and the Ligurian units are absent. In the subsurface an extensive involvement of the Umbria-Marche carbonate units can be seen from the main belt to the front ("Ferrara" folds of late Pliocene age). The northern section (Fig. 4b), on the other hand, crosses a portion of the Apennines which is dominated by outcrops of Ligurian units under which the basement is steep and sloping north-eastwards. Mesozoic carbonates are not involved in the frontal part of the belts (late Pliocene "Piadena" fold) because of a basal *décollement* within the thick clastic units. Both profiles show a marked tilting of Quaternary strata at the margin of the Apennines foothills where Plio-Quaternary sediments crop out.

An about 500 m thick tabular unit with prograding clinoforms can be followed all over most of the Po Plain, corresponding to the outcropping shallow marine *Sabbie Gialle* ("yellow sand") formation. This unit is overlain by a tabular unit of similar thickness with parallel subhorizontal reflections indicating an aggrading package of continental deposits, which also onlap onto tilted and eroded strata in the PedeApennines. This prograding/aggrading couplet represents the final stage of the filling of the Apennines foredeep basin with sediments changing from deep marine in the underlying units to shallow marine to continental. The stratigraphic packages in the subsurface were dated on the basis of stratigraphic correlations using both surface (Channell *et al.*, 1994; Vaiani, unpubl. PhD Thesis) and well data (D. Rio, pers. comm.). The above mentioned prograding/aggrading couplet deposited in the last 1.0 Ma with the fast prograding occurring in about 200 ka.

On the western side of the northern cross section a dipping reflector joins the surface with the basement top. This feature is present also a few km to the south where it appears to bound the western flank of the Pleistocene Pontremoli graben. The overall geometry in the cross section suggests a possible role of gravity tectonics in controlling the origin of the Pontremoli (Artoni *et al.*, 1992) and, perhaps, other small extensional basins lying over the north-eastward sloping basement.

4. DISCUSSION

The results obtained with this study (Fig. 5) would support a two-phase evolution of the Northern Apennines in the Plio-Quaternary. During the Pliocene, particularly in the early Pliocene, a marked horizontal motion occurred giving rise to extensional basins in Tuscany and on the Tyrrhenian side and to major thrusting and folding on the Adriatic side. Apparently, the magnitude of horizontal motion decreased in time towards the end of Pliocene-early Pleistocene. On the other hand, the post-1.0 Ma evolution is characterised by a predominance of vertical motions, with uplifting and widening of the main Apennines range and uplifting of the Tuscany intermontane basins. The progressive tilting of Quaternary strata in the Apennines foothills is related to this process. In the Tyrrhenian offshore and in the Po Plain, on either side of the uplifted region, the possible combination of reduced subsidence and increase of sedimentary input due to emersion, likely originated the fast prograding units dating to 1.0-0.8 Ma. That subsidence continued in these areas is required by the aggrading package of continental sediments there observed.

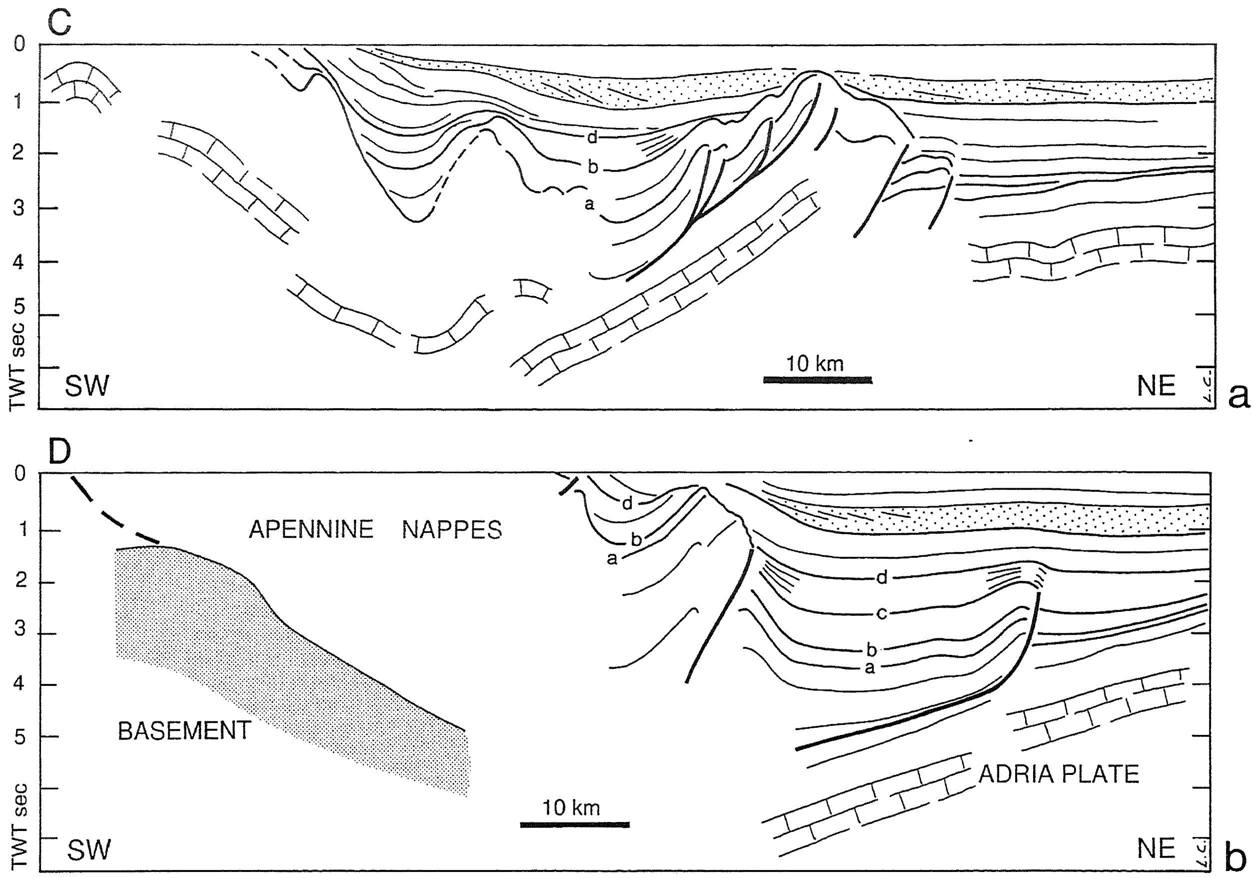


Fig. 4 - a) Southern cross-section ("Ferrara" folds with involved Mz carbonates). b) northern cross-section (Pontremoli-Piadena). See Figure 1a for location.

a) Sezione Sud (pieghe di Ferrara con coinvolgimento delle rocce carbonatiche Mz). b) Sezione Nord (Pontremoli-Piadena). Vedi Fig. 1 per la posizione.

In summary, the events recognized on either side of the Apennines fold-and-thrust belt show largely comparable timing and stratigraphic response. This fact suggests the control of some sort of regional process. The following considerations support the elaborated geodynamic interpretation.

The crustal thinning observed in Tuscany (Fig. 1) is likely related to the late Messinian-early Pliocene extension, with sedimentation that continued later within the grabens (Fig. 2). However, the Pleistocene uplift that affected a large portion of Tuscany, causing a topographic uprising of 400-500 m and a deep erosion of the sedimentary fill of the grabens, occurred much later and the two events cannot be easily corralated to one another. The shallow asthenosphere detected by S wave dispersion (Mueller & Panza, 1984) and attenuation (Mele *et al.*, in press) underneath Tuscany would explain both topographic elevation and high heat flow in the area.

Folding at the front of the Apennines belt in the Po Plain subsurface, died out in the early Pleistocene. A tabular unit of Quaternary sediments, unaffected by deformation, covers the tectonic structures. The progressive shallowing upward of the sedimentary fill suggests a decrease of subsidence rate and, likely, also an increase of sediment input due to the contribution from the emerging Apennines belt. A link between uplift of the Apennines range and shallowing of depositional environments is also suggested by the progressive folding of Quaternary strata in the Apennines foothills.

As mentioned above, the post-Langhian (at least) evolution of the Northern Apennines can be accounted for by lithospheric delamination of the Adriatic plate. This process led to back-arc-like extension and magmatism in the Tyrrhenian basin and to an eastward migration of foredeep basins on the Adriatic side. The recentmost evolution of the Apennines seems, however, to be at odd when compared to the previous deformation history, and some additional process is required. If, as previously suggested, high heat flow and topographic elevation in Tuscany connected with the shallow asthenosphere, can be related to the observed recent (late Pleistocene) uplift, a tentative hypothesis can be offered.

The geodynamic setting conforms to a continental lithosphere delamination where the detachment progressive eastward migration seems to slow down up to a stop, as indicated by the decrease in horizontal motion. In such situation, a sudden detachment and vertical sink, maybe associated with a slab break-off, of a portion of the Adriatic lithosphere may produce part of the observed tectonic regime changes: namely, the uplift of a large portion of Tuscany, the emersion and widening of the Apennines range with tilting of strata at the foothills, and

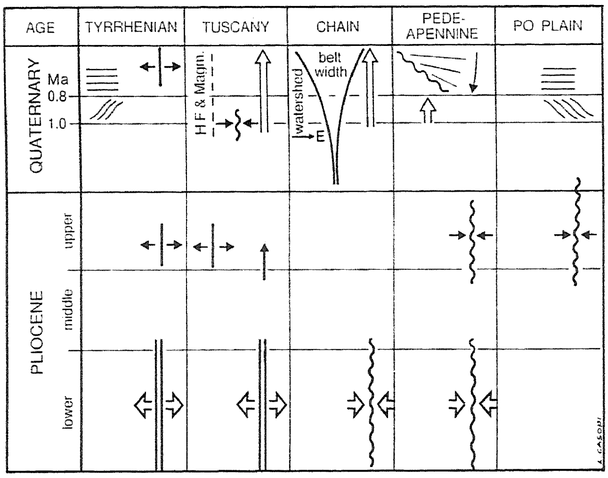


Fig. 5 - Summary chart of tectonic events recognized in the Northern Apennines, from the Tyrrhenian coast to the Po Plain. No time scale is implied.

Carta sinottica degli eventi tettonici riconosciuti nell'Appennino settentrionale dalla costa tirrenica alla Pianura padana. Non è riportata alcuna scala di riferimento temporale.

the decrease in subsidence/sedimentary input ratio in the Po Plain. Seismic tomography indicates that a detached slab configuration is possible and a preliminary geophysical modelling suggests that this mechanism can account for the observable geological features (Carminati *et al.*, 1997 submitted)

5. CONCLUSIONS

The detailed analysis of seismic stratigraphic Plio-Quaternary packages was performed for the Po Plain foredeep basin and the extensional basins of western Tuscany, located on either side of the Apennines fold-and-thrust belt. As a result, it can be shown that the major events in the two areas are comparable both in timing and stratigraphic response, suggesting the presence of a regional geodymanic control. In general, it was recognised a change from an early Pliocene dominant horizontal tectonics — with extensional features in western Tuscany and contractional features in the Apennine front — to a middle-late Pleistocene mainly vertical tectonics. Such an evolution can be accounted for if a relatively sudden detachment, and perhaps a slab break-off, of the subducted Adriatic continental lithosphere occurred underneath Tuscany.

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