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Sequential balancing of growth structures, the late Tertiary example from the central Apennine

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Key words. – Foreland basin, Central Apennines, Growth folds, Sequential balancing.

Abstract. – During the late Tertiary, the external front of the Central Apennines migrates towards the Adriatic foreland basin of the Marche and Abruzzi regions. The outermost synsedimentary growth structure, i.e. the buried Tortoreto-Campomare imbricate fan, was analysed using a seismic reflection line and borehole data. The growth structures record the interaction of tectonic and sedimentary processes at a scale of a few kilometres. The syntectonic sedimentary units form progressive unconformities along the Tortoreto-Campomare thrust panel and are used to unravel the geometric evolution of this buried external front of the Apennines.

A sequential balancing method is used to restore unconformity surfaces to their most plausible initial configuration. This methodology allows the reconstruction of nine evolutionary stages for the studied structure since the Pliocene (≈ 4 Ma). These stages define the local geometry of the foredeep basin during and after each unconformity. As each unconformity surface represents a palaeotopography, nine successive topographic surfaces have been restored. The progressive unconformity formed close to the hinge of the Tortoreto-Campomare thrust panel. The cut/seal relationships between the tip of the thrusts and the stratigraphic units constrain the timing of thrusting, and define a local break-back sequence. However, synchronous and out-of-sequence thrusting also occurred at different stages of the structure growth. The time interval of activity and the thrust displacements calculated by cross section restorations allow the estimation of compressional rates, these ranging between 0.12 mm/y and 4.25 mm/y. The former value is comparable to displacement rates in previous literature. Despite limitations, this sequential balancing technique is promising and useful for the study of growth folds.

Restauration séquentielle d'une coupe géologique dans des plis synsédimentaires, l'exemple du Tertiaire récent de l'Apennin central

Mots clés. – Bassin d'avant pays, Apennins central, Plis synsédimentaires, Restoration sequentielle.

Résumé. – Au cours du Tertiaire supérieur, le front externe des Apennins central migre en direction du bassin d'avant-pays adriatique des Marches et des Abruzzes. La structure synsédimentaire plus externe, i.e. le cône imbriqué de Tortoreto-Campomare, a été analysé en utilisant une ligne sismique et des données de forage. Les structures synsédimentaires enregistrent l'interaction de processus tectoniques et sédimentaires sur une échelle de quelques kilomètres. Les unités sédimentaires forment des discordances progressives le long du cône imbriqué de Tortoreto-Campomare. Cette discordance progressive est utilisée pour reconstruire l'évolution géométrique du front externe des Apennins central.

Une méthode de restauration séquentielle est utilisée pour restituer les surfaces des discordances dans leur configuration initiale. Cette méthode permet de reconstruire neuf stades d'évolution de la structure étudiée depuis le Pliocène (≈ 4 Ma). Ces étapes définissent la géométrie du bassin d'avant-pays pendant et après chaque discordance. Comme chaque discordance représente une surface paléotopographique, on reconstruit ainsi neuf surfaces topographiques successives. La discordance progressive a été formée à proximité de la charnière du pli. Les relations spatiales entre l'extrémité des chevauchements et les unités stratigraphiques imposent une limite temporelle au mouvement et définissent une séquence « break-back » locale au chevauchement. On peut aussi définir pendant les différentes phases de croissance de la structure des séquences de chevauchements synchrones et « out-of-sequence ». Les différentes étapes reconstituées par la restauration séquentielle permettent aussi d'estimer des vitesses de déformation qui se situent entre 0,12 mm/a et 4,25 mm/a. Ces valeurs peuvent être comparées avec les vitesses de déplacement décrites dans la littérature. Malgré les limites inhérentes à cette technique de restauration, elle apparaît très prometteuse et particulièrement adaptée à l'étude des plis synsédimentaires.

VERSION FRANÇAISE ABRÉGÉE

Le front de déformation des Apennins centraux, associé à une chaîne de collision depuis l'Oligocène [Patacca *et al.*, 1991] migre régulièrement en direction du bassin d'avant-pays adriatique des Marches et des Abruzzes. Dans cette région de l'Italie centrale, nous étudions trois structures orientées nord-sud qui se sont formées au cours du Tertiaire supérieur. De façon synchrone, dans cette partie du bassin se déposent des grès turbiditiques de cônes sous-marins profonds [Casnedi, 1983; Crescenti *et al.*, 1980; Ori *et al.*, 1991] et des conglomérats chenalisés [Ori *et al.*, 1991] du Pliocène inférieur. Ces faciès passent vers le haut a des dépôts moins profonds de plate-forme et de plage au Pliocène supérieur et au Pleistocène [Crescenti *et al.*, 1980; Ori *et al.*, 1991].

La structure la plus interne, celle de Roccafinadamo (fig. 1), est active dès le Pliocène basal et elle est scellée par le Pliocène inférieur au nord de la vallée du Vomano (fig. 1A). La seconde structure, celle de Nereto-Zaccheo est scellée par le Pliocène supérieur/Pleistocène. Quant à la structure plus externe et donc plus récente, elle correspond au cône imbriqué de Tortoreto-Campomare ; c'est un pli synsédimentaire qui est actif jusqu'au Pliocène supérieur terminal et qui est cacheté par le Pleistocène. Cette structure est constituée par un faisceau de failles et de plis qui sont continus sur des dizaines de kilomètres au nord et au sud de la zone étudiée. Les données sismiques et de forages disponibles permettent de préciser la géométrie en subsurface de la structure de Tortoreto-Campomare (figs. 1A et 2A). Il faut souligner l'importance des structures synsédimentaires car elles enregistrent l'interaction entre les processus tectonique et sédimentaire sur une échelle plurikilométrique. Les unités sédimentaires forment des discordances progressives [au sens d'Anadon *et al.*, 1986 ; Riba, 1976] le long du cône imbriqué de Tortoreto-Campomare (fig. 2A). Ces discordances progressives passent à des discordances angulaires qui sont utilisées pour reconstruire l'évolution géométrique du front des Apennins centraux dans ce secteur. Les âges des différentes séquences sédimentaires déformées et limitées par les discordances angulaires, sont déduits à partir d'une synthèse de datations biostratigraphiques nombreuses [Crescenti, 1971 ; Crescenti *et al.*, 1980 ;

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Ori *et al.*, 1991]. Ces datations sont utilisées par assimilation avec la zonation la plus récente du Pliocène [Iaccarino, 1985; Patacca *et al.*, 1990] (fig. 3). La connaissance des âges des différentes unités stratigraphiques est fondamentale pour calculer les taux de raccourcissement de chaque faille du cône imbriqué.
La méthode utilisée pour reconstruire la géométrie de la structure synsédimentaire de Tortoreto-Campomare est la restauration séquentielle [DeCelles *et al.*, 1991; Burbank and Verges, 1994]; les différentes étapes de la restauration sont encadrées par les discordances. Chaque surface de discordance est restaurée dans son état initial avec un point fixe localisé dans la charnière du synclinal le plus oriental de la coupe. Le point fixe change donc pour chaque discordance; le synclinal le plus externe est localisé entre 1 ou 2 km à l'est des anticlinaux du faisceau de failles du Tortereto-Campomare (fig. 4). Les surfaces restaurées ne sont pas horizontales mais elles représentent la topographie du bassin sur laquelle chaque unité sédimentaire a été déposée. Les pentes restaurées montrent un angle maximal de 23° (fig. 4 étape E). Ces valeurs de l'inclinaison sont similaires à celles décrites dans des structures comparables (table I). La restauration séquentielle permet de reconstruire neuf étapes évolutives de la structure étudiée depuis le Pliocène (≈ 4 Ma), correspondant à la géométrie du bassin d'avant-pays à l'issue de la formation des discordances successives. Les discordances représentent les surfaces paléotopographiques; par conséquent la méthode utilisée permet de reconstruire neuf surfaces topographiques successives. La discordance progressive a été formée à proximité de la zone de charnière du pli. Vers l'est, les mêmes discordances deviennent conformes aux surfaces sub-horizontales de l'avant-fosse adriatique; alors qu'elles passent à des surfaces d'érosion vers l'ouest, dans le bassin de «piggy-back» (fig. 2).
Les relations spatiales entre l'extrémité des chevauchements et les unités stratigraphiques imposent une limite temporelle au mouvement. A l'échelle de l'Apennin central, le front de déformation de la chaîne migre par une succession de «piggy-back»; la même séquence de développement affecte les structures de Roccafinadamo, Nereto-Zaccheo et Tortoreto-Campomare qui se terminent respectivement au Pliocène inférieur, Pliocène inférieur terminal et au Pliocène supérieur terminal. Toutefois, la restauration séquentielle montre que dans la structure de Tortoreto-Campomare la séquence de développement local des chevauchements est «break-back», avec soit des séquences synchrones soit des séquences «out-of-sequence» durant plusieurs phases de croissance de la structure (fig. 4).
La vitesse de raccourcissement de la structure Tortoreto-Campomare est de 1,85 mm/a, soit 7,4 km de raccourcissement en 4 m.y. Les vitesses de déplacement calculées pour chacune des failles du cône imbriqué sont situées entre 0,12 mm/a et 4,25 mm/a. La variabilité de cette valeur est liée à l'existence de deux niveaux de décollement convergents dans la même structure frontale de Tortoreto-Campomare. Les limites de la technique de restauration et celle de l'interprétation de données géologiques et géophysiques sont aussi discutées. Néanmoins, les vitesses locales de raccourcissement et de déplacement calculées peuvent être comparées avec celles publiées dans la littérature dans des contextes analogues (tab. II), notamment avec celles calculées pour des failles actives durant le Quaternaire [Nicol *et al.*, 1994]. Donc, la méthode de restauration séquentielle, telle qu'elle a été utilisée ici, s'avère encourageante pour comparer les plis synsédimentaires anciens avec les structures récentes.

INTRODUCTION

In the Adriatic side of Central Italy (fig. 1A), Pliocene and Pleistocene foredeep deposits record the latest evolutionary stages of the Apenninic chain. Orogenic deformation migrated eastward from the Oligocene to the Present after the collision of the Apulian plate with the Corso-Sardinia block [Boccaletti *et al.*, 1980; Rehault *et al.*, 1984; Sartori *et al.*, 1987; Patacca *et al.*, 1991]. This eastward migration of the fold-thrust front is coeval with the flexure of the Apulian plate [Royden and Karner, 1984] and the formation of the main foreland basins of the Apennines (Macigno, Cervarola, Marnoso Arenacea, Laga and Pliocene foredeep basins) [Ricci Lucchi, 1986].

Superposed on these large scale dynamic processes, tectono-sedimentary processes related to growth structures affected the foredeep evolution. In the Adriatic foredeep, infilled during the Pliocene by deep water turbidite and shallow water deposits [Ori *et al.*, 1991], the effects of these smaller scale tectono-sedimentary processes are particularly well observed in the outermost subcrop front of the Central Apennines. The Tortoreto-Campomare thrust-related growth structure (fig. 1), made up of a stack of five thrusts and related folds (fig. 1B), belongs to the external front of the Central Apennines. It was analysed on seismic lines (fig. 2), depth-converted and calibrated by bore-hole data (fig. 2) [Artoni, 1993; Casero *et al.*, 1994]. Examples of such synsedimentary thrust-related growth structures in foreland basin are also preserved north of the Apennines beneath the Po Plain [Pieri and Groppi, 1981; Zoetemeijer *et al.*, 1992], and in other orogens, i.e. in the South Pyrenean Ebro basin [Riba, 1976; Anadon *et al.*, 1986; Specht *et al.*, 1991], where spectacular progressive unconformities were formed. The growth structure also account for surficial processes, i.e. erosion, sediment transport and deposition, which constantly modify the morphology of the folds. Both compressional deformation and surface processes occur synchronously with the lithospheric flexure. The respective role of structural or sedimentary processes and lithospheric flexure in shaping the orogen has become the subject of recent numerical modelling [Beaumont *et al.*, 1990; Johnson and Beaumont, 1994]. The interplay of all these processes can be focused throughout the sequential balancing of growth structures, either from outcrop exposures or when imaged in seismic reflection profiles. The sequential balancing and the cut/seal relationships between thrust faults and stratigraphic units are also useful in evaluating the thrusting rates. This technique, applied to the Tortoreto-Campomare thrust sheets, reconstructs the kinematic evolution of the structure and of the surficial topography for incremental time steps of ≈ 400 ka, following the rules of line length section balancing [Woodward *et al.*, 1989, and references therein]. The calculated thrust displacement rates are modified by tectonic and depositional parameters, as we will see in the chapter tectonic and stratigraphic problems, which need to be evaluated in this kind of cross section balancing.

REGIONAL GEOLOGIC FRAMEWORK

In this area of Central Italy three main north-trending stack of thrust sheets, with a piggy-back thrusting sequence, control the sedimentation [Artoni, 1993; Casero *et al.*, 1994] (fig. 3). The inner one, i.e. the Roccafinadamo thrust sheets were active during the early Pliocene (figs. 1 and 3). It

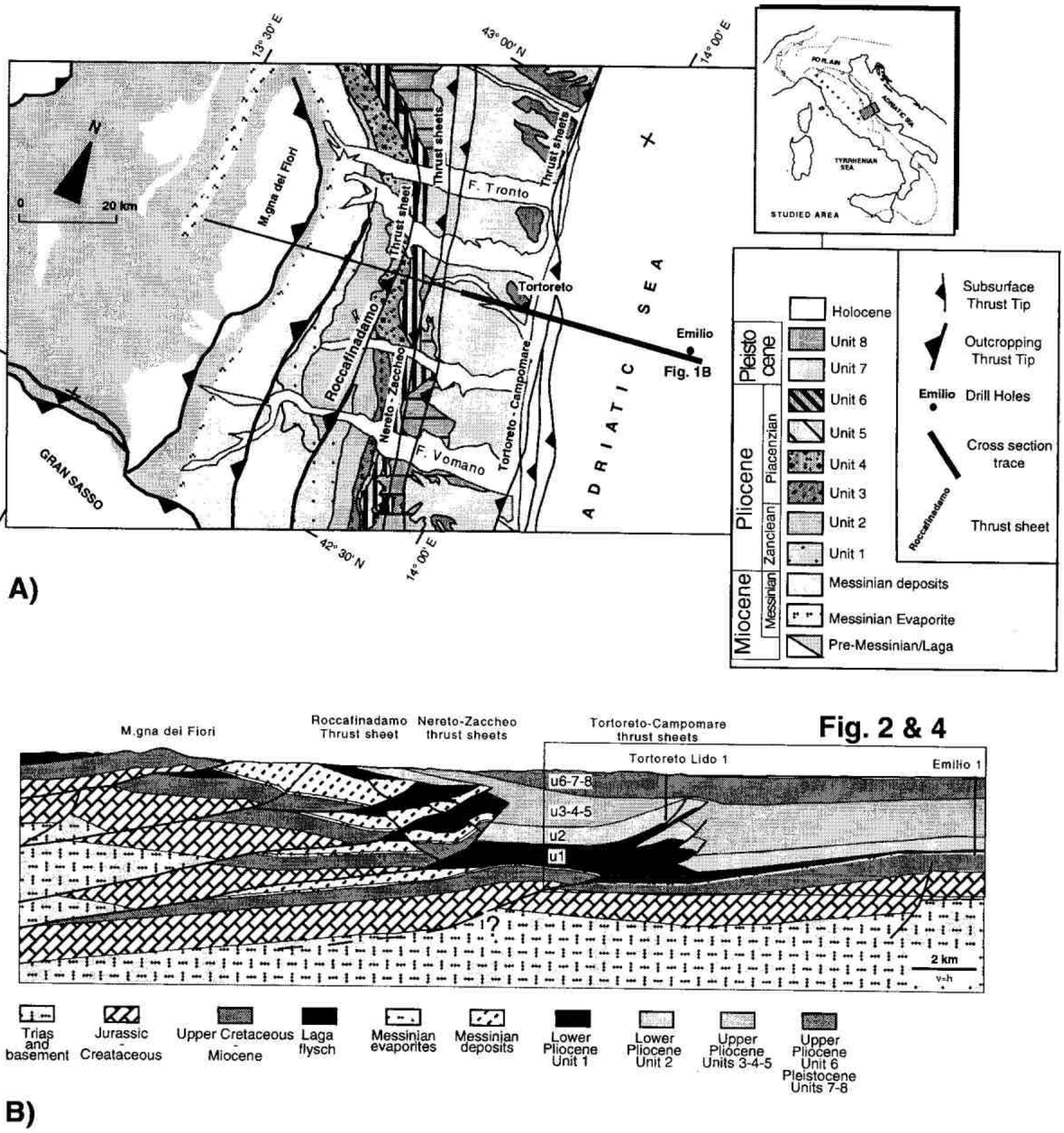


FIG. 1. – A) Location map and geology of the studied area. Units 1-8 comprise the Lower Pliocene to Pleistocene Adriatic foredeep deposits (see fig. 3). – B) Regional structural cross-section showing the imbricate thrusts west of the Tortoreto-Campomare thrust sheets, and the detachment levels on top of which the fold-and-thrust belt is developed. The portion of cross-section in the rectangle is analized in this study.

FIG. 1. – A) *Localisation et cadre géologique de la zone d' étude. Les unités 1-8 représentent les sédiments des bassins de l'avant-fosse adriatique du Plio-Pleistocène* (voir fig. 3). – B) *Coupe structurale régionale montrant les unités structurales à l'ouest de la structure Tortoreto-Campomare et les niveaux décollés au dessus desquels les unités se sont développées. La portion de coupe dans le rectangle est étudiée dans ce travail.*

crops out in the area of the River Vomano, being sealed by the Lower Pliocene further north (fig. 1A). The outer two stack of thrust sheets are named Nereto-Zaccheo and Tortoreto-Campomare, which extend in the subsurface and are buried by Pliocene and Pleistocene sediments. The easternmost north-trending Tortoreto-Campomare thrust sheets run parallel to the Adriatic coast (fig. 1A); "Campomare trend" of Crescenti *et al.*, [1980]. Following the terminology related to mountain fronts [Boyer and Elliott, 1982; Morley, 1986; Vann *et al.*, 1986; Dunne and Ferrill, 1988], the Tortoreto-Campomare thrust sheets is best defined as a blind thrust system [Dunne and Ferrill, 1988], which results from sedimentation during and after the thrust emplacement. Two detachment levels split into five subcrop thrusts (fig. 1B and 2), such a blind imbricate fan system [sensu Boyer and Elliott, 1982] accounting for the Tortoreto-Campomare anticlinal structure (fig. 4). Each thrust is associated with an anticlinal fold and syntectonic sediments contain progressive unconformities along both flanks of the structure. The most spectacular progressive unconformities are located near the hinge of the highest anticline of this imbricate fan.

The Tortoreto-Campomare structure outlines the youngest deformational front in this sector of the Apennines. It is buried beneath Pliocene and Pleistocene clastic sediments that were deposited during the growth of this fault-related fold. The surrounding Pliocene Adriatic foredeep is mainly infilled by deep water turbiditic deposits [Ori *et al.*, 1986; Ricci Lucchi, 1986; Ori *et al.*, 1991]. Shallow water deposits appear diachronously during the late

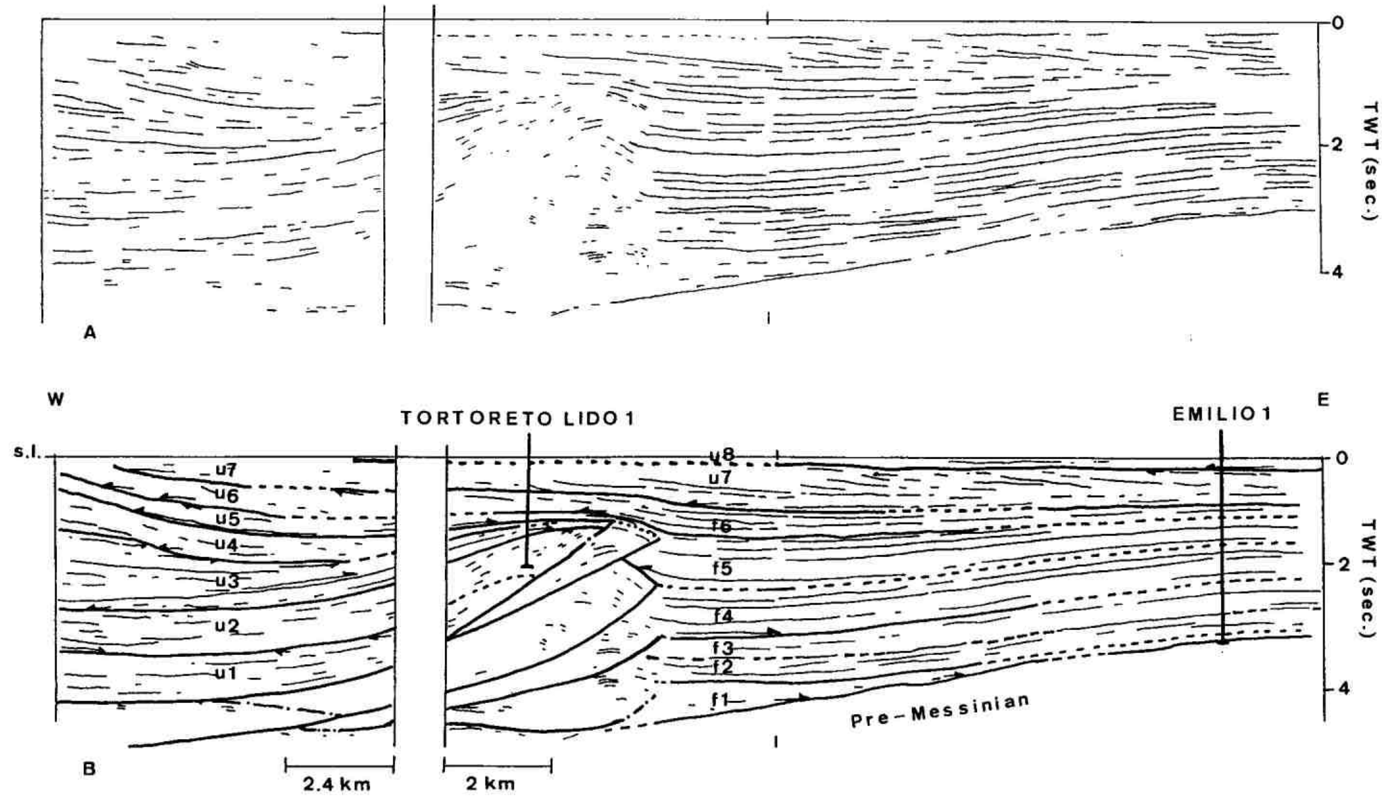


FIG. 2. – A) Not interpreted line drawing of the seismic lines. – B) Interpreted line-drawing of seismic lines and boreholes used for the calibration and depth conversion of the cross section in figure 4. The location is in figure 1. The stratigraphic units (i.e. u1-u8) are numbered as in figure 3, and are bounded by thicker line marks; f1-f6 labels refer to the same stratigraphic units in a foredeep setting.

FIG. 2. – A) *Pointé non interpreté des lignes sismiques utilisées.* – B) *Pointé interprété de la ligne sismique et localisation des forages utilisés pour la restitution en profondeur de la coupe de la figure 4. Cette coupe est localisée sur la figure 1. Les unités stratigraphiques* (u1-u8) *sont numérotées avec les mêmes numéros que la figure 3 ;* f1-f6 *sont les mêmes unités stratigraphiques que dans l'avant-fosse.*

Pliocene-early Pleistocene along the entire Apennine chain, thus forming prograding sigmoids in the formerly offshore area of the Marche and Abruzzi regions [Accordi *et al.*, 1969; Ori *et al.*, 1986; Ori *et al.*, 1991].

GEOPHYSICAL AND WELL DATA

The Tortoreto-Campomare thrust sheets has been imaged on several different seismic profiles. One of them was selected for the modelling; it is part of a survey made in 1975, which comprised three seismic reflection lines, one onshore and two offshore. The resulting composite regional line has been depth converted by using the data of two key drill holes (Tortoreto Lido 1 and Emilio 1) [Artoni, 1993; Casero *et al.*, 1994] (fig. 2 and 4). The Tortoreto Lido 1 well is located on top of the higher thrust sheet; whilst, the Emilio 1 is located 18.5 km to the east (fig. 1).

MAIN STRATIGRAPHIC UNITS

In the Marche and Abruzzi areas, foredeep siliciclastic deposition started in the Messinian and continues to the present [Accordi *et al.*, 1969; Cantalamessa *et al.*, 1986; Ori *et al.*, 1986; Centamore *et al.*, 1990; Ghisetti *et al.*, 1994]. In the late Miocene to Pleistocene chronostratigraphic scheme (fig. 3), compiled from published stratigraphic charts [Cantalamessa *et al.*, 1986a; Cantalamessa *et al.*, 1986b; Centamore *et al.*, 1990; Ori *et al.*, 1991; Ghisetti *et al.*, 1994] and implemented by the authors along the studied cross-section [Artoni, 1993; Casero *et al.*, 1994] (fig. 3), the main unconformities provide important informations for understanding the basin evolution [Hubbard *et al.*, 1985]. Thus, eight stratigraphic units have been recognized above the Messinian evaporites (fig. 3). These stratigraphic units have been dated by planktonic foraminifera [Crescenti, 1971; Crescenti *et al.*, 1980]. These biozones relate to the entire Pliocene (Lower-Middle-Upper Pliocene), and compare with biozones of Iaccarino [1985, column (1) in fig. 3], which define the formal early and late Pliocene.

As described here, the infill history of the basin, started with deep water clays and marls. These oldest deposits are characterized by the occurrence of *Sphaerodinellopsis* sp. [Crescenti *et al.*, 1980] (lower part of Unit 1, fig. 3), thus recording the come back of Atlantic ocean water into the Mediterranean sea after the Messinian salinity [Hsü *et al*., 1977; Cita and Corselli, 1990]. The Lower Pliocene is characterized by turbiditic deposition : the Unit 1 is made up of thick layers of sandstone turbidites (Cellino Formation [Casnedi, 1983]) and the Unit 2 is made up of thinner turbiditic sandstone layers interbedded with clays (LP1 sequence of Ori *et al.* [1991]). The sandstone turbidite bodies of Unit 1 belong to the *Sphaerodinellopsis* and *Gb. margaritae* biozones [Crescenti *et al.*, 1980], while Unit 2 is attributed to the *Gb. puncticulata-Gb margaritae* biozone (fig. 3) [Crescenti *et al.*, 1980 related to Iaccarino, 1985].

The base of the Unit 3 (fig. 2) is an onlapping surface, while its top is made up of the erosional surface corresponding to the base of "Middle Pliocene" [Crescenti *et al.*,

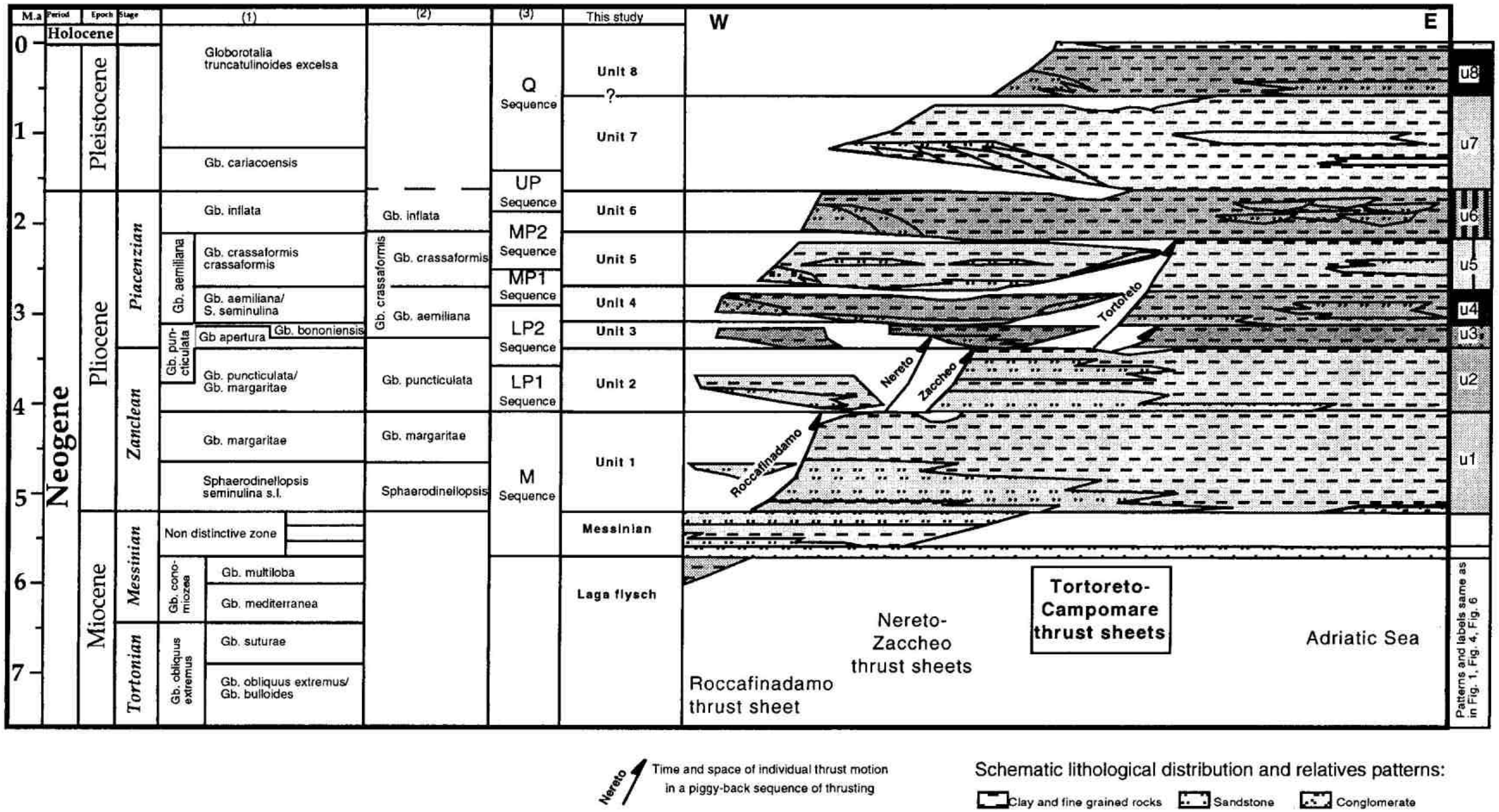
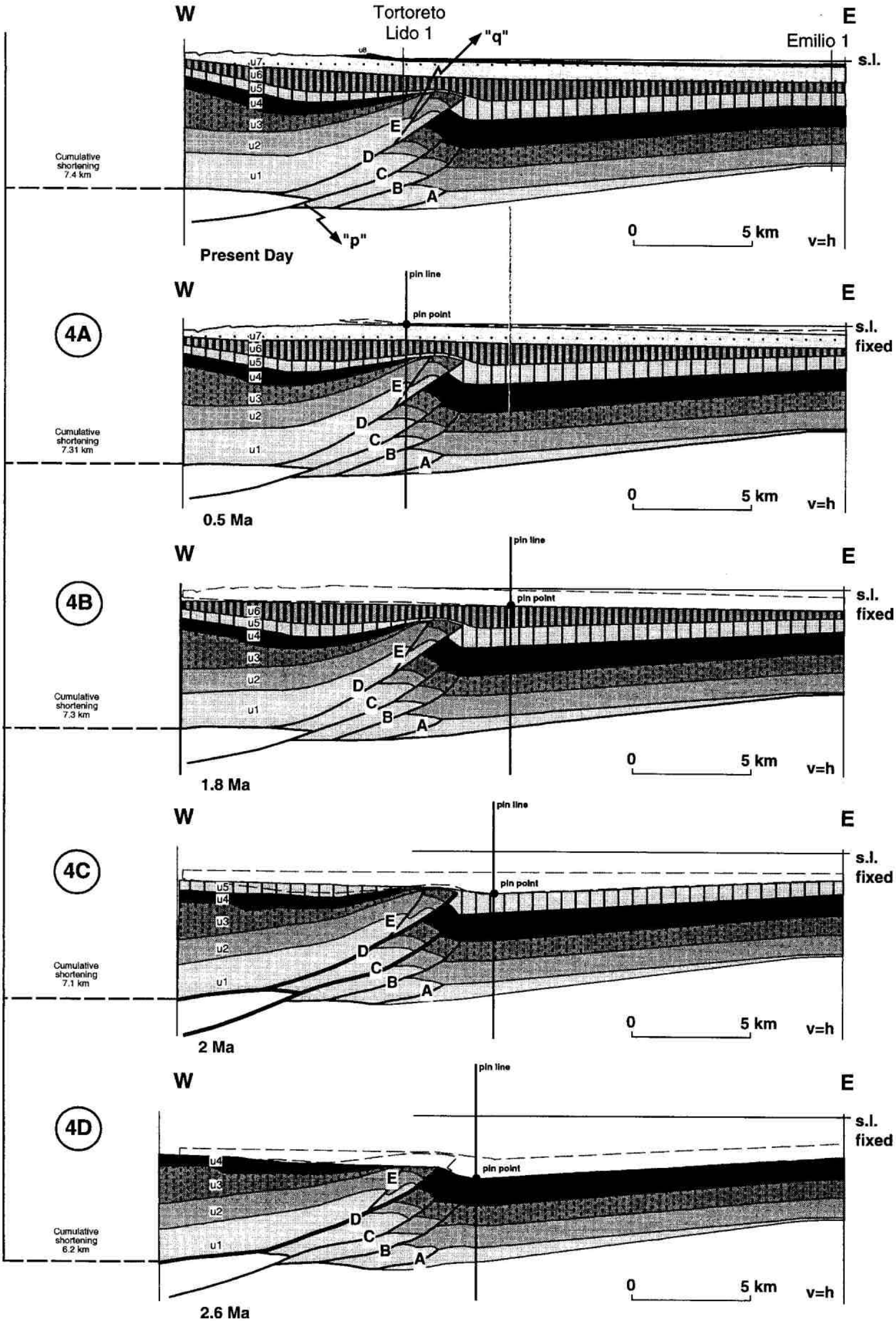


FIG. 3. – Chronostratigraphic scheme of the studied area. The stratigraphic record is clearly controlled by thrust activity. The thrust sheets show a piggy-back thrusting sequence. The biostratigraphic zonation is that of (1) Iaccarino [1985] and Iaccarino and Salvatorini [1982], (2) Crescenti *et al.* [1980]. Stratigraphic scheme of Ori *et al.* [1991] is presented in column (3). The absolute ages are from Patacca *et al.* [1991], except for the base of Pliocene at 5.2 Ma [Harland *et al.*, 1990].

FIG. 3. – *Schéma chronostratigraphique de la région étudiée. Les hiatus sont clairement controllés par le mouvement des chevauchements. Les chevauchements montrent une séquence « piggy-back » de mise en place. Les biozones sont celles de* (1) *Iaccarino [1985] et Iaccarino & Salvatorini [1982],* (2) *Crescenti* et al. *[1980]. La série stratigraphique de Ori* et al. *[Ori* et al., *1991] est montrée dans la colonne* (3). *Les âges absolus sont ceux de Patacca* et al. *[1991], à l'exception de la base du Pliocène à 5.2 Ma [Harland* et al., *1990].*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4A
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2.6 Ma

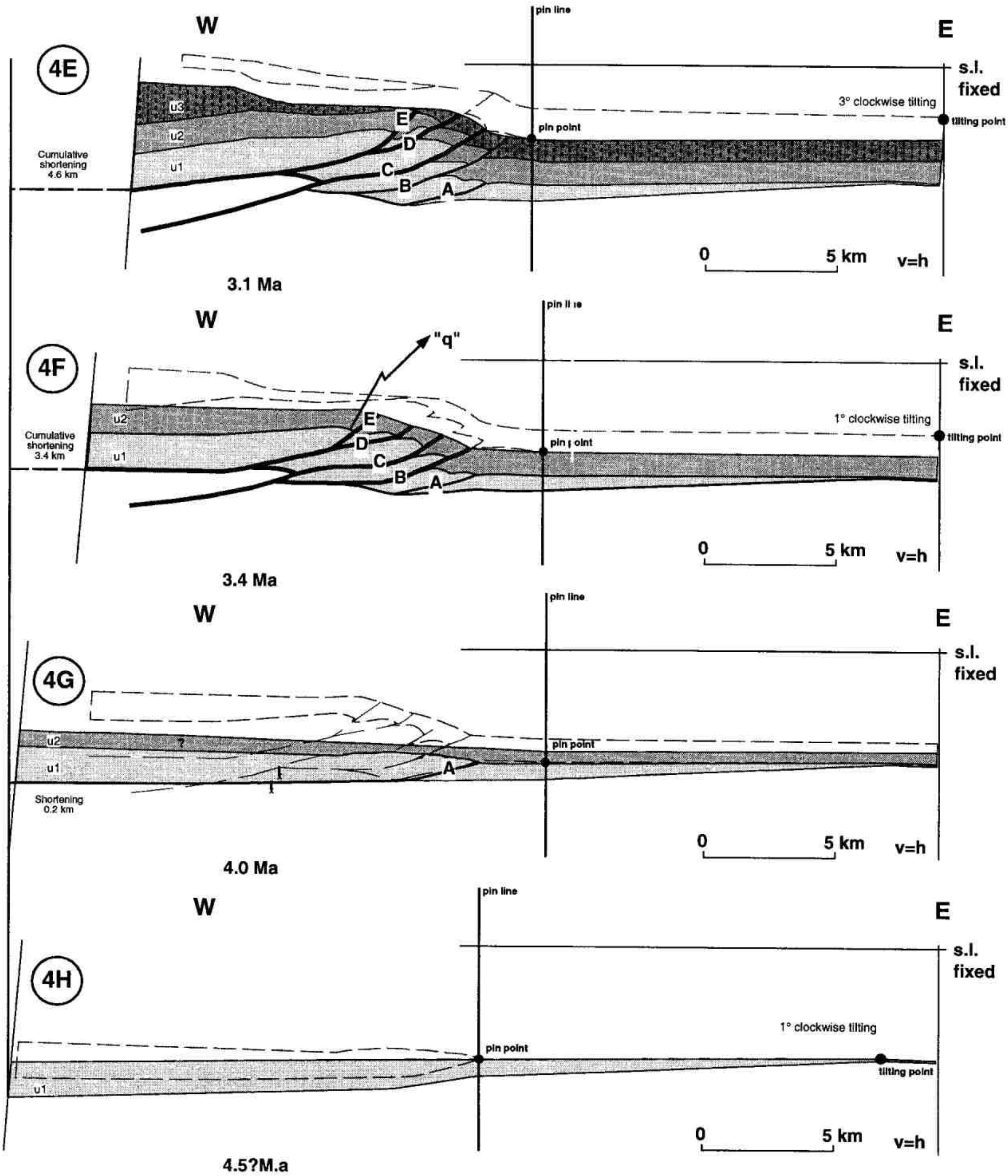

FIG. 4. – Results of sequential balancing of Tortoreto-Campomare thrust sheets. The cross sections are line length balanced. The dashed line outlines the geometry of the unconformity after deformation. Sea level has been kept fixed. The restoration templates define palaeotopographic surfaces.

FIG. 4. – Résultats de la restauration séquentielle de la structure Tortoreto-Campomare. Les coupes ont été équilibrées en conservant les longueurs. Les hachures matérialisent la géométrie de la discordance après la déformation. Le niveau de la mer est fixe. Ces restaurations définissent une surface paléotopographique irrégulière.

1980] or to the MP1 unconformity of Ori *et al.* [1991]. This unconformity occurs also at a depth of 2 600 m.b.s.l. in the Emilio1 well but with little if any erosion. Turbidites are still present in the Unit 3, attributed to the *Gb. puncticulata* biozone of Iaccarino [1985] because of the occurrence of *Gb. bononiensis* microfauna in the shales near the top of the unit [see Ori *et al.*, 1991].

The conglomerates of Unit 4 (in the lower part of MP1 sequence of Ori *et al.* [1991]) and Unit 5 (upper part of MP1 and lower part of MP2 sequence of Ori *et al.* [1991]) overlie the above mentioned erosive unconformity. These conglomerates are channellized and contain limestone clasts. According to Ori *et al.* [1991], they were deposited in a deep water environment. They are associated with sandstone horizons, channel levee complexes and basin plain deposits [Ori *et al.*, 1991]. This facies association shows a fining upward trend [Ori *et al.*, 1991] while along the section the thickness changes considerably from west to east (e.g. from 600 to 0 m in Unit 4) (fig. 4). The biostratigraphic age of Units 4 and 5 are only inferred, being attributed to the *Gb. aemiliana – S. Seminulina* and *Gb. crassaformis* biozone, respectively [Crescenti *et al.*, 1980, to be compared with Iaccarino, 1985].

Unit 6 (upper part of MP2 sequence and the UP sequence of Ori *et al.* [1991]), is placed within the *Gb. inflata* biozone [Crescenti *et al.*, 1980]. It has a lenticular shape, with foreshore and shoreface deposits laterally equivalent to channel levee complex and basin plain deposits [Ori *et al.*, 1991]. Unit 7 and 8 (Q sequence of Ori *et al.* [1991]) are characterized by continental/shallow marine facies grading to mound turbidites eastward [Ori *et al.*, 1991]. They continue the general shallowing-upward trend and eastward shift of the depocenter initiated with Units 1.

The geometrical relationships among Units 3 to 7 create a progressive unconformity close to the crest of the Tortoreto-Campomare growth structure, as demonstrated by the line drawing of the seismic line (fig. 2).

METHOD : SEQUENTIAL BALANCING OR THE STEP-BY-STEP EVOLUTION OF A GROWTH FOLD

A progressive unconformity [Birot, 1937; Riba, 1976; Anadon *et al.*, 1986] is a sequence of unconformities formed on the limbs of folds growing during sedimentation. The unconformities bound wedge shaped syntectonic stratigraphic units (figs. 2 and 4), converging into a single unconformity close to the crest of the growth fold (figs. 4 and 5). The progressive unconformity can be used to define the growth of folds and thrust related anticlines [Medwedeff, 1989; Mount *et al.*, 1990; Vergés and Riba, 1991; De Celles *et al.*, 1991; Spetch *et al.*, 1991]. In fact, the unconformity represents the upper or topographic surface of the fold. This surface can be used as a marker horizon which records the future changes in fold shape. Obviously the stratigraphic units record the fold shape changes too. The usefulness of progressive unconformities for the reconstruction of the fold kinematics has been already emphasized by Vergés and Riba [1991], De Celles *et al.* [1991] and Burbank and Vergés [1994]. The syntectonic stratigraphic units, belonging to the progressive unconformity create particular geometries when the fold is growing (fig. 5). In fact, they can either onlap, offlap or overlap the anticlinal crest [Burbank and Vergés, 1994] (fig. 5). Onlapping and offlapping units indicate that for a given span of time the anticline crest was an exposed relief (on the sea floor in the Tortoreto-Campomare example). The overlapping units constrain the time when the crest of the anticline was finally buried (fig. 5). Onlap, offlap and overlap are controlled by the ratio between the shortening rate (F) and sedimentation rate (S) [Vergés and Riba, 1991; Burbank and Vergés, 1994]. In particular, shortening rate (F) relatively lower than the sedimentation rate (S) are likely to produce onlap and overlap geometry (fig. 5B, 5C); whilst, shortening rate (F) relatively higher than sedimentation rate (S) are likely to create onlap and offlap geometries (fig. 5D). Therefore within the syntectonic stratigraphic units, the onlap geometry does not represent any relative value of the ratio shortening rate (F)/sedimentation rate (S); whilst, the overlap and the offlap geometries suggest respectively low and high value of this ratio. In the same growth fold the (F)/(S) ratio changes in time (fig. 5A).

At each growth stage of the structure, the folding processes produces uplift and enhances erosion. The structure assumes a new shape and a new unconformity is created. Still younger sediments seal it with an onlap or overlap relationship. If erosion is active during fold growth, an older overlapping and eroded unit can simulate an onlap relationship (Unit 3b in fig. 5A). The onlapping, offlapping or overlapping stratigraphic units constrain the slope of a depositional surface by both the depositional processes (if known or recorded) and the geometrical relationships at the unconformity. This depositional surface constrains the shape to which to restore the stratigraphic unit bounded by the unconformity [De Celles *et al.*, 1991]. Usually, the sequential balancing technique [Cooper and Trayner, 1986; Ford, 1987] restores the stratigraphic units to a flat surface instead of taking into account the depositional slope. The sequential balancing of Tortoreto-Campomare structure outstrips the stratigraphic units above each unconformity restoring their bottom to a given depositional surface.

The syntectonic stratigraphic units can either seal the thrust and the related fold or they can be cut by the thrust (fig. 5). The cut/seal relationships between the fold and the fault and the age of the stratigraphic units define the timing of the shape evolution in the growth structure. The age span of syntectonic stratigraphic units represents the time when the thrust-related fold was growing (the thrust was active); whereas the age of the base of the overlapping and more horizontal stratigraphic units (fig. 5) defines the time when the fold stopped to grow. In the Tortoreto-Campomare structure the time is given by the chronostratigraphic scheme (fig. 3), which is needed to calculate the displacement rate of each thrust.

Progressive unconformities, onlap, overlap or offlap of stratigraphic units and cut/seal relationships between thrust and stratigraphic units are observed in the studied cross section (figs. 2 and 4). They are used to define how the growth fold shape changed in time and how the location of thrust activity migrated in space and time. Then, the kinematics of the Tortoreto-Campomare imbricate fan has been reconstructed with the aid of the sequential balancing technique, which takes into account the unconformities tectonically induced by the fold growth and their progressive development with onlap, overlap and offlap relationships. The restoration template surface is constrained by the geometry of the preserved unconformity surfaces and the terminations of the overlaying and underlaying strata on the unconformity. The basal unconformity of each stratigraphic unit is restored to its position before the deposition of the overlying unit. In the foredeep depozone [DeCelles and Giles, 1996] the depositional surface is horizontal. In fact, east of the Tortoreto-Campomare crest, a turbiditic basin plain is present with very flat stratigraphic horizons (fig. 2), high sedimentation rate [Ricci Lucchi, 1986] and no growth structure. Therefore, even though any topographic relief were created, it would have been easily smoothed. Instead, close to the Tortoreto-Campomare crest, the shape and thickness of the thrust sheet are continously changing as sediments are continously deposited, deformed and eroded. If no onlap or offlap geometries are preserved, averaged slope inclinations have been used. The inclinations used are in the range of slope inclinations observed in recent active compressional fronts (see table I) and Pratson and Haxby [1996], expecially the slope inclination relative to a single structure of comparable length [see for example Philip and Meghraoui, 1983]. The restored template is defined step by step. It is built up by unfolding the unconformity surface around a pin point which is the most forelandward hinge on the unconformity. The pin point change for every restored unconformity surface (fig. 4); the vertical line passing through

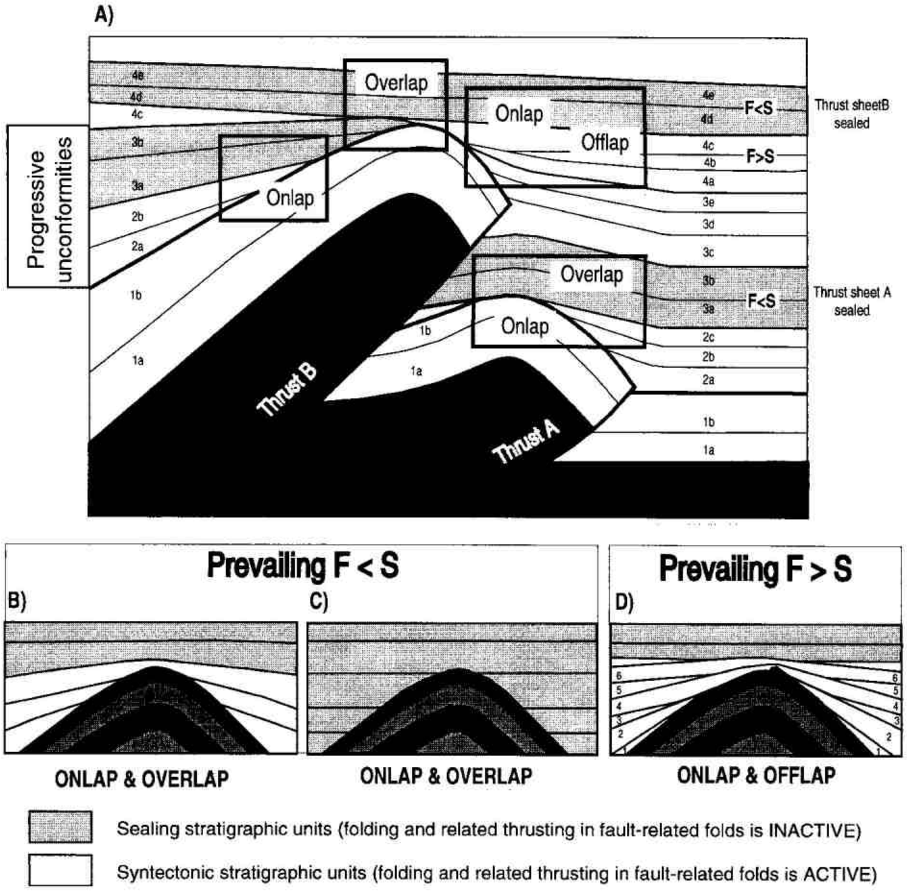

FIG. 5. – Relationships between stratigraphic units and growth folds (5A). The onlap and offlap constrain the timing of thrust activity. The overlap correspond to the sealing of the thrust sheet. ("F" = shortening rate, "S" = sedimentation rate). The overlap and the offlap are related to the ratio shortening rate (F)/ sedimentation rates (S) (figs. 5B, 5C, 5D). See discussion in the text.

FIG. 5. – *Relations géométriques entre les unités stratigraphiques et les plis synsédimentaires. Les « onlaps » et « offlaps » contraignent les périodes d'activité des chevauchements. Les « overlaps » permettent de dater la fin des mouvements. (« F » = vitesse de raccourcissement, « S » = vitesse de sedimentation). Les « overlap » et « offlap » sont liés aux rapports vitesse du recourcissement* (F)/ *vitesse de sédimentation* (S) *(figs. 5B, 5C, 5D). Voir discussion dans le texte.*

this pin point is the pin line for the restoration step (fig. 4). Restored templates, defined step-by-step, allow to move back the thrust sheets by increment of displacement; useful in restoration of thrust-related folds and calculation of deformation rates. All the points belonging to the thrust sheets are moved back the same displacement increment. We can simulate contemporaneous movements of different thrust sheets as in the stage 4F (fig. 4). Each template represents the deformed condition of the cross section at the time the unconformity was formed. The restored surface needs not to be flat and horizontal, as assumed in most single-step balanced sections [Woodward *et al.*, 1989; and references therein]; instead, it should represent the corresponding palaeo-topography (e.g. the present day depositional surface is not flat). Moreover in the restored condition the syntectonic stratigraphic units do not assume a flat geometry as is suggested in the balanced cross sections of Central Apennines in which the Pliocene-Pleistocene syntectonic wedges are laying on an almost horizontal surface [Bally *et al.*, 1986; Calamita *et al.*, 1994], while the sedimentary wedge is clearly deposited on already rotated pre-syntectonic series. Then, each restoration stage shows the restored basal unconformity and the geometry this surface had in the previous restoration stage (dashed) (fig. 4). The final geometry of a fold is controlled by the intermediate growth stages experienced by the fold [Cooper and Trayner, 1986]. If the intermediate stages are not taken into account, the balanced cross section can be overrestored and will give unrealistic results. The restoration technique gives also some insights on the kinematics of folding as it will be discussed in the results.

The lithospheric deflection due to the load of the Apennine chain is included in this model and it generates the foredeep wedges of units 4-3-2-1 (figs. 4D to 4G). Therefore, we consider a tilting point at the east end of the cross-section (figs. 4E-4F and 4H), which changes during the restoration, as the pin point does. The tilting around this point causes the obliquity of the loose line on the west side of the cross-section (fig. 4).

RESULTS

The sequentially restored cross sections (fig. 4) illustrate the evolution of the Tortoreto-Campomare growth imbricate fan over a time span of 4 m.y. from the early Pliocene to the present. These nine stages, including the present day, reflect the main depositional and tectonic events of this portion of the Pliocene-Pleistocene Apenninic foredeep with incremental time steps of 400,000 years. More stages could be defined by increasing the stratigraphic resolution.

TABLE I. – Slope attitudes compiled from published bathymetric maps and cross sections.

TABL. I. – *Valeur angulaire des pentes de talus compilées à partir des cartes bathymétriques et des coupes publiées.*

SLOPE INCLINA TION	LENGTH (distance between lowest and uppermost elevation)	- FOOTHILL LOCATION DATA SOURCE	- DEPOSITIONAL ENVIRONMENT - Prevailing exposed lithology
18°	1.5 km	- Kef el Mes/El Asnam Algeria [Philip and Meghraoui, 1983]	- Continental - Conglomerate
29°	1.4 km	- Matapan Trench Hellenic Arc [Le Pichon et al., 1982]	- Deep water (between 1600 m and 2400 m deep) - Sandstone
6.8°	20 km	- Middle America Trench Nicoya Peninsula/Costa Rica [Lundberg, 1982]	- Bathyal to Abyssal Between 600 m and 3600 m water depth - Pelagic deposit and coarse breccia.
4.3°	81.2 km	- Peru Forearc [Kulm et al., 1982]	- Shallow water to Abyssal Between 0 m and 6400 m - Subduction complex Turbidite in the trench
1.9°	102.3 km (large distance)	- Andaman Island Sunda Arc [Moore et al., 1982]	- Coast line to abyssal plain. Between 0 m and 2950 m - Pelagic-hemipelagic mudstone. Silt
13°	3.5 km (short distance)	- Andaman Islands Sunda Arc [Moore et al., 1982]	- Bathyal-Abyssal Between 1136 m and 1818 m depth - Pelagic-hemipelagic mudstone. Silt.
7°	11.9 km	- Sumatra Sunda Arc [Moore et al., 1982]	- Abyssal Between 3200 m and 4800 m depth - Pelagic-hemipelagic mudstone. Silt
5°	30 km	- Java Sunda Arc [Moore et al., 1982]	- Abyssal Between 3200 m and 6400 m depth - Pelagic-hemipelagic mudstone. Silt
9°	23 km	- Barbados Ridge Central America [Westbrook, 1982]	- Shallow water to Abyssal Between 0 m and 4000 m depth - Flysch and pelagic sediment

The Tortoreto-Campomare growth structure is an imbricate fan with two detachment levels which split into five thrusts. The shallowest detachment level absorbs the movements of the thrusts A, D, E, and lies along the Messinian evaporites, immediately beneath the Lower Pliocene Unit 1 (figs. 1B and 4), involving westward the basement [Artoni, 1993; Casero *et al.*, 1994]. The deepest detachment is linked to the thrusts C and B (figs. 1B,4) and cuts the Messinian evaporites. In published balanced cross-section of the area [Bally *et al.*, 1986; Calamita *et al.*, 1994; Ghisetti *et al.*, 1993], the deepest detachment lies on the Triassic Burano evaporites. Possibly, the deepest detachment inverts a pre-Messinian normal fault (figs. 1B), as thickness changes in the Upper Cretaceous-Miocene stratigraphy suggest [Artoni, 1993].

The sequential restoration shows that the Apennine thrust front was emergent during its evolution from 3.4 Ma to 2.6 Ma (figs. 4D to 4F). The termination of each fault surface is defined by the bottom surface of the corresponding sealing unit (fig. 6A). The tip of the thrust does not necessarily correspond to the tip point [Boyer and Elliott, 1982; McClay, 1992], as it might have been eroded and sealed when the thrusts reach the surface (figs. 4D to 4F). In this case, the apparent tip point of the thrust does not have zero displacement. Folding in the Tortoreto-Campomare structure is thrust-related, a fold being associated with each thrust. The five tectonic slices have comparable shape characters; thus involving moderately east dipping series. Only the top one displays a clear anticline wide and rounded (fig. 2). The decrease in thrust displacement, the folds associated with the thrust (see thrust B-C-D, fig. 4), and the high inclination of the thrust surfaces suggest a fault-propagation folding mechanism [Jamison, 1987; Mitra, 1990; Suppe, 1983]. No kink band can be recognized on the Tortoreto-Campomare structure (figs. 2, 4). Therefore, the modelling of the structure with the kink method [Suppe, 1983; Suppe and Medwedeff, 1990] has neither been attempted.

Although, the sequential balancing method has its own limitations (see § Tectonic and stratigraphic problems), a very simple folding kinematics can be reconstructed. In this model, the development of a single thrust-related fold in the Tortoreto-Campomare structure is rather progressive, as nine restoration steps could be defined. As a representative example, we consider the folding of a surface, i.e. the planar boundary between units 1 and 2 (fig. 4). It is rotated 9° anticlockwise in four steps (figs. 4G-4D) west of the thrust E. At later stages, this stratigraphic boundary between units 1 and 2 forms a clear open syncline (figs. 4C-4B). The same surface, east of the thrust E, has been rotated clockwise by the thrusts A, B, C and D forming the forelimb of the Tortoreto-Campomare thrust sheets. The younger unconformity surfaces have similar evolution, of course, less rotated and shortened. All the unconformities are rotated within the track imposed by the thrusts formed at the early stage 4F (fig. 4F).

The kinematics of the whole Tortoreto-Campomare thrust sheets results by reading the stages of the sequential restoration (fig. 4) from the older event (fig. 4H) to the youngest (fig. 4A), the opposite way the restoration has been done. At the beginning (fig. 4H), the Tortoreto-Campomare structure was a gentle anticline related to the thrust A, which created a relief causing the thinning of the Unit 2 (fig. 4G). The initial anticline is dissected by the synchronous movement of the thrust B, C, D and E (fig. 4F). The synchronous formation of the thrust sheets at the stage 4F (fig. 4F) is strictly connected to the shift of the Adriatic foredeep during the early Pliocene. The four thrust sheets formed at stage 4F (3.4 Ma) were deformed in the following stages (figs. 4E-4A). The thrusts were progressively inactivated toward the hinterland : thrust B is inactive at stage 4E (3.1 Ma); thrust C at stage 4D (2.6 Ma); thrust D is the most longstanding, becoming inactive at stage 4C (2 Ma). The presence of two cross cutting detachment levels (figs. 1B, 2B and point "p" fig. 4) does not allow to interpret the Tortoreto-Campomare structure as a single thrust-related anticline detached on the Messinian evaporites and dissected by thrusts younging toward west.

The model shows out-of-sequence thrusting [McClay, 1992] superimposed on a break-back sequence; although the whole fold-and-thrust belt has a piggy-back thrusting sequence. After the formation of the gentle anticline during the deposition of unit 2 (fig. 4G), synchronous movement along faults B, C, D and E occurred (fig. 4F). Then thrusting was mainly localized on D and only smaller displacement occurred along C and E (figs. 4C-4E). Thrust stacking continues in a break-back sequence as thrusts D continues to move. The final configuration of a thrust stack does not imply a unique thrusting sequence. In the Tortoreto-Campomare stack, the sequence of thrusting has changed through time.

The folding associated with thrusting produced uplift. This is differential along the cross section. A point "q", on the top unconformity of units 1 and close to the termination

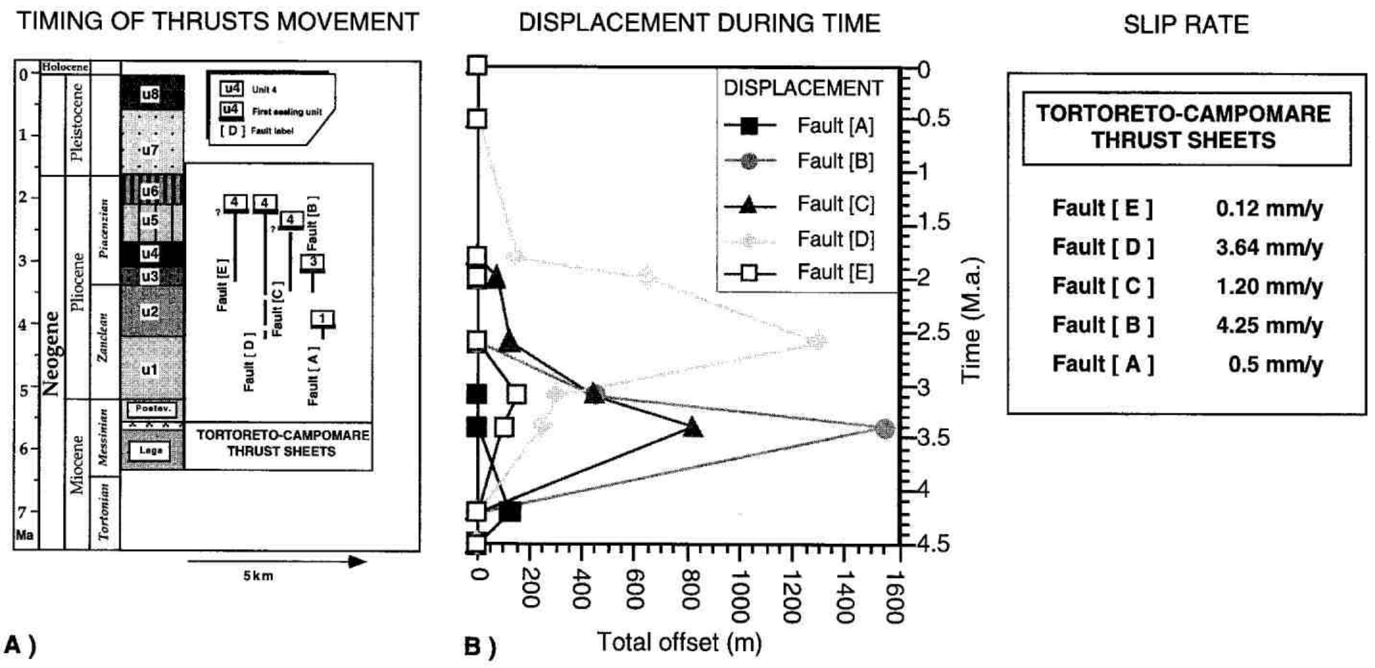

FIG. 6. – Timing of thrust emplacement (6A), showing the onset and the end of individual thrust activity. A dominant break-back sequence is evidenced but minor synchronous and out-of-sequence thrusting are also expressed. The overall shortening rate of the belt is 1.85 mm/y which is distributed to the slip rate of each single fault (6B).

FIG. 6. – *Datation de l'activité des chevauchements* (6A). *La séquence de chevauchement est clairement rétrograde, mais on note aussi des jeux synchrones et hors-séquence. Les datations de l'activité des chevauchements et les déplacements définissent le taux de raccourcissement de la chaîne de 1.85 mm/a qui correspond le long de chaque faille à diverses vitesses de chevauchement* (6B).

of thrust E (fig. 4), records difference in elevation of 2.3 km, with respect to the fixed sea level. This value represents the maximum relative uplift of the structure. The uplift is coeval to the deflection of the Adriatic continental lithosphere [Royden and Karner, 1984]. In the restoration sequence, the lithospheric deflection is represented by clockwise tilting of the whole section by increments of 1°-3° (fig. 4). The restoration stages show a total tilt of 5° (fig. 4).

The study of growth folds is important in refining the steps of foredeep and thrust-sheet-top basin formation. Since the stage 4F (fig. 4F), the Tortoreto-Campomare thrust sheets divide the Pliocene-Pleistocene Adriatic foreland basin in a foredeep depozone [DeCelles and Giles, 1996] on the east side and a thrust-sheet-top-basin, or wedge-top-depozone [DeCelles and Giles, 1996], on the west side. The growth of the Tortoreto-Campomare imbricate stack shifted the foredeep depocentre of units 2, 3 and 4 towards the east and the coeval thrust-top-basin towards the west. Those shifts are produced by a total shortening of 7.4 km which took place along both detachment levels. The imbricate stack accommodated this shortening in 4 m.y. which implies an average shortening rate of 1.85 mm/y. The overall shortening rate of the imbricate stack does not correspond to the displacement velocity along each individual thrust, which range between 0.12 mm/y and 4.25 mm/y (fig. 6B). These estimates are within the range of other published thrusting rates (0.073-4.6 mm/y) (see table II), implying that the thrusting at the mountain fronts have similar rates although variable in each single thrust sheet. The rates of displacements change during time (fig. 6B). Results indicate that each thrust has a peak of displacement which decreases with time (fig. 6B). The peaks represent periods of major reorganization of the basin, i.e. when the thrust stack was uplifted and it separated the wedge-top depozone [DeCelles and Giles, 1996] from the foredeep depozone (see fig. 4). The main peak of activity of the Tortoreto-Campomare imbricate stack is between 3.4 Ma and 2.6 Ma (fig. 6B), between the stages 4F and 4D (fig. 4). The validity of the method, used to model the growth structure, is strengthened by the deformation rates obtained (fig. 6B), which are comparable to deformation rate of structures analyzed with other methodologies and geological record of different ages and also with well refined dating data [Nicol *et al.*, 1994; Rockwell *et al.*, 1988] (table II).

TECTONIC AND STRATIGRAPHIC PROBLEMS

Without considering the problems due to the resolution of seismic profile images in complex area, such as fold-and-thrust belt, and the lack of good constraints in the deep part of the Tortoreto-Campomare thrust sheets, this study highlights the tectonic and stratigraphic problems inherent in cross-section balancing across growth structures.

Tectonic and tectono-stratigraphic problems

Unconformities are generally irregular surfaces which represent palaeotopography. Restoration of an irregular surface introduces problems. The choice of a palaeotopographic surface to which an unconformity is restored is not straightforward and the surface must be simplified. On the other hand an irregular surface to which to restore an unconformity is needed to represent a balanced and realistic geometry of the thrust stack at each stage. Each stratigraphic unit has a portion close to the bounding unconformity surfaces which is eroded or incomplete because of non-deposition. The amount of missing sedimentary record reflects the balance between the tectonic movement of the topographic

TABLE II. – Rate of individual thrust emplacement taken from the recent literature.

TABL. II. – *Vitesses de chevauchements triées de la littérature récente.*

THRUSTING RATE	AREA/ OROGEN DATA SOURCE	METHOD	TIME INTERVAL derived from the available dating
4.5 mm/y Ahnert's estimate 7.7 mm/y Johson's estimate	Keystone-Muddy Mountain System Southern Nevada [Willemin, 1984]	Mathematical modeling of a simpliefied thrust sheet including rheology and hangingwall erosion.	Late Cretaceous Sivier orogenies
0.82 mm/y	Lost Hill anticline California [Medwedeff, 1989]	Subsurface analysis Structural modeling	Late Miocene to Late Pleistocene or Holocene
4.3 mm/y	Wheeler Ridge Anticline California Keller et al. (1986) in [Medwedeff, 1989]	Podology Structural geology	0.12 m.y. in Late Pleistocene-Holocene
1.1±0.3 m	Monica Mountains Anticlinorium California [Lin and Stein, 1989]	Seismological modeling	1987 earthquake event
3.8-6.8 mm/y	Whittier Narows California [Davis et al., 1989]	Structural Geology Seismology	averaged recent earthquake events
2.5-5.2 mm/y	Elysian Park California [Davis et al., 1989]	Structural Geology Seismology	averaged recent earthquake events
2.1 mm/y (mean shortening rate)	Sierra Marginales Ebro basin Spain [Burbank et al., 1992]	Dating of progressive	39.8-36.2 Ma (Oligocene)
4.6 mm/y	Oliana anticline and duplex Ebro basin Spain [Burbank et al., 1992]	Geometric relationship of growth strata Magnetostratigraphic dating	39.8-36.2 Ma (Oligocene)
2.5/4.5 mm/y maximum	Po Plain Northern Apennine [Zoetemeijer et al., 1992]	Forward modeling	Late Miocene-Late Pliocene
0.073±0.019 m/ky	Waipara area North Canterbury New Zeland [Nicol et al., 1994]	Geology, geomorphology, Quaternary geology, pedology	78±19 k.y. (Quaternary)

surface, the rate of erosion and of sediment supply. The interaction between these processes determines the palaeotopographic surface of each stage of the fold growth. This interaction, however, is complex and difficult to model. Then the choice of the amount of erosion and the amount of non-deposition are fundamental, changing the geometry of the palaeotopography and thus of the thrust system below it. The best estimate in the reconstruction of figure 4 is to maintain in each restored stage the volume of the sedimentary units actually preserved. This means that the amount of the erosion which acts at the same time as the fold grows is not estimated, while we implicitly assume that the stratigraphic record is missing because of non-deposition. It also implies that, in the model obtained, the topography could have been higher and/or stratigraphic units may originally have been thicker.

The amount of shortening does not include ductile strain. This cannot be measured as the imbricate stack is covered by the uppermost Pliocene and Pleistocene units.

Subsidence and sediment decompaction are not considered in the restoration. These parameters would also affect the geometry of the ancient topographic surfaces and the geometry of each stratigraphic sequence at the stages considered in the reconstruction modifying the real elevation.

The effects of large scale lithospheric processes on the small growth fold are hard to detect. Nevertheless, in the sequential balancing here presented, the lithospheric flexure causes an overall 5° anticlockwise tilt of the base of the Pliocene during a time interval which lasts from the early Pliocene to the Present. This tilt is affecting the orientation of the thrust surfaces and of the topographic surface. However, the choice of the tilting point (fig. 4) has been necessarily taken at the eastern end of the cross section. This implies that this tilting point has no vertical movement due to flexure, but on a larger scale this may be not true.

Stratigraphic problems

The seismic lines and bore-hole data available do not constrain the detailed sedimentary evolution around the hinge of the folds during their growth; especially in the deeper part of the section which were not reached by drilling and where the seismic signal is noisy; in fact, in the line drawing (fig. 2) the deep part of the Tortoreto-Campomare thrust sheets shows variably oriented and discontinuous reflectors. Even though the Plio-Pleistocene Adriatic foredeep history was well defined by Ori *et al.* [1991] and Crescenti *et al.* [1980], a detailed bathymetric history from the Pliocene to the present has not yet been defined. This is the main reason why sea level has been kept fixed during the steps of the reconstruction (fig. 4). So the role of eustacy in the formation of the stratigraphic units has not been taken into account for the various stages (fig. 4), and the uplift of the structure relative to sea level could not be defined. Moreover variations in sediment supply have not been considered in the reconstruction. Eustatic change and sedimentary input, together with tectonics, can create progressive unconformities. They control the distribution of sedimentary units as well as the burial of the structures; moreover, they control the non-deposition and/or erosion in the sedimentary record hiding part of the history of the growth structure.

Another problem is related to dating. The biozones defined in the area [Crescenti *et al.*, 1980] are not related to a formal time scale. However, this planktonic foraminiferal biozonation has been calibrated with the absolute time scale based on palaeomagnetic data of ODP Leg 107 [Kastens *et al.*, 1990] and the stratigraphical scale proposed by Patacca *et al.* [1991]. Nevertheless, it is uncertain whether these absolute ages used in dating the unconformity surfaces correspond to the absolute ages calibrated with the magnetostratigraphy of a basin more than 300 km apart.

The cut/seal relationships are not always well preserved and the dating lacks sufficient resolution. Surface erosion, which changed the morphology of the thrust sheets during and after thrust activity, removed part of the syntectonic stratigraphic records and of the onlap-overlap relationships (e.g. the unconformity below units 2 and 3). These missing records are the main reason for the uncertainties on the activation of fault D and the time of cessation of thrust activity along faults C and E, which must have occurred during the deposition of units 2, 3 and 4 for faults C, D and E respectively (fig. 6A).

The above tectono-stratigraphic problems introduce errors in the rate estimates. The real rate at which these processes happened cannot therefore be tightly constrained. Estimated thrust displacement rates (fig. 6B) are averages. It is not known whether the present day configuration was reached with a constant or a non-linear rate of thrust movement, sediment deposition, erosion, sea level change and lithospheric flexure. We even know less about the feed-back between these different scale processes which must have affected the observed geological records.

CONCLUSIONS

The Tortoreto-Campomare thrust sheets are a stack of thrust-related folds which grew during the deposition of Pliocene clastic sediments, and is buried beneath Upper Pliocene and Pleistocene units. The stratigraphic succession defined (fig. 3) allows to reconstruct nine evolutionary stages for this structure (fig. 4), corresponding to nine stratigraphic well recognized Pliocene and Pleistocene units, with a duration of ≈ 400,000 years. Each step reproduces the palaeotopography recorded from the geometry of each restored unconformity surface. The palaeotopography is of course simplified but it does not over-restore or create impossible geometry in the structure below it.

The sequential balancing demonstrates break-back (figs. 4E-4C) and synchronous thrusting (e.g. fig. 4F) sequences in the frontal stack. These are obliterated by an out-of-sequence thrusting event. These thrusting sequences are local and superposed on a piggy-back thrusting sequence of the whole foothill area in the Central Apennine. The cut/seal relationships between fault terminations and stratigraphic sequences define a thrusting sequence which changes with time. In a thrust stack, the sequence of thrusts must be related to the time span considered.

The Tortoreto-Campomare imbricate stack accommodated a shortening of 7.4 km in 4 m.y., i.e. an average shortening rate of 1.85 mm/y. Thrust displacement rates range from 0.12 mm/y to 4.25 mm/y. Therefore, the overall deformation of the mountain front is partitioned to each thrust sheet in different amount and at different time. Two detachment levels converging to the same structure (fig. 1B) is a reason of the different deformation partitioning and, therefore, different slip rates. On the other hand, we have to remind that the displacement rates and the difference between the higher and the lower value are strictly dependent on the preserved geological record and stratigraphic resolution. In particular, the age of the stratigraphic unit sealing the thrust is the most important constraint for rate calculation. The calculated deformation rates are still average values. Nevertheless, these values are comparable to thrust displacement rates calculated in other areas (table II) and in growth structure studied with other methods, well refined dating and geological record of different ages, also recent [Nicol *et al.*, 1994; Rockwell *et al.*, 1988]. In fact, the lowest value (0.12 mm/y, fig. 6B) is close to a very detailed slip rate calculation [Nicol *et al.*, 1994] of a fault related to an anticline active during the Quaternary in New Zealand, during a time interval of about 80,000 years. Such well constrained slip rates cannot be considered representative of the slip rate along the whole active mountain front. In fact, the Tortoreto-Campomare thrust sheets shows that the displacement rates are different even within the same imbricate structure; each fault has its own slip velocity which change during time.

We believe that the methodology proposed here is useful for integrating all the structural, tectonic, depositional and erosional processes acting on the growth fold and in the basin they form. Then, the same methodology is suitable for creating a strict link between the geological record and the processes acting at present, emphasizing the measurement of the rates of tectonic and sedimentary processes. This method is a useful and promising one for studying and visualizing the dynamics of tectonic and sedimentary processes.

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