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BALANCED SECTIONS AND SEISMIC REFLECTION PROFILES ACROSS THE CENTRAL APENNINES

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ABSTRACT

Balanced cross sections between the Adriatic Median line and the Umbria-Marche Apennines are based on the integration of surface and subsurface data that are derived from seismic reflection profiles and wells.

Décollement tectonics in many folded belts are best illustrated by reflection profiles which permit the separation of an underlying basement from the overlying decoupled sediments. In the Central Apennines the best support for an interpretation that excludes basement involvement comes from magnetic maps. These suggest that only in the Toscana, a magnetic basement is involved in overthrust structures.

Reflection seismic profiles in the Umbria-Marche region do not permit us to clearly identify continuous reflectors corresponding to a near-basement top. This is probably due to two factors: 1) the thick Triassic Burano anhydrites attenuate and absorb much of the seismic energy; 2) the nature of the basement does not offer an acoustic impedance contrast that is sufficient to differentiate basement from the overlying Burano formation.

The deepest wells of the region have not encountered basement. The Perugia 2 well has penetrated only a slightly metamorphosed Triassic Verrucano section. The Alessandra 1 well in the Central Adriatic has only penetrated Upper Permian redbeds. The top of these redbeds corresponds to a reflector that can be followed towards the Adriatic Coastal Plain. We project this basal reflector underneath the Umbria-Marche Apennines where at depth we recognize numerous subhorizontal reflectors that correspond to unidentifiable Mesozoic beds. Thus, we combine the geometric extrapolation of a Permian foreland reflector with the occurrence of deep subhorizontal reflectors to guide us in the construction of balanced cross sections.

Our sections were originally drawn on a 1:100,000 scale because regional surface and seismic data did not justify a more detailed scale. Therefore, the details of deformation phenomena observed in the field by so many authors had to be ignored. Any shortening estimates based on such detailed observations probably will have to be added to our rather conservative shortening estimates.

The stratigraphy of the region had to be simplified and does not reflect often significant thickness changes that are either due to structural thickening or else due to the intercalation of turbidites and other allochthonous sedimentary units. Our seismic

profiles also do not permit us to resolve thickness changes due to the well-known Jurassic extensional tectonics. Finally, we were unable to determine the original stratigraphic thickness of the Burano formation and therefore we assumed an original thickness of about 2 km. Thus, our basic stratigraphic assumptions are weak but at this time, we do not see another way to reconcile the seismic data with the requirements imposed by the balanced cross section methodology.

The principal results of our study are:

1) The Apennine décollement system extends to about 20-30 km west of the Adriatic median line.

2) Magnetic data and models, as well as the seismic reflection profiles, suggest that the magnetic Paleozoic (or Precambrian) basement is not involved in the structures of the Umbria-Marche Apennines.

3) Surface geology permits us to recognize a number of tectonic decoupling levels (i.e., base Messinian, Scaglia Cinerea, Scisti a Fucoidi, Rosso Ammonitico), but these cannot be easily illustrated on a 1:100,000 scale. Our sections suggest that the main regional décollement level is the anhydritic Burano formation. Towards the west in and beyond the region of Perugia, a deeper decoupling level involves the slightly metamorphosed Verrucano formation.

4) The main décollement level is about 5 km deep under the Adriatic Sea and reaches to depths of about 15 km in the area of Perugia.

5) On our longitudinal sections, the former Anzio-Ancona line represents only the frontal overthrust of the Umbria-Marche arc (Terminillo-Sibillini) which dips towards the north to depths of about 14 km in the upper Val Tiberina. In other words, the Ancona-Anzio line is a «lateral ramp».

6) We estimate that shortening of the Sibillini thrust is in the order of 50 km in the Fossombrone segment and about 120 km in the Sibillini segment. The increase in shortening towards the south is another expression of the well-known anticlockwise rotation that has been postulated by paleomagnetic researchers and interpreted by some of them as Tertiary rotational décollement structure. It should be remembered that these shortening estimates exclude additional amounts of shortening that has been postulated on the basis of detailed strain studies made by structural geologists.

7) The above-mentioned increase in shortening is also tied to the development of foreland «duplex» structures in the southern segment of our study area; (a) the Roccafinadamo structure, (b) the Montagna dei Fiori structure, (c) and the Laga (Aquasanta) thrust sheet. Note that all these N-S striking structures die out towards the north.

8) Our reconstructions imply that the space that is today occupied by the Cervarola and Tuscan units during pre-Messinian times was occupied by the Umbria-Marche basin of the Adriatic promontory passive margin.

9) Our seismic profiles also permit to estimate shortening in excess of 170 km for the Cervarola unit which occupied the area of today's western Tyrrhenian sea. If we accept that the Cervarola unit at least in part belongs to the lower Tuscan unit, and if we allow for a reasonable palinspastic width of the upper Tuscan unit, we can easily see that the west margin of the Adriatic promontory originally extended well to the west of the present position of Corsica.

We do not pretend that our cross sections and shortening estimates are accurate. They represent simple order of magnitude-type approximations. Our main intention was to investigate the limits and the consequences of a methodology that was successfully developed in a number of folded belts in North America.

RIASSUNTO

Viene presentata una serie di sezioni geologiche bilanciate che interessano l'area compresa tra la linea mediana dell'Adriatico e l'Appennino umbro-marchigiano. Queste sezioni sono basate su dati geologici di superficie integrati con dati di sottosuolo derivati dalla interpretazione di profili sismici a riflessione, da sondaggi e da logs acustici con i quali sono stati calibrati, dove possibile, i riflettori sismici.

La tettonica di scollamento di falde sovrascorse su un basamento monoclinale immergente verso le catene è ormai nota per numerose regioni montuose. Nelle Montagne Rocciose del Canada e del Wyoming e nella catena degli Appalacchi degli Stati Uniti orientali i profili sismici a riflessione mostrano dei riflettori continui che permettono di separare il basamento dalle unità scollate sovrastanti.

Nell'Appennino centrale il migliore supporto per escludere il coinvolgimento del basamento nella tettonica di scollamento è forse la Carta Magnetica d'Italia (AGIP, 1981). Il modello presentato recentemente da ARISI ROTA & FICHERA (1985) indica che soltanto in Toscana il basamento magnetico è coinvolto nelle strutture di questa regione.

D'altra parte i profili sismici a riflessione dell'Appennino umbro-marchigiano non consentono di identificare chiaramente riflettori relativamente continui corrispondenti al tetto del basamento. Questo fatto può essere attribuito alla combinazione di due fattori: 1) la potente formazione anidritica del Burano attenua ed assorbe la maggior parte dell'energia sismica rendendo difficoltosa la definizione dei livelli sottostanti; 2) la natura del basamento non offre un contrasto di impedenza acustica (coefficiente di riflessione) sufficiente per distinguerlo dalla sovrastante formazione del Burano.

I sondaggi più profondi della regione non hanno incontrato il basamento. Il sondaggio PERUGIA 2 ha interessato una successione leggermente metamorfosata del Verrucano. Il sondaggio ALESSANDRA 1 (vedi fig. 56, sez. 3) ha incontrato una successione clastica rossastra del Permiano superiore. A partire da questo ultimo sondaggio si può seguire un riflettore sismico verso il sottosuolo della pianura costiera adriatica. Tale riflettore, così come altri dell'avampaese adriatico, può essere proiettato verso la regione

nell'Appennino umbro-marchigiano dove in profondità si evidenziano altri riflettori suborizzontali, corrispondenti a livelli stratigrafici profondi di età non determinata.

In conclusione, nonostante l'impossibilità di osservare dei riflettori continui sotto l'Appennino umbro-marchigiano, si possono utilizzare i riflettori dell'avampaese adriatico e collegarli con segmenti di riflettori suborizzontali profondi in modo da guidare la costruzione delle sezioni strutturali bilanciate.

Le nostre sezioni originali sono state costruite alla scala 1:100.000 perché a nostro giudizio sezioni con un maggiore dettaglio non sono giustificate dai dati geologici di superficie disponibili e dalla qualità variabile delle informazioni ricavate dai profili sismici.

Di conseguenza nei nostri profili non sono stati inseriti i concetti di deformazione dettagliata sviluppati da ALVAREZ et alii (1976 e 1978), MARSHAK et alii (1982), LAVECCHIA (1981) e LAVECCHIA et alii (1981a,b; 1983). Riteniamo infatti che i fenomeni di deformazione dettagliata descritti da questi Autori rappresentino un raccorciamento ulteriore rispetto a quello espresso sui nostri profili sismici. In altre parole tenendo conto delle varie possibilità di errore, riteniamo che i raccorciamenti da noi indicati siano molto conservativi.

Anche la stratigrafia della regione è stata semplificata. Numerosi sondaggi nel Mare Adriatico e nella pianura costiera adriatica offrono buone possibilità di controllo sullo spessore delle varie formazioni, così come avviene anche nelle sezioni descritte nell'Appennino umbro-marchigiano. È importante però puntualizzare che nelle zone dei rilievi gli spessori stratigrafici sono alterati da inspessimenti strutturali; questo aspetto è stato da noi trascurato nelle sezioni. Fino ad ora le linee sismiche non consentono di risolvere i dettagli relativi alle ben note serie «complete» e «condensate» dovute alla distensione giurassica.

Un altro aspetto stratigrafico di grande importanza riguarda lo spessore della formazione anidritica del Burano. La formazione è stata incontrata da alcuni sondaggi ubicati nei nuclei delle anticlinali della regione, pertanto non si conosce lo spessore originale della Formazione Burano non deformata. L'interpretazione delle linee sismiche ci ha condotto ad accettare uno spessore regionale della Fm. Burano superiore a 2 km.

Siamo consci che le nostre assunzioni sono azzardate, tuttavia per il momento non vediamo alternative che permettano di conciliare le informazioni ottenute dai profili sismici a riflessione con le esigenze imposte dalla metodologia delle sezioni geologiche bilanciate.

I risultati principali del nostro lavoro sono:

1) Il fronte del sistema di scollamento dell'Appennino umbro-marchigiano si trova a circa 20-30 km ad Ovest della linea mediana del Mare Adriatico.

2) I dati magnetici ed i profili sismici indicano che il basamento magnetico paleozoico (o precambriano) non è coinvolto nelle strutture dell'Appennino umbro-marchigiano.

3) La geologia di superficie consente di riconoscere alcuni livelli di scollamento tettonico (es. base del Messiniano, Scaglia Cinerea, Scisti a Fucoidi e Rosso Ammonitico). Tuttavia gli stili tettonici dettagliati legati a questi livelli non sono facilmente illustrabili alla scala 1:100,000. Le nostre sezioni geologiche indicano che il livello di scollamento principale è la formazione anidritica del Burano. Verso Ovest, nella zona di Perugia, il livello di scollamento basale si approfondisce fino a coinvolgere il Verrucano.

4) La base della zona di scollamento principale si trova ad una profondità di ca.5 km sotto il Mare Adriatico e si immerge verso una profondità di ca.15 km nell'area di Perugia. La nostra interpretazione è in contrasto con quelle presentate da LAVECCHIA et alii (1984a,b). Questi Autori hanno proposto un livello di scollamento meno profondo (tra 4 e 6 km). Siamo d'accordo con i modelli della sismica a rifrazione proposti da LAVECCHIA et alii (1984b), riteniamo però che il rifrattore (velocità di 6,2-6,8 km/sec.) attribuito da questi Autori al basamento corrisponda al tetto del Burano che altrove ha una velocità tipica di 6.4 km/sec. Secondo la nostra interpretazione almeno un'altra falda di sovrascorrimento si trova tra questo rifrattore ed il nostro livello di scollamento basale.

5) Sulle nostre sezioni longitudinali la linea Ancona-Anzio rappresenta soltanto il fronte di sovrascorrimento dell'arco umbro-marchigiano (Terminillo-Sibillini) che si immerge verso Nord ad una profondità di circa 14 km nell'area dell'alta Val Tiberina. In altre parole la linea Ancona-Anzio è una «rampa laterale».

6) Stimiamo che per il sovrascorrimento dei Sibillini il raccorciamento sia dell'ordine di 50 km nel settore di Fossombrone e di 110 nel settore dei Sibillini. L'aumento del raccorciamento verso Sud è in realtà l'espressione strutturale della ben nota rotazione antioraria dell'Appennino proposta dai ricercatori sul Paleomagnetismo (CHANNEL et alii, 1978) e da essi già interpretata come dovuta ad uno scollamento rotazionale terziario. Ricordiamo ancora che i nostri profili non permettono di includere i raccorciamenti addizionali considerati negli studi di dettaglio di LAVECCHIA et alii (1983) LAVECCHIA (1985), ALVAREZ et alii(1976; 1978), e altri.

7) L'aumento del raccorciamento verso Sud è soprattutto legato allo sviluppo dei seguenti complessi strutturali di tipo «duplex»: a) falda di Roccafinadamo; b) falda della Montagna dei Fiori; c) falda della Laga (Acquasanta). Facciamo notare che anche i raccorciamenti di questi complessi, con andamento N-S, diminuiscono rapidamente procedendo verso Nord.

8) Le nostre ricostruzioni implicano che lo spazio oggi occupato dalle unità del Cervarola e Toscanidi durante il Pre-Messiniano corrispondeva al bacino sedimentario umbro-marchigiano; questo bacino si estendeva oltre la costa tirrenica odierna.

9) Anche sulla scorta dei profili sismici a riflessione, nei quali si individua chiaramente la base dell'unità Cervarola, risulta agevole estrapolare che questa unità strutturale è stata trasportata oltre 170 km e che durante il Miocene occupava l'area del Tirreno settentrionale odierno. Se si ammette che la unità di Cervarola è derivata, almeno in parte, dall'unità Toscanide inferiore si può facilmente concludere che il margine occidentale del cosiddetto Promontorio Adriatico si estendeva oltre l'area della Corsica, prima che questa isola venisse ruotata nella posizione odierna.

Non pretendiamo che i nostri profili e i raccorciamenti stimati siano esatti. Nostro intendimento è stato quello di indagare le conseguenze ed i limiti di una metodologia applicata con successo nelle catene montuose dell'America.

INTRODUCTION AND ACKNOWLEDGMENT

We present an interpretation of the Umbria-Marche Apennines that is based mainly on seismic reflection profiles and exploration wells. Because our basic data are subject to different interpretations, we felt that it was particularly important to provide a reasonable measure of documentation.

Our views are an attempt to apply principles that were developed in other folded belts, particularly in the Rocky Mountains of Canada to the Central Apennines. Therefore, in our conclusions we will contrast the Central Apennines with some of these other folded belts. Our interpretation should be viewed as a step in a long series of successive approximations. We therefore do not claim a conclusive solution of the tectonics of the Apennines. We believe, however, that it is worthwhile to provide a working hypothesis that may be useful for future scientific research as well as for the exploration of hydrocarbons.

REGIONAL OVERVIEW

Proceeding from east to west, we differentiate the following structural-physiographic provinces (fig. 1 and fig. 2).

The Adriatic Monocline corresponds to the Central Adriatic sea where structurally relatively undisturbed Mesozoic and Paleogene reef and fore-reef carbonates overlie Permian red beds and a deeper basement of unknown age and character. The Mesozoic-Paleogene carbonates are buried beneath a cover of Neogene clastic sequences that represent the foredeep fill of the Apennines and the Dinarides. The Adriatic monocline dips towards the west.

The Adriatic foreland folds form the leading edge of the Apennines décollement system. Most of the folds are associated with thrust faults. A number of them involve only the Tertiary strata but most of the structures of this area involve parts of the Mesozoic carbonate sequence. The eastern half of this province lies under the Adriatic sea, but the western half corresponds to the Adriatic Coastal Plain of Italy where gently folded Pliocene clastics characterize the surface geology. Mte. Conero near Ancona is the only outcropping Mesozoic structure in that province.

A *foothills zone*, which we subdivide into an outer and an inner zone, separates the foreland from the mountains of the Apennines. On the surface the outer foothills belt is dominated by gently folded Pliocene sediments, while the inner foothills belt is characterized by a more accentuated morphology reflecting the Miocene and Mesozoic outcrops of the area. The intensity of the structural deformation increases from east to west.

The *Romagna-Umbria-Marche folded belt* is morphologically subdivided into an eastern fold belt that is bounded by the Sibillini thrust system to the east. A low topographic relief zone – *the interior plain* – is located between Gubbio and Perugia. To the west a series of structures corresponds to the Mte. Malbe-Mte. Martano trend (north of Perugia to west of Spoleto). Compressional tectonics dominate in this area but a neo-tectonic extensional style is occasionally superposed on the older structures. The stratigraphy of the area is shown on the Umbria-Marche columns of fig. 11.

The *Mte. Cervarola-Mte. Falterona* units consist of shallow imbricated thrusts involving mostly Paleogene clastics and some Miocene.

Further west we differentiate a higher (internal on fig. 11) Tuscan unit which consists of complex sedimentary folds and thrust
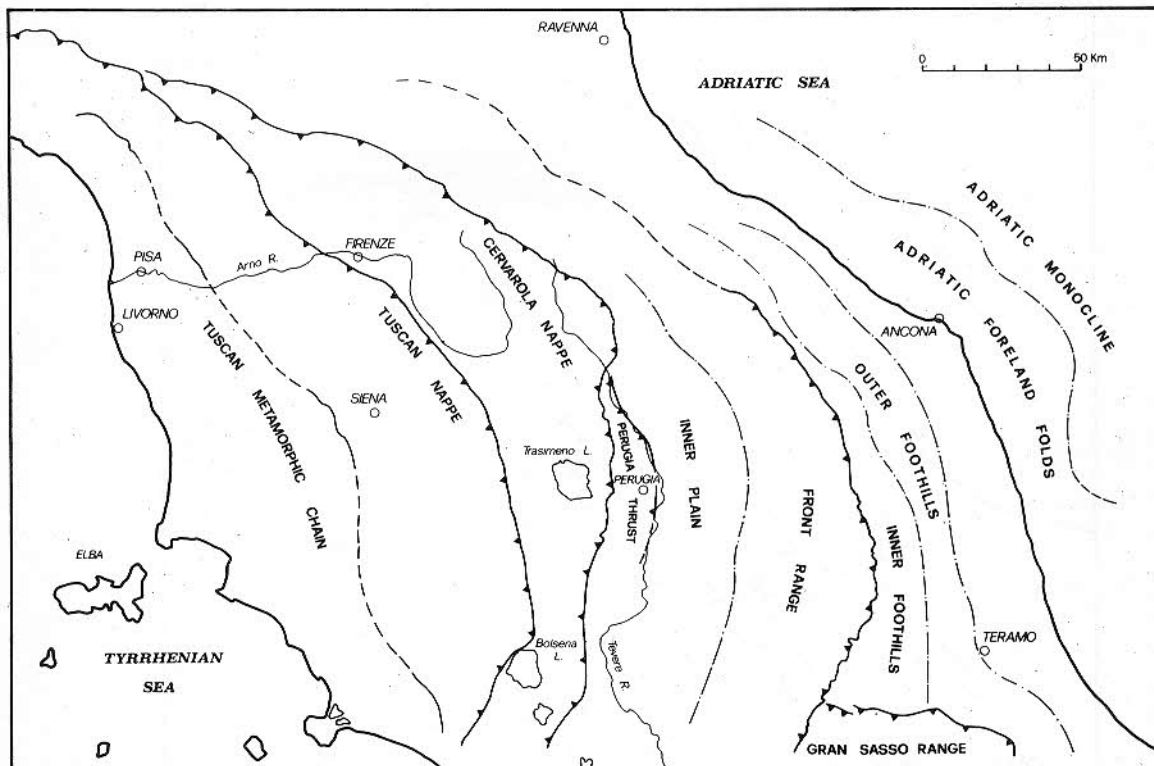
Fig. 1 - Province map. This map represents an informal subdivision of central Italy into physiographic provinces.

sheets from a lower (external unit on fig. 11) metamorphic unit which involves the Paleozoic basement.

The previously mentioned Cervarola unit is viewed by many to be the sheared-off top of a unit that is transitional between the lower metamorphic Tuscan unit and the Umbria unit (for discussion, see DALLAN NARDI & NARDI, 1974).

All the units so far described are overlain discordantly by the allochthonous *Ligurides* and the *Alberese-Canetolo* units. In this paper we will not concern ourselves with the complex stratigraphic and structural evolution of these higher allochthonous elements.

Postorogenic volcanic complexes of the Mte. Amiata area and the Vulcani Laziali cut discordantly across all structural units.

Readers interested in getting a more detailed overview over the area are referred to the papers by DALLAN NARDI & NARDI (1974) and the Carta strutturale dell'Appennino settentrionale (BOCCALETTI & COLI, 1982).

DISCUSSION OF EARLIER WORK

We are following in the footsteps of some of Italy's most illustrious geologists, like BONARELLI, SACCO, LOTTI & SCARSELLA just to mention a few. In the context of this paper, it is not possible to credit all the contributions of our predecessors but most fortunately PAROTTO & PRATURLON (1981) have provided a splendid summary of the evolution of geological concepts in our region. More recently some very fundamental contributions have been provided by researchers from the Universities of Perugia (R. COLACICCHI, G. PIALLI & G. LAVECCHIA), Camerino (E. CENTAMORE, M. CHIOCCHINI, G. DEIANA & F. CALAMITA), and Ancona (U. CRESCENTI). Their work was particularly helpful for our study (see references). In the following, we limit ourselves to highlight only selected aspects of previous work.

The early work is summarized in LOTTI's monumental Descrizione geologica dell'Umbria. LOTTI (1926) himself noted and recogni-
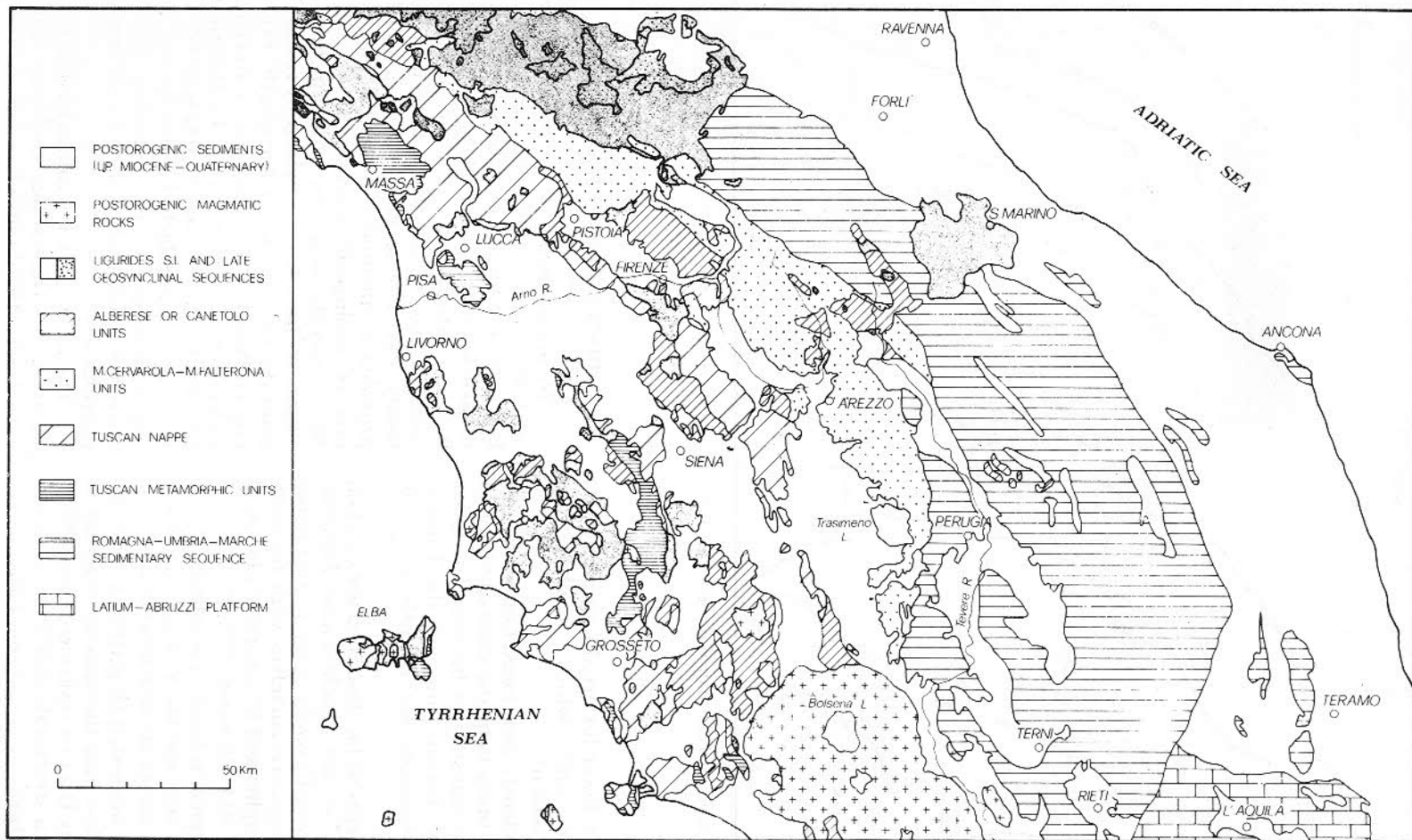
Fig. 2 - Simplified tectonic map of the north-central Apennines.

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Legend:

- POSTOROGENIC SEDIMENTS (UP. MIOCENE — QUATERNARY)
- POSTOROGENIC MAGMATIC ROCKS
- LIGURIDES S.I. AND LATE GEOSYNCLINAL SEQUENCES
- ALBERESE OR CANETOLO UNITS
- M. CERVAROLA — M. FALTERONA UNITS
- TUSCAN NAPPE
- TUSCAN METAMORPHIC UNITS
- ROMAGNA — UMBRIA — MARCHE SEDIMENTARY SEQUENCE
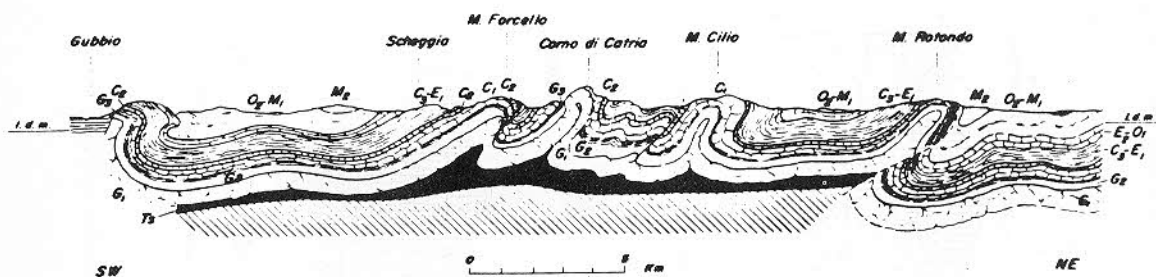- LATIUM — ABRUZZI PLATFORM

0   50 Km

Fig. 3a - BALDACCI et alii, 1967 show dècollement of the Mesozoic Umbria sequence over an elevated basement block.

Ts: evaporiti del Trias superiore. G_1: Calcari massicci G_2: Calcari selciferi e Rosso ammonitico. G_3: Scisti ad Aptici. C_1: Maiolica. C_2: Marne a Fucoidi. C_2-E_1: Scaglia « rossa ». E_2-O_1: Scaglia rosa e cinerea. O-$_2M_1$: formazione Marnoso-arenacea. M_2: arenarie grigie del Pontico.
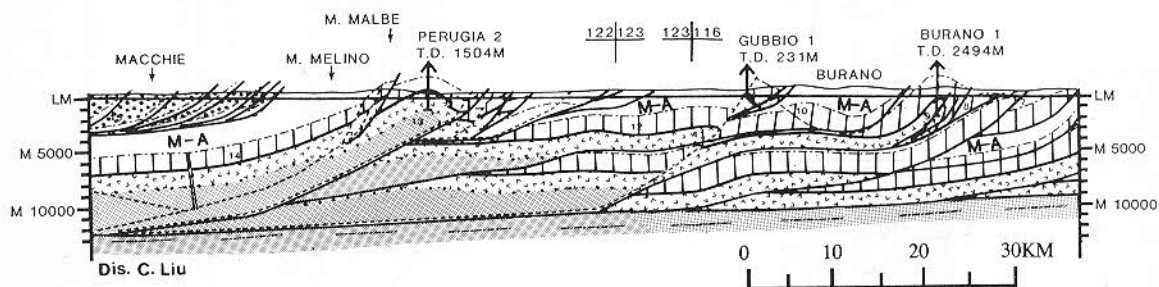
TOPS:

M-A   Marnoso Arenacea

    Cervarola

    Scaglia, (1)

    Triassic-Burano

    Verrucano   (Pre-Burano, Phyllite)

-------   putative basement

FAULTS:

———   Thrust faults

- - - - -   Normal faults

- - - - -   Normal faults that follow pre-existing thrust faults

Fig. 3b - The interpretation proposed in this paper shows a much deeper basement, that is projected from the Adriatic sea. The Verrucano metasediments encountered in the Perugia 2 well are not part of the magnetic basement. The dashed line at the bottom may be viewed either as a hypothetical top Verrucano reflector or, alternatively, as a «putative» top of basement.

zed the well known «umbro-marchigiana facies» and the corresponding «facies abbruzzese». He also recognized some of the main structural themes of the region such as recumbent folds, thrust faults, and normal faults. During the 1930's and 1940's, the debate over the allochthoneity of much of Italy was carried on by many foreign geologists. Of particular importance is the contribution by R. BEHRMAN (1936), who accepted a general allochthoneity for much of the Apennines but treated much of the Umbria-Abruzzi Apennines as essentially autochthonous. SCARSELLA made an outstanding contribution in the form of the Servizio Geologico d'Italia Map

Sheets 132 (Norcia), 139 (l'Aquila), and 140 (Teramo). He clearly shows a major overthrust that extends from the region of Cittaducale to the front of the Sibillini Mountains.

The Ancona-Anzio line debate grew in part out of the work of SCARSELLA and his colleagues. The term was introduced by MIGLIORINI (1950) but today many geologists would prefer to follow SALVINI & VITTORI (1982) and refer only to a more restricted Olevano-Antrodoco-Posta line. Many authors, like SCARSELLA (1951), emphasized the facies contrast between the deep-water Umbria-Marche sequence and the reefal Abruzzi se-
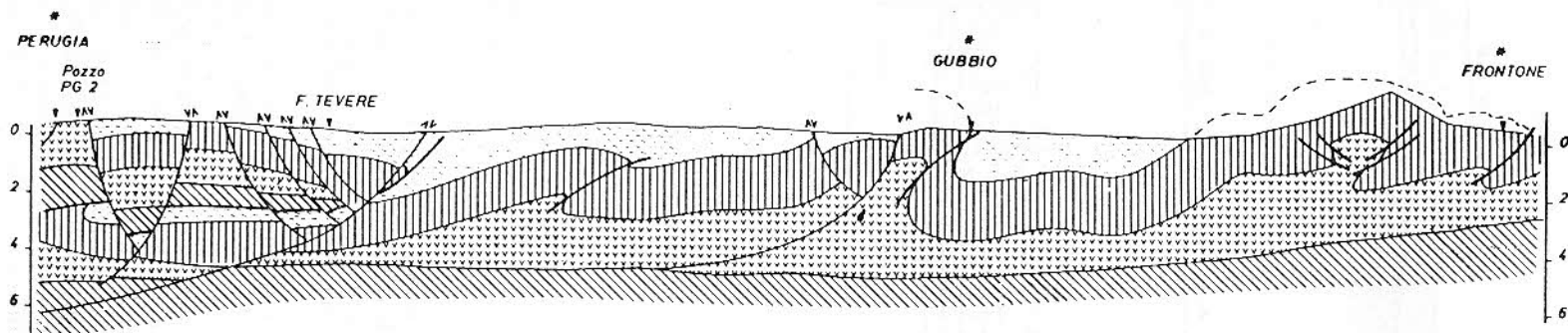
Fig. 4a - LAVECCHIA *et alii*, 1984. This model is based on a refraction ray-tracing model and shows simple dècollement to the east and a basement (Verrucano) thrust sheet to the west.

1) Formazioni fliscioidi marnoso arenacee (Miocene Inf.-Sup.); 2) Multilayer sedimentario dell'Umbria occidentale e dell'Appennino umbro-marchigiano (Lias Inf.-Miocene Inf.); 3) Formazione delle Anidriti di Burano (Trias Sup.); 4) «Basamento» pre Trias Sup.; 5) Punti di scoppio: Perugia (Pg), Gubbio (Gu), Frontone (Fr); 6) Faglie dirette.
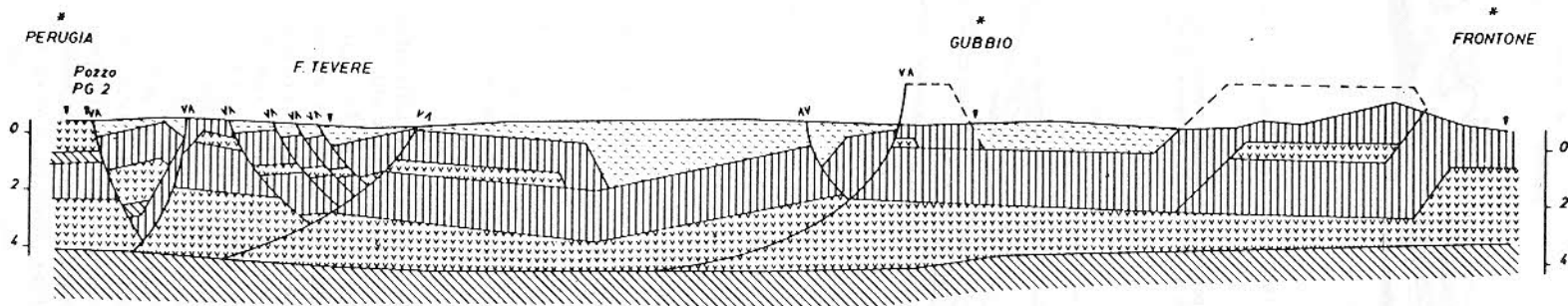
Fig. 4b - LAVECCHIA *et alii*, 1984. Another model also supported by refraction ray-tracing, shows a different style of deformation and only a very minor amount of basement thrusting to the west.

quence across the Ancona-Anzio line. That theme was again taken up by CASTELLARIN *et alii*, 1978. These authors document on the base of stratigraphic arguments that a Jurassic extensional system was responsible for the Mesozoic to Paleogene facies contrasts between Umbria and Abruzzi. During Messinian times, according to CASTELLARIN *et alii* (1978), dextral strike-slip faulting occurred with displacements in the order of 15-50 km. Finally, during lower and middle Pliocene, compressional overthrusting took over.

Some authors interpreted the Ancona-Anzio as left-lateral strike-slip system (WIJKERSLOOTH, 1934) and other authors as dextral strike-slip fault. In keeping with SCARSELLA's mapping, DALLAN NARDI *et alii* (1971) suggested an overthrust of the entire Umbria-Marche element involving transcurrent-overthrust movements along the Ancona-Anzio line.

Somewhat independent from the debate over the Ancona-Anzio line, there have been various studies that characterize the style of deformation of the Umbrian folds. Again, avoiding an exhaustive review of many papers, we refer to fig. 3a and 3b, and 4a and 4b, to illustrate some versions of décollement interpretations of the same area. BALDACCI *et alii*, 1967 (fig. 3a) proposed a simple décollement interpretation, a concept which has been later detailed in a number of studies by LAVECCHIA (1979; 1981; 1982) and which forms the basis of two recent interpretations (see fig. 4a and 4b) that are based on refraction seismic data (LAVECCHIA *et alii*, 1984a and b). Fig. 3b also shows our own interpretation of the same area which, in contrast to previous work, postulates more extensive overthrusting and a much deeper basement than visualized by previous authors. Note that ROEDER (1984) offered structural sec-
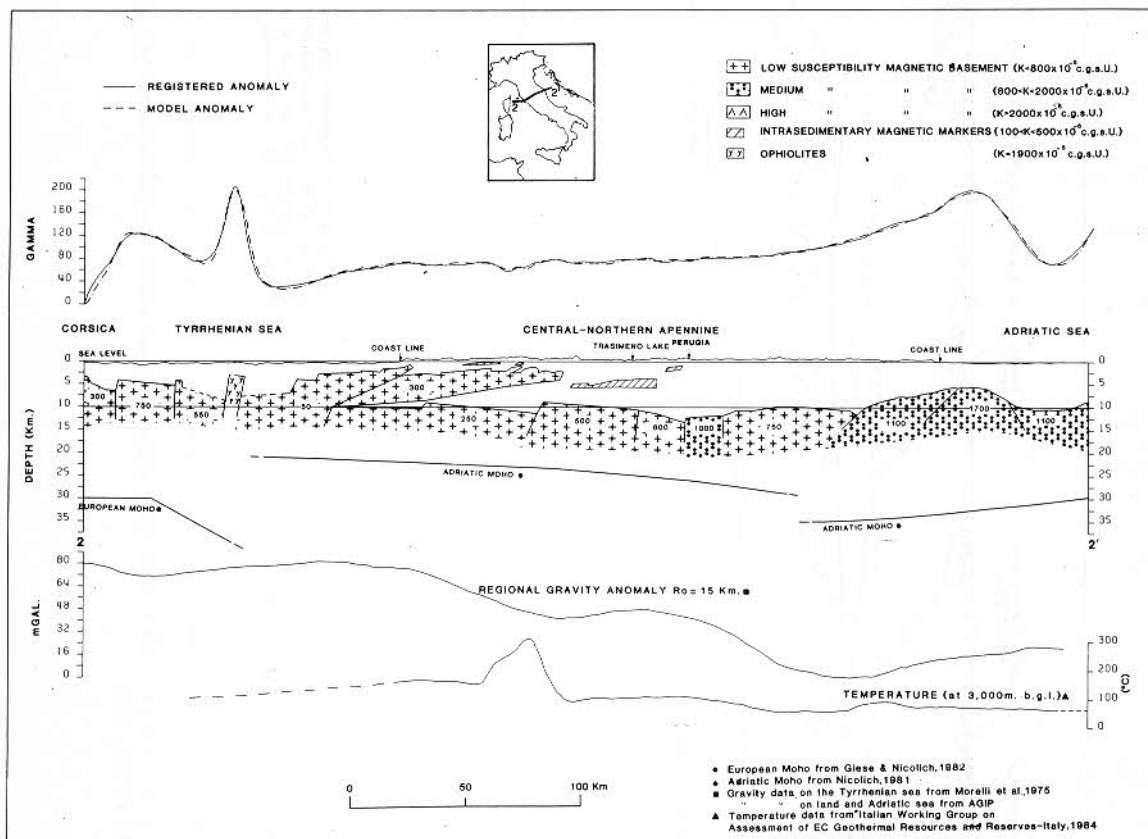
Fig. 5 - ARISI ROTA & FICHERA's (1985) interpretation is based on magnetic and gravity data. Note that the basement top in the Perugia area is about 10 km deep. Note the basement involvement in the Toscana. The offshore Adriatic basement high is below our basement level.

Ipotesi di tettonica distensiva e gravimetria, lungo la sezione Punta Ala - Ancona: 1) Coperture terrigene terziarie e quaternarie; 2) *Multilayer* sedimentario meso-cenozoico; 3) Evaporiti; 4) «Basamento»; 5) Limite crosta-mantello; 6) Limite superiore del *Low Velocity Level*; 7) Ipotetiche *detachment faults* distensive crostali tangenti a sistemi coniugati di faglie dirette rotazionali (listriche e planari) e non.

Fig. 6 - LAVECCHIA *et alii*, (1984) show on their section relatively small amounts of compressional shortening and a basement at about 4-5 km in the Perugia area.

tions that were in principle very similar to our own. This paper amplifies and documents ROEDER'S views.

Recent geophysical data offer two alternative regional interpretations (figs. 5 and 6). The model proposed by LAVECCHIA et alii, 1984b shows a relatively shallow basement and conventional décollement folding. On the other hand ARISI-ROTA & FICHERA (1985) use magnetic data to show a much deeper basement and no basement involvement in the fold systems of Umbria.

The question of the allochthoneity of the Umbria-Marche region has also been debated by paleomagnetic experts. Some (LOWRIE & ALVAREZ (1974; 1975; 1976) consider the Umbria-Marche as essentially autochthonous and explain the paleomagnetic evidence in terms of a counterclockwise rotation of the whole Italian Peninsula. Others (CHANNEL et alii, 1978) explain the paleomagnetic data in terms of rotated décollement systems.

A most important contribution for the understanding of our area is the Structural Map of the Northern Apennines which was published under the auspices of the Consiglio Nazionale delle Ricerche (BOCCALETTI & COLI, 1982). Fig. 7 abstracts selected basic structural elements of that map as well as some of the names and localities we will refer to in this paper.

METHODS

In our study we tried to better understand the regional structural setting of the central Apennines and to relate data from the Adriatic foreland to the structures in the central Apennines.

We felt that the study of reflection seismic profiles would shed some light on the question of the relative allochthoneity of the Central Apennines and that the same study may also clarify the overall nature of the «Olevano-Antrodoco-Posta line». Aside from practical reasons related to the exploration of hydrocarbons, we thought it would be worthwhile to test the applicability of experience obtained in other folded belts to the Central Apennines. Our interpretations look like a «Canadian Model» b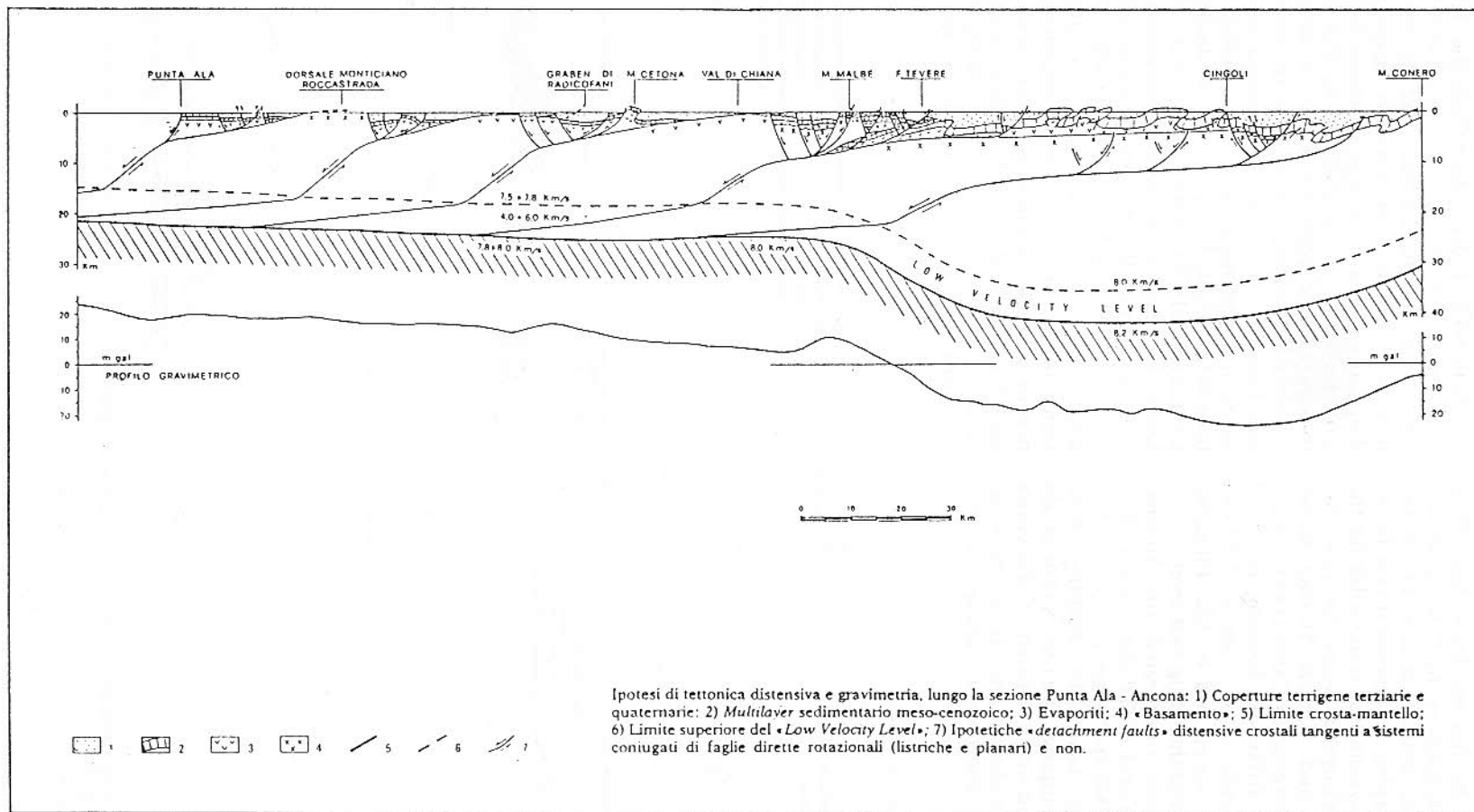ecause we were trying to compare the central Apennines with other areas where the Canadian model has been tested (BALLY et alii, 1966; DAHLSTROM, 1969; 1970; GORDY & FREY, 1975; GWINN, 1964;

1970; HARRIS & MILICI, 1977; 1981; PRICE, 1981; ROEDER et alii, 1978; ROYSE et alii, 1975; SUPPE, 1980a,b; 1985).

We studied a large number of seismic reflection profiles, calibrated them using wells, and constructed a number of balanced regional cross sections (plates 8 and 9). In all this we followed interpretational procedures that are common in folded belt exploration. The reader familiar with surface geology of our area may be perplexed by the degree of simplification which is adopted throughout this paper. The structural details, which are so spectacular on outcrops, simply do not show up on the seismic scale, yet we have to attempt to reconcile the overall surface geology with the seismic. A regional scale of 1:100,000 only permits one to reconcile a simplified version of the surface geology with reflection seismic data.

DEFINITION OF BASEMENT

In the Central Apennines, as in many other folded belts of the world, it is difficult to define the basement because the depth of the basement and the nature of the basement cannot be recognized using existing reflection seismic data. To be sure the magnetic maps published by AGIP (1981; 1984) and the models provided by ARISI ROTA & FICHERA (1985) rather strongly suggest that the «magnetic basement» is not involved in the deformation of the Umbria-Marche Apennines and its Adriatic foreland. If a magnetic basement was to be involved in the deformation of these regions, magnetic maps would probably show some very conspicuous anomalies. This is an important comment because it supports our basic premise of a gently westward dipping basement monocline. Of course, that same premise is also based on the presumed analogy of the Apennines with other foreland folded belts.

Note that the refraction data interpreted by LAVECCHIA et alii (1984a; 1984b) indicate a much shallower basement in the Apennines. We believe that LAVECCHIA et alii high basement velocities correspond to the Burano formation. As mentioned earlier, our subsurface information suggests velocities of the Burano evaporites in the order of 6.4 km per second. These velocities are in the same range as the basement velocities assumed by LAVECCHIA et alii (1984b).

A.W. BALLY, L. BURBI, C. COOPER & R. GHELARDONI
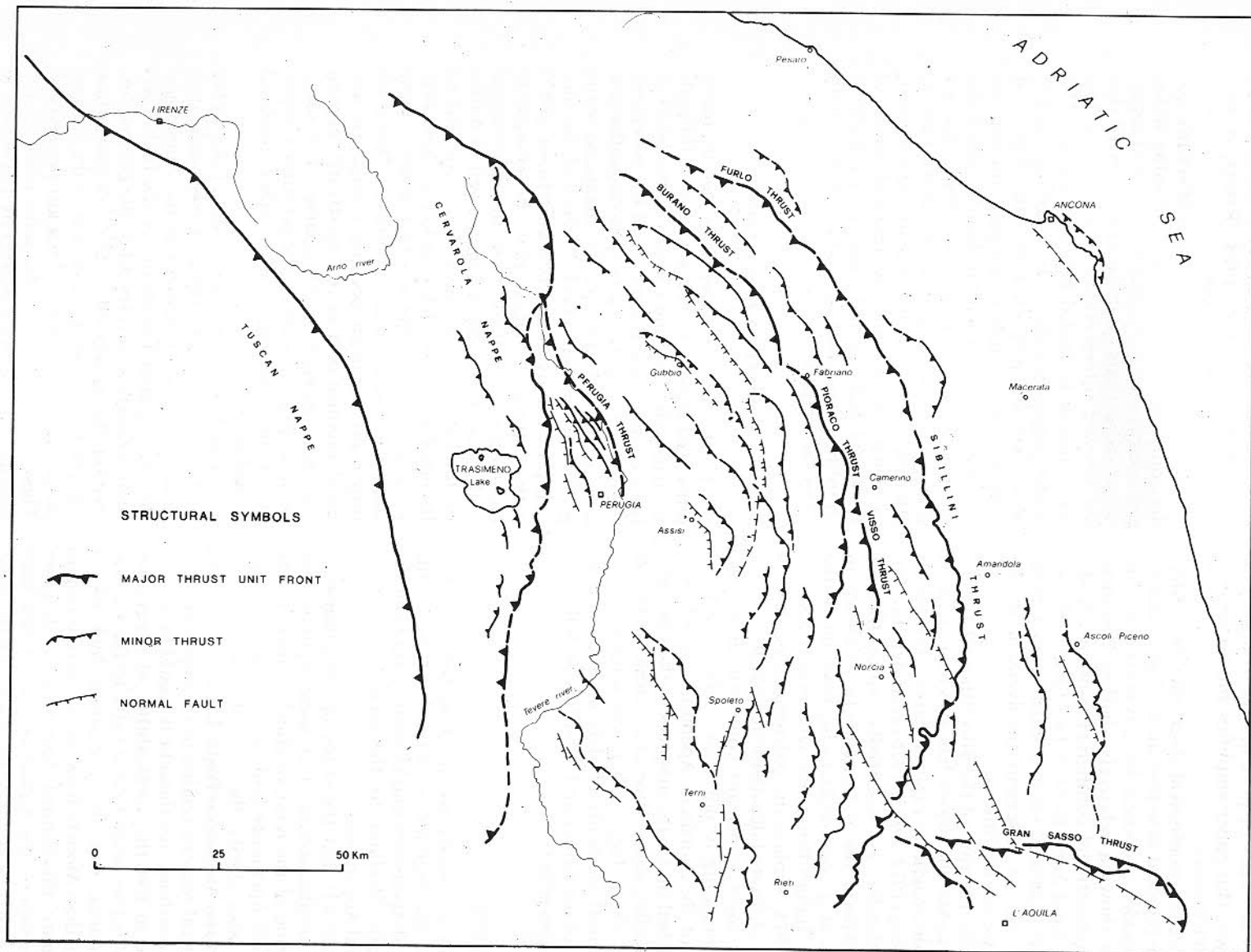
Fig. 7 - Tectonic sketch map of the east-central Apennines. This map has been abstracted from the Carta Strutturale dell'Appennino setten-
trionale (BOCCALETTI, COLI et alii, 1982). Only major thrust faults and normal faults are shown. Transversal discontinuities are not shown be-
cause we believe them to be of limited importance.
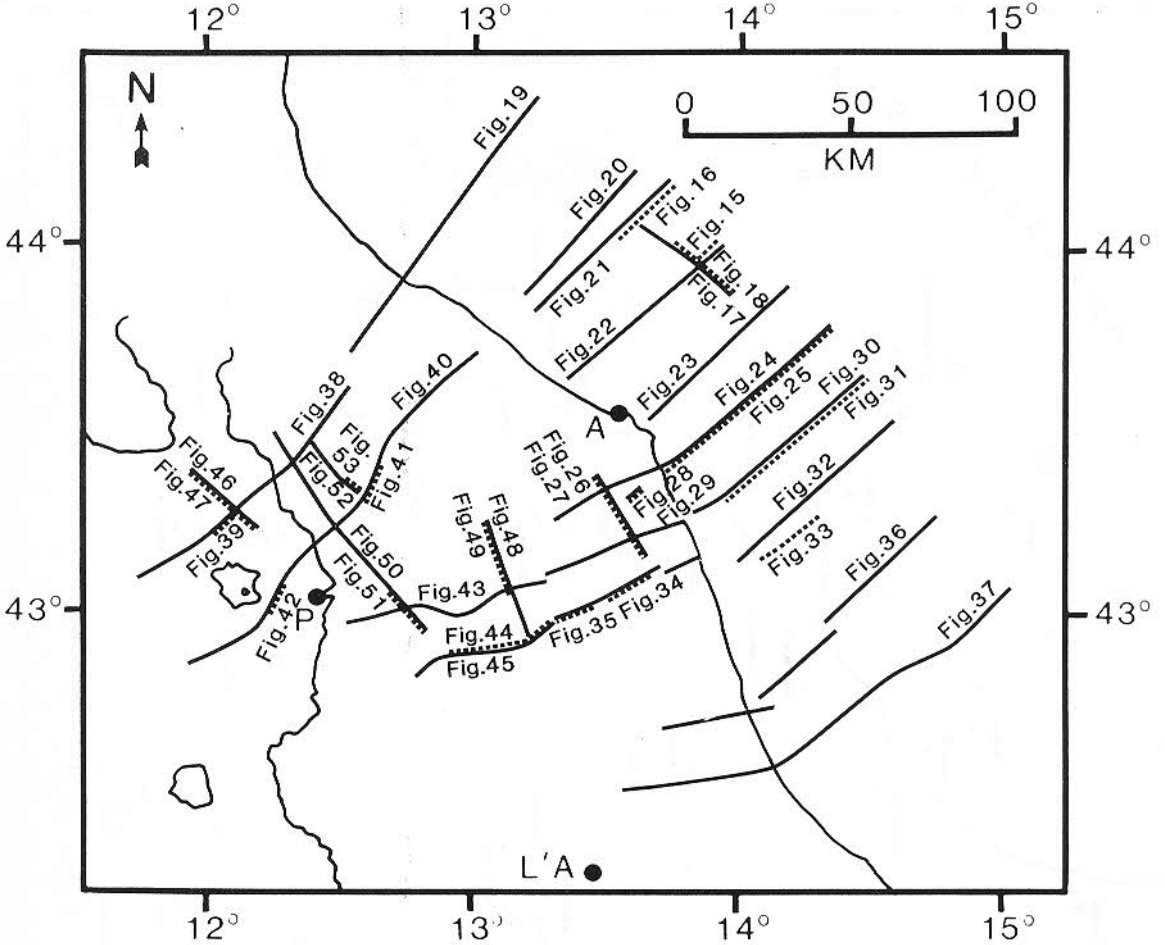
Fig. 8 - Location of seismic line drawings and profiles.

Coming back to the models of ARISI ROTA & FICHERA (1985), there is general agreement that farther west in the structures of Toscana Apennines a magnetic basement is involved, a point which is fairly well shown on the AGIP magnetic maps of 1981 (see also fig. 10). Note, however, that our sections tend to ignore the local basement relief that is suggested by ARISI ROTA & FICHERA (1985). This is because our data do not allow us to resolve local detail and because the general experience in folded belts is that magnetic depth determinations beyond 10 kilometers are somewhat imprecise and should only be accepted if corroborated by other data. For the purposes of this paper, it may suffice to say that we agree with overall basement depths between 10-13 km under the Central Umbria Apennines.

Note also that the magnetic map (fig. 10) shows a very large magnetic anomaly offshore Mte. Conero. According to a section published by ARISI ROTA & FICHERA (1985), that anomaly may be explained by a basement high that tops at about 5 km below sea level and has a relief in excess of 10 km. On our seismic profiles, we see very shallow diffractions reminiscent of an igneous structure of young Tertiary age. Note that the Mte. Vulture in the Basilicata to the south is characterized by a similar magnetic anomaly. We therefore speculate that shallow young Tertiary igneous bodies occur in the Adriatic Foreland.

The magnetic arguments for a deep basement that is not involved in the deformation of the Umbria-Marche Apennines are satisfactory and they support our basic premise,

— A.W. BALLY, L. BURBI, C. COOPER & R. GHELARDONI

BALANCED SECTION

LONGITUDINAL SECTION

WELL

0   50 Km

ADRIATIC SEA

RAVENNA

ANNA 1

AMEDEA 1

CANOPO 1

TAVULLIA 1

ALESSANDRA 1

JUDITH 1

CORNELIA 1

PESARO M. 1

ANCONA M.1

CARTOCETO 1

GABRIELLA M.1

FOSSOMBRONE 2

ANCONA

FIRENZE

Arno R.

WLS

ELS

ESINO 1

BURANO 1

LIVORNO

GUBBIO 1

CONRAD 1

MIZAR 1

SIENA

S. FILIPPO 1

FERMO 2

S. CLAUDIO 1

S. MARIA 1

DANTE 1

Trasimeno L.

LORO PICENO 1

RIGEL 1 bis

PERUGIA 2

RAPAGNANO 4

EDMOND 1 tris

PERUGIA

ESMERALDA 1

ELBA

ASCOLI PICENO

TORTORETO LIDO 1

NERETO 1

Bolsena L.

ELS

TYRRHENIAN SEA

WLS

Campotosto L.

Tevere R.

ANTRODOCO 1

VILLADEGNA 1

ROCCAFINADAMO 1

Vico L.

L' AQUILA

Bracciano L.

Fig. 9 - Location of regional geological sections and key wells.

SCALE 1:2000'000

0   20   40 50 Km

——	Contour interval 100 gammas	
—	Contour interval 25 gammas	
—	Contour interval 5 gammas	
+	Magnetic high	
-	Magnetic low	

Boundary of areas surveyed
with different flight altitude
or different flight paths
direction and grid

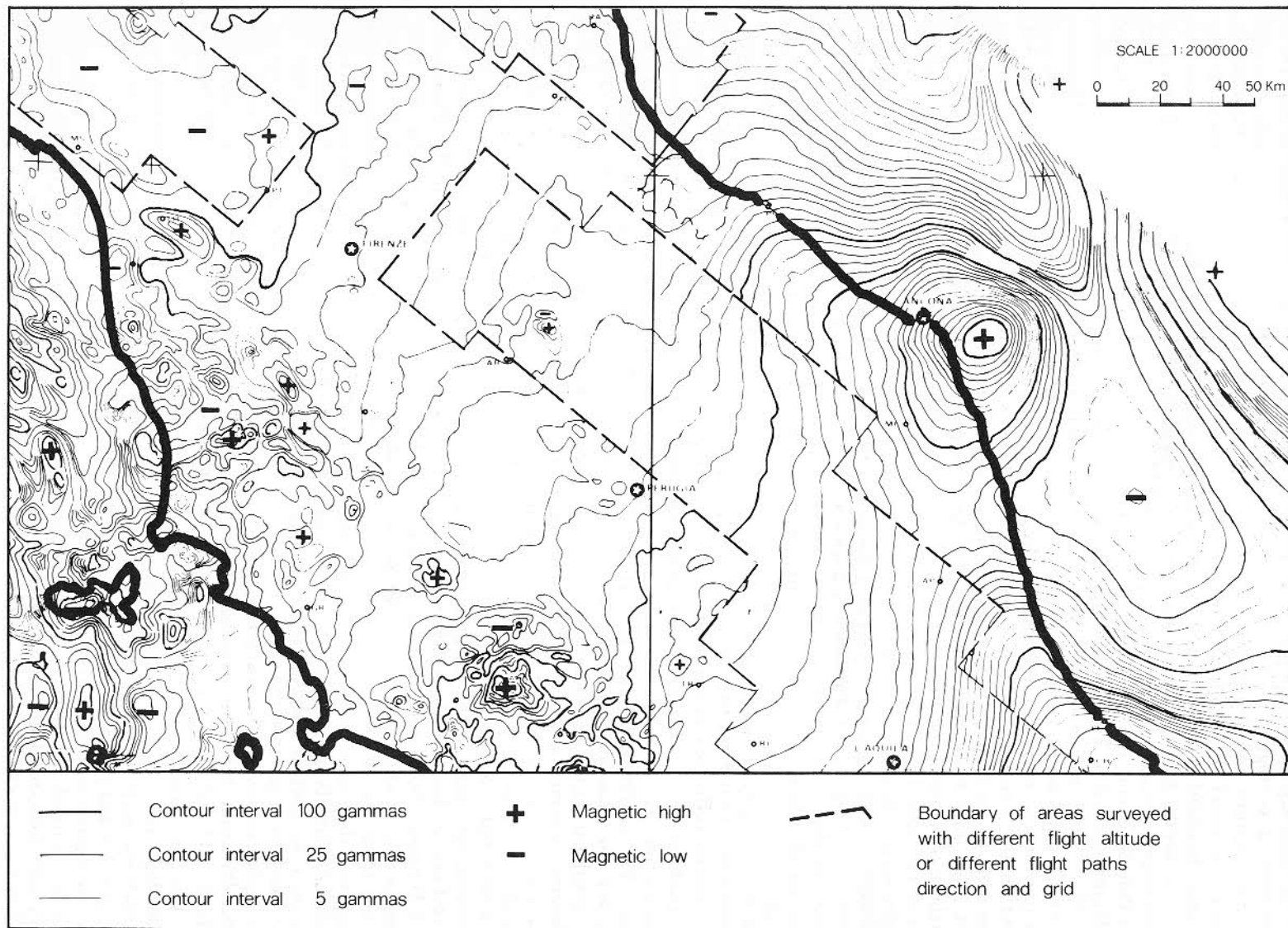*Fig. 10* - Residual Magnetic Field Map, after AGIP, 1981. Note the monotonous contours under the Umbria-Marche Apennines and contrast them with the obvious anomalies that correspond to the metamorphic Toscana units, and to the Mte. Amiata and the Vulsini volcanoes. Note also a large anomaly to the east of Ancona, which we suspect to represent a Pliocene igneous body. (See also fig. 5).

but the same arguments are quite unsatisfactory from a geological perspective because the basic nature and depth of the basement underlying most of the Apennines and the Adriatic foreland remains quite obscure and the real depth of any igneous basement remain elusive. Much of what is known about the Paleozoic and the basement in Italy is well summarized in Volume 20 of the Memorie della Società Geologica Italiana (VAI, 1979). This publication suggests that we do not quite know what would constitute basement in the Central Apennines even if we were able to see it on reflection seismic profiles. The only *bona fide* basement in the northern Apennines occurs in the Toscana (BAGNOLI *et alii*, 1979; BURGASSI *et alii*, 1979) where we are dealing with a Hercynian metasedimentary and igneous complex and discordantly overlying Upper Paleozoic sediments which, as they have been described, would have an ill-defined magnetic signature and which because of their low-grade metamorphism, the intensity of folding and the presence of intrusions would not provide any reasonably cohesive reflectors on our profiles.

Looking for additional relevant basement information, we can go to the southern Alps where VAI (1979; 1982) has recently summarized the situation. He points out that in the southern Alps, we have early to mid-Paleozoic radiometric ages for the metamorphic complex of the Ivrea zone, a hercynian basement for most of the southern Alps, and a deformed but essentially non-metamorphic Paleozoic basement in the Carnian Alps: the paleo-Carnian folded belt which is overlain by a Permo-carboniferous molasse sequence. There is also a radiometric age of 446 m.y. reported from the Assunta well near Venice suggesting the existence of an early Paleozoic basement. Finally, one cannot escape the suspicion that part of the Adriatic basement may well be a part of Precambrian Africa, that could conceivably be overlain by at least upper Paleozoic platform sequences (BALLY, 1981; figs. 15 and 16).

We did state earlier that below many folded belts mountainward-dipping basement monoclines can be followed on reflection seismic profiles, but it should be noted that usually one cannot map the top of the basement directly, instead, in most cases, near-basement reflectors are identified. For instance, in the Canadian Rocky Mountains (BALLY *et alii*,

1966) and in Wyoming (ROYSE *et alii*, 1975), the Precambrian basement monocline is outlined by a Cambrian reflector immediately overlying the Precambrian basement. In the Appalachians a similar basement monocline is outlined by the Cambrian Rome Formation that overlies it (HARRIS & MILICI, 1977; HARRIS *et alii*, 1981; COOK *et alii*, 1982; 1983), and in the Alpine foreland a number of profiles permit to trace the top of the pre-Mesozoic basement under the sub-alpine Molasse and part of the Helvetic thrust sheets (BACHMANN, 1982; 1983). In the Arctic Islands of Canada décollement is limited to the carbonates and evaporites that overlie a generally flat Cambro-Ordovician carbonate sequence (FOX, 1983; 1985).

To be able to apply the analogies from other folded belts to the Apennines, we used the upper Permian red bed reflector encountered in the Alessandra 1 well as a near-basement reference level. Even this reflector could not be followed into the Adriatic foothills and therefore our seismic interpretations and cross sections are simply based on an extrapolation of the dip of the Adriatic foreland monocline underneath the Central Apennines. We felt justified in pressing our analogy from other folded belts because as will be seen later on many seismic profiles we observe deep subhorizontal reflectors which, however, are shallower than the extrapolated «near-basement» top. Our next fixpoint was the Perugia 2 well, which penetrated phyllites with «Verrucano» affinities. We do not know how these phyllites correlate with the Permian rocks encountered in the Alessandra 1 well, but assume that because the Mte. Malbe region hardly shows up on the magnetic maps, that we are dealing essentially with only slightly magnetic intrasedimentary markers (ARISI ROTA & FICHERA, 1985) and with relatively low seismic velocities. Farther to the west on our cross-sections, we did not attempt to differentiate magnetic basement from Verrucano because we had no reflection seismic profiles to work with and because that area was outside the scope of our study.

To conclude and by way of explanation of our regional profiles, we include in our pre-Burano section the following:

– A Verrucano metasediment section in the Central Apennines which may be younger than the Permian reflector seen below the Adriatic Sea.

— A magnetic basement that is below the deepest reflector seen on seismic profiles and that is involved in the structures of the metamorphic Tuscan unit.

STRATIGRAPHY

a) Introduction

Our area is famous for its many classical stratigraphic studies. We refer to the studies of Sacco (1904-5; 1935a,b; Lotti (1926), Renz (1936). Most recently geologists of the University of Ancona (Crescenti, 1969; 1975; Crescenti et alii, 1969; 1980) of the University of Camerino (Calamita et alii, 1977; 1979; 1982a,b; Cantalamessa et alii, 1980a,b; and Centamore et alii, 1969; 1971; 1976; 1978) and the University of Perugia (Colacicchi et alii, 1970; 1975; 1976; 1986a,b) have made many basic contributions. Let us also note the important papers by Castellarin et alii (1978), and Coltorti & Bosellini (1980) which have done much to clarify the tectonic setting of the Jurassic stratigraphy. An outstanding summary of the stratigraphy of the area is offered in the new «La Geologia delle Marche» (Centamore & Deiana, 1986).

Because there are already so many fine studies we can dispense with a detailed discussion of the Stratigraphy of the region and limit ourselves to include a correlation chart (fig. 11) and to discuss seismic interval velocities (fig. 12) as well as some special stratigraphic problems.

b) Seismic Interval Velocities

Seismic interval velocities are important for our time-to-depth conversions of seismic reflection profiles. They are also useful to help in identifying some key reflectors. Fig. 12 is a table that lists our main velocity information.

For our depth conversion we either used velocities from nearby wells or else we used the rounded values listed on the right margin of fig. 12. The use of interval velocities for manual depth conversions of reflection seismic profiles provides a measure of consistency but may also constitute a source of error. Note that the velocity spread for various intervals shown on fig. 12 is rather large.

This is mostly due to changes in lithology and burial history of various formations. Even though locally our velocity assumptions may cause some significant errors we do not believe that more accurate velocities would change our overall structural interpretation.

c) Permo-Triassic Correlations

Overlying the diverse Paleozoic basement of central Italy units and their associated synpostorogenic flysch and molasse sediments of upper Paleozoic age, we find the «Verrucano» sequence, which Cassinis et alii (1980) describe as a tectofacies of typically lower and middle Triassic age. We visualize this facies to be deposited in an extensional basin that is superposed on a folded belt, i.e., an episutural basin much like the Pannonian basin (Bally & Snelson, 1980). In this context we have only two significant penetrations in our study area. The first is the Alessandra 1 well, where Permian red sandstones with remarkably low velocities (about 3900 m/sec) have been penetrated for about 800 m. The second penetration is the Perugia 2 well where phyllites were encountered.

As already mentioned, we do not really know how to correlate the Permian red beds that were encountered in the Alessandra 1 well with the phyllites of the «Verrucano» sequence that was encountered in the Perugia 2 sequence. The fact that at Perugia the sediments were moderately metamorphic does not in itself preclude that both formations are roughly equivalent. However, it should again be noted that most people now believe that much of the «Verrucano» of the Toscana is Triassic in age (Cassinis et alii, 1980). Whatever the correlation may be, we prefer to include the «Verrucano» near Perugia within the sedimentary sequence and not to include it in the «magnetic basement».

We are facing additional difficulties with the correlation and distribution of the Upper Triassic evaporites and carbonates of the Burano formation. A number of wells in the offshore as well as the type locality well at Burano penetrate varying thicknesses of the Burano formation. Thus thicknesses in excess of 2000 meters occur in the Burano and a lesser thickness in the Perugia 2 well. In the Burano well steep dips in excess of 70° dominate the lower half of the penetrated section, suggesting intensive deformation in the core

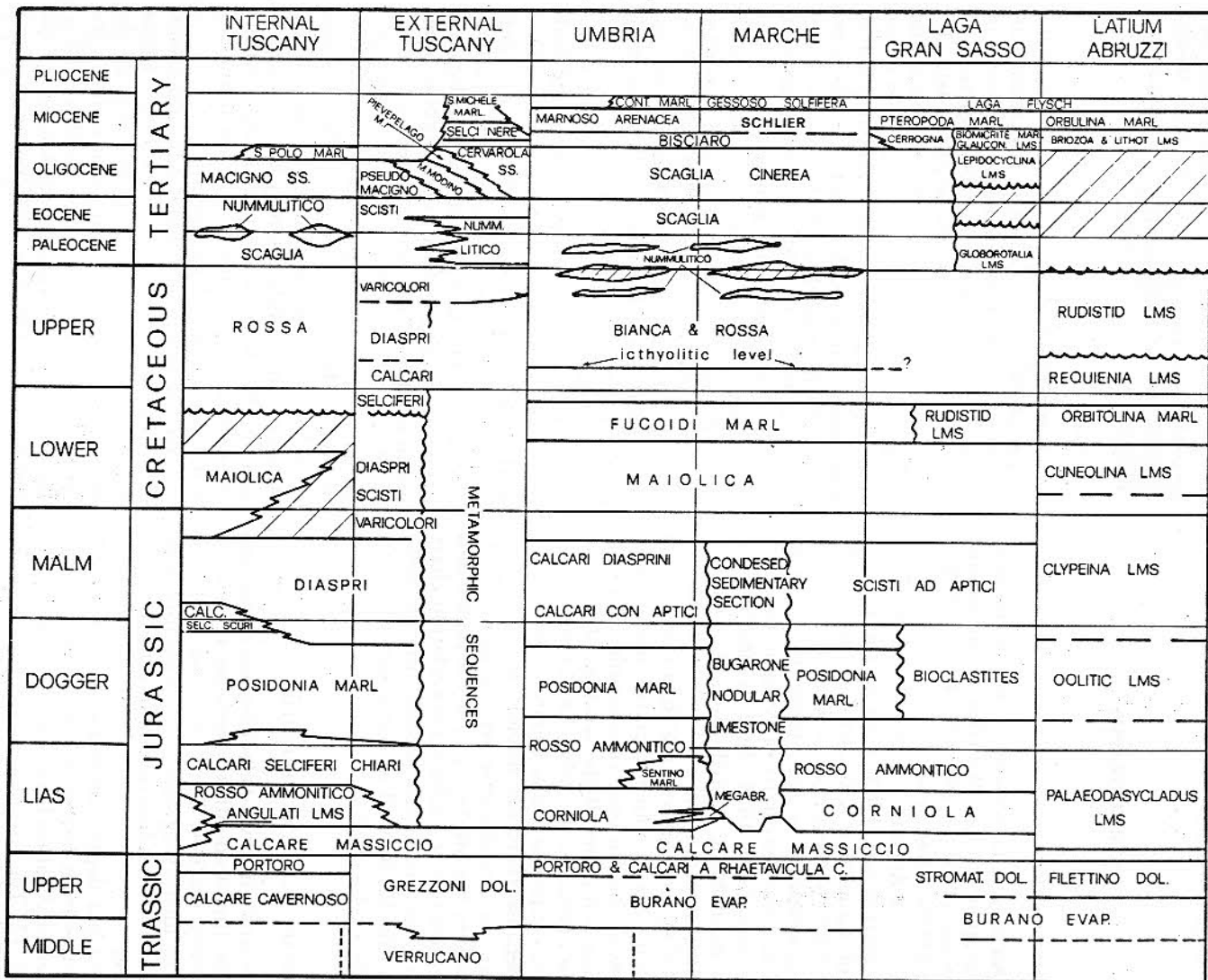|		INTERNAL TUSCANY	EXTERNAL TUSCANY	UMBRIA	MARCHE	LAGA GRAN SASSO	LATIUM ABRUZZI
PLIOCENE	TERTIARY						
MIOCENE			PIEVEPELAGO M. / S MICHELE MARL / SELCI NERE	CONT. MARL / MARNOSO ARENACEA / BISCIARO	GESSOSO SOLFIFERA / SCHLIER	LAGA FLYSCH / PTEROPODA MARL / CERROGNA / BIOMICRITE MARL GLAUCON. LMS	ORBULINA MARL / BRIOZOA & LITHOT LMS
OLIGOCENE		S POLO MARL / MACIGNO SS. / PSEUDO MACIGNO	CERVAROLA SS. / M. MODINO	SCAGLIA CINEREA		LEPIDOCYCLINA LMS	
EOCENE		NUMMULITICO	SCISTI / NUMM.	SCAGLIA			
PALEOCENE		SCAGLIA	LITICO	NUMMULITICO		GLOBOROTALIA LMS	
UPPER	CRETACEOUS	ROSSA	VARICOLORI / DIASPRI / CALCARI	BIANCA & ROSSA / icthyolitic level		?	RUDISTID LMS / REQUIENIA LMS
LOWER		MAIOLICA	SELCIFERI / DIASPRI / SCISTI	FUCOIDI MARL / MAIOLICA		RUDISTID LMS	ORBITOLINA MARL / CUNEOLINA LMS
MALM	JURASSIC	DIASPRI / CALC. SELC. SCURI	VARICOLORI	CALCARI DIASPRINI / CALCARI CON APTICI	CONDESED SEDIMENTARY SECTION / SCISTI AD APTICI		CLYPEINA LMS
DOGGER		POSIDONIA MARL	METAMORPHIC SEQUENCES	POSIDONIA MARL / ROSSO AMMONITICO	BUGARONE NODULAR LIMESTONE / POSIDONIA MARL / BIOCLASTITES		OOLITIC LMS
LIAS		CALCARI SELCIFERI CHIARI / ROSSO AMMONITICO ANGULATI LMS / CALCARE MASSICCIO		SENTINO MARL / CORNIOLA / CALCARE MASSICCIO	MEGABR. / ROSSO AMMONITICO / CORNIOLA		PALAEODASYCLADUS LMS
UPPER	TRIASSIC	PORTORO / CALCARE CAVERNOSO	GREZZONI DOL.	PORTORO & CALCARI A RHAETAVICULA C. / BURANO EVAP.		STROMAT. DOL. / BURANO EVAP.	FILETTINO DOL.
MIDDLE			VERRUCANO				

Fig. 11 - Stratigraphic Correlation Chart of the Central Apennines. Note that the Verrucano is included in the Triassic and that the red beds encountered in Alessandra 1 (fig. 15) are dated as Permian.

CENTRAL ITALY VELOCITIES IN M/SEC TWO WAY TIME

	ONSHORE	W-ADRIATIC OFFSHORE FOLDS	E-ADRIATIC OFFSHORE MONOCLINE	RANGE	ADOPTED FOR DEPTH CONVERSION
PLEISTOCENE	–	1962	2004	2410–1605	2000
PLIOCENE	2636	2767	2328	3634–1819	2600
MESS. (U. MIOC.)	3475	3777	3800	5277–3027	3400–4000
SCHLIER BISCIARO	3842	3060	2875	4648–2573	3400
CINEREA	3360	3080	3448	4126–2680	3400
SCAGLIA	4990	4726	4013	5600–3471	4500
MAIOLICA	5420	5795	4727	6398–3960	5200
APTICI	5228	5473	4697	6050–4362	
ROSSO AMMON.	4720	5502	3938	5792–3667	
CORNIOLA	6046	6037	5072	6420–4813	6000
LIAS INF.–"MASS."	6290	–	5888	6386–5728	
TRIAS. SUP.	6598	6195	6394	6696–6010	6400
PERMIAN	–	–	3889	– –	

Fig. 12 - Seismic interval velocities in m/sec two way time. This tabulation is based on acoustic logs of representative wells.

of the Burano anticline. Outcrops in a gypsum quarry near Perugia exhibit the intensive deformation of the Upper Triassic evaporites. The complex structural behavior of the Burano anhydrites is discussed in some detail by CIARAPICA & PASSERI (1976) & COLI (1980).

All this suggests that the Burano formation offers a highly mobile décollement level that may often be associated with diapiric phenomena. In fact, we suspect that some of the details of the Mte. Malbe structure near Perugia may be best explained by secondary diapirism that is superposed on thrusting.

A picture of the facies distribution of the Triassic in the Central Apennines is offered by PASSERI (1979). From that map it is fairly obvious that the distribution of the Upper Triassic evaporites coincides with the Central Apennine fold belt, and therefore these evaporites are mainly responsible for the tectonic style of that folded belt.

The Burano formation with its anhydrites and dolomites has some very high densities and velocities (typically about 6400 m/sec) that contrast with the lower velocities of the underlying Permo-Triassic. It is suggested that some of the deep flat reflectors in the interior Central Apennines may be related to the Verrucano-Burano transition. Because we had such great difficulties coming up with a reasonable thickness for the Verrucano and the Burano formations we somewhat arbitrarily kept the thickness for both formations in the 2000 m range. For the Burano formation that thickness may be greatly distorted by diapiric phenomena or by flow in the core of folds.

As mentioned earlier, a quick inspection of our sections will show that we are carrying the Burano formation as an apparently relatively undisturbed layer. Here again we were forced to make a simplistic and probably incorrect assumption that would permit us to draw some first order balanced cross sections. We have no illusions that if we had good data the main upper Triassic décollement level would be far more complexly deformed.

d) JURASSIC EXTENSIONAL TECTONICS

Numerous papers have occupied themselves with Jurassic stratigraphy in central Italy (BERNOULLI; 1972; BERNOULLI & JENKINS, 1974; BERNOULLI et alii, 1979; BOSELLINI, 1973; BOSELLINI & WINTERER, 1975; CASTELLARIN, 1972; CENTAMORE et alii, 1971; CENTAMORE et alii, 1986; COLACICCHI et alii,

1975; 1976; CRESCENTI, 1969; CRESCENTI *et alii*, 1969; COLTORTI & BOSELLINI, 1980; and WINTERER & BOSELLINI, 1981). The present consensus is that the Jurassic is characterized by three main sequences: A thick «complete» sequence, which corresponds to a basinal facies and includes an interval extending from the Hettangian to the Tithonian. This sequence contrasts with the reduced and condensed sequences where the basinal members of the sequence are progressively more condensed and onlap on the underlying Hettangian-Sinemurian Calcare Massiccio.

Together with many other authors, we suspect that the basinal facies is deposited in half-graben systems. We visualize that these half-graben systems may be connected by transfer segments (BALLY *et alii*, 1985), so that ideally one ought to see the following: stratigraphic onlap on the half-graben monocline, beds that are rotated into listric normal faults scarps, and beds that abut against subvertical faults corresponding to the transfer segments. Even though we tried diligently to see whether, based on surface or seismic data, we could reconstruct a plausible pattern of extensional tectonics, so far we were not particularly successful in documenting a convincing case. As already suggested by CASTELLARIN *et alii* (1978), we know that slide-scarps and slump-related features may somewhat modify the primary tectonic features that we expect from our idealized model. COLTORTI & BOSELLINI (1980) provide an interesting Jurassic paleotectonic picture over part of our area. The situation is further complicated by obvious inversion structures of Jurassic halfgrabens (COOPER & BURBI, 1987, this issue).

With regard to our structural cross sections, it should be noted that none of the Jurassic extensional tectonics are evident on these sections. This is mainly because on the seismic profiles we could not see any Jurassic extensional tectonics. The actual Jurassic basin fill rarely exceeds 500 m, so that even allowing for considerable water depth, the actual relief between high and lows is not all that spectacular and would probably not be easily detectable on seismic profiles that in general have poor resolution for the Mesozoic.

On the other hand, based on surface observations there is little doubt that the distribution and tectonics of the highs and the intervening half-graben basins critically influences the tectonic style as we would encounter it at the scale of a single subsurface structure.

In connection with the formation of the half-graben system, it should be pointed out that the consensus now is that the Jurassic extensional system of the Apennines was basement-controlled, that is, that we are looking at a typical attenuated transitional continental margin of the Gulf of Biscay type. The concept is reasonably convincing because after the initial stretching, we clearly recognize the deposition of extensive pelagic sequences such as the Maiolica, or the Scaglia and farther west rather widespread radiolarian sequences. It is fairly plausible that if one had to look for a passive margin break-up unconformity that the base of the Maiolica would come reasonable close to it. This age would roughly tie with the age of the Liguride ophiolites to the west.

All these good arguments are well founded in plate tectonic liturgy (D'ARGENIO & ALVAREZ, 1980; WINTERER & BOSELLINI, 1981). There remains however, a suspicion that things may not be that simple. First, we see pelagic sequences in the Adriatic foreland where today the crust is not particularly attenuated. In the Central Adriatic, we see on the profiles quite spectacular seismic stratigraphy where the pelagic facies onlaps on Cretaceous-Paleocene reefs suggesting basinal water depths in the order of about 1500 meters but no underlying extensional basement structure.

From our reconstructions, it could be speculated that Jurassic extensional tectonics are limited to the allochthonous thrust sheets of the mountains which in their palinspastic position fit on top of the attenuated lower half of the attenuated 20 kilometer crust of the western Apennines. The underlying «autochthonous» Adriatic monocline with its much thicker 30 km plus crust, would then represent essentially crust that was not extended during the Jurassic.

If one combines this concept with the notion that the normal faults that presumably characterize the Jurassic extension seen on outcrop are basically rooted in a thick evaporitic sequence, one could consider an alternative possibility that the Jurassic struc-
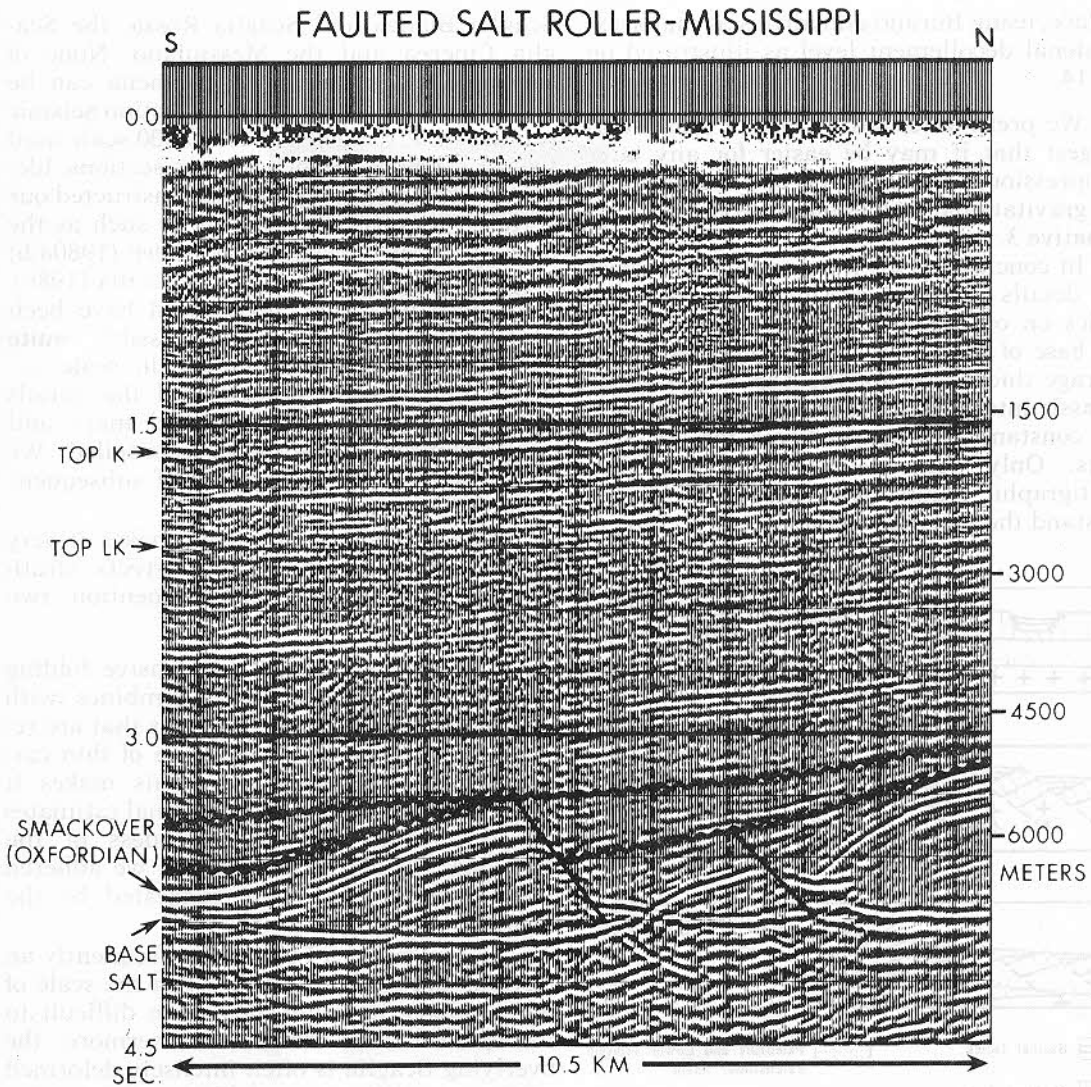
FAULTED SALT ROLLER-MISSISSIPPI

Fig. 13 - Salt rollers bounded by listric normal faults which flatten at the base of salt. Seismic profiles from Mississippi (BALLY 1981). Similar structures commonly occur offshore Gabon and Angola, and offshore Brazil. They are also known from the Gulf of Lyon.
Jurassic extensional tectonics in the areas underlain by the Burano evaporites may possibly be due to Jurassic gravitational tectonics of this type, see fig. 14.

tures may also be compared with the «roller» structures that are so characteristic of the Jurassic Smackover trend in Louisiana (fig. 13) and the salt structures of Gabon, Cabinda, Brazil and some areas of the Nova Scotia offshore.

Thus, we are looking at three basic alternatives to explain the distribution of Calcare Massiccio «platforms» at the beginning of lower Cretaceous in the Umbria basin. Each of these alternatives would control the di-

stribution of condensed, reduced, and complete Jurassic basinal sequence (see fig. 14).

1) A simple distribution of Massiccio carbonate platform which may or may not be controlled by earlier basement structures.

2) Tilting and rotation of the Burano and Massiccio formations along basement-involved structures.

3) Gravitational sliding of the Burano-Massiccio sequence over an earlier basement

surface, using Burano anhydrites as major extensional décollement level as illustrated on fig. 14.

We prefer alternatives Nos. 2 and 3 and suggest that it may be easier for any later compressional décollement to coincide with the gravitational décollement proposed in alternative 3.

In conclusion, we were unable to project the details of the Jurassic extensional tectonics on our regional sections. We defined the base of the Jurassic by using reasonably average thicknesses for the Top Scaglia-Base Jurassic interval. We also assumed a reasonably constant Burano thickness for our sections. Only very detailed mapping and stratigraphic studies will help to better understand the specifics of Jurassic stretching.
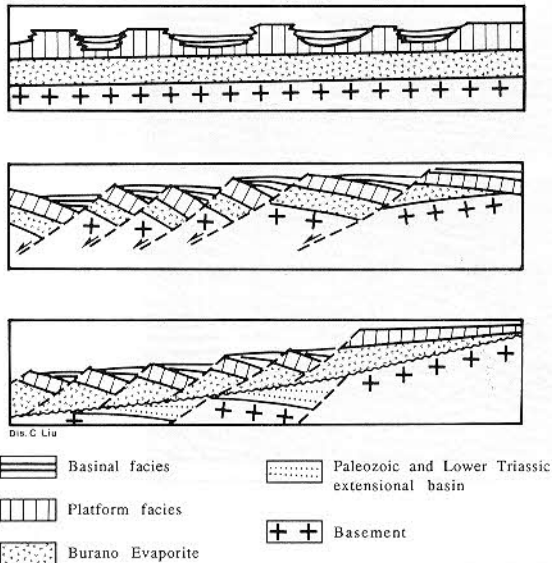

Basinal facies

Platform facies

Burano Evaporite

Paleozoic and Lower Triassic extensional basin

Basement

Fig. 14 - Cartoon showing three alternative interpretations of the Jurassic in Umbria: 1) Platforms and Basin; 2) Listric fault blocks involving the basement; and 3) Gravitational gliding.

e) COMMENTS ON DÉCOLLEMENT LEVELS AND STRATIGRAPHY

The local tectonic style as we see it in outcrops of the Umbria-Marche Apennines is controlled by frequent ductility contrasts that occur within the stratigraphic sequence. Thus we observe compressional décollement phenomena associated with the Ammonitico rosso, the Maiolica, the Scisti a Fucoidi, the

Scaglia Bianca and Scaglia Rossa, the Scaglia Cinerea and the Messiniano. None of these local décollement phenomena can be resolved at the scale of our reflection seismic profiles or at the original 1:100,000 scale used for the construction of our cross sections. Ideally, we should have carefully constructed our surface sections using principles such as the ones used and illustrated by SUPPE (1980a,b; 1983; 1985) and BARCHI & LAVECCHIA (1986). On a regional scale, this would have been quite time-consuming but possibly quite fruitful because the difference in scale between our seismic profiles and the details that one observes on geological maps and outcrops need to be better reconciled. We hope this will be a direction of subsequent studies.

Internal deformation also makes it very difficult to come up with «correct» stratigraphic thicknesses. Let us mention two examples:

1) There is frequently intensive folding within the Maiolica which combines with probable rapid primary thickness that are related to the presence or absence of thin carbonate turbidite sequences. This makes it most difficult to have good regional estimates for the «true» primary thickness of the Maiolica. On our cross sections, we adhered to thicknesses that were suggested by the local authors.

2) The Scisti a Fucoidi are frequently an obvious décollement level, yet at the scale of our sections, it would have been difficult to incorporate that detail. Furthermore the overlying Scaglia is often intensely deformed suggesting disharmonic folding and intensive deformation, which in part has been described in the macrotectonic studies done by LAVECCHIA *et alii* (1983). Here again, it is difficult and time-consuming to incorporate the local detail into the regional balanced cross sections.

All these difficulties are a matter of scale but they are also due to the fact that most of the surface maps in the area – with the exception of the outstanding Cagli, Pergola, and Fabriano 1:50,000 sheets (SERVIZIO GEOLOGICO D'ITALIA, 1972; 1975; 1979) simply do not show enough structural detail. In conclusion: most of the shortening that we see on the local scale is not really accounted for in our regional sections (plates 8 and 9),

and in our view should probably be added to the amount of shortening that is displayed in our sections.

f) TERTIARY STRATIGRAPHY

Many authors have published fine stratigraphic summaries on the Tertiary of the Apennines and the Adriatic foreland. Starting with the overall reviews of SESTINI (1970) and DALLAN NARDI & NARDI (1974), we come to more recent papers by CRESCENTI (1975), CRESCENTI et alii (1980) and CANTALAMESSA et alii (1982) & BELLORINI (1982), CANTALAMESSA et alii (1986).

Our seismic profiles permit to add some detail to the Tertiary stratigraphy of the Adriatic foreland, and the reasonably high quality data would permit in principle much more detailed seismic stratigraphic studies of the Tertiary from Scaglia Cinerea on up. However, because our focus was on regional structural geology we refrained from doing any detailed work, but it is obvious to us that such a study would help a fairly detailed kinematic analysis of the timing of deformation of different structural trends. Also, an indication of what can be done with seismic stratigraphy is contained in papers by DONDI et alii 1982, 1985; CURZI, 1986; ORI et alii, 1986a,b; SCHWANDER, 1987, in press.

A significant observation on most sections in the Adriatic Sea is the downlap surface that is associated with the «Messiniano» reflector. Pliocene formations show very distinct downlap patterns on that unconformity. This is reminiscent of many other foredeeps of the world where similar relations have been explained as unconformities that are related to migrating peripheral bulges of the type modeled recently by QUINLAN & BEAUMONT (1984).

Another important aspect is the occurrence of widespread pre-Mid Pliocene unconformities that onlap discordantly on older structures that involve lower Pliocene and older reservoirs, e.g., in Cellino area (CASNEDI, 1983; 1986) and probably a number of anticlines farther north.

Further down in the Tertiary stratigraphic record and more to the west in Umbria, the formazione Marnoso Arenacea and the much thinner Schlier formations are roughly about the same age, but the thick Laga flysch is somewhat younger (see fig. 64). Now that

we have some first approximation balanced cross sections, and restorations it would be timely to attempt more precise correlations and try to fine-tune the age of deformation in the Apennines.

Finally the Cervarola overthrust mass is quite well expressed on some seismic profiles in the area west of a line from Upper Val Tiberina and Perugia. This should not come as a surprise but it emphasizes that in the subsurface the Marnoso-Arenacea-Umbrian stratigraphy extends quite some distance to the west underneath the Cervarola thrust sheet.

SEISMIC DOCUMENTATION

a) INTRODUCTION

Because our study attempts to integrate reflection seismic profiles with geologic surface and subsurface data, we have the tricky task of documenting our interpretations with some of the basic seismic data on which they were based. We choose two different forms of graphic documentation: (1) line drawings of regional seismic profiles and (2) selected fragments of the profiles themselves. The material contained in this paper is representative of much of the information that was available until about 1984, but we expect that as new techniques become available much better seismic profiles will be obtained in the future. These could significantly modify the conclusions of this paper.

Our line drawings are a form of selective reporting because they definitely are personal and subjective interpretations. We feel that we were conservative. We did exclude multiples, diffraction patterns, and many spurious data from our line drawings. However, we did sometimes use diffractions to locate faults. Most of the lines on our drawings represent coherent reflectors that could be followed over some distance. In most cases we identified stratigraphically only a few reflectors except when we had well-control. In the Adriatic sea we used seismic-stratigraphic principles, but we are aware that some of our correlations are rather tenuous. However correlation-related uncertainties should not seriously alter our regional structural sections.

Far more important uncertainties occur within the Apennines where the stratigraphic

identification of deep reflectors is practically impossible. Here we were more interested in the presence or absence of deep reflectors, and their generally flat nature.

Note that during our study we were not aware of LAVECCHIA *et alii* (1984b) refraction data. We believe that it may now be interesting to see whether these refraction surveys can be reconciled with our interpretation to provide yet another model.

Note that the seismic profiles of the Adriatic offshore and the foothills region use a sea level datum, whereas the sections in the Apennines use a datum at 500 m above sea level. All our profiles are in time and their horizontal scale varies considerably. In the mountains, surveys frequently follow curved roads that have little relation to regional and local dip and structure. We have attempted to give some rough horizontal scales on our line drawings. For our structural sections, we manually depth-converted our seismic profiles using the best possible interval velocities and we then projected the seismic data on our cross sections. All this will make it often difficult for the reader to reconcile the regional structural cross section with the specifics of the adjacent seismic reflection profiles. It is for this reason that in the following we will describe the seismic documentation separately from our structural cross sections.

b) ADRIATIC MONOCLINE AND THE STRATIGRAPHIC CALIBRATION OF OUR PROFILES

Regional structural cross sections across folded belts best start in the autochthonous foreland, i.e., in an area of little décollement. This procedure simply offers a non-deformed standard on which to hang our cross sections. The Adriatic monocline is our autochthonous foreland and one of the best calibration points on that monocline is the Alessandra 1 well (fig. 1/15) (*). This well permits us to identify a number of important reflectors (e.g., Top Schlier-Bisciaro, Top limestone Scaglia and Top Permian). Very important is the penetration of about 800 m of Upper Permian red clastics with remarkably low velocities of about 3900 km/sec. these clastics are overlain by Juro-Triassic dolomites with

velocities of about 6000 m/sec which thus provide an impedance contrast that is responsible for a reflector that can be followed over large areas of the Adriatic Sea. Fig. 1/16 is a seismic profile located some 30 km to the northwest of the Alessandra 1 well which shows the Permian reflector.

On figs. 1/15 and 1/16, it can also be seen that in the Central Adriatic there occur some very conspicuous reefal buildups. We did not make a detailed seismic stratigraphic analysis of these buildups but we include figs. 1/17 and 1/18 to provide some additional illustrations of carbonate buildups that show a relief in the order of 500-1000 meters. This is less than the reported contrast between the Abruzzi platform and the transition toward the Umbria basinal facies. However, the seismic profiles of the Adriatic sea carbonate platform may, at least in principle, be compared with the Abruzzi-Umbria facies transition.

Some of our rather crude depth conversions suggest that the buildups are located on vaguely defined highs, but we have so far not seen any obvious structural anomalies (e.g., elevated or tilted blocks) associated with the carbonate platforms.

c) FORELAND FOLDS AND FOOTHILLS

We have provided fairly extensive captions for most of our line drawings. Therefore, our comments here will attempt to sum up the key aspects of our documentation.

Figs. 2/19, 2/20, and 2/22 are located in the Riccione-Ancona Adriatic offshore. On all three line drawings, we can see the position of the Cretaceous-Paleogene reefal buildups near the median line of the Adriatic. A prominent reflector corresponds to the top Messinian evaporite bed and/or the basal Pliocene onlap on Miocene and older beds. Note the downlapping lower and middle Pliocene strata that fill up the foredeep moat between the Central Adriatic and the first large overthrust anticlines located in the near-coast offshore. This seismic stratigraphic configuration is typical for the Adriatic as a whole and may serve as a model for many of the earlier foredeep deposits that are now found deformed in the Central Apennines (see fig. 64). The Permian reflector can be traced with reasonable confidence towards the coast on line drawings 2/20 and 2/21.

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(*) The first number refers to the plate and the second to the figure number.

The near-coast offshore structures are interpreted as thrust-faulted anticlines because of their obvious asymmetry and vergence toward the foreland. Underneath the anticlines seismic resolution deteriorates. Note also that onshore Riccione (fig. 2/19) seismic resolution deteriorates and that only synclinoria show reasonable data on regional seismic profiles. Subhorizontal reflectors occur at 4 seconds underneath the syncline that is located to the west of the Tavullia structure. The projection of the well on our section is structurally incorrect and only intended to illustrate stratigraphic calibration in that area.

Figs. 3/24 and 25 are a line drawing and a seismic profile onshore and offshore Porto Recanati. These profiles differ from the preceding profiles. In this segment of the Adriatic, the offshore structures go well beyond the median line. They also have a distinct westward i.e. Dinaride vergence. The seismic data show pre-Messinian convergence on these structures and a distinct eastward thickening of the «Scaglia-Messinian» interval. All this suggests that we are looking at the westernmost outpost of the Dinarides.

We also see on these profiles the reflection seismic expression of the large magnetic anomaly that is observed offshore Mte. Conero (figs. 2/23, 3/24 and 25). Disrupted reflectors and numerous diffractions suggest the presence of an igneous body of post-Messinian and pre-Quaternary age. However, the paleomagnetic depth determination of ARISI ROTA & FICHERA indicates a much deeper (say 5 km) basement structure. Note that the magnetic anomaly (see fig. 8) is remarkably similar to the magnetic anomaly that is related to the Mte. Vulture volcanic complex in Northern Basilicata. Other magnetic anomalies of this type are in the area between Vasto and Campobasso.

Figs. 3/26, 27, 28, and 29 are profiles located onshore and to the west of the preceding profiles, i.e., in the area east of Macerata. Seismic profile fig. 26 and Line drawing fig. 27 is a northwest-southeast longitudinal section which clearly shows the presence of subhorizontal reflectors to about 6 seconds depth. While the top of the Messinian and the Scaglia can be established with reasonable confidence in the upper portion of the section, any of the lower reflections are rather difficult to identify. An important point, however, is the fair coherence of these deep subhorizontal reflectors suggesting continuous subhorizontal sedimentary layers. We will note these same points when we discuss our longitudinal profiles figs. 6/46 to 7/53.

Figs. 3/28-29 were selected to illustrate that occasionally one can observe some obvious décollement levels on seismic profiles. Note the strong diverging Messinian reflector (arrow) indicating an overthrust with northeastern vergence.

Figs. 4/30-31 are line drawings and profiles that are located onshore and offshore Porto Civitanova Marche. Note that overthrusted anticlines display a dominant vergence to the east and only occasional vergence to the west. Proceeding further west towards the Sibillini thrust fault (Borgiano) the deep seismic information is lacking. On the seismic profile itself (fig. 4/31), it can be seen that evidence for the asymmetry of the anticlines (i.e., their vergence) is fair and that reflectors extend to almost 4 seconds permitting their use as «form lines» for structural interpretations.

Figs. 4/32-35 are located onshore and offshore Porto San Giorgio. The offshore structure shown (see fig. 33) has a westward vergence and could also be an asymmetrical diapir. The anticlinal complex in the offshore area contains Sta. Maria a Mare oil field (see PERRODON, 1983). Note the deep mountainward dipping reflectors on the southwest end of the profile. The seismic details on figs. 34 and 35 show deep subhorizontal reflectors. This section ties to the seismic profile that traverses the Sibillini Mountains.

Figs. 4/36 and 37 (onshore and offshore Tortoreto Lido and Roseto) show a number of eastward-verging thrust faulted anticlines. Most of these structures formed in lower to mid-Pliocene times as shown by updip reflection convergence on anticlines. The structure to the southwest of the projected position of Mizar 1 is an evaporitic diapir and a diapiric interpretation could also be adopted for the structure to the east of the projected position of Rigel. Contrast the updip convergence on both sides of the Rigel structure with the convergence limited to the southwest flank of all the remaining structures. Asymmetrical convergence would suggest overthrust-controlled folding with a vergence to the east, whereas symmetrical convergence on both flanks of anticlines is more suggestive of diapirism.

Note that onshore the quality of the data deteriorates but that synclinal areas again permit deep resolution. Note also the deep reflectors in the Villadegna area, which is located in the foreland immediately to the northeast of the Gran Sasso range. A west-vergent overthrust is also displayed west of Villadegna.

To sum up, our seismic profiles across the Adriatic foreland show a Permian reflector in the north Central Adriatic, a Mesozoic and Eocene carbonate sequence with reefal buildups in the Central Adriatic, Oligocene and Miocene sediments of the distal Apennines foredeep that fill in a carbonate topography. A pre-Lower Pliocene unconformity and downlap surface forms the base of the Plio-Pleistocene Adriatic foredeep which, during much of the Pliocene, is filled with turbidites. Finally, shallower prograding sediments of Upper Pliocene and Pleistocene age complete the evolution of the Adriatic foredeep.

Most structures of the Adriatic foreland are thrust-faulted anticlines with a dominant eastern vergence but in some areas offshore Porto Recanati and Porto San Giorgio, we observe a dominant or westerly Dinaride vergence. This implies that in the offshore area, Dinaride and Apenninic vergences interfere with each other. Some diapiric structures occur in the southern half of our area. Data quality typically deteriorates towards the Apennines but we can infer the downdip westward extension of the Adriatic monocline with reasonable confidence towards and beneath the Apennines. There is no evidence of any basement involvement on our seismic profiles. This supports the magnetic interpretations of Arisi Rota & Fichera (1985).

d) Mountains west of the Sibillini-Furlo thrust

If compared with the foreland, sections across the Apennines in general contain less detailed information; on the other hand, they show very significant and ubiquitous subhorizontal reflectors. These are so much more surprising because on the surface the whole area is characterized by intensive folding and thrust faulting. The first group of sections (figs. 5/38-39) mostly relates to our structural cross section 1 (fig. 8/54). On fig. 5/38 (Ur-

bania to Valle di Chiana), we see a few stray subhorizontal reflectors underlying the folds and thrust faults of the Umbria Front Ranges. Further west, persistent subhorizontal reflectors underlie most of the Marnoso-Arenacea outcrops of the region. Note that these outcrops reveal a considerable amount of structural deformation which obviously does not reach deeper than the shallowest group of subhorizontal reflectors. East of Cortona we see a group of subhorizontal reflectors between 5 and 6 seconds which, depending on velocity assumptions, corresponds to between 7 and 8.5 km depth. The stratigraphic age of these flat reflectors is unknown and therefore they can only serve as a form guide for our balanced cross sections.

Also near Cortona we observe a good seismic cross section of the flat Cervarola thrust sheet (figs. 5/39). Note the imbricated nature of the front of that thrust sheet. The reflectors themselves are probably due to an impedance contrast that occurs between the scisti varicolori-nummulitico level and the overlying Falterona sandstones. Note that the Cervarola thrust sheet flattens out at about 3 seconds or perhaps about 4 km depth.

Figs. 5/40-42 are line drawings and seismic details that document our interpretation of the regional cross section 2 (fig. 8/55). A quick inspection of fig. 5/40 shows that there is practically no useful information under the Umbrian Front Ranges in that sector of the Apennines. Contrast this with the much more informative longitudinal section illustrated on figs. 7/48 and 53. Obviously the tightly deformed strata of the Umbria-Marche Front Ranges have a tendency to absorb much of the seismic energy. Of great importance, however, are the subhorizontal reflectors occurring down to 4 and 5 seconds that occur in the Central Apennines. In the area of Gubbio and Perugia, it is possible to pick a reasonable top Scaglia reflector (see fig. 5/41). Depending on our velocity assumption, we feel that the bottom of the flat reflectors is in the order of 10 km deep, a value which is in the same order of the basement modeled by Arisi Rota, & Fichera, 1985 (see also fig. 5).

The Gubbio anticline itself—a wedge bounded by an overthrust to the east and a normal fault to the west—does not show on our seismic profile but some strong «top scaglia» reflectors occur east and west of that

anticline. Unfortunately, it is not possible to determine the geometry of normal faults. Thus, we do not know how «listric» the normal fault may be nor at what depth that fault would flatten. The same comment applies to the normal fault system that occurs on the west side of the Mte. Malbe complex near Perugia. Fig. 5/41 also suggest a westward vergent anticline that occurs at depths east of the Gubbio anticline. The west vergent structure is not directly tied to the more superficial «out of the syncline» shallow west-verging faults described by DeFeyter and Menichetti (1986). Fig. 5/42 Shows deep flat reflectors to the west of Perugia.

Figs. 5/43-45 provide the documentation for our structural profiles 4 and 5 (figs. 8/51 and 52). Fig. 5/43 shows the overall scarcity of reflectors in the Camerino-Assisi transect. Nevertheless, the flat reflectors that are found near 3 seconds east and west of Assisi provide a significant constraint to the construction of structural profiles. In contrast to the preceding section, figs. 6/44-45 provides relatively good information concerning the overall flat nature of the reflectors that underlie the Sibillini overthrust and the mountains to the west. This section ties to fig. 4/32 where in the vicinity of Sarnano we can identify some deep flat Mesozoic reflectors between 4 and 5 seconds. These reflectors can be followed with reasonable continuity all the way into the Foligno area. What is even more remarkable in view of the strongly deformed surface structures, that flat reflectors come in already at depths of less than 1 kilometer below the surface. We must ask ourselves whether these shallow reflectors are spurious or genuine. Certainly, additional detailed interpretations of the surface geology will try to resolve this problem. The seismic data (fig. 6/45) illustrate some of the details of the seismic profiles in that area and document particularly well the continuity of the flat reflectors underlying the Sibillini thrust.

e) LONGITUDINAL PROFILES

In our area, we were generally impressed by the good quality of our longitudinal seismic profiles. This is probably due to the fact that most of these strike profiles are located along the axis of broad synclinoria of the Marnoso-Arenacea formation, which appear to provide a better medium for the propagation of seismic waves.

Figs. 6/44 and 45 is a line drawing and a seismic profile along the axis of a synclinorium that extends behind the Sibillini front from south of Camerino towards and past Matelica. Fig. 6/44 is the basis for our eastern longitudinal regional section 8 (fig. 9/61). Note the flat reflectors that extend down to 4 seconds. The top of the Scaglia in easily projected from the surface on the profile and corresponds to the strong reflectors seen on fig. 6/45. Also on fig. 6/45, we indicated with some broad bars the location of some of the transversal faults that are indicated on the Carta Strutturale dell'Appennino Settentrionale (BOCCALETTI & COLI, 1982; see also BOCCALETTI et alii, 1977; 1982). It should be noted that none of these transversal trends disrupt the underlying reflector in any significant manner. This suggests to us that at least in this area the importance of recent transversal tectonics has been overrated. Figs. 6/44 and 6/45 strongly support the lateral continuity of the thrust sheets shown on our cross sections, a theme which is further documented by figs. 6/46 and 47, a longitudinal northwest-southeast striking profile that goes from the region of Sansepolcro to the region east of Mte. Subasio near Assisi. Here again we observe continuous flat reflectors to about 4 seconds or depending on velocity assumptions to about 10 km. We can pick the «top Scaglia» reflector with reasonable confidence but are unable to identify specifically any of the lower stratigraphic reflectors. Fig. 6/47 shows an example of the seismic detail in that area.

Figs. 7/48 and 49 is yet another longitudinal profile that is located to the northeast of Gubbio and shows the same flat reflectors which we have observed on the other profiles.

Perhaps the best evidence for deep seismic reflectors west of a strike section that is located southwest of Sta. Maria Tiberina (fig. 6/47). This profile shows abundant coherent flat reflectors down to about 5 seconds or 11-12 km, depending on velocity assumptions. The flat nature and continuity of these reflectors is confirmed by crossing dip-lines. This further supports the interpretation of the magnetic data (ARISI ROTA & FICHERA, 1985).

It may be concluded from our seismic documentation in the Umbria-Marche Apen-

nines that deep subhorizontal reflectors are ubiquitous and that any structural interpretation of this region is constrained by these data.

COMMENTS REGARDING THE PROCEDURES INVOLVED IN THE PREPARATION OF BALANCED CROSS SECTIONS

A series of regional geological cross sections (see Index map, fig. 9) was constructed with the aid of logs from a number of key wells, tabulated well velocities (see fig. 12), and regional seismic profiles.

Of particular use was a set of regional geological surface sections put together by R. GHELARDONI and his colleagues prior to our study. GHELARDONI'S profiles were in a sense more factual because they more carefully recorded local details and stratigraphic thicknesses. In attempting to draw balanced cross sections at the 1:100,000 scale, we were often compelled to disregard potentially important local detail. Also we strived to maintain reasonably persistent stratigraphic thicknesses that in some cases ignore local variations that may be real or else, due to structural complications.

Our cross sections are speculative, because they attempt to resolve the deep regional geology with the intent of providing a generic frame of reference. With time and additional seismic surveys and drilling, our sections will need to be redrawn. Consequently, our sections form only a working hypothesis or a first step in what no doubt will remain an arduous and costly learning process.

Typically, in the construction of our sections, we followed a sequence of steps that will be described in the following pages. The line drawing was manually depth-converted. The first step in the interpretation of regional seismic profiles and the calibration of reflectors was discussed in the preceding chapter. We used either velocities from nearby wells or else the more general velocities listed on fig. 12. The use of typical velocities for certain intervals provides a degree of consistency but may also constitute a major source of error. Note that the velocity spread for single formations on fig. 12 is rather large. The spread in velocities is no doubt related to changes in lithology and to the burial history of various formations. It would seem to be desirable to make a more systematic study of velocity-lithology relations in our area, which would involve the close collaboration of stratigraphers with geophysicists.

Even though we realize that our velocity assumptions cause a significant local source of error we do not believe that more accurate velocities will change our overall structural interpretation. Later in this paper, we will come back to this point.

For the depth-conversion, we used only key horizons in the relatively good data areas of the Adriatic foreland, but in poor data areas of the Apennines we tended to convert single but stratigraphically unidentifiable prominent reflectors to their estimated depth. The depth-converted features were directly transferred and projected on the regional cross section. The projection introduced another source of error because we had little choice but to project along regional surface strike.

Without the benefit of subsurface structural maps in the area of intensive seismic coverage it is often risky to be limited to simple strike projections. Our experience in a number of other folded belts suggest that the surface and subsurface strike may differ substantially if one is dealing with multiple décollement levels (BALLY et alii, 1966; BALLY et alii, 1985). At this time it should be noted that this problem of discordant relationships may turn out to be a major pitfall in the subsurface interpretation of seismic profiles.

Balanced cross sections are attempts to find an internally consistent structural solution which charts a path that respects as many of the seismic, surface, and subsurface data as possible. The weaker the data base, the more uncertain the interpretation! In the following, we briefly discuss a number of the underlying assumptions. The papers by DAHLSTROM (1969; 1970) outline the essential thoughts quite well. A large and more modern literature that is heavily burdened by jargon (i.e., BOYER & ELIOTT, 1982; SUPPE, 1983; 1985) refines the essentials outlined by DAHLSTROM. It should also be noted that much of the modern academic literature is «idealistic» to the extent that most of the time the seismic data base is insufficient to warrant the theoretically required high precision. On the other hand, surface data are rarely sufficient to predict deep structure.

The primary reason that led to develo-

ping the basic balanced cross section methodology in Canada (BALLY *et alii*, 1966; DAHLSTROM, 1969) was simply that reflection seismic profiles revealed a basal mappable décollement level below which no significant deformation occurred. Consequently, assuming flexural slip folding (i.e., parallel folding) as an added premise, it was thought reasonable to offer internally consistent cross sections and combine them with a fairly precise quantitative reconstruction of the strata prior to their deformation.

In the Apennines, however, the seismic profiles simply do not permit to recognize a «basement», or else a near-basement reflector, below which no structural deformation occurs. Because of this difficulty, our regional cross sections show a «putative basement» which is essentially a line below which no décollement is expected and which extrapolates the Adriatic foreland monocline to the west and beneath the Apennines. In other words, our «putative basement» is conceptual.

Flexural slip is certainly the dominant deformational style in the Apennines, but the state of mapping (with the exception of three 1:50,000 sheets) today does not permit to adequately reconcile the details of the surface geology with subsurface interpretations on a scale of 1:100,000. In other words, our schematic structural cross sections, albeit balanced, are no more than the naked mannequin of the fashion designer, and the visible surface geology is more like the clothing that dresses that mannequin.

Theoretically, levels of detachment can be calculated in various manners. These calculations are difficult to apply to the Apennines because there is considerable difficulty to obtain reliable thickness information for most formations. This is particularly true for the Jurassic where the thickness distribution is controlled by geometrically ill-defined extensional tectonics, and for the Triassic Burano evaporites for which we simply do not have any reliable thickness estimate.

A first set of rules for balanced cross sections is that the thrust always cut up sections in the direction of transport. Many conventional sections across folded belts unfortunately ignore this rule! Also it is expected that thrust faults thrust older over younger strata, and often appear to thicken stratigraphic intervals. Reasonable exceptions do occur under circumstances that in most cases involve either a marked deviation from flexural slip folding or early extensional tectonics.

Consistency of displacement is another cardinal requirement for balanced cross sections. There are however a number of situations where apparent disparities in displacement can be attributed to special circumstances. Note also that this requirement is, strictly speaking, only applicable for the case that the line of section coincides quite accurately with the path of transport of the displaced unit. Because the path of transport can be established only after detailed structural analysis, the consistency of displacement rule has merely the function of providing a «discipline» that prevents the geologists from being excessively arbitrary with regard to displacements. In our cross sections, we have generally respected the rule but in few cases the rule may have been violated for simple drafting convenience.

Another rule insists on the conservation of volume. It assumes that sedimentary volume is not significantly decreased or increased by the deformation. Recently a number of papers (ALVAREZ *et alii*, 1976; 1978) have emphasized the importance of solution cleavage particularly in the Apennines, justly indicating that the conservation of volume premise is not strictly applicable to our area. Note that ignoring the effect of solution cleavage will lead to more conservative amounts of shortening. Therefore solution cleavage, and most other macrotectonic features seen in outcrops in the Apennines, tend to increase the amount of shortening suggested by our cross sections by a substantial amount. In our first approach to the area, we choose to ignore these problems, because we have no way to evaluate whether the outcrop observations on deformed anticlines also apply to the long flat segments shown on our cross sections.

While it is desirable to achieve perfect volumetric balance, in view of the scale of our sections and the general weakness of the data base, we are at this time satisfied with simple length measurements on a number of key horizons on our sections.

Axial or downplunge projections are often desirable in folded belts, but it is felt that in the Central Apennines the concept has only limited applicability. Frequent en echelon transfer systems in the Apennines prevent

the extensive use of such projections. Regional culminations and depressions are rare. But above all seismic longitudinal profiles (see fig. 6/46-7/53), contrary to the experience in the Rocky Mountains, do not confirm that axial culminations and depressions can easily be projected at depth (see Longitudinal Sections plate 61 and 62). This is probably because much of the thrust-faulting is «guided» by the seismically poorly mappable Jurassic extensional systems.

Much ink has been spilled on the relative progression of deformation in folded belts. The consensus is that the deformation proceeds from the inside to the outside of the foldbelt and from top to bottom (see discussion in BALLY et alii, 1966; 1985; DAHLSTROM, 1969; 1970). Although local reversals of this general progression have often been postulated, there has in our judgment never been conclusive proof of such reversals. In the Apennines we postulate a similar kinematic progression.

Finally a few words about structural style. It has been known for years that different foreland belts have different structural styles. A more modern perspective suggests that most of the foreland fold belts are underlain by gently sloping basement monoclines, and that the style differences are basically due to the ductility contrasts within the sedimentary sequence or in simple words the style is controlled by the number and thickness of the incompetent layers.

There are also stylistic differences between authors. While our sections show curved folds and are generally devoid of angular bends, it can easily be seen that authors like LAUBSCHER (1978; 1979) and SUPPE (1980a,b; 1985) use different techniques. The LAUBSCHER-SUPPE technique is characterized by its «cubistic» aspects which is based on the frequently observed box-like nature of the folds, i.e., they attribute, with considerable justification, a major role to kink-folding. The technique is quite applicable to areas where we have a lot of systematic dip and dipmeter control. The technique becomes more artificial in areas where that control is not available and where the seismic reflection profiles do not show the postulated angular features and corresponding diffraction patterns. It is, however, our feeling that SUPPE'S methodology is quite applicable to surface structures in the Apennines and sy-

stematic application of these techniques would improve our cross sections.

In conclusion of our comments on balanced cross sections, the following quote (from course notes by M. JACKSON) sums up the philosophy we like to follow: «A cross section that is balanced is not necessarily correct, but one that is not balanced is invariably wrong unless a valid explanation is provided in the cross section. Structural balancing not only produces a more accurate cross section but it also tests ideas that we build into the cross section. However, we must be aware of the limitation to balancing».

DISCUSSION OF CROSS SECTIONS

a) INTRODUCTION

The seven cross sections and the two longitudinal sections that form the main part of this project are self-explanatory. They are all balanced according to the principles summed up earlier. Specific comments and uncertainties are listed on the cross sections themselves. These are best discussed in separate groups, i.e.:

Sections 1-3 located north of the Esino Valley;

Sections 4-5 located between the Esino and Aso Valleys;

Sections 6-7 located south of Aso Valley;

Two longitudinal sections.

b) CROSS SECTIONS 1, 2 AND 3

Section 1 (Amedea-Terontola-Mte. Amiata) - Fig. 8/54.

Section 2 (Anna-Burano-Perugia-Mte. Amiata) - Fig. 8/55.

Section 3 (Alessandra-Esino-Deruta-Orvieto) - Fig. 8/56.

We use Section 2 (plate 5) as a general guide to make some key points.

In the offshore near the Median line we observe a large reefal buildup of Jurassic-Lower Cretaceous age. Note that the reefal platform is also well shown on Section 3 (Alessandra-Judith wells).

Moving further west towards the Adriatic coast there are a number of structures that involve the Jurassic-Cretaceous carbo-

nate sequence. These structures do not show significant décollement along the Burano evaporites and the Alessandra well suggests that the Burano may not be present in the form of evaporites in that area of the Adriatic.

The next family of structures is located in the Adriatic foreland, that is the area between the coast and the first Mesozoic outcrops. On all three sections, we see the gradual involvement of the Burano formation, e.g., at Canopo, Cartoceto and Esino wells. The seismic profiles that cross some of these structures are reasonably good but it should be pointed out that neither the wells nor the seismic data give a strong indication of the small scale polyphase folding that is so spectacularly displayed in a number of Mesozoic anticlines that outcrop in the adjacent Apennines.

Further to the west but still in front of the main Umbrian thrust, there is a row of complex structures that extends from the outcropping Fossombrone anticline with its northern plunge continuation, as well as the Mte. Acuto anticline west of Cingoli. On our three cross sections the trend is deliberately interpreted in three different ways, to show some of the problems and opportunities associated with this structural trend.

Section (1, fig. 8/54) shows a pronounced domal duplex structure underlying the surface anticline. So far, the deep structure is not yet mappable. Note that on Section (1), the Messiniano that was sheared off the top of the underlying anticline is accumulated as pile of imbricates that extends from Montemaggiore al Metauro towards San Marino. Section (2, fig. 8/55) proposes quite a different interpretation involving east-dipping faults overthrusting the southern projection of the Cartoceto structure. There are some east-dipping faults suggested on the surface map, and MARABINI & VAI (1985) have made a detailed study of a similar area farther north in the Vena del Gesso area in the Santerno Valley.

The theme of east-dipping thrust faults will be discussed farther below, under a special heading, however a third alternative interpretation of the Fossombrone trend and its southern continuation is displayed in Section (3, fig. 8/56), that suggests the existence of sizeable pre-Mid-Pliocene unconformities that would allow erosion of very significant

volumes of Miocene and lower Pliocene sediments.

The Fossombrone trend extends to the south to include the Aquasanta-Montagna dei Fiori structures and their structural extension. We visualize similar alternative interpretations along the trend and the solution of these will have to await more detailed studies, which will only be fruitful if accompanied by detailed 1:25,000 scale mapping, and by a careful study of the intra-Pliocene stratigraphy and its unconformities. The trend of frontal Mesozoic folds in many areas yields poor seismic data.

Moving further west from the Fossombrone anticline, we cross the main Umbrian fold belt, which is dominated by an outer anticlinorium that extends all the way from the Sibillini Mtns. to the Furlo area, and by a more interior anticlinorium, that includes the Mte. Cucco-Mte. Catria-Piobbico complex. These two trends and the intervening synclinorium may well be a surface structural geologist's delight but are definitely a geophysicist's nightmare. The few seismic transects yield hardly any useful information, which may well be due to the complex surface conditions that characterize the area. As shown on our cross section, the area shows relatively little duplication by thrusting. At least in the three sections discussed here, the structural appearance is shingle-like and even allowing for changes along strike, there is geologically a much lower probability of a significant repetition of the Mesozoic. Contrast this with the continuation of this structural trend further south where all sections (figs. 9/58-60) show significantly increased displacements, leaving a reasonably coherent lower thrust sheet below.

West of the Burano anticline is an area that on the surface is mostly underlain by fair to strongly deformed Marnoso-Arenacea beds. The reflection seismic profiles in that area have been part of a detailed survey by AGIP. The key characteristics of the area are widespread gentle dips for the underlying Mesozoic which in turn are underlain by significant subhorizontal dips that in that region extend to over 9 km depth. The seismic data have not yet been calibrated by a well. The anticline east of Gubbio which is bounded by a thrust fault to the east and a normal fault to the west provides a window to the stratigraphy of this area. The Gubbio

anticline of course is well known for all the studies that have been dedicated to the Scaglia and for the precise position of the Cretaceous Eocene boundary and its Iridium-rich shales that, according to some, indicated the effect of a meteorite impact which had deadly consequences for many dinosaurs!

Our interpretation allows for a structurally duplicated sequence to the east and to the west of Gubbio.

The reader is urged to place the structures in the wider Gubbio area in a palinspastic context to realize how far away and apart the nearest well control is. In folded belts, it is always most important to realize that the present day stratigraphic control is badly distorted by telescoping due to thrusting and that therefore, stratigraphic reconstructions cannot be easily carried out if the control points are so widely separated.

West of the flat lying area, we enter into the Mte. Malbe-Mte. Acuto complex located to the north of Perugia. There is little doubt that this feature consists, in essence, of a repetition of anhydrites and Verrucano that may be sliced into at least three superposed thrust sheets. Note also that on our section we greatly simplified the structure of Mte. Malbe and the adjacent Mesozoic outcrops of the Mte. Acuto area. It is not possible to adequately depict what these structures are on the scale of our section. Note that MINELLI (1968) shows a more complete interpretation of the Mte. Tezio-Mte. Acuto area. We have some doubts the normal faults in that area dip to the east. However, we would like to reemphasize that the Mte. Malbe structure is probably severely affected by diapirism and/or dissolution of the Triassic evaporites. This is perhaps the reason why it is so difficult to find an undisturbed stratigraphic sequence in that area.

Finally, to the west of Mte. Malbe it should be noted, as is shown in Sections (fig. 8/54) and (fig. 8/55), the Cervarola unit is shown to be a subhorizontal, but completely imbricated thrust sheet, an interpretation that is based on the reflection seismic data (fig. 5/42 and 5/38 and 39). Underlying the Cervarola unit the seismic data are not all that good but generally suggest a relatively flat sequence of beds. We therefore conclude that the Umbrian region extends well under the Mte. Cetona area and possibly further

west. Again, note the wide extent of unknown territory!

We did not spend sufficient time to justify elaborating detailed sections across the Toscana. We therefore limit ourselves to show three very crude alternatives on figures 54 and 55 and also on fig. 59. In the Toscana our sections merely intend to suggest that palinspastically, the Toscana units fall well beyond the present center of the Tyrrhenian Sea.

c) CROSS SECTIONS 4 AND 5

Section 4 (Conrad-Civitanova-Camerino-Foligno) - Fig. 8/57.

Section 5 (Offshore Porto San Giorgio-Sarnano-West of Spoleto) - Fig. 9/58.

The following description is tied to Section 5 (fig. 9/58), largely because this profile happens to coincide with a regional seismic profile that has much better seismic data under the frontal units of the Apennines than we can see on most other profiles. A first glance gives the impression that particularly Section 5 shows a much increased amount of shortening if compared with profiles further north. Section 5 appears to show the transition between the northern and the southern sections (fig. 9/59 and 60).

In the offshore area, there is relatively little deformation and with the exception of one major structure, the Triassic Burano formation does not appear to be involved in the deformation. In Section 4, the vergence is toward the east like in most segments of the northern Adriatic. However, on Section 5 we interpreted a western «Dinarides» vergence for the structures in that area. The unusual vergence of that zone is only poorly documented but also seen on other seismic profiles (fig. 3/24-25; fig. 4/33-34).

A pronounced Pliocene synclinorium east of the Loro Piceno-Mogliano trend should be studied in more detail in an attempt to date the progression of the deformation in that area. The Loro Piceno-Mogliano trend is the approximate extension of the Montagna dei Fiori structural trend to the south. The two flat thrust sheets which are positioned in front and below the main overthrust of the Sibillini are mainly responsible for the apparent overall increase in shortening going toward the south. The subhorizontal nature of

these sheets is supported by the numerous relatively flat to gently westward dipping reflectors that are observed on the seismic traverse across the Sibillini Mtns. While the specific ages of the formations that are involved in the flat thrust sheets is not established, we favor an interpretation involving two large thrusts sheets. Here again, like at Fossombrone, we are dealing with a trend that is located in front of the mountains.

Further west we are in the area of the main outcropping structures of the Umbrian folded belt. Like on our northern sections, the main Umbrian unit has a most intriguing and complex structural geology at the surface. The unit is bounded to the east by the outcropping leading edge of the Terminillo-Sibillini-Fiastrone-Mte. Confaito thrust sheet, and on the west by the Mte. Catria-Mte. Cucco-Mte. Maggio-Trevi arc. Within these units we can observe décollement tectonics in excruciating detail at the surface. BARCHI & LAVECCHIA (1986) and BARCHI et alii (in print) have carefully balanced a surface section across the Sibillini Mountains. COOPER & BURBI (1987, this issue) show detailed field cross sections for the Sibillini front. From these sections, it can easily be inferred that flat dips may be expected in the shallow subsurface - as confirmed by our seismic profile. Our sections indicate that most structures are breached into the Jurassic and lower formations and that near-surface seismic mappability with the exception of northern Sibillini transect is rather poor.

To the west under the plain of Foligno, our section is poorly controlled by our reflection seismic data. The section was drawn in analogy to the flat lying areas in the vicinity of Gubbio. Note that like on our northern sections, the Verrucano is shown to be involved in the thrust sheets, and forms the dominant formation of the anticlinal trend that extends from Monte Martano west of Spoleto to the Mte. Malbe area near Perugia.

d) CROSS SECTIONS 6 AND 7

Section 6 (Mizar-Tortoreto-Mgn. dei Fiori-Terni) - Fig. 9/59.
Section 7 (Rigel-Villadegna-Antrodoco-Mte. Soratte) - Fig. 9/60.

The two southernmost sections of our set of sections again show a substantial increase in overall displacement. Section 7 also extends in what conventionally is called the Abruzzi platform province.

In the Adriatic offshore to the east, we see east-verging structures that emphasize that the western vergence implied in Section 5 is an exception in this segment of the Adriatic. Most structures in the offshore seem to involve the evaporitic Burano formation and a number of them are clearly diapiric in nature (e.g., Mizar, and the most easterly structure on Section 6). The diapiric growth of some of these structures is evident but we lack detail to come up with a cohesive picture. There appears to be considerable evidence for diapiric growth during the Mesozoic as suggested by convergence patterns on anticlines of reflection profiles. (Note that some of these patterns are not easily separated from multiples!) However, the seismic profiles also show compressional tectonics which must have occurred during the Pliocene and may be superposed on earlier diapiric patterns.

On land, we can observe a regional synclinorium that is flanked by the Tortoreto trend on the one side and the Villadegna trend on the other. Much of the syncline is filled with lower Pliocene sediments, which among others offered significant reservoirs for the Cellino field (CASNEDI et alii, 1976; CASNEDI, 1983; 1986). Our regional lines were not adequate to make a detailed study of the structures that flank this synclinorium.

An important structure in the Villadegna area has been tested by the well. Note on our Section 7 (fig. 9/60), a pronounced set of east-dipping faults that is associated with that structure. These faults are postulated on the base of east-dipping reflectors that can be seen on our seismic profiles (fig. 4/37). Here again more detailed surface mapping will eventually have to complement the structural interpretation presented on our section.

The next structural complex is the Cima Alta ridge, which in effect is the strike continuation of the Montagna dei Fiori. Detailed structural mapping of the Vomano anticlinorium and seismic data will be needed for a more complete understanding of the area.

Overlying the Montagna dei Fiori trend is the Acquasanta trend which aside from its culmination near Acquasanta could well have separate culminations elsewhere in the region. Our interpretation is based on little

data and basically inspired by the notion of a westward dipping «basement» and the seismic evidence from the Sibillini profile. On the surface map there is little evidence for the southern continuation of the Acquasanta unit, but we feel the surface map in this area may be quite inadequate and that normal faulting may not have been adequately evaluated. Simple space considerations are compelling us to assume the presence of the Acquasanta sheet on our southernmost section.

The Mte. Giano-Mte. Gelato unit on our southernmost section and its western continuation on the down-dropped side of the Antrodoco normal fault is in effect the allochthonous Abruzzi platform. Its tectonic style is dominated by extensive post-compressional or «neotectonic» normal faulting. While the occurrence of normal faulting in the area is obvious, there are numerous questions left regarding the scope of normal faulting. Note that the Mte. Giano unit probably has a northeasterly path of transport and the overall shortening as measured on our section has little meaning because significant parts of our cross section arrived at their position from a position located some distance to the south of our line of section. We assume that we are dealing with sets of listric normal faults, as suggested by the rotation of the beds into the fault plane. A key problem remains the depth at which the normal faults shallow out. Two options are shown on section 7 (fig. 9/60). In the Mte. Giano Unit the normal faults are shown to be limited to the surface sheets and we presume that they will merge with the underlying pre-existing thrust fault. The other alternative is shown by the Antrodoco fault system, which is shown to merge into the regional basal décollement system and to offset a number of pre-existing thrust sheets. The deep closure on the profile is strictly «neotectonic» in origin.

The Antrodoco area itself is structurally most complex. The Antrodoco well is a monument to bold forward-looking exploration carried out a long time ago, but unfortunately the well was an economic failure! On the other hand, the information gained was very valuable. We still have difficulties to explain the unusually thick Burano formation in the wells. Also the relationship of thrust-faulting to normal faulting in the area

is not clear and finally the details of structural styles on either side of the «Ancona-Anzio» line are quite obscure. Mapping on a 1:10,000 scale would be very important in this area.

Section 7 clearly shows the main Umbrian overthrust. The term and the concept of the «Ancona-Anzio» line was most unfortunate if indeed we are simply dealing with a lateral ramp of the Umbria (Sibillini) thrust sheet. Our cross section shows this thrust sheet to be merging in the regional basal décollement in the region north of Rome. Note, however, that our line of section probably is also at an oblique angle to the path of transport of the Sibillini thrust sheet.

e) LONGITUDINAL SECTIONS

Eastern longitudinal section (Burano-Camerino 7-Retrosi) - Plate 8.
Western longitudinal section (Uselle-Varoni) - Plate 9.

Ideally, a set of balanced cross sections ought to be correlated with a set of longitudinal sections, that will serve as a check for internal consistency. In the Apennines the case for longitudinal sections is further strengthened by the existence of a fair number of reasonable quality reflection seismic profiles that parallel our longitudinal sections. As one would expect these profiles exhibit mostly flat reflectors and occasionally some converging reflectors which may be interpreted as lateral ramps of thrust sheets. We have projected the approximate depth converted position of these reflectors on our longitudinal sections.

The main difficulty in combining longitudinal sections with *balanced* cross sections is that any significant mistake leads to re-balancing all other sections. It is most unlikely that a set of balanced cross sections will tie with a longitudinal section in the first attempt. The reason for this is that the overall correlation of major structural trends is not clear until after the cross sections are drawn and balanced. On the other hand, for internal consistency, both cross sections and longitudinal sections should have most major structural units correlated.

Re-balancing all sections is a time-consuming iteration process and at this time our longitudinal profiles serve mainly to point

out major problems and inconsistencies. Also, we feel that re-drawing our balanced cross sections would be premature, because the correlation of major structural trends would be greatly aided by the existence of a new tectonic map that depicts both surface and subsurface structural trends.

Our eastern longitudinal section (fig. 9/ 61) is supported by the seismic reflection profile shown on figs. 6/46 and 47. As expected, the section shows up a number of inconsistencies. Note that the Acquasanta sheet (top sheet on the right side) extends well to the north northwest on this section while the same thrust sheet is far more limited on the western longitudinal section, suggesting to us another discrepancy.

The western longitudinal section (plate 9) appears to have greater consistency, but this is only because there is greater flexibility in interpretation. Note that on both longitudinal sections we left out all normal faults that are shown on the cross section. This permits an easier overview over the correlation of various units. It is quite conceivable that the above—mentioned inconsistent extent of the Acquasanta unit can be resolved by extending that sheet toward the intersection with profile 2. This would require re-balancing a number of cross sections.

To avoid giving the wrong impression, the above-mentioned consistency problems are quite common, which is probably the main reason why there is only one published longitudinal cross section across a folded belt that is also consistent with a number of balanced sections (BALLY et alii, 1966). To be sure, we are dealing here with second order problems that in no way invalidate the significant features of our balanced cross sections.

COMMENTS ON EAST-DIPPING FAULTS («BACKTHRUSTS»)

Some comments on east-dipping faults in the Apennines are in order. Since the early foothills exploration days in the Canadian Rocky Mountains, geologists have become aware of so-called «triangle» zones, i.e. zones that were characterized by opposite anticlinal dips at the surface and gently mountainward dipping reflections in the subsurface. The problem has been reviewed by JONES (1982) and BALLY et alii (1985). MARABINI & VAI (1985) have provided the detailed

documentation of a similar situation in the Vena del Gesso area and on our sections, similar interpretations have been tentatively adopted in a few zones in the Apennine foreland.

We suggest that in the Apennines and the Adriatic foreland, a number of situations would generate west-vergent (i.e. east dipping) faults, as follows:

Thrust faults belonging to the Dinaride system. These probably only occur in the Adriatic Sea and may be recognized by their association with eastward increasing foredeep thicknesses.

East-dipping out-of-the-syncline faults which are common flexural slip accommodations (DE FEYTER et alii, 1986; DE FEYTER & MENICHETTI, 1986) limited to the extent of the synclines. This type would include «fishtail» faults of the type described by DRODZDEWSKI et alii, 1980.

East-dipping faults in the cores of anticlines that are simple conjugates related to a general west-dipping thrust fault system.

East-dipping fault systems of the type discussed by JONES (1982). These would be due to a regional wedging of the thrust belt into the foreland.

The general experience here is that it is sometimes quite difficult to differentiate thrust faults with a mountainward vergence from onlap unconformities. The best confirmation can often be otained from seismic reflection profiles. As suggested by some of our sections, we suspect that this situation may occur on the Pesaro sheet of the geologic map of Italy and in the Villadegna area.

On the other hand, we feel that the extent of «backthrusting» postulated by CALAMITA (1986) and CALAMITA & DEIANA (1986) is probably quite exaggerated and certainly not adequately documented. We conclude therefore that east-dipping thrusts certainly occur in the Apennines, but that the time is ripe to provide a better surface geologic and seismic documentation of this phenomenon before too much significance is attached to it.

SOME CONCLUSIONS AND REGIONAL CONSIDERATIONS

In the following, we first list some of the more important conclusions that we can de-

rive from our balanced cross sections, then we will place these conclusions within the context of the structural evolution of the Central Apennines, and finally we will compare and contrast the Central Apennines with some aspects of other folded belts.

a) CONCLUSIONS

Our most important conclusions are:

1) The front of the Apennine overthrust occurs some 20-30 km to the west of the Adriatic median line. In the offshore Adriatic foreland, the continuity of the eastward verging Apennine front is occasionally disrupted by segments that show a distinct westerly or «dinaride» vergence. Such segments are particularly prominent offshore Mte. Conero and offshore Porto San Giorgio.

2) Magnetic data and our reflection profiles indicate that a magnetic Paleozoic (or Precambrian) basement is *not* involved in the structures of the Umbria-Marche Apennines and its Adriatic foreland. Thus, there is no evidence for a high autochthonous or parautochthonous basement as previously suggested for the Northern Apennines by KLIGFIELD (1979) and REUTTER et alii (1983, or more recently, for central Umbria by BOCCALETTI & COLI (1983) and LAVECCHIA et alii (1984a). Frequent deep and flat reflectors are seen both in the foreland and in the Central Apennines. These deep reflectors cannot be specifically identified but they provide significant geometrical constraints for our cross sections. Based on well penetrations, and the balancing of cross sections, these reflectors correspond mainly to flat-lying repetitions of Mesozoic sediments. In the Central Apennines, deep reflectors can be seen to depths exceeding 5 seconds.

3) Surface geology displays numerous decoupling levels (e.g., Messiniano, Schlier, Scaglia Cinerea, Scisti a Fucoidi, Maiolica and Ammonitico Rosso). Unfortunately, our seismic does not permit us to recognize these obvious décollement levels.

The scale of our cross sections, originally drawn at a 1:100,000 scale, also does not permit us to show the important details that can be seen on the surface. More important, however, our balanced cross sections fully support the suggestion made by many previous workers (e.g., fig. 3a, 4a, and 4b) that the most important décollement horizon in the Apennines is the anhydritic Burano formation. Towards the west, the basal décollement surface deepens. Thus, near Perugia and probably also west of Spoleto, the Triassic Verrucano formation is involved in the thrust sheets. To complete the picture, we note that in the Toscana, the metamorphic Paleozoic basement is involved to form the core of the lower metamorphic Tuscan thrust sheets as suggested by KLIGFIELD (1979), ARISI ROTA & FICHERA (1985), and BATINI et alii (1983; 1984; 1986).

4) The basal décollement level, i.e., the level below which no décollement structures occur, is at about 5 km depth beneath the Adriatic Sea and it deepens towards the west to 12-14 km in the area west of Perugia.

5) Our longitudinal sections indicate that the Olevano-Antrodoco-Posta line (formerly Anzio-Ancona) is best explained as the lateral ramp of the Sibillini-Umbria thrust sheet. This had already been shown by SCARSELLA on the Norcia sheet (Servizio Geol. d'Italia, 1942). Also on our longitudinal section, we find that the base of the Sibillini thrust merged with the regional décollement levels which is interpreted to occur at depths between 12-14 km in the Val Tiberina near Città di Castello.

6) A number of different types of east-dipping thrusts («backthrusts») occur in our area but we feel that more surface geologic and seismic documentation will be required before giving this phenomenon much significance.

7) Normal faulting increases towards the south. At this time, we have difficulty establishing the listric nature of normal faults on our seismic profiles, even though at least in one case we feel that we have established that a normal fault merges into a thrust fault in the outcrops of the Forca di Presta area. Nevertheless, by analogy to other areas, e.g., western U.S. Basin and Range, we suspect that most normal faults in the area are listric.

8) A check on the internal consistency of our balanced cross sections is the palinspastic restoration of major structural units. Figure 63 gives the restored position of some key elements and also offers an approximate idea of the amounts of shortening in the Central Apennines.
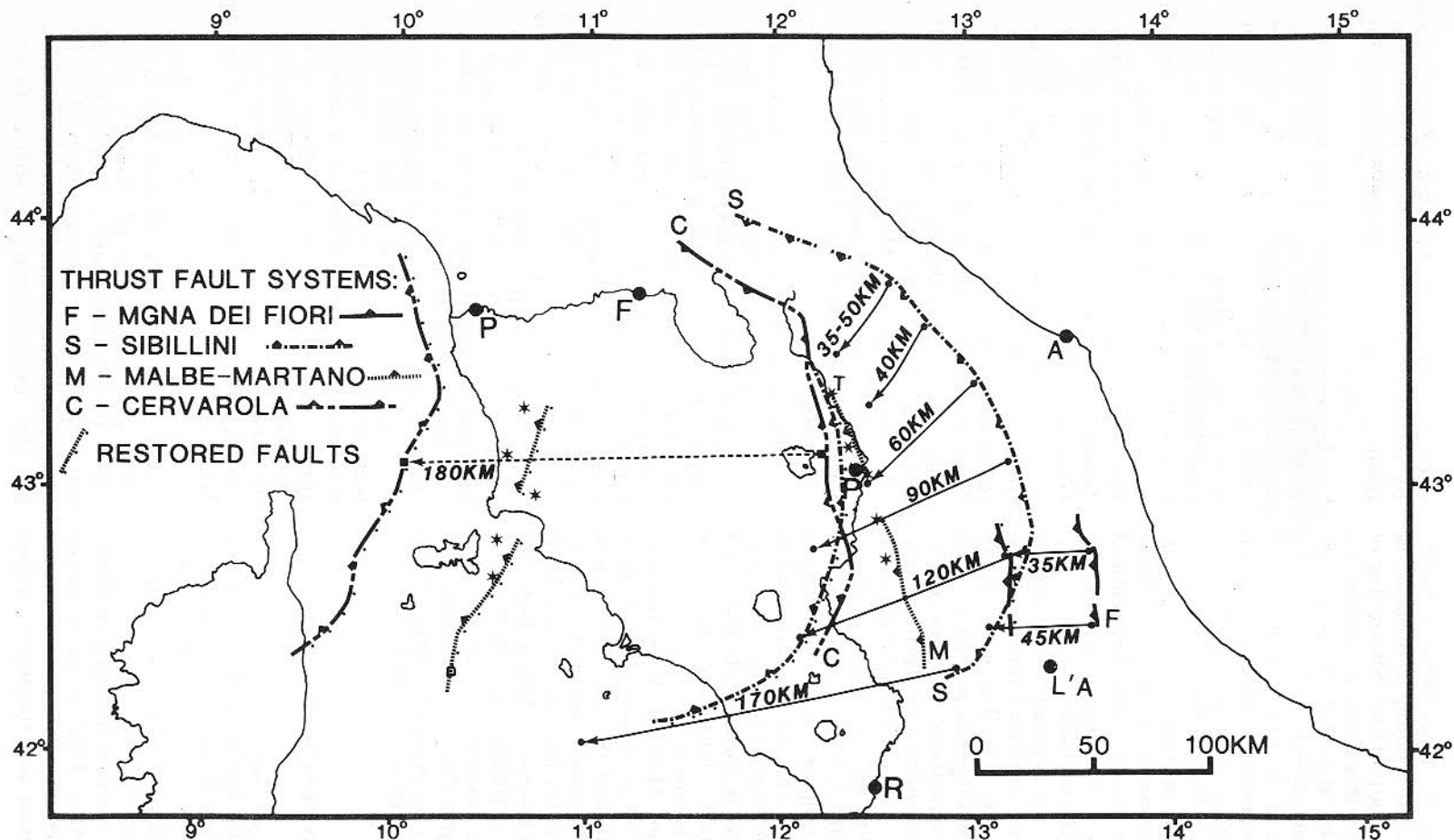
Fig. 63 - Reconstructed position of major thrust faults: Dots and arrows indicate amounts of shortening of Sibillini thrust sheet. Note the approximate coincidence of the reconstructed Sibillini thrust front with present Cervarola thrust front. This could reflect a significant regional pre-Burano basement ramp in the area underlying the Cervarola front. Stars show the present and reconstructed position of the Mte. Malbe-Monte Martano unit. Cervarola frontal thrust reconstructs in the area of the northern Tyrrhenian sea and suggests the Cervarola Basin was formed prior to the rotation of Corsica.

The Montagna dei Fiori thrust complex indicates an overall shortening in the order of 35 to 45 km (say about 40 km). Shortening of the Sibillini thrust sheet and its subsurface continuation in the Mte. della Cesana complex increases from about 35-50 km in the Sassocorvaro area of Section 1 to about 120 km in the Sibillini area of sections 5 and 6. On section 7, even after allowing for the Mte. Giano Unit coming from out of the plane of our cross section, we still end up with an estimate of about 170 km of the Sibillini thrust sheet. We feel this amount should be reduced to about 140 km to be consistent with the more northerly cross sections.

9) Note that the southernly increasing shortening of the Sibillini-Umbria thrust sheets reflect the well-known counterclockwise rotation that has previously been proposed by paleomagnetic workers (CHANNEL et alii, 1978) as evidence for Tertiary rotational décollement. The southward increase in shortening is tied to the development of several duplex-type structural complexes; (a) the Roccafinadamo complex. (b) the Montagna dei Fiori complex, and (c) the Acquasanta thrust sheet (fig. 9/59 and fig. 9/60). Note that all these units have a north-south strike and that their overall shortening decreases rapidly towards the north.

10) The Monte Malbe - Mte. Martano zone of Central Umbria shows shortening in the order of 120 km near Perugia increasing to over 180 km in the south. We estimate that the Cervarola complex has been transported over a distance in excess of 180 km. Our very rough shortening estimates are likely to be quite conservative because they do not allocate any shortening due to small-scale folding and cleavage solution (ALVAREZ et alii, 1976; 1978; LAVECCHIA et alii, 1983).

b) REGIONAL CONSIDERATIONS

Let us now put our conclusions into a broader context (for background, see MERLA, 1952; DALLAN-NARDI & NARDI, 1974a; OGNIBEN, 1986; BOCCALETTI et alii, 1981; 1982). During the Eocene and before they were rotated into their present position, Corsica and Sardinia were adjacent to the coast of southern France (ARGAND, 1922, trnsl. CAROZZI, 1977; DERCOURT et alii, 1986). On its present eastern coast, Corsica was rimmed by a then north-verging Alpine fold belt characterized by thrusting, high-pressure, and low-temperature metamorphism during late Cretaceous-Eocene times.

An open «Liguride» ocean estimated by KLIGFIELD (1979) to be 200 to 800 km wide separated Corsica and Sardinia from the stretched continental margin of the Adriatic promontory. A complexly deformed accretionary Liguride belt with Apennines vergence may well have been formed during upper Cretaceous, but was certainly established during the Eocene (Ligure phase of DALLAN-NARDI & NARDI, 1974). We visualize that the late Oligocene Macigno foredeep of the Tuscan zone was associated with the Liguride front, even though most clastics filling that foredeep probably derived from the Alps. The Macigno foredeep was in the order of 200 km wide and towards the east merged with the pelagic deposits of the scaglia cinerea (see fig. 64). Note that the Macigno foredeep developed at the same time as the Corsica forearc basin (REUTTER, 1981; ZITELLINI et alii, 1986).

The rotation of Corsica and Sardinia occurred during early Miocene time, i.e., according to BURRUS (1984) between 24 m.y. and 19 m.y. In the Gulf of Valencia, in the Provence and in Sardinia, Oligocene rifting started over 30 m.y. ago and preceded the rotation of Sardinia and Corsica and the opening of the Northwestern Mediterranean basin (BIJU DUVAL, 1977; CERCHI & MONTADERT, 1982a, b; BURRUS, 1984). We conclude with KLIGFIELD (1979; 1986) that the early rifting and the rotation of Corsica and Sardinia coincided with the main deformation in the Tuscan realm. KLIGFIELD et alii (1986) suggest that a major folding event involving metasediments in the Alpe Apuane occurred around 27 m.y. ago (e.e., before the rotation of Corsica) and that later, structures appear to have been formed about 12 m.y. ago. We have to place the overthrusting of the Tuscan nappe and the Alberese-Canetolo complex in the same Upper Oligocene-Lower Miocene time bracket.

We realize that some authors (DALLAN NARDI & NARDI, 1978; BOCCALETTI & COLI 1983) prefer a westward vergence for the upper Tuscan thrust and an origin that is located between the Apuane realm and the Umbria realm. We remain, however, impressed by the overwhelming evidence favoring
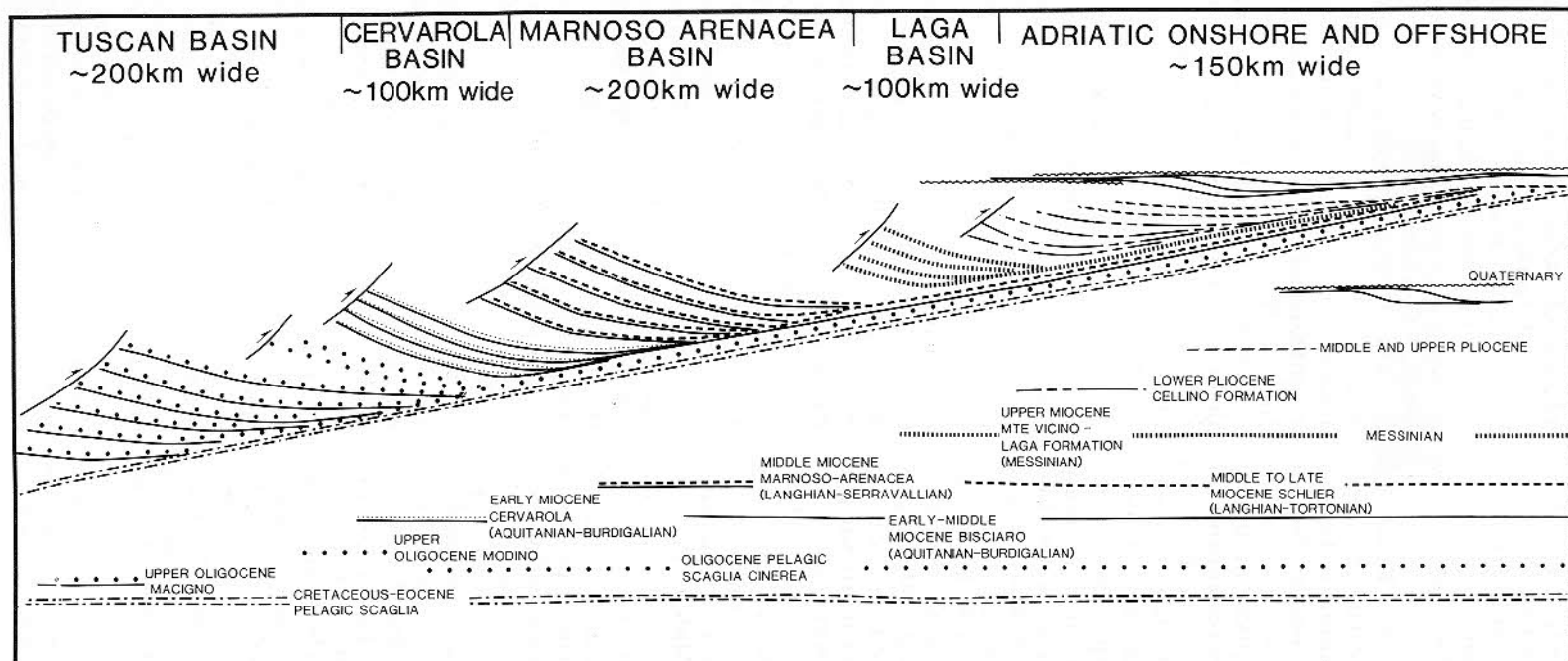
Fig. 64 - A sketch illustrating the asymmetrical migrating foredeeps of the Central Apennines. The approximate basin width indicated are crude estimates in part based on our balanced cross sections. Aside from the Quaternary and Upper Pliocene foredeeps, all earlier foredeeps were filled with turbidite sequences. The direction of sediment transport was mostly longitudinal. The thrust faults shown are meant to be illustrative of folding and thrusting on the internal side of the foredeep basin. We visualize a foredeep that continuously is migrating towards the east with no relaxation and no discontinuity of the thrusting activity. (Sketch inspired by RICCI LUCCHI, 1986).

an eastern or northeastern vergence of these units as shown by the work of CARMIGNANI & GIGLIA (1979); CARMIGNANI et alii, 1978; 1980; and by MORETTI (1986). Thus, we favor an easterly vergence for all the Tuscan and higher units.

As already suggested by KLIGFIELD (1979), the deformation of the Tuscan nappes overlaps in time with the rotation of Corsica and Sardinia, and is also responsible for genesis of the Modino-Cervarola and the Marnoso-Arenacea foredeep. Implicit in this is that the detachment tectonics responsible for the Cervarola thrust complex, the Umbrian thrusts and folds and the Adriatic foreland folds all occur *after* the rotation of Corsica and the opening of the Gulf of Lyons-Liguria basin was completed. Thus, in the Central Apennines we note shortening of the Cervarola thrust in excess of 150 km during a post-Serravallian to pre-Quaternary interval. Of that shortening in excess of 50 km occurred before the deformation of the Umbrian fold belt, and the remaining 100 km-plus shortening occurred when the Cervarola unit was riding piggyback on the Umbro-Adriatic décollement system. The deformation in Umbria and the Adriatic foreland occurred essentially during the Pliocene as shown by folded Messinian occurring in some of the synclinoria of Umbria, and the obvious convergences in Lower and Middle Pliocene strata that are seen on seismic profiles across many structures of the Adriatic foreland.

To sum up: compressional deformation in the Tusco-Umbrian segment of the Apennines began during the Oligocene and was essentially completed at the end of the Pliocene. As compressional deformation proceeded, an associated asymmetrical foredeep migrated toward the Adriatic foreland (see fig. 64). A realistic model for the earlier foredeeps shows on seismic profiles of the Adriatic foreland, i.e., we are looking at a foredeep which is interrupted by thrusted anticlines and an easterly decrease in shortening. This situation is well-known from the Po plain (PIERI & GROPPI, 1981; PIERI, 1983; CASTELLARIN et alii, 1985) and has also been discussed by CASNEDI et alii (1976), ORI et alii (1986a, b), DONDI et alii (1985), RICCI LUCCHI (1985b), and ROSSI (1986).

Thus, we visualize a perennially migrating foredeep and not one that is broken up by deformational fronts representing discrete phases of deformation that interrupt by times of tectonic quiescence. The symbolic thrust faults shown on fig. 64 are only intended to show boundaries between major foredeep sequences that have been previously described in literature.

The Miocene deformation of the Apennines can be readily related to extension and backarc-basin tectonics in the wake of the rotating islands of Sardinia and Corsica, but the specific relations between the Middle to Upper Miocene and Pliocene compressional deformation to corresponding extension in the Central Apennines and the Tyrrhenian offshore are not so clear.

The synchroneity of the Upper Miocene and Pliocene compression and extension has already been emphasized by ELTER et alii (1975). The same argument has then been pursued by others including SCANDONE (1979), BOCCALETTI & COLI (1983), and MALINVERNO & RYAN (1986). More detailed documentation of Neogene extensional tectonics has been published for the Umbro-Tuscan region and the adjacent northern segment of the Tyrrhenian sea (FEDERICI, 1973; PASQUARE et alii, 1983; BOCCALETTI & COLI, 1983; FABBRI & CURZI, 1979; MANTOVANI et alii, 1985; FABBRI et alii, 1981; RECQ et alii, 1984; TRINCARDI & ZITELLINI, 1984; and ZITELLINI et alii, 1986). From these publications, there emerges that the dominant direction of extension in the Tyrrhenian sea is east-west, while we have NE-SW extension in the Toscana. Extension appears to start in some areas during the upper Miocene and last through the lower Pliocene. Significant extension does not occur during and after the middle Pliocene.

Post compressional normal faulting has also been mapped and described in the Umbria-Marche regions (LAVECCHIA et alii, 1981b; 1984a; G. MINELLI, 1986) and is also shown on our cross sections.

Based on the published information and the lack of obvious evidence for large amounts of extension we sense that the amount of upper Miocene and later extension in the Umbro-Tuscan segment of the Apennines does not come close to the much larger amounts of essentially post Messinian compression in the area. MALINVERNO & RYAN (1986) have made a plausible and permissible argument that ties compression in the Southern Apennines and Sicily to synchronous ex-

tension onshore and above all to the formation of the Tyrrhenian sea. These authors believe that arc migration itself is the driving force responsible for the deformation of the Apennine orogenic belts. In the Central Apennines MALINVERNO and RYAN'S argument may well be valid for that part of the compressional deformation that is co-eval with the rotation of Corsica and Sardinia, but in our judgment it will be difficult to document a similar one-for-one relation between lesser late Miocene and younger «backarc» extension and the large amount of shortening in the Umbro-Adriatic region.

Extension that is contemporaneous with compression in the Adriatic foreland has nevertheless permitted the rise of the magmas feeding the Tusco-Roman volcanic complexes. ALVAREZ (1972) and CIVETTA et alii (1978) noted an eastward decrease in age of the Tusco-Roman magmatic episodes ranging from about 9 m.y. on the islands of Capraia and Elba to less than 1 m.y. in the Tusco-Roman volcanic complexes. ALVAREZ explains this relationship as due to an eastward migrating subduction zone, while CIVETTA et alii visualize a westward subducting slab.

Our cross sections suggest that the Late Miocene and Pliocene shortening observed in the Umbro-Adriatic thrust belts would necessarily lead to the formation of a subducted continental or transitional lithospheric root, which however, in this segment of the Apennines, still needs to be documented. Depending on the thickness of the stretched tuscoumbrian Mesozoic crust, it is conceivable that only insignificant amounts of lower crust were subducted. Thus, we are looking at the separation of the crustal thrust sheets of the Toscana and the overlying sediments from the subducted adriatic lithosphere.

In this context, it would appear to be plausible to explain the elevated Moho of Central Italy (see GIESE & NICOLICH, 1985, and fig. 5) as a Neogene Moho which is related to mantle diapirism and uplift. LOCARDI (1982; 1985) is offering such a model involving also the rise of mantle metasomatic fluids. He does however point out that the peculiar perpotassic alkaline magmatism of this sector and its lead-isotopic characteristics do not support an origin related to the dehydration of a subducted oceanic or continental slab. On the other hand, the very substantial late Miocene and Pliocene shortening observed in the Central Apennines pretty well demands the subduction of in excess of 100 km of continental and transitional lithospheric mantle. However, we see no compelling evidence for subducting substantial amounts of the upper crust and sediments and thus there is perhaps no necessity to postulate a dehydration of the subducted slab. We feel that in the Central Mediterranean mantle upwelling and A-subduction, i.e., the subduction of continental or transitional lithosphere are linked together, but that in essence only mantle material and at best only minor volumes of the lower crust get subducted. Because we lack the specialized geochemical background to reconcile our perspective with the one offered by our volcanological colleagues, we feel that this problem will offer a particularly fertile area for future cooperation of structural geologists, geophysicists, and volcanological geochemists.

c) COMPARING THE CENTRAL APENNINES WITH OTHER FOLDED BELTS

Our cross sections bear an obvious similarity with sections across other folded belts. This is easily explained: one of us has been working in a number of other folded belts, using principles that were first developed in the Canadian Rocky Mountains. A number of geologists have successfully applied modifications of that experience to other folded belts with the net effect that many cross sections acquire a typical «Canadian look». Of course, different schools have different styles. Much as the art historian can differentiate the paintings of the school of Siena from the schools of Florence and Perugia – without impuning the inherent saintliness of the persons portrayed – we can distinguish a «LAUBSCHER» from a «ROEDER» and a «SUPPE», etc.

LAUBSCHER (1978, 1979), SUPPE (1980a, b; 1985), and also DRODZEWSKI et alii, (1980) resolve their folds in a kink fold style which in our view is amply justified if the data available permit detailed resolution. We anticipate that after more detailed mapping in the Apennines, kink fold-style interpretations will replace our style of cross sections. This is easy to anticipate because on a smaller scale kinkfolding is so widely observed in Umbria.

However, at the scales we are dealing with, we cannot resolve the necessary detail at this time without doing a large amount of additional field work. Furthermore, our seismic profiles do not permit to resolve kink folding on a larger scale. We foresee that in the not so distant future cross sections across foreland folded belts will be drawn with the aid of computers (see KLIGFIELD, GEISER & GEISER, 1986). Such sections will permit to better integrate surface data with subsurface data and they will be particularly useful in the integration of observations done at different scales.

Our simplified cross section procedure prevents us to analyze the very real differences one perceives when comparing outcrops of different folded belts. On the other hand, a «common denominator» for all cross sections permits us to better focus on the major regional differences between the Central Apennines and a number of other fold belts.

Let us first compare the Apennines with the Canadian Rocky Mountains (BALLY et alii, 1966; DAHLSTROM, 1970; PRICE & MONTJOY, 1970; PRICE, 1980; GORDY et alii, 1975; 1977). We already concluded that in Canada the basement is better defined seismically, while in the Apennines there is no obvious near basement event. In fact, the nature of the basement suggests that in the Apennines it may be most difficult to obtain a continuous reflector from a basement sediment interface.

In the Canadian Rockies, décollement develops along many different decoupling levels within the Paleozoic and the Mesozoic. On the other hand, in the Apennines major décollement is along the Triassic evaporitic Burano formation, additional levels are quite conspicuous in the field (e.g., Scisti a fucoidi, Scaglia cinerea and also the Messiniano) but do not find a clear expression on the scale of 1:100,000 or else on the seismic profiles.

There are also striking differences between the regional setting of the Western Cordillera and the Central Apennines. In Canada in the interior Cordillera to the west of the foreland folded belt, we see very wide belts of metamorphic and intrusive rocks, a large number of exotic terranes, and finally to the west we see a former island arc (the Coast Range) and a major subduction zone where oceanic lithosphere dives into the astheno-

sphere. Superposed on «laramide» and earlier structures, we find in Canada a widespread system of low-angle normal faults and strike slip faults of a syn- and post-compressional age (see MONGER et alii, 1986). Notice that further south in Montana, the post-orogenic extension becomes more intensive yet (see BALLY, 1984).

Contrast the Canadian Cordillera (MONGER et alii, 1986) with the Apennines where a relatively narrow belt of metamorphic cores in Toscana is juxtaposed to the west by the extensional Tyrrhenian Sea. Note that in the Gulf of Lions and in the Tyrrhenian Sea the opening of small oceanic basins coincides in part at least with the compressional deformation in the Apennines. Thus, in some poorly understood manner, extension and compression in part occur simultaneously. It is our intent to eventually complete our restorations by extending our cross sections into the Northern and the Southern Apennines, and to see whether we can come up with a reasonable story that ties semi-quantitatively the opening of the Gulf of Lions and of the Tyrrhenian Sea to the development and the evolution of the Apennines. This will be necessary to verify the concepts proposed by MALINVERNO & RYAN (1986).

It should also be pointed out that aside from differences in scale and plate tectonic setting, the compressional deformation in the Canadian foreland folded belt, lasted for about 90 million years, i.e., from the Upper Jurassic to the Paleocene. In contrast, the Apennines were essentially formed during later Paleogene to Neogene times, i.e., during about 40 m.y. with a main compressional phase in the Umbria and Marche lasting about 5 million years during the Upper Miocene and Pliocene.

A comparison of the Central Apennines with sections across the Wyoming folded belts (ROYSE et alii, 1975; BALLY, 1984) show only one or two regional décollement levels in Wyoming. Thus the structures in Wyoming appear to be simpler. But here again there is a strong modification due to the late tectonic extensional tectonics. Let us mention one additional outstanding feature: the foreland basement in Wyoming is clearly involved in the compressional deformation as shown in the Farmington uplift area near Salt Lake City.

The seismic in the Wyoming and Colorado foreland reveals fairly straight reverse faults that appear to merge into a crustal decoupling level somewhere near the Moho. In other words, the mantle does not appear to be involved in basement deformation, as can be shown fairly conclusively by gravity models. Thus, sections across the Wyoming Rockies (SMITHSON et alii, 1978; 1979; BALLY & SNELSON, 1980; ALLMENDINGER et alii, 1985; LOWELL, 1985) show a clear case where the basement is involved in reverse faulting and our Central Apennine sections could be used to show that basement uplifts of the Wyoming-type as well as upthrusts, probably do not exist in the Umbria-Marche Apennines and its foreland

We may also compare the Appalachian folded belt with the Central Apennines. Needless to say, the Appalachian folded belt is much larger than the Apennines. In the Appalachian Valley and Ridge, the Cambrian Rome shale is the major décollement level, but we also recognize several subsidiary décollement levels. In the Appalachians, like in many other foreland fold belts, there are substantial changes in structural style along strike. These are typically due to lateral changes in the ductility contrasts occurring within differing stratigraphic sequences. Such changes along strike are analogous to the changes in structural style between the Central Apennines, and the Abruzzi Apennines. We believe that the overall allochthonous nature of the Apennines will continue to the south as, for instance, suggested by MOSTARDINI & MERLINI (1986), but that, like the Appalachians, we will be dealing with differing tectonic styles depending on whether we deform platform or transitional or basinal sequences.

Coming back to the Appalachians, we find it of particular interest that there the basement uplifts of the Blue Ridge, and the inner metamorphic belts are all underlain by basal décollements (shear zones) that separate crystalline basement units. The basal décollement extends from the foreland straight under the metamorphic and igneous terranes of the eastern Appalachians. This statement is reasonably well supported by the deep crustal reflection profiles (ROEDER et alii, 1978; COOK et alii, 1982; 1983).

Transposed onto the Apennines, the Appalachian experience means that the inner cores of the Tuscanides also are overthrust over the downdip extension of the foreland basement. Thus in folded belts of this type everything is allochthonous and decoupled from the underlying lithosphere. In simple words this means that the essence of orogenic processes is the mechanical separation of the parts or all of the continental crust and sediments from the underlying deeper lithosphere, i.e., the upper mantle. To restate a point made earlier, this would mean that the undeformed Adriatic lithosphere ought to form lithospheric root somewhere under the western Apennines and the Tyrrhenian Sea.

Let us finally compare the deformation styles of the Central Apennines and the Dinarides. Figure 65 is a simplified sketch section that extends from Mte. Argentario to the Sava River. The figure is in part inspired by publications of ALJINOVICH & BASKOVITCH (1984), AUBOUIN (1972); BLANCHET (1972); GIESE et alii (1982); MILJUSH (1973a,b; 1978); and WIGGER (1984). The Dinarides appear as a more or less symmetrical counterpart of the Apennines. Structures in the Dinarides also use Triassic evaporites as main décollement level. Note that like in the Apennines, the interior units of the Dinarides see the involvement of Paleozoic sediments and possibly of the underlying crystalline basement. Finally, to the east a major ophiolitic thrust sheet indicates the former presence of an ocean. Even though we did not make a study of reflection seismic profiles, amounts of shortening in the Dalmatian and the High Karst Zones appear to be in the same order of magnitude as the amounts of shortening in the Central Apennines. This suggests that the palinspastic eastern edge of the Adriatic promontory falls well within the Pannonian basin of Hungary.

If we combine the last comment with the notion that, based on our approximate reconstruction, the western margin of the Adriatic promontory falls somewhere in the space now occupied by the Gulf of Lyon (i.e., palinspastic position of Tuscan units), it can be concluded that the Adriatic promontory in a transect centering around the Central Adriatic Sea had an original width well in excess of 1200 km. This may be compared with the width of Saudi Arabia or else with the width of the Florida-Bahama plateau from the Gulf of Mexico to the Atlantic Ocean.
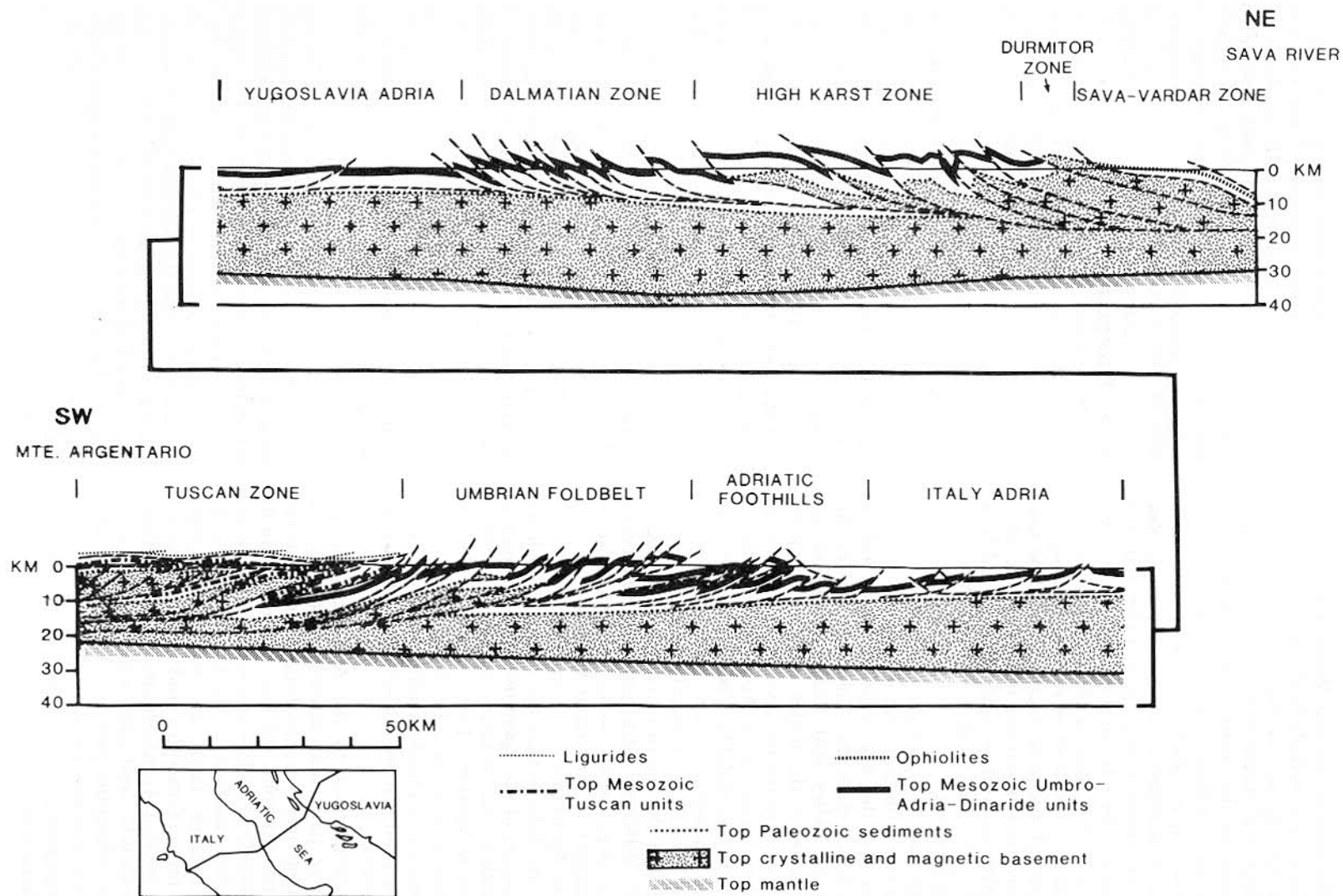
NE

DURMITOR
ZONE

SAVA RIVER

| YUGOSLAVIA ADRIA | DALMATIAN ZONE | HIGH KARST ZONE | |SAVA-VARDAR ZONE |

0 KM
10
20
30
40

SW

MTE. ARGENTARIO

| TUSCAN ZONE | UMBRIAN FOLDBELT | ADRIATIC FOOTHILLS | ITALY ADRIA |

KM 0
10
20
30
40

0   50KM

A.W. BALLY, L. BURBI, C. COOPER & R. GHELARDONI

.... Ligurides   ''''''''''''' Ophiolites

─ · ─ · ─ Top Mesozoic   ▬▬▬ Top Mesozoic Umbro–
          Tuscan units   Adria–Dinaride units

·············· Top Paleozoic sediments

⊞⊞⊞ Top crystalline and magnetic basement

░░░░ Top mantle

Fig. 65 - A schematic cross section from the Tyrrhenian sea to Yugoslavia. (Mte. Argentario to Sava River). For explanation and comments, see text.

Finally, our comparison with the Dinarides suggests that our methodology may well apply to that area and that balanced cross sections across the Dinarids into the Pannonian Plain may help substantially in resolving the complex topologic relationship between the deformation of the Adriatic promontory and the deformation of the Alpine fold belt, which has been overthrust by the Eastern Alpine thrust sheets which in effect are the northward extension of the Adriatic promontory (see also LAUBSCHER, 1971).

CONCLUSIONS

We set out to investigate the applicability of the Rocky Mountain folded belt model to the Central Apennines of Italy. Our balanced cross sections combined with AGIP's analysis of the magnetic survey clearly shows that the Central Apennines may be interpreted using the experience gained in Western Canada and in Wyoming.

Having said that the Rocky Mountains model in general works in Italy, we feel that we have to emphasize some major differences, as follows:

The reflection seismic data in the Apennines and the Adriatic foreland do not permit us to recognize a fairly continuous near basement reflector. Consequently, we have to *assume* a gently westward dipping décollement surface. This surface—our putative basement—is being visually extrapolated from the Adriatic foreland toward the west and underneath the Apennines. The probable reason for the near absence of a «basement» reflector is due to the nature of the basement and possible absorption of seismic energy by the Triassic evaporites.

In contrast to a number of other folded belts, the structure in the Apennines is dominated by the distribution of Triassic evaporites. Thus, the best analogues for the Apennines are probably the Zagros Mountains and to a lesser extent the Parry Island folded belt of Northern Canada (FOX, 1983; 1985) and the Jura Mountains (LAUBSCHER, 1965; 1978; 1979). Seismic data from the Zagros are scarce but seismic data from the Parry Islands and the Jura Mountains clearly demonstrate the evaporitic décollement level.

The situation of Italy is further complicated by the Jurassic extensional tectonics.

Jurassic extension has been postulated on the basis of surface studies in the Southern Alps and in the Apennines. The arguments favoring extension are mostly based on stratigraphic observations. We have as yet to document anything coming near a description of a Jurassic structural pattern. We suspect that such a pattern would reveal a system of listric half-grabens, that are connected by transform segments. Unfortunately, there is not a hint of any evidence of Jurassic extensional tectonics on our reflection seismic profiles. We suspect that this is due to the lack of resolving power of our seismic profiles or else possibly to the limitation of widespread extensional tectonics to the outcropping Sibillini thrust sheet and their general absence in the Adriatic foreland. The situation in the Allochthonous thrust sheet may also be compared with the reefal buildups in the central Adriatic Sea and in the Abruzzi, which are not demonstrably controlled by any pre-existing extensional tectonics.

Additional widespread décollement levels can be observed on the surface (base Messinian, Scaglia Cinerea, Scisti a Fucoidi, Rosso Ammonitico, and many other minor levels). All these cannot be resolved by conventional reflection seismic profiles. We choose to ignore these features. Consequently, the amounts of shortening shown on our cross sections are conservative and much of the shortening observed in detailed studies should be added to the large scale regional shortening suggested by our profiles.

The main décollement level descends from about 5 km under the Adriatic Sea to about 15 km under the Central Apennines. Regionally further west, it is likely that the main décollement level is close to the Moho. This implies that basement and sediments are separated mechanically from the underlying mantle. That mantle would form a lithospheric A-subduction related root, the existence of which still needs to be demonstrated.

The Anzio-Ancona line, or at least the Terminillo-Sibillini segment of that feature, is by us interpreted as a lateral ramp.

The Sibillini thrust appears to have been rotated in anticlockwise manner as already postulated by paleomagnetic workers. Much of the increased shortening in the south of our area is due to the appearance of N-S striking duplex structures; *a)* the Roc-

cafinadamo structure, *b*) the Montagna dei Fiori structure, and *c*) the Laga (Aquasanta) thrust sheet.

Our palinspastic reconstructions are crude first approximations. They suggest that the Sibillini thrust in its reconstruction coincides reasonably well with the present-day position of the leading edge of the Cervarola thrust sheet. With it, the Umbrian domain falls into the present day Toscana and the adjacent Tyrrhenian sea, the Cervarola unit falls in its reconstruction into the northwestern Tyrrhenian sea, while the Tuscan units would position in the area now occupied by Corsica and the Eastern Gulf of Lyon (Provencal Basin).

We speculate that the basic structural style of the Dinarides is similar to the style of the Central Apennines to the extent that a main Triassic evaporitic *décollement* level appears to be evident. Allowing for similar palinspastic restoration techniques, we suggest that the original Adriatic Promontory was well over 1200 km wide.

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