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Tectonic framework and petroleum potential of the southern Apennines

P. Casero, F. Roure, and R. Vially

ABSTRACT

The southern Apennines comprise a stack of platform and basinal Mesozoic to Palaeogene units (Western platform and Lagonegro–Molise allochthons) which have come from far away, and lie tectonically on top of both the autochthonous (Puglia and the foredeep's outer wall) and parautochthonous (overthrust-belt) carbonate units of the eastern platform. Surface and subsurface data have been used here to build a trans-Apenninic geological cross-section from the Adriatic coast to the Tyrrhenian Sea, as well as a subsurface structural map at the top of the carbonates on the eastern platform.

The timing of the deformation has been effectively constrained by paleontological dating of:

(1) the shallow- to deep-water facies transition that affects the platform domains as they migrate from the tectonically-generated bulge to the foredeep area; and
(2) the basal unconformities of the piggy-back basins that post-date the accretion of the underlying units to the allochthon (accretionary wedge).

The potential source-rocks in the southern Apennines have been systematically sampled and analysed. Besides the terrigenous Plio-Quaternary beds of the foredeep that constitute the source-rock for biogenic gas, only local organic-rich horizons have been found in the evaporitic Messinian sequences or in the Cretaceous cherty argillitic beds of the allochthon. However, by comparison with data from surrounding areas (Sicily, central Apennines, and the Adriatic Sea), the main source-rock for oil in the southern Apennines appears to be the upper Triassic to lower Jurassic bituminous dolomite of the autochthon and parautochthon (eastern platform), that crops out elsewhere. A hypothetical late Palaeozoic source-rock has also been modelled.

Structural and biostratigraphical data have been combined with estimated kinetic parameters of the potential source-rocks to reconstruct their burial and thermal history accurately, and to model their petroleum potential. The oil and gas windows have been calculated and superimposed on the geological cross-section, and related to the known occurrences of oil and gas in the southern Apennines. A major implication of the model is that, even considering the deep burial of the Triassic source-rock in the axial part of the foredeep, oils generated early may still be preserved in traps in the overthrust belt, because the hydrocarbons escaped cracking during their travel across the foredeep; they were already trapped in shallow, hence relatively cold, horizons (for example, Cretaceous or early Miocene calc-arenite).

INTRODUCTION

The interpretation of conventional regional seismic lines and the correlation of numerous exploration wells, combined with surface studies and palaeontological analyses, recently led us to propose an up-to-date synthesis of the structural evolution of the southern Apennines, from the Abbruzzi to the Gulf of Taranto, between the Adriatic coast and the Tyrrhenian Sea (Fig. 29.1; Casero *et al.* 1988, in press; Roure *et al.* 1988; 1990, in press). Simultaneously, we combined the geometric and kinematic constraints deduced from the structural and biostratigraphical study to build regionally balanced cross-sections along selected profiles crossing the southern Apennines, and thus to reconstruct the burial history of the potential source-rocks identified in the area. Numerical codes developed at IFP (Institut Français du Pétrole) were then used to trace the thermal evolution of the source-rocks, and, according to estimated kinetic parameters, to propose the spatial evolution of the oil and gas windows through time on the restored geometries of the cross-sections, from the pre-compressive stages to the present. Finally, we have compiled all available data concerning the known occurrences of oil and gas to define the major petroleum exploration plays in the southern Apennines, and to compare the present hydrocarbon distribution with that predicted by the model.

TECTONIC FRAMEWORK

We shall summarize here the geological background of the southern Apennines (Fig. 29.1), and focus the discussion on a single generalized cross-section and a subsurface map at the top of the carbonates (Fig. 29.2, 29.3). Further information and detailed reviews can be found elsewhere (Mostardini and Merlin 1988; Casero *et al.* 1988, in press). From the top of the structural pile to the autochthon, four major lithostratigraphical assemblages have been distinguished:

1. The western platform, which comprises Mesozoic platform carbonates and represents the backbone of the belt at the surface. Most peaks in the southern Apennines are made of this unit (Monte Pollino, Monte Alpi, Monte Raparo, and Matese), which extends westwards from the continental divide to the Tyrrhenian coast. The initial thickness of the eastern platform is rarely preserved. The Mesozoic limestones are effectively detached from their Palaeozoic basement along an intra-Triassic decollement level, and the entire unit is dissected and thinned by west-facing listric peri-Tyrrhenian normal faults (Fig. 29.2a).

2 and 3. The Lagonegro/Molise basinal units, which represent the allochthonous infill of the Molise depression, a smooth and relatively shallow area that extends eastward from the Apenninic ridge (western platform) to the Apen-

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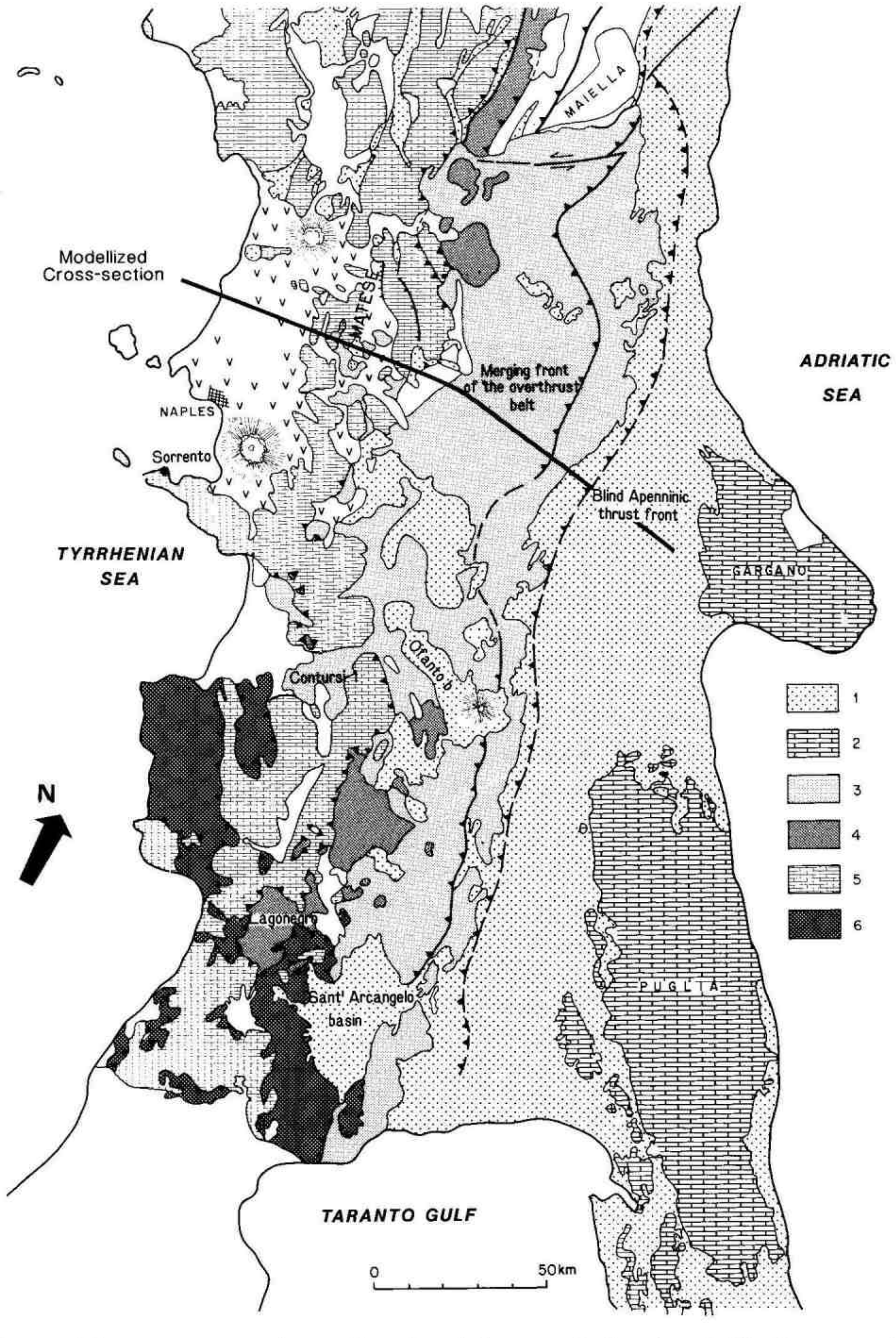

Fig. 29.1. Structural map of the southern Apennines and location of the generalized section. 1, Plio-Quaternary; 2, eastern platform Mesozoic limestones; 3 and 4, Lagonegro–Molise basinal units—Mesozoic pelagic limestones and cherts—4; late Cretaceous to Eocene red and green argillites and Oligocene to Neogene turbidites—3; 5, Western platform Mesozoic limestones; 6, Liguride ophiolitic unit.

ninic thrust front (Fig. 29.1). It can be divided into two distinct packages, with contrasting lithologies:

(a) Westward, the competent Jurassic to early Cretaceous pelagic limestones and cherts of the Lagonegro units that lie locally on top of Triassic dolomites, and are clearly detached from their Palaeozoic basement;

(b) Eastward, late Cretaceous to Eocene red and green argillites, which in turn overly Oligocene to Neogene turbidites, with the Molise or Bradano allochthon, comprising mélânges or broken formations, at the structurally lowest level (tectonic sole; Roure *et al.* 1990). These are all plastic nappes which have been detached from their initial Lagonegro Mesozoic substratum.

4. The so-called eastern platform, made of 5-to 7-km-thick Mesozoic limestones that crop out in the Puglia foreland (flexural bulge) and can be followed beneath the allochthon in the flexed autochthonous outer wall of the foredeep. Deep Adriatic wells have encountered early Triassic to Permian volcano-clastic beds in the substratum

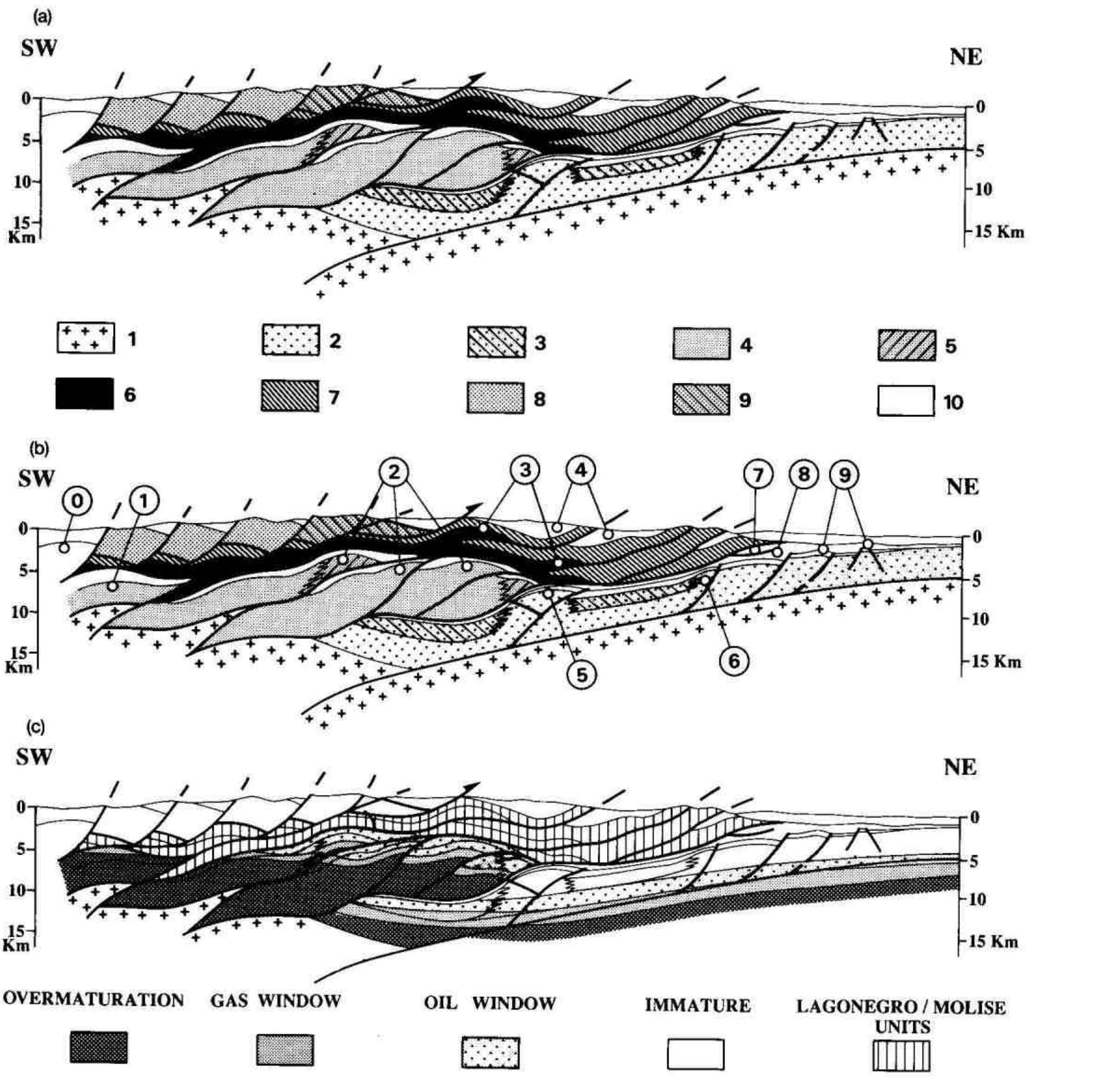

Fig. 29.2. **a** Generalized cross-section of the southern Apennines (see Fig. 29.1 for location). 1, lower Triassic and Palaeozoic basement; Mesozoic eastern platform; 2, autochthon and parautochthon, 3, Cretaceous transitional facies, 4, overthrust belt, 5, Cretaceous basinal facies; 6, Mesozoic Lagonegro basinal units; 7, Cainozoic Molise basinal units; 8, Western platform; 9, transitional facies; 10, Plio-Quaternary. **b** Oil and gas plays in the southern Apennines (numbers refer to the petroleum plays described in the text). **c** Calculated oil and gas windows in the southern Apennines.

of the eastern platform. Westwards, these Mesozoic limestones were subsequently detached from their Palaeozoic basement and nowadays form a parautochthonous overthrust belt that is deeply buried beneath the Bradanic allochthon (Fig. 29.2(a), 29.3). The subsurface map at the top of the eastern platform limestone shows a substantial shortening between the overthrust belt (Benevento or Costa Molina trends) and inverted structures of the autochthon (Tempa Rossa or Tursi trends). Fold axes in the parautochthon effectively form arcuate belts that locally mask the underlying axes of the foredeep running parallel to the NW–SE Puglia trend. Lithostratigraphical data from recent wells that reached either the overthrust belt or the inverted structures of the foredeep show rapid lateral changes from platform to more pelagic facies in the upper Cretaceous horizons of the eastern platform, and are thus in agreement with outcrop data recently published from both the Abbruzzi (to the north) (Clermonté and Pironon 1979) or Maiella regions (Accarie 1987; Bernoulli, pers. comm.). The present location of the suture between the overthrust belt and the autochthon, as well as the geometry of the inverted structures of the foredeep, could thus result from a tectonic heritage from Cretaceous palaeogeography, when limited areas of active subsidence separated intervening platform highs. In addition, when the southern Apennines sections are compared with similar sections in the Abbruzzi region, another transition from shallow to deep-water Cretaceous carbonates may be expected west of the overthrust belt. This should be taken into account by exploration geologists.

The timing of deformation is effectively constrained by the shallow-to-deep water transition observed in the sedimentary facies of the platform domains when they enter the flexural trough in front of the Apenninic wedge. Platform sinking occurred during the Miocene (Langhian to Serravalian) to the west in the Matese Mountains, but only during the Pliocene on the Puglia foreland to the East (Müller *et al.* 1988). Deformation and accretion of the Lagonegro–Molise basinal units into the Apenninic prism is indicated by the unconformity at the base of the piggy-back basins where Messinian to Pliocene syntectonic deposits have been trapped. According to our data, the space-time advance of the deformational front, post-early Messinian in Monte Alpi, post-late Tortonian in the Matese area, and probably only Pliocene (post-Messinian evaporite) in the Abbruzzi, is clearly expressed along the entire Apennines.

Apart from some minor oil discoveries in the allochthon or in the piggy-back basins (Fig. 29.2(b)), most of the hydrocarbon occurrences in the southern Apennine are restricted to the carbonates on the eastern platform (both in the overthrust belt or in the autochthon, from the inverted structures of the foredeep to the bulge, [Fig. 29.2(b)] or in the syn-orogenic Plio-Quaternary sandstones of the foredeep (Fig. 29.4, 29.5), i.e. in very recent (Plio-Quaternary) structures.

POTENTIAL SOURCE-ROCKS

Since we could not have direct access to hydrocarbon samples during this study, we could not attempt to make a correlation between the oils and the potential source-rocks found in the southern Apennines. Nevertheless, we analysed the organic contents and the T_{max} (Rock-Eval pyrolysis) of the numerous samples collected during our field studies in the Mesozoic beds in the Lagonegro–Molise units, as well as in the Neogene terrigenous sequences in both the allochthon (Irpinian flysch and piggy-back basins) and the foredeep. Similarly, since the autochthonous Triassic formations of the eastern platform were unaccessible, we collected some coeval deposits from the surrounding Triassic platform outcrops of the central Apennines (Pietre Nere in Gargano and Gran Sasso). The results are given in Table 29.1.

Besides some very local organic-rich layers in the Lagonegro–Molise allochthon (Albian to Cenomanian dark argillites interbedded with radioliaritic cherts) and some thin levels of black shales interbedded with Messinian evaporites, the only realistic source rocks seem to be:

1. The Plio-Quaternary terrigenous sequences in the foredeep, which represent the organic source for the biogenic gas trapped in the Bradanic trough, and all along the Apenninic foredeep (Mattavelli 1987; Mattavelli *et al.* 1983; Tissot *et al.* 1989; Pieri and Mattavelli 1986; Mattavelli and Novelli 1987).

2. Late Triassic–early Jurassic bituminous dolomites of the eastern platform, which are probably very similar to the known source-rocks in the Adriatic prospects and Sicily (Mattavelli *et al.* this volume, p. 369; Tissot *et al.* 1989; Brosse *et al.* in press).

Unlike the pelagic Scaglia-type carbonate units in the central Apennines or the Adriatic Sea north of the Gargano promontory, no Cretaceous Fucoïdes-like, marly formation has ever been found interbedded in the more neritic carbonate facies of the southern Apennines platform units. Nevertheless, it is important to notice that Albo-Cenomanian organic-rich, cherty-argillitic sediments were also deposited during the same time interval in the Lagonegro–Molise basin, and are coeval with bauxite events in the surrounding platform domains. Euxinic conditions in the Apulian basins thus occurred synchronously, and are coeval with emergences in the intervening platforms. Unknown Albo-Cenomanian organic-rich layers may still be discovered in the internal parts of the eastern platform, where late Cretaceous pelagic horizons have recently been drilled [Fig. 29.2(a) and (b)].

For the numerical modelling of the oil and gas potential attempted along our cross-sections, (Table 29.1), we attributed different kinetic parameters to the various known potential source-rocks in the southern Apennines, according to their marine or continental origins. We also assumed an additional source-rock in the late Palaeozoic substratum.

Table 29.1. Potential source rocks in the southern Apenines.

	Western platform	Lagonegro/molise basinal units	Eastern platform
Tertiary	*Tortonian* TOC <0.5%		*Messinian shales* TOC: 0.95–1.25% Source potential (S2): 3–5.2 kg Hc/t: type II
Cretaceous		*Albian to Cenomanian* Radiolaritic cherts and argilites TOC = 7% Source potential (S2): 31 kg Hc/t: type II	
Jurassic Triassic	*Bituminous dolomite* TOC: 1–20% Source potential (S2): 20–167 kg Hc/t Composite type I–type II		*Bituminous dolomite* TOC: 1–20%, average: 7% Source potential (S2): 20–167 kg Hc/t Composite type I and type II
Palaeozoic	Hypothetical type III		Hypothetical type III Permo-Carboniferous

NUMERICAL MODELLING OF OIL AND GAS POTENTIAL

The aim of our modelling was to evaluate the petroleum potential of the southern Apennines overthrust-belt. The MATOIL software (Registered Trade Name) used for this study is a one-dimensional simulation program that reconstructs the burial history, the thermal evolution, and the maturation of the source-rocks through time, according to their specific kinetic parameters and for a given sedimentary column.

The source-rock distribution and organic content of the sedimentary pile is given in Table 29.1. Burial history has been deduced from cross-section balancing, according to restored pre- and syn-compressive geometries. The pre-compressive history and heat-flow evolution were constrained by comparing the measured tectonic subsidence curves with the curves predicted by a uniform stretching model, for an initial late Triassic to Lias distensive event. Thermal reconstruction of the compressive stage results from a calibratifon of well temperatures (AGIP 1977). By combining both the burial and heat-flow histories, we were able to calculate the thermal evolution of each potential source-rock through time. To simplify our model, we have assumed an instantaneous thrusting (5 m years since the Pliocene compared with 200 or 250 m years since the Triassic), with no friction and no fluid circulations that could induce lateral thermal disturbances. We thus computed the relaxation of a simple vertical thermal disturbance, with a constant heat-flow at the bottom of the sedimentary pile. Nevertheless, additional factors specific to overthrust belts had to be taken into account:

1. Sufficiently high deformation velocity can induce a transitory thermal disequilibrium. For very high convergence rates (i.e. in very active subduction zones like the southern Apennines), a thermal equilibrium may never be reached by the source-rocks for the time interval during which they are buried in the deepest parts of the foredeep.

2. Petrophysical parameters (including porosity and permeability) are clearly affected by thrusting, but also by dewatering processes that occur in the tectonic wedge or beneath the allochthon.

3. Overthrusting itself, as well as fluid circulations in the tectonic wedge, also induce lateral thermal disturbances that are superimposed on the regional heat-flow (Endignoux and Wolf, in press).

The results of our modelling are summarized in Fig. 29.2(c), which shows the present geometry of the oil and gas windows along the generalized cross-section of the southern Apennines. Clearly, source-rock maturation results from a constant balance between the high deformation velocities and the thermal readjustments.

According to our balanced cross-sections and biostratigraphic analyses, shortening rates reached a value of 1 to 2 cm/year in the southern Apennines during late Neogene times, which prevented the Mesozoic source-rocks from becoming overmature during their progression across the deepest parts of the foredeep. The uppermost thrust sheets and duplexes of the eastern platform overthrust belt show the best oil and gas potential, especially if early-generated hydrocarbons have migrated to the top of the Mesozoic carbonates (cold trap). The outer wall of the foredeep may also offer good prospects ('pop-up' structures and inverted normal faults).

Geological constraints are not yet sufficiently well known to reconstruct the burial and thermal histories of the Lagonegro–Molise and western platform domains, and thus our simulation only addresses the eastern platform domain and the foredeep, which are indeed the two main areas of known hydrocarbon occurrences in the southern Apennines.

HYDROCARBON OCCURRENCES AND PETROLEUM PLAYS

By integrating the results obtained by the modelling of the potential source-rock maturation history with the known hydrocarbon accumulations, it has proved possible to define and classify all known and potential hydrocarbon plays in the southern Apennines. Below, the setting of each family of prospects within the proposed structural model is indicated with reference to both the cross-section and structural maps (Fig. 29.2b, 29.3, 29.4). For each type of play a concise description of the controlling features is given. Plays are discussed from the inner zones towards the foreland (SW to NE).

1. In the inner part of the chain, beneath the allochthonous nappes of the western platform and of the Lagonegro basin, closed structural features involving the carbonates of the Genzana basin equivalent represent a potential oil play. Source-rock maturation has largely been attained, and thrust anticlines could be found at reasonable depth due to the thinning of the nappes (low-angle tilted mega blocks), This play has never been explored. The Contursi 1 well (1963) completely penetrated the nappes but was unfortunately stopped in the over-lying Miocene beds without reaching the target. The main reluctance concerning this play is, of course, linked to the difficulty and cost of acquiring seismic showing data from under the calcareous nappes in these mountainous areas.

2. This play consists of closed, thrust-fold-type structures involving the carbonates of the eastern platform (buried overthrust belt), underneath the Lagonegro–Molise nappes. The reservoir is represented by both lower Miocene packstones and Cretaceous fractured limestones. This play has recently been consistently explored, most of all along the eastern margin (thrust-fold cascade) of the overthrust belt. Oil accumulations found at Castelpagano and Benevento in the north, and at Caldarosa, Costaolina and Monte Alpi in the south, are presently under evaluation. In our opinion the western margin of the overthrust belt, the transition to the *Genzana basin*, if seismically detectable, could have great oil potential.

3. Sub-commercial heavy-oil accumulations (Ielsi, S. Croce) have been found in fractured Triassic dolomitic reservoirs in the lower Lagonegro–Molise basinal section. Traps are nappe anticlines, but this play seems to represent only modest potential.

4. Shallow biogenic gas accumulations, i.e. Nova Siri Scalo, may occur within the terrigenous section of the piggy-back basins [Fig.2(b) and 4]. Traps can consist either of lower Pleistocene sands in drape structures or of mixed

traps (on-laps and late orogenic folding) involving middle–upper Pliocene beds. The generally moderate subsidence and the limited areal extension of the basins limit the importance of this play.

5. This is a structural play (oil and/or gas) consisting of inverted, up-thrust ('pop up') structures, discontinuously set along the inner margin of the autochthonous eastern platform. These structures may be related to transcurrent faults; they occur at major changes in the trend of the overthrust belt. The reservoir is represented by porous Miocene bioclastic packstones and fractured Cretaceous shelf limestones. This play, although often very deep and difficult to define seismically, has great future potential.

6 to 9. These plays refer to the Bradanic foredeep area (Fig. 29.5). Sella *et al.* (in press), at the Italian Geological Society meeting in 1988, presented an attempt to classify and describe the different types of accumulations in the Bradanic trough. Although our play classification differs strongly in the interpretation of the outer deformations, Sella's paper is a basic reference with respect to stratigraphy, geochemistry, and reservoir petrology.

6(a). This group of oil plays includes all the inverted structures affecting the eastern platform limestones along the regional flexed-foredeep outer-wall beneath the allochthonous wedge. The Celenza 2 (oil shows) structure is now the most internal example. Commercial oil accumulations under the allochthonous ramp have been found at Monte Strombone and Monte Taverna. This play, although relatively unexplored, has considerable future potential, especially along the more internal, and deeper, trend.

6(b). This thermogenic gas play consists of closed structural features involving the eastern platform carbonates along the outer slope of the Bradanic trough. These structures can be interpreted either as gentle compressive folds of late Pliocene age (late compressive phase) or (Sella *et al.* in press) as antithetic tilted blocks (middle Pliocene flexural phase). Both models probably apply (i.e. the Reggente field structure seems clearly compressive, while the Palmori field is more like a tilted block), but in some cases (i.e. Mezzanelle, Grottole–Ferrandina), features described as tilted blocks are bounded on the outer flank by master faults that are convex to the east. The reservoir, as usual, is represented by both Miocene calc-arenites and Cretaceous fractured limestones.

7. Mixed-origin gas accumulations in middle Pliocene sands are involved in thrust folds under the outer allochthonous ramp (i.e. Roseto–Montestillo field). Thrust folding was induced by the late Pliocene compressional remobilization of the allochthonous nappe, and probably dissects previous gas accumulations (duplexing).

8(a). This is the 'classic' Bradanic-trough gas play. Middle–Upper Pliocene sand beds (Montestillo–Palino–Candela members) are folded and/or truncated against the outer (frontal) ramp of the allochthon. More external gentle duplex folds can also be found (i.e. Ascoli Satriano field). This play appears to have been largely explored.

8(b). On-lap type stratigraphic traps in middle Pliocene sandy beds (Mo and lower Pa levels) on top of lower Pliocene flexed pelagic marls represent a potential thermogenic gas play that is essentially unexplored in the Bradanic trough. The Soriano field (AGIP) can be included in this category based on the information published (Sella *et al.* in press). According to Sella, gas accumulations also exist in Upper Pliocene shaling-out sand levels. Nevertheless, we do not have any evidence to distinguish them from gently draping traps.

9. This composite family of biogenic gas plays includes all of the gently folded traps involving upper Pliocene and basal Pleistocene thin-bedded, fine-sand levels, which drape over substratum highs (i.e. Santa Caterina, Grottole–Ferrandina, Mezzanelle). This play also appears to have been extensively explored, but small size and/or very gently folded features can certainly still be found.

CONCLUSIONS

Geochemical analyses are still required in the southern Apennines to clearly demonstrate the origin of the oil trapped in the eastern platform carbonates. Most probably, as in Sicily and in the Adriatic Sea, the oil comes from late Triassic to early Jurassic bituminous dolomites. The origin of local oils shows in the Lagonegro Molise allochthon (Ielsi, S. Croce) is more problematic. Migration from the underlying platform carbonates seems unlikely. A proximal origin, with the Albian–Cenomanian organic-rich argillites is more probable, but still needs to be demonstrated by appropriate analyses.

Despite the deep burial of the Triassic source-rocks during their progression across the foredeep, the high deformation velocity prevented them from undergoing complete thermal re-equilibration and cracking. Oils generated early and preserved in cold traps are, according to our numerical modelling, the favoured solution to explain the present occurrence of hydrocarbons in the inner part of the foredeep (Tempa Rossa or Tursi trends), as well as in the overthrust belt (Benevento, Costa Molina trends). Alternatively, a shallower organic rich horizon, in the Cretaceous, could also account for the accumulations observed.

Besides the biogenic gas occurrences in the Brandano trough, the thick syn-orogenic Neogene deposits are of relatively poor petroleum value, probably due to extensive dilution (as turbidites) of their organic content.

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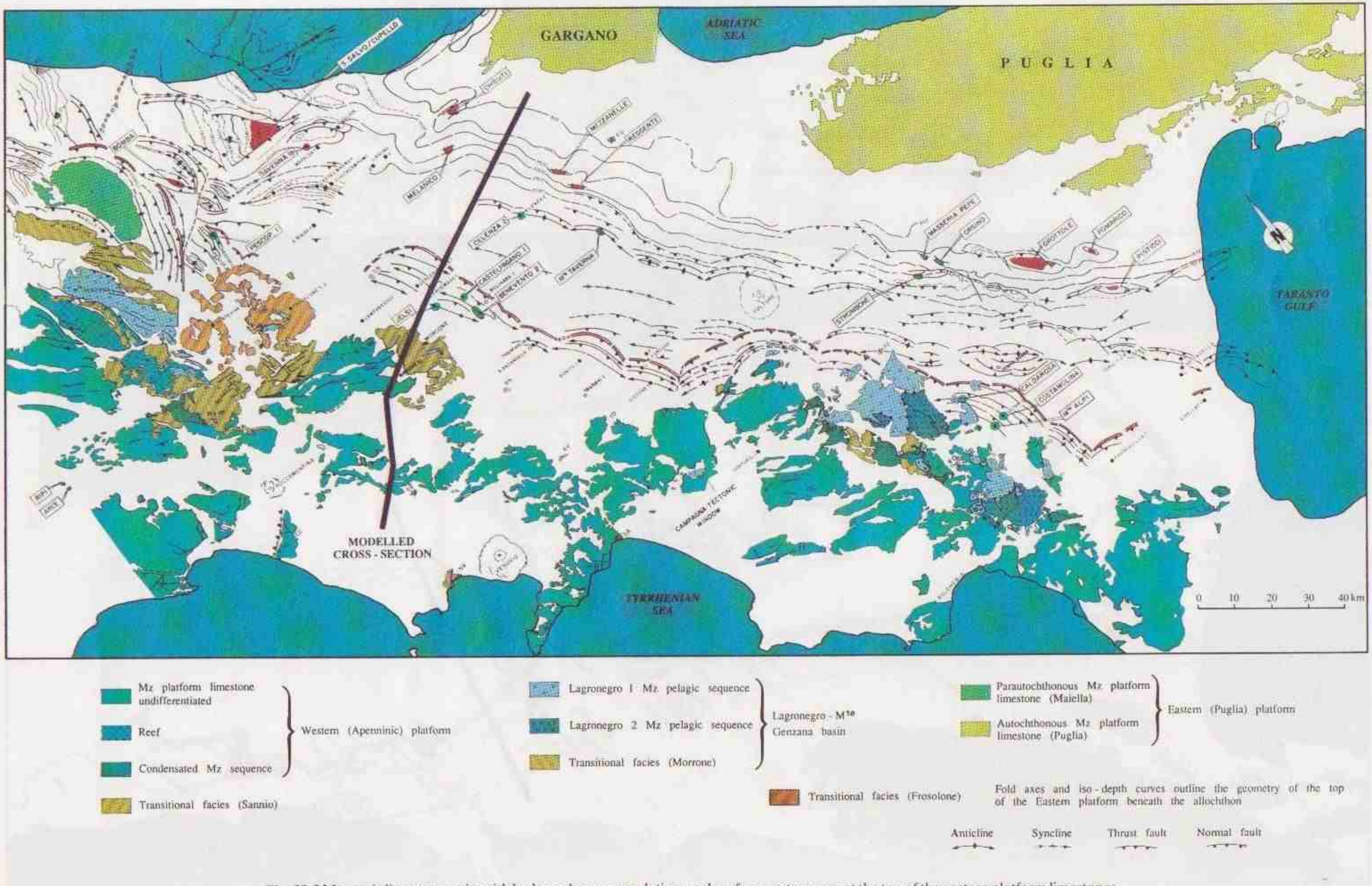

Fig. 29.3 Mesozoic limestone units with hydrocarbon accumulations; subsurface contours are at the top of the eastern platform limestones.

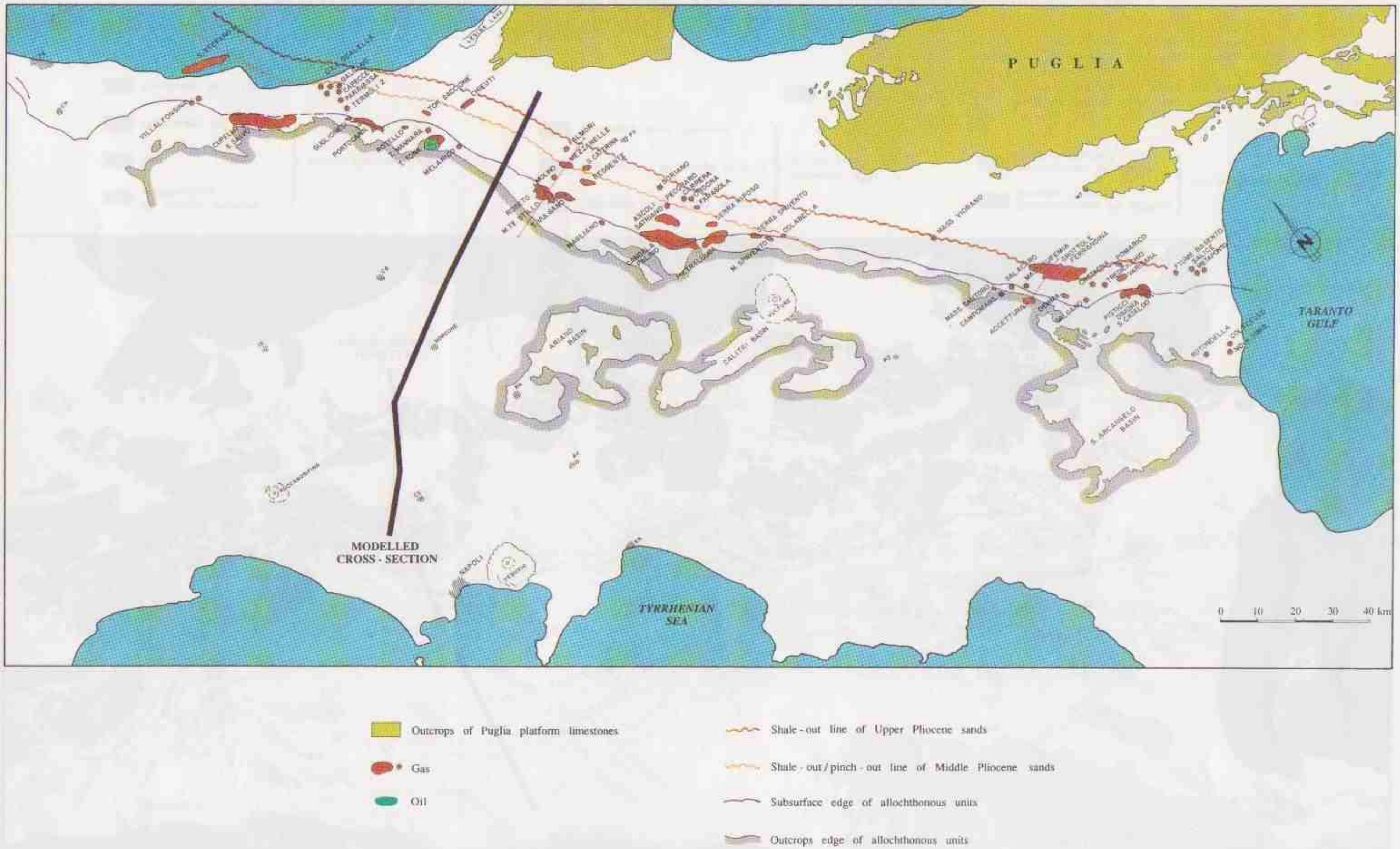

Fig. 29.4 Southern Apennines hydrocarbon accumulations in the terrigenous section.

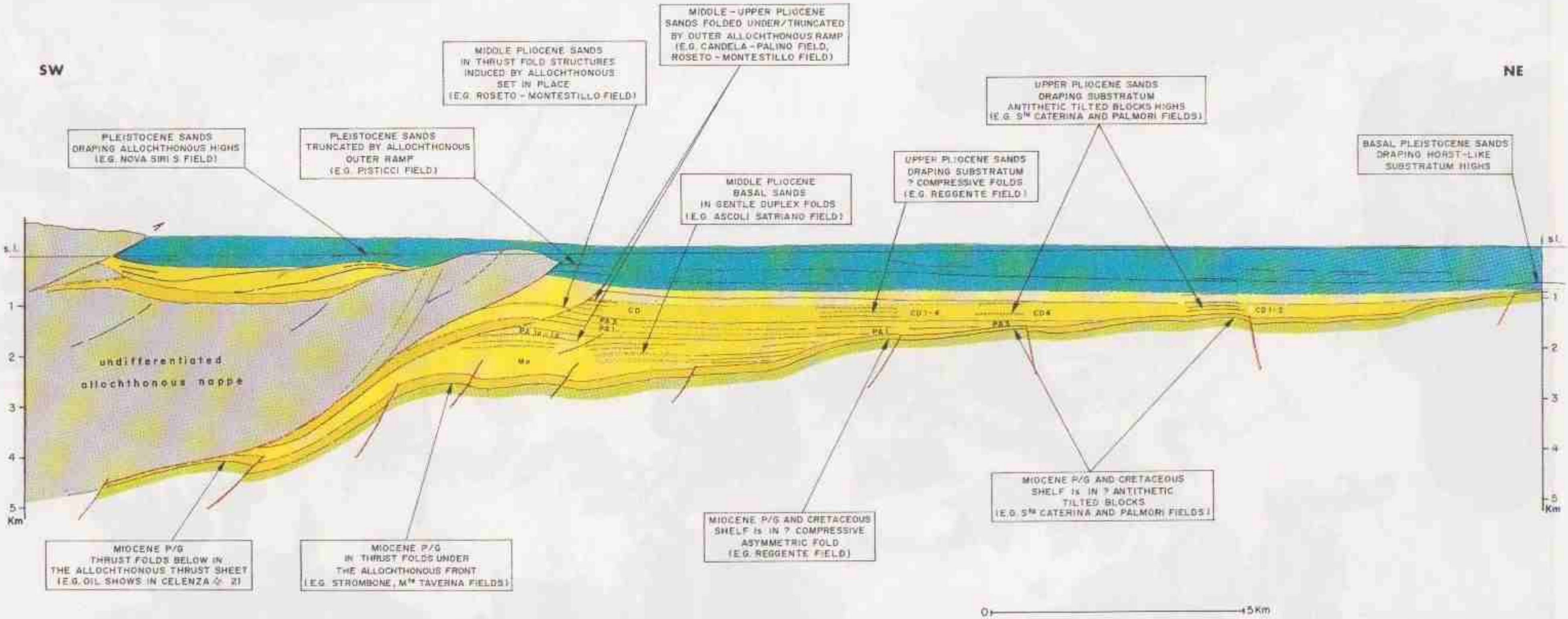

Fig. 29.5 Repertoire of hydrocarbon plays in the Bradanic trough