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Tectonic Setting of the Petroleum Systems of Sicily

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ABSTRACT

Petroleum systems in Sicily are divided between the Neogene fold and thrust belt of the Sicilian accretionary prism and its foreland. By far, more production has been established in the foreland on the Ragusa platform, where generally heavy oil from Triassic and Jurassic source rocks has been trapped in similarly aged fractured carbonate mound reservoirs. Traps are structures recurrently rejuvenated since the Cretaceous. Although models of source maturation and migration history emphasize Pliocene–Pleistocene charge related to subsidence in the foreland, occurrences of light oil and exploration data suggest intermittent periods of charge since the Mesozoic. Hydrocarbon deposits in the immediate vicinity of the thrust front, in the narrow foredeep depression, are also heavy and have characteristics in common with those more remote in the foreland from the front; they do not appear to have been significantly influenced by or mixed with oils from within the fold belt, although variations in their chemistry have yet to be investigated in terms of source correlation. Thrust sheets in the fold and thrust belt carry similar Mesozoic stratigraphy to the foreland, namely, a series of carbonate platforms and basins with potentially similar source rocks, and can reasonably be expected to have undergone a similar pre-Neogene history.

Commercial hydrocarbons in the fold belt, however, are limited to thermo- and biogenic gas-charged Tertiary reservoirs and questionably Tertiary-sourced oil offshore to the west. These all currently are viable exploration plays. Numerous seeps and tar deposits indicate that at least one petroleum system was active in the fold belt, but only one tar occurrence links that system to the Mesozoic carbonate section. Recent structural studies have indicated that a two-phase history of thrust emplacement and its redeformation by duplexing on lower detachments characterizes much of the Sicilian fold and thrust belt and affords exploration targets that have yet to be satisfactorily tested. Furthermore, structural petrological and fluid-inclusion studies in

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Neogene-thrusted rocks of the lower portions of the frontal fold belt indicate that a light hydrocarbon system used Neogene detachment surfaces as a preferential migration route in at least part of the accretionary prism.

Insofar as the foreland may give an insight into the early history of the fold belt platforms and basins, a general sense of the hydrocarbon migration history in the fold belt might include the following: (1) early maturation and migration of a variety of oils into carbonate mound reservoirs during a long period of time in the latter half of the Mesozoic and Paleogene (like in the foreland plays), bolstered by (2) a charge of immature oil generated during rapid depression in the foredeep immediately adjacent to the moving thrust front (yet to be demonstrated), and (3) generation of higher maturity oil and gas in the thrust wedge during stacking of thrust sheets and remigration and mixing with the earlier generated fluids (an untested play).

INTRODUCTION

Sicily lies astride a segment of the Apennine–Maghreb Mountain chain (Figure 1) that stretches from the Alps in Europe to the Atlas Mountains in North Africa and records most of the tectonic events involved in the complex interaction of Europe and Africa prior to and during the opening and closing of western Tethys. The island is surrounded by three seas (Figure 1) that frame the geology of Sicily. To the south, the western Mediterranean Sea is underlain by the Pelagian platform that includes onshore Sicily as well as Malta. Paleomagnetic data show no difference in apparent polar wandering paths between southeast Sicily and North Africa (Meloni et al., 1997, and references therein; Speranza et al., 2000, and references therein), thus firmly tying the geology of Sicily to that of North Africa, a situation that has persisted since the Permian (Stampfli et al., 2001). Mesozoic carbonates dominate the geology of the Pelagian platform and are built on stretched North African continental crust. A useful analogy to visualize the pre-Alpine situation might be a setting similar to and comparable in size to the modern Bahama Banks (adjusted of course for the biotic assemblage) adjacent to Tunisia and Libya. The Moho under the Pelagian platform is as shallow as 20 km (13 mi), and the Moho under Sicily ranges from 25 km (16 mi) in depth along the southern coast outside the fold belt to 30 km (19 mi) under the fold belt and 35 km (22 mi) along the northern edge of the island (Dal Piaz and Nicolich, 1991; Nicolich, 2001). Given something like 10 km (6 mi) for the thickness of the thrust stack (Catalano et al., 1993) and an allowance for pre-Permian sediments, it is evident that the continental crust of Sicily has undergone considerable thinning.

The Ionian Basin lies to the southeast of Sicily. It is the last remnant of Mesozoic oceanic crust in the central Mediterranean (Catalano et al., 2001), where it is subducting under the Calabrian Arc (Figure 1). The abyssal plain of the Ionian Sea (Finetti, 1981, 1985; Morelli, 1985) is separated from Sicily by a continent-ocean transition at the Malta escarpment. To the north, the Tyrrhenian Sea is composed of Neogene oceanic crust developed in a back-arc environment (Kastens et al., 1988).

The Pelagian crust, with its carbonate-dominated cover, has been colliding with a north-dipping subduction zone since the Miocene, and its northern fringe is deformed in the Sicilian thrust belt. Thus, although Sicily lies in the Apennine–Maghreb accretionary prism, its tectonic character is that of a foreland fold and thrust belt. It is composed of a complex stack of thrust sheets involving the Mesozoic platform and elements of Alpine crust, of the precollision forearc region, and of various syntectonic deposits. As a result, the prism is much more similar with retroarc fold and thrust belts around the world in terms of its architecture than it is to oceanic accretionary prisms, but its hydrocarbon systems are heavily influenced by details peculiar to Sicily's setting, particularly factors that isolate the foreland area from the fold belt proper.

In recent years, major discoveries have been made at the Val d'Agri fields in Basilicata on mainland Italy (La Bella et al., 1996), said to total nearly 1 billion bbl of oil recoverable (Holton, 1999), in environments that are similar to the fold and thrust belt in Sicily. Obviously, the sparsely explored fold and thrust belts of Italy may harbor major hydrocarbon potential, but the geology is difficult. Here, we review that geological history of Sicily, with a special emphasis on how it relates to hydrocarbon occurrences and thereby more generally to the behavior of fluids in the system.

HISTORY OF HYDROCARBON EXPLORATION

Hydrocarbons have been known in Sicily for many centuries from a variety of surface manifestations. For example, bitumen-impregnated limestones were used for building purposes in southeastern Sicily, largely because

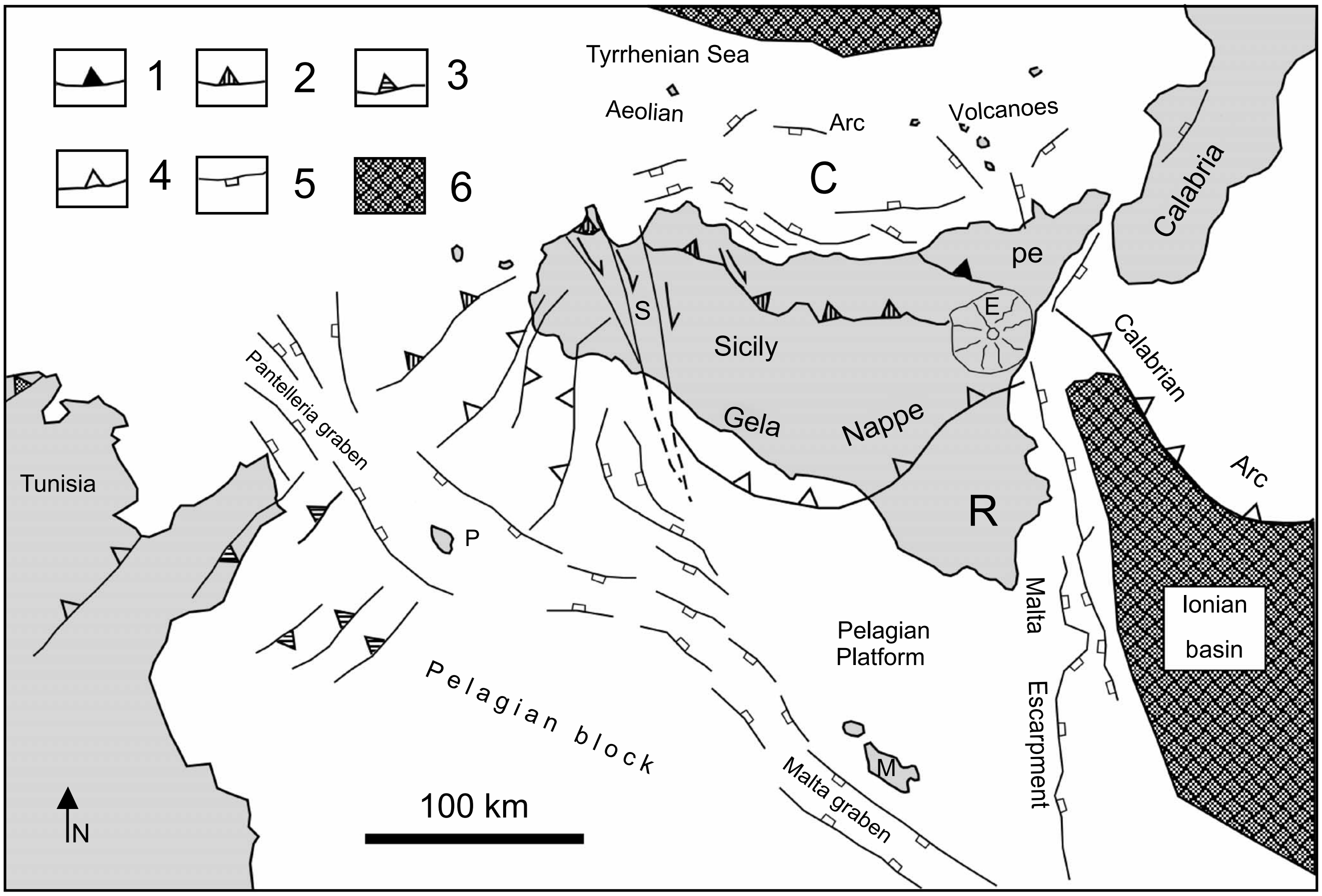

FIGURE 1. Tectonic sketch map of the Sicilian region. S = Segesta fault zone; C = Cefalù Basin; R = Ragusa plateau; pe = Peloritani nappe; E = Mt. Etna; P = Pantelleria Island; M = Malta; 1 = basal thrust carrying Peloritani Mountain sheet, including fundamentally European basement into the Sicilian accretionary prism; 2 = nappes associated with Neotethyan and northern platformal sections; 3 = foreland uplifts; 4 = deformation front of the Sicilian and Calabrian accretionary prisms and frontal front in Tunisia; 5 = extensional fault systems; 6 = oceanic crust in the Tyrrhenian and Ionian basins. Modified after Pepe et al. (2000) and Casero and Roure (1994).

of their ease of workability, and as a medium to fashion tubing for aqueducts, because of their impermeability (Kafka and Kirkbride, 1959; Mattavelli et al., 1993). Surficial asphalt deposits were exploited during the 19th and early 20th centuries, and several shallow wells were drilled before World War II. J. E. Thomas, a founder and the first president of the AAPG, recognized the southeastern dip of the Ragusa plateau away from its western-bounding normal faults (Figure 2) and the possibility that the structural culmination there afforded a focus for migrating hydrocarbons (A.W. Bally, 2003, personal communication). He initiated surface geological studies in the areas in the 1940s that predated the first modern exploration permits, which were signed beginning in the 1950s. Those studies eventually led to the discovery of Ragusa field in 1953 at the Ragusa-1 well (Figure 3). This was the first major oil discovery in Mesozoic reservoirs. Other discoveries followed both in Tertiary rocks and in the Mesozoic: Gela in 1956, Cammarata-Pozzillo in 1959, and the first offshore discovery in Gela-21, also in 1959. Onshore exploration peaked in 1959 and tapered off in 1970, in response to the heavy quality of oil discovered, difficult geology and marginal seismic quality, low oil prices, and the passage of a stricter Sicilian hydrocarbon law.

After 1969, part of the Sicilian offshore was opened to exploration, with the discovery of light oil at Nilde in 1972 and at Mila in 1978. The price boom of the late 1970s and the advent of digital seismic acquisition in Sicily spurred activity, and heavy crude was discovered at Perla in 1979, Vega in 1980, and Prezioso in 1983. A modest onshore resurgence of activity in the 1980s followed adjustments to the hydrocarbon law and better seismic acquisition and processing. Several small discoveries were made. Other parts of the offshore were opened at that time, but little success was realized. Since 1992, activity has been dormant both onshore and offshore, although the hydrocarbon law has once again been modified (this time to be similar to Italian law). Currently, several permits are held by several operators, but activity is minimal.

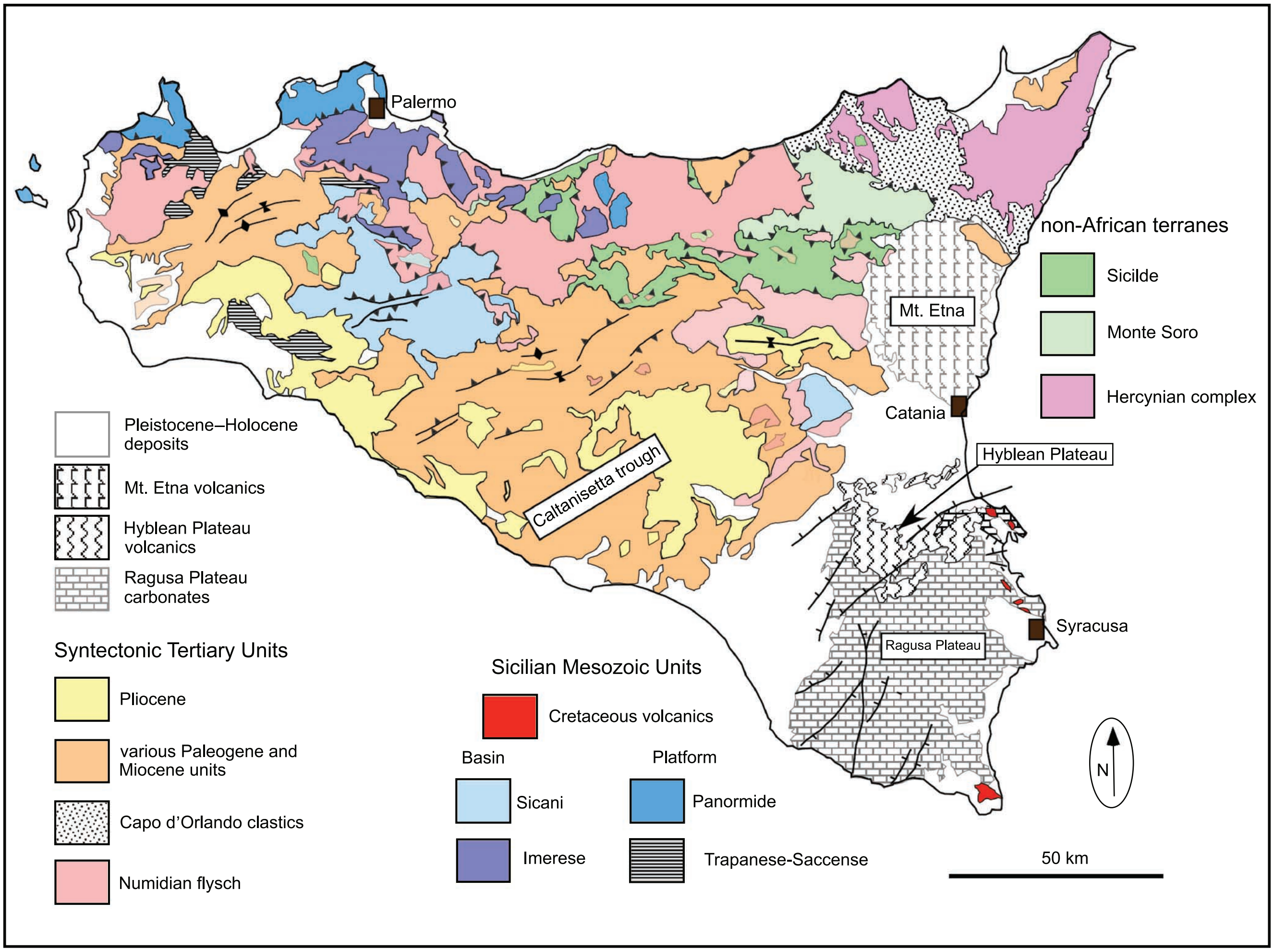

FIGURE 2. Geological map of Sicily generalized from Bigi et al. (1983).

Altogether, some 350 wells have been drilled, of which only 21 are offshore. Reserves are some 500 MMBO, with about half already produced. Gas totals about 500 bcf, of which just under two thirds has been produced. The principal fields are listed in Table 1, and the geological aspects of the various plays linked to those discoveries are tabulated in the Appendix in this chapter.

REGIONAL GEOLOGICAL FRAMEWORK

Tectonic Setting of Sicily in the Apennine–Calabrian–Maghreb System

The entire island of Sicily north of the Gela nappe front (Figure 1) is a strongly arcuate Neogene fold and thrust belt in the active accretionary prism that stretches continuously from the Apennine fold belt and Calabrian Arc in Europe to the Maghreb system of North Africa. It lies above a north-dipping seismogenic (Gasparini et al., 1985) subduction zone, along which most of the remnants of Tethys have been consumed and into which African lithosphere is currently being subducted (Amato and Cimini, 2001). The volcanic arc associated with the Sicilian sector is located to the north of the island itself in the Aeolian Islands, beyond the extensional Cefalù Basin. Synorogenic extension in the Cefalù Basin began synchronously with shortening in the accretionary prism, initially as a subaerial wedge-top basin, but it was much amplified later by extension and back-arc spreading in the Tyrrhenian Sea (Pepe et al., 2000). Extension in the Tyrrhenian Sea dates from rifting and clockwise rotation of Sardinia in the Tortonian to back-arc oceanic spreading in the late Pliocene to Quaternary.

Tectonic Elements in the Pelagian Platform

The Sicilian accretionary prism is thrust upon the Ragusa plateau, exposed in southeast Sicily, and bordered on its north by the chiefly volcanic Hyblean Plateau (Figures 2, 3). The Ragusa plateau is the major subaerial exposure of the Pelagian platform (Figure 1)

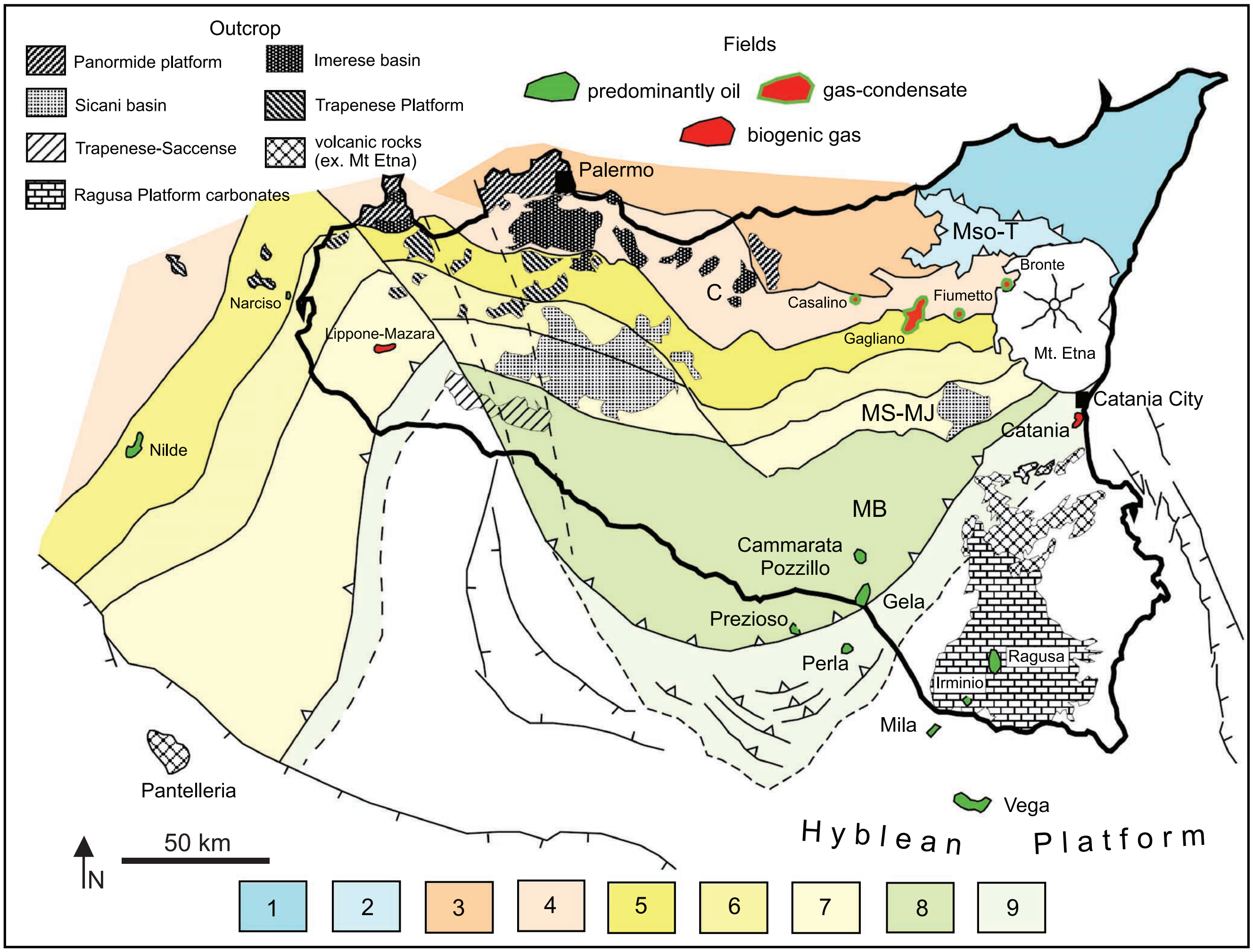

Figure 3. Map showing the sequential southward progression of foredeep (flysch) basins that envelope the Mesozoic hydrocarbon-bearing sequences. All units north of the Gela nappe front are allochthonous. Outcrop of the Mesozoic rocks and the hydrocarbon fields are shown in patterns. 1 = Peloritan crystalline terrain of European origin; 2 = Mt. Soro flysch, Neotethyan seafloor section; 3 = inner Numidian flysch and related Panormide platformal rocks; 4 = outer Numidian flysch and related Imerese domain basinal deposits; 5 = inner Messinian foredeep; 6 = central Messinian foredeep; 7 = outer Messinian foredeep; 8 = Gela nappe; 9 = Gela foredeep and the Carla trough (Tunisian trough). Areas mentioned in the text: C = Caltavuturo; MS–MJ = Monte Scalpello–Monte Judica; MB = Monte Bubonia; Mso-T = Monte Soro and Troïna. Modified after Roure et al. (2002, their figure 2).

outside of the island of Malta. Several of the important hydrocarbon deposits in Sicily are trapped in structures in the Ragusa plateau, i.e., Vega, Mila, Ragusa, and Irminio fields (Figure 3; Table 1).

Since about 0.5 Ma, the northern part of the Pelagian platform, including Malta, has been decoupled from the rest of Italy, from the Pelagian block of North Africa, and the Ionian Basin by recurrent tectonic activity of two major tectonic zones. This triangular-shaped area is bounded on the east by the Malta escarpment and the southwest by the Pantelleria and Malta graben (Figure 1), otherwise known as the Medina wrench system (Jongsma et al., 1987).

At the east end of the island, just south of Mount Etna, the thrust front intersects the northern extent of the Malta escarpment, locally known as the Siracusa escarpment, to connect to the Calabrian Arc at a major inflection in the Neogene thrust front (Figure 1). The Malta escarpment extends to the south-southeast for some 250 km (150 mi) to the Malta graben, separating the Pelagian platform from the Ionian abyssal plain to the east. The ocean-continent transition at the escarpment dates from pre-Alpine time and could have suffered inversion in the Alpine collision. Late Miocene to Quaternary block faulting is documented on the escarpment (Groupe Escarmed, 1983). Contemporary volcanism is concentrated at the junction of the Siracusa escarpment and the thrust belt in the Mount Etna area. Pre-Etnan basaltic volcanism began at about 5 Ma and was later superceded by the trachyandesites and

Table 1. Principal oil and gas fields of Sicily.

	Location	*API (°)*	*Reservoir*	*Age*	*Depth (m)*
Nilde	offshore; west	39	Nilde limestone	middle Miocene	1560
Narciso	offshore; west	29	Fortuna limestone	Oligocene	1920
Lippone-Mazara	onshore; west	gas	Terravecchia sandstone	Tortonian	630
Prezioso	offshore; Hyblean	19.5	Gela limestone	Triassic	4950
Gela	onshore; Hyblean	10	Noto-Gela	Triassic	3200
Cammarata-Pozillo	onshore; Gela nappe	7–10	Siracusa limestone	Liassic	3200
Ragusa	onshore; Hyblean	19.3	Gela dolomite	Triassic	1750
Mila	offshore; Hyblean	36	Noto limestone	Triassic	3400
Irminio	onshore; Hyblean	31	Noto limestone	Triassic	2500
Vega	offshore; Hyblean	16	Siracusa limestone	Liassic	2500
Catania	onshore; east	biogas	Ribera sandstone	Pleistocene	500
Gagliano-Fiumetto	onshore; fold belt	gas-condensate	Collesano sandstone	early Miocene	1600–2200
Bronte	onshore; fold belt	gas-condensate	Collesano sandstone	early Miocene	1250

trachytes of Etna itself (Behncke, 2001). The bimodal volcanic progression suggests that rifting, in conjunction with the arc setting of Etna, is fundamentally important (Serri et al., 2001), but the details of the magma genesis are controversial. Flexure-related reactivation at the ocean-continent transition may take the form of a tear or a rift in the subducting lithosphere that permits differential flexure or rollback of the slab and access of magma generated in the surrounding mantle and downgoing slab to the surface (Di Geronimo et al., 1978; Gillot et al., 1994; Continisio et al., 1997; McGuire et al., 1997; Monaco et al., 1997; Gvirtzman and Nur, 1999; Doglioni et al., 2001).

Transecting the Pelagian platform south of Sicily are the Pantelleria and Malta graben (Figure 1), which intersect the Malta escarpment southeast of Malta itself and eventually are masked by the accretionary prism at the Mediterranean Ridge some 200 km (120 mi) to the east. This is a complicated mosaic of thrust, normal, inversion, and transcurrent faults, generally forming a right-lateral system whose activity dates from the late Aquitanian to Pliocene in Malta (Dart et al., 1993). Quaternary sedimentary infill and associated volcanic rocks (Illies, 1981; Groupe Escarmed, 1983; Cello, 1987; Calanchi et al., 1989) indicate that this zone has recently been active. Jongsma et al. (1987) have suggested on plate kinematic grounds that this broad zone of deformation forms a transform plate boundary marking as much as 100 km (62 mi) of right-lateral motion between Africa and a Hyblean microplate (Mazzoli and Helman, 1994). The relative offset in the internal nappes of the Maghrebs vs. Sicily (Figure 1) is of comparable size, but the motion may be overestimated. The offset may represent a lateral ramp, however, as the structures may not be perfect piercing points. Indeed, Casero and Roure (1994) have traced facies patterns across the zone with little offset.

Possibly more important to Sicily itself but poorly documented in the literature is the Segesta lineament, a north-northeast trend bisecting the major fold belt syntaxis in western Sicily (Figures 1, 3). This feature juxtaposes differing facies and structures across strands of a (presumably) tear fault in the allochthonous units. Within the allochthons, the Segesta zone probably functions as a lateral ramp to the thrust sheets and aids the internal kinematics of the fold belt, which involves significant rotations (see below). Its projection into the foreland on the Pelagian platform is subtle; it displaces pre-Tertiary sedimentary facies (Casero and Roure, 1994), presumably through reactivating older crustal-scale structures.

Heat Flow, Volcanism, and Recent Uplift

Heat flow is generally elevated across Sicily (Figure 4), especially so along the Malta and Pantelleria graben and in the Aeolian Islands, but also in a trend across the Ragusa and Hyblean plateaus north through Mount Etna. Mount Etna has been mentioned in connection with its relationship to the Malta escarpment (Figure 1), but all three of these areas are characterized by young volcanism, generally basaltic in character (Serri et al., 2001, and references therein). Della Vedova et al. (2001) emphasize water circulation in connection with the southeastern Sicily anomalies, but the area has experienced recurrent volcanism since the Jurassic (Figure 5). Basalts and tuffs occur in the Jurassic Streppenosa, Modica, and Buccheri formations and prominently in the Late Cretaceous Amerillo Formation (Patacca et al., 1979; Scandone et al., 1981, Rocchi et al., 1996). Scandone et al. (1981) report similar rocks from dredge sites to the east on the Malta escarpment. The same area of southeastern Sicily also shows high and variable magnetic anomalies (Chiappini et al., 2000), which, if caused

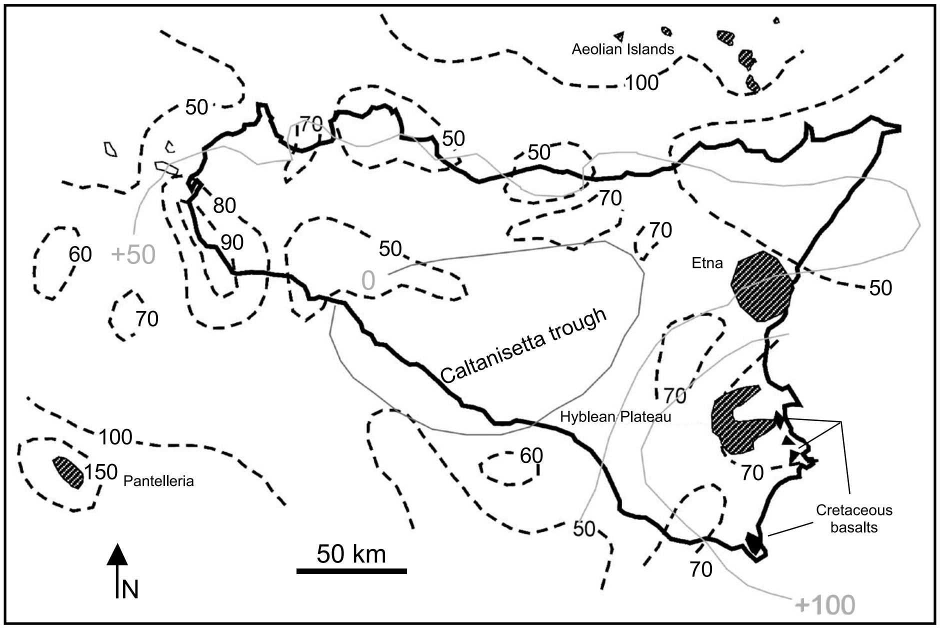

FIGURE 4. Heat flow and Bouguer anomaly sketch map of Sicily, also showing distribution of in-situ volcanic rocks, mostly basalts, and Mt. Etna. Heat flow in milliwatts per square meter after Della Vedova et al. (2001). Bouguer anomaly in milligal after Carrozzo et al. (1986). Locations of volcanics after Serri et al. (2001).

by volcanics distributed in the section, suggest that a very large area of southeastern Sicily experienced volcanism for a major part of the Mesozoic. Insofar as that volcanism may have been associated with periodic extension, heat flow is likely to have been at least mildly elevated for the majority of the post-Triassic history of the area.

Elsewhere in Sicily, heat-flow anomalies occur mainly in areas where carbonates occur at or near the surface and where structural studies suggest that stacking of carbonates characterizes the fold belt. The coincidence of a large area of uniform normal heat flow with a normal Bouguer signature in the Caltanisetta trough in central Sicily (Figure 4), where carbonate stacking is minimal, may indicate that the high heat flow is a ramification of the near-surface lithologies and associated water circulation.

GEOLOGY OF SICILY ITSELF

Stratigraphy of Sicily

The stratigraphy of Sicily has been approached from many vantage points. The most convenient, in view of the complexity of the physical stratigraphy, is to divide the coverage into that of the Ragusa plateau outside the fold belt (columns 7 and 8 in Figure 5) and that in the fold belt (columns 1–6). Figure 5 is offered here to summarize the general distribution of units in Sicily and to link them to the occurrences of hydrocarbons. In the southeast, on the Ragusa plateau, Patacca et al. (1979) remains the standard reference and is used here in column 7 of Figure 5. It supercedes the nomenclature developed by Rigo and Barbieri (1959) and Schmidt Di Friedberg (1965), which used formational names from disparate and tectonically separated localities. Nevertheless, this older nomenclature has persisted in the petroleum industry and is shown in column 8 of Figure 5 for reference only.

The Sicilian terranes of African origin (columns 3–8 in Figure 5) are broadly similar to sequences elsewhere in Italy and are composed of thick, platformal sequences of shallow-water carbonates with intervening deep-water, basinal sections of cherty limestones and radiolarian cherts, both superceded by open-marine and pelagic limestones and argillites. This tectonostratigraphic arrangement developed during and after Triassic and Early Jurassic crustal thinning and intracontinental rifting along the northern African margin. The platform-basin system persisted through the Jurassic and the Cretaceous into the Paleogene, with the filling of the basinal region and the development of shoaling indicators such as bauxitic horizons and rudist reefs on the platforms. In the southeasternmost parts of Sicily, the Ragusa plateau represents the exposed portion of the autochthonous Pelagian platform (Patacca et al., 1979), separated from the thrust front by the narrow Gela foredeep of middle to upper Pliocene and Pleistocene sediments (Figure 2). From Oligocene onward, the stratigraphy is dominated by clastics and marls that herald the impending deformation, molasse deposited in the foredeep of the southward-advancing thrust belt, and suprawedge piggyback basins.

Tectonostratigraphic Components of the Sicilian Accretionary Prism

Sicily is composed of several tectonostratigraphic provinces telescoped together during the Neogene orogeny between the Serravelian and the present (Figure 6). The bulk of the island has clear affinities with African geology, but in the northeastern corner of Sicily, the Peloritani Mountains are composed of fundamentally

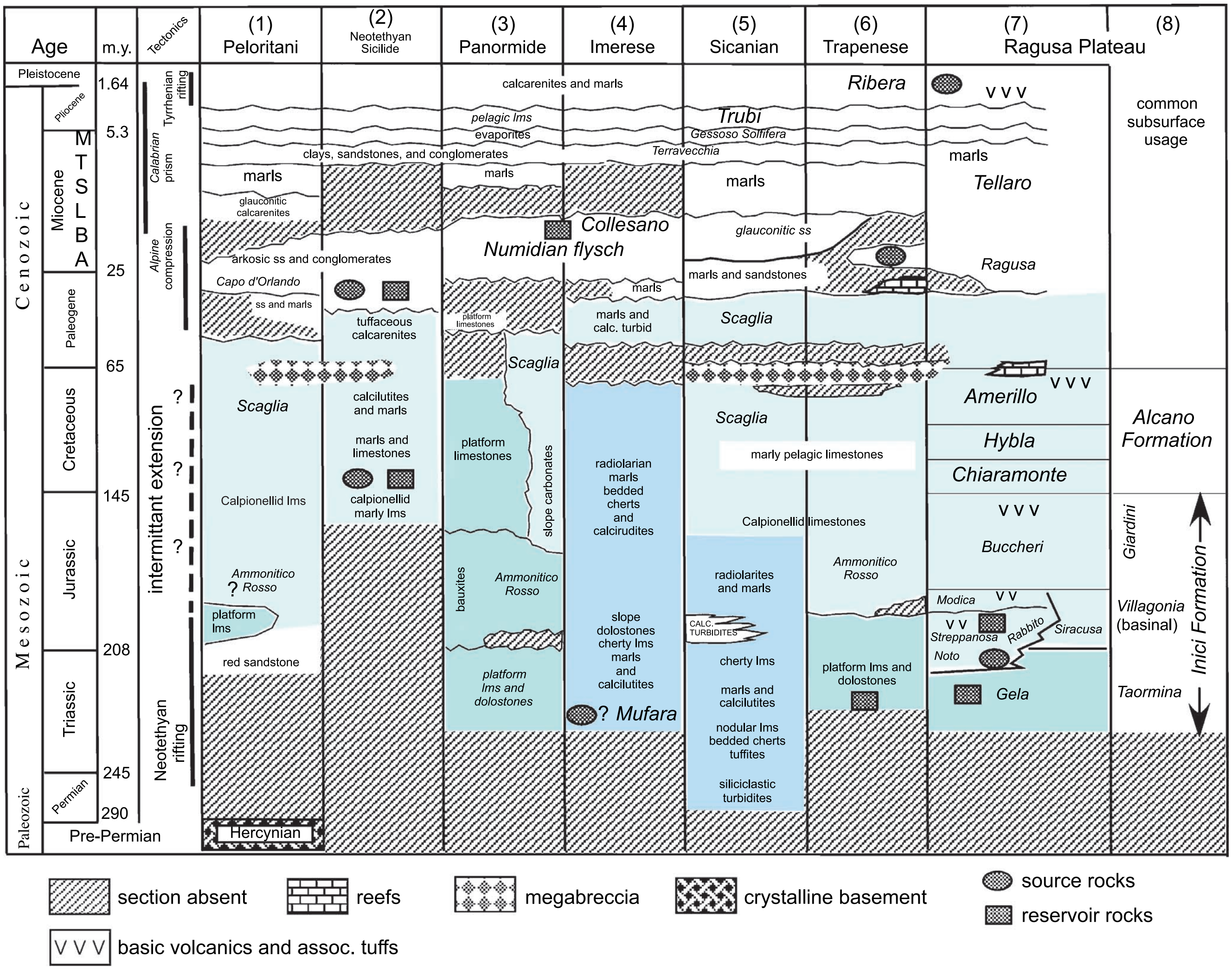

FIGURE 5. Stratigraphy of Sicily and associated source and reservoir rocks. Columns correspond to the various lithostratigraphic domains. Formation names in italics, rock types in standard font. Columns 1–6 for the fold belt after Catalano et al. (1993, 2000) and Ronchi et al. (2000). Usage of formation names for the Ragusa platform (column 7) from Patacca et al. (1979) and in column 8 as is commonly used in the subsurface, e.g., in well logs, after Rigo and Barbieri (1959) and Schmidt Di Friedberg (1965). Shades of blue denote various important carbonate environments: dark blue = basinal facies, medium blue = platforms, and light blue = various open-marine and pelagic facies, including the Streppenosa basin. Miocene stages: M = Messinian, T = Tortonian, S = Serravalian, L = Langhian, B = Burdigalian, A = Aquitanian. Timescale from Harland et al. (1989). lms = limestones.

European Hercynian basement and tectonically juxtaposed Mesozoic sedimentary rocks, both overlain by late Oligocene and younger coarse terrigenous strata, Messinian evaporitic, marly, and calcarenitic strata (Maccarrone et al., 2000). The Peloritani Mountains lie in thrust contact above a Late Jurassic, Cretaceous, and Paleogene sequence (Figures 2, 3, 6) of flyschlike turbidites (especially well exposed in the Monte Soro and Troïna areas) (Figure 3) that, by reason of a major late Eocene unconformity, is commonly interpreted to have been deformed during late Alpine events (Roure et al., 1990, and references therein). The Monte Soro and Peloritani lie in thrust contact over a Cretaceous to lower Miocene assemblage of flysch units, the Sicilide nappe, apparently deposited in the Tethyan ocean and thrust onto the fundamentally African Sicilian section. Hence, the northeast appears to be Tethyan and European in origin and is foreign to the African terranes over which it has been thrust.

Within the fold and thrust belt, the Mesozoic is represented by several platformal and intervening basinal units that are now interdigitated in the allochthons (Figure 6). The Panormide platformal unit outcrops in the north along the coast (Figures 2, 3), where it lies structurally above all other African terranes and below the Tethyan underpinnings of the Peloritani. In western Sicily, to the south and west of Palermo, the Trapanese–Saccense platformal units lie structurally below the Panormide and intervening basinal facies, where they

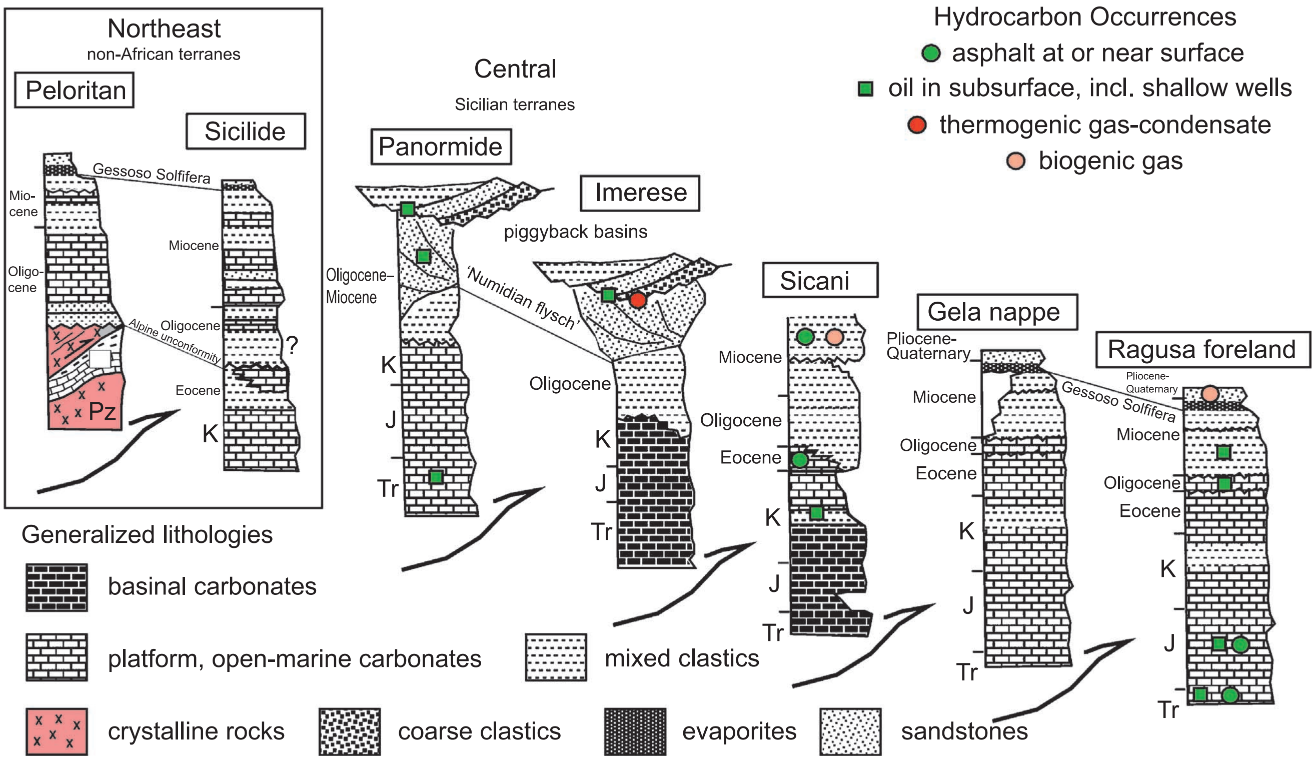

FIGURE 6. Tectonostratigraphic relationships between the various allochthonous units in Sicily and the Ragusa foreland and occurrences of hydrocarbons. See Figure 5 for more conventional stratigraphic detail. Inset shows relationship in the northeast: Peloritan (European nappe emplaced over Tethyan Sicilide, which, in turn, are emplaced over Sicani terrane). In central Sicily, the Panormide and Imerese are thrust over the Sicani. Emplacement ages especially of the more internal units are a matter of controversy (see De Capoa et al., 2000, and references therein). Emplacement of the Peloritani and Sicilide units over the Panormide, for example, is commonly considered Aquitanian, but De Capoa et al. (2000) argue for an age no older than Burdigalian. The more external units were emplaced in the Messinian, and the Gela nappe is commonly considered Pliocene–Pleistocene in age. Elements of figure after Roure et al. (1990).

are imbricated and thrust above their foreland equivalents in the subsurface (Catalano et al., 2000).

Two major basinal units are involved in the thrust belt. The Imerese unit is the major Mesozoic basinal unit southwest of Palermo to the south of the city of Cefalù (Figure 2) in structural windows through overlying thrust sheets containing the Panormide unit, Numidian flysch, and Neogene synorogenic sediments. A similar unit occurs south of the Imerese and in east-central Sicily 25 km (16 mi) southwest of Mount Etna, the Sicani unit. Both are composed of deep-water carbonate sections with important occurrences of alkali basaltic rocks that are related to the Triassic–Jurassic fragmentation of the carbonate platform (Lucido et al., 1978; Guarnieri et al., 2000).

Associated with the Panormide and Imerese units in the north is a nappe of Numidian flysch, which represents distal offshore African Neotethyan deposition that was caught up in the accretionary prism in the early phases of deformation in Sicily. It lies in thrust contact over both the platform and basinal units and in apparent depositional relationship to upper Miocene units in the fold belt. Thus, it represents a sedimentary unit deposited into and tectonically emplaced onto the northern side of the Sicilian passive margin before Neogene imbrication of the Mesozoic section itself. Presumably, it was derived from the Tethyan ocean floor, accretionary complex, or the trench immediately north of Sicily prior to the arrival of the northern reaches of the Pelagian platform.

Paralleling the north-to-south progression of Neogene deformation is a continuous sequence of foredeep deposits ranging in age from Aquitanian in the north to middle Pliocene in the Gela foredeep (Figure 3). Presently, they are either involved in the thrust sheets with their substrate or form piggyback basins carried southward with the progression of the thrust front. They form a large part of the outcrop in Sicily (Figure 2). These units record

- the systematic deepening of deposition as the Pelagian platform and its northern equivalents entered the foredeep and approached the leading edge of the Sicilian accretionary prism and
- synorogenic wedge-top deposition in piggyback basins during the southward progression of the thrust belt.

Emplacement of the Thrust Sheets of Sicily

Outside the Ragusa plateau in the southeast, all the platforms and basinal units alike are entirely allochthonous (Figure 3), being detached along surfaces in the Triassic and locally in the Permian (Roure et al., 1990) much like the mainland Apennine chain (Bally et al., 1986). Highly deformed red and green argillites in the Cretaceous and Paleogene section mark the base of many of the thrust sheets. Although previously thought to be olistostromes (Rigo de Righi, 1957; Broquet et al., 1984), these "argille varicolore" are more probably tectonic in origin and are the sole representatives of melange in the Sicilian accretionary prism (Roure et al., 1990).

Relationships among the thrust sheets are complex. Paleomagnetic data clearly indicate that the sheets have undergone large differential rotation with respect to the foreland and North Africa, generally a clockwise rotation (Channell et al., 1980, 1990; Oldow et al., 1990; Speranza et al., 1999), thus contributing to the strong arcuate character of the Gela front. Also contributing to the rotational history of sheet emplacement and the asymmetry of the Gela salient are several strike-slip faults, functioning primarily as lateral ramps during thrust emplacement, but also locally facilitating escape blocks from west to east (Monaco et al., 1997) and linking extensional elements near the north coast (Abate et al., 1998; Renda et al., 2000). The allochthonous structures onshore are pervasively overprinted by normal faults that presumably contributed to the maintenance of a critical taper as the fold belt has developed and underwent uplift (Roure et al., 1990).

STRUCTURAL STYLES AND TRAPS

General Statement

The surface geology of Sicily is exceedingly well mapped, particularly by programs at the universities in Palermo and Catania [e.g., in the Ragusa plateau by Lentini (1984) and Grasso (1999) and in key areas of the fold belt, such as those by Di Stefano and Vitale (1993) and Catalano et al. (1978)]. *The Structural Model of Italy* (Bigi et al., 1983) summarized those efforts up to 1983 and stands as a standard small-scale reference. What is clear from the mapping are both the complexity of the structural geology and the shallow level of exposure, especially in the fold belt. This is a subaerial fold belt with much of its young carapace intact. Neogene units dominate exposure in Sicily (Figure 2), and although they are intimately involved in the deformation, in many cases, they obscure the deeper structure. The lateral discontinuity of the thrust systems in Figure 2 illustrates the point. Note also that there are several cases in Figure 2 where thrust sheets that are stacked in standard older-over-younger relationships are cut by thrust faults that emplace younger units over older units. Seismic imaging is consequently difficult and further hampered by the rough terrain and the dominantly carbonate character of much of the section.

Structural Styles and Traps in the Foreland

Structures in the southeastern Sicily harbor the overwhelming bulk of the discovered hydrocarbon deposits in Sicily, especially the liquid ones. The discoveries on the Ragusa plateau are located on a north-northeast-trending high bounded by normal faults (Figure 2) that attracted Thomas' attention to Sicily in the 1940s. Local dip reversals on the otherwise southeast-dipping plateau that have survived from the Oligocene to the present seem to afford the best traps.

The traps throughout the southeast are intimately related to the stratigraphic architecture of the Triassic and Jurassic carbonate section in the Streppenosa basin (Figures 3, 5), isolated and modified by recurrent normal faulting that initiated during the Tethyan regional extension. Most of the fields are related in some way to different facies of carbonate buildups in the otherwise subsiding Streppenosa intraplatformal basin (Patacca et al., 1979). Ragusa, Gela, Irminio, Mila, and possibly Perla fields sit on reef mound highs in the basin. Cammarata field appears to be developed in resedimented carbonate derived marginally from a nearby high, and Vega appears to be near a particularly sharp edge of a carbonate buildup. Insofar as these are Mesozoic, ramp-style biohermal mounds (as opposed to true reefs) in the carbonate platform, Pedley (1990) has argued that the shelf-edge fields are localized and sharpened by syndepositional faulting. Indeed, Ragusa and Gela both have undergone repeated rejuvenation, evidenced through the many unconformities and thinned section across the structure both in the Early Jurassic and intermittently since (Kafka and Kirkbride, 1959; Rocco, 1959). Lindsey et al. (2002) described the structural setting of Irminio in terms of a reverse fault that separates the field from Ragusa, presumably a Neogene reactivation of an earlier normal fault.

No commercial deposits of oil and gas have been discovered outside the Streppenosa basin in the southeastern Sicily foreland (Figure 3), that is, elsewhere on the more stable platform in areas characterized by the development of Siracusa formation (see column 7; Figure 5). Only gas and oil shows have been encountered in the handful of wells involved, which has led Pedley (1990) to surmise that cap rocks have not developed to seal traps and/or that the traps are isolated from hydrocarbon sources by low-permeability facies, thus affording no carrier horizons to charge the structures.

Architecture in the Fold and Thrust Belt

A complete review of the structure of the Sicilian fold and thrust belt is beyond the scope of this chapter, but several points are germane to a discussion of the petroleum systems for two major reasons. The details of the structure, of course, dictate the traps in the petroleum systems, but in addition, palinspastic restorations of the Neogene deformation would define the distribution of potentially source-bearing rocks in basinal sections relative to traps as the system evolved. Insofar as the Streppenosa basin is the major source region for the Pelagian platform hydrocarbon occurrences (see below), similar potential source intervals are of major interest in the thrust belt.

Block rotations aside, the Sicilian fold and thrust belt conforms to the forward-vergent, piggyback style of deformation familiar from fold belts worldwide. Its architecture is defined by several dominant detachment levels. Ignoring the intracrystalline detachment under the Peloritani, horizons near the base of the Mesozoic carbonate section form the basal detachment of the whole system (Figure 6) as in the Apennines. The decollement typically ramps across the Mesozoic carbonate section into one or more horizons in the Cretaceous and Paleogene argillites or into the Miocene and Pliocene evaporates and shales, the latter especially near the thrust front. The thrust front is commonly a triangle zone that developed above the detachment localized in the Miocene or Pliocene.

Tectonic inversion of the older Mesozoic normal faults is evident in the Gela trough, and their preservation into the Neogene is an important trapping mechanism. Within the fold and thrust belt itself, pre-Neogene inversion structures have probably been a significant factor in migration and trapping, but the Neogene overprint has, for the most part, precluded their recognition. Major unconformities in the fold belt, however, where Paleogene sections lie over older Jurassic basinal facies as in the Monte Scalpello–Monte Judica area (Broquet, 1968; Pion-Leflaive et al., 1990; Larroque, 1993) and in the Imerese domain near Caltavuturo (Figure 3), may in fact represent Alpine inversion features (Casero and Roure, 1994).

As evident in Figure 2, there is considerable complication in the thrust sheets because of both duplexing of the Mesozoic and numerous minor detachment levels, which give rise to the most obvious exploration targets. The Gagliano gas-condensate field (Figure 3; Table 1), for example, with approximately 700 bcf initially in place, is the largest and most important onshore field in the fold and thrust belt. Production is from the Miocene Collesano formation (Figure 5), in thrust slices composed of the section from the Mesozoic carbonates to Oligocene–Miocene (Numidian) flysch, yet the field lies below minor folds in the flysch associated with intraformational detachments.

The map pattern of the Sicilian fold and thrust belt (Figure 2) is a patchwork of klippen, piggyback basins, breached anticlines, and tectonic windows, suggesting that deeper structure has caused redeformation of the now-exposed nappes and had a strong influence on outcrop pattern. Bello et al. (2000) have combined two- and three-dimensional seismic data, well information, and gravity and magnetic data to develop a comprehensive picture of the deformational history of the fold belt in eastern Sicily (Figure 7A). A two-phase picture of accretionary wedge development resulted from their study, with an initial emplacement of allochthonous units over the now-buried northern reaches of the Pelagian platform in the latest Oligocene and Miocene. Forward progression of the wedge on sub- and intra-Mesozoic detachments cut southward redeforming higher thrust sheets and duplicating the Mesozoic section at depth as far south as the Numidian flysch belt in the Gagliano area (Figures 3, 7). Windows occur where the shallower, older thrusts have been exposed in folds above buried ramps that branch from the sub-Mesozoic detachment (Figure 7). Pliocene–Pleistocene piggyback deposition has been preserved south of the tip of the deeper second-generation Mesozoic wedge, where backthrusts have facilitated its emplacement, and north of the younger south-vergent ramps. Because the syntectonic basins appear to occupy flats in the younger deformational system, they date the southward progression of the basal detachment. This younger phase of deformation presumably facilitated thickening of the thrust wedge and its southward advance through a process of tectonic underplating of younger para-autochthonous thrust wedges under older, higher thrust sheets. The outcrop of Sicani basinal section (Figures 2, 3) in east-central Sicily is particularly important in that it implies the exposure of the deeper structure containing potential source in the fold belt.

Similar structural relationships occur in the west, where Catalano et al. (2000) report a superstructure of basinal carbonate facies Mesozoic rocks (the Imerese and Sicani domains of Figures 2, 3) along with Numidian flysch, which was emplaced during the Miocene and redeformed above younger thrust sheets that are composed of the platformal Trapanese and Saccense carbonates during the latest Miocene to the Pleistocene (Figure 7B).

The deeper parts of Figure 7B differ from their interpretation, which deserves some comment. Their plates I and II show three major detachments. The highest emplaces the basinal Imerese–Sicani section over the platformal Trapanese–Saccense with an undetermined

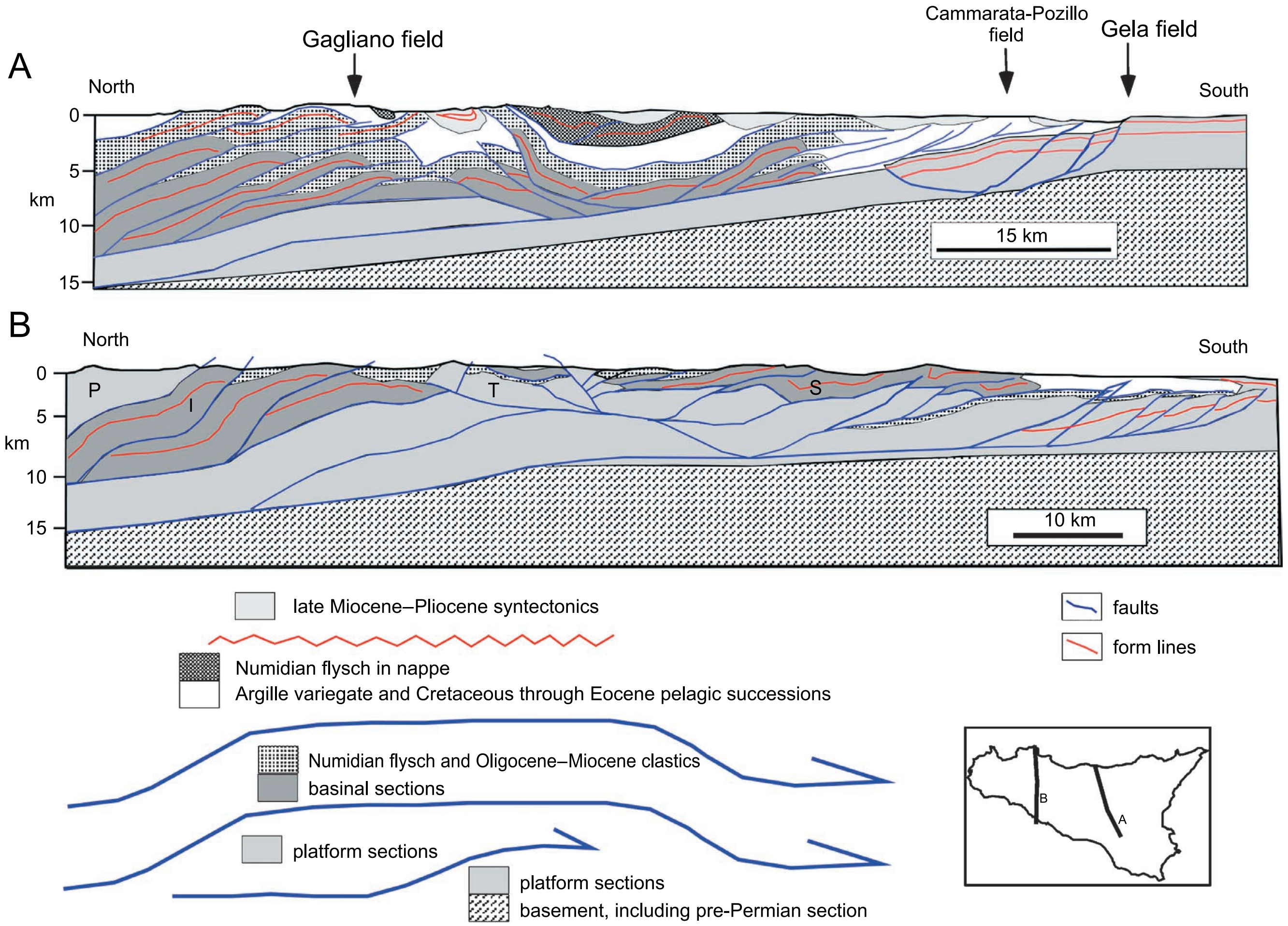

Figure 7. Generalized crustal-scale structure sections across Sicily. The major oil and gas fields indicated in the figure are shown in analogous positions to their true locations. Key indicates the emplacement sequence: para-autochthonous sheets of platform rocks of the Hyblean domain refold higher sheets during emplacement. Section A redrawn and modified from Bello et al. (2000). Section B reinterpreted as described in the text from Catalano et al. (1996, 2000). Section B is also extended into the offshore to the south and to the north where the Panormide domain is thrust on Imerese. Late normal faulting overprint is neglected. P = Panormide, I = Imerese, T = Trapanese, and S = Sicani domains (terranes).

distance. The underlying Trapanese–Saccense, in turn, is thrust some 50 km (30 mi) to the south on a detachment overlying Oligocene–Miocene terrigenous rocks, carrying the basinal section piggyback style. Finally, the deepest detachment redeforms these two upper nappes on a sequence of para-autochthonous thrust slices that stretches to the south coast. Hence, the overall shortening of Catalano et al. (2000) telescopes the section to about a third of its original length and implies that the basinal section originally lay outboard (to the north) of both slabs of Trapanese–Saccense platform. Figure 7B accepts the shallow seismic and well-controlled interpretation from Catalano et al. (2000) but takes a more conservative point of view on the shortening, similar to the sections in Catalano et al. (1996). The shallow deformation is attributed to the duplexing of the platformal underpinnings of the allochthonous basinal section in a similar fashion to Bello et al. (2000), which is generalized here in Figure 7A. The net effect is to more intimately associate the basinal sections with the platforms, thus also taking a more optimistic viewpoint on the exploration potential of the west, especially in light of the many hydrocarbon occurrences there (Figure 8).

The younger phase of the fold-belt development generated the most attractive exploration play in the Sicilian fold belt. Duplexes, ramp anticlines, and refolded higher sheets can generate closures in the buried structure that constitute an as-yet unrealized play in both the carbonate Mesozoic and its overlying siliciclastic cover. As Bello et al. (2000) demonstrate, newer, better seismic data are necessary over much of Sicily to test this play.

SOURCE ROCKS AND OIL-TO-SOURCE CORRELATION

Source Distribution

Proven thermogenic source rocks throughout the central Mediterranean are associated with Mesozoic basinal facies and the margins of those basins. The best developed occur in Triassic to Jurassic anoxic intraplatformal basins and troughs (Zappaterra, 1994) that developed on the margins or wholly in platformal areas, where relatively straightforward source-to-reservoir migration routes are available to charge traps. In Sicily, the Streppenosa basin (Figure 8 and column 7 of Figure 5) is an archetypical example, where the bulk of Sicily's oil fields lies (Figure 3).

Tertiary source facies have been established in the fold belt (Figure 5). However, the distribution of Mesozoic source facies is problematic. Although the Sicani and Imerese basinal facies outcrop in the fold belt, their generative potential is yet to be established. The Mufara Formation is a putative source interval but yet to be typed to any hydrocarbon. The subsurface distribution of basinal facies under late orogenic cover is unmapped. For example, Catalano et al. (2000) infer a clear physical connection between these basinal units and the Streppenosa basin itself, whereas Zappaterra (1994) draws a distinction in the tectonic evolution of the two and an intervening platformal barrier between them. Better seismic imaging north of the Gela nappe front is clearly needed here to constrain the subsurface structural geometry well enough to allow realistic palinspastic restorations of the fold belt and, in turn, specific stratigraphic relationships between the various Mesozoic facies belts.

Ragusa Foreland

By far, the greatest focus of geochemical studies in Sicily has been on the Mesozoic systems of the Hyblean Plateau in southeastern Sicily, primarily on the Noto and Streppenosa formations. The oils of this area are largely heavy (API < 20°), with high sulfur contents of 3–9%, except for two notable accumulations at Mila and Irminio (Figure 3), which have API values in excess of 30°. The heavy oils are generally water undersaturated, with varying salinities. At Cammarata–Pozzillo and Ponte Dirillo fields, for example, salinities range from 80,000 to 90,000 ppm, and at Ragusa, salinities are 100,000 ppm, whereas at Gela, they vary considerably more, from 20,000 to 100,000 in different horizons (Dalla Casa et al., 1981). Gas is associated at Gela and Ragusa, with as much as 80% of the gas being CO_2.

Pieri and Mattavelli (1986) linked the detailed chemistry of the heavy oils to early, immature generation instead of biodegradation, as did Novelli et al. (1988), who typed them to sources primarily in the Noto formation (Rhaetian in age). The Noto contains primarily types I and II kerogen that are sometimes in excess of 1% by volume, whereas the Streppenosa is considerably leaner and dominated by type III. Brosse et al. (1988) studied kerogen both in the Noto and Streppenosa formations distributed between black shales and clayey laminites and, alternatively, in a variety of laminated limestones, micrites, wackestones, packstones, dolomitic breccias, and their recrystallized equivalents. They found that the best oil potential was in clay-rich facies in the Noto formation, and that the kerogens have a

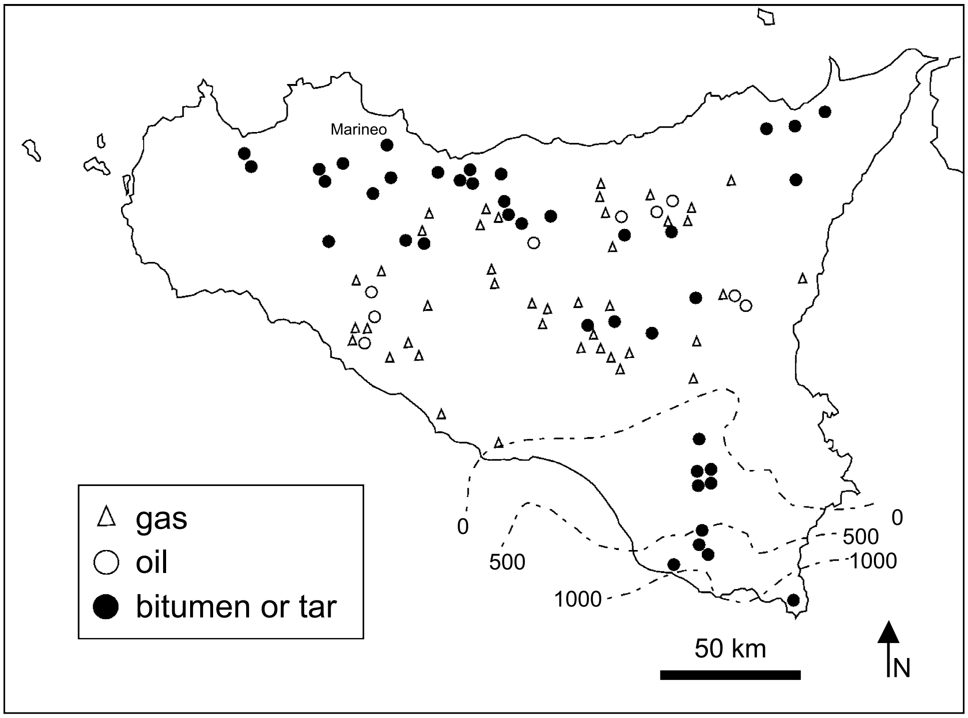

FIGURE 8. Seeps and asphalt occurrences in Sicily. Dashed lines are isopachs (in meters) on Streppenosa Formation, outlining the Streppenosa (source rock) Basin. Isopachs after Patacca et al. (1979); seep and asphalt locations after Rigo de Righi (1957) and Colombo and Sironi (1959). A major issue in source rock distribution for Sicily is if the Streppenosa basin closes off as shown or is connected in some way with the basinal sections to the north (Figures 2, 3).

variety of kinetic characteristics. However, all appeared to have early generative capabilities, so that the occurrence of light oil in the Ragusa foreland appears to be a ramification of the geological history that is as yet unexplained.

The maturation modeling studies of Novelli et al. (1988) emphasized rapid Pliocene–Pleistocene burial and heating during the Gela foreland subsidence in connection with the generation of the heavy oils, a conclusion corroborated by Brosse et al. (1989) specifically for the Gela area. Brosse et al. (1989), however, contrasted Ragusa with Gela and found that variations in the pre-Tertiary subsidence history and in the kerogen composition from different facies could lead to maturation, hydrocarbon generation, and migration as early as the Jurassic in the deepest depocenters of the Streppenosa basin (Figure 8). Ocampo et al. (1993) found that biomarkers uniquely typed a Noto source rock to oils of the small Ponte Dirillo field (very near Gela), but that significant differences in Gela oils suggested a different generation and/or source history.

Exploration data would also suggest that multiple periods of hydrocarbon trapping have occurred. Multiple migration events are evident in the reservoir in Irminio with the first migration as early as the middle Cretaceous (Lindsey et al., 2002). Isopachs on various stratigraphic levels of the Ragusa field show a thin section above the reservoir (Kafka and Kirkbride, 1959), indicating recurrent rejuvenation of the trap well before the depression in the Gela foredeep. Furthermore, flattening exercises on various horizons in connection with exploration studies seem to suggest that Oligocene structural highs that have survived through the foreland basin flexure and associated faulting to remaining highs today are the most successful exploration targets, implying that a major period of petroleum migration occurred prior to the emplacement of at least most of the fold and thrust belt. Numerous dry holes have been drilled on Pliocene–Pleistocene traps in the Ragusa foreland. Although there may be many reasons for the dry holes, the occurrences of traps charged with light oil, as well as the structural history of successful traps, would suggest that a more complicated maturation-migration history is involved throughout the Ragusa plateau. In any case, the simple model attributing maturation and migration to subsidence in the fold-belt foreland is insufficient to account for the distribution of oil fields.

Fold-belt Oils and Tars

Although many hydrocarbon seeps and asphalts occur in the fold belt (Figure 8), no modern geochemical studies have been made to type them to sources. No discoveries in the Mesozoic sequence have been recorded in the onshore fold belt, although one tar south of Palermo at Marineo (Figure 8) occurs in Triassic dolomite. Most of the occurrences seem to be similar to the heavy oils in the foreland, but several have more paraffinic characteristics. Heavy-metal concentrations vary widely. The source of these hydrocarbons is uncertain but is likely to be similar in depositional and tectonic setting to the source in the Streppenosa basin. Because rich Mesozoic source rocks, such as the Noto formation, are of limited distribution outside the Streppenosa basin (Figure 5), other candidates have been proposed. The Triassic Mufara Formation is common in the north, but of limited total organic carbon. Likewise, younger formations have some carbon content, but their total organic carbon and maturation levels have received little study. A systematic study of the chemistry of these occurrences in connection with their structural setting would be of value in assessing the petroleum potential of the fold and thrust belt. Again, better seismic imaging would contribute much to the geographic aspects of such a study.

Melange, Mud Diapirs, and Fluid Flux through the Fold and Thrust Belt

Connections between overpressure generation, dewatering processes, and deformation in accretionary prisms and fold and thrust belts are documented in a rich literature (e.g., Langseth and Moore, 1990; Shipley et al., 1995) and are intimately related to hydrocarbon migration. Prisms with at least partially subaerial histories, such as Sicily, are similar to many retroarc fold and thrust belts and differ from intraoceanic prisms in that meteoric water factors into the system, providing hydrodynamic recharge otherwise unavailable and an additional diagenetic influence over potential reservoir rocks. Both detachment-related melange and mud diapirs indicate that Sicily is no departure from the norm, but also that meteoric recharge, overpressure, and deformation in the wedge are linked to at least one period of petroleum migration.

Guilhaumou and Larroque (1993), Larroque (1993), and Guilhaumou et al. (1994) have studied the argille varicolore that are associated with detachment surfaces and mud diapirs in the Monte Scalpello and Monte Bubonia areas (Figure 2). Detachment surfaces in the duplex at Monte Scalpello that carry the Tertiary section are characterized by a sheared Late Cretaceous and Tertiary argillaceous matrix containing blocks of argillite. Calcite veins in the blocks have low-salinity fluid inclusions with low homogenization temperatures (<100°C). Basal detachment surfaces, i.e., those carrying the Mesozoic carbonate succession, are marked by mélange of sheared argillitic matrix and brecciated blocks of mudstones, sandstones, and radiolarian cherts carrying Lower Cretaceous fossils. The blocks contain several generations of quartz and calcite veins with two types of fluid inclusions. One set containing low-salinity water exists in a range of veins, from quartz veins with inclusions that have homogenization temperatures of 150°C to overprinted veins of calcite with inclusions homogenized at more than 200°C. Significantly, the calcite veins also have high-temperature pyrobitumen inclusions. A second set of water-depleted inclusions in the calcite veins carry light oil with no gas. The surrounding melange is in thermal disequilibrium with the veins, recording only a lower thermal overprint in the form of clay transformation. The authors concluded that the detachment channelized several periods of fluid flux through the melange. Overpressure resulted in naturally hydrofractured rocks with passing hot fluids that, in at least one case, were associated with hydrocarbons from a deeper source.

Similar lithologies to the upper detachment melange at Monte Scalpello occur in a body that crosscuts stratigraphy at Monte Bubonia (Figure 3) and breaches the core of an anticline in the Gela nappe (Larroque, 1993). The matrix is sheared red and green argillites, with blocks of *Nummulites*-bearing Eocene calcarenites, Numidian flysch, and various elements of the Mesozoic and Paleogene section. Importantly, carbonate blocks containing superimposed crack-and-seal calcite veins are also present. Isotopic studies indicate that cements in the carbonates are normal-marine cements, but the veins relate to hydrothermal fluids. No oils were encountered in these upper detachment rocks, suggesting the possibility that, at least locally, the hydrocarbon source rocks lay deeper in the section than that accessed by the upper fluid pathways. Presumably, the source rocks were in the Triassic–Jurassic part of the section, which was represented in blocks of the lower detachment and not of the upper detachment.

Offshore Oils

Tertiary-reservoired oils in the offshore west of Sicily at Nilde and Narciso (Figure 3) likewise have not been conclusively typed to sources but are assumed to be derived from associated Oligocene–Miocene source rocks.

Gas and Gas-condensate

Biogenic gas has been produced at two fields in the fold belt. At the Lippone-Mazara field (Figure 3) in western Sicily, gas that was produced from the Tortonian Terravecchia sandstone (Figure 5) is presumed to derive from surrounding shales, whereas at Catania, south of Mount Etna, Pleistocene Ribera sands reservoir gas again sourced from the surrounding shales. Thermogenic gas and associated condensate derived from the surrounding Miocene Collesano formation charge the Gagliano field.

RESERVOIRS

Sicilian reservoirs include a variety of complex fractured carbonates in the Triassic and Jurassic of the Hyblean platform. They have complex episodes of charge and diagenetic alteration. Lindsey et al. (2002) describe a sequence of events in Irminio field involving the emergence of the reservoir in the Lias, a period of oil migration in middle Cretaceous time, followed by an influx of hot water and bitumen baking. A second period of charge began in the Paleogene and continued well into the Neogene, when a period of stylolitization and dedolomitization also occurred.

The distribution of these reservoirs is controlled by the Mesozoic paleogeography, in that the best reservoirs are concentrated in and fringe the carbonate mound buildups in the Streppenosa basin, where cyclic effects of dolomitization, karstification and subaerial dissolution, emersion, burial, and fracturing that promote reservoir quality are coupled with periods of fine-grained deposition that afford suitable seals. Presumably, similar reservoir rocks occur elsewhere in Sicily, where the Neotethyan extended terranes afford similar histories. At locations in the Gela nappe, for example, Mesozoic carbonates exhibit cataclastic fabrics with marine dolomitic cements.

Cretaceous units similar to those elsewhere in Italy (Mattavelli et al., 1993) are potential reservoirs, such as debris flows and turbiditic units in the basinal facies, but these have yet to be tested in Sicily. Tertiary terrigenous sandstones that are related to the time-transgressive advance of the fold and thrust belt provide the other major play in Sicily, as at Nilde or Catania (Figure 3). These are units deposited in the migrating foredeep basin or in the piggyback basins. Reservoir quality depends on cementation history, of course, and on the provenance of the sands, either carbonate or siliciclastic.

SUMMARY AND CONCLUSIONS

Hydrocarbons occur in two main megasystems in Sicily: in the Ragusa plateau and in the fold and thrust belt. The Ragusa plateau is separated from the fold and thrust belt by a very young and narrow foredeep (Figure 2). Currently, the plateau carbonates dip southeastward away from a strong normal fault system along its western edge, thus setting up a high along the main Ragusa–Irminio–Mila oil field trend. The plateau is partially underlain by the intraplatformal Streppenosa basin of Triassic and Jurassic age, which extends to the south offshore well away from the fold belt. It contains the well-established Noto and Streppenosa source rocks, which have been typed to the predominantly (but not exclusively) heavy-liquid hydrocarbons in most of the fields. Several lines of evidence suggest that a multiphase maturation and migration was involved in charging the fields:

- multiple ages of mild deformation, as reflected in thinning isopachs over structures
- long history of potentially elevated heat flow
- petrographic studies of the diagenetic history of reservoir rocks
- observations that Oligocene structures that have survived to the present are more likely to contain substantial hydrocarbons
- variations among the oils involved

Although there would seem to potentially be some charge into heavy-oil fields in the narrow foredeep, notably Gela and Perla, from petroleum systems in the frontal parts of the fold and thrust belt, oil-bearing fluid inclusions from basal detachment-related melange are much lighter and do not suggest that heavy oils were a component of the flux. Other fluid inclusions suggest that fresher water would also be generated and potentially flush foredeep reservoirs as easily as they may be charged. Consequently, the bulk of the oils appear to have been sourced from within the foreland itself, and the Ragusa plateau has served as its own kitchen, transport, and trap system using the large fetch area of the Streppenosa source basin.

Light oils occur in Irminio and Mila, but it is unlikely that these light oils originated outside the foreland for the reasons above. All of these deposits are located in the zero isopach of the Streppenosa basin, so it appears that the foreland oils are sourced from the deeper parts of the Mesozoic dominantly carbonate section of the intraplatformal basin during multiple phases of generation and migration. Modeling studies suggests that maturation and migration were certainly aided by flexure of the foreland and Neogene burial, but the deeper parts of the Streppenosa basin may have generated hydrocarbons as early as the Jurassic. Cretaceous charge has also been proposed for Irminio (Lindsey et al., 2002).

Unsuccessful tests are common in the Ragusa plateau and its offshore. Many of them are located on young structural highs and poorly positioned to test older closures. Structures in the foreland have undergone several stages of rejuvenation, with the distinct possibility that many of them have been either ruptured or spilled either during Alpine structural influences on the area or during the emplacement of the Sicilian fold and thrust belt. Hence, the hydrocarbon system in the foreland is a complex one but appears to be unlinked, for the most part, to the fold belt, except as a potential analog for the early prefold belt phases of hydrocarbon generation elsewhere in Sicily.

Hydrocarbons in the fold and thrust belt are limited to biogenic and thermogenic gas onshore, numerous seeps and outcropping tar deposits, and oil of questionable source in offshore fields west of Sicily. All of these deposits are confined to Tertiary reservoirs (with the exception of one occurrence of tar in Triassic rocks) largely because few valid tests of pre-Tertiary traps have been performed in the fold belt. Nevertheless, several plays are possible, as outlined in the Appendix. That a live petroleum system was active at one time is indicated by the fluid-inclusion studies in the Monte Scalpello area and numerous seeps and tars in the outcrop; but whether liquids have survived in commercial quantities remains a question. Relatively new concepts of the structural architecture in the fold belt offer the possibility that future tests of buried closures would confirm or deny the potential of the fold belt. Establishing sedimentological similarities and/or physical connections between the rich Streppenosa intraplatformal basin and the Jurassic basinal sections in the fold belt would be a great step forward in demonstrating an effective Mesozoic source in the fold belt. Better seismic imaging in a systematic survey would also be a step forward.

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APPENDIX: SICILIAN PETROLEUM PLAYS

Sicilian petroleum systems can be classified according to their structural and geodynamic province (Figure 2), starting from the hinterland toward the foreland. Efficient petroleum systems, as indicated by the main oil and gas fields, are characterized first, followed by other, underexplored and potential plays. Only plays that have been successful in discovering hydrocarbons have been listed. The Mesozoic carbonates in the fold and thrust belt have been disappointing to date. This should be a major play, but a realistic test of structures in the thrust stack has not yet been made. Focus has largely been on the shallower, surface anticlines and not those involved in the deeper, younger sheets described by Bello et al. (2000) and Catalano et al. (2000).

Petroleum Systems in the Fold Belt

Petroleum System of the Outer Numidian Domain, Exemplified by the Casalini, Bronte-San Nicola, and Gagliano and Fiumetto Fields

1) Reservoir: Argillaceous sandstone of the Collesano formation [Tortonian(?)]; porosity with microfractures 6–15%; low permeability
2) Trap: Imbricated thrust folds that are low amplitude, south verging, and involving well-bedded carbonate substratum (basinal Imerese units); structural closure by bedding dips on three flanks and by fault toward the south; vertical closure exceeding 200 m (660 ft)
3) Seal: Argillites from the paleo-oceanic Sicilides units
4) Source rock: Argillites from the Collesano formation or siliceous shales of the Crisanti Formation (Liassic)
5) Maturation: At regional scale, these two formations become increasingly buried toward the north and laterally enter the gas window
6) Migration: Lateral and updip from the north
7) Hydrocarbon type: Gas (90% methane) and condensate (62° API) with gas-oil ratio averaging 7000

Petroleum System of the Inverted Inner Messinian Foredeep, Exemplified by Nilde, Norma, and Narciso Fields

1) Reservoir: Fractured and most likely karstified bioclastic Serravalian–lower Tortonian(?) carbonates at the top of former passive-margin sequence (Nilde limestone or lateral equivalent of the Fortuna Formation)
2) Trap: Steeply dipping, imbricated thrust folds verging toward the southeast
3) Seal: Shales at the base of the upper Tortonian Terravecchia Formation
4) Source rock: Carbonate source according to oil analyses made by Agip; no potential source rock has yet been evidenced in the former passive-margin sequence at Nilde, but a lateral contribution of outer Numidian sources is also possible
5) Maturation: During Messinian times, at the onset of inversion episodes
6) Migration: Lateral and updip from the west, where Numidian series become increasingly thick, both stratigraphically and by tectonic duplication
7) Hydrocarbon types: Light oil in Nilde (38° API), becoming progressively heavier toward the east (21–25° API in Narciso); farther east, away from the oil kitchen, only heavy oil and CO_2 occur (Nora Nl, Orlando 1 and 2)

Petroleum System of the Outer Messinian Foredeep, Exemplified by Lippone-Mazara Fields

1) Reservoir: Argillaceous turbiditic sandstones of the central part of the lower Messinian Terravecchia Formation
2) Traps: East-trending thrust folds and pop-up structures of the Sicani domain resulting from inversion of high-angle structures of the former African passive margin
3) Seal: Argillites from the Terravecchia Formation
4) Source rock: The same argillites
5) Maturation: Biogenic gas
6) Migration: Synchronous with folding (i.e., Messinian)
7) Hydrocarbon type: Gas/methane = 99%

Petroleum Systems of the Hyblean Foreland

Gela-type Play: Gela, Ragusa, Ponte Dirillo, and Prezioso Fields

1) Reservoir: Porous and fractured dolomites of the Gela Formation (Norian–Rhaetian)
2) Traps: Multistage faulted anticlines, with late-stage transpersonal reactivation during Apennine compressional episodes (upper Pliocene)
3) Seal: Black shales of the Streppenosa Formation
4) Source rocks: Black shales and bituminous limestones of the Noto formation (Rhaetian) and Streppenosa Formation (Hettangian)
5) Maturation: Deep burial already affected source rocks during the Mesozoic southwestward of the Hyblean Plateau, resulting in early oil generation and expulsion
6) Migration: The Noto and Streppenosa formations constitute in the south lateral basinal equivalents of shallow-water platform dolomites of the Gela Formation. This global architecture of the foreland allows a direct connection between very thick source rocks and reservoir sequences. During the Late Jurassic, Cretaceous, and Cenozoic, continuous subsidence led to the burial of source rocks into the oil window. Since the Messinian, the progressive uplift of the Hyblean Plateau has resulted in a regional tilting of the margin, thus inducing long-range migration pathways from the oil kitchen toward the traps. Vertical migration is also locally controlled by high-angle faults, thus allowing a remigration of hydrocarbons from Mesozoic toward Miocene

reservoirs (i.e., in the Ragusa area, where bituminous calcarenites are cropping out and mined).

7) Hydrocarbon types: Low-maturity heavy oil with sulfur; oil gravity increases with the distance of migration
8) Special cases: Mila and Irminio fields are members of this same petroleum system, but they are located near the facies transition between the Streppenosa–Noto and Gela formations; for instance, the Mila reservoirs are rather reefal and thus distinct from those of the nearby platform; hydrocarbons are light (30° API), and the reserves appear to be the product of multiple periods of migration (Lindsey et al., 2002)

Perla-type Play: Perla and Vega Fields

1) Reservoir: Partially dolomitized and fractured oolitic limestones and algal pelsparites from open-platform environment (Siracusa and Inici formations); intergranular and intercrystalline and vuggy porosity (12–16%)
2) Traps: Mixed, stratigraphic, and structural; a facies transition from platform carbonates of the Siracusa formation and shales from the Villagonia (Modica) formation occurs toward the northeast; this facies boundary has been reactivated by numerous north-verging reverse faults during Late Cretaceous inversion episodes, thus increasing further the stratigraphic closure
3) Seal: Pelagic marly limestones of the Buccheri (Giardini) formation
4) Source rock: Mainly black shales of the Noto and Streppenosa formations; because of regional migration trends, a contribution of lateral equivalents of the Siracusa formation in a back-reef position should be also considered
5) Maturation: In case the source rock belongs to the deep Noto–Streppenosa basin, maturation would be rather old, as in the Gela play; instead, if source rocks are located in the back-reef area, they would have entered the oil window more recently, i.e., during the deposition of the Pliocene–Quaternary flexural sequence
6) Migration: Vertical along high-angle fractures (in case the source is located in the Noto–Streppenosa basin) or lateral and updip from a hypothetical oil kitchen located toward the southwest
7) Hydrocarbon type: Moderately mature and not biodegraded heavy oil (12–16° API) with sulfur

Catania and Cisina Gas Fields in the Pliocene–Pleistocene Foredeep of Gela

1) Reservoir: Multilayered Pleistocene sandstones
2) Traps: Trapping anticlines and/or recent transpressional reactivation of fractures
3) Seals: Interbedded argillites
4) Source rocks: Interbedded argillites
5) Maturation: Biogenic gas
6) Migration: From the argillites toward nearby sandstones

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