The Talara Basin Province of Northwestern Peru: Cretaceous-Tertiary Total Petroleum System

By Debra Higley

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Cover.—The Sechura Desert of northwestern Peru is typical of the hyperarid conditions that exist along the west coast of South America where the cold Humboldt (Peruvian) Current generates very little precipitation, especially along the northern coast of Chile and the entire coast of Peru. The tan landscape is almost devoid of any vegetation, except for limited areas where sufficient moisture exists to sustain some growth. The faint wind streaks show the prevailing southwest-to-northeast wind throughout the desert. A low mountain (1,580 ft high) is barely visible on the peninsula that juts into the cold Pacific Ocean. The darker area in the desert southeast of Sechura Bay appears to be an oasis area where a hardy variety of cotton is possibly grown with the use of irrigation. This photograph demonstrates the importance of elevation by the increase in vegetative cover (darker area along the eastern side of the photograph) as the land rises into the Andes Mountains. The west-flowing Cascajal River exits the Andes Mountains, begins to cross the Sechura Desert, and apparently disappears beneath the sandy soil of the desert before reaching the cultivated field near the coast. The south-flowing Piura River, partially obscured by clouds, can also be seen as it traverses the desert. Both of these rivers flow only when there is sufficient precipitation, or icemelt/smowmelt from the Andes Mountains.

[Image modified from NASA photograph STS056-075-015, April 1993, available at URL <http://earth.jsc.nasa.gov/sseop/efs/geon.htm/>]

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Gale A. Norton, Secretary

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Foreword

This report was prepared as part of the World Energy Project of the U.S. Geological Survey. For this project, the world was divided into 8 regions and 937 geologic provinces (Klett and others, 1997). Of these, portions of 128 geologic provinces were assessed for undiscovered petroleum resources. The petroleum geology of these provinces is described in a series of reports like the one presented here. The primary documentation for these assessments is located in U.S. Geological Survey World Energy Assessment Team (2000). The petroleum geology of these priority and boutique provinces is described in the contained series of reports. Province names, codes, and boundaries, oil and gas fields, and a geologic map of South America are shown in Schenk and others (1999).

The purpose of the World Energy Project is to assess the quantities of oil, gas, and natural gas liquids that have the potential to be added to reserves within the next 30 years. These volumes either reside in undiscovered fields whose sizes exceed the stated minimum-field-size cutoff value for the assessment unit (variable, but must be at least 1 million barrels of oil equivalent (MMBOE)) or occur as reserve growth of fields already discovered. One MMBO is equivalent to 6 billion cubic feet of gas (BCFG). Field growth (increase through time of estimated recoverable resources) may result from discovery of new productive facies or formations within the field, production of a greater percentage of original-oil-in-place through improved secondary or tertiary recovery methods, and perhaps a recalculation of reserves that were originally underestimated. Hypothetical assessment units are described to explore the potentials of possible new or underevaluated petroleum plays and formations. Analogs from other areas of the world are used to determine environments of deposition of source and reservoir rocks, to describe the burial history of the area, and to assess possible reservoir properties of formations within the hypothetical assessment unit.

The total petroleum system (TPS) constitutes the basic geologic unit of the oil and gas assessment and includes all genetically related petroleum that occurs in shows and accumulations (discovered and undiscovered) that (1) has been generated by a pod or by closely related pods of mature source rock, and (2) exists within a limited mappable geologic space, along with the other essential mappable geologic/geochemical elements (source, reservoir, seal, and overburden rocks) that control the fundamental processes of generation, expulsion, migration, entrapment, and preservation of petroleum (modified from Magoon and Dow, 1994). The minimum petroleum system is that part of a total petroleum system that encompasses discovered shows and accumulations, along with the geologic space in which the various essential elements have been proved by these discoveries.

Graphical depiction of the elements of a total petroleum system and contained assessment units is provided in the form of events charts that show the times of (1) deposition of essential rock units; (2) trap formation; (3) generation, migration, and accumulation of hydrocarbons; and (4) preservation of hydrocarbons.

A numeric code identifies each region, province, total petroleum system, and assessment unit; these codes are uniform throughout the project and will identify the same type of entity in any of the publications. The codes for the regions and provinces are listed in U.S. Geological Survey World Assessment Team (2000). The code is as follows:

	Example
Region, single digit	**6**
Province, three digits to the right of region code	6**081**
Total petroleum system, two digits to the right of province code	6081**01**
Assessment unit, two digits to the right of petroleum system code	608101**01**

Oil and gas reserves quoted in this report are derived from Petroconsultants' Petroleum Exploration and Production database (Petroconsultants, 1996) and other area reports from Petroconsultants, Inc., unless otherwise noted. Figure(s) in this report that show boundaries of the total petroleum system(s), assessment units, and pods of active source rocks were compiled using geographic information system (GIS) and graphics software. Political boundaries and cartographic representations were derived, with permission, from Environmental Systems Research Institute's ArcWorld 1:3-million digital coverage (1992), have no political significance, and are displayed for general reference only. Center points of oil and gas fields, shown on these figures, are reproduced, with permission, from Petroconsultants (1996). The primary source of geochemical data for this report is the GeoMark (1998) database.

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The Talara Basin Province of Northwestern Peru: Cretaceous-Tertiary Total Petroleum System

By Debra Higley

Abstract

More than 1.68 billion barrels of oil (BBO) and 340 billion cubic feet of gas (BCFG) have been produced from the Cretaceous-Tertiary Total Petroleum System in the Talara Basin province, northwestern Peru. Oil and minor gas fields are concentrated in the onshore northern third of the province. Current production is primarily oil, but there is excellent potential for offshore gas resources, which is a mostly untapped resource because of the limited local market for gas and because there are few pipelines. Estimated mean recoverable resources from undiscovered fields in the basin are 1.71 billion barrels of oil (BBO), 4.79 trillion cubic feet of gas (TCFG), and 255 million barrels of natural gas liquids (NGL). Of this total resource, 15 percent has been allocated to onshore and 85 percent to offshore; volumes are 0.26 BBO and 0.72 TCFG onshore, and 1.45 BBO and 4.08 TCFG offshore. The mean estimate of numbers of undiscovered oil and gas fields is 83 and 27, respectively. Minimum size of fields that were used in this analysis is 1 million barrels of oil equivalent and (or) 6 BCFG.

The Paleocene Talara forearc basin is superimposed on a larger, Mesozoic and pre-Mesozoic basin. Producing formations, ranging in age from Pennsylvanian to Oligocene, are mainly Upper Cretaceous through Oligocene sandstones of fluvial, deltaic, and nearshore to deep-marine depositional origins. The primary reservoirs and greatest potential for future development are Eocene sandstones that include turbidites of the Talara and Salinas Groups. Additional production and undiscovered resources exist within Upper Cretaceous, Paleocene, and Oligocene formations. Pennsylvanian Amotape quartzites may be productive where fractured. Trap types in this block-faulted basin are mainly structural or a combination of structure and stratigraphy. Primary reservoir seals are interbedded and overlying marine shales.

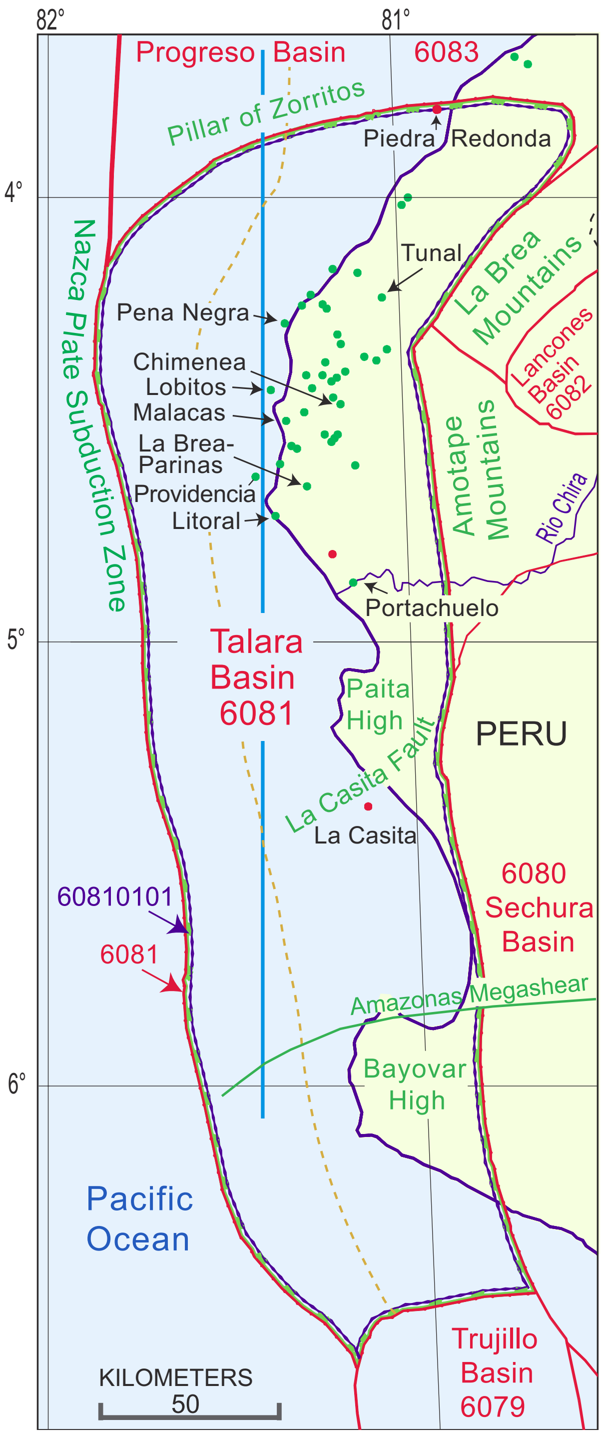
Most fields produce from multiple reservoirs, and production is reported commingled. For this reason, and also because geochemical data on oils and source rocks is very limited, Tertiary and Cretaceous production is grouped into one total petroleum system. The most likely source rocks are Tertiary marine shales, but some of the Cretaceous marine shales are also probable source rocks, and these would represent separate total petroleum systems. Geochemical data on one oil sample from Pennsylvanian rock indicates that it was probably also sourced from Tertiary shales.

Introduction

The Talara Basin province is located on the continental shelf along the northern coast of Peru (fig. 1). Its eastern limit is delineated by the La Brea–Amotape Mountains of the Coastal Range, and the associated uplift that separates the basin from the Lancones and Sechura Basins (fig. 1). The southeast boundary is east of the La Casita fault and the Paita High uplift, between the Talara and Secura Basins; the south boundary is the Trujillo Basin. The west boundary of the province is the approximate location of the Nazca Plate subduction zone under the South American Plate.

The Pillar of Zorritos is a basement uplift and associated fault zone that is the northern limit of the Talara Basin province (figs. 1 and 2). This boundary coincides with the southern edge of the Dolores-Guayaquil megashear zone (fig. 3) and has a complex structural setting that includes transcurrent (wrench) faulting as well as high- and low-angle faults of various ages (American International Petroleum Corporation (AIPC), no date; Marocco and others, 1995; Pindell and Tabbutt, 1995; Zúñiga-Rivero and others, 1998b, 1999). Location of this megashear and the basin boundary exhibits some variation, depending upon who has mapped the fault system. Zúñiga-Rivero and others (1999) indicated that the Talara Basin province extends northward to their location of the Dolores-Guayaquil megashear, which is approximately 50 km (30 mi) north of the southern limits shown in figures 1 and 3.

Talara Basin is one of 10 basins spread over approximately 67 million acres along the west coast of South America (Zúñiga-Rivero and others, 1998a). Schenk and others (1999) show 13 offshore basins that border and lie west of the coast. Maximum width of the Peru continental shelf is about 130 km (80 mi) (Zúñiga-Rivero and Hay-Roe, 1998). Grossling (1976) listed the potential oil and gas prospective areas of Peru as including 1,000,000 km^2 (400,000 mi^2) onshore and 24,000 km^2 (9,300 mi^2) offshore. The area of the Talara Basin province and the included Cretaceous-Tertiary Total Petroleum System (TPS) (608101) and Cretaceous-Paleogene Basin



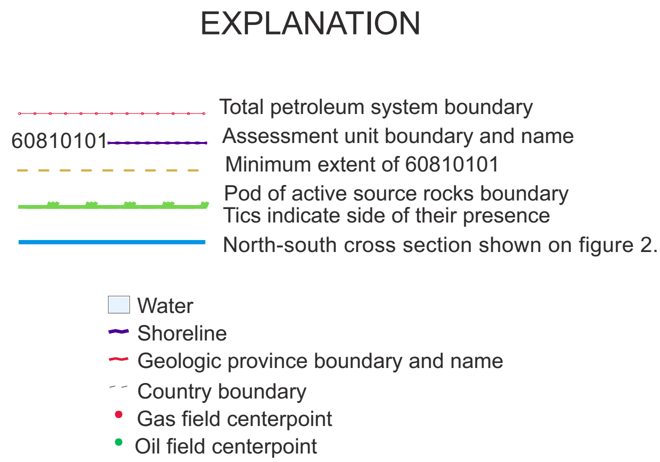


Figure 1 (facing column and above). The Talara Basin province (6081) and adjoining provinces, northwestern Peru. Shown are the common boundaries of the basin, the Cretaceous-Tertiary (608101) Total Petroleum System, and the Cretaceous-Paleogene Basin (60810101) assessment unit. Minimum extent of 60810101 is approximated by 1,000-m (3,000-ft) water depth. Map projection is Robinson. Central meridian is 0°.

(60810101) Assessment Unit (AU) is 28,000 km^2 (11,000 mi^2); the minimum extent of TPS 608101 is 23,000 km^2 (8,900 mi^2), which is landward of the dashed line in figure 1. About 85 percent of the basin is offshore, and major portions are under license for petroleum leases.

Acknowledgments

Dan Spancers, a petroleum geologist from Denver, provided essential information on oil and gas exploration and development in Peru and Ecuador. This document benefited from reviews by Christopher J. Schenk, William R. Keefer, and Ronald R. Charpentier of the U.S. Geological Survey.

Province Geology

Structural and Depositional History

In many if not all of Peru's coastal basins, tectonic movements during the Paleozoic established a geologic framework that greatly influenced later structural and depositional patterns (Zúñiga-Rivero and others, 1998b). The position, shape, and size of 10 offshore Tertiary basins in Peru, including the Talara Basin, are substantially controlled by Late Cretaceous–early Tertiary tectonic activities that involved Paleozoic and Mesozoic strata; these strongly affected the region by divid-

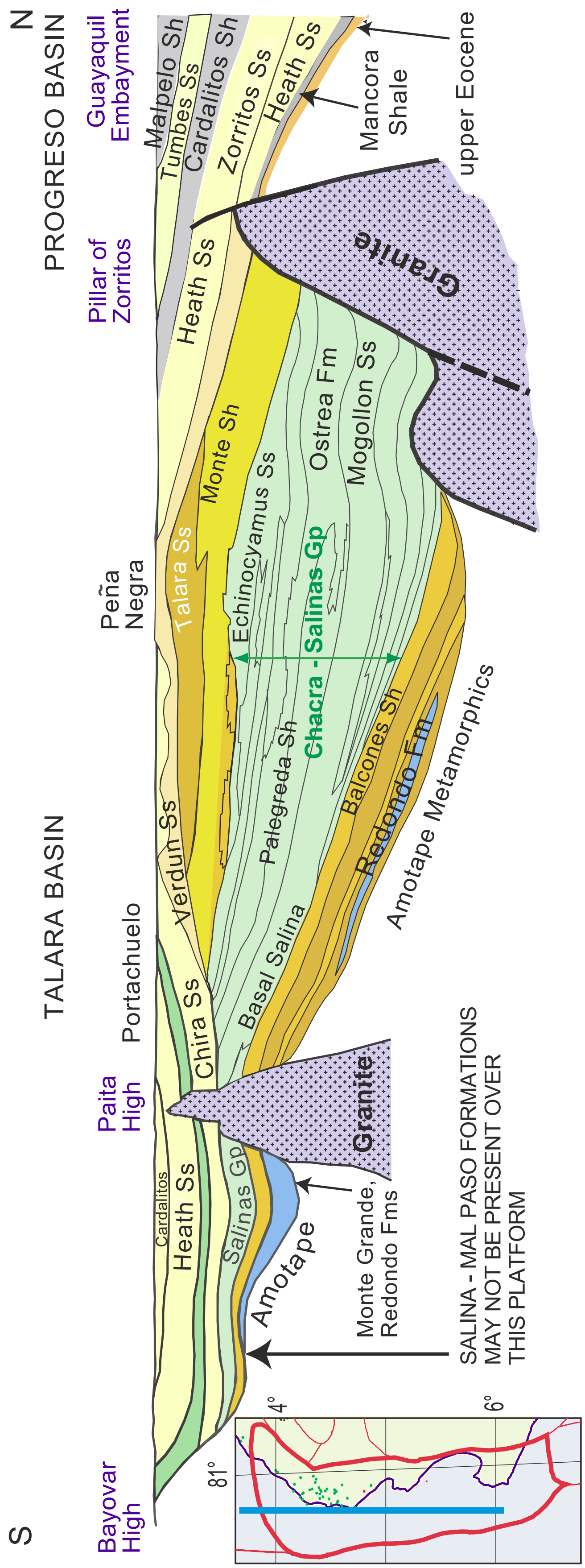


Figure 2. North-south stratigraphic cross section across the Talara and southern Progreso Basins (modified from Raez Lurquin, 1999). Approximate location of line of section is shown on figure 1 and as the blue line on the inset map to the left. Not all formations shown are labeled. Section is not to scale.

ing larger basins into a series of more restricted areas of late Tertiary sedimentation (Zúñiga-Rivero and others, 1998a).

The Talara Basin province resulted from Paleogene tectonic activity. The basin overlies a larger basin that records the imprint of Cretaceous tectonic events. This older basin also underlies parts of the Neogene structures of the adjacent Progreso and Secura-Salaverry Basin provinces (figs. 1, 3). These provinces are separated from the Talara Basin province by faulted intrusive igneous rocks. Talara and these adjoining coastal basins have been characterized as forearc basins; they lie seaward of the Coastal Range and were identified by Lonsdale (1978) as representing a “trench-slope break” or an “outer-arc ridge” environmental setting. Kingston (1994) believed the basin configurations may be better named trench-slope basins. Zúñiga-Rivera and others (1998a), however, indicated that the basins, instead of being forearc as there was no associated volcanic arc, were linear downwarps that filled with clastic sediments from the continent combined with shallow- and deep-water marine limestones.

Shown in figure 4 are sedimentary strata, major periods of erosion and nondeposition, and oil and gas source and reservoir rocks in the Talara Basin province and the adjoining Progreso Basin province. A north-south cross section of the offshore Talara and southern-most Progreso Basin provinces (fig. 2) was constructed by integrating seismic sections and well data (Raez Lurquin, 1999). Shown are structural and stratigraphic relations among the Cretaceous and Tertiary sedimentary rocks that overlie basement quartzites of the Pennsylvanian Amotape Formation. Lower Tertiary and Cretaceous strata are relatively continuous across the cross section. It is only the youngest Tertiary rocks (Miocene and Pliocene) that reflect the separation into different sedimentary basins along the coast and offshore (Zúñiga-Rivero and others, 1998a). This separation is also visible in the Talara Basin province as the Miocene and Pliocene Zorritos, Cardalito, Tumbes, and Mal Pelo Formations occur near the northern and southern limits of the basin (fig. 2). Based on seismic data, thick sequences of Paleozoic and Mesozoic strata underlie most of the Peruvian continental shelf and slope, whereas Tertiary sediments show more variations in thickness, structural characteristics, and areal extent (Zúñiga-Rivera and others, 1998a).

The northern boundary of the Talara Basin province coincides with a part of the right-lateral Dolores-Guayaquil megashear, and the left-lateral Amazonas megashear is near the southern boundary, across the north side of the Bayovar (Paita) High. General locations of these shear zones, shown in figures 1 and 2, are superimposed on the generalized geologic map of the region (fig. 3). Surface exposures in the Manabi, Progreso, Talara, and Sechura Basin provinces are primarily Tertiary and Quaternary nonmarine sediments. Modern seismic and sequence-

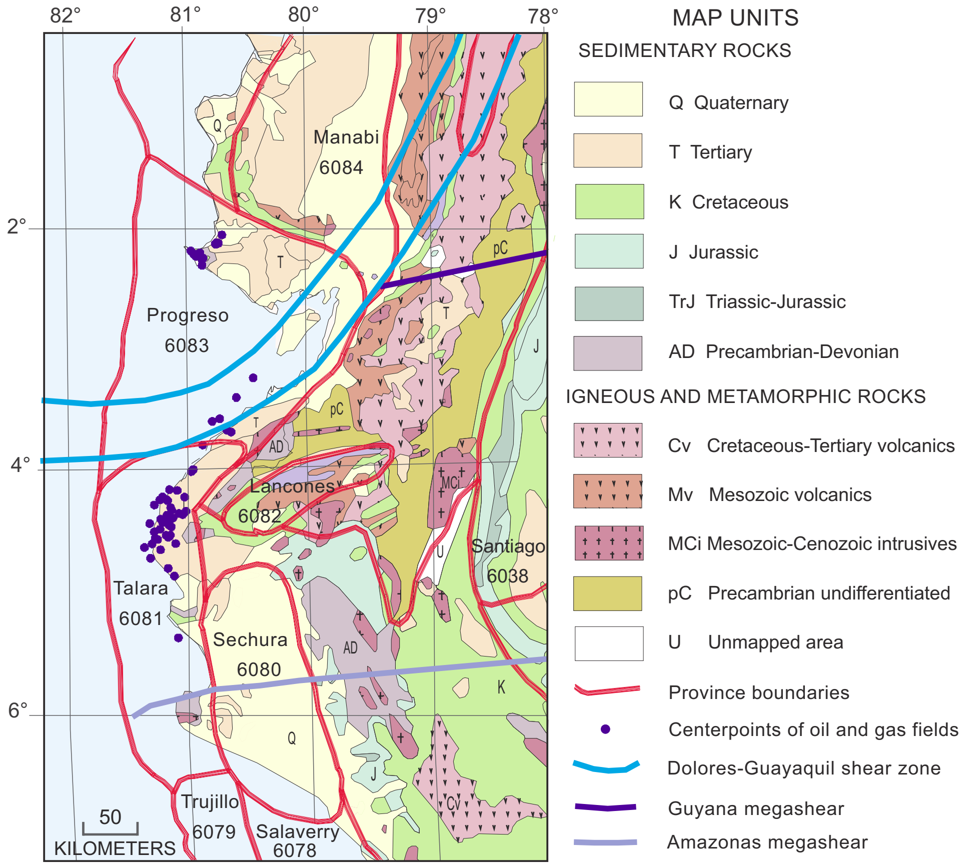


Figure 3. Simplified geologic map of the Talara and Progreso Basin provinces and surrounding area. Shown are the generalized locations of the Dolores-Guayaquil megashear zone and the Guyana and Amazonas megashears. Oil and gas field centerpoints and the geologic map are modified from Schenk and others (1999) 1:5,000,000-scale map of South America. Source of field centerpoints is Petroconsultants database (1996).

stratigraphic analysis of the Sechura Basin indicate there is a relation between tectonic history and submarine fan deposition; these fans originated at a tectonic zone that separates the Talara and Sechura basins and is characterized by thrust and secondary normal faults (Zúñiga-Rivero and others, 2001).

Isaacson and Diaz Martinez (1995) evaluated the Devonian through Permian history of western Bolivia to southern Ecuador and distinguished the following four phases as being characteristic of Paleozoic sedimentation across western South America.

1. Shallow-marine clastic deposition through the Devonian (Lochkovian-Frasnian), with an increase in sedimentation during the Early to Middle Devonian (Emsian-Eifelian). Lithofacies distribution and sediment thicknesses indicate primarily a western source.
2. Uppermost Devonian–lower Carboniferous (Famennian-Visean) strata are characterized by glaciomarine and fan-deltaic sedimentation. Clasts were derived from underlying sedimentary units and andesitic, granitic, and tuffaceous rocks.
3. A middle-Carboniferous (Serpukhovian-Bashkirian) hiatus in sedimentation occurred; its age and duration varied across the region.
4. Siliciclastic and carbonate deposition occurred in late Carboniferous–early Permian time (Moscovian?-Artinskian). Intra-arc basins may have existed near present-day coastal Peru. Following the middle-Carboniferous hiatus, sedimentation continued in a back-arc region. Epeirogeny or magmatic-related tectonics may have influenced regional sea-level fluctuations and unconformities between Devonian and Carboniferous strata in Peru; during the Devonian, these events would have restricted formerly open seaways along eastern Peru, western Bolivia, and northern Argentina and Chile (Isaacson and Diaz Martinez, 1995).

The overall shape of the depositional area during Paleozoic and Mesozoic time has not been delineated in detail, but the Peruvian coastal region was probably part of an extensive basin that covered the whole region and extended farther to the east and west; seismic profiles show that the sedimentary strata extended westward, all the way to the axis of the Peru-Chile Trench (Nazca subduction zone on figures 1, 3) (Zúñiga-Rivero and others, 1998a).

Late Cretaceous time in northern Peru was marked by low volumes of terrigenous sedimentation due to limited

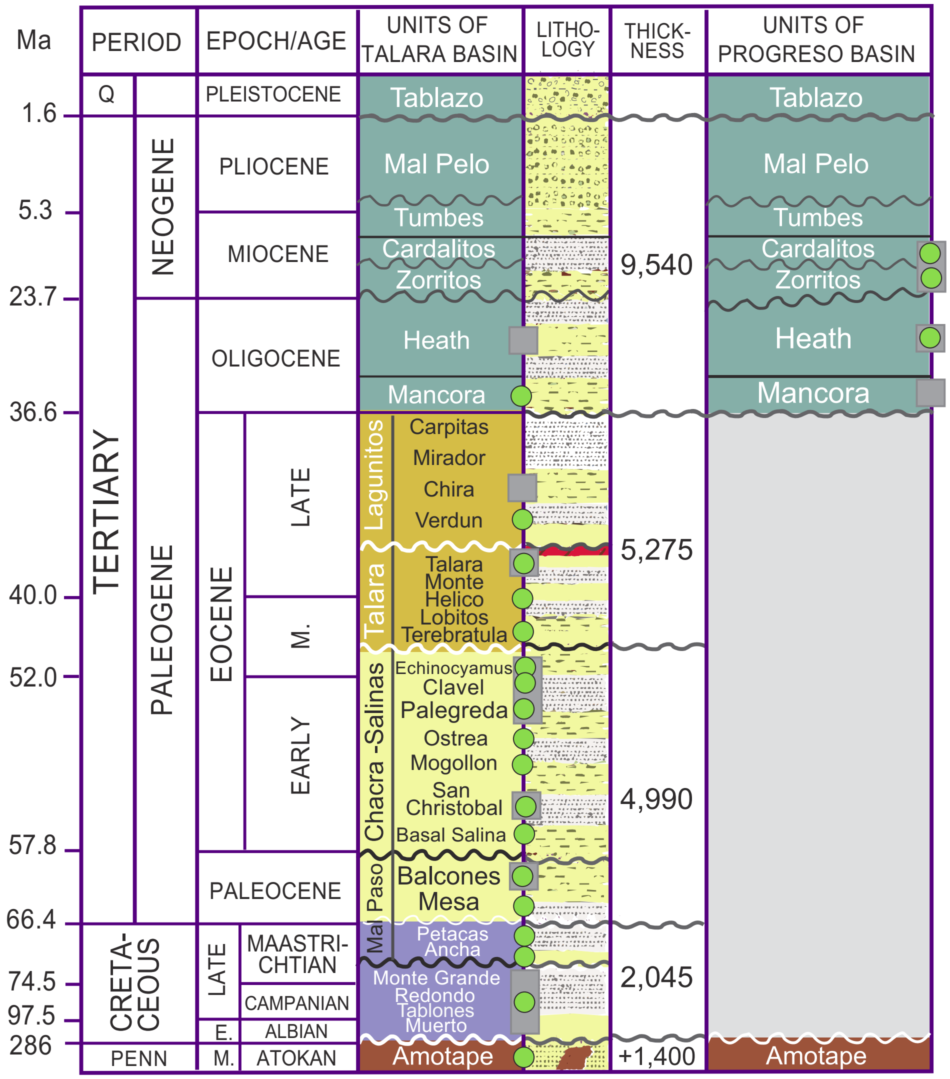


Figure 4. Stratigraphic column of the Talara and southern Progreso Basin provinces. Wavy lines and gray zones bracket periods of erosion or nondeposition. Primary reservoir formation names are marked with green dots. Possible source-rock intervals are labeled with a small gray box. Modified from AIPC (no date), Gonzales Torres (1999), Kingston (1994), Kraemer and others (1999), Perupetro (1999), Petroconsultants (1996), and Seranne (1987).

Andean relief, combined with upwelling and other oceanographic factors (Ziegler and others, 1981). Oceanic crust formed during the Early Cretaceous (Aptian-Albian) (Jaillard and others, 1995); Cretaceous mid-oceanic ridge basalt (MORB) unconformably overlies the Pennsylvanian basement rocks. Between Late Cretaceous and late Eocene time, the oceanic-floored allochthonous terranes of southern coastal Ecuador underwent a complex geologic evolution that included island-arc-related and marginal-basin sedimentation, plate and intra-plate collisions associated with shear deformation, basin subsidence, and several phases of uplift (Jaillard and others, 1995).

Thickness of the combined Cretaceous through Tertiary stratigraphic sequences across the coastal basins varies from about 8,500 to 18,000 m (28,000 to 58,000 ft) (Zúñiga-Rivero and Hay-Roe, 1998). Paleogene (66.4 to 23.7 Ma) sediments in the Talara Basin province cover more than 23,000 km^2 (9,000 mi^2) on top of the regional Paleozoic-Mesozoic basin (Zúñiga-Rivero and others, 1998b).

Based on examination of seismic, well, aeromagnetic, and gravity data, the creation of the Talara Basin province in Paleocene and Eocene time resulted from both subduction of the Nazca Plate under the South American Plate and depositional events that were related to transtensional (pull-apart) and extensional tectonics (Raez Lurquin, 1999). Origin of the eastward-spreading Nazca Plate was the East Pacific Rise. It uncoupled in Tertiary time from the continental South American Plate and began to form the subduction zone that is evidenced by the Peru-Chile Trench, also known as the Nazca subduction zone, which is located near the west margin of the Talara Basin province. This is a convergent continental margin. Tertiary subduction of the Nazca Plate under the South American Plate caused uplift and erosion of the Andes Mountains and created an active Peruvian continental borderland with a complex mix of structural and stratigraphic styles. Successive systems of clastic sedimentation during Paleocene and Eocene time resulted from large-scale synsedimentary extensional tectonics represented by high-angle faults that delineate horst-and-graben structures; relative movement of the faults was directly related to the configuration and movement of basement rocks (Raez Lurquin, 1999). The Paleocene-Eocene boundary is marked by an unconformity that underlies a thick succession of continental-derived sandstones and conglomerates of the lower Eocene Chacra-Salinas Group (fig. 4) (Seranne, 1987).

The late Paleocene, earliest Eocene, and early-late Eocene tectonic events are the most important deformational phases that influenced the geologic framework of southern coastal Ecuador; they represent progressive accretion to the continental margin (Jaillard and others, 1995). Jaillard and others (1995) believed that creation of repeated forearc basins can be attributed to subsidence from crustal erosion of the upper plate; each subsidence event succeeded an important compressive phase that must have favored coupling and tectonic erosion.

New forearc basins that were created in northern Peru and southern Ecuador in early-middle Eocene time filled with clastic shelf deposits of the Chachra-Salinas Group, which is unconformably overlain by coastal to continental coarse-grained sandstones of the middle to early-late Eocene (Jaillard and others, 1995) Talara Group (figs. 2, 4). These relations record a major Andean orogenic phase that reflects the results of collision of coastal Ecuador with the Andean margin (Jaillard and others, 1995).

During late Eocene through early Oligocene time (about 38.5 to 33 Ma), there was about a twofold increase in westward acceleration of the South America Plate across the mantle, triggering the Incaic phase of Andean tectonism that was manifested by thrusting of the eastern and western Andean flanks along most of the length of the Andes (Cande and Kent, 1992). Onset of the Incaic orogeny is marked by the regionally continuous erosional unconformity at the top of the Talara Group in the Talara Basin province, and the base of the Oligocene Mancora Formation in the southern Progreso Basin province (figs. 2, 4, 5). Uplift of the Andes and Coastal Range mountains is associated with both erosion and deposition of considerable volumes of offlapping detritus in both the back-arc and forearc regions (Cande and Kent, 1992); this uplift contributed to a thick sequence of Oligocene and Eocene sediments in the Talara Basin province. The Talara Basin province stratigraphic sequence (fig. 4) is primarily Eocene, has an aggregate thickness of as much as 8,500 m (28,000 ft), and overlies more than 1,500 m (5,000 ft) of Paleocene and as much as 2,045 m (6,700 ft) of Cretaceous strata (Zúñiga-Rivero and others, 1998b).

Sebrier and others (1988) believed that evolution of late Paleogene-Neogene basins, such as Talara, began during Oli-

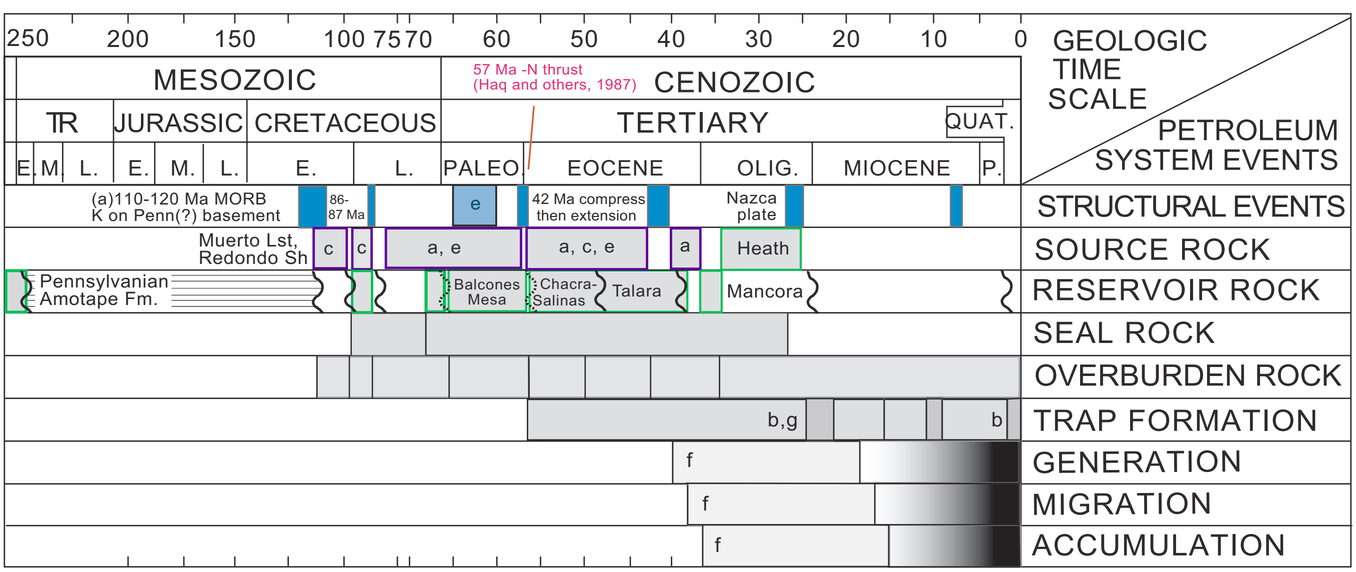


Figure 5. Total petroleum system events chart for the Cretaceous-Paleogene Assessment Unit 60810101, Talara Basin province. Gray and turquoise rectangles mark the time sequences of primary events. "P" in the geologic time scale is Pliocene time. MORB is Cretaceous (K) mid-oceanic ridge basalt on Pennsylvanian (Penn) basement rocks. Compression tectonism of the Andes Mountains during Eocene time (42 million years ago) was followed in Oligocene time by partitioning of the Farallon continental plate into the Cocos and Nazca Plates (Handschumacher, 1976; Marocco and others, 1995; Pilger, 1984). There is no published information available on hydrocarbon source rocks or timing of petroleum generation and migration; these interpretations are speculative. Ages of unconformities (wavy black lines) were determined from Sebrier and others (1988), Seranne (1987) and the sources (a) through (d) listed below. Letters (a) through (g) refer to the following sources: (a) AIPC (no author or date), (b) Jaillard and others (1995), (c) Perupetro (1999), (d) Petroconsultants (through 1996), (e) Zúñiga-Rivero and Hay-Roe (1998), and Zúñiga-Rivero and others (1998a), (f) Kingston (1994), (g) Shepherd and Moberly (1981).

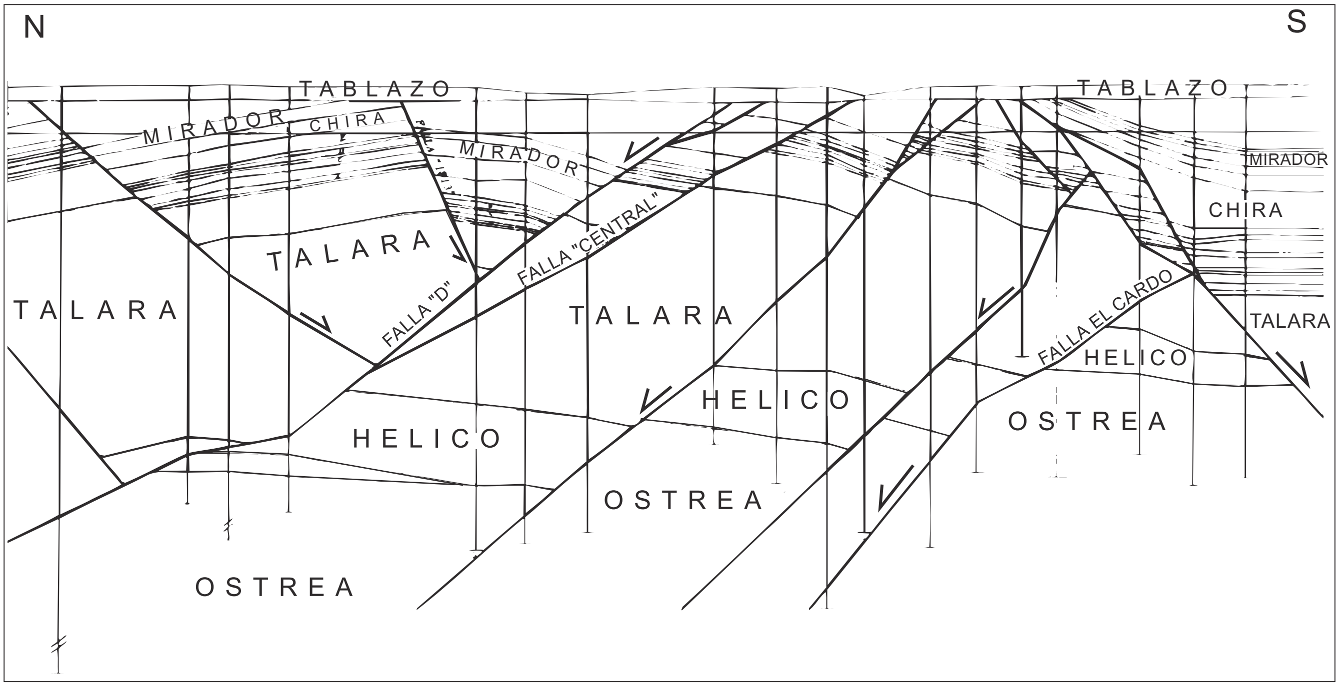


Figure 6. Diagrammatic (not to scale) north-south regional cross section across the northwestern Talara Basin province (modified from Montagna and others, 1999, reprinted by permission of author, 6/24/02). Shown are vertical and lateral offsets of formations that resulted from fault (falla) movement; arrows show relative movement. The Pleistocene Tablazo Formation unconformably overlies Oligocene and older formations. Unlabeled vertical lines are wells.

gocene time, about 28–26 Ma, after a long period of relative quiescence following the 42-Ma late Eocene compressive episode. The entire area then emerged until the formation, during latest Oligocene-Miocene (fig. 5), of new forearc basins that were subsequently filled by fine-grained shallow-marine sandstones and shales (Jaillard and others, 1995). Late Oligocene is characterized by initiation of intermontane basins with reactivation of Andean tectonism that ended in latest Miocene (about 7 Ma); structural analysis of these Neogene and Paleogene basins shows that their evolution was controlled by regional tectonic stress (Jaillard and others, 1995; Marocco and others, 1995). Synsedimentary folding and fracturing show that there was a clockwise rotation of the direction of stress in the Neogene; this explains variations in the behavior of the faults that border the basins and the different stages of their evolution (Jaillard and others, 1995; Marocco and others, 1995). A trough at the northern border of the Talara Basin province may have been created in Neogene time by opening of the Gulf of Guayaquil along the Guayaquil-Dolores megashear (Shepherd and Moberly, 1981) at the southern boundary of the Progreso Basin province (figs. 1, 3).

Upper Eocene Lagunitos Group strata unconformably overlie the Talara Group and are overlain by the Oligocene Mancora and Heath Formations (fig. 4). The Neogene sedimentologic history of the bounding Progreso Basin province began with an Oligocene transgressive cycle and associated deposition of the Mancora and Heath Formations (AIPC, no date). These formations were also present in the Talara Basin province, except where removed by erosion (figs. 2, 4). Deposition was followed by peneplanation of the Heath Formation and subsequent deposition of the Miocene Zorritos Formation in the northern part of the province; this was associated with a period of block faulting (AIPC, no date).

Normal faulting is an important aspect of the structural style of the Talara Basin province, as are low-angle gravitational slide faults and large vertical transcurrent faults (Zúñiga-Rivero and others, 1998b). Complex structural features of the offshore Talara and southern Progresso Basin provinces include extensive growth faulting with associated rollover-type folding (AIPC, no date). Bianchi (2002) mapped faults in the offshore area of the Litoral field (fig 1), where the major faults are oriented approximately north-south. Seismic and subsurface data indicate that the faulting is most intense in the eastern (onshore) portions of the northern basins and decreases in a seaward direction (Zúñiga-Rivero and others, 1998a). Figure 6 shows some of the complex faulting in a regional north-south cross section in the northwestern Talara Basin province. Location of the cross section is in the area of the La Brea–Pariñas to Tunal oil fields in figure 1. Fault movement during times of deposition and erosion resulted in variable thicknesses of formations across the region. The primary target for reservoirs is the upper Eocene Verdun Formation (Montagna and others, 1999), which is represented by the close-set lines above the Talara Group in figure 6.

Exploration History

For many centuries, Peruvians used oil seeps, such as those near the La Brea–Pariñas oil field (fig. 1), largely to seal joints in wooden boats and also for fuel to light their homes. The Spaniards used pitch to caulk their ships and to waterproof ropes. Discovery of the first field in the province, La Brea–Pariñas, was in 1869; production is reported commingled from Eocene formations and the Cretaceous Ancha and the Pennsylvanian Amotape Formations (Petroconsultants, 1996). Production within the basin has been mostly from Eocene sandstones (38 fields). One field, the Piedra Redonda (fig. 1), produces from sandstone of the Oligocene Mancora Formation, and two fields include production from the Paleocene Balcones and Mesa Formations (Petroconsultants, 1996). Four fields record production from Cretaceous and Pennsylvanian formations (Petroconsultants, 1996). The Litoral field (discovered in 1960) (fig. 1) has about 44 MMBO of commingled production from the Eocene Salina, Clavel (also known as Pariñas), Terebratula, and Basal Salina Formations (Bianchi, 2002). Background statistics for oil and gas fields in the province are listed in table 1.

Talara Basin province cumulative production exceeds 1.68 BBO (Perupetro, 1999) and 1.95 trillion cubic feet of gas (TCFG) (Petroconsultants, 1996) (table 1); offshore wells have produced about 285 MMBO. The Petroconsultants database did not contain production information on the La Casita gas field (fig. 1). Daily production from offshore wells is about 15 thousand barrels (Raez Lurquin, 1999). Forty-two oil and (or) gas fields are located in the basin; known recoverable oil and gas for these fields is 2.90 billion barrels of oil equivalent (BBOE) (modified from Petroconsultants, 1996).

Zúñiga-Rivero and others (1998a, 1998b) listed cumulative production of 1.6 billion barrels of light crude and an estimated 3.5 TCF of associated gas, mainly in the central and northern parts of the onshore sector; this estimate includes wells in the shallow offshore (out to the 370-ft water depth) that have cumulative production of about 280 MMB of light crude and about 700 BCF of gas. Zúñiga-Rivero and others (1998a, 1998b) generalized known recoverable (estimated ultimate potential) reserves and resources are greater than 2 BBO or 25 TCFG for the offshore Talara Basin province.

Gonzales and Alarcon (2002) estimated the volume of generated, migrated, trapped, and recoverable hydrocarbons for the Talara Basin province. The hydrocarbon source rocks used in their analysis were shales and limestones of the Cretaceous Redondo Formation (fig. 4); the characteristics of the Redondo Formation in the hydrocarbon-generation area of their model included a thickness of 473 m, specific grain density of 2.525 g/cm^3, 1.4 percent total organic carbon (TOC),

Table 1. Background statistics for oil and gas fields in the Talara Basin province, 6081.

[Years of production are 1869 through 1996. Data are shown for all fields and formations regardless of producing formation. Most production is reported commingled. The number (n) of data points follows each column. MMBO, million barrels of oil; MMBOE, million barrels of oil equivalent; CUM, cumulative; BCFG, billion cubic feet of gas; cfg/BO, cubic feet of gas per barrel of oil; mD, millidarcy. Sources of data are Perupetro (1999a), and the Petroconsultants (1996) and GeoMark (1997) databases. Petroconsultants resource estimates are known, not grown, statistics]

	Oil fields	n	Gas fields	n
Number of oil fields		26		
Number of oil and gas fields and gas fields		13		3
Listed fields with 1 MMBOE CUM and greater		9		0
Cumulative oil production (MMBO)	1,685 [1]		0	0
Cumulative gas production (BCFG)	1,950	3		0
Median gas-oil ratio (cfg/BO)	1,045	8		
Ranges of gas-oil ratio (cfg/BO)	69–4,574	8		
Median water saturation (percent)	42	15		0
Range of water saturation (percent)	30–55	15		0
Median API gravity (degrees)	31.8	36		
API gravity (degrees) – ranges	16–41	36		
Median percent sulfur in oils	0.06	20		
Range of sulfur in oils (percent)	0.03–0.26	20		
Median net perforated thickness (m and (ft))	30 (98)	13	17 (56)	3
Maximum net perforated thickness (m and (ft))	245 (800)	13	20 (66)	3
Median maximum drill depths of fields (m and (ft))	1,500 (4,90)	39	2,880 (9,460)	3
Maximum depths of drilling of fields (m and (ft))	2,570 (8,430)	39	3,300 (10,840)	3
Range of water depths (m and (ft))	82–230 (25–70)	9	35–66 (115–220)	2
Range of porosity (percent)	15–25	48		0
Range of permeability (mD)	20–1000	16		0

[1] Data from Perupetro (1999a).

vitrinite reflectance (R_o) of 1.11 percent, a hydrogen index of 91, and 1,625 ppm of extracted hydrocarbons. Gonzales and Alarcon (2002) published the following estimates:

1. Volume of thermally mature source rock in the hydrocarbon generation area of the Talara Basin province is 8.27×10^{17} cm^3,
2. Total volume of generated hydrocarbons is 2.75×10^5 MMBO and 2.25×10^4 TCFG.
3. Total trapped oil and gas of 2.48×10^5 MMBO and 2.03×10^3 TCFG, calculated using a 30 percent expulsion efficiency and 30 percent emplacement efficiency in reservoirs.
4. Total volume of recoverable oil and gas is 2.48×10^4 MMBO and 162.4 TCFG, based on a 10-percent recovery factor.
5. Volumes of lost hydrocarbons are 3.72×10^3 MMBO and 2.4 TCFG, based on 15 percent of the hydrocarbons lost from traps due to migration along faults and other processes.
6. Total volume of recoverable hydrocarbons from the Talara Basin province, including current production, is 3.72 BBO and 9.344 TCFG. Production through 2000 is 1.5 BBO and 3.5 TCFG (Gonzales and Alarcon, 2002).
7. Volume of remaining recoverable hydrocarbons (excluding current production) is 2.22 BBO and 5.844 TCFG.
8. Remaining recoverable hydrocarbons are 70 percent onshore, or 1.554 BBO and 4.09 TCFG, and 30 percent offshore, or 666 MMBO and 1.75 TCFG.

USGS estimated mean recoverable oil, gas, and natural gas liquids (NGL) resources from undiscovered fields in the basin are 1.71 BBO, 4.79 TCFG, and 255 million barrels of NGL (table 2). Minimum size of fields used in this analysis is 1 MMBO, or 6 BCFG. Figure 7 shows the proposed frequency distribution of undiscovered oil and gas fields within the province. The mean estimate is 83 undiscovered oil fields and 27 undiscovered gas fields. Ranges in undiscovered resource distributions from table 2 show the USGS estimates for undiscovered oil, gas, and natural gas liquids (NGL) resources for the Talara Basin province that have the potential to be added to reserves within the next 30 years (USGS World Energy Assessment Team, 2000). These estimates for TPS 608101 used data from Petroconsultants (1996), GeoMark (1998), and referenced publications in the analyses of the areal and temporal distribution of drilling and production. Estimated mean recoverable oil and gas resources from undiscovered onshore (15 percent) and offshore (85 percent) fields are 257 MMBO and 719 BCFG, and 1.45 BBO and 4.08 TCFG, respectively.

Travis and others (1975) estimated the offshore potential at 1 BBO, but believed that the onshore portion had low potential for future discoveries. Kingston's (1994) estimated offshore potential of 1.2 BBO and 1.4 TCFG was based on comparing the areal distribution of possibly productive areas in the onshore to that of the offshore. The southernmost parts of the onshore and offshore basin areas appear to be gas prone, but oil resources could be present in unexplored areas according to Zúñiga-Rivero and others (1998b, 1999). Offshore Peru has excellent potential for gas-hydrate resources based on work by Miller and others (1991); these potential resources were not

Table 2. Assessment results summary for the Cretaceous-Tertiary Total Petroleum System (608101), Cretaceous-Paleogene Basin Assessment Unit (60810101) (USGS World Energy Assessment Team, 2000).

[MMBO, million barrels of oil; BCFG, billion cubic feet of gas; MMBNGL, million barrels of natural gas liquids; MFS, minimum field size assessed (in MMBO or BCFG); Prob., probability, including both geologic and accessibility probabilities of at least one field equal to or greater than the MFS. Results shown are fully risked estimates. All liquids in gas fields are included under the natural gas liquids (NGL) category. F95 represents a 95-percent chance of at least the amount tabulated. Other fractiles are defined similarly. Fractiles are additive under the assumption of perfect positive correlation. Shading indicates not applicable]

Code and field type	MFS	Prob. (0-1)	Undiscovered resources											
			Oil (MMBO)				Gas (BCFG)				NGL (MMBNGL)			
			F95	F50	F5	Mean	F95	F50	F5	Mean	F95	F50	F5	Mean
60810101 Cretaceous-Paleogene Basin Assessment Unit of the Cretaceous-Tertiary Total Petroleum System														
Oil fields	1	1.00	484	1,625	3,214	1,711	719	2,517	5,504	2,739	40	147	347	164
Gas fields	6						523	1,887	4,133	2,057	21	81	192	90
Total		1.00	484	1,625	3,214	1,711	1,243	4,404	9,637	4,795	62	227	539	255
6081 Total: Assessed offshore portions of the Talara Basin Province														
Oil fields		1.00	411	1,381	2,732	1,455	611	2,139	4,678	2,328	34	125	295	140
Gas fields							445	1,604	3,513	1,748	18	69	163	77
Total		1.00	411	1,381	2,732	1,455	1,056	3,743	8,191	4,076	53	193	458	217
6081 Total: Assessed onshore portions of the Talara Basin Province														
Oil fields		1.00	73	244	482	257	108	378	826	411	6	22	52	25
Gas fields							78	283	620	309	3	12	29	14
Total		1.00	73	244	482	257	186	661	1,446	719	9	34	81	38

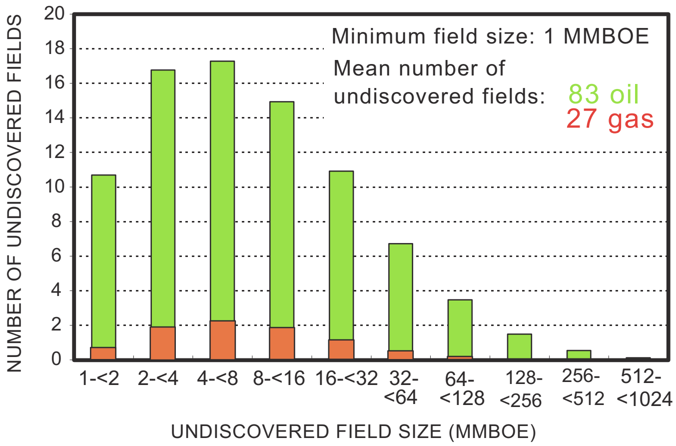


Figure 7. Mean estimate of size distributions of undiscovered oil (green) and gas (red) fields in the Talara Basin province. Distributions are based on grown oil and gas assessments from the USGS World Energy Assessment Team (2000).

assessed in the present study.

Twenty oil fields and one gas field have known recoverable resources of 1 MMBOE and greater. Twenty oil and two gas fields have grown recoverable resources of greater than 1 million barrels of oil equivalent (MMBOE) (fig. 8). Figure 8 shows the field-size distribution, based on periods of discovery for known oil resources, versus the number of fields in each size range. Grown oil fields versus the number of fields in each size range are also displayed. Assigning a growth factor to fields (fig. 8) resulted in little or no change in field size for those that were discovered early in the history of exploration and are already mature; the second third of discovered fields exhibits a slight increase in field size, and the latest third exhibits the greatest increase. Discovery-history curves in mature basins commonly show that the largest fields are discovered early in the history of exploration and field size tends to decrease through time. In the Talara Basin province, the largest field is La Brea–Pariñas (1869) with grown recoverable oil and gas resources greater than 1 BBO and 1 TCFG. Two other large fields that were discovered early in the history of exploration were Los Organos–El Alto and Lobitos, which have discovery dates of 1901 and grown recoverable oil resources of about 350 MMBO. The irregular distribution of discovery thirds reflects the frontier aspect of exploration in the basin. There are only nine fields that have cumulative production greater than 1 MMBOE, and 39 with known recoverable reserves plus resources of greater than 1 MMBOE.

Figure 9 shows the known recoverable reserves and resources of oil and gas based on data from Petroconsultants (1996); these are divided into the first, second, and third discovery-thirds of all fields regardless of field size. Three of the four largest fields were discovered early in the history of

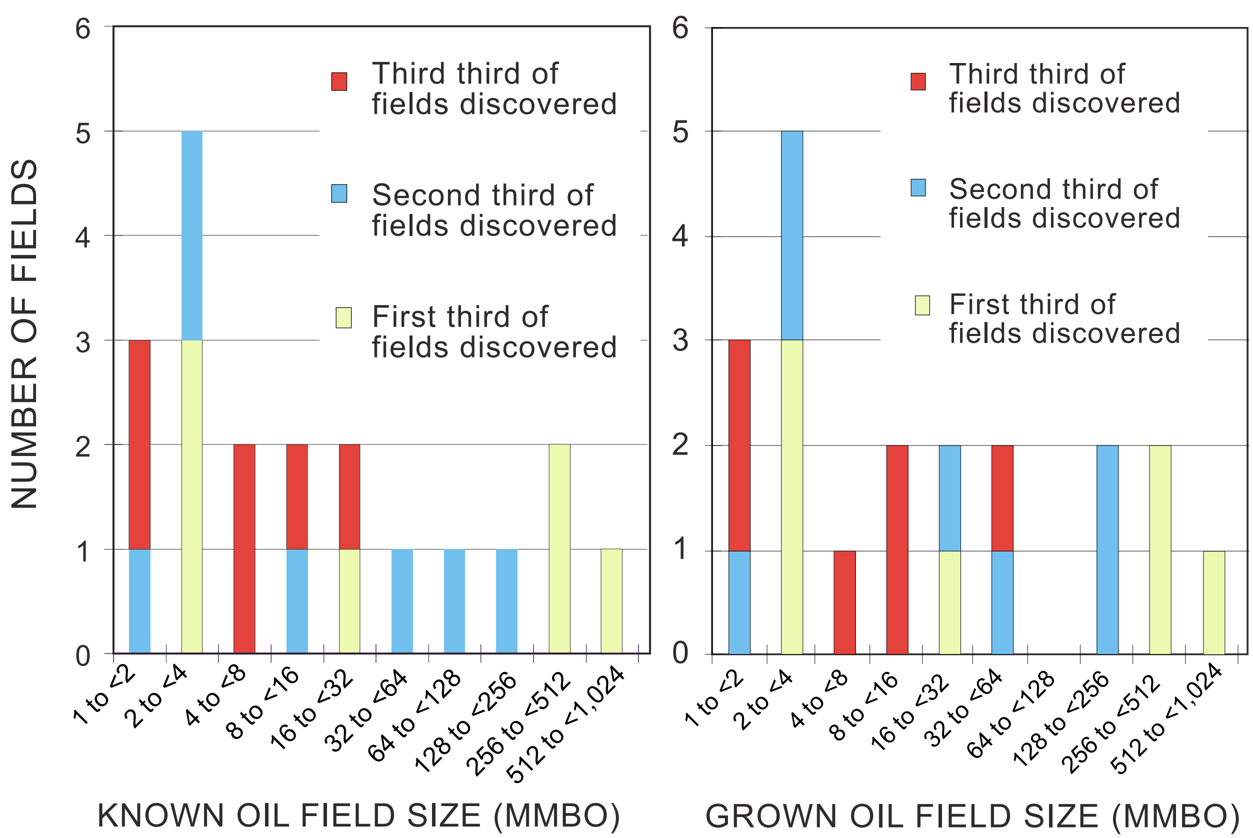


Figure 8. Discovery thirds of known and grown oil field size (MMBO) versus the number of oil fields in the Talara Basin province.

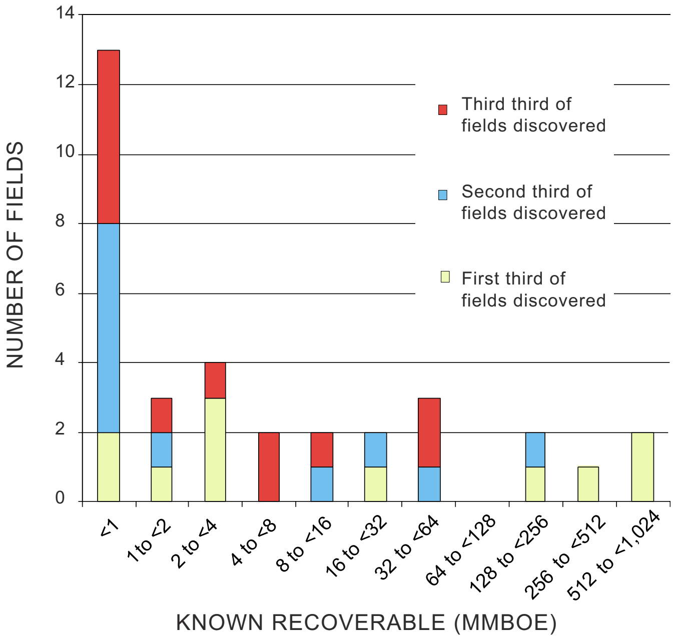


Figure 9. Discovery thirds of known recoverable oil and gas, in millions of barrels of oil equivalent (MMBOE), versus the number of fields for the Talara Basin province. Known recoverable reserves and resources data modified from the Petroconsultants database (1996) were divided into the first, second, and third thirds of discovered fields.

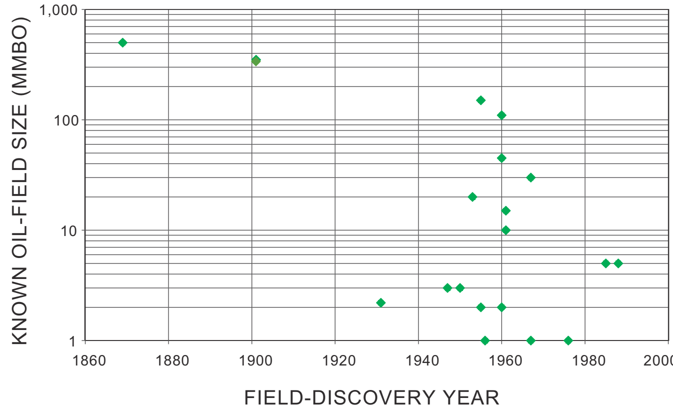


Figure 10. History of field discoveries and volumes of known oil-field size across the Talara Basin province (Petroconsultants, 1996). A sharp increase in the volume of known recoverable hydrocarbons generally indicates a major field discovery or combined effects of numerous field discoveries, as started in about 1949. Minimum field size is 1 million barrels of oil (MMBO) recoverable.

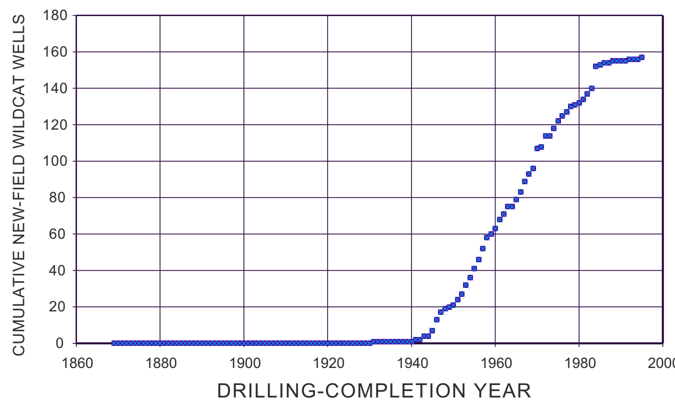


Figure 11. Cumulative number of new-field wildcat wells and associated completion dates (Petroconsultants, 1996). Increased exploration frequently follows discovery of large fields, such as after the 1955 discovery date of Pena Negra field. More than 143 million barrels of oil (MMBO) have been produced from the field (Chavez and Rodriquez, 2002).

exploration in the basin, but there is an irregular distribution of known recoverable reserves and resources for fields. The smallest oil and gas fields were mainly found in the latter two-thirds of the exploration history. Figure 10 shows the discovery year for each field versus the known recoverable oil field size for fields in the Talara Basin province; minimum known field size cutoff is 1 MMBO. Some fields, such is La Brea–Pariñas, were originally two separate fields that were later merged into one; discovery date of the earliest was used. Although the three largest fields were discovered early in the history of exploration in the basin (1869, 1901, and 1901), the next field, Portachuelo (Mirador), was not discovered until 1931. A noticeable increase in exploration began about 1950, expanded further around 1960, but was then followed by a decrease in new field discoveries. This trend is mirrored by the linear trends in cumulative number of new-field wildcat wells versus field discovery year (fig. 11). There are currently more than 12,000 onshore wells. Low rates of drilling until about 1945, and the discoveries of the Malacas (1947) and Chimenea (1950) fields, were followed by a steady and stable increase in exploration to the early 1980s, with a subsequent slight decrease in drilling rate. Figure 12 shows discovery dates for fields versus the reservoir depth(s). Because most fields produce from multiple reservoirs, the chart shows a range of depths for most of them. Maximum and median drill depths were 1,500 m (4,900 ft) and 2,570 m (8,430 ft), respectively, for the 39 oil plus oil and gas fields (table 1) (Petroconsultants, 1996).

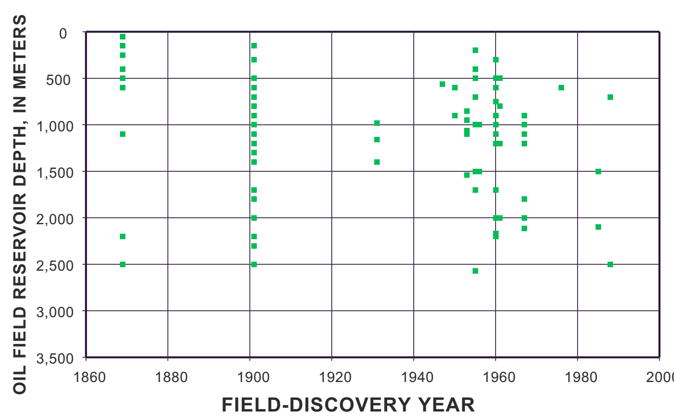


Figure 12. Field discovery date versus depths in meters of all reservoir intervals.

Petroleum Occurrence

Hydrocarbon Source Rocks

There is little published geochemical information on potential hydrocarbon source rocks in the Talara Basin province. Pindell and Tabbutt (1995) indicated that there are five main Mesozoic-Cenozoic settings for source-rock deposition and preservation in the Andean basins of South America. One of these settings may be appropriate for the Talara Basin province. This is along the Andean forearc in areas where terrigenous sedimentation at various times was slow due to low Andean relief (Ziegler and others, 1981) and where upwelling and other oceanographic factors presumably produced conditions that concentrated organic matter in marine shales. A possible example is the Upper Cretaceous (Campanian) Redondo Shale (fig. 2).

Probable Cretaceous hydrocarbon source rocks in the Talara Basin province are the Albian Muerto Limestone and the marine shales of the Campanian Redondo Formation (fig. 4) (AIPC, no date; Perupetro, 1999; Zúñiga-Rivero and others, 1998a, 1998b). Gonzales and Alarcon (2002) proposed that the Cretaceous Redondo Formation is the primary hydrocarbon source rock in the basin and included the Cretaceous Muerto and Oligocene Heath Formations as potential source rocks. Perupetro (1999) indicated that potential Tertiary hydrocarbon source rocks are shales of the Eocene San Cristobal Formation (lower Eocene of the Salina Group), the Chacra Group (lower Eocene Echinocyamus and Clavel (Pariñas) Formations), the lower Talara (middle Eocene), and the Chira-Heath (upper Eocene–lower Oligocene) Formations. Kraemer and others (2001) believed that the Heath Formation is the primary source rock in the southern Progreso Basin province (fig. 4). Lower Eocene Palegreda neritic marine shales and the Paleocene Balcones Shale (Mal Paso Group) are also believed to be important organic-rich source rocks in the Talara Basin province by AIPC (no date) and Zúñiga-Rivero and others (1998a, 1998b). Gonzales and Alarcon (2002) however, indicated that the Balcones Formation—as well as the Eocene Chira, Salina, and San Cristobal Formations and the Paleocene Petacas Formation—were not of source-rock quality based on TOC, hydrocarbon indices, and other data. Shales of the Cretaceous Monte Grande Formation are primarily of terrestrial (type-III kerogen) origin and are potential sources of dry gas; there is no evidence of dry gas generation in the basin (Gonzales and Alarcon, 2002).

AIPC (no date) evaluated the total organic carbon (TOC) of 151 samples of Tertiary shales collected from outcrops and well cuttings at locations between Zorritos (just north of the Talara Basin province) and Talara (near the Portachuelo oil field) (fig. 1). Eighty-one Eocene shales ranged from 0.11 percent to 1.92 percent TOC, 15 Mancora Shale samples ranged from 0.08 percent to 4.95 percent TOC, 35 Heath shales were 0.24 percent to 3.86 percent TOC, 13 Zorritos shales varied from 0.22 percent to 13.12 percent TOC, and 7 Cardalitos shales ranged from 0.15 percent to 1.62 percent TOC. Gonzales and Alarcon (2002) indicated that geochemical analyses of 13 shale and limestone samples that ranged in age from Early Cretaceous (Albian) to Oligocene age showed TOC contents ranging from 1.1–1.3 percent. Values above 1 percent TOC are potential source rocks, whereas those below this have low to marginal potential.

Distribution of API gravity of oils for fields in the Talara and Progreso Basin provinces is shown in figure 13. Although they have a similar distribution, Talara Basin province oils tend to be slightly heavier than those of the Progreso Basin province. Weight percent sulfur and API gravity of oils are both influenced by migration history, biodegradation, evaporation and mixing of oils, and other geologic and geochemical factors. Biodegradation can result in an increase in sulfur as the microorganisms preferentially eat light-chain hydrocarbons that have a lower percent of sulfur, which caused some of the scatter in figure 13. Many of the Tertiary oils, particularly those with API gravity less than 23, exhibit some biodegradation, commonly with a second phase of hydrocarbon migration, based on examination of gas chromatogram/mass spectrometer charts. Three biodegraded Tertiary oil samples are shown in green in figure 14. The oil sample on the far left also has a second phase of migration. Figure 14 shows API gravity versus weight percent sulfur for oils from the Progreso and Talara Basin provinces. Sulfur content of the 20 oils analyzed in the Talara Basin province ranges from 0.03 to 0.26 percent, with a median of 0.06 percent (table 1) (GeoMark, 1998). There is one sample population for the analyzed oils of the Talara Basin and Progreso Basin provinces. The one Pennsylvanian Amotape Formation oil is grouped with the Tertiary oils in the Talara Basin province. Pennsylvanian Amotape Formation reservoir rocks are mostly quartzite, and any associated Paleozoic shales would probably be overmature for hydrocarbon generation. This Pennsylvanian oil from the Portachuelo field may have been sourced from Tertiary shales and migrated

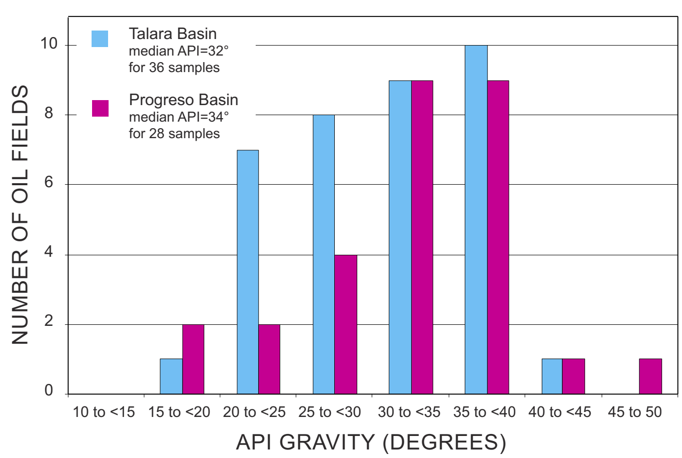


Figure 13. API gravity of oil fields in the Talara (6081) and Progreso (6083) provinces. Light oil is commonly characterized by an API of 31°–55°, medium-grade oil by 22°–31°, and heavy oil by less than 22°.

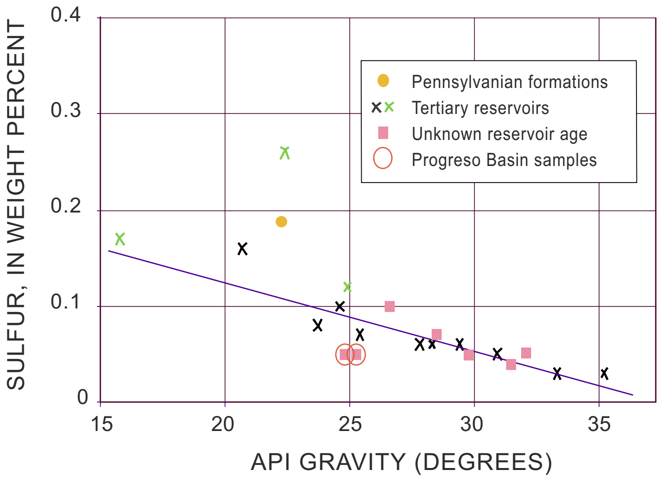


Figure 14. API gravity and weight percent sulfur of oils from selected fields across the Talara and Progreso Basin provinces, Ecuador and Peru (GeoMark, 1998). Based on the distribution of data, there appears to be one oil population for these provinces. Scatter in data can result partly from analytical methods and from biodegradation of oils from Tertiary reservoirs. Three Tertiary oils that indicate biodegradation are shown in green.

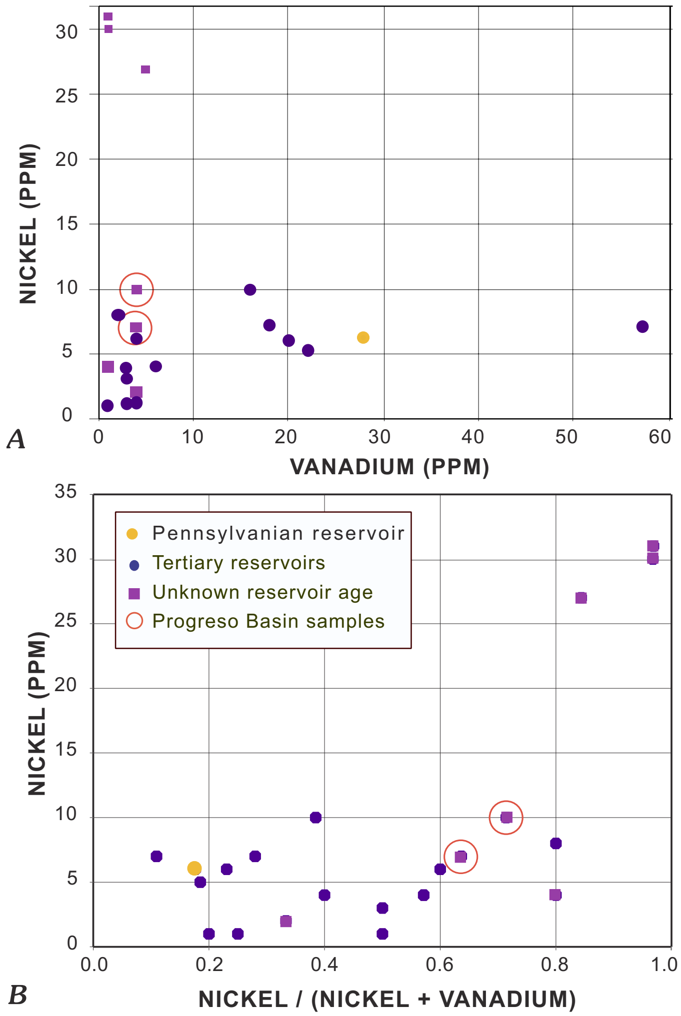


Figure 15. The ratio of nickel and vanadium (Ni/V) in parts per million (ppm), in oils from the Talara and Progreso Basin provinces. The Ni/V ratio tends to be constant through time and can indicate different age and lithology of source rocks. Distribution of data for *A* and *B* show one sample population for oils from the Talara and Progreso Basin provinces. Talara Basin province samples are generally less than or equal to 10 ppm Ni and 30 ppm V; one sample from a Paleocene reservoir contains about 7 ppm Ni and almost 60 ppm V. The one Pennsylvanian Amotape oil is characteristic of a Tertiary source. Talara samples that contain greater than 25 ppm nickel are probably also a Tertiary source, based on other geochemical data. Isolation of these samples may represent a more terrigenous source for these than for the other samples.

along fault and fractures into the Amotape, or it could be associated with mixing of oils from several source rocks. Field oil production is from the Upper Cretaceous Redondo and the Eocene Salina Formations and is reported as commingled. Zúñiga-Rivero and others (1999) stated that the Amotape Formation can be a commercial reservoir in areas where it is highly fractured and capped by the Cretaceous Redondo Shale. Because the overlying Muerto, Tablones, and Redondo Formations contain probable source rocks, these would be likely sources for oil in Amotape reservoirs.

Concentrations of nickel (Ni) and of vanadium (V) in hydrocarbons can be influenced by depositional environment (marine versus nonmarine), shale versus carbonate source rocks, migration history, and by factors that remove lighter chain hydrocarbons and result in concentration of Ni and V on the longer chain atoms, onto which these elements are preferentially attached. However, the ratio of Ni to V in oils is quite stable through time. Because Ni and V atoms exhibit similar chemical properties, they, and the hydrocarbon molecules that contain them, are generally influenced similarly through their burial history. Median values are 5.5 ppm Ni and 4.0 ppm V for the 20 oil samples analyzed in the Talara Basin province. Ratios of nickel and vanadium for the analyzed oils (figs.15*A*, 15*B*) show one sample population that includes Paleocene and Eocene oils for the Talara Basin province and probable Tertiary oils of the Progreso Basin province. Visual examination of groups of oil samples could indicate several sets of Talara Basin province source rocks, but this is misleading. Each "group" of three or more Tertiary samples in the Talara Basin province is a mix of Eocene and Paleocene oils, as opposed to them being segregated by formation. The Pennsylvanian Amotape Formation oil (figs. 14, 15) is grouped among the Tertiary oils, which suggests that it was probably sourced from the same marine shales.

The Talara Basin province oils were from source rocks of similar origin, such as shales deposited in a marine setting, based on the distribution of data in figures 15*A* and 15*B*. Probable exceptions to this are the three oil samples located in the upper left corner of figure 15*A* and upper right corner of 15*B*. Although these oils are from an unknown, but probable Tertiary, source having similar V concentrations to the other Tertiary oils, the Ni content is much greater at 27 to 31 ppm.

This may be due to a difference in depositional environment. These oils could have been sourced from nonmarine or mixed marine-nonmarine shale that contained a greater initial ratio of nickel to vanadium. Mixing of oils from several source rocks may also have influenced the Ni and V contents of these oils, as well as other oils. Gas chromatograms of the same three oils exhibit an early stage of biodegradation followed by a second pulse of migration of hydrocarbons into the reservoir. These secondary hydrocarbons show minor to extensive biodegradation, as indicated by concentration of heavier chain hydrocarbons relative to lighter ones. Conversely, the sample located near 60 ppm V in figure 15*A* is highly biodegraded oil from the Salina Group in Tunal field (fig. 1). Gas chromatograms in the Talara and Progreso samples exhibit some loss of light-chain hydrocarbons, whether due to leakage upward along fault systems or from biodegradation and concentration of heaver relative to lighter hydrocarbons. Many also show two pulses of hydrocarbon migration with relatively non-degraded secondary oils. This is indicated in figure 13 by the median API gravity of 32° for Talara Basin province oils; most oils listed in the GeoMark database are light to medium gravity.

The ^{13}C distribution of saturated and aromatic hydrocarbons from oils across the Talara and Progreso Basin provinces is shown in figure 16. Oils were identified using data from the GeoMark (1998) and Petroconsultants (1996) databases. Shown is one sample population for all analyzed oils in the Talara and Progreso Basin provinces. The two Progreso Basin oils in figures 15*A* and 15*B* are unidentified but are probably Eocene in age. The 20 Talara oil samples are primarily from the Eocene Talara, Clavel (Pariñas), and Chacra Sandstones, and the Mogollon and Basal Sandstones of the Salina Group. One oil sample is listed in the GeoMark database as being from the Pennsylvanian Amotape Formation in the Portachuelo field (fig. 1). Grouping of this one sample (fig. 16) with the other mostly Eocene samples indicates that it is derived from Tertiary source rocks.

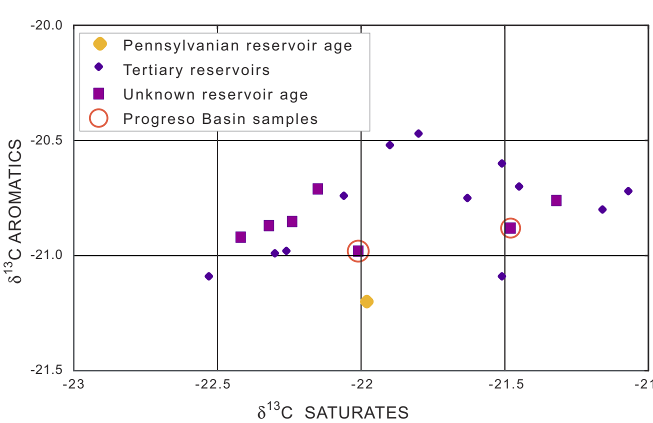


Figure 16. Distribution of $\delta^{13}C$ isotopes for saturated and aromatic hydrocarbons, Talara and Progreso Basin provinces (GeoMark, 1998). Clustering of data indicates that sampled oils from the Talara and Progreso Basin provinces have a common source rock.

Maturation and Migration

Paleozoic through Tertiary source rocks across Colombia, Ecuador, and Peru became thermally mature for oil generation during the Neogene phases of basin development (Pindell and Tabbutt, 1995). Maturation of source rocks within the entire stratigraphic column probably began during Miocene time, when the sediments across the Talara Basin province approached their maximum thickness. Kingston (1994), however, believed that the section was thick enough by the end of Eocene time for source rocks to have generated hydrocarbons. The thickness of sedimentary rocks in the Talara Basin province exceeds 8,000 m (26,000 ft) for mid-Cretaceous carbonates and sandstones, combined with conglomerates through clays of Paleocene and Eocene age (Raez Lurquin, 1999). Hydrocarbon generation during Eocene time was possible for Cretaceous source rocks, but Eocene source rocks may not have been buried deep enough for this to have occurred. Gonzales and Alarcon (2002) placed the onset of hydrocarbon generation and migration as late Eocene, based on their model of hydrocarbon generation, migration, and accumulation for shales and limestones of the Cretaceous Redondo Formation.

Onset of migration and emplacement was probably in Miocene time, soon after the start of Late Eocene or Miocene hydrocarbon generation, because of the proximity of probable source to reservoir rocks. Faulting and fracturing across the Talara Basin province would have enhanced vertical migration of hydrocarbons. Gas chromatograms of Paleocene oils from several fields that are scattered across the basin give evidence of two or more stages of migration; minor to extensive biodegradation is overprinted by later migrated oil that is non-biodegraded or exhibits minor biodegradation of light-chain hydrocarbons. Gas chromatographic–mass spectrographic data plus the presence of active seeps indicate that active migration is still occurring in the basin. Median API gravity is 31.8° for 36 oils across the basin (table 1).

Zúñiga-Rivero and others (1998b) concluded that (1) much or all of the hydrocarbon migration occurred following a mild compressive phase because the areal distribution of oil and gas is indicative of original entrapment in anticlinal or domal closures; and (2) subsequent normal faulting modified the structure and also redistributed the hydrocarbons to some extent, possibly assisting in the second pulse of migration. Sanz (1988) believed that lateral migration of hydrocarbons was limited in onshore Talara Basin province fields; the oil was generated in shales immediately adjacent to and overlying the reservoir. Sanz (1988) did not present any geochemical evidence, however, to support this opinion, which was based on analyses of well and outcrop samples. The northern portion of the Talara Basin province is extensively faulted, providing potential conduits for vertical migration of hydrocarbons. It is likely, however, that there was a mix of vertical and lateral migration of hydrocarbons.

Gonzales and Alarcon (2002) indicated, based on magnetic, gravimetric, seismic, and geochemical data, that (1) hydrocarbon migration was primarily from Cretaceous source rocks deeper in the basin, laterally toward faults, and 20–600 m vertically along the faults into the mostly structural traps; (2) subsequent vertical migration along fault systems, and lateral migration distances, were 10–50 km, based on the above geophysical and geochemical data and on changes in API gravity of oil in reservoirs that are progressively farther away from the kitchens, and (3) there were several periods of migration, based partly on early biodegradation of oils followed by later non-biodegraded oils.

Reservoir Rocks

There are more than 40 oil and (or) gas fields in the Talara Basin province (table 1), with production from as many as a dozen formations per well; and all production is reported commingled (Petroconsultants, 1996). The primary reservoirs are Eocene-age nearshore-marine sandstones. Three fields that produce oil and gas from quartzites of the Pennsylvanian Amotape Formation also have oil from Eocene and (or) Cretaceous sandstones; a fourth field, the now-abandoned Zorro field, produced about 100,000 BO from only the Amotape Formation. Oil and gas in four other fields is from sandstones of the Cretaceous Redondo Formation and the Cretaceous Ancha and Petacas Formations of the basal Mal Paso Group. One field produces gas from the Oligocene Mancora Formation.

Reservoirs are mainly sandstones in the following formations:

- Pennsylvanian Amotape Formation fractured quartzites,
- Upper Cretaceous Redondo Shale, and the Upper Cretaceous Ancha and Petacas Formations of the Mal Paso Group,
- Paleocene sandstones of the Mesa and Balcones Formations, upper Mal Paso Group,
- Lower to middle Eocene Chacra and Salinas Groups (including the Basal Salina, San Cristobal, Mogollon (Manta), Ostrea (Tangue, Pardo), Palegreda, Clavel (Pariñas), and Echinocyamus Formations),
- Middle and upper Eocene Talara Group (including the Terebratula, Hélico, and Talara (Pozo, southern basin, Media and underlying Yapato in the north) Formations),
- Upper Eocene Verdun Formation of the Lagunitos Group,
- Oligocene Mancora Formation.

Quartzites of the Amotape Formation are unconformably overlain by Cretaceous limestones, sandstones, and shales, which in turn are in unconformable contact with Tertiary rocks. The thick sequence of Upper Cretaceous through Eocene strata in the Talara Basin province accumulated primarily in fluvial to deltaic depositional environments, with some offshore marine turbidites (AIPC, no date). Although the pre-Neogene strata are laterally continuous through the basins, the vertical sequence is also cut by internal unconformities (Zúñiga-Rivero and Hay-Roe, 1998) (figs. 2, 4). Eroded Mesozoic and Paleozoic strata were the initial source of clastic detritus; petrographic analysis confirms that the sandstones are quartz rich with a small proportion of volcanic material (Raez Lurquin, 1999). The source of Paleocene and Eocene sediments was from the northeast to southeast; the origins were highlands that resulted from compressional uplift of the Andes and other mountainous areas (Perupetro, 1999; Pindell and Tabbutt, 1995; Raez Lurquin, 1999). Sandstones interfinger westward with marine and nonmarine shales (Pindell and Tabutt, 1995), creating stacked sandstone reservoirs with interbedded shale seals and potential source rocks. Zúñiga-Rivero and others (1998a) indicated their stratigraphic and structural interpretations are based on approximately 13,037 line-km (8,100 line-mi) of seismic profiles that have been run in the basin, of which 88 percent is offshore in water depths of as much as 5,000 m (1,500 ft). Early onshore seismic surveys were generally of poor quality due mainly to a thick cover of calcareous shallow-marine Pleistocene deposits, but modern marine seismic surveys have generated fair to excellent data (Zúñiga-Rivero and others, 1998a).

The Paleocene-Eocene sedimentary sequence is entirely clastic (fig. 4) and is characterized by shallow-marine, deltaic, and fluvial sandstones, marine shales, and turbidites; underlying sediments are about 75 percent clastic but include some thick and widespread oolitic, reefy, and micritic limestones that were considered by Zúñiga-Rivero and others (1998b) to be the most important hydrocarbon source rocks. Eocene strata include littoral and beach sandstones, and (in places) coarse conglomerates, as well as turbidite channel sandstones (Zúñiga-Rivero and others, 1998b). Sandstone and conglomerate grains show a high degree of roundness and a sorting that is characteristic of the most resistant rocks, indicating several phases of recycling before the final sedimentation (Raez Lurquin, 1999).

Bianchi (2002) listed porosity and permeability ranges for the following formations (Note: no information was provided on sources of data or number or types of analyses):

1. Hélico Formation sandstones, 12–15 percent porosity, 2–5 millidarcies (mD) permeability,
2. Clavel (Pariñas), 11–19 percent porosity, 60–120 mD permeability,
3. Manta (Mogollon) 8–11 percent porosity, 0.15 mD permeability, and
4. Basal Salinas Sand, 11–16 percent porosity, 14–20 mD permeability.

Porosity of reservoir intervals for the Mogollon Formation in the Pena Negra field (fig. 1) ranges from 9 to 10.6 percent, and water saturation is 45.1 to 46.3 percent (Chavez and Rodriquez, 2002). The Eocene Hélico Formation in the field area consists of a lower conglomeratic sandstone and an upper fine- to medium-grained sandstone (Robles Chavez and Lopez Chavez, 2002). The depositional environments were three separate sets of deep-water marine turbidites, with the better quality sandstones present within the channel systems; grain size decreases from east to west. These channel sandstones are laterally discontinuous, resulting in compartmentalization of the reservoir. The Hélico Formation has a vertical thickness of 152 m (500 ft); its average porosity is 12 percent in the PN3 offshore platform of the Pena Negra field.

Bianchi (2002) indicated that the Clavel (Pariñas) Formation is fluviodeltaic and transport directions were mainly toward the northwest and southwest. Clavel (Pariñas) Formation reservoirs within the Lobitos and Providencia fields are composed of fluviodeltaic sandstones with interbedded shales and clay (fig 17); reservoirs are extensively faulted, with hydrocarbons trapped in horsts, grabens, and other structures (Lopez and others, 2002). The thickness of the Clavel (Pariñas) Formation in the Lobitos and Providencia fields is about 180 and 305 m (600 and 1,000 ft), respectively; the depth to the top of the formation varies from 825 to 1,280 m (2,700 to 4,200 ft) in Lobitos and 395 to 580 m (1,300 to 1,900 ft) in Providencia; permeability and porosity in reservoirs ranges from 30 to 50 mD, and 12 to 18 percent, respectively (Lopez and others, 2002). Results are based largely on analysis of scattered geophysical well logs across the field areas, within which more than 800 wells have been drilled.

The Mogollon Formation in the northern half of the Talara Basin province ranges in thickness from about 180 to

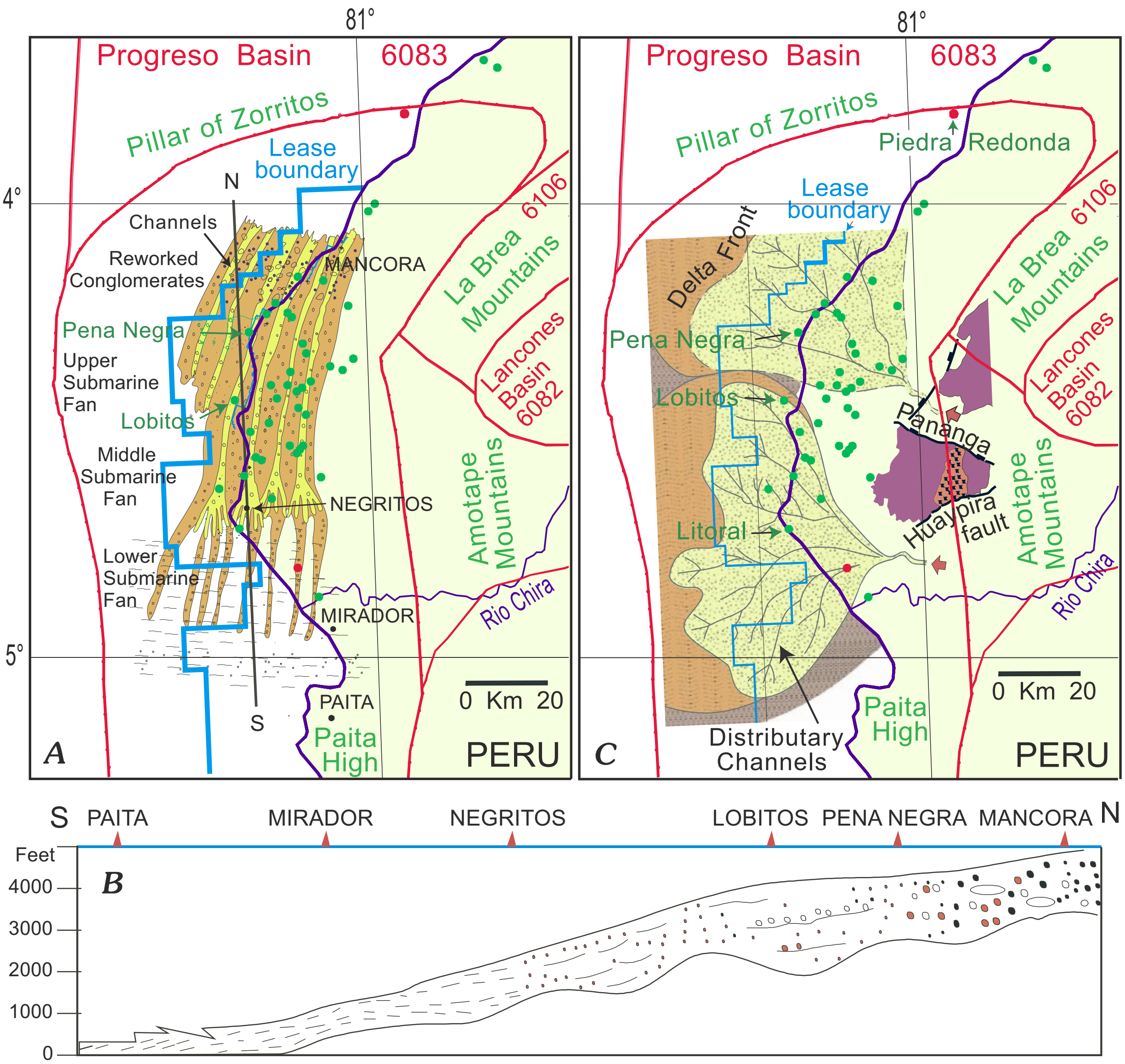


Figure 17. Depositional models for the Eocene Mogollon (*A*, *B*) and Clavel (Pariñas) (*C*) Formations, northern Talara Basin province. The Mogollon Formation has a progressive southward decrease in depositional energy, from reworked conglomerates in fluviodeltaic channels, to shales beyond the submarine fans (modified from Chavez Cerna and Rodriques Rios, 2002). Line of cross section is marked by N and S. Fluviodeltaic systems of the Clavel (Pariñas) Formation exhibit westward decrease in depositional energy with associated decrease in sediment grain size; primary reservoirs are distributary channel sandstones (modified from Lopez Chavez and others, 2002). Yellow is onshore, dark purple is igneous intrusions, and green and red dots are oil and gas field centerpoints, respectively.

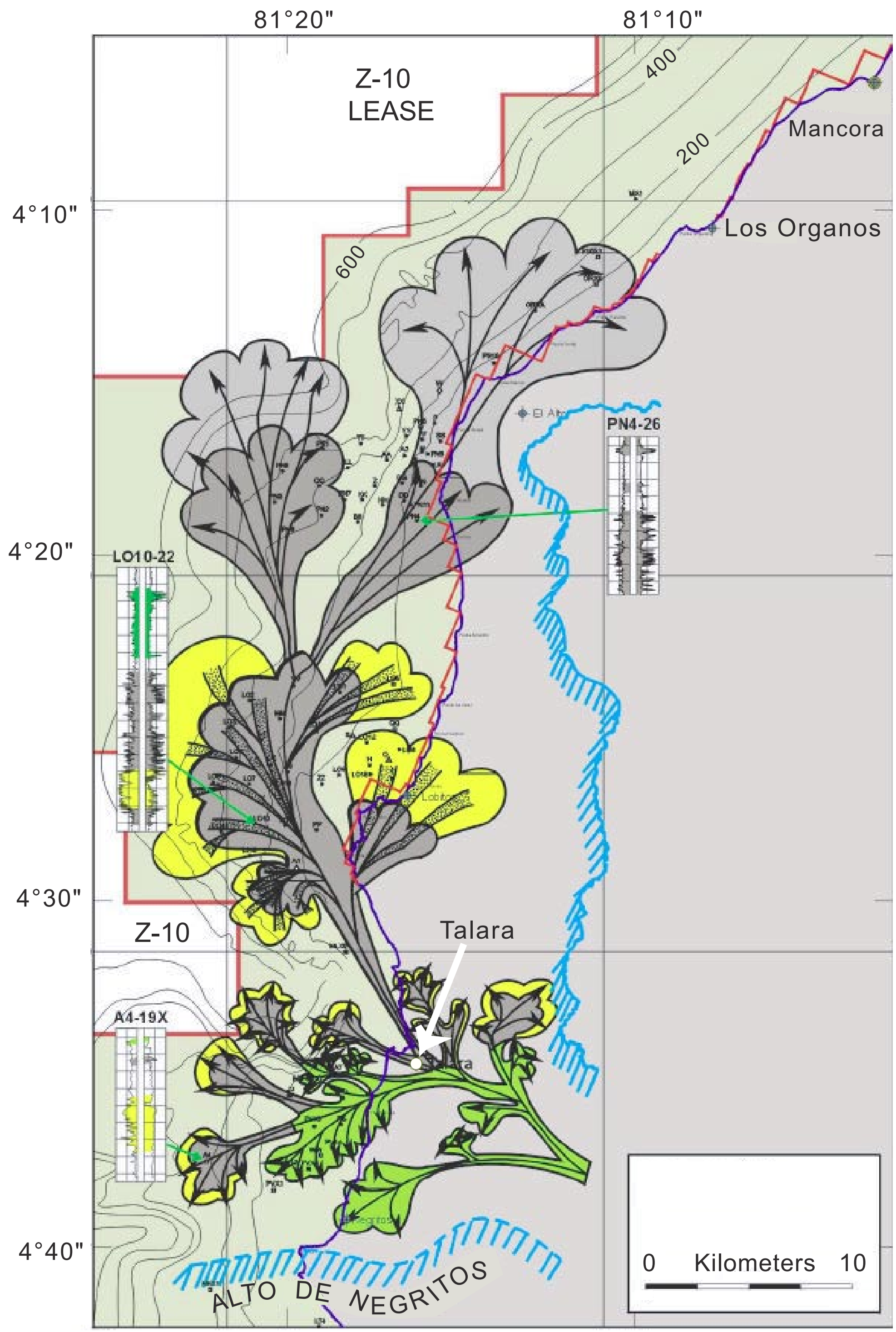


Figure 18. Fluviodeltaic depositional model of the basal Salina Formation, northern Talara Basin province (Gonzales Torres, 1999; reprinted by permission of author, 6/24/02). Sediment transport direction and source of these (gray, green, and yellow) stacked lobes was primarily from Paleozoic and Cretaceous rocks of the Alto de Negritos. Offshore contour interval is 100 ft. Blue line corresponds to the coastline, and the red line segregates lease blocks.

640 m (600 to 2,100 ft) and is composed of shale, sandstone, and conglomerate that originated in fluviodeltaic to submarine depositional environments; transport directions were from the northeast and depositional energy decreased seaward and to the south (fig. 17) (Chavez and Rodriquez, 2002). The formation is extensively fractured, with faults oriented primarily east-northeast in the area of the Tunal and Pena Negra fields (fig. 1); the field axes are oriented mainly northeast-southwest and some production is bounded by the faults (Benito and Arispe, 2002).

Gonzales Torres (1999) indicated that Basal Salina sandstones in the northern third of the basin (1) consist mostly of turbidite fans and incised valley fill that prograde to the southwest, northwest, and northeast, (2) are part of a complex stacked fluviodeltaic sequence that was deposited in early Eocene and late Paleocene time, and (3) were sourced primarily by erosion of Paleozoic and Cretaceous rocks of the Alto de Negritos (Negritos High) (fig. 18). In general, grain size and depositional energy increases southward along this progradational sequence (Gonzales Torres, 1999). The system extends more than 50 km (30 mi) north of the Alto de Negritos (fig. 18). Gonzales Torres (1999) also indicated that reservoirs in the Basal Salina Formation contributed almost 40 percent of new petroleum production in the Talara Basin province during the last 15 years.

The Neogene sedimentary history of the southern Progreso Basin province and northern Talara Basin province followed an Oligocene transgressive cycle and deposition of fluvial and marine sandstones and shales of the Mancora and Heath Formations (AIPC, no date; Kraemer and others 1999, 2001). There is no known Neogene production from the Talara Basin province (fig. 4).

Traps and Seals

Late Oligocene and Miocene time is characterized by separation of the Nazca Plate from the South American Plate, with active subduction at the Peru-Chile trench and creation of the Neogene portion of the southern Progreso Basin province, located at the north border of the Talara Basin province (Jaillard and others, 1995). The region, in middle Miocene time, experienced block faulting, mostly extensional tectonics, and renewed growth of the Andes Mountains east of Talara. Although earlier tectonic activity affected patterns of folding, faulting, and deposition across the basin, the middle to late Tertiary extensional regime was associated with high-angle normal faulting that trapped and redistributed hydrocarbons, causing development of the current fault-block reservoirs (Zúñiga-Rivero and others, 1998a, 1998b). Structurally, the area is a system of faulted blocks—the size of the blocks is nonuniform and can vary from 100 to 1,500 acres or more (Raez Lurquin, 1999). Structural trap types are generally moderate- to high-angle normal faults, low-angle gravitational slide faults, and transcurrent faults (AIPC, no date; Petroconsultants, 1996; Zúñiga-Rivero and others, 1998b). Based on seismic interpretations, normal faulting appears to decrease westward from the intensely faulted onshore area of the basin (Zúñiga-Rivero and others, 1999).

Seismic records indicate a variety of trapping features for Talara and bounding basins that include rollovers and updip closures against faults, and stratigraphic pinch-outs (turbidite channel deposits) and onlap onto old highs (Zúñiga-Rivero and others, 1998a). Sediment sources are primarily from the east, northeast, and southeast (Perupetro, 1999; Pindell and Tabbutt, 1995), and depositional patterns associated with these fluvial, shoreline, turbidite, marine and other facies strongly influence types and locations of seals. Zúñiga-Rivero and others (1998b) indicated that marine shales segregated and sealed both shallow and deepwater sandstone beds. Interbedded and overlying marine shales are the primary reservoir seals. Some units are composed of multiple sandstones separated by shales. Lateral seals are (mainly normal) fault offsets, and lateral depositional or erosional pinch-outs of the mostly marine sandstones into shales (Zúñiga-Rivero and others, 1998b).

Conclusions

The Paleogene Talara Basin province overlies an older regional basin. Movement through time of the continental plates resulted in a complex block-faulted basin, characterized by normal faults, low-angle gravitational slide faults, and large vertical transcurrent faults. Complex structural features of the offshore Talara Basin province include extensive growth faulting with associated rollover-type folding. Seismic and subsurface data indicate that the faulting was most intense in the eastern (onshore) portion of the basin and decreased in a seaward direction.

Oil geochemical studies indicate that there is one Tertiary hydrocarbon source rock for Tertiary production in the Talara Basin province, as evidenced by distributions of (1) ratios of Ni/V, (2) saturated versus aromatic ^{13}C, and (3) API gravity versus weight percent sulfur among approximately 20 analyzed oils. Gas chromatograms for many of these oils indicate an early stage of biodegradation and (or) water washing followed by a second phase of migration into reservoirs. This biodegradation resulted in some scatter in the geochemical data.

Possible Tertiary hydrocarbon source rocks are marine shales of the (1) Balcones Formation (lower Paleocene), (2) the San Cristobal, Palegreda, Clavel (Pariñas), and Echinocyamus Formations of the lower Eocene Chacra-Salina Group, (3) the upper Eocene Talara Formation, (4) the upper Eocene Chira Formation, and (5) the Oligocene Heath Formation. Shales of the Cretaceous Monte Grande Formation are primarily of terrestrial (type-III kerogen) origin and are potential sources of dry gas, although there is no evidence of dry gas generation in the Talara Basin province. Probable Cretaceous hydrocarbon source rocks are the Albian Muerto Limestone and marine shales of the Campanian Redondo Formation, which are also potential source rocks for the unconformably underlying Pennsylvanian Amotape Formation. Geochemical data on one oil sample from the Amotape quartzite indicate that it has a Tertiary source. Pennsylvanian shales would probably be overmature for hydrocarbon generation.

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