U.S. Department of the Interior
U.S. Geological Survey

Bulletin 2206–B

Text version for 508 complinacy

U.S. Geological Survey, Reston, Virginia: 2004
Version 1.0

The Progreso Basin Province of Northwestern Peru and Southwestern Ecuador: Neogene and Cretaceous-Paleogene Total Petroleum Systems

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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 contained 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 volumes of oil, gas, and natural gas liquids that have the potential to be added to reserves within the next 30 years. These volumes reside in undiscovered fields whose sizes exceed the stated minimum-field-size cutoff value for the assessment unit or occur as reserve growth of fields already discovered. The minimum value is variable, but must be at least 1 million barrels of oil equivalent (MMBOE). 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 under evaluated 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. The TPS includes all genetically related petroleum that occurs as shows and accumulations (discovered and undiscovered) that (1) have been generated by a pod or by closely related pods of mature source rock and (2) exist within a limited mappable geologic space. This is combined 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 Energy Assessment Team (2000). The code is as follows:

o	**Region**, single digit	**6**
o	**Province**, three numbers to the right of the region code	6**083**
o	**Total Petroleum System**, two digits to the right of the province code	6083**01**
o	**Assessment unit**, two numbers to the right of the petroleum system code	608301**01**

Oil and gas reserves quoted in this report are derived from Petroconsultant's Petroleum Exploration and Production database (Petroconsultants, 1996) and other area reports from Petroconsultants, Inc., unless otherwise noted. Figure 1 boundaries of the total petroleum systems, 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 (fig. 1) 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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Abstract

The Progreso Basin province (6083) in northwestern Peru and southwestern Ecuador consists of the Paleogene Santa Elena block and Peru Bank, and the Neogene Tumbes-Progreso subbasin. The Santa Elena block and Peru Bank are part of the Cretaceous-Paleogene Total Petroleum System (TPS)(608302), which contains the Cretaceous-Paleogene Santa Elena Block Assessment Unit (60830201). The Tumbes- Progreso subbasin includes the Neogene TPS (608301) and associated Neogene Pull-Apart Basin Assessment Unit (60830101). The complex tectonic history of the Progreso Basin province influenced depositional and erosional patterns across the region, and also the location, timing, and types of seals, traps, possible source and reservoir rocks, and hydrocarbon generation and migration. Marine shales that are interbedded with and overlie reservoir intervals are the probable hydrocarbon source rocks. Timing of hydrocarbon generation and migration was probably Miocene and younger, following creation of the Tumbes-Progreso subbasin by movement along the Dolores-Guayaquil megashear.

More than 220 million barrels of oil (MMBO) and 255 billion cubic feet of gas (BCFG) have been produced from the Progreso Basin province. The means of estimated recoverable oil, gas, and natural gas liquids (NGL) resources from undiscovered fields in the province are 237 MMBO, 695 BCFG, and 32 MMB NGL, respectively. The means of estimated recoverable oil, gas, and NGL resources from undiscovered onshore fields are 45 MMBO, 113 BCFG, and 5 MMBNGL, and from undiscovered offshore fields are 192 BBO, 582 BCFG, and 27 MMBNGL. These are USGS grown undiscovered resources that were determined by using a minimum field size of 1 million barrels of oil equivalent.

Introduction

The Progreso Basin province is located along the coast of northern Peru and southern Ecuador (fig. 1). The province area is 47,000 km^2 (18,000 mi^2) and includes the Neogene Tumbes- Progreso subbasin and the Paleogene Santa Elena block. Included with the Santa Elena block is the Peru Bank, which has a similar stratigraphic sequence (fig. 2). The Peru Bank is a wedge of Cretaceous Neogene sediments unconformably overlying the Pennsylvanian Amotape Formation; this feature was isolated from the Neogene erosion that removed the Paleogene through Cretaceous strata from most of the Tumbes-Progreso subbasin.

Rotational movement along the Guayaquil-Dolores megashear zone in Neogene time may have created a trough in the Progreso Basin province (Shepherd and Moberly, 1981)(fig. 1). This trough is the Tumbes-Progreso subbasin, a Neogene pull-apart basin that is located between the Talara Basin and the Santa Elena block. The Tumbes-Progreso subbasin contains Holocene through Oligocene sediments unconformably overlying Amotape basement (fig. 2); remnant Cretaceous through Eocene formations may be present in areas of the subbasin. The Tumbes-Progreso subbasin can be further divided into the Tumbes area, which is bounded on the north by the northern boundary of the Dolores-Guayaquil megashear (fig. 1), and the Progreso area, which has the megashear as its southern boundary. They are grouped into one subbasin for this study. Progreso and Tumbes are named after towns in Ecuador and Peru, respectively.

The Santa Elena block with its Peru Bank (fig. 1) contains the Cretaceous-Paleogene Total Petroleum System TPS)(608302) with its Cretaceous-Paleogene Santa Elena Block Assessment Unit (AU)(60830201). The Tumbes- Progreso subbasin includes the Neogene TPS (608301) and

Neogene Pull-Apart Basin AU (60830101). The TPS approach is used in this report to determine undiscovered recoverable oil and gas resources by compiling information about tectonic, depositional, and diagenetic factors that control hydrocarbon generation, migration, and accumulation in reservoirs, and integrating it with exploration and production histories. Primary sources of well, field, and geochemical data are the Petroconsultants (1996) and GeoMark (1998) databases.

The Progreso Basin province has a complex structural history that includes transcurrent (wrench) faulting as well as high- and low-angle faults of various ages (American International Petroleum Corporation [AIPC], no date, “A review of the petroleum potential of the Tumbes Basin, Peru”: Denver, Colo., 46 p.; Marocco and others, 1995; Zúñiga-Rivero and Hay-Roe, 1999). The west boundary of the province is the,approximate location of the Nazca Plate subduction zone under the South American Plate (fig. 1).

The province is also located at the junction of the Dolores- Guayaquil megashear and the Chongon-Colonche fault. The Chongon-Colonche fault, also known as the Chanduy fault (Ráez Lurquin, 1999), is located along the north boundary of the province and separates it from the Manabi Basin and the Chongon-Colonche Cordillera (fig. 1). South of the Chongon-Colonche fault, the stratigraphic succession of the Santa Elena block is characterized by a thick upper Paleocene sequence and by the development of the deeply subsided sedimentary sequence of Neogene age (Zorritos Formation and younger strata) in the Progreso Basin province (Jaillard and others, 1995)(fig. 2). The Cenozoic deposits of the Tumbes-Progreso subbasin form at least seven Oligocene to Pleistocene stratigraphic units with a total sedimentary thickness of more than 9,000 m (30,000 ft) (Kraemer and others, 2001). To the southeast, the La Brea Mountains of the West-Central Cordillera separate the Progreso Basin province from the Lancones Basin province. The Talara Basin province marks the southern boundary of the Progreso Basin province; the provinces are segregated by the Dolores-Guayaquil megashear zone and the Pilar de Zorritos uplift (fig. 1).

The figure 3 simplified geologic map of the Progreso and Talara Basin provinces and surrounding areas shows oil and gas field centerpoints and generalized locations of the Amazonas, Dolores-Guayaquil, and Guyana megashears. The Dolores-Guayaquil megashear is a regional tectonic wrench zone that begins in the offshore area northwest of the Talara Basin province and extends along the coast northeastward through the Progreso Basin province into Colombia, where it is called the Romeral Lineament (AIPC, no date; Kraemer and others, 1999). The Dolores-Guayaquil megashear is shown in figure 1 as an about 50-km-wide (30 mi) generalized zone of faulting because of varying opinions as to its specific boundaries and bordering features. Zúñiga-Rivero and Hay-Roe (1999), for example, include the Peru Bank in the Talara Basin province. Their location of the Dolores-Guayaquil megashear is approximated by the northern boundary of this zone shown in figure 1. The AIPC (no date) named the Dolores-Guayaquil fault zone at the Pilar de Zorritos the Troncho Mocho fault and placed their Dolores-Guayaquil megashear about 65 km (40 mi) north of this boundary. Other sources of information include Kraemer and others (1999), Marocco and others (1995), Pindell and Tabbutt (1995), Ráez Lurquin (1999), and Zúñiga-Rivero, Keeling, and Hay-Roe (1998b).

Acknowledgments

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

Province Geology

Structural History

Offshore Peru and Ecuador contains Cretaceous mid oceanic ridge basalt that unconformably overlies a basement of metamorphosed sandstones of the Pennsylvanian Amotape Formation (fig. 2). The south coastal area of Ecuador is an accreted terrane that is underlain by an oceanic crust that formed during the Middle Cretaceous (Aptian-Albian) (Jaillard and others, 1995). The figures 4 and 5 events charts for the Neogene (608301) and Cretaceous-Paleogene (608302) Total Petroleum Systems show the major structural events in the subbasins that formed the petroleum systems, including the times of (1) deposition of source, reservoir, and seal formations; (2) development of structural and stratigraphic traps; and (3) generation, migration, and accumulation of hydrocarbons. Between Late Cretaceous and late Eocene time the oceanic-floored allocthonous terranes of southern coastal Ecuador underwent a complex geologic evolution that included (1) sedimentation in island arc and marginal basin settings, (2) plate and intraplate collisions that were associated with shear deformation, (3) basin subsidence, and (4) several phases of uplift (Jaillard and others, 1995). The tectonic evolution of the Tumbes-Progreso subbasin was controlled by plate convergence kinematics during the Cenozoic (Kraemer and others, 2001).

Coastal Ecuador (Tumbes-Progreso subbasin to Colombia) has experienced a 70-degree clockwise rotation since the mid-Cretaceous, based on paleomagnetic studies (Roperch and others, 1987). Late Cretaceous to middle Paleocene was a time of infilling of fluvial to marine sediments in a marginal basin (Karig and Moore, 1975). Presence of a thick, coarse-grained sequence of Cretaceous (Santonian-Campanian) strata that contains low amounts of quartz detritus (Cayo Fm) indicates that the sediment source was not a sialic landmass, and that the basin was bordered by an island arc that was active at least since the Coniacian (about 89.9 to 85.8 m.y.a.) (Jaillard and others, 1995). In late Paleocene time, accretion of the Cayo remnant arc (located north of the province) to the Andean continental margin caused a major deformational phase that affected only the southern part of coastal Ecuador. There, deformation ended with deposition of overlying thick, coarse grained, quartz-rich turbidites that infilled an early fore-arc or slope basin. A subsequent tectonic event in the early Eocene is believed to have resulted in uplift of the entire area (Jaillard and others, 1995). Late Paleocene and early Eocene tectonism in the Santa Elena block records the most intense episodes of deformation with associated gently dipping shear planes, subisoclinal folds, and pervasive cleavage with subsequent tight vertical folds and faults; present-day structure of the middle Eocene beds displays only reverse faults and gentle folding with dips generally less than 30 degrees, which are probably due to late Eocene tectonism (Jaillard and others, 1995).

During and following late Eocene time, deformation shifted eastward to the Andes Mountains (Jaillard and others, 1995). This Eocene Incaic orogeny in the Tumbes-Progreso subbasin caused right-lateral and rotational movement associated with the northern and southern borders of the Dolores-Guayaquil megashear. In the Tumbes-Progreso subbasin, this orogeny resulted in intense erosion and denudation of the Eocene section (AIPC, no date). Within the Tumbes-Progreso subbasin normal faults have a sigmoidal shape with an “echelon” arrangement, indicating right-lateral strike-slip deformation (Kraemer and others, 2001).

The Eocene Incaic orogeny resulted in emergence of the southern coastline of Ecuador (Santa Elena block) (Jaillard and others, 1995), associated erosion of the Cretaceous and Paleocene section, mostly in the Tumbes-Progreso subbasin, and deposition of many of the reservoir rocks and probably also hydrocarbon source rocks in the Progreso Basin province (fig. 1). The remaining geosynclinal rocks of the Mesozoic island arc sequence in the Tumbes-Progreso subbasin were overlain by Eocene molasse sediments that were deformed and subsequently overlain by Oligocene and Miocene clastics (AIPC, no date). Zúñiga-Rivero, Keeling, and Hay-Roe (1998a) indicate that a portion of the southern Tumbes-Progreso subbasin has Oligocene sediments directly overlying Upper Paleozoic strata, although their subbasin boundary is the northern limit of the Dolores-Guayaquil megashear in figure 1.

AIPC (no date) determined that a gravity minimum lies along and landward of the western terminus of the Dolores-Guayaquil megashear zone (fig. 1); high-angle complex fault zones were inferred from the linear alignments of gravity data, combined with 2D seismic reflection data in the offshore area, and by surface geologic evidence in the onshore area east of the Zorritos field. The gravity anomalies appear to be splays off the Dolores-Guayaquil megashear and they outline the bifurcation of the Tumbes-Progreso subbasin around the Peru Bank (AIPC, no date).

Intermontane basins began to form in late Oligocene time with reactivation of Andean tectonism, and movement ceased in the latest Miocene (about 7 m.y.a.) (Marocco and others, 1995). Kraemer and others (1999, 2001) identified three main tectonostratigraphic stages from Oligocene to the present that are separated by regional unconformities and at least eight sequences, as identified on eight 2D seismic lines. The following interpretations are from (1) Kraemer and others (1999, 2001) analysis of 800 km (500 mi) of marine 2D seismic data and on records from 18 exploratory wells (figs. 6, 7), and (2) the AIPC (American International Petroleum Corporation, no date) analysis of 1,850 km (1,150 mi) of 2D seismic.

1. The initial tectonic stage (late Oligocene-early Miocene) (fig. 6, stage I) corresponds to the deposition of fluvial and marine deposits of Mancora, Heath, and Zorritos sequences in a narrow unstable platform that was open to the northwest. Peneplanation of the Heath Formation was followed by deposition of the Zorritos Formation and then by a period of block faulting (AIPC, no date). Late Oligocene-early Miocene was the time of separation of the Nazca Plate from the South American Plate with active subduction at the Peru-Chile trench and creation of the Neogene (Tumbes-Progreso) fore-arc basins (Jaillard and others, 1995) and deposition of the thick Miocene section that forms the reservoir and associated probable source-rock intervals in the Tumbes Progreso subbasin (fig. 2). Miocene sediments thicken rapidly to the west across the Pilar de Zorritos (AIPC, no date).
2. The second tectonic stage (middle to late Miocene) (fig. 6, stage II) began with a regional drop in relative sea level and associated deep erosion of the former platform; valleys were subsequently filled and covered by the marginal marine and deltaic sediments of the Cardalitos, Tumbes, and Mal Pelo sequences. During this stage, an episode of open folding produced a general tilting of these deposits toward the north-northwest. The middle Miocene is also associated with block faulting across the Progreso and Talara Basin provinces and renewed uplift of the Andes Mountains (AIPC, no date). Upper Miocene sediments were deposited during a relative sea-level rise, until the paleotopography was completely buried.
3. The third tectonic stage (Pliocene to Present) (fig. 6, stage III; fig. 7) began with the onset of normal faults that dip to the northwest, and the deposition of Mal Pelo and La Cruz sequences that are covered by Holocene deposits of the Tablazo Formation. Included are formation of horst and graben structures and gravity- and basement-involved faulting, mostly in the Tumbes-Progreso subbasin (AIPC, no

date). Normal faulting remained active during the Pleistocene and is still active, as evidenced by recent deformation of sea-floor sediments.

Exploration History

Centerpoints of oil and gas fields in the Progreso Basin province are shown in figure 1. Fewer than 100 wildcat wells were drilled in Ecuador or Peru during 1980 to 1990; average success ratio for producing wells was 60 percent for Ecuador and 30 percent for Peru (Kronman and others, 1995). The Petroconsultants (1996) database lists cumulative production data for 13 of the 19 Progreso Basin province oil and (or) gas fields, but only limited data for the other 6, which have discovery dates of 1956 to 1991. Six of the 19 fields are located in the Tumbes-Progreso subbasin, and 13 are in the Santa Elena block. Reported production is commonly commingled for several Tertiary units in the Tumbes-Progreso subbasin and for both Tertiary and Cretaceous formations in the Santa Elena block. Because there are limited data for a number of wells in the database, the statistics given herein should be taken as minimum production volumes and estimated recoverable resources. Background statistics for oil and gas fields are listed in table 1.

More than 220 million barrels of oil (MMBO) and 255 billion cubic feet of gas (BCFG) have been produced from the Progreso Basin province. Ranges in field-size distribution listed in table 2 show the U.S. Geological Survey estimates for undiscovered oil, gas, and natural gas liquids resources for the province that have the potential to be added to reserves within the next 30 years (USGS World Energy Assessment Team, 2000). The mean estimated oil, gas, and natural gas liquids resources in undiscovered fields are 237 MMBO, 695 BCFG, and 32 MMB of NGL, respectively (table 2). Mean estimated recoverable oil, gas, and NGL resources in undiscovered onshore fields are 45 MMBO, 113 BCFG, and 5 MMBNGL; undiscovered offshore recoverable resources are 192 BBO, 582 BCFG, and 27 MMBNGL. Minimum size of fields that were used in this analysis is 1 MMBO and (or) 6 BCFG. Figure 8 shows the proposed frequency distribution of undiscovered oil (A) and gas (B) fields within the Progreso Basin province. The mean estimate is 26 undiscovered oil fields and 14 undiscovered gas fields. Size distributions show few large undiscovered oil or gas fields; estimates include only one undiscovered oil field containing as much as or more than 32 MMBO, and also only one gas field containing as much as or more than 96 BCFG. Number of undiscovered fields increases as the field size decreases; estimates are for about 6 undiscovered oil fields in the 1 to 2 MMBO size and 4.5 gas fields in the 6 to 12 BCFG range.

Figure 9 shows field-size distribution based on periods of discovery for known recoverable volumes in current oil fields, compared to the number of fields in each size range. Discovery history curves in mature basins commonly show the largest fields are discovered early in the history of exploration and field size tends to decrease through time. In this case, the largest is the Ancon field in the Santa Elena block, discovered in 1921. Recoverable oil and gas resources for this field are 134 MMBO and 167 BCFG. There are only eight fields that have known or grown recoverable resources of 1 MMBOE or greater. Known recoverable oil and gas in the province is 374 MMBOE for current oil and gas fields that have a minimum known recoverable of 1 MMBOE. The curve of known recoverable compared to number of fields (fig. 10) shows a slightly more symmetrical shape, mainly because the Petroconsultants database lists 11 fields that exhibit known recoverable oil and gas resources of 1 MMBOE or greater. The distribution of known recoverable oil (1 MMBO and greater) relative to the discovery year is shown in figure 11. The Zorritos field was discovered in 1863 and produced more than 3.7 MMBO from the Heath Formation by the 1965 shut-in date (Pardo and Pisconte, 2002). This discovery was followed by the Santa Paula (1919) and Ancon (1921) fields. Cumulative number of new-field wildcat wells compared to the drilling completion year (fig. 12) shows a flat linear trend for the Zorritos discovery and a gradual upward climb beginning with the Santa Paula and Ancon discoveries and continuing to the 1996 database date. Drilling depth would appear to have no appreciable effect on the intensity of later exploration (fig. 13) because maximum drill depth is 2,896 m (9,500 ft) and median depth is shallow at 448 m (1,470 ft)(table 1).

Table 1. Background statistics for oil and gas fields in the Progreso Basin province (6083), Peru and Ecuador. [Reported production is commonly commingled for several Tertiary stratigraphic units. Cumulative production for 12 of the 19 oil and (or) gas fields is listed in the 1996 Petroconsultants database. The oil column includes both oil and oil and gas fields. The number (n) of data points follows each column. Table abbreviations: million barrels of oil equivalent (MMBOE); estimated ultimate recoverable oil and gas (EUR); cumulative (CUM); and cubic feet of gas per barrel of oil (CFG/BO). Sources of data are the Petroconsultants (1996) and GeoMark (1998) databases.]

	Oil fields	n	Gas fields	n
Fields with 1 MMBOE EUR and greater		9		2
Fields with 1 MMBOE CUM and greater		5		0
Years of production	1863–1995		1970–1992	
Median gas-oil ratio (CFG/BO)	577	5		
Ranges of gas-oil ratio (CFG/BO)	454–1,000	5		
Median API gravity (degrees)	34	28		
Range in API gravity of oils	18–48	28		
Median percentage of sulfur in oils	0.26	4		
Range of sulfur in oils (percent)	0.05–0.5	4		
Median net perforated thickness–meters and (feet)	15 (49)	5		
Maximum net perforated thickness–meters and (feet)	36 (118)	5	122 (400)	1
Median depths of drilling–meters and (feet)	448 (1,470)	16		
Maximum depths of drilling–meters and (feet)	2,896 (9,500)	16	2,505 (8,220)	2
Range of water depths–meters and (feet)	32–64 (105–210)	2	37–102 (121–335)	2
Range of porosity (percent)	11–24	3	14.8–17	2

The mean estimated undiscovered resources for the Santa Elena block are 200 MMBO, 224 BCFG, and 11 MMBNGL for the Cretaceous-Paleogene TPS (608302). Production from the Neogene TPS (608301) is primarily from Miocene sandstones in the Tumbes-Progreso subbasin; the mean estimated undiscovered recoverable resources (table 2) are 37 MMBO, 471 BCFG, and 21 MMBNGL (USGS World Energy Assessment Team, 2000). Travis and others (1976) estimated offshore-undiscovered resources of 335 MMBO for this Neogene Pull-Apart Basin AU (60830101). In the Tumbes-Progreso subbasin of the Neogene TPS Albacora field, cumulative production is approximately 100 MMBO and 107 MMCF gas, and 4 MMBO was produced from the Zorritos field during its 102-year life (Perupetro, 1999). Although gas hydrate resources were not assessed as part of this study, offshore Ecuador and Peru exhibit excellent potential for these resources (Miller and others, 1991).

Petroleum Occurrence

Hydrocarbon Source Rocks

There is little published geochemical information on shales and (or) limestones that could serve as potential hydrocarbon source rocks in the Talara or Progreso Basin provinces. The probable hydrocarbon source rocks for the Progreso Basin province (fig. 2) are Cretaceous and Tertiary marine shales that are interbedded with and overlie the reservoir intervals. Statistics on oils were compiled using the GeoMark (1998) and Petroconsultants (1996) databases.

The following geochemical evidence from oils indicates that Tertiary marine shales are the probable hydrocarbon source rocks for the Tumbes-Progreso subbasin and the Santa Elena block. A potential source rock for the Santa Elena block is marine shales of the mid-Cretaceous Calentura Formation (fig. 2), which is composed of a 200-m-thick (660 ft) succession of shales, black laminated limestones, and thin-bedded turbidites that were deposited in a sediment-starved, deepmarine pelagic environment (Jaillard and others, 1995). These Calentura strata are located in the area of Guayaquil and the Chongon-Colonche Cordillera (fig. 1)(Jaillard and others, 1995).

Probable source rocks in the Tumbes-Progreso subbasin are the upper Oligocene to possibly lower Miocene Heath Formation and the Miocene Cardalitos Formation (Zuñiga-Rivero and others, 1998a); Kraemer and others (2001) believe the Heath Formation to be the primary source rock. Sanz (1988) also speculated that deep marine shales that are interbedded with Heath Formation turbidite sandstones are the source of oil in the Zorritos and Cope fields, southern Tumbes-Progreso subbasin (fig. 1). He does not present geochemical evidence to support this opinion, which is based on analysis of well and outcrop samples. Marine shales within the Heath and Cardalitos Formations are likely source rocks in the Santa Elena block.

Sulfur concentrations for two probable Tertiary oils in the Santa Elena block range from 0.05 percent to 0.5 percent, with a median of 0.26 percent (table 1) (GeoMark, 1998). Sulfur percentages and API gravity of oils are influenced by migration history, biodegradation, evaporation of oils, and other geologic and geochemical factors. Biodegradation can result in an increase in sulfur as the microorganisms preferentially metabolize light-chain hydrocarbons with lower percentages of sulfur. Resulting oils therefore tend to have lower API gravities and greater sulfur concentrations. Many of the Tertiary oils in the Progreso and Talara Basin provinces, particularly those with API gravity less than 23° (fig. 14), exhibit some early biodegradation; these commonly have a second phase of non bio degraded to slightly bio degraded hydrocarbons.

Most oils of the Progreso Basin province are in the range of light to medium API gravity; the median is 34°. Biodegradation has caused some of the scatter in figure 15, which shows the ratio of API gravity of oils to the weight percent of sulfur. The Tertiary oils of the Talara Basin province and the Santa Elena block of the Progreso Basin province are generated from a probable Tertiary source rock or range of Tertiary source rocks. The oil sample shown for the Pennsylvanian Amotape Formation of the Talara Basin province is also grouped within the Tertiary oils. This Amotape oil sample may include Tertiary oils since production is reported commingled for Pennsylvanian, Cretaceous, and Eocene reservoirs at this location. Amotape Formation reservoir rocks are mostly quartzite, and any associated Paleozoic shales would probably be over mature for hydrocarbon generation.

The percentages of nickel and vanadium in oil can be influenced by depositional environment (marine as opposed to nonmarine), shale as opposed to carbonate source rocks, biodegradation, migration history, and other factors that remove lighter chain hydrocarbons and tend to concentrate metallic elements in the longer chain atoms, onto which these elements are preferentially attached. However, the ratio of nickel to vanadium in oils is stable through time. Because nickel and vanadium atoms exhibit similar chemical properties, they and the hydrocarbon molecules that contain them are generally influenced similarly through their burial history.

Scatter in data in the nickel-vanadium charts (fig. 16) for the Progreso and Talara Basin provinces results primarily from the oils having different source rocks. Geochemical data reported by GeoMark (1998) on two oils from the Santa Elena block of the Progreso Basin province were from the Ancon and Ecud fields; although the oil source was unidentified, the possible reservoir is the Eocene Santo Tomas Formation. Gas chromatograms of the oils indicate a minor loss of light chain hydrocarbons and show only minor evidence of later pulses of migration.

The probable Tertiary oils of the Progreso Basin province are grouped with Tertiary oils of the Talara Basin province (fig. 16). Talara Basin province samples are generally less than or equal to 10 parts per million (ppm) nickel and 30 ppm vanadium; one sample from a Paleocene reservoir contains about 7 ppm nickel and almost 60 ppm vanadium. The one Pennsylvanian Amotape oil is characteristic of a Tertiary source. Visual examination of groups of oil samples in figure 16 could indicate different sets of source rocks, but this is misleading. Each “group” of three or more samples is a mix of Eocene and Paleocene oils, as opposed to their being segregated by formation. Distribution of data suggests that the Tertiary and unknown oils were from Tertiary source rocks that were deposited in similar environments, such as all were marine shales. A probable exception to this is the three oil samples that contain greater than 25 ppm nickel (fig. 16 *A*, *B*). Although these oils are from an unknown but probable Tertiary source, they have vanadium concentrations that are similar to other Tertiary oils, whereas the nickel content is much greater at 27 to 31 ppm. This may be due to differences in depositional environment. These oils could have been generated from nonmarine or mixed marine-nonmarine shale that contained a greater initial ratio of nickel to vanadium. Gas chromatograms of these three oils show an early stage of extensive 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. Biodegradation has little influence on the relative concentrations of nickel to vanadium. Mixing of oils from several source rocks may also have influenced the nickel and vanadium contents of other oils.

The ^{13}C distribution of saturated and aromatic hydrocarbons from oils across the Progreso and Talara Basin provinces is shown in figure 17. The Talara and Progreso Basins contain one group of Tertiary and Pennsylvanian reservoirs. The formations that produced the two Progreso Basin oils shown in figure 17 were unidentified but are probably Eocene in age based on grouping with other oils and on producing formations in the sampled wells. The 20 Talara Basin oil samples are primarily from the Eocene Talara, Parinas, and Chacra Sandstones, and the Mogollon and Basal Sandstones of the Salina Group. One Talara Basin oil sample is listed in the GeoMark database as being from the Pennsylvanian Amotape Formation in the Portachuelo field. Grouping of this one sample with the other mostly Eocene samples is indicative of a common Tertiary source.

Maturation and Migration

Paleozoic through Tertiary source rocks across Colombia, Ecuador, and Peru became thermally mature for oil generation during Neogene phases of basin development (Pindell and Tabbutt, 1995).

The probable timing of source-rock maturation for Tertiary and older reservoirs is Miocene and younger across the basin (figs. 4, 5)(Jaillard and others, 1995; Pindell and Tabbutt, 1995). However, Kingston (1994) believed that possible source rocks would have been thermally mature by at least late Eocene time in the Santa Elena block of the Progreso Basin province, even given the low heat gradient expected in a fore-arc setting (fig. 5).

AIPC (no date) evaluated the total organic carbon (TOC) of 151 outcrop samples and well cuttings of Tertiary shales collected between Zorritos (just north of the Talara Basin [fig. 1]) and Talara (near the Portachuelo oil field); these included (1) 81 Eocene shale samples that ranged from 0.11 to 1.92 percent TOC; (2) 15 Mancora samples, 0.08 to 4.95 percent TOC; (3) 35 Heath shales, 0.24 to 3.86 percent TOC; (4) 13 Zorritos shales, 0.22 to 13.12 percent TOC; and (5) 7 Cardalitos shales, 0.15 to 1.62 percent TOC. Values below 1 percent TOC would have low to marginal value as hydrocarbon source rocks, whereas concentrations equal to or above 1 percent TOC are potential source rocks. Kraemer and others (1999) believed that the Heath Formation is a hydrocarbon source rock for the Mancora and Zorritos Formations, and that a TOC value of 1.6 percent and greater is needed for the Heath Formation to be a source rock.

Probable onset of hydrocarbon migration was in mid- Miocene time, after the opening of the Gulf of Guayaquil by movement along the Dolores-Guayaquil megashear and creation of the Tumbes-Progreso subbasin. Close association of potential source and reservoir rocks indicates that accumulation of oil in reservoirs could have begun soon after the start of hydrocarbon generation. GC/MS data combined with active seeps indicate that there is still active migration in the basin.

Reservoir Rocks

Listed on the stratigraphic column of the Tumbes-Progreso and the Santa Elena portions of the Progreso Basin province (fig. 2) are formation names, notations for reservoir and potential hydrocarbon source rocks, and times of erosion and (or) nondeposition. Jaillard and others (1995) listed the Santa Elena Formation as being Maestrichtian through late Paleocene in age (fig. 2), whereas GeoMark (1998) and Petroconsultants (1996) indicated an Eocene age. The upper Eocene Seca Formation of Jaillard and others (1995) is probably the Santo Tomas, and their Eocene Punta Ancon Formation is the Atlanta/Olistrostrome Formation (fig. 2). Reservoir and source-rock intervals and times of migration, generation, and emplacement of hydrocarbons are shown on the events charts (figs. 4, 5).

The Lower Cretaceous Pinon Formation is composed of altered and metamorphosed tholeiitic lava associated with the midocean ridge basalts (MORB); the overlying Calentura Formation is pelagic shale (a possible source rock), tuff, and greywacke, and the Upper Cretaceous Cayo Formation is a reservoir facies in the Santa Elena block (figs. 4, 5) (Goossens and Rose, 1973; Lebrat and others, 1987). The Cayo Formation crops out on both sides of the Chongon-Colonche fault; it consists of about 2,000 m (6,600 ft) of upward-fining, coarse grained volcaniclastic sandstone and conglomerate, including high- to low-density turbidites with shaly intercalations (Jaillard and others, 1995). The Cayo Formation was mainly deposited in a shallow-marine environment with west-directed transport (Benitez, 1990). Conformable contacts with underlying fine-grained deposits of the Calentura Formation (Benitez, 1990; Marksteiner, R., and Aleman, A., 1991, Coastal Ecuador, technical evaluation agreement: unpublished internal report, Amoco Production Company and Petroecuador, v. 1, 218 p.) indicate that an important tectonic and geodynamic change occurred by Late Cretaceous (late Coniacian-early Santonian) time (Jaillard and others, 1995). The Cayo and Calentura Formations are the approximate age equivalents of the Villeta and Napo Formation in the Putumayo and Maranon Basins of Colombia, Ecuador, and Peru.

The Cretaceous Pinon Formation in the Santa Elena block is the age equivalent of the Caballos and Hollin Formations in the Putumayo and Maranon Basins of Colombia, Ecuador, and Peru.

A listing of production from the Upper Cretaceous to Paleocene Santa Elena Formation by Petroconsultants (1996) probably includes production from the underlying Cayo Formation. The Santa Elena Formation is pelagic black chert and tuff (Jaillard and others, 1995); probable reservoirs are marine sandstones. Deposition of the Santa Elena Formation was followed by substantial tectonic subsidence that accommodated thick, uppermost Paleocene turbidites of the Azucar Group (Jaillard and others, 1995). The upper Paleocene to lower Eocene Azucar Group is only located south of the Chongon- Colonche fault and is composed of at least 1,500 m (5,000 ft) of conglomerates, pebbly sandstones, sandstones, and shales (Bristow and Hoffstetter, 1977) that form reservoirs and seals.

Direction of the paleocurrent was from the northeast; the Azucar Group is faulted and contains east, northeast-to-west-, and southwest-trending folds with vertical axial planes (Jaillard and others, 1995). Sediments were deposited on submarine fans largely by high-density (with minor low-density) turbidite flows (Moreno, 1983; Benitez, 1983). Source of sediments are the underlying Santa Elena and Guayaquil Formations (lateral equivalent in the Chongon-Colonche Cordillera) and continental basement and volcanic rocks (Marksteiner, R., and Aleman, A., 1991, Coastal Ecuador, technical evaluation agreement: unpublished internal report, Amoco Production Company and Petroecuador, v. 1, 218 p.). The Azucar Group is unconformably overlain by the lower Eocene El Rosario Formation, which produces mostly oil from fluvial conglomerates in the La Mata Chivato 1 and Santa Paula fields in the Santa Elena block. Early Eocene time is marked by a widespread depositional hiatus across the province; formations south of the Chongon-Colonche Cordillera fault zone are difficult to differentiate and the lower Eocene El Rosario Formation, and other early Eocene units can vary in thickness by as much as 350 m (1,100 ft) (Jaillard and others, 1995).

Five fields in the Santa Elena block produce oil and gas from the lower to middle Eocene Wildflysch Olistrostrome; reservoirs are marine chert facies (Petroconsultants, 1996). The Wildflysch Olistrostrome is unconformably overlain by the middle to upper Eocene Socorro Formation, which consists of laminated shales, siltstones, and fine-grained sandstones that were deposited in an outer shelf environment; these have interbedded thick-bedded turbidite sandstones (Jaillard and others, 1995) that are the primary reservoir facies. Biostratigraphic analysis of flute casts in turbidites in middle and upper Eocene strata in the Santa Elena block indicate the sediments were sourced from the south and are similar to those of the Talara Basin province; the primary difference is that strata near the Ancon field (fig. 1) are closer to the subduction zone and exhibit spectacular turbidites that are not exposed in outcrop in the Talara Basin province (Raez Lurquin, 1999). The Socorro Formation grades upward into the Seca (probably the Santo Tomas) Formation, which is a shallow shelf sequence of laminated shales, siltstones, and marls, and thin-bedded sandstones and subordinate turbidites (Jaillard and others, 1995) that are the main reservoir intervals. The Santa Elena block produces from mostly Eocene reservoirs of the Atlanta sandstone/Olistrostrome; maximum thickness of the Eocene section is 4,800 m (15,780 ft)(AIPC, no date). The Carmela and Ancon fields both produce oil and gas from Atlanta/ Olistrostrome strata.

Primary oil and gas reservoirs of the Tumbes-Progreso subbasin are the upper Oligocene to possibly lower Miocene Heath Formation, and marine sandstones of the Miocene Zorritos and Cardalitos (Subibaja) Formations. The Zorritos Formation in offshore Peru is 1,500 to 2,000 m (5,000 to 6,500 ft) thick with alternating sequences of sandstone and shale; sandstones are mostly fine grained to silty and were deposited in continental to middle neritic environments (AIPC, no date). Thickness range of the sedimentary section in the Tumbes-Progreso subbasin is 6,000 to 15,000 m (20,000 to 50,000 ft), increasing seaward (AIPC, no date; Zuñiga-Rivero and Hay-Roe, 1998). Kraemer and others (1999) believed that the Mancora and Zorritos Formations sandstones form good quality reservoirs.

The Quaternary La Cruz Formation is a greenish-gray shale with benthonic and planktonic foraminifera of sublittoral depositional environments, and the Quaternary Tablazo Formation is primarily marine coquinas, sand, and gravel (AIPC, no date; Sanz, 1988). Two fields in the Santa Elena block produce from the Tablazo Formation and Eocene formations; because Quaternary shales are probably immature for oil, the source could have been Eocene or other Tertiary marine shales or those of underlying Upper Cretaceous shales. These formations are also potential reservoir rocks in the Peru Bank, an isolated wedge of Neogene-Paleozoic sediments that was not affected the Neogene erosion that had removed the Paleogene through Cretaceous strata from most of the Tumbes-Progreso subbasin. Sedimentary thickness at the Peru Bank is about 16,000 m (52,000 ft) (Zúñiga-Rivero and others, 1999). Zúñiga-Rivero, Keeling, and Hay-Roe (1998a) indicated that water depth in places around the Peru Bank is less than 200 m (650 ft).

Traps and Seals

Primary traps in the Progreso Basin province are structural. Seismic data indicate a variety of trapping mechanisms for the Talara and Progreso Basin provinces, from rollovers and updip closures against faults to turbidite channel deposits and onlap onto paleohighs (AIPC, no date). Moderate folding in the Progreso Basin province probably controlled accumulation of oil and gas from Cretaceous source rocks, but the middle to late Tertiary extensional regime was associated with the characteristic high-angle normal faulting that redistributed the hydrocarbons, leaving them primarily in fault-block reservoirs (Zúñiga-Rivero, Keeling, and Hay-Roe, 1998a). Evidence for growth faulting in the province (figs. 6, 7) is mostly from concurrent deposition of Paleocene to lower Miocene formations on top of the metamorphosed Amotape and Precambrian basement rocks (AIPC, no date). Kraemer and others (1999)(figs. 6, 7) identified two main groups of traps for the Neogene section of the offshore Tumbes-Progreso subbasin: (1) stratigraphic unconformity traps that formed at the beginning of the second tectonostratigraphic stage (middle to early late Miocene, stage II, fig. 6); and (2) structural roll-over traps that were produced by normal growth faulting during the third stage (late Miocene to present, stage III, fig. 6).

Sediment sources were mainly from the east, northeast, and southeast (Perupetro, 1999; Pindell and Tabbutt, 1995); depositional patterns associated with these fluvial, shoreline, turbidite, marine, and other facies strongly influenced types and locations of seals. Overlying and interbedded marine shales are the major reservoir seals, both for shallow and deep-water deposits. Lateral seals are (primarily normal) fault offsets and lateral depositional or erosional pinch-outs of the mostly marine sandstones into shales.

Conclusions

The Progreso Basin province of southwestern Ecuador and northwestern Peru is composed of the Santa Elena block and Tumbes-Progreso subbasin. The province has a complex history that includes transtensional, extensional, and compressive tectonics. The province is dissected by the northeasttrending Dolores-Guayaquil megashear zone. The western boundary of the province is approximated by the zone where the Nazca Plate is being subducted under the South American Plate.

The onset of hydrocarbon generation was probably during the Miocene. Migration of hydrocarbons likely beginning in middle Miocene time, after opening of the Gulf of Guayaquil by right-lateral and rotational movement along the Dolores-Guayaquil megashear and associated creation of the Tumbes-Progreso subbasin. The probable short migration distances result from close vertical association between most reservoir intervals and the marine shales that are the likely source rocks. Probable hydrocarbon source rocks are the Oligocene and Miocene Mancora, Heath, Zorritos, and Cardalitos Formations across the province, as well as the Lower Cretaceous Calentura Formation in the Santa Elena block.

Production in the Santa Elena block is from Upper Cretaceous through Eocene and from Holocene formations; reservoirs are mostly sandstone that was deposited in deep and shallow marine, shoreline, deltaic, and fluvial environments. Tablazo Formation oil was probably sourced from Eocene and older marine shales. Oil and gas in the Tumbes-Progreso subbasin is produced from the Oligocene Heath Formation and the Oligocene and Miocene Zorritos Formation. The primary seals across the province are overlying and interbedded shales of mostly marine environments. Primary traps are structural; middle to late Tertiary extensional tectonics resulted in highangle normal faulting that redistributed hydrocarbons and left them mainly in fault-block reservoirs. Expected stratigraphic and combination stratigraphic-structural traps would include updip pinch-outs of turbidite, fluvial, and marine sandstones against shales.

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Figure Captions

Figure 1 (facing page). The Progreso Basin province (6083), Ecuador and Peru. Shown are boundaries of provinces, the Neogene Pull-Apart Basin (60830101) Assessment Unit (AU) of the Neogene (608301) Total Petroleum System (TPS), and the Cretaceous-Paleogene Santa Elena Block (60830201) AU of the Cretaceous-Paleogene (608302) TPS. Minimum extent of 60830101 is approximately 1,000-meter (3,000-foot) water depth. Blue lines labeled 3, 4, and 5 are locations of figure 6 cross sections. Map projection is Robinson. Central Meridian is 0.

Figure 2. Stratigraphic units of the Santa Elena block and Tumbes-Progreso subbasins. Wavy lines and gray zones are periods of erosion or nondeposition. Primary reservoirs are marked with green dots. Possible source rock intervals are labeled with a small gray box. Modified from Benitez (1990), Gonzales (1999), Jaillard and others (1995), Kingston (1994), Kraemer and others (1999), Perupetro (1999), Petroconsultants (1996), and Seranne (1987). Jaillard and others (1995) named the Atlanta/Olistrostrome interval the Punta Ancon Formation. Ma, age in millions of years.

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. Geology is modified from Schenk and others (1999) 1:5,000,000 scale map of South America.

Figure 4. Events chart for the Neogene Total Petroleum System (608301) and the Neogene Pull-Apart Basin Assessment Unit (60830101) of the Progreso Basin province. Dark gray and blue shading mark the time intervals of primary events. Oceanic crust formed during the Aptian-Albian (Jaillard and others, 1995). MORB is Cretaceous (K) midoceanic ridge basalt on Pennsylvanian (Penn) basement rocks. Eocene (42 Ma) compressional tectonism of the Andes was followed in Oligocene time by partitioning of the Farallon Plate into the Cocos and Nazca Plates (Handschumacher, 1976; Marocco and others, 1995; Pilger, 1984). Events include (1) Santa Elena block lower Paleocene (Santa Elena Formation) to upper Eocene (Socorro Formation and Wildflysch Olistrostrome) and Quaternary Tablazo Formation, and (2) Tumbes-Progreso subbasin early to middle Miocene Zorritos, Heath, and Cardalitos (Subibaja) Formations. There is no documented information on hydrocarbon source rocks or on the timing of generation and migration. Time periods of unconformities (wavy black lines) were determined from American International Petroleum Corporation (no date), Gonzales (1999), Kingston (1994), Kraemer and others (1999), Perupetro (1999), Petroconsultants (1996), and Seranne (1987). Letter codes refer to references: a, Baldock (1982) and Egüez and others (1991); b, Jaillard and others (1995); c, GeoMark (1998); d, Petroconsultants (1996); e, Zúñiga-Rivero, Keeling, and Hay-Roe (1998a); f, Pindell and Tabbutt (1995); g, Shepherd and Moberly (1981); and h, Haq and others (1987).

Figure 5. Events chart for the Cretaceous-Paleogene Total Petroleum System (608302) and Assessment Unit (60830201), Santa Elena block of the Progreso Basin province. Dark gray and blue mark the time sequences of primary events. Oceanic crust formed during the Aptian-Albian (Jaillard

and others, 1995). MORB is Cretaceous (K) mid-oceanic ridge basalt on Pennsylvanian (Penn) age basement rocks. Eocene (42 Ma) compressional tectonism of the Andes was followed in Oligocene time by partition of the Farallon Plate into the Cocos and Nazca Plates (Handschumacher, 1976; Marocco and others, 1995; Pilger, 1984). Events include (1) Santa Elena block early Paleocene (Santa Elena Formation) to late Eocene (Socorro Formation and Wildflysch Olistrostrome [WO]) and Quaternary Tablazo Formation, and (2) Tumbes-Progreso subbasin early to middle Miocene Zorritos, Heath, and Cardalitos (Subibaja) Formations. Time periods of unconformities (wavy black lines) were determined from American International Petroleum Corporation (no date), Gonzales (1999), Kingston (1994), Kraemer and others (1999), Perupetro (1999), Petroconsultants (1996), and Seranne (1987). Letter codes refer to the following references: a, Kingston (1994); b, Jaillard and others (1995); c, GeoMark (1998); d, Petroconsultants (1996); e, Haq and others (1987); f, Pindell and Tabbutt (1995); and g, Shepherd and Moberly (1981).

Figure 6. Three main stages (I, II, and III) in the tectonic evolution of the Neogene Tumbes-Progreso subbasin within the Dolores-Guayaquil megashear zone (modified from Kraemer and others, 1999, reprinted by permission from the primary author, 06/19/02). Approximate locations of sections 3, 4, and 5 are shown in figure 1. The 2D seismic section of this reconstruction is shown in figure 7.

Figure 7. North-south 2D seismic section of the northeast-oriented normal-faulted stage III that is shown as section 5 in figures 1 and 6 (modified from Kraemer and others, 1999, reprinted by permission from primary author, 06/19/02). Growth sediments of the Mal Pelo and La Cruz sequences are covered by Holocene strata that also exhibit deposition that is concurrent with fault movement, which is still occurring over areas of the basin.

Figure 8. Mean estimates of size distributions of undiscovered (*A*) oil and (*B*) gas fields in the Progreso Basin province. Distributions are based on grown oil and gas assessments. MMBO, million barrels of oil; BCFG, billion cubic feet of gas.

Figure 9. Discovery halves of known oil and gas field sizes for all fields in the Progreso Basin province. Generally, the largest fields are discovered early in the history of exploration and field sizes decrease through time. Although Ancon, the largest oil field, was discovered in 1921, this trend is less apparent in this frontier basin because there are only a few fields. MMBOE, million barrels of oil equivalent.

Figure 10. Discovery thirds of known recoverable oil and gas relative to the number of fields for the Progreso Basin province based on known recoverable oil and gas data from the Petroconsultants database (1996). Data were divided into the first, second, and third one-thirds of discovered fields. MMBOE, million barrels of oil equivalent.

Figure 11. History of field-discovery dates and volumes of known recoverable oil across the Progreso Basin province. Sharp increases in the volume of recoverable hydrocarbons generally

indicate a major field discovery or combined effects of numerous field discoveries. Production in this basin is too scattered for clear trends, aside from discovery in the early 1990s of fields such as Pacoa, San Pablo 1, and La Mata Chivato 1 (fig. 1). Minimum field size is 1 million barrels of oil (MMBO) recoverable.

Figure 12. Cumulative number of new-field wildcat wells and associated completion dates (from Petroconsultants, 1996).

Figure 13. Field discovery date in the Progreso Basin province relative to reservoir depths in meter (m).

Figure 14. American Petroleum Institute (API) gravity of oil fields in the Talara (6081) and Progreso (6083) Basin provinces. Light oil is commonly characterized by an API of 31° to 55°, medium grade oil by 22° to 31°, and heavy oil by less than 30°.

Figure 15. API gravity (degrees) and weight percent sulfur of oils from fields across the Progreso (6083)(red circles) and Talara (6081) Basin provinces, Ecuador and Peru. Based on the distribution of data and other factors, there is one sample population for the provinces with a probable Tertiary source rock or set of source rocks. Scatter in data results partly from analytical methods and from biodegradation of oils from Tertiary reservoirs. Three Tertiary oils that exhibit biodegradation are shown in green.

Figure 16 (facing page). The relative concentrations of nickel and vanadium in oils from the Progreso (6083) and Talara (6081) Basin provinces. *A*, Relative concentrations of nickel and vanadium. *B*, Concentration of nickel relative to the ratio of nickel to nickel plus vanadium. The ratio of nickel and vanadium tends to be constant through time and can indicate different source rocks and types of source rocks, such as limestones or marine shales. Distribution of data for *A* and *B* indicates that there is one Tertiary source rock, or rocks, for oils from the provinces. The two Progreso Basin province probable Tertiary samples are grouped with those of the Talara Basin province.

Figure 17. Distribution of delta ^{13}C isotopes for saturated and aromatic hydrocarbons, Progreso and Talara Basin provinces (GeoMark, 1998). Clustering of data indicates that sampled oils from the Talara and Progreso Basin provinces have common Tertiaryage source rocks. This is also true for the one oil sample from the Pennsylvanian Amotape Formation.

Tables

Table 1. Background statistics for oil and gas fields in the Progreso Basin province (6083), Peru and Ecuador. [Reported production is commonly commingled for several Tertiary stratigraphic units. Cumulative production for 12 of the 19 oil and (or) gas fields is listed in the 1996 Petroconsultants

database. The oil column includes both oil and oil and gas fields. The number (n) of data points follows each column. Table abbreviations: million barrels of oil equivalent (MMBOE); estimated ultimate recoverable oil and gas (EUR); cumulative (CUM); and cubic feet of gas per barrel of oil (CFG/BO). Sources of data are the Petroconsultants (1996) and GeoMark (1998) databases.]

Table 2. Summary of assessment results for undiscovered resources in the Progreso Basin province (1) Neogene Total Petroleum System (TPS)(608301) and Neogene Pull-Apart Basin Assessment Unit (AU)(60830101), and (2) the Cretaceous-Tertiary TPS (608302) and Cretaceous-Paleogene Santa Elena Block AU (60830201)(World Energy Assessment Team, 2000). [Categories are million barrels of oil (MMBO); billion cubic feet of gas (BCFG); million barrels of natural gas liquids (MMBNGL); minimum field size assessed (MFS in MMBO or BCFG); and probability (Prob.), 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 similarly defined. Fractiles are additive under the assumption of perfect positive correlation. Shading indicates not applicable.]

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Suggested citation:
Higley, D.K., 2004, The Progreso Basin Province of Northwestern Peru and Southwestern Ecuador: Neogene and Cretaceous-Paleogene Total Petroleum Systems: U.S. Geological Survey Bulletin 2206–B, 25 p.
Available at URL http://pubs.usgs.gov/bul/b2206-b/