Mesozoic–Cenozoic Andean Paleogeography and Regional Controls on Hydrocarbon Systems

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Abstract

Palinspastic paleogeographic maps of western and northern South America, including the entire 8500-km “Andean system” from Trinidad to Cape Horn, are presented for nine Mesozoic–Cenozoic time intervals. The maps show (1) the spatial record of formational lithostratigraphic units; (2) continental, shallow marine, and deeper marine paleoenvironments and the location of active magmatic arcs through time; (3) progressive structural and tectonic development; (4) relative motions of adjacent plates affecting the Andes; and (5) paleolatitude. Phases and causes of geologic development are summarized from the maps and other information. Depositional systems are related to tectonic evolution, with implications drawn for hydrocarbon systems and history. It is shown that tectonic, depositional, and hydrocarbon histories are closely interrelated, having occurred in fairly discrete pulses through time, each with its own significance to hydrocarbon potential.

Resumen

Se presentan mapas paleogeográficos palinspásticos de Suramérica septentrional y occidental, de todo el “Sistema Andino” de 8500 km de largo desde Trinidad hasta el Cabo de Horn, para 9 intervalos de tiempo del Mesozoico–Cenozoico. Las mapas muestran: la distribución de las unidades litostatigráficas formacionales; paleoambientes continentales, marinos someros, y marinos mas profundos y la ubicación de los arcos magmáticos a través del tiempo; el desarrollo progresivo estructural y tectónico; los movimientos relativos de las placas adyacentes afectando los Andes; y las paleolatitude. Se resumen las fases y las causas del desarrollo geológico a través de los mapas y de otra información. Se relacionan los sistemas deposicionales a la evolución tectónica, y sus implicaciones para los sistemas y la historia hidrocarburífera. Las historias tectónicas, deposicionales, y hidrocarburíferas están íntimamente relacionadas, habiendo ocurrido en pulsos bastante discretos a través del tiempo, cada uno con su propio significado para el potencial hidrocarburífero.

INTRODUCTION

During the period 1988–1992, we conducted an extensive and comprehensive analysis of the Andean system of western and northern South America (Pindell et al., 1992) to refine the paleogeographic evolution, to define the main tectonic and sedimentary relationships controlling basin development, and to assess the hydrocarbon history and habitat along the chain. That study included the following elements: (1) up-to-date assessments of relative and absolute plate motions, (2) creation of an integrated paleogeographic database and plotting program with over 8400 lithochronologic control points compiled mainly from the public domain and our personal studies, (3) palinspastic reconstruction of Phanerozoic compressional and extensional bulk strain and block displacements along the chain, (4) documentation of regional and local Phanerozoic geologic histories and integration with modern concepts of geologic processes, (5) in-depth assessments of Neogene–Recent “Andean phase” strain and orogenic history, and (6) considerations of hydrocarbon history and habitat along strike. The present paper presents an abbreviated version of the aforementioned study’s Mesozoic–Cenozoic paleogeographic assessment, regional tectonic history, and aspects of basin development and hydrocarbon history.

Much of the length of the Andes has been the site of arc magmatism during Mesozoic and Cenozoic time. It is therefore useful to think of the Andes as an evolving arc system whose development was dominated by arc processes which were in turn controlled by the motion of South America relative to the mantle and the adjacent plates. We find that, in general, the concepts on arc behavior synthesized by Dewey (1980) describe quite
well the successive periods of historical development of the Andean chain. Dewey's arc models stress the significance of a kinematic framework defined by the position of the subducting slab in the mantle. The motion of the overriding plate (South America) relative to the slab helps to control many elements of the arc, such as the dip of the Benioff zone, topographic expression of the arc system, convergent or divergent tectonics within the arc, back-arc extension or foreland thrusting, chemistry and intensity of magmatism, erodability of the arc as a source of sediment, and sense of shear at trench-parallel faults within the arc. Synthesis of these types of geologic observations at arc segments over time can be used to infer past aspects of subduction and to iteratively deduce paleogeographic development. These in turn can be applied to understanding plate boundary history and basinial dynamics, with direct implications for hydrocarbon history and habitat. The synthesis presented here adheres to this philosophy. It is useful for understanding regional Andean evolution, arc behavior over time, and Andean basinial dynamics with implications for hydrocarbon systems.

2. The Amaime-Chuicha complex of the western flank of the central Cordillera of Colombia and northern Ecuador, Early Cretaceous accretion (Aspden and McCourt, 1986) or Late Cretaceous accretion, preferred here (see Pindell and Erikson, 1994) (Figures 5, 6)
3. The western Cordillera of Colombia, latest Cretaceous–early Paleogene accretion (Bourgeois et al., 1987; Daly, 1989; Pindell and Erikson, 1994) (Figure 6)
4. The Panamanian arc and basement (Choco terrane), Eocene–Recent accretion (Pindell and Dewey, 1982; Grosser, 1989; Pindell, 1993) (Figures 7–9)
5. The Pinón Formation and Costa Province, Late Cretaceous–early Paleogene accretion (Daly, 1989) (Figures 3, 6)
6. Manú arch, northern Ecuador (Daly, 1989) (Figure 5)
7. Rocos Verdes complex, southern Chile, Late Cretaceous back-arc closure and arc accretion (Dalziel, 1986) (Figures 2–5).

Prior to their respective times of accretion, these terranes were not a part of the autochthonous South American shield and are shown on the paleogeographic maps as arriving or developing at the various times due to relative plate motions.

To assess extension and shortening, we broke the Andes south of central Colombia into 23 segments along strike. We then assigned estimated azimuths and values of shortening or extension for each segment by tectonic event. Strain values were estimated for each segment working back in time so that values were compounded for each previous tectonic event. For example, values for the late Miocene–Recent shortening range from 20–35 km for segments in Ecuador and southern Patagonia to 250–300 km for segments in the central Andes. Older shortening were then added to these values for the appropriate times. Shortening was approximately removed on the maps by homogeneously stretching each segment in the direction opposite to shortening, as estimated by structure and plate motions, if known. Likewise, judging from red bed thicknesses and subsequent sedimentation rates due to thermal subsidence, Triassic–Jurassic extension of a few tens of kilometers is estimated for Ecuador to northern Argentina, ranging to about 100 km for both the central Colombian segment (eastern Cordilleran back-arc basin; Figures 2, 3) and the collective rifts of southern Patagonia (Figures 1–3). In these cases, extension was removed by closing individual rifts between transfer zones.

Margin-parallel and other strike-slip offsets must also be nested into the successive palinspastic restorations. For example, the pre-Neogene reconstruction of the numerous blocks between high-strain zones in the northern Andes (central Colombia to western Venezuela) is achieved by finite-difference solution (Dewey and Pindell, 1985, 1986). The maps restore 110 km of dextral shear and 25 km of shortening in the Merida Andes, 115 km of sinistral shear along the Santa Marta fault, 30 km

**PALEOGEOGRAPHIC MAPS**

The goal of creating paleogeographic maps (Figures 1–9) is to portray the relative positions of plates, paleosedimentation patterns and environments, structural and tectonic features, paleolatitude, and other information as it existed in the past. To improve the accuracy of spatial reconstruction through time, it is necessary to estimate and restore bulk strain by working backward in time so that the maps represent palinspastic reconstructions of geologic development. Creation of such maps involves a fairly straightforward process of integration (Ziegler et al., 1985; Pindell, 1985). Nevertheless, the methodology we used to estimate bulk strain in the palinspastic reconstructions deserves some explanation.

**Palinspastic Reconstruction**

Satisfactory assessment of former terrane accretion, back-arc and inter-arc extension, intra-arc and foreland shortening, and margin-parallel slip are the main elements of bulk palinspastic reconstruction of strain. For the Andes, our objective is to recreate the original geographic and geometric attributes of depocenters and structural provinces through time. This allows geologic processes and systems to be more readily inferred relative to inferences derived from the present-day deformed geologic record.

Accreted terranes and episodes of Mesozoic–Cenozoic accretion include the following:

1. The Caribbean nappes of northern South America, diachronous Maastrichtian–Miocene accretion (MacDonald et al., 1971; Tschanz et al., 1974; Stephan et al., 1980; Case et al., 1984; Aven Lallemand, 1990; Pindell and Barrett, 1990) (Figures 7–9)
of total shortening across Sierra Perijá, and 65 km of
dextral shear along the Oca fault, west of the Perijá
(Figure 9). Finite-difference solution with these values
yields a total shortening in the northernmost eastern
Cordillera of Colombia in excess of 150 km, with a net
direction toward the east-southeast.

In a system with as many diverse opinions on
evolution as the Andes, particularly in light of the
multiple deformation events, it is unrealistic to expect
different methods or biases of estimating strain to yield
bulk strain values through time that agree with high
precision. We can only strive at this point for internal
consistency in the methods applied, ensuring that the
values used are in line with most others offered. This
study has integrated numerous types of information in
the hopes of satisfying the majority of data. We are thus
confident that the successive palinspastic restorations
provide an autochthonous framework of features for the
past that is far closer to former reality than the present-
day geography of features and that allows a much more
accurate depiction of the original shapes and former rela-
tionships of basins and uplifts. Successive palinspastic
restorations can be seen on the maps by shifts in the
positions of the fault (present-day) and bolder (former)
geographic lines.

Construction of the Maps

Figures 1–9 are simplified reductions of more detailed
maps created in Mercator projection at 1:5,000,000. On
palinspastically restored base maps of western and
northern South America, these simplified maps show the
following features: (1) the migration of plates and
terranes that have affected the Andes, (2) paleosedi-
mation patterns by paleoenvironment and formation
name, (3) designation of main source rock and reservoir
rock intervals, (4) primary structural and tectonic
features, (5) the trace of arc magmatism, and (6) paleolati-
tude. Fault geographic lines (coast lines, political bound-
aries, and lakes) are present-day positions; bolder equiv-
alent are relative palaeopositions of the same. Depicted
paleoenvironments include continental, shallow marine
(less than ~200 m paleowater depth), deeper marine
(greater than ~200 m), and the axis of the magmatic arc,
which takes preference over other paleoenvironments
(e.g., the shallow marine Triassic Payande unit of Colom-
bia is covered by the arc pattern) (Figure 1).

The maps were created as follows. Phanerzoic time
(including the Paleozoic) was divided into 16 intervals
for which a general tectonic or depositional style
prevailed. The age of each map (in Ma) is shown in its
key and falls about midway within the time increment.
On geographic base maps, all of the lithostratigraphic
data in the databases (lithology, thickness, formation,
and contact relationships) within a given map's time
increment, both isotopic and stratigraphic, were plotted
in present-day coordinates. Next, structures with known
ages matching the various time increments were added
in present-day coordinates. At this point, the maps were
present-day plots of lithologic and paleostructural data
for each increment in time.

Next, the base map geographic features, the struc-
tures, and the lithologic data were palinspastically
restored as previously outlined. The differences in the
positions of the fault and bolder geographic lines allow
visual observation of the palinspastic differences for each
segment along strike. Structural lines crossing segment
boundaries with different shortening values were then
made continuous by smoothing any offset that might
have existed after restoration. Paleoenvironment bound-
aries were drawn separating regions of equivalent paleo-
environment, indicated by the patterns, as defined by the
raw lithostratigraphic data. Paleolatitudes (after Scotese
et al., 1987), key cross sections, notes on paleogeographic
development, tectonic processes, and sandstone prove-
ance were then added to complete the 1,500,000 scale
maps. The Mesozoic and Cenozoic intervals of these
maps were then reduced and simplified to create Figures
1–9 in this paper. Lithostratigraphic data, notes, and cross
sections were removed, and formation names of regional
extent were added, with notations for source and
reservoir units. Thus, the maps in Figures 1–9 are graphi-
cally as accurate as the larger versions but lack the
control points, lithologic designations, and interpreta-
tional detail.

Phases of Paleogeographic Evolution

Primary Andean developments, their causal mecha-
nisms, and their impact on Andean hydrocarbon systems
are summarized in Table 1 and are more fully outlined in
the following paragraphs.

Beginning in the Late Permian in the central Andes
and continuing along the entire Andes by the Triassic,
back-arc extension formed a series of restricted troughs
(extensional arc in the sense of Dewey, 1980) in which red
beds, arc volcanics, and marine strata accumulated
(Figure 1). Some of the marine units such as the Santiago
and Pucara arc, or were, oil-prone source rocks whose
deposition probably fits models of rifted basins with
marine access and restricted circulation. Other rift basins
farther south did not experience a marine transgression
and instead accumulated nonmarine organic-rich source
rock units such as the Los Molles Formation of the
Neuquén basin and, a little later, the Pozo D-129 unit of
the San Jorge basin (Figures 2, 3). In the north, westward-
propagating intracontinental rifting between Yucatan
and Venezuela heralded the Proto-Caribbean seaway,
which opened in a fan-like fashion (Figures 1, 2). In
Patagonia, a series of en echelon rifts developed along
preexisting structural trends associated with pre-
Mesozoic accretion of arc terranes (Figures 1–3). This
period of extension and breakup is directly tied to the
breakup of Pangea: Andean back-arc extension was
probably due to subduction zone rollback, with which the
South American craton did not keep pace (Dewey,
1980). All of the back-arc troughs along the Andes
became sites of thermal subsidence in the Middle
Jurassic–Early Cretaceous (Figure 2), depending on
location. Arc morphology was subdued, typically with
volcanic islands surrounded variably by marine
seaways.
<table>
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<tr>
<th>Andean Development</th>
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<tr>
<td>Triassic–Jurassic rift basins along arc axis and northern passive margin.</td>
<td>Subduction zone rollback, rifting from Yucatan during Panagean breakup.</td>
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<tr>
<td>Early Cretaceous expansion of epicontinental seas and area of sedimentation.</td>
<td>Thermal subsidence after rifting, rising long-term eustasy.</td>
<td>Transgressive reservoir sandstone deposition, carbonate deposition, locally reservoir.</td>
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<td>Albian onset of convergent tectonism and foredeep geometry in central Andes.</td>
<td>Aptian onset of north Africa–South America separation In equatorial Atlantic, initiate convergent arc.</td>
<td>Initial (Albian) source rock deposition, central Andean foreland, continue transgressive reservoirs.</td>
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<tr>
<td>Middle Cretaceous drowning of northern shelf platform, expansion and deepening of epicontinental seas elsewhere.</td>
<td>High long-term sea level, distant strand lines, starvations of clastic materials from depocenters.</td>
<td>Best regional source rock interval deposited regionally, in areas intersected by oxygen minimum zone.</td>
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<tr>
<td>Late Cretaceous arc collision and onset of east-dipping subduction in north and south. Begin foredeep geometry in Colombia/western Venezuela and southern Chile/Argentina, infilling of epicontinental seaways.</td>
<td>Westward drift of South America closed back-arcs, convergence continued by subduction at new Benioff zones. Late Cret lowering of long-term sea level.</td>
<td>End source rock deposition, begin progradational reservoir rock deposition as seas regressed. Possible local onset of maturation at thrust zones and sedimentary builds.</td>
</tr>
<tr>
<td>Paleogene removal of seas from much of craton, uplift and creation of continuous Andean barrier, begin large scale eastward shedding of detritus from Andes. Begin eastward migrating foredeep in Venezuela.</td>
<td>Incac uplift due to W acceleration of South America across mantle, rapid subduction rates. Onset of oblique Caribbean collision.</td>
<td>Deposition of important fluvial reservoirs in foreland areas (sub-Andes), major phase of maturation and eastward oil migration. Eastward migrating maturation mechanism in Venezuela.</td>
</tr>
<tr>
<td>Late middle Cenozoic waning of orogenesis and foreland development. Continue Caribbean foredeep migration.</td>
<td>Slowing of South America across the mantle and of subduction. Continue Caribbean–South America relative motion.</td>
<td>Filling of Incac structures by migration from Incac kitchens, deposition of additional fluvial reservoirs in foreland.</td>
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<tr>
<td>Late Cenozoic rejuvenation of orogenesis (Andean), rapid uplift, molassic deposition and foredeep development. Caribbean foredeep now in Maturin and Trinidad area.</td>
<td>Acceleration of South America across mantle and of subduction rate, and, in north, intensification of Panamanian collision. Progressive younging of crust entering Andes trench.</td>
<td>Second primary maturation phase in Andes, eastward migration of thrust front/foredeep axis and local eastward jumping of foreland deformation. Primary maturation phase in eastern Venezuela Basin.</td>
</tr>
</tbody>
</table>

For much of the Andes, epicontinental marine and nonmarine deposition east of the arc dominated the Early Cretaceous, indicating generally stable tectonic conditions typified by mainly thermal subsidence (Figure 3). However, extensional tectonism persisted along the Chilean portion of the back-arc, with the Rocos Verdes basin of southern Chile developing a basement of oceanic crust (De Wit, 1977). Such extension appears to have been continuous from the Jurassic, still related to rollback. In the north, southward transgression across the passive portion of the margin was underway. Probable southward-propagating opening of a back-arc basin along Colombia left the central Cordillera as a remnant arc passive margin after Triassic–Middle Jurassic.
plutonism had ceased (Figures 3, 4). The Andean arc, which was ensialic in the central Andes, probably trended offshore at Ecuador to connect with the Amaime-Chuucha arc terrane (Figures 3, 4). These continued north into the Greater Antilles arc and the North American arcs of Mexico and the Chortis block to the northwest (Pindell, 1993).

During the Aptian, this Aleutian-like intraoceanic arc apparently flipped polarity, with the associated creation of blueschists and other metamorphic rocks at the onset of west-dipping Aptian–Albian subduction along the eastern side of the arc. These metamorphic rocks are now found in ombducted masses all around the Caribbean and along the eastern limit of the Amaime terrane in Colombia. From the Albian, the arc migrated eastward toward the remnant Colombian and northern Ecuadorian margin and the Proto-Caribbean seaway to the north. Plutonism in this east-facing arc is well known in the Antilles. Likewise, the Buga batholith of the Amaime terrane (~99 Ma) (Aspden and McCourt, 1986) may represent Antilles equivalent arc magmatism during closure of the Colombian back-arc (Pindell, 1993; Pindell and Eriskson, in press).

By the end of Albian time (Figure 4), marine water depths in the north were sufficient for initiation of source rock deposition and preservation. South America was migrating toward the Amaime terrane. Peruvian orogenesis in the northern Central Andes had started, probably related to the same causal mechanisms that flipped the offshore arc to the north. Pindell (1993) suggested that this orogenesis was due to the early Aptian onset of the opening of the equatorial Atlantic (Pindell and Dewey, 1982; Pindell, 1985), which markedly accelerated South America westward across the mantle, thereby transforming the Central Andes into a convergent arc in the sense of Dewey (1980). Peruvian orogenesis lightly loaded the interior craton, creating additional accommodation space and water depths for marine units such as the Napo and Chonta formations. Evidence for compression is found along the entire length of the Andes and Amaime-Chuucha terrane, except perhaps in northern Argentina, although the intensity varies considerably. The back-arc of Chile, including the Rocas Verdes basin, began to close, and continental rift basins of central Argentina were influenced by compression and foredeep deposition (Dalziel and Forsythe, 1985; Hallam et al., 1986).

The middle Cretaceous (Figure 5) marked the maximum extent of the seas across the craton, especially in the north where Andean trends intersected the passive margin trends. There, thermal subsidence of numerous Jurassic intracratonic and back-arc rifts combined to produce a broad, slowly subsiding epicontinental platform. The strand line was so far inland that deposition did not keep pace with subsidence. Pelagic material accumulated at relatively high rates due to upwelling-enhanced productivity to produce world class source rocks (e.g., La Luna Formation). Preservation was maintained by the interaction with the shelf surface of the oxygen minima zone. In Ecuador and Peru, foredeep subsidence allowed accumulation and preservation of organic-rich shales (e.g., Napo and Chonta formations). Farther south, in Bolivia and Argentina, tectonism and associated lithospheric flexure were relatively less and shallow marine to nonmarine molasse mainly accumulated.

By the end of the Cretaceous (Figure 6), falling long-term sea level and infilling of epicontinental accommodation space heralded the removal of the seas from the craton, with generally regressive deposits marking the migrating marine margins. The Campanian (?) accretion of the Amaime-Chuucha terrane (Pindell and Eriskson, in press) loaded the central Cordillera and created the Umí-Colon basin to the east with asymmetric foredeep geometry. The deposits in this basin prograded northward toward the Proto-Caribbean seaway, leaving a paralic to nonmarine depocenter in the wake of the marine basin. After accretion of the Amaime, continued South American–Caribbean plate convergence in the northern Andes was accommodated by initiation of east-dipping subduction of Caribbean crust outboard of the terrane. Progressive accretion of offscraped upper Caribbean plate materials probably formed most of Colombia’s western Cordillera, west of the already accreted Amaime terrane. The eastward continuation of the Panamanian arc (Figure 6) defined the western and southern margins of the Caribbean plate from the Santonian or the Campanian (Pindell and Barrett, 1990). This arc probably first encountered the Andes within Ecuador because this was the boundary between voluminous and widespread plutonism and volcanism to the south (rapid subduction of normal Farallon plate) and limited and localized volcanism or plutonism to the north (slow, shallodipping? subduction of the 12-25-km-thick Caribbean plate).

Along the Andes, sands prograded into the foreland area from both the east and west. Throughout the central Andes, marine accumulations became restricted to only locally transgressive areas. Farther south, where Atlantic influences could be felt, marine conditions continued to prevail. A general decrease in Late Cretaceous subsidence rates within the sub-Andean foredeep basins could have been due to the waning of Peruvian compresional deformation.

In the early Paleogene (Figure 7), westward drift of South America caused the relative eastward advance of the Caribbean plate, which had a slight northward component of relative motion as well. The triple junction defined by the eastward continuation of the Panamanian arc and the Andean trench thus migrated slowly northward, leading to much faster subduction of Farallon crust along the Andes in its wake. In turn, the volume of arc magmatism appears to have increased northward, first in Ecuador and then into Colombia. By early-middle Eocene time, crustal elements and accreted material of the southeastern Caribbean plate (Caribbean nappes) began to load the western and Maracaibo portion of the northern margin’s shelf, creating a northward-deepening foredeep geometry (Trujillo and Misoa formations) that triggered oil maturation along the northern shelf of northwestern South America (Pindell, 1991).

(text continues on p. 124)
Figure 1—Triassic–Early Jurassic (about 190 Ma) paleogeographic map of the Andes. Scale is denoted by latitude and longitude ticks approximately 110 km apart.
Triassic - Early Jurassic
(190 Ma)
(Data for 245 - 188 Ma)

Palinspastic
Paleogeographic Map
Tabbutt & Pindell, 1994

- Deep Marine
- Shallow Marine
- Continental
- Magmatic Arc
- Source Unit
- Reservoir Unit

Figure 1 (continued)
Figure 2—Middle-Late Jurassic (about 145 Ma) paleogeographic map of the Andes.
Middle - Late Jurassic
(145 Ma)
(Data for 188 - 145 Ma)

Palinspastic
Paleogeographic Map
Tabbutt & Pindell, 1994

- Deep Marine
- Shallow Marine
- Continental
- Magmatic Arc
- Source Unit
- Reservoir Unit

Figure 2 (continued)
Figure 3—Neocomian (about 125 Ma) paleogeographic map of the Andes.
Neocomian
(~125 Ma)
(Data for 144 - 120 Ma)

Palinspastic
Paleogeographic Map
Tabbutt & Pindell, 1994

- Deep Marine
- Shallow Marine
- Continental
- Magmatic Arc
- Source Unit
- Reservoir Unit

Figure 3 (continued)
Aptian - Albian
(~105 Ma)
(Data for 119 - 97 Ma)

Palinspastic
Paleogeographic Map
Pindell & Tabbutt, 1994

Figure 4—Aptian–Albian (about 105 Ma) paleogeographic map of the Andes.
Figure 5—Cenomanian–Santonian (about 90 Ma) paleogeographic map of the Andes.
Figure 5 (continued)
Figure 6—Campanian–Maastrichtian (about 70 Ma) paleogeographic map of the Andes.
Figure 6 (continued)
Figure 7—Paleocene–Eocene (about 45 Ma) paleogeographic map of the Andes.
Figure 8—Oligocene–middle Miocene (about 25 Ma) paleogeographic map of the Andes.
Figure 8 (continued)
Figure 9—Late Miocene–Recent (about 10 Ma) paleogeographic map of the Andes.
Neogene
(~10 Ma)
(Data for 16.7 - 1.7 Ma)

Palinspastic
Paleogeographic Map
Tabbutt & Pindell, 1994

- Deep Marine
- Shallow Marine
- Continental
- Magmatic Arc
- Source Unit
- Reservoir Unit

Huachipampa
Pampean Ranges
Santa Cruz

Figure 9 (continued)
In the late Eocene–early Oligocene, between anomalies 13 and 18 (−33.38.5 Ma) (Cande and Kent, 1992), there was a marked (about twofold) westward acceleration of South America across the mantle (e.g., Müller et al., 1993). We suggest that this triggered the Incaic phase of Andean tectonism (intensification of the convergent arc) (Dewey, 1980), marked by eastward and westward thrusting at the Andean flanks along most of the length of the Andes. The chain was uplifted drastically at this time, with erosion and deposition of considerable volumes of offlapping erosional materials in both the back-arc and fore-arc regions. In the southern Andes, compression and uplift were not as severe and the eastward extent of eroded molasse was limited. The persistent epicontinental marine basins of southern Argentina maintained contact with the Atlantic Ocean throughout the Paleogene.

In the middle Tertiary (Figure 8), relative advance of the Caribbean plate continued and more buoyant parts of the Costa Rica–Panama arc began to collide, initiating Panama’s orocline geometry and eastward thrusting of Colombia’s Central Cordillera over the Guadalcanal foredeep basin. The Caribbean foredeep south of the Caribbean nappes was located in central Venezuela at this point (La Pascua and Robledo formations), with an east-west strike-slip regime developing between the two plates in the Falcon area north of Lake Maracaibo. A late Oligocene–early Miocene slowing of the rate of motion of South America relative to the mantle may have been responsible for the period of generally finer grained deposition (less convergent arc) in the Andean foreland basins, such as the middle Magdalena’s Mugrosa Formation in the north (Figures 8, 9). Although the intensity of shortening for this period based on individual accumulation rates seems less than for the Incaic phase, the Andes to the south continued to develop at this time into a continuous geographic barrier between marine systems of the fore-arc and the foreland. They provided a continuous source of molasse for the remainder of the Tertiary.

Finally, in the middle Miocene–Recent (Figure 9), increased “Andean” orogenic uplift and development of present-day relief (rejuvenation of convergent arc) appears to have been driven by several factors: (1) another, but less drastic, westward acceleration of South America across the mantle; (2) a progressive decrease in the age of crust entering the trench along the length of the Andes, causing resistance to subduction; and (3) rapidly increased rates of subduction of the Nazca plate in the Miocene, which increased volcanism along the chain and may have thermally softened the belt, making it more deformable (Pitman et al., 1992). Erosion of the chain has produced massive volumes of Miocene–Recent molassic detritus, creating thick foredeep sections that extend well to the east and across most of the western fore-arc basins.

Eastward advance of the thrust belt has cannibalized parts of the former (e.g., Incaic) foredeeps, thereby creating the sub-Andes fold and thrust belt. In the north, thrusting has jumped cratonward to the Eastern Cordillera and the Merida Andes of Colombia and Venezuela. The continued Panamanian collision has assisted with east-west convergence in this area, leading to more than 100 km of lateral tectonic escape by the roughly triangular Maracaibo block toward the free face of the Caribbean Sea. To the south, eastward migration of the thrust front generally cannibalized the earlier foredeep and pushed the evolving foredeep axis cratonward. Numerous inter-Andean basins began to develop, especially in Peru and Bolivia, where the width of deformation was the greatest, possibly assisted by late Paleozoic evaporitic décollement horizons. Segmentation of the subducting Pacific plate further influenced magmatism and deformation style along strike, with flat-slab, nonmaggmatic segments driving foreland deformation in the Pampean and other ranges (Figure 9).

**HYDROCARBON CONSIDERATIONS**

**Settings for Source Rock Accumulation and Preservation**

The paleogeographic maps (Figures 1–9) show that five main Mesozoic–Cenozoic settings exist for source rock deposition and preservation in the Andean system. These are indicated by formation names followed by a circled “s” symbol. The first setting is restricted rift basins with varying access to the sea during times of back-arc extension. Examples include the Pucara and Santiago formations, deposited in the Triassic–Jurassic back-arc basins of Peru and Ecuador (Figure 1). The second setting is thermally subsiding passive margin sections that developed during periods of slow sediment accumulation and high long-term relative sea level, where upwelling and the oxygen-minimum zone intersected the shelf. Examples are the middle Cretaceous La Luna, Quecreal, Gaurier, and Villeta formations in the north and the Lower Cretaceous Inoceramus Shale in the south (Figures 4, 5). The third setting, related to the second but noteworthy on its own, is the rift structures that cross southern South America, aulacogens of the South Atlantic (e.g., San Jorge basin; Figures 2, 3), in which nonmarine and marine source rocks were deposited early on.

The fourth setting is the tectonically downflexed foredeep basins that formed east of the developing Andes at times of high long-term eustatic sea level (during Peruvian orogeny), when the epicontinental strand line was far to the east. Examples are the middle Cretaceous Napo and Chonta formations of the north-central and central Andes (Figure 5). The thick Devonian–Carboniferous source-prone section of Bolivia and southern Peru was probably also deposited in this tectonic setting during the sinistrally transpressive accretion of the Arequipa massif (approximate location on Figure 1). The fifth setting is along the Andean fore-arc at various times in areas where terrigenous sedimentation was slow due to low Andean relief, vegetational retention, or dry climate (Ziegler et al., 1981) and where upwelling and other oceanographic factors presumably helped with bioproductivity and maintenance of suboxic bottom conditions. A possible example is the Upper Cretaceous Redondo Shale of the Talara basin of Peru.
As for the marine source rocks in all these settings, both eustasy and tectonism helped to control source rock deposition and preservation. Both combined to control accommodation space and water depth, while high eustatic sea levels maintained a distant strand line in some settings during middle Cretaceous time and limited the input of sand.

**Classes of Sandstone Reservoir Deposition**

Formations with known or potential reservoir potential are indicated in Figures 1–9 by a circled "r" symbol following the formation name. Although production is achieved from some carbonate units, such as the latest Cretaceous Yacoraite Formation of the northwestern Argentine basin (Figure 6) and the Cogollo Group limestones of the western Maracaibo basin (Figure 4), quartzose sandstones provide most of the Andean reservoirs. Sandstones came from four primary provenances throughout the Phanerozoic: metamorphic rocks of the Precambrian shield, reworked sedimentary rocks of the Andean thrust belt, masses of crystalline basement exposed in the thrust belt, and plutons and volcanoes of the magmatic arc. In the sub-Andean basins, the most important reservoir sandstones were derived from the metamorphosed, highly quartzose Precambrian shield areas to the east of the Andean belt. Formation of fault-controlled rift basins which then thermally subsided (Permian–early Mesozoic) was followed by flexural deflection of the crust due to shortening and loading of early Andean thrust belts and sedimentary rocks (late Mesozoic–early Cenozoic). These processes created a “downhill” condition from the shields to the back-arc and foredeep region (the present eastern Andes). This broad, gentle slope allowed westward-migrating fluvial sands to become clean, mature, and highly quartzose. Their point of final deposition and their westward extent was a function of the position of the strand line and paleoslope of the marginal seas. These were in turn dependent on eustatic sea level and the intensity of orogenetic development (downward foredeep flexure or thermal uplift and subsidence) at the time. Thus, fluvial to coastal to shallow marine blanket-like sandstone deposits are common along the western margins of the Precambrian shields and eastern flanks of flexural foredeep and thermally subsiding rift basin sections.

Easterly derived sandstone horizons generally coalesce with their vertical neighbors toward the east (i.e., shales pinch out to the east where basinal conditions were less developed). Likewise, shield-derived sandstones pinch out toward the west away from the fluvial and coastal input of the eastern source area. This creates an interlenging of sandstones (reservoirs) and shales (seals) that become sand-dominated to the east and shale-dominated to the west. In contrast, due to their general narrow and elongate character and the influence of more local faulting, the facies of the early Mesozoic rift basins tend to be less extensive and lithologic changes (pinching out of sandstones) are more abrupt than those of the foredeep basins.

The second source of sand was the uplifted and exposed thrust sheets in the deformation belts of the Cordillera. The likelihood of these sandstones functioning as reservoirs depends on two factors: (1) the lithology of the strata being eroded and (2) the extent of sorting that occurred during the transport of the detritus. If the thrust sheets that were eroded did not contain lithologies (e.g., quartz grains) conducive to maintaining porosity upon redeposition and lithification, reservoir potential will be low. Local variations in the exposure can be very important in reservoir development. Since much of the strata exposed in the Cordillera is either fine-grained (carbonates, shales, or siltstones) or poorly sorted sandstones, the ability of the depositional system to enhance the sands by sorting is critical. In general, those sediments that were deposited proximal to the thrust sheets tend to be poorly sorted and make poor reservoirs, while those more distal to the region of deformation may be mature enough to serve as reservoirs. Along the western side of the Andes, sandstone units within deltas that formed in the fore-arc region often function as reservoirs. These deltas were associated with fluvial systems that drained the arc system or the interior adjacent to the deformation front.

The source of the third sandstone class is again from the Andes, but specifically from metamorphic or plutonic basement core areas that do have a significant quartz component. The Santander and Garzon massifs of the mainly sedimentary eastern Cordillera of Colombia are examples (Figure 9). Although these areas are presently exposed, they have not always been so. Thus, their contribution of reservoir quality clastics is periodic, commonly contaminated by Andean volcanic and sedimentary sources. Additionally, massifs that are presently covered by sediments or volcanics may have been exposed and eroded during an earlier period. Uplift and exposure of the metamorphic terranes tend to coincide and persist after compressional deformation.

The final sandstone class is the volcanogenic sandstone from the Andean magmatic rocks. Although most of the plutonic rocks of the Andes are described in the literature as “granitoids” or “granitic,” these are often intermediate in silica content and only occasionally have high concentrations of free quartz that can produce good quality reservoir sandstones. Thus, “sand” eroded from magmatic areas of the Andes does not usually produce quality reservoir sandstones. There are hypothetical exceptions, such as from areas where plutons may be tonalitic (intermediate but with free quartz crystals). But tonalites are rarely distinguished in the literature from “granitoids,” which are typically dacitic or andesitic dominated by feldspars and pyroxenes that degrade into clays.

In the sub-Andean basins, there have been western and eastern sources of sands, with the latter usually producing the better quality reservoir sandstone (higher quartz content). The region of interlenging of western and eastern sources of sandstone has been an important zone throughout the history of the basins for hydrocarbon potential. Depending on the type of basin flanking the Andes at various times, however, a wide swath of basinal deposits (marine and lacustrine shales,
limestones, evaporites, cherts, and fine clastics) often intervened. These are the sediment sequences that tend to have source rock potential. Such was the case during at least two styles of tectonic history: back-arc rifting and subsequent thermal subsidence (Triassic–Early Cretaceous) and foredeep basin flexure due to eastward overthrusting from the west (middle Cretaceous–early Cenozoic). In most regions along the present eastern Andes, eastward-migrating thrusts carrying sediments originally deposited in the central basin have overridden or interthrust the quartz-rich easterly derived flanking sandstones, so that updip migration from beneath or within the thrusts has tended toward the quartz sandstones. Prior to the Cenozoic, westerly derived sandstones from the Andes interfingered with the basinal deposits and are in many places now metamorphosed and structurally interwoven with the intervening basinal sedimentary sections.

Locally during the Paleocene, and more commonly by the Eocene, eastward migration of clastic sediment from the developing Andes mountains drowned out the eastern source such that clastic migration was eastward away from the Andes, or at least to foreland fluvial trunk systems that ran parallel to the Andes. At least part of the cause of this drastic change was that late Eocene compression and orogenesis (Incaic phase), and hence erosion, were sufficiently intense that the shear volume of Andean clastics overwhelmed the component from the eastern source. The line between clastic realms simply shifted eastward to the point where there was essentially no topographic depression (foredeep) for easterly derived sands to fill. This occurred despite the fact that subsidence rates accelerated in most areas of the eastern foredeeps during this phase of Cenozoic deposition. This condition led to a geometry in which the basal surface of Cenozoic sandstones dips westward, while the Eocene–Recent geomorphic surface has dipped generally eastward. Thus, the latter Cenozoic "brown beds" form a thick cover above the Cretaceous section, thickening toward their westerly source area. These Cenozoic molassic beds are only locally important from a reservoir standpoint because their porosity is limited and they lack seals within them. Nevertheless, they are critical for hydrocarbon systems in that they have played a major role in driving Cenozoic maturation by burial. Accurate dating of these beds is critical for accurate prediction of hydrocarbon maturation in many of the basins.

**Regional Maturation Mechanisms**

Our assessment of Andean tectonics and sedimentation allows general statements to be made about the generation and accumulation of hydrocarbons. As previously outlined, the Andes have evolved in a series of tectonic pulses, mainly controlled by changes in plate motions, each of which has played some role in the overall hydrocarbon history. That source rock units as old as Ordovician and as young as Neogene have both become mature in the Neogene phase(s) of basin development attest to the significance of these pulses in relation to hydrocarbons. This is because the Cenozoic phases of orogenesis and associated basin subsidence (addition of overburden) have been extremely intense and rapid. In addition, subsequent events have affected slightly different areas of the original autochthonous depocenters, with relatively fresh source rock horizons quickly entering the oil maturation window during these successive periods of rapid tectonic and sedimentary loading.

Early Mesozoic rifts were sites of restricted environment source rock deposition. High heat flow associated with rifting may have driven early maturation in parts of these basins, perhaps into Early Cretaceous time, as indicated in Colombia's eastern Cordilleran back-arc basin by detrital asphalt pebbles in the Haueterivin section (Campbell and Burgl, 1965) (Figure 3). Starting first in the Peruvian and southern Ecuadorian region, middle Cretaceous onset of convergent arc behavior (late Albian, Peruvian orogeny) helped to create the first "foredeep" conditions, which were sites of additional source rock deposition (Napo and Chonta formations), due to tectonically and eustatically created accommodation space. These are correlative to the higher quality passive margin source rock units of Colombia, Venezuela, and Trinidad to the north.

Maturation of all these Cretaceous source rock units, as well as the remaining source potential of the Triassic–Jurassic units, would become a function of burial, hydrothermal effects, or structural thickening during the subsequent successive tectonic pulses. However, anomalous basement heat should be a factor in areas that have undergone Cenozoic rifting, volcanism, or ridge subduction. Examples of this type of area include the central Andean Altiplano (Figures 8, 9), the arc axis, various strike-slip basins of the fore-arc, the Nazca–Antarctica–South America triple junction in Chile (Figure 9), and western Colombia, where an extinct ridge system entered the trench from Oligocene to late Miocene time (Hardy, 1991) (Figure 9). In the sub-Andes basins, each successive advance of the thrust front and its associated molassic foredeep depocenter shifted the belt of hydrocarbon maturation correspondingly eastward.

In the north, foreland thrusting with development of foredeep depocenters occurred in the Campanian–Maastrichtian (Umir-Colon and Mito Juan formations), in the late Eocene–Oligocene Incaic phase (eastward thrusting and deposition of the Guanday Group and equivalents), and in the middle (?) Miocene–Recent Andean phase (Neogene molasse units, uplift of eastern Cordillera). The first phase probably did not initiate oil generation, but the second and third phases certainly did. Incaic oil migration reached the Llanos basin, as the eastern Cordillera was not yet elevated. In the central Andes, the Peruvian phase may have triggered local maturation, but the Incaic and Neogene phases were stronger and fully capable of generating hydrocarbons. In the southern Andes, evidence for Cretaceous compressional deformation is meager, and Incaic deformation is relatively less than to the north, but Neogene phases were strong. At the extreme southern end of the chain, the Rocos Verdes marginal basin was closed during the middle Cretaceous and experienced moderate Incaic and Neogene phases of convergent deformation and orogenic sedimentation.
In addition to these primary phases of tectonism and associated pulses of maturation and migration, the original regional extent of source rock occurrence is another critical factor in assessing remaining potential. For much of the eastern and sub-Andes belts, the swath of source rocks was fairly narrow, located in back-arc areas due to rifting or Cretaceous tectonic loading. In contrast, toward the north in Colombia and western Venezuela, the Cretaceous source rock depocenter was far wider in the east-west dimension because of the more regional occurrence of Jurassic lithospheric rift basins that underwent thermal subsidence and marine transgression in the Cretaceous. With each successive phase of tectonism and foredeep deposition, more and more of the swath of source rocks was exhausted from west to east.

In the Cenozoic, the earlier Icaic phase probably triggered maturation of huge quantities of oil because few of the source rocks had been depleted by that time. Subsequent phases not only had less source rock area to mature but the quality of the remaining source rocks was poorer due to greater depositional proximity to the shield. Therefore, along much of the Andes, Neogene phases of tectonism have probably generated relatively lesser volumes of oil. However, in the north, the original source rock limit was sufficiently far east that the advent of Colombia’s eastern Cordillera thrust belt and foredeep basin occurred well within the limits of excellent source rocks. Hence, more Neogene oil was probably generated, although not necessarily trapped, in Colombia’s eastern Cordilleran foothills and the Llanos basin than in more southward segments of the sub-Andes belts. In addition, the intermontane Maracaibo basin of western Venezuela also underwent a major Neogene phase of generation due to the uplift of and sedimentation from the Merida Andes, Santander massif, and Sierra Perijá. With respect to oil generation, the Neogene of the northern area is more like the Eocene of more southward parts of the Andes.

Another factor to consider that applies mainly to the southern Andes (northwestern Argentine basin and southward; Figures 2, 3, 4) is that Jurassic–Cretaceous rifts, associated with both the opening of the Atlantic and back-arc extension, cross the continent westward to at least the sub-Andes belts (Figures 1–3). Early source rock deposits in these basins represent “paths of oil potential” extending eastward from under the Andes foothills and foredeeps. The western ends of these paths have entered maturation as they were progressively overthrust and buried by the Andes and foredeep sediments. These basins possess an important pulse of Neogene maturation that may be in addition to an Icaic pulse. In areas between these rift basins, source rocks are of poorer quality and Neogene oil generation is therefore limited.

The considerations just discussed suggest an episodicity of oil generation in the Andes that is directly tied to the episodicity of thrust belt development and foredeep deposition. This applies to both the sub-Andes basins and the western fore-arc margin because episodes of uplift will also drastically accelerate fore-arc sedimentation and burial maturation. This process is modified by climate to varying extents. For example, aridity greatly reduces the volume of clastic material derived from uplifted areas, particularly along parts of the western flank of the Andes (Ziegler et al., 1981), with a corresponding reduction in burial maturation in the adjacent basin. Despite such deviations, knowledge of the precise age of uplift and associated basin subsidence can be used to predict the onset of peak pulses of maturation. Migration routes and trapping can then be assessed by considering the paleogeography and structural configuration of the basin at the time. It should be noted, however, that successive orogenic episodes are likely to affect trapping potential and thermal conditions of structures developed during previous orogenic episodes. There is a tendency for old oil generated during earlier orogenic phases to be remigrated, lost from the system, or driven to gas during subsequent phases of tectonic development.

CONCLUSIONS

Our analysis shows that tectonic, depositional, and hydrocarbon histories are closely interrelated, having occurred in fairly discrete pulses through time, each with its own significance to hydrocarbon potential. Source rock units can be deposited during periods of rifting, passive margin sedimentation, and foredeep development during long-term sea level highstands, when the strand line is far from the depocenter, and along the forearc when clastic dilution is low and oceanic conditions are favorable. Quality reservoir units can be deposited, depending on reworking and transport history, during cratonic transgression and regression and when quartz-bearing blocks or strata in the Andes are eroded during uplift. Oil generation can be triggered by early rift-related heat flow, but more commonly by accumulation of sufficient overburden, either thrust wedges or orogenic erosional products. In the sub-Andes, successive eastward-advancing tectonic phases drove overburden development which, where sufficient, triggered associated phases of hydrocarbon generation. The newly created potential of each successive phase in a given area was dependent on the quality and distribution of source rocks there. Neogene phase(s) generated large volumes of oil from Mesozoic source rocks in the northern and southern Andes where the platformal and rift-bounded source rock units, respectively, extended well east of the Icaic (late Eocene–Oligocene) foredeep basins. The middle Paleozoic source rock units of the central sub-Andes were also affected by eastward-stopping phases. In all areas, preservation of older oil was reduced by Neogene destruction of preexisting (Icaic) structures, which in many cases were once filled.

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